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Application of RAMS and Life Cycle Cost Analysis on Maintenance: A Case of Railway Signaling Systems

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A Thesis in MSc. Railway Engineering (Traction and Train Control)

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

The undersigned have examined the thesis entitled '**Application of RAMS and Life Cycle Cost Analysis on Maintenance: A Case of Railway Signaling Systems**' presented by **Nyambu Said Rajab**, a candidate for the degree of **Master of Science** and hereby certify that it is worthy of acceptance.

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ABSTRACT

The railway signaling system's role is to control and regulate the movement of trains safely and efficiently while ensuring maximum utilization of the existing track. Maintenance of this system accounts for a big portion of the overall maintenance costs due to the frequent failures and the need to maintain a high level of dependability of the railway network. As a vital area of operation and maintenance, signaling system maintenance strategies need informed decision-making support since they affect both operation and financial performance of the railway operator.

This research studied an integrated RAMS and LCC analysis to optimize the maintenance of the signaling system. Equations were formulated for assigning costs to repair/restore asset failures, service loss, and life cycle cost during the operation and maintenance phase. Thereafter, a case study on the AALRT signaling system corrective maintenance was carried out.

The axle counter failures account for more than 80% of all signaling system failures. Preventive measures such as scheduled resets during out-of-service hours can be adopted to reduce the occurrence of failures during in-service hours. With 4.9% of the signaling failures causing traffic interruption, it is clear that the signaling system greatly contributes to SAF and therefore must be repaired or restored quickly to minimize the effect on the service. On corrective maintenance performance, repair time cost accounts for more than 50% of the corrective maintenance cost. A review of the corrective maintenance procedures is needed to minimize the time spent on maintenance as this greatly affects the costs and revenues of the operator. Modifying the maintenance cycle according to the MTBF can improve the reliability by processing maintenance work timely. Proposals have been made on methods for optimizing the maintenance of railway signaling systems for a reliable railway network.

Keywords: *Signaling system, failure, maintenance, RAMS, Life Cycle Cost, optimize.*

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ACRONYMS AND SYMBOLS

Term	Meaning
ATS	Automatic Train Supervision
CBA	Cost-Benefit Analysis
CM	Corrective Maintenance
ERTMS	European Railway Train Management System
ETB	Ethiopian Birr
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode, Effects and Criticality Analysis
FRACAS	Failure Reporting, Analysis and Corrective Action System
FTA	Fault Tree Analysis
IATP	Intermittent Automatic Train Protection
IM	Infrastructure Manager
LCC	Life Cycle Cost
MAMT	Mean Active Maintenance Time
MDT	Mean Down Time
MLT	Mean Logistic Time
MTBF	Mean Time Between Failure
MTBM	Mean Time Between Maintenance
MTTR	Mean Time to Restore
NPV	Net Present Value
O&M	Operation and Maintenance
PM	Preventive Maintenance
RAMS	Reliability, Availability, Maintainability and Safety
RBC	Radio Block Center
RBD	Reliability Block Diagram
RRT	Relative Restoration Time
RT	Restoration Time
SAF	Service Affecting Failure
TBF	Time Between Failure
TFF	Time to First Failure
TTM	Time to Maintain
TTR	Time to Restore

Term	**Meaning**
UT	Up Time
WO	Work Order
WT	Waiting Time
λ	Failure rate

CHAPTER 1 INTRODUCTION

This chapter describes the research area and states the problem statement, objective, scope and limitations of the research. It ends by outlining the structure of the thesis.

1.1 Background

Railway infrastructure is a complex system, which, once installed is very difficult and costly to modify. Thus, the performance of this system depends on the maintenance and renewal activities during its life cycle. The replacement and repair of components in this system is a continuous process that might generate huge expenses if not carefully performed. To guarantee optimal long-term results, the effects of maintenance decisions must be evaluated. The goal of the Infrastructure Manager (IM) is to optimize the maintenance budget, increase the reliability and maintainability of the system and keep predefined safety levels. The fact that railway infrastructure has a long technical lifetime and is subject to different types of failures calls for the need for a clear maintenance plan in order to control unexpected expenses [1].

Performance requirements set by government and railway operators include among others, passenger and freight traffic increase at minimal operation cost, reduced travel time, reduced life cycle cost, and safety level improvement. These requirements put strong demands on operation and maintenance optimization on railways. IMs aim to keep railway network highly available for a high quality of service to end users [1].

Reliability, Availability, Maintainability and Safety (RAMS) and Life Cycle Cost (LCC) analyses are tools used to optimize the performance of the railway network and make it economically viable. RAMS analysis is used to evaluate system performance subject to failure and maintenance by analyzing historical corrective maintenance (CM) and preventive maintenance (PM) data obtained from work orders and maintenance tasks. On the other hand, LCC analysis is an economic technique used to assess the most cost-effective option among competing alternatives considering investment, operation and maintenance, and unplanned interruptions throughout the assets’ life cycle [2].

The managers responsible for determining maintenance actions face an abundance of condition data and have a complicated task of transforming the data into information that will support maintenance actions [3]. During the operation and maintenance of the railway infrastructure, data on failures, maintenance reports, work orders performed, etc., are collected and managed. IMs need maintenance analysis and planning tools that enable them to systematically analyze and optimize budget needs, minimize the total costs for the required RAMS level, and guarantee the quality of the railway assets in the long run [4].

The railway system can be divided into four subsystems: the track structure, rolling stock, traction power supply, and signaling subsystems. Various components of the signaling system work together to control, supervise and ensure safe and efficient use of the railway network. Train detection equipment (track circuits and axle counters) are used to locate the position of the train on the track, and, together with colored signals control the traffic on the railway line to avoid collision. Balises are used to transmit electronic messages from the track to the train; this information is also used by the operation control center to control the movement of trains. Advanced systems such as the European Rail Traffic Management System (ERTMS) or Automatic Train Control system (ATC) are used to control and supervise the railway network by interpreting the inputs from other signaling subsystems and creating restrictions on the train route to ensure safe operation.

Systems such as axle counters, signals, and level crossings provide input to interlocking system and radio block center (RBC). The interlocking system receives information, processes it and updates restrictions on system components. For example, they can provide information to onboard signaling systems through the GSM-R system, by means of the base transceiver stations (BTS) located along the track. The onboard signaling system is composed of a centralized computer that processes the different inputs, giving supervision during the train’s operation. An odometry system takes input from tachometers and a speed radar located underneath the train and constantly measures the speed and acceleration of the train. The balise antenna, located underneath the train, picks information from the balises placed on the track. The driver-machine interface (DMI) allows the train driver to interact with the onboard computer.

The railway signaling system is used to control and regulate the movement of trains safely and efficiently while ensuring maximum utilization of the track. Since it ensures safe operation, its reliability, availability, and maintainability directly affect the capacity and availability of the railway network in terms of both infrastructure and rolling stock [5]. The maintenance of railway signaling systems accounts for a big portion of the overall maintenance costs due to the frequent failures and the need to maintain a high level of dependability of the railway network [5]. LCC analysis, an engineering economics technique, can be employed to achieve maintenance strategies that minimize the life cycle cost while meeting dependability requirements.

The complexity of the railway signaling system calls for the need to find ways to optimize their maintenance and operation while ensuring safety. Improving the dependability of railway signaling systems will have benefits for the whole railway [5]. Various researchers have sought to optimize the maintenance of railway signaling systems: dependability and maintenance analysis [5]; RAMS and LCC analysis [1], [6]; RAMS-based evaluation of signaling systems [7]; maintainability analysis [8]; maintenance optimization [9].

1.2 Problem Statement

Signaling systems ensure safe operation of the railway network, hence, their reliability, availability, and maintainability directly affect the capacity and availability of the railway network [5]. In railway infrastructure, costs are subject to numerous uncertainties associated with the operation and maintenance phase. The performance of this infrastructure depends on the maintenance and renewal of components, which is a continuous process that might generate huge expenses if not carefully performed. To guarantee optimal long-term results, the effects of maintenance decisions must, therefore, be evaluated.

The signaling system can be considered as the backbone of the railway network. Its reliability and availability have a direct influence on the quality of service provided by the railway operator. Over the years, increasing demands from governments and railway operators make the performance of the signaling system an important issue. Reliability requirements, budget limits, and operational conditions, such as the time available for maintenance, are becoming increasingly strict. As a vital area of operation and maintenance, signaling system maintenance strategies need informed decision-making support since they affect both operation and financial performance of the railway operator.

Informed decision-making results in an optimized maintenance strategy with enhanced reliability, maintainability and safety, and an optimized total cost of ownership.

Informed maintenance decisions can only be arrived at when the costs and performance of alternative decisions are considered on a life-cycle basis, including the corresponding availability and reliability, since the signaling system performance influences the costs and revenues of the operations. Long-term, reliable estimates of the costs associated with maintenance activities make the approach of life-cycle costing considering the stochastic nature of failure using RAMS analysis a necessity.

A lot of research has been conducted on RAMS and LCC separately on railway infrastructure. Most of the research has focused on the track, with little focus being put on the signaling system. Recently, an approach combining both RAMS and LCC analyses has attracted attention in the railway sector, but still, specific focus on the signaling system is lacking.

1.3 Objectives

The purpose of this research is to explore the areas that can optimize the maintenance of railway signaling systems during the operation and maintenance life cycle phase, by combining both RAMS and LCC analyses.

The main objective of this research is to study the RAMS and LCC performance of signaling systems subject to failure and maintenance. The specific objectives are:

i. Identify the critical factors affecting the RAMS of signaling systems.
ii. Explore RAMS and LCC methodologies for railway signaling systems and identify the factors influencing them.
iii. Perform RAMS and LCC analysis related to failure and maintenance activities.
iv. Propose methods to optimize the maintenance of railway signaling systems.

1.4 Scope

This research explores the areas that can optimize the maintenance of railway signaling systems to give the required RAMS level at an optimum maintenance cost. The analysis used the case of Addis Ababa Light Rail Transit signaling system. This research focuses on:

- The trackside signaling equipment on both East-West and North-South lines.
- Corrective maintenance performance only, using data recorded in the maintenance records.

1.5 Structure of the Thesis

The thesis consists of five chapters as briefly explained below:

Chapter 1, *Introduction*, introduces the research area, the problem statement, the objectives of the thesis, and the scope and limitations of the research.

Chapter 2, *RAMS and LCC on Maintenance*, provides the theoretical framework used in the research and gives a summary of the various works related to this research.

Chapter 3, *RAMS and LCC Analysis of the AALRT Signaling System*, describes how the research was performed, giving reasons for the different methods chosen.

Chapter 4, *Results and Discussion*, summarizes the results of the research.

Chapter 5, *Conclusions and Recommendations*, summarizes the conclusions extracted from the results, recommends best maintenance practice and suggests further work.

CHAPTER 2 RAMS AND LCC ON MAINTENANCE

This chapter summarizes the theory driving the research. It defines the concepts of maintenance, RAMS, and LCC and links them to the operation and maintenance of railway signaling systems. A brief summary is given for the case study of the Addis Ababa Light Rail Transit system used in the thesis. Also introduced is the concept of system of systems, which is then linked to railway signaling systems. The chapter concludes with a review of previous works related to this research topic.

The system life cycle is a sequence of phases, each containing tasks, covering the life of a system from initial concept through to decommissioning and disposal (see Figure 1). This life cycle has a V-shaped representation with the top-down branch (left side) representing the system development ending with manufacturing of the system components, and the bottom-up (right side) representing the assembly, installation, receipt and the operation of the system. The figure also describes the various RAMS activities carried out at each phase of the system life cycle [10]. This research focuses on the operation and maintenance phase of the system where RAMS is optimized by analysis of real-life failure data.

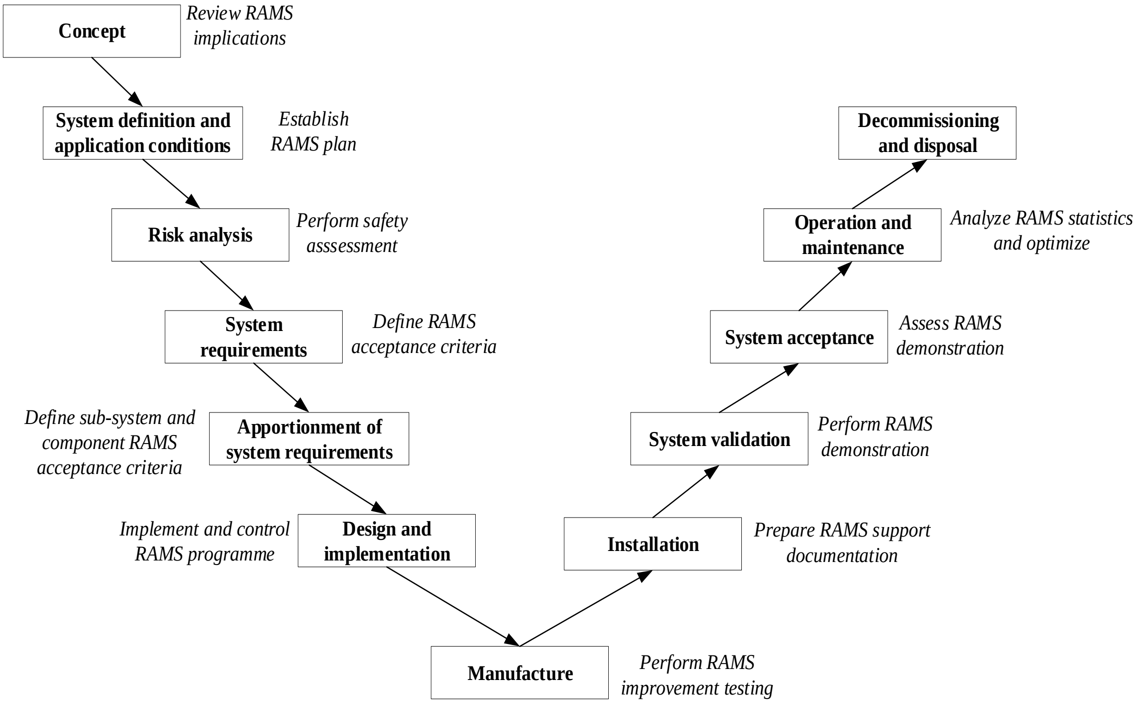

Figure 1: V-representation of the system life cycle [10]

2.1 Operation and Maintenance

The objective of this life cycle phase is to operate, maintain and support the total combination of components and subsystems such that the compliance with system RAMS requirements is maintained. The deliverables of this phase include updated system and support documentation, plans and records suitable to trace the RAMS tasks undertaken within this phase, reports of RAMS analyses and evaluations, etc. [10].

Maintenance is defined as the combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function [11]. Maintenance can be of corrective or preventive type. In corrective maintenance, the maintenance is carried out after fault recognition and is intended to put an item into a state in which it can perform the required function. In preventive maintenance, the maintenance is carried out at predetermined intervals or according to prescribed criteria and is intended to reduce the probability of failure or the degradation of the functioning of an item [11]. The different maintenance approaches are illustrated in Figure 2.

To create dependable systems, factors which could influence the RAMS of the system need to be identified, their effect assessed and the cause of these effects managed throughout the life cycle of the system by the application of appropriate controls to optimize system performance [10].

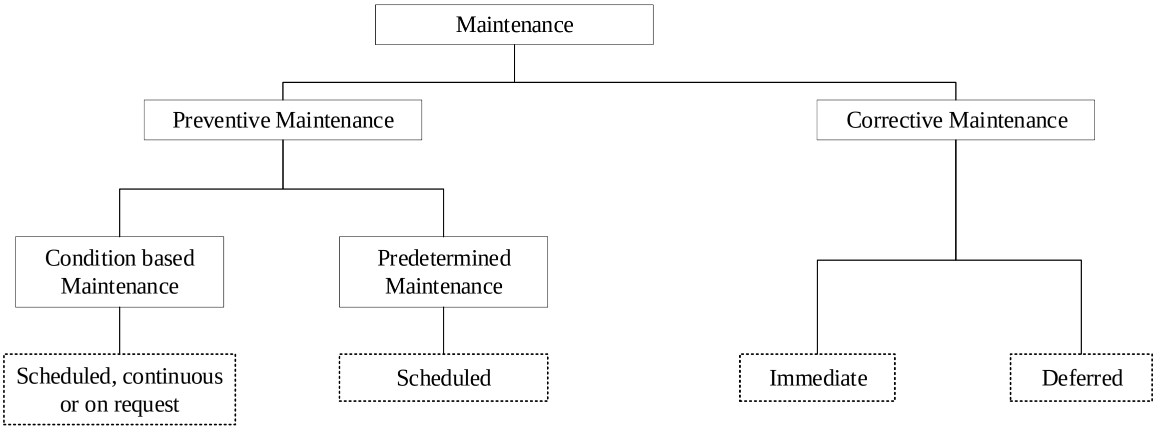

Figure 2: Maintenance approaches [11]

2.2 RAMS in Railway

The standard BS EN 50126-1 defines RAMS as:

- ***Reliability*** is the probability that an item can perform a required function under given conditions for a given time interval [10].
- ***Availability*** is the ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided [10].
- ***Maintainability*** is the probability that a given active maintenance action, for an item under given conditions of use, can be carried out within a stated time interval when the maintenance is performed under stated conditions and using stated procedures and resources [12].
- ***Safety*** is the freedom from unacceptable risk of harm [12].

RAMS analysis is a proof of quality of a system[1] and is guided by a number of standards such as BS EN 50126-1 [10], IEC 62278 [13] and MIL-HDBK 217F [14]. RAMS can be considered as a characteristic of a system and it acts as a performance indicator for its quality and performance. RAMS analysis entails the study of the failure, maintenance, and availability of a system so as to predict its expected failure rate (λ), Mean Time Between Failures (MTBF), Mean Time to Restore (MTTR), etc. at any life cycle phase of the system. These parameters can then be used to estimate the life cycle costs associated with delays, service suspension and maintenance actions.

As shown in Figure 3, the RAMS performance of a railway system is influenced in three ways, that can interact: by sources of failure introduced internally within the system at any phase of the system life cycle (system conditions), by sources of failure imposed on the system during operation (operating conditions) and by sources of failure imposed on the system during maintenance activities (maintenance conditions) [10].

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[1] The word *system* can also denote a product or equipment.

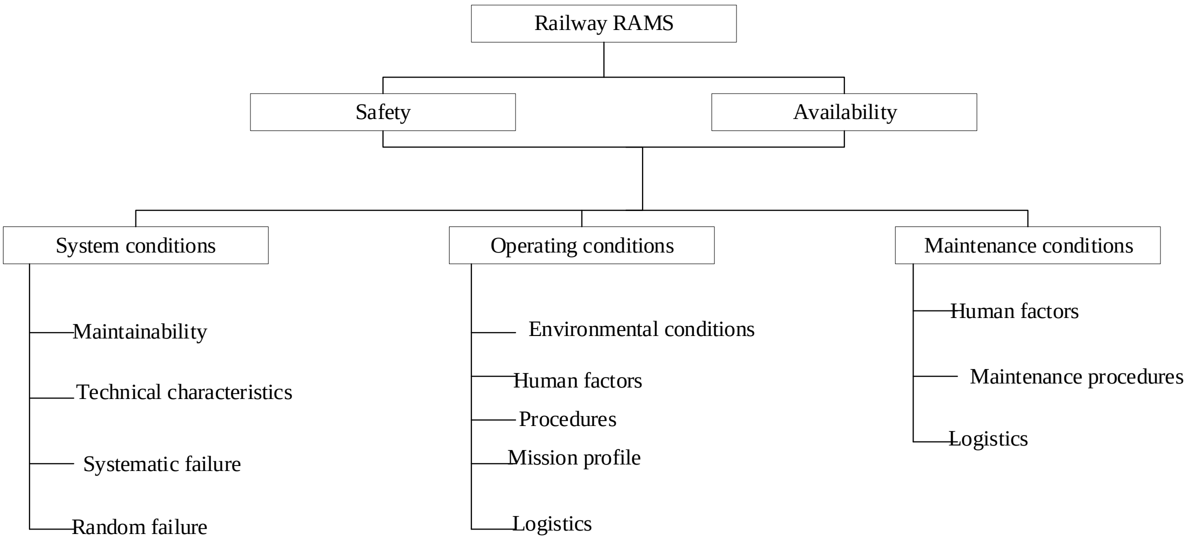

Figure 3: Factors influencing railway RAMS (adapted from [10])

For the railway signaling system, the system conditions include maintainability, redundancy level, external disturbances, internal disturbances (errors in requirements, design inadequacies, manufacturing deficiencies, inherent weaknesses, software errors), etc. The operating conditions include environment (temperature, humidity), human errors, human corrective actions, aging, train density, etc. The maintenance conditions include maintenance policy/procedure, corrective action taken, skills of maintenance personnel, spare parts availability, lubrication (change in friction coefficient), renewal of system components (interval of renewal), corrective replacement of system components (failure rate of components, deferred maintenance time), logistics, etc.

A failure is the termination of the ability of an item to perform a required function [11]. Failures in a system can be categorized as systematic failures or random failures. Systematic failures are due to errors in the system life cycle activities which cause the system to fail deterministically under particular conditions of inputs or under particular environmental conditions [10], e.g. errors in requirements, design and realization inadequacies, manufacturing deficiencies, inherent weaknesses, software errors, and operating instruction deficiencies [15]. Random failures are due to causes which can be described by statistical distributions such as the operating mode, the environment, stress degradation and wear out [10]. From the effect of failure in the railway operation, failures of railway signaling systems can be classified into [10]:

i. Significant (immobilizing failure): a failure which prevents train movement or causes a delay to service greater than a specified time and/or generates a cost greater than a specified level.

ii. Major (service failure): a failure which prevents the system from achieving its specified performance but whose cost or delay effect is below the minimum threshold specified for a significant failure.

iii. Minor failure: a failure that does not prevent the system from achieving its specified performance.

2.2.1 The Means to Achieve Railway RAMS Requirements

RAMS is a measure of the technical performance of a system. Poor RAMS performance will result in unnecessarily high LCC due to excessive operation and maintenance costs. On the other hand, very high RAMS performance can lead to high design cost if it is not optimally determined.

The means of achieving the RAMS requirements relate to controlling the factors which influence RAMS throughout the system life cycle and are based on the concept of taking precautions to minimize the possibility of an impairment occurring as a result of an error during the life cycle phases [13]. Precaution can be prevention (concerned with lowering the probability of the impairment) or protection (concerned with lowering the severity of the consequences of the impairment) [13].

In the case of the railway signaling system, the targets of optimization include maintenance procedures, maintenance strategies, and technical and operational performance of the components. The optimization can be realized through a combined RAMS and LCC analysis. The RAMS analysis aims to predict the system reliability by failure rate analysis and the serviceability and availability by maintainability analysis, while LCC aims to realize the most cost-effective alternative to achieve the required RAMS target. The RAMS characteristics determine essential parameters of the system such as the usability and acceptability of the system, the operation and maintenance costs, and the users' safety and health risk when operating the system.

a. Reliability

The commonly used parameters for reliability are failure rate (λ), MTBF, MTFF, number of failures in the system per month or per year, and number of train-delaying failures. The failure rate is the probability of failure per unit of time of items in operation. It is sometimes estimated as the ratio of the number of failures to the accumulated operating time for the items. The reliability of the railway signaling system can be measured in terms of train delay hours, total train delays, and punctuality of passenger or freight train. The train delay should be clearly defined, say, a train being late by 5 minutes. A delay that directly affects the train is a primary delay, while a delay caused by a primary delayed train is a secondary delay. Reliability analysis answers the question: what kind of failures and how often do they occur? – knowledge of the system to be analyzed regarding failure rate and the impact on operation and lifetime of a system/component.

b. Availability

In simple terms, availability is a percentage value of the amount of time the system is delivering services divided by the amount of time it is expected to deliver services. The time the system is not delivering services is known as downtime. Availability is normally expressed as the percentage of the time the system is fully operational. Many circles use the term “five nines” to discuss availability. Five nines refer to the percentage 99.999%, which is a generalized commitment on availability and has been viewed as the desired goal by equipment manufacturers or system operators, at least at the core level. There are 525,600 minutes in a year and multiplied by 0.99999 is equal to 525594.744 minutes of uptime and downtime of 5.256 minutes per year. Table 1 explains the connection between percentage and minutes of downtime per year.

Table 1: Availability percentage and downtime

Availability	Downtime per year
99.999%	5 min 15 s
99.99%	52 min 36 s
99.9%	8 h 46 min
99%	3 days 15 h 40 min

The availability of an item depends on the reliability, recoverability, and maintainability of the item, and the maintenance support performance [16], [17]. Maintenance support performance (or maintenance supportability) is the ability of a maintenance organization to have the correct maintenance support (provision of resources to maintain an item) at the necessary place to perform the required maintenance activity at a given instant of time or during a given interval [11], [17]. A reliable system requires less maintenance and good maintainability shortens the repair time. There are different ways to determine a system's availability such as inherent availability, achieved availability and operational availability [16].

Inherent availability only takes corrective maintenance into account. It is based on an ideal support environment, which assumes that tools, spare parts, and personnel are readily available [16].

$$Inherent\ Availability, A_i = \frac{MTBF}{MTBF + MTTR} \tag{1}$$

Achieved availability is based on the fact that a system needs maintenance and considers preventive and corrective maintenance. It is based on an ideal support environment but with consideration of preventive maintenance [16].

$$Achieved\ Availability, A_a = \frac{MTBM}{MTBM + MAMT} \tag{2}$$

Operational availability is the availability in an actual operational environment and it includes preventive and corrective maintenance, logistics delay time and administrative delay time [16].

$$Operational\ Availability, A_o = \frac{MTBF}{MTBF + MTTR} = \frac{MTBM}{MTBM + MDT} \tag{3}$$

where MDT includes preventive and corrective maintenance, logistics delay time and administrative delay time.

The availability of the railway signaling system can be measured in terms of trip achievement levels, i.e., actual trips achieved against planned trips by taking into account the trip cancelations due to signaling system failures. Availability analysis answers the question: to what extent is the system available for operation or use? It helps to guarantee the availability of the system without traffic interruptions, i.e. the maintenance activities are carried out after normal service time.

c. Maintainability

Maintainability is a function of the design of the system, the availability of skilled personnel, the maintenance procedures, the availability of test equipment, and the environment in which the maintenance must be performed. Parameters for maintainability are MTTR, Mean Time Between Maintenance (MTBM), Mean Maintenance Hours (MMH), MDT, etc. Maintainability aims to answer the question: how good or bad is the maintenance? This helps to identify an approach for an optimal maintenance strategy.

2.3 Methods and Tools for RAMS Analysis

Various tools and methods are used for RAMS analysis. Some of these tools and methods are briefly described as follows.

2.3.1 Failure Mode and Effects Analysis (FMEA) (IEC 60812 [18])

FMEA analyzes an item to identify all possible failure modes, their likelihood of occurrence, and their effects on the performance of the item and of the system that embeds it. Each component of the system is analyzed in turn to give a set of failure modes for the component, their causes, and effects on the component and on the system level, procedures for failure detection and recommendations. Risk assessment is derived from looking at each individual component (bottom-up approach). Prioritizing the failure modes in terms of criticality (FMECA) helps to develop priorities for continuous improvement. Prior to the completion of FMECA, functional analysis is necessary for understanding the function of each subsystem and the functional failure modes of each subsystem, and determine the criticality of failures that result in, or contribute to, major accidents and/or service disruptions.

In conducting the FMEA study, the following information is documented:

- ✓ *Failure Mode Code*: An acronym and serial number identification.
- ✓ *Description*: Explanation of the failure mode, which describes how the system/subsystem or equipment may fail.
- ✓ *Effects on the Service Availability*: Refers to the Key Performance Indicators affected.
- ✓ *Effects on Operation*: Consequences of this Failure Mode on the system operation.
- ✓ *Failure Rate*: Frequency of occurrence of this Failure Mode, expressed as the inverse of the Mean Time Between Failure (MTBF).
- ✓ *Restoration Rate*: Inverse of the Mean Time to Restore (MTTR).

2.3.2 **Fault Tree Analysis (FTA)** (IEC 61025 [18])

FTA focuses on system failure and is used to analyze events, or combinations of events, that lead to a hazard or serious consequence on the main system and to perform the probability calculation of the top event. A fault tree displays the various combinations of component failures and human errors that can result in the main system failure. Risk assessment is derived by first identifying the failures (top-down approach).

The analysis starts with the event which is the immediate cause of a hazard or serious consequence (“top event”) and proceeds in several steps through the use of logical operators (AND, OR, etc.). Intermediate causes are analyzed in the same way, down to the bottom (basic) events where the analysis stops. FTA is a graphical method with a set of standardized symbols used to draw the fault tree. A complete fault tree represents the logical function linking the basic events (components failures) to the top event (system failure).

2.3.3 **Reliability Block Diagram (RBD)** (IEC 61078 [19])

RBD focuses on system success and shows the logical connection of components needed for the successful operation of a system. It is used to model the set of events that must take place and the conditions to be met for the successful operation of the system.

The target of the analysis is represented as a success path consisting of blocks, lines and logical junctions. A success path starts from one side of the diagram and continues via the blocks and junctions to the other side of the diagram. A block represents a condition or an event, and the path can pass it if the condition is true or the event has taken place. If the path comes to a junction, it continues if the logic of the junction is fulfilled. If it reaches a vertex, it may continue along all outgoing lines. If there exists at least one success path through the diagram, the target of the analysis is operating correctly. Mathematically, an RBD is similar to a fault tree; it represents the logical function linking the states of the individual components (failed or working) to the state of the whole system (failed or working). Therefore, the calculation is similar to that of fault trees.

In RBD, units (components or subsystems) are logically linked in series, parallel, or combination of both series and parallel. When units are linked in series, the failure of any unit results in system failure, and the reliability of a series-configured system is the product of individual reliabilities, represented by

$$R = \prod_{i=1}^{n} R_i \tag{4}$$

where n is the total number of units in the system, R_i is the individual reliability values.

Units linked in parallel allow for redundancy, and the system remains operational even if only one unit is operational. The reliability of a pure parallel system can be calculated from individual unreliability as:

$$R = 1 - \prod_{i=1}^{n} F_i \tag{5}$$

where n is the total number of units in the system and F_i represents the individual unreliability of each unit defined as $1 - R_i$.

2.3.4 **Markov analysis** (IEC 61165 [20])

Markov analysis is a state-space analysis technique particularly useful for analyzing redundant systems, as well as systems where the occurrence of system failure depends on the sequence of occurrence of individual component failures. It is also suited for analyzing systems with complex operation and maintenance strategies such as cold standby components, prioritized repair actions, and limited resources for corrective maintenance activities. Markov analysis assumes constant probabilities (or rates) for all occurrences (failures and repairs), and that events are statistically independent.

2.3.5 **Petri Nets** (IEC 62551 [21])

A Petri net is a graphical and mathematical tool for describing relations existing between conditions and events. It describes the global behavior of a system by modeling local states, local events, and their relations to each other. It focuses on modeling the states of components that comprise the system so that the state of the system can be inferred from the states of its components.

2.3.6 **Hazard and Operability (HAZOP) analysis** (IEC 61882 [22])

HAZOP studies deal with the identification of potential deviations from the design intent, examination of their possible causes and assessment of their consequences.

2.4 Probability and Life Distributions for Reliability Analysis

Over the years, various probability distributions of continuous random variables have been developed. Each distribution is characterized by four descriptors of longevity as described below [23].

Failure Probability Density Function (pdf): In reliability analysis, the random variable *t* means time to failure, T is a random variable denoting the failure time and $f(t)$ is the failure probability density function of the random variable, i.e. the probability of failure prior to time *t*. The failure pdf is the failure probability of a period of time from *t* to $t+\Delta t$.

$$f(t) = Pr\{t \leq T \leq t + \Delta t\} \tag{6}$$

Reliability function: The reliability function *R(t)* is the probability of the component not failing prior to time *t*.

$$R(t) = Pr\{T > t\} = \int_{t}^{\infty} f(x)dx \tag{7}$$

Failure Cumulative Distribution Function (cdf): It is the probability that the component may fail within time *t*. It is also known as the unreliability function or failure probability function.

$$F(t) = 1 - R(t) = Pr\{T \leq t\} \tag{8}$$

Failure (or hazard) rate: Is the rate of possible failures for the survivors to time *t*.

$$h(t) = \frac{f(t)}{1 - F(t)} = \frac{f(t)}{R(t)} \tag{9}$$

Some of the distributions useful for performing reliability and maintenance analysis-related studies are briefly described in Table 2.

Table 2: Probability Distributions for Reliability Analysis

Distribution	**Description**	**Functions**
Exponential distribution	Is the only distribution with constant hazard rate, hence exhibits memory-less property (i.e., the probability of failure in a specific time interval is the same regardless of the starting point of that time interval).	Pdf: $f(t) = \lambda e^{-\lambda t}$ Cdf: $F(t) = 1 - e^{-\lambda t}$ $R(t) = 1 - F(t) = e^{-\lambda t}$ Hazard (failure) function: λ
Normal distribution	Can be used to represent the wear-out region of bath-tub curve where fatigue and aging can be modeled. It is also used in stress-strength interference models in reliability studies.	Pdf: $f(t) = \frac{e^{-\frac{(t-\mu)^2}{2\sigma^2}}}{\sigma\sqrt{2\pi}}$ $R(t) = \int_{t}^{\infty} \frac{e^{-\frac{(t-\mu)^2}{2\sigma^2}}}{\sigma\sqrt{2\pi}} dt$ $F(t) = \int_{-\infty}^{t} \frac{e^{-\frac{(t-\mu)^2}{2\sigma^2}}}{\sigma\sqrt{2\pi}} dt$

Distribution	**Description**	**Functions**
Lognormal distribution	Is characterized by location parameter μ and shape parameter σ.	Pdf: $f(t) = \frac{e^{-\frac{(\ln t-\mu)^2}{2\sigma^2}}}{\sqrt{2\pi\sigma^2}}$ $R(t) = 1 - \Phi\left[\frac{\ln t - \mu}{\sigma}\right]$ $F(t) = \Phi\left[\frac{\ln t - \mu}{\sigma}\right]$
Weibull distribution	Widely used in reliability calculations due to its flexibility in modeling different distribution shapes. Can be used to model time to failure of electronic railway signaling components. Very useful in classifying failure types, scheduling preventive maintenance and inspection activities.	Pdf: $f(t) = exp\left[-(\frac{t-\gamma}{\eta})^{\beta}\right]$ Taking $\gamma = 0$, $f(t) = exp\left[-(\frac{t}{\eta})^{\beta}\right]$ Cdf: $F(t) = 1 - exp\left[-(\frac{t}{\eta})^{\beta}\right]$ Hazard function: $z(t) = \frac{\beta t^{\beta-1}}{\eta^{\beta}}$

2.5 Corrective Maintenance

Although every effort is made to make engineering systems as reliable as possible through design and preventive maintenance, from time to time they fail and must be restored to their operational state. Thus, repair or corrective maintenance is an important component of maintenance activity [24]. Corrective maintenance is an unscheduled maintenance action composed of unpredictable maintenance needs that cannot be preplanned or programmed on the basis of occurrence at a particular time. The action requires urgent attention that must be added, integrated with, or substituted for previously scheduled works [24]. This incorporates compliance with "prompt action" field changes, rectification of deficiencies found during equipment/item operation, and performance of repair actions due to incidents or accidents.

Corrective maintenance may be classified into five major categories: fail-repair, salvage, rebuild, overhaul, and servicing [24].

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

ii. *Salvage:* Is concerned with the disposal of non-repairable items and use of salvaged items from non-repairable equipment in the repair, overhaul, or rebuild programs.

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

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

v. *Servicing:* Some corrective maintenance actions may need servicing.

Different authors have laid down different sequential steps for performing corrective maintenance. For purposes of this research, it is assumed that corrective maintenance is composed of five major sequential steps: fault recognition, localization, diagnosis, repair, and checkout. The downtime of an item is majorly composed of active repair time, administrative and logistic time, and delay time. The active repair time can be split into: preparation time, fault localization time, spare item obtainment time, fault correction time, adjustment and calibration time, and checkout time [24].

Reduction in corrective maintenance time is useful to improve maintenance effectiveness. Some strategies for reducing the system-level corrective maintenance time are as follows [24]:

i. *Efficiency in fault recognition, location, and isolation:* Well-designed fault indicators, good maintenance procedures, well-trained maintenance personnel are helpful in lowering corrective maintenance time.

ii. *Effective interchangeability:* Good physical and functional interchangeability is useful in removing and replacing parts or items, reducing maintenance downtime, and creating a positive impact on spares and inventory needs.

iii. *Redundancy:* Redundant system that can be switched in when one fails and the system continues to operate while the faulty part is being repaired. This lowers the system downtime.

iv. *Effective accessibility:* Often a significant amount of time is spent accessing the failed part. Proper attention to accessibility during design can help reduce part accessibility time and, in turn, the corrective maintenance time.

v. *Human factor considerations:* Attention paid to human factors during design in areas such as readability of instructions, size, shape, and weight of components, selection and placement of dials and indicators, size and placement of access, gates, and readability, and information processing aids can help significantly reduce corrective maintenance time.

For the case of railway signaling equipment, effective maintenance strategies would lead to increased safety in train operation and reduced frequency of maintenance. The main objectives of any maintenance strategy are to reduce the frequency of maintenance, maintenance cost, MTTR and increase MTBF. Signaling system defects include defects of all types of signal gears and equipment including signal failure, point machine failure, axle counter failure, panel failure, balise failure, level crossing failure, interlocking failure, etc.

2.6 Reliability and Life Cycle Cost

The total costs incurred over the period of ownership of an equipment are often referred to as Life Cycle Costs [25]. These costs are influenced by [25]:

i. *Reliability:* determines the frequency of repair, fixes spares requirement, and determines loss of revenue (together with maintainability).
ii. *Maintainability*: affects training, test equipment, downtime, and manpower.
iii. *Safety:* affects operating efficiency and maintainability.

Life cycle cost (LCC) analysis is an assessment technique used to evaluate costs incurred during the life cycle of a system to help in long-term decision making [1]. Life cycle costing is a concept used to calculate the whole cost of a system from design to disposal and can be used as the basis for management decision. Its primary objective is to evaluate and/or optimize the life cycle cost of a product while satisfying specified performance — reliability, availability, maintainability, safety, and other company-specific requirements. Although LCC analysis is most effectively applied in the early design phase of a product, it is not limited to any specific phase and can, therefore, be performed during any phase of a system life cycle.

According to the IEC 60300-3-3 standard [26], the life cycle of an asset can be subdivided into six phases. Regarding costs, for a user or an owner of an asset, these phases are connected with the LCC of the asset as follows: (i) acquisition costs: concept and definition, design and development, manufacturing and installation; (ii) ownership costs: operation and maintenance; and (iii) termination costs: disposal. Acquisition and termination costs are not subject to ownership time variations and can be considered as fixed cost parameters. Operation conditions and maintenance policies are the two important variables which have a great effect on the ownership costs. The operation costs include costs of labor (personnel), materials and energy. The maintenance costs can be divided into scheduled maintenance costs and unscheduled maintenance costs. Both types of maintenance costs can be further subdivided into costs of labor, tools, delays, etc.

A life cycle costing approach considering the stochastic nature of failure using RAMS analysis can be used to estimate maintenance costs and ultimately optimize the maintenance strategy. Life cycle costs can be reduced by enhanced reliability, maintainability and safety levels but will be increased by the activities required to achieve such levels, hence, there is the need to find a set of parameters which optimizes the total cost of ownership [25].

The goal of RAMS is to create input data for the assessment of the suitability of a system in a life cycle, i.e., to provide data on failure rates of the system, possible failure modes, mean downtimes, maintenance operations, hazards and their consequences, etc. The output of RAMS analysis can then be used for the calculation of life cycle costs. Input on known component failure data is used to perform RAMS calculation at component level then the system RAMS can be obtained using, say, Reliability Block Diagrams (RBD).

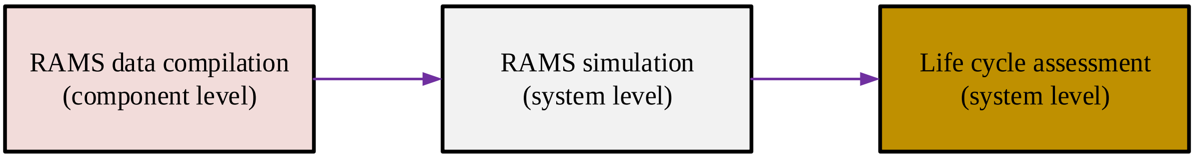

Figure 4: RAMS cycle

In order to estimate the life cycle costs of the railway signaling system in the O&M phase, the factors influencing the performance of the signaling system and their relationships must be identified [4]. The factors which influence the life cycle costs include the RAMS targets for the signaling system, the amount of preventive maintenance, corrective maintenance, and the market prices of labor and spare parts.

LCC provides the theoretical concepts needed to balance short-term and long-term costs and performance (revenues) [4]. Informed maintenance decisions can only be arrived at when the costs and performance of alternative decisions are considered on a long-term, life-cycle basis, including the corresponding availability and reliability, since the signaling system performance influences the costs and revenues of the operations [4]. In order to arrive at long-term, reliable estimates of the costs associated with maintenance activities, life-cycle costing considering the stochastic nature of failure using RAMS analysis must be carried out. In life-cycle costing, the maintenance strategy (MS) with the lowest LCC over the life span of the system is considered as the cost-effective solution to be implemented in the infrastructure operations [4], [16]. The life cycle costs are the criterion used to assess alternative courses of action, in this case, maintenance strategies. These costs are presented in three different ways [4]:

i. The Total Present Value (TPV) is the sum of all discounted cash flows. In the LCC method, it mostly concerns costs; incomes can be expressed as negative costs. The larger the TPV, the less attractive the investment compared to alternative investments or maintenance strategies.

$$Total\ Present\ Value\ (TPV) = \sum_{t=0}^{n} \frac{c_t}{(1+r)^t} \tag{10}$$

C_t is the sum of all costs incurred in period t, r is the discount rate, n is the number of years for which the project will operate, and t is the analysis period.

Net present value (NPV) is the difference between the discounted benefits and costs over the analysis period. A positive NPV indicates that the investment is justified at a given discount rate.

$$Net\ Present\ Value\ (NPV) = \sum_{t}^{n-1} \frac{b_t - c_t}{(1+r)^t} \tag{11}$$

bt is the sum of all benefits incurred in period t

ii. The Internal Rate of Return (IRR) is the percentage earned on the amount of capital invested in each year of the life of the project after allowing for the repayment of the sum originally invested. It shows the profitability of an investment compared to alternative investments or maintenance strategies. The IRR is the discounting rate at which the present values of costs and benefits are equal, i.e. NPV = 0.

iii. The Annual Equivalent or Annuity (ANN) is the sum of interest and amortization, which has to be paid every year to finance the investments and maintenance. With the annuity, projects of different life spans can be compared. In the case of this research, ANN determines the annual maintenance cost of the signaling system.

$$ANN = \frac{(1+t)^n \times t}{(1+t)^n - 1} \times TPV \tag{12}$$

2.7 Economic Evaluation Methods for LCC Analysis

Table 3 briefly describes the various methods used for life cycle cost analysis.

Table 3: Economic Evaluation Methods for LCC Analysis [16]

Method	**What it does**	**Comments**
Net Present Value (NPV)	NPV uses discount factors to discount the cash flows to present value, based on a required rate of return to each year's projected cash flow (both in and out). A positive NPV is worth investing. With LCC's focus being costs rather than income, the cost is treated as positive and income as negative, and the alternative with minimum NPV is chosen.	Takes the time value of money into account. Generates the return equal to the market rate of interest. Not usable if the alternatives have different life lengths.
Simple Payback	Calculates the time required to return the initial investment; the investment with the shortest payback time is chosen.	Simple calculation. Result easily interpreted. Does not take inflation, interest or cash flow into account.
Discount Payback Method (DPP)	Same as the simple payback method, but it takes the time value into account.	Takes the time value of money into account. Ignores all cash flow outside the payback period
Equivalent Annual Cost (ECA)	Expresses the one-time NPV of an alternative as a uniform equivalent annual cost, thus takes the present worth of annuity into account. Comparing different alternatives with different life lengths.	Different alternatives with different life lengths can be compared. Just gives an average number. It does not indicate the actual cost during each year of the LCC.
Internal Rate of Return (IRR)	Is a discounted cash flow criterion which determines an average rate of return by reference to the condition that the values be reduced to zero at the initial point of time. The alternative with the highest IRR is the best alternative. Can only be used if the investments will generate an income.	Result gets presented in percentage which gives an obvious interpretation. Calculations need a trial and error procedure. IRR can only be calculated if the investments will generate an income.
Net Saving (NS)	It is the difference between the present worth of the income generated by an investment and the amount invested. The alternative with the highest net saving is chosen. Can be used to compare investment options.	Easily understood investment appraisal technique. NS can only be used if the investment generates an income.

The operation and maintenance phase is an important phase of the asset life cycle during which the asset must be maintained satisfactorily for effective performance. The maintenance needs of an asset must be quantified so as to achieve a cost-effective maintenance strategy. Some of the reasons for maintenance costing include [27]:

- Determine maintenance cost drivers
- Provide input in equipment life cycle cost studies
- Control costs
- Make decisions concerning equipment replacement
- Compare maintenance cost effectiveness to industry averages
- Develop optimum preventive maintenance policies
- Compare competing approaches to maintenance
- Provide feedback to upper-level management

The calculation of individual cost components is possible using a variety of procedures and estimations, e.g., analogous cost estimating, parametric cost estimating, or engineering cost estimating [26]. Many factors influence maintenance costs, including asset condition (age, type, and condition), operator expertise and experience, maintenance policy, skills of maintenance personnel, the operational environment, equipment specification, and regulatory controls.

The maintenance solution should be robust, i.e. remain the preferred alternative under varying conditions, such as more/less transport than expected, a higher/lower interest rate and a quicker/slower asset degradation. Two methods can be used to test the robustness [4]:

i. *Sensitivity analysis.* In sensitivity analysis, the input values are systematically varied, with percentages of ± 10%, 20%, and 30%. The most sensitive input parameters are identified by the deviation percentage of the outcomes.
ii. *Uncertainty analysis.* Due to the statistical nature of the RAMS parameters, the LCC estimation is associated with some degree of uncertainty, and sensitivity analysis might be insufficient. Uncertainty analysis considers the input parameters of a model to be random variables, from which samples are drawn.

2.8 Addis Ababa Light Rail Transit Signaling System

2.8.1 Overview of AALRT

The Addis Ababa Light Rail Transit (AALRT) is a double track light rail system that provides a total right-of-way (ROW) of 31.05 km. It has two lines, East-West (EW) line (17.4 km) and North-South (NS) line (16.97 km) with a common section of 2.662 km length. The network is street-running, integrated and harmonized with other public transport modes but segregated from road traffic to achieve faster trips and improve the passenger experience.

Signaling systems play an important role in the control, supervision, and protection of railway traffic. The AALRT signaling system incorporates two main systems of control and supervision: iTS system for Automatic Train Supervision (ATS) and iTC system for Intermittent Automatic Train Protection (IATP). Each system encompasses a number of signaling equipment which are localized as indoor, outdoor (trackside) and onboard. The implementation of the signaling system is in a distributed manner, i.e., some are available only in depots, in mainline stations, or central control stations, whereas some of them exist in all.

The IATP subsystem consists of both onboard and trackside equipment. The onboard equipment consists of the vehicle controller, odometer, balise antenna, and driver machine interface. The trackside equipment consists of the following:

i. Axle counter: for track occupancy detection.
ii. Point machine: to decide train run-route.
iii. Balise: input from the track to the onboard signaling system (e.g. speed, position).
iv. Lineside Electronic Unit (LEU).
v. Trackside wireless unit.
vi. Color signals: display permission or restrict light to the train entering a track section.
vii. Level crossing equipment: coordinate the road and railway traffic at the level crossing.

The architecture of the whole railway infrastructure is managed by a software tool (iCMTC) which allows the dispatchers to see which items compose a section of the railroad (signaling, power supply, track components, etc.) The specific location of each item is defined, together with its model and serial number.

The AALRT uses a Computer-based Interlocking (CBI) system to control the signaling and interlocking devices in a manner as to realize the safe and efficient operation of trains. The CBI receives the input from the different systems (e.g. signals, axle counters, LEUs, point machine) and calculates and returns as an output the train operation restrictions to ensure safe traffic operation. The CBI equipment are clustered in 8 decentralized stations EW1, EW7, EW16, EW20, EW22, NS27, NS10, and NS6; each supervises a specific track section. Each CBI system has a 2 out of 2 channel configuration Zone Logic Computer (ZLC) responsible for performing all interlocking functions within its jurisdiction. Adjacent ZLCs together with the onboard vehicle controller provide information exchange for the safe movement of the train from one CBI to the next. The ZLC is responsible for controlling and driving trackside signaling equipment — operating point machines, signals, axle counters, balises, and other equipment.

2.8.2 Railway Signaling System as a System of Systems

The IEC 62278 standard [13] defines a system as an assembly of subsystems and components connected together in an organized way to achieve a specified functionality. The functionality is assigned to subsystems and components within the system. The behavior and state of the system is changed if the subsystem or component functionality changes [13]. A system responds to inputs to produce specified outputs, whilst interacting with the environment [13].

Baldwin et al. [28] define the term System of Systems (SoS) as an arrangement of independent and interdependent systems that delivers unique capabilities. An SoS must have at least five basic attributes [28], [29].

- *Autonomy*: the ability of a constituent system to complete its own goals within limits and without the control of another entity;
- *Belonging*: the ability of a constituent system to choose to contribute value to the goals of another system in exchange for value to its own goals;
- *Connectivity*: the dynamic nature of information flows between constituent systems;
- *Diversity*: different systems have different goals;

- *Emergence*: formation of new properties as a result of a developmental or evolutionary process.

The operation of a railway signaling system rests on the interoperability of the different subsystems or components [15]. These subsystems depend on each other to provide a safe and efficient train operation on their specific track section. The supervision and protection of the railway network is impossible if any subsystem or component fails or interoperability is lacking. Hence, a railway signaling system can be considered as an SoS [15].

2.9 RAMS and LCC of Signaling Systems: Previous Research

Various studies have been conducted on the reliability, availability, maintainability, and safety of railway signaling systems. Other research has focused on the life cycle cost at different phases of the system life cycle. These researches have focused on different topics that collectively address the RAMS and LCC performance of railway signaling systems.

Evaluation of system reliability requires a clear understanding of the component reliabilities. However, in most cases component reliability data is not readily available; failure data is not well recorded and maintenance personnel may forget to record the data. Component failure behavior is not necessarily constant or homogeneous; it may change over time because of possible maintenance regimes, service intensity, operation conditions, location and environmental conditions [30]. These factors attribute to an unknown component lifetime distribution or a mixture of distributions, which complicates the estimation of a component lifetime and thus fails to inform the necessary maintenance planning [30]. In order to estimate the component lifetime at a particular time period with limited real-life data and uncertain lifetime distribution, Mokhtarian et al. [30] propose a nonparametric Bayesian approach. The authors study the effectiveness of the nonparametric Bayesian method in the estimation of the component reliability and the necessary conditions of the available data to achieve such effectiveness. They use a Bayesian nonparametric method, based on the Dirichlet Process Mixture Model using Markov Chain Monte Carlo algorithm. The results show that this method offers significant flexibility to account for uncertain lifetime distributions. The results also show that the Lognormal kernel is preferred over the Gaussian and Weibull kernels for a good estimate of the hazard rate of the components.

Hsu and Chiu [23] perform reliability analysis of the signaling system of a metro system using Reliability Block Diagrams and Fault Tree Analysis. Using actual operation data from the Kaohsiung Metro, the authors analyze the reliability of the system and compare the outcome with the reliability figures as stipulated in the design contract. The results show that the actual operational reliability figures are better than the contract target. The authors suggest a 2-out-of-3 redundant system for the on-onboard automatic train protection system.

Yamato et al. [8] study the relationship between the availability and maintenance of railway interlocking systems. The authors evaluate availability from the viewpoint of a train disturbance and its recovery. The study considers the effect of different patterns of recovery, based on actual operation procedures. The authors introduce a new index that simultaneously contains the effect of disturbance on railway passengers' convenience and maintenance staff's convenience. The results show that railway passengers' convenience has a close relation to availability and the maintenance staff's convenience has a close relation to maintainability. The authors go ahead to propose the use of this analysis to estimate the life cycle cost of a signaling system.

High levels of reliability and high security are the basic characteristics and requirements of railway signaling systems. The interlocking system is mainly used to ensure the safe operation of running trains. High reliability and high safety levels are the two most common characteristics and requirements of the system. He and Ren [31] use the Markov model to analyze the RAM indices of the All-electronic Computer Interlocking System when its execution layer is equipped with the single configuration or the dual-redundant configuration. The authors also compare these indices with those of the traditional computer-based interlocking system. The analysis results show that the reliability and availability of the All-electronic Computer Interlocking System are not as good as the traditional interlocking system, but its maintainability is much better than the traditional one. A redundant configuration in the All-electronic Computer Interlocking System greatly improves the reliability, availability, and maintainability of the system. The authors conclude by suggesting the use of the single configuration on not-so-busy track lines with lower efficiency, and the redundant configuration on busy track lines. The redundancy is also justified by Su and Wen [32] who investigate the reliability and safety of Regional

Computer Interlocking Systems using Markov model and compare them with centralized computer interlocking systems.

Most signaling equipment consist of electrical and electronic components. Contrary to common perception, these components are subject to aging (deterioration). Various authors have sought to study this aging phenomenon and examine its effects on the operation and maintenance of railway signaling systems. Antoni [33] uses the Weibull and Bertholon models to describe the aging phenomenon of railway signaling equipment and it can be seen that the deterioration is statistically significant. By evaluating different lifetime estimation methods for different components of the railway signaling system, the author finds that the Weibull distribution may not be the best model since the failures can either be random failures or failures due to wear or deterioration; he concludes that the Bertholon distribution should be considered in such a case.

Calle-Cordón et al. [1] present a methodology that combines RAMS and LCC analyses in linear transport infrastructure. The methodology is demonstrated in two real use cases, focusing on the analysis of maintenance costs associated with interventions on railway switches and crossings and road pavements. The authors report that maintenance costs can be reliably estimated by integrating with the LCC the stochastic nature of failure using RAMS analysis.

Patra et al. [2] demonstrate the estimation of the cost-effectiveness of ERTMS. The authors observe that achieving the optimal cost-effectiveness is one of the significant ways to address the efficiency of a system, and involves maximizing the availability and minimizing the life cycle cost of the system over its life cycle. An important way of maximizing the cost-effectiveness of the system is to optimize the maintenance policy. The degradation and repair process of the system is modeled by Petri Nets using failure, maintenance, and cost data as parameters for the model. The results show the effects of the maintenance factor, detectability, inspection interval and deferred maintenance time on the cost-effectiveness of the system.

Maintenance of railway assets accounts for a significant percentage of the total costs of running the railway network. Stenström et al. [34] study the corrective and preventive maintenance costs by analyzing historical maintenance data to determine the shares of CM and PM, together with a cost-benefit analysis (CBA) to assess the value of PM. Collected data comprise of infrastructure related CM activities, i.e. functional failure data, and PM data from inspections and rectification of potential failures. By including train delays as a CM cost, the authors observe that the CM represents approximately 70% to 90% of the total maintenance cost. When train delay cost is excluded, CM stands at 50% to 70% of the maintenance cost.

CHAPTER 3 RAMS AND LCC ANALYSIS OF THE AALRT SIGNALING SYSTEM

The chapter describes the research methods followed in this thesis. The selection of the methods is influenced by the theory presented in Chapter 2.

3.1 Stipulating Railway Key Performance Indicators (KPIs)

Different parameters can be used to rate the service provided by a railway operator. One such parameter from the passenger point of view is the punctuality of the train service. Punctuality of a train service is a key performance indicator (KPI) valued highly by train passengers [35] and is most widely used as a reliability measure. Punctuality is simply defined as the probability of train arrival at the final destination within a certain margin of the scheduled arrival time. Availability from the rail operator point of view can be defined around the ability of the signaling system to be in a state to control, supervise and ensure safe operation of trains, and is measured by the train service delivery level. For the evaluation of a railway system, objective measures like cancellations, delays and train evacuations can be measured [35].

The key performance indicators (KPIs) adopted in this research are briefly described below.

- ✓ **Train Service Delivery (TSD):** This measure quantifies the compliance with the planned schedule. It gives the percentage of service achievement in a given period of time, taking into account the planned trips[2] and canceled trips.

$$TSD = \left[\frac{No. of\ actual\ completed\ trips}{Total\ no. of\ scheduled\ trips}\right] \times 100 \qquad (13)$$

- ✓ **Punctuality (P)**: This research sets a punctuality target of 95% with 5 minutes delay for the day, i.e. a train loses punctuality for the day if its arrival at the final

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[2] A trip is the movement of a train from the first to the last station on the scheduled route.

destination is delayed by more than 5 minutes. The service punctuality is calculated as:

$$Punctuality, P = \left[\frac{No.\,of\ completed\ trips\ with < 5\ min\ delay\ at\ station}{Total\ no.\,of\ actual\ trips}\right] \times 100 \qquad (14)$$

For the purposes of reliability and availability analysis, a list of subsystems which comprise the signaling system has to be developed. Table 4 shows the results of a preliminary identification of the signaling subsystems that affect each of the Key Performance Indicators (KPIs).

Table 4: Signaling Critical Subsystem Selection

Signaling Critical Subsystem Selection		
Signaling Subsystem	**KPIs**	
	Train Service Delivery (TSD)	**Punctuality (P)**
IATP	IATP failure can cause a train not to depart	IATP failure can delay a trip
ATS	ATS failure can cause a train not to depart	ATS failure can delay a trip
Level Crossing (LC)	LC failure can cause collision with motorists hence cancellations	LC failure can cause collision with motorists hence delays

3.2 Selection of RAMS and LCC analysis methods

Among the methods and tools for RAMS analysis described in section 2.3, this research adopted FMEA and RBD. The critical subsystem selection (Table 4) determined the focus of this research (only electromechanical/electrical/electronic systems that are essential to meet the train service availability were considered). For life cycle cost analysis, the Net Present Value method was adopted.

3.2.1 Failure Mode and Effects Analysis (FMEA)

A preliminary FMEA was carried out for the signaling system described in section 2.8.1 so as to analyze the possible effects of each failure on the system, from the viewpoint of the operation and maintenance, and the KPIs (TSD, P). The objective was to determine the RAM critical functions and the applicable requirements for each subsystem. The results are presented in Table 5.

Table 5: Failure Mode and Effect Analysis (FMEA) for the AALRT Signaling System

Signaling Subsystem	Description	Failure Mode Code	Failure Description	KPIs	
				P	TSD
Rail Signaling	Train detection	S01	Unable to detect trains due to a failure on the axle counter. Unable to set routes for a line section requiring the suspension of services on the affected section. This failure can result in delays or evacuations. Suspension of services on a line section will impact on punctuality and service availability.	Yes	Yes
		S02	Unable to detect switch position. Unable to detect switch position which will need the driver or dispatcher actuation, thus affecting punctuality.	Yes	No
		S03	Train detected in a clear section. This failure prevents trains from being allowed to move at maximum speed, or might even be stopped. This impacts on service punctuality.	Yes	No
	Protect the system against incompatible routes	S04	Unable to switch point machine. This failure may result in train evacuation. Inability to remotely operate point machines may affect punctuality.	Yes	No
	Manage Shunting Signals	S05	Failure of the interlocking. This failure may result in train evacuation if it cannot be repaired in time.	Yes	No
		S06	Permissive signal aspect is displayed at the entrance of an occupied section. Signal passed at danger may result in collisions and hence train evacuations.	No	No
		S07	Non-permissive aspect is displayed in a clear section. Trains may reduce speed or stop hence affecting departure times and punctuality.	Yes	No
		S08	Proceed aspect is displayed. Trains have permission to proceed when they should not (signal failure). Unnoticed signal passed at danger may lead to a collision with a subsequent train evacuation.	No	No
	Manage Point Machines	S09	Incorrect point machine position monitoring. Inability to remotely operate point machines may affect train departures and commercial speed, hence impacting on punctuality.	Yes	No
		S10	Uncontrolled point machine position. Train moves to an incorrect track section. Inability to remotely operate point machines may affect train departures and commercial speed, hence impacting on punctuality.	Yes	No
		S11	Possible train movement to an incorrect track section. This failure may prevent trains from departing from stations, therefore affecting departure times. Inability to detect wayside equipment may affect commercial speed.	Yes	No
Traffic Lights/ Level Crossing	Degraded mode operation	S12	Proceed aspect is sent both for road vehicles and for train. This failure results in a reduction of commercial speed due to the degraded mode operation and hence, a delay on the departure times.	Yes	No
		S13	Stop command sent to train. Train must stop at intersection. Impacts on punctuality.	Yes	No
	Manage the signaling of level crossings	S14	Permissive aspect is displayed. Motorists/pedestrians have permission when they should not (failure of traffic regulator). Train may reduce its speed to avoid potential collision and hence, causing delay.	Yes	No
	Coordinate Road traffic lights	S15	Non-permissive aspect is displayed. Motorists/pedestrians don't have permission when they should (failure of traffic regulator). A potential collision may appear if motorists/pedestrians do not respect road traffic lights due to the failure of the traffic regulator. Hence, train speed would be diminished and departures times affected.	Yes	No

3.2.2 Reliability Block Diagram (RBD) creation

After identifying the signaling subsystems to be analyzed, their contribution to reliability and availability, their interaction with other subsystems, and their redundancy was identified. Every subsystem was assigned a component. The signaling system consists of various subsystems, configured in series and parallel. This research focused on the trackside subsystems. Although the subsystems have several components, a basic model was constructed demonstrating the interaction of five different subsystems (see Table 6). The approach in this study was to construct a basic model where each subsystem is represented by a single component. The reasons for specifically selecting these components for the trackside signaling model are:

- each component is the main component in the respective subsystem;
- these combined components contribute to a significant percentage of cancellations and delays in operation for the case study (AALRT);
- these components are serialized, and the failure data is available.

Table 6: Subsystems and main components of the trackside signaling system

Subsystem	Representation	Number required
Train detection	Axle counter (AC)	1/1
Train run/stop authorization	Signal (S)	1/1
Point operating mechanism	Point machine (PM)	1/1
Train – ground communication	Balise (B)	1/1
Rail – road traffic control	Level Crossing equipment (LC)	1/1

Figure 5 shows the RBD developed for the particular case of the AALRT.

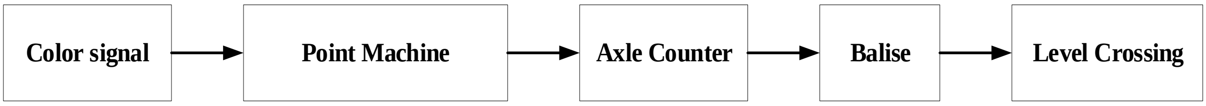


Figure 5: RBD for the case study

3.2.3 Effect of In-Service Failures on Availability and Reliability

The signaling system is a vital part of the railway network. Its reliability and availability have a direct influence on the quality of service provided by the railway operator. As such, signaling failures may cause delays and affect service punctuality. When a failure occurs during service hours (i.e., while the train is in service), it is referred to as an in-service failure. In-service failures which disrupt the railway service by causing trip cancellations, delays, or train evacuations, are regarded as Service-Affecting Failures (SAF). SAF failures have a direct consequence on service availability and reliability. The case study (AALRT) uses cancellations and delays to measure performance. In this research, the overall contribution of all system failures (rolling stock, power, communication, etc.,) to the cancellation and delays, and the specific contribution from the signaling system was calculated.

3.3 Data Collection and Processing

Failure and corrective maintenance data were obtained from work orders (WO) related to the railway signaling system of the 31-km Addis Ababa Light Rail Transit. The data was for a three-year period between 20th September 2015 and 20th September 2018. A total of 1675 WOs were recorded as failure and maintenance activities of axle counters, point machines, and signals. No WO was recorded for balises; it was noted that no balise failed within the three-year period of operation.

Data processing was performed, looking at the quality of the data recorded for each parameter (amount of data and quality of information) so as to identify the parameters that give more information about the failures. The input for data processing contained, among others, the following information:

- *Asset ID*: to uniquely identify the asset.
- *In-service date*: initial service date, or restoration date if equipment previously failed.
- *Failure date*: a recorded date (time) when a failure was detected.
- *Start and finish date*: date and time of intervention type.
- *Cause of failure*: design, electrical, software, external, lack of maintenance or incorrect operation, mechanical, no failure found, not defined, etc.
- *Corrective actions taken*: restore/replacement, software restart/update, lubrication, adjustment, cleaning, etc.
- *Maintenance costs*: costs generated by the intervention type.

- *Traffic interruption*: yes/no.

The causes of failure for the signaling system recorded in the corrective maintenance data include the following:

- Electrical causes such as power loss, cable fault (low insulation of cable).
- External reasons such as rail vehicles, vandalism, obstacles.
- Mechanical causes such as dust, insufficient friction, shortage of lube.
- Not defined (the cause of failure was not defined in the WO).
- Unknown – it was impossible to find any cause of failure.

When the failure of a signaling system asset occurred, the different possible corrective actions performed to return it to the operational state include the following:

- Replacement
- Reset/Restart
- Self-recovery
- Lubrication
- Cleaning
- Adjustment
- Manual locking

The railway signaling equipment continuously monitor the railway at all times, hence are regarded as continuously operating items (COI). When an equipment fails, it is repaired within a finite restoration time. Thus, the state of the equipment at time t can be described by a state variable $s(t)$:

$$s(t) = \begin{cases} 1, & if\ equipment\ is\ functioning\ at\ time\ t \\ 0, & if\ equipment\ is\ in\ failure\ state\ at\ time\ t \end{cases} \tag{15}$$

Failure and maintenance data processing considered the typical failure episode for an individual asset shown in Figure 6. Three possible states for the equipment were considered:

- Available state or Up time (UT): the equipment is fully functional.
- Not available – Waiting time (WT): the time between when a failure occurs until the corrective action is started. During the waiting time, the WO is opened, the failure is identified, the maintenance personnel is informed, the spare parts and tools needed are gathered and the personnel goes where the failure is located.
- Not available – Restoration time (TTR): corrective action (repair or replacement) is performed and the WO is closed.

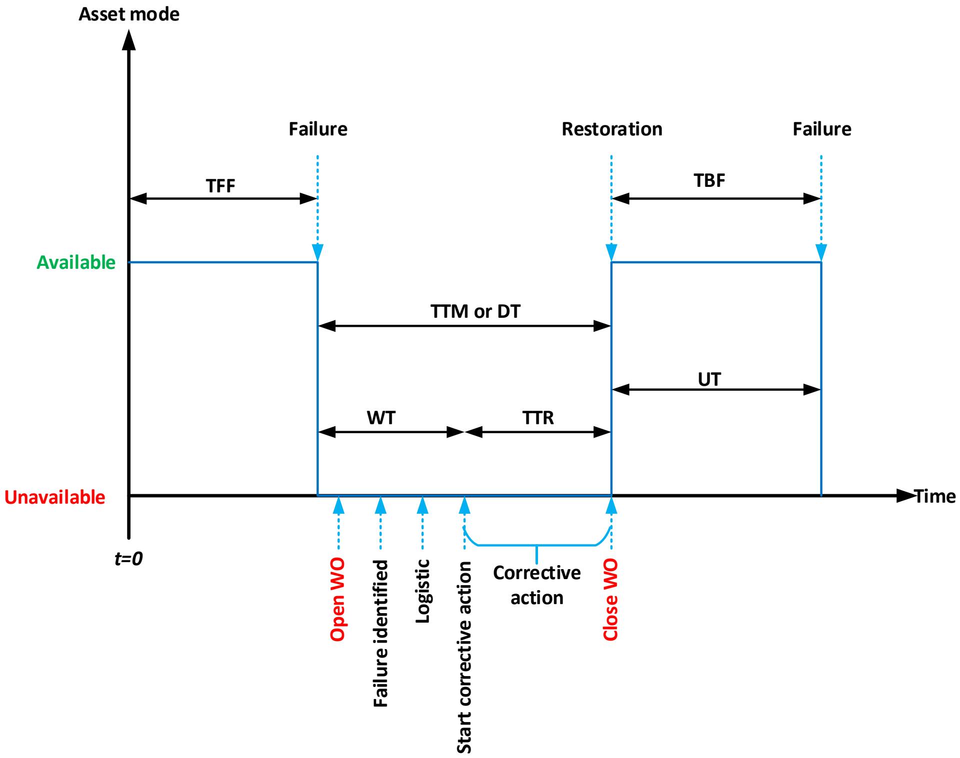


Figure 6: Failure scenario

From Figure 6 the following parameters are defined:

- ✓ Time to First Failure (TFF): the time elapsing from when the equipment was put into operation until it fails for the first time.
- ✓ Time Between Failures (TBF): the time duration between two consecutive failures of a repaired equipment.
- ✓ Up Time (UT): Operating time between failures – total time duration of operating time between two consecutive restorations.

- ✓ Time to Maintain (TTM) or Down Time (DT): the time when the equipment is not available for operation.

$$TTM \; = \; t(finish\; corrective\; action) - \; t(failure\; occurred) \tag{16}$$

- ✓ Waiting Time (WT): the time in which the WO has been opened and the equipment is waiting for a corrective action to be taken.
- ✓ Time to Restore (TTR): the time in which the failure has already been identified and the corrective action is taking place.

$$TTR = t(finish\; corrective\; action) - t(start\; corrective\; action) \tag{17}$$

The Relative Restoration Time (RRT) against the total time to maintain for each WO is given by the equation below and gives an idea of the efficiency of the corrective action.

$$RRT = \frac{TTR}{DT} \times 100 \tag{18}$$

3.4 RAMS Analysis

RAMS analysis considered the various system assets (axle counter, signal, point machine, balise, LC equipment) as systems on the SoS and their subsystems as the minimum level, since the corrective maintenance performed is the replacement or repair of these subsystems. RAMS analysis of failure and corrective maintenance records was conducted based on historical data from the WOs related to the railway signaling system. This analysis followed a methodology based on the fact that given a set of equipment, at some instant in time an event (failure) may occur to some or all of them. The RAMS analysis process adopted for every asset and intervention type is shown in Figure 7.

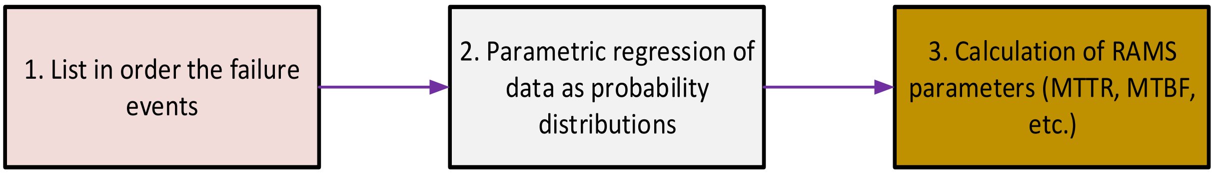


Figure 7: RAMS analysis process

From the failure scenario shown in Figure 6, the RAMS parameters in Table 7 were calculated. From the commonly used techniques for system RAMS analysis, this research adopted the RBD because it is the most logical and natural representation of a system, showing how units (components or subsystems) are linked in series, parallel, or both. With the RBD configuration, the RAMS of the signaling system will depend on the RAMS obtained for each subsystem (in this case axle counters, signals, point machines).

Parameters for reliability (MTBF) and maintainability (MTTR) were calculated and then operational availability was calculated as the quotient of the MTBF (mean time available) to the sum of MTBF and MTTR. Another maintainability measure, RRT, which gives an overview of the efficiency of the maintenance activities in terms of logistic time and actual restoration time, was calculated for point machines only. This is because, from the case study data, only the point machine maintenance times have separate logistic and restoration times; for the axle counter and signal, logistic and restoration times are grouped together. It is therefore assumed that for axle counter and signal the whole downtime is equal to TTR.

Table 7: RAMS parameters (*adapted from EN 50126-1* [10])

Reliability
Mean Time Between Failure, $MTBF = \frac{Total\ Operating\ time}{Total\ number\ of\ failures}$
Failure rate: $\lambda = \frac{f(t)}{R(t)}$. With constant λ, then $\lambda = {}^{1}/_{MTBF}$
Availability
Mean Up Time (MUT)
Mean Down Time (MDT)
Availability, $A = \frac{MUT}{MUT+MDT}$
Operational Availability, $A_o = \frac{MTBF}{MTBF+MDT}$
Maintainability
Mean Time To Maintain (MTTM) $= \frac{Total\ TTM}{Total\ number\ of\ failures}$
Mean Time To Restore (MTTR) $= \frac{Total\ TTR}{Total\ number\ of\ failures}$
Restoration/repair rate μ = ${}^{1}/_{MTTR}$ (when constant)

Operational Restoration/repair rate $\mu_o = {}^{1}/_{MTTM}$ (when constant)
Safety
Mean Time Between Safety System Failure (MTBSF)
Hazard Rate H(t) and Tolerable Hazard Rate (THR)
Time to Return to Safety (TTRS)

Several approaches can be used to model single-parameter reliability and maintainability performance. Two of these approaches are Point Processes and probability distributions. Point processes include the Homogenous Poisson Process for constant failure/repair rates and the Non-Homogenous Poisson Process for modeling the time dependency of these rates. For simplicity, this research adopted probability distributions.

The typical behavior of the failure rate of a component is commonly described by the ‘bathtub curve’ (see Figure 8). Originally assumed to apply to electronic components, this curve describes the variation of the failure rate of components during their lifetime. The failures exhibited in the first part of the curve (the burn-in period), where the failure rate is decreasing, are called early failures or infant mortality failures. The middle portion is referred to as the useful life and failures are assumed to occur randomly, exhibiting a constant failure rate. The latter part of the curve describes the wear out failures and it is assumed that failure rate increases as the wear out mechanisms accelerate [25].

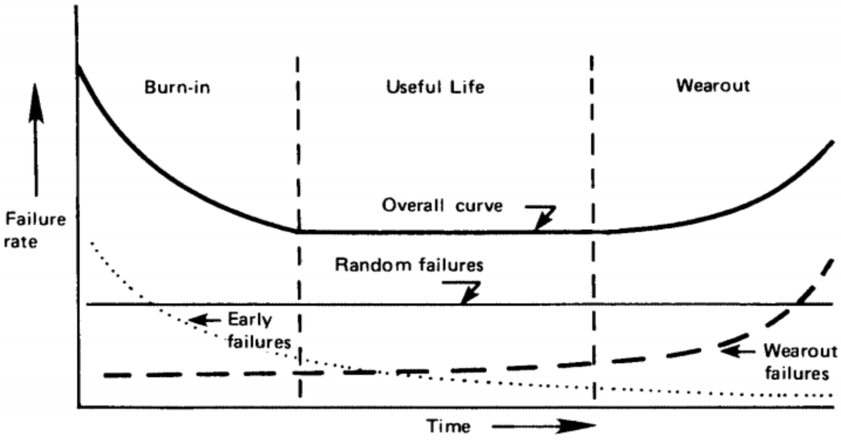


Figure 8: Bathtub curve (Source: [25]**)**

Parametric regression to identify the best-fit distribution for the failure data was done using PTC Windchill Quality Solutions and Minitab software. The RAMS parameters were calculated using Excel 2016.

3.5 Life Cycle Cost (LCC) Analysis

The LCC analysis focused on the ownership LCC because of its sensitivity to variations, which calls for the need to be optimized. Initial investment and operation have well-defined costs, while maintenance and consequential costs, which depend on maintenance policies, have a stochastic nature and are quantifiable with statistical data analysis. This study considered costs arising from failure and corrective maintenance (an intervention due to unexpected failure).

An integrated RAMS and LCC methodology was adopted. This methodology rests on the statistical analysis of maintenance interventions and data from the accounting system to estimate costs [1]. The results of the RAMS analysis and the maintenance costs obtained formed the input for the parametric cost models that implement the LCC calculation. Using Monte Carlo simulation in Excel 2016, where input parameters take a stochastic character, a stochastic prediction was obtained for the LCC of the signaling system. A sensitivity analysis was carried out to identify the most significant LCC parameters.

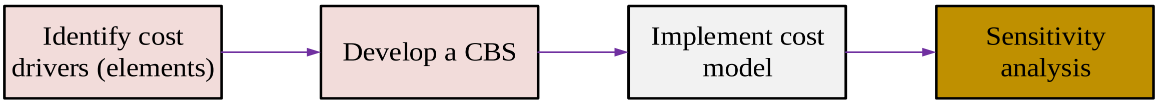


Figure 9: Steps in LCC Analysis

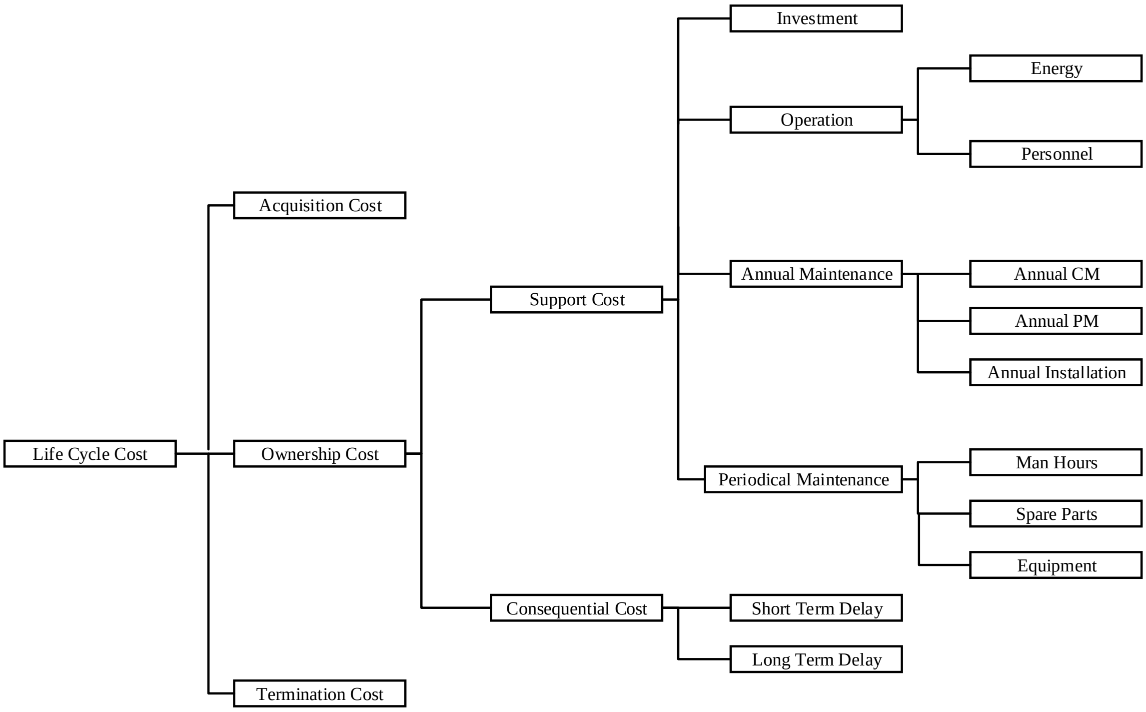


Figure 10: LCC Cost Breakdown Structure

Maintenance costs may arise from inspection, corrective maintenance, preventive maintenance, and overhaul. This study considered maintenance costs arising from corrective maintenance only. The cost drivers for corrective maintenance cost calculation include man-hours per corrective action, cost of labor, number of workers involved in the maintenance action, failure rate, restoration rate, component cost, equipment cost and restoration time. The cost models are highly dependent on the system under study. The costs were modeled as follows:

Annual Corrective Maintenance Cost:

$$CY_{CM} = Man\ hours + Spare\ parts + Equipment + Consequential\ Cost$$

$$= \sum_{i=1}^{m} \sum_{j=1}^{n} \lambda_{ij} \left[C_L n_L \left(MTTR_{ij} + MLT_{CM} \right) + C_{Pij} + C_{Eij} + C_{delay} MDT_j \right] \qquad (19)$$

Life Cycle Cost:

$$LCC = \sum_{k=1}^{periods} \sum_{i=1}^{actions} \sum_{j=1}^{components} \frac{1}{(1+r)^k} \frac{1}{MTBF_{ij}} \{C_{Pj} + MTTR_{ij}(n_{Li}C_L + C_{Ei})\} \qquad (20)$$

Where,

n is the number of assets;

r is the discount rate;

$MTBF_{ij}$ is the Mean Time Between Failure;

λ_{ij} is the failure frequency for action *i* and unit *j*;

$MTTR_{ij}$ is the Mean Time to Restore;

MLT_{CM} is the Mean Logistic Time associated with corrective maintenance;

MDT_j is the Mean Down Time of unit j;

n_L is the number of workers involved in the maintenance action;

C_L is the labor cost;

C_P is the cost of spare parts;

C_E is the cost of the tools (equipment) to carry out the intervention.

C_{delay} is the cost of delay (service loss);

For the cost models in this research, the following assumptions were made:

- The lifetime of the signaling system to be 35 years.
- The discount rate is taken to be 10.5% (r=0.105).
- The average labor cost is C_L = 215 ETB/hr.
- Delay cost is C_{delay} = 232 ETB/min.
- The number of workers n_L=2 for replacement and 1 for restart/reset intervention.
- The equipment cost for replacement C_E=100 ETB/hour for the different replacements.
- The cost of spare parts is C_P=500 ETB per service failure.

CHAPTER 4 RESULTS AND DISCUSSION

The chapter summarizes the results of the analysis presented in Chapter 3.

An examination of the time to failure of the different trackside signaling equipment was done considering the visual results on the probability plots and the Anderson-Darling (adjusted) statistics for the goodness-of-fit measure. For a particular data set and distribution, the better the distribution fits the data, the smaller the Anderson-Darling (adjusted) statistic will be. The point machine failures and axle counter failures follow a 2-parameter Weibull distribution while signal failures follow a 3-parameter lognormal distribution.

4.1 Corrective Maintenance Analysis

For every work order, associated values for the analyzed parameters include values for failure mode, values for cause of failure and values for corrective action taken. The different values found for the parameters are shown in Table 8.

Table 8: Parameter Values for Signaling Equipment of AALRT

Item	Failure mode	Failure cause	Corrective action
Axle counter	Occupied, Negative axle	Electrical, NOT defined, Unknown	KEY Reset, PUSH BUTTON Reset
Point Machine	Motor cannot start, Cannot release or lock, Switch rail failure, Immovable contact heel, No indicator	Electrical, Mechanical, Software, NOT defined	Cleaning, Lubrication, Restart, Software update, Manual lock, Adjustment,
Color signal	Signal OFF, Broken cover, Flashing, Occupied, Tripping	Electrical, Mechanical, NOT defined, Unknown	Restart, Replacement, Self-recovery, NOT defined

An examination of the different systems that comprise the signaling system showed that axle counter failures account for more than 80% of all the signaling system failures (see Figure 11). While examining the failures by year, the highest number of failures was recorded in the third year of operation (see Figure 12), with axle counters accounting for the highest number of failures (axle counter failures increased steadily from the start of operation). The general trend of the failure rate of point machine and signal light is a decrease in failure rate, indicating the burn-in period of early failures or infant mortality failures. This is true because the signaling system is still in the first phase of its life cycle. However, the axle counter experienced an increasing failure rate.

For the failure mode parameter, the most common values recorded were “Occupied” and “Negative axle” as depicted in Figure 13. For the “Occupied” failure mode the signal light at the entrance of a clear section displayed a red aspect for the train driver to stop, while axle counters’ evaluation boards showed the presence of axles in clear sections. The “Negative axle” failure mode is exclusively for axle counters where the evaluation board registers the presence of one or more axles in a clear section, or a ‘very small wheel’.

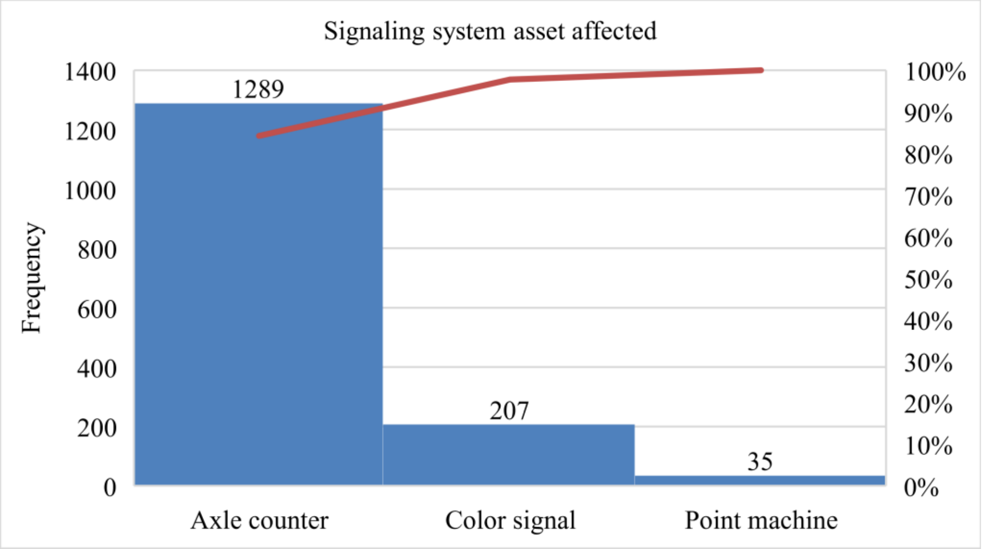


Figure 11: Pareto diagram for the signaling system asset affected

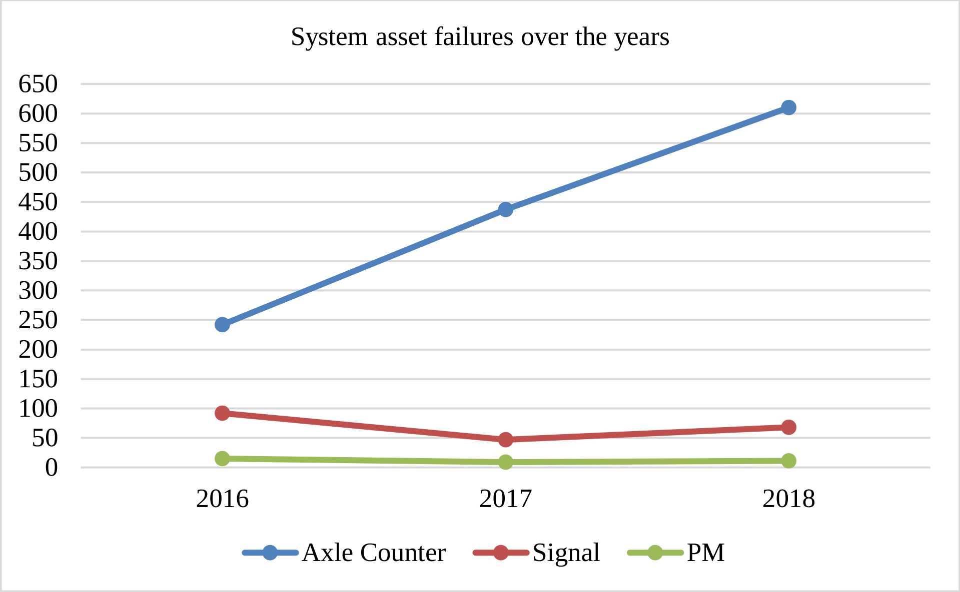


Figure 12: Signaling system asset failure trend

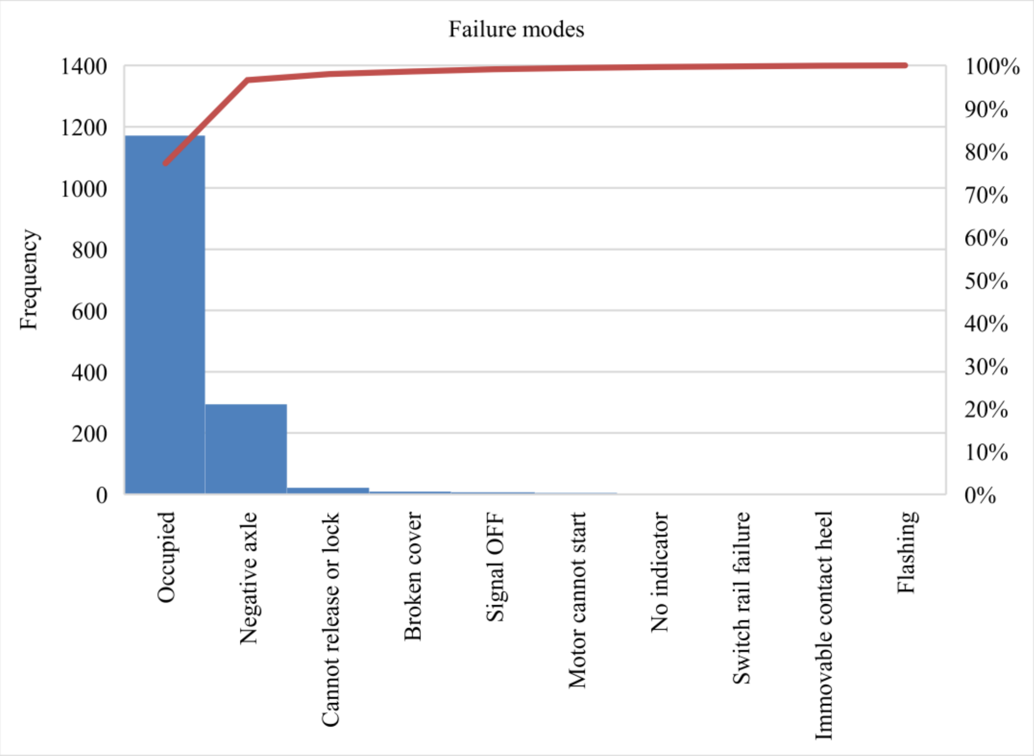


Figure 13: Pareto diagram for failure modes

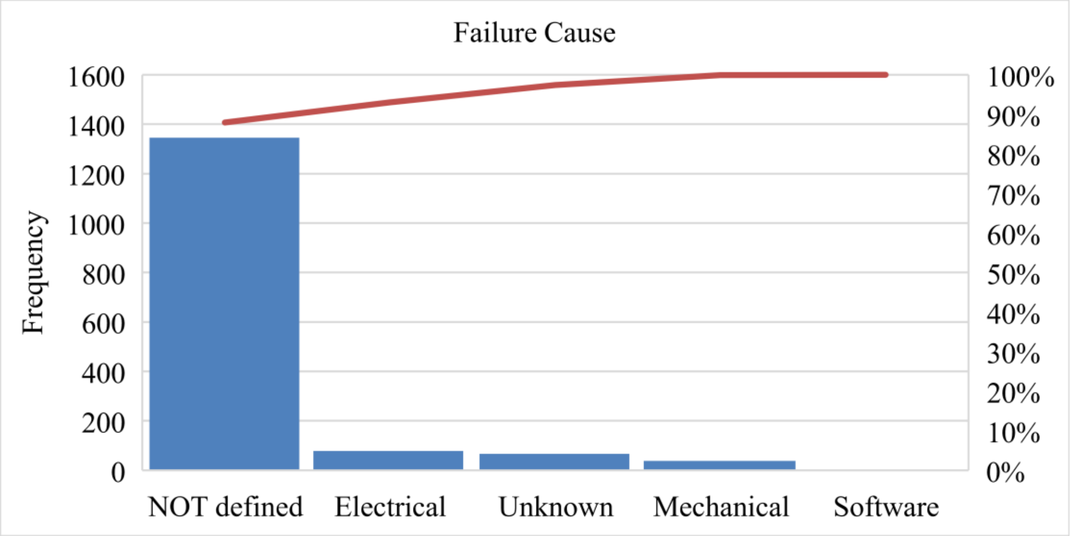


Figure 14: Pareto diagram for failure causes

Various observations are made after a careful study of the failures recorded for a particular signaling asset. The most common failure cause for the axle counter is “not defined”. This points to lack of more information about the failure cause; as such, there is a need for more information acquisition by the maintenance personnel. Even though the axle counting subsystem is a fully automatic system whose restoration after failure is by key reset or push button reset, 26% of the restoration times were above the average restoration time (31 minutes). For the point machine, 20% of the corrective actions took more than the average restoration time (70 minutes). The signals with an average restoration time of 45 minutes had 28% of the corrective actions taking more than the average restoration time. This trend gives an idea on the maintainability of the subsystems; unreasonably long time is spent on restoration. The reason for this may include maintenance personnel not communicating the time immediately after finishing the corrective action, or laxity in responding to the failures. It is proposed that improvement measures be put in place to reduce the restoration time and increase the efficiency and effectiveness of the performance of the corrective maintenance actions. The most common corrective action for point machine is cleaning and adjustment (each at 20%), key reset for axle counters (68.43%) and “Not defined” for signals (57.97%). The axle counting subsystem experiences the most frequent failures, and restoration is by resetting the system. Scheduled resets, especially during out-of-service hours, could reduce the occurrence of the axle counter failures during in-service hours.

Several weak points in the trackside signaling assets were identified during the analysis: low reliability of axle counters, high frequency of failures in the axle counting subsystem, unreasonably long times to maintain, poor and/or incomplete identification of failures, etc. The huge number of work orders with "not defined" and "unknown" is indicative of weak failure reporting rules, lack of more information about the failures, and poor knowledge transfer. These weak points give an idea of the areas that can be exploited in order to improve the overall performance of corrective maintenance. Suggestions for improvement include: revising the failure reporting rules, reducing the dependency on the expertise of personnel, creating a Failure Reporting, Analysis and Corrective Action System (FRACAS), and improving inter-departmental knowledge transfer.

4.2 Performance Evaluation

4.2.1 RAMS of the Signaling System

The AALRT signaling system was designed to have the following RAMS targets [36]:

Availability:

i. The availability of the computer system of individual subsystems is $\geq 99.998\%$;
ii. The availability of the whole signaling system is $\geq 99.99\%$;
iii. The probability of wrong side failure of safety equipment in the whole signaling system is $\leq 10^{-9}$/hr.

Reliability:

i. IATP system: MTBF $\geq 2.0\times10^{5}$hr;
ii. ATS system: MTBF $\geq 2.0\times10^{5}$ hr;
iii. Outdoor balise beacon: MTBF$\geq 10^{6}$hr;
iv. Axle counter: MTBF $\geq 1.75\times10^{5}$hr;
v. Mean correct counts of axle counter: $\geq 1\times10^{9}$ axles.

Maintainability:

i. Electrical and electronic trackside equipment (except point machine): MTTR ≤ 30 min;

ii. Level crossing signaling equipment: MTTR ≤ 30 min.

All safety-related equipment in the signaling system were designed to have a safety integrity level (SIL) of 4.

Some of the RAM parameters calculated for the different subsystems are given in the respective Tables 9, 10 and 11.

Table 9: Point Machine RAM statistics

Period	No. of Failures (A)	WT (hr.) (B)	TTR (hr.) (C)	DT (hr.) (D)	Operating Time (hr.) (E)=8760-D	Failure rate (failures/yr) (F)	MTBF (hr.) (G)= E/A	MTTR (hr.) (H)=C/A	MDT (hr.) (I)=D/A	Operational Availability (J)=G/(G+I)
9/20/15 - 9/20/16	15	18.5333	22.35	40.8833	8719.1167	0.003895	581.2744	1.4900	2.7256	99.533%
9/21/16 - 9/20/17	9	9.9	7.95	17.85	8742.15	0.003423	971.3500	0.8833	1.9833	99.796%
9/21/17 - 9/20/18	11	13.9833	10.7	24.6833	8735.3167	0.003174	794.1197	0.9727	2.2439	99.718%

The efficiency of the corrective maintenance on point machines is given by the Relative Restoration Time (RRT) against the total time taken to maintain. This is given below for the three years of operation:

Year 1 (9/20/15 – 9/20/16): $RRT = \frac{TTR}{DT} \times 100 = \frac{22.35}{40.8833} \times 100 = 54.67\%$

Year 2 (9/21/16 – 9/20/17): $RRT = \frac{TTR}{DT} \times 100 = \frac{7.95}{17.85} \times 100 = 44.54\%$

Year 3 (9/21/17 – 9/20/18): $RRT = \frac{TTR}{DT} \times 100 = \frac{10.7}{24.6833} \times 100 = 43.35\%$

This shows a decrease in the efficiency of corrective maintenance on point machines.

Table 10: Signal RAM statistics

Period	No. of Failures (A)	TTR (hr.) (B)	Total Operating Time (hr.) (C)=8760-B	Failure rate (failures/yr) (D)=A/C	MTBF (hr.) (E)=C/A	MTTR (hr.) (F)=B/A	Operational Availability (G)=E/(E+F)
9/20/15 - 9/20/16	92	94.8	8665.2	0.010617	94.1870	1.0304	98.918%
9/21/16 - 9/20/17	47	32.4333	8727.5667	0.005385	185.6929	0.6901	99.63%
9/21/17 - 9/20/18	68	28.2	8731.8	0.007788	128.4088	0.4147	99.678%

Table 10 shows that the highest number of signal failures occurred in the first year of operation, representing the early (infant mortality) failures. Moreover, the MTTR was the highest in that year and this resulted in the operational availability of the signals being the lowest in that year.

Table 11: Axle counter RAM statistics

Period	No. of Failures (A)	TTR (hr.) (B)	Total Operating Time (hr.) (C)=8760-B	Failure rate (failures/yr) (D)=A/C	MTBF (hr.) (E)=C/A	MTTR (hr.) (F)=B/A	Operational Availability (G)=E/(E+F)
9/20/15 - 9/20/16	242	221.7	8538.3	0.028343	35.2822	0.9161	97.469%
9/21/16 - 9/20/17	437	203.8	8556.2	0.051074	19.5794	0.4664	97.674%
9/21/17 - 9/20/18	610	248.33	8511.67	0.071666	13.9536	0.4071	97.165%

A fully functioning signaling system requires that all its subsystems are working correctly — axle counter, signal, point machine subsystems can be regarded as series subsystems. Using RBDs, the overall system RAM is given in Table 12.

Table 12: AALRT Signaling system RAM statistics

		Point Machine	Signal	Axle Counter	**Signaling System**
Year 1	Reliability (hr)	581.27	94.19	35.28	1710.74
	Availability (%)	99.533%	98.918%	97.469%	95.96%
	Maintainability (hr)	1.49	1.03	0.92	0.98
Year 2	Reliability (hr)	971.35	185.69	19.58	1864.32
	Availability (%)	99.796%	99.63%	97.674%	97.11%
	Maintainability (hr)	0.88	0.69	0.47	0.62
Year 3	Reliability (hr)	794.12	128.41	13.95	1813.65
	Availability (%)	99.718%	99.678%	97.165%	96.58%
	Maintainability (hr)	0.97	0.41	0.41	0.54

Table 12 clearly shows that the operational RAM figures are below the design target; the AALRT is operating below the design RAM target and has room for improvement. It can be seen that the RAM of the signaling system is most affected by the axle counting subsystem which has the lowest values of reliability, availability, and maintainability.

4.2.2 Railway System Performance

Depending on the severity of the failure, in-service failures may affect train operations. These Service-Affecting Failures (SAF) may cause delays, trip cancellations or train evacuations. In this case study, the percentage of signaling system failures that caused traffic interruption (SAF) was 4.9%. The highest contributor was the axle counter failures (2.74%) followed by point machine failures at 1.11% and the least interruption was from signal failures at 1.05%. To evaluate the AALRT system performance, objective measures were used to calculate the key performance indicators (KPIs) as shown in Table 13. It is clear that the signaling system greatly contributes to SAF and therefore must be repaired or restored quickly to minimize the effect on the service.

Table 13: AALRT System KPIs

Year	Planned Trips	Actual Trips	No. of Trips Cancelled	Cancel due to signal sys failure	No. of Trips Delayed	Delays due to signal sys failure	TSD	Punctuality	**Signal Sys Contribution**	
									TSD	Punctuality
2016	83,056	82,242	814	61	6,699	1,032	99.02%	91.85%	7.49%	15.41%
2017	86,089	83,641	2,448	241	7,587	1,345	97.16%	90.93%	9.84%	17.73%
2018	89,908	86,260	3,648	423	8,233	1,598	95.94%	90.46%	11.60%	19.41%

The average punctuality of major European light rail operators is around 95 percent, where trains arrive at the final destination within the international margin of five minutes, although some operators use a three-minute margin and still manage a punctuality of around 95 percent (arrival time is checked only at the end of the trip and not at intermediate stations). Table 14 compares the average punctuality of the AALRT with other light rail operators and it can be seen that the AALRT still has room for improvement when compared with international benchmarks.

Table 14: Punctuality Comparison Among Selected Rail Operators

Country	**Margin used**	**Punctuality**
Dubai Red Line (2017) [37]	5 minutes	99.23%
London Docklands LRT (2017) [37]	5 minutes	99.11%
Copenhagen Metro – Denmark (2017) [37]	5 minutes	98.7%
Milan Line 5 – Italy (2017) [37]	5 minutes	93.0%
Barcelona – Spain (2017) [37]	5 minutes	94.72%
Nottingham Express Transit – UK (2018) [38]	5 minutes	93.3%
Addis Ababa LRT – Ethiopia (case study) (2018)	5 minutes	91.08%

4.3 Life Cycle Cost Analysis

The corrective maintenance costs of the various signaling assets were calculated. Three specific contributors to this cost — spare parts cost, delay cost, and repair time cost — were considered (see Figures 15, 16 and 17). To measure the maintenance performance, an analysis of the cost of corrective maintenance was done with the aim of finding the shares constituting the cost. Figure 18 shows that in the three years of operation the repair time cost represents the highest percentage of the corrective maintenance cost, followed by train delay cost. This means that more time was spent on repair/restoration, thus resulting in huge costs incurred.

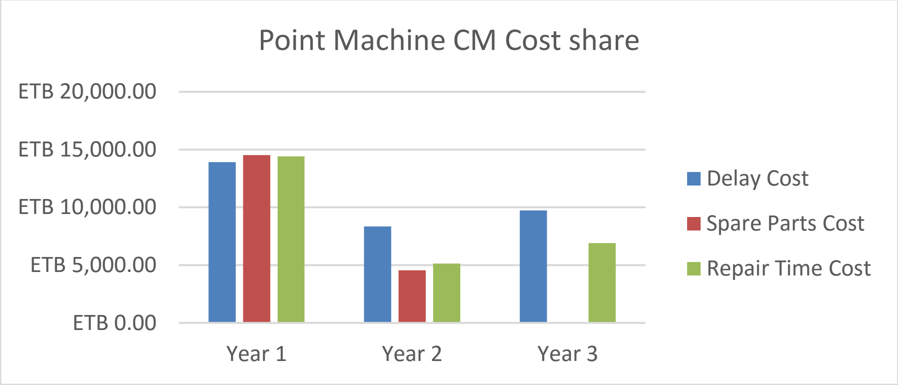


Figure 15: Point Machine CM cost proportion

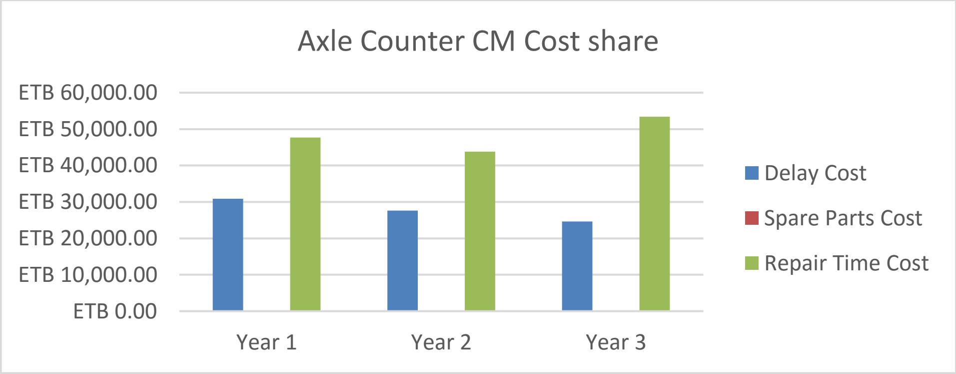


Figure 16: Axle Counter CM cost proportion

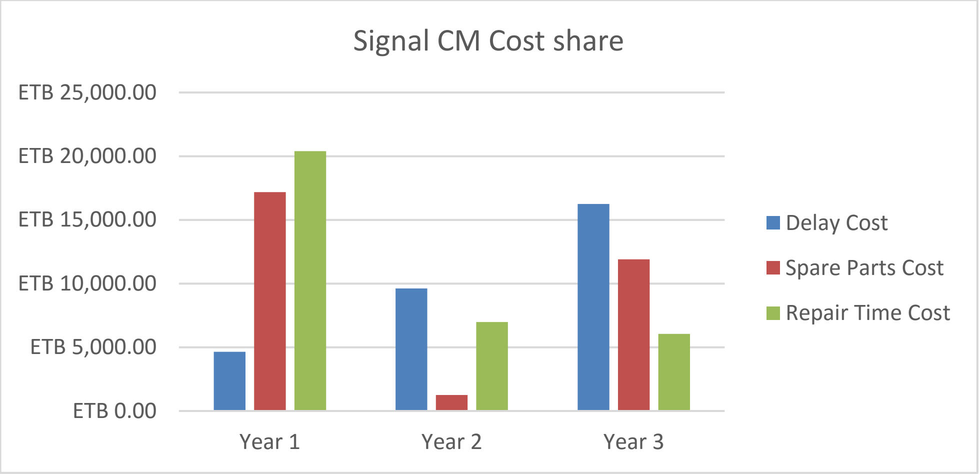


Figure 17: Signal CM cost proportion

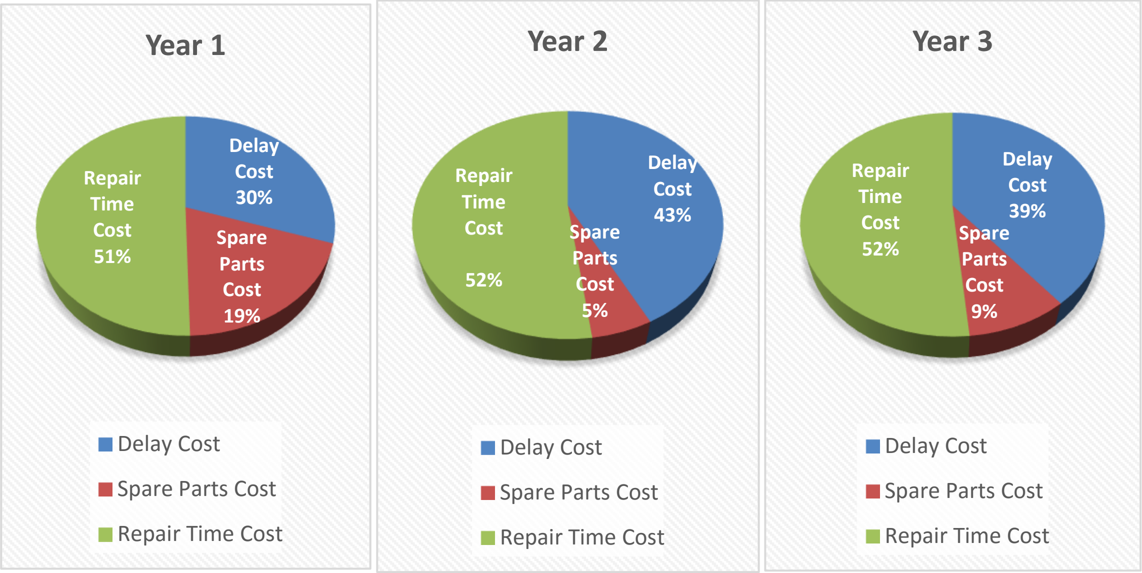


Figure 18: Annual CM cost proportion for the signaling system

For each individual signaling asset, a sensitivity analysis was carried out to show how variations in the LCC parameters affect the LCC value. Figures 19 – 21 show the percentage change in the total LCC value when different LCC parameters are changed by 10%. It is clear that the parameters MTTR, MTBF, cost of spare parts (C_P), and discount rate (r) have a significant effect on the life cycle cost of the signaling assets. Moreover, the parameters MTTR, number of workers (n_L), labor cost (C_L), spare parts cost (C_P), and cost of tools (C_E) have a positive contribution to the LCC value, while MTBF and discount rate (r) have a negative contribution to the LCC value. From the sensitivity analysis, it is clear that some LCC parameters are more critical than others for purposes of maintenance optimization.

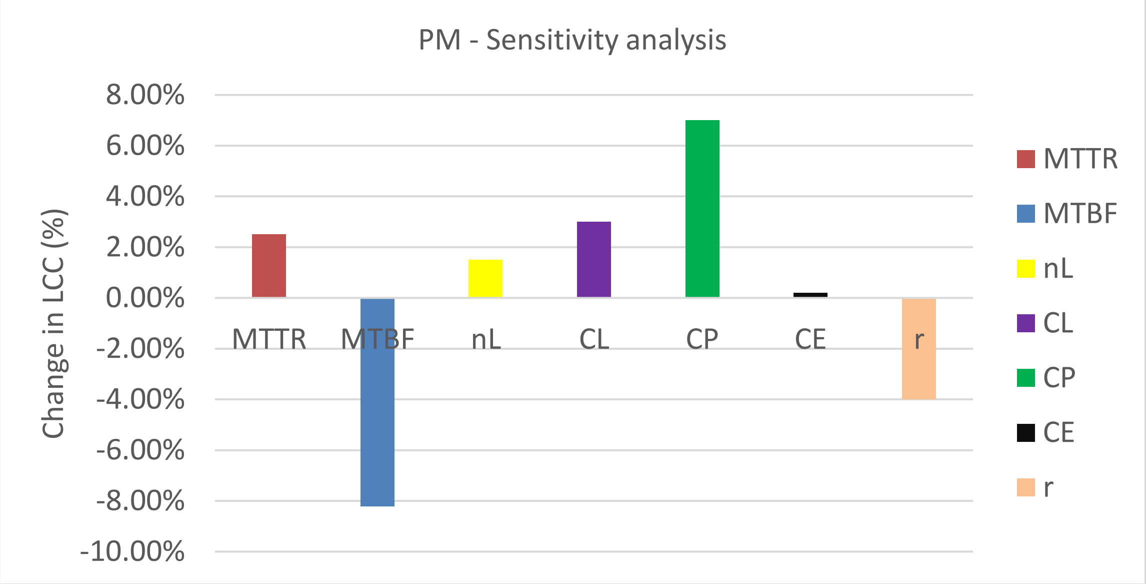


Figure 19: Sensitivity analysis for Point machine LCC cost

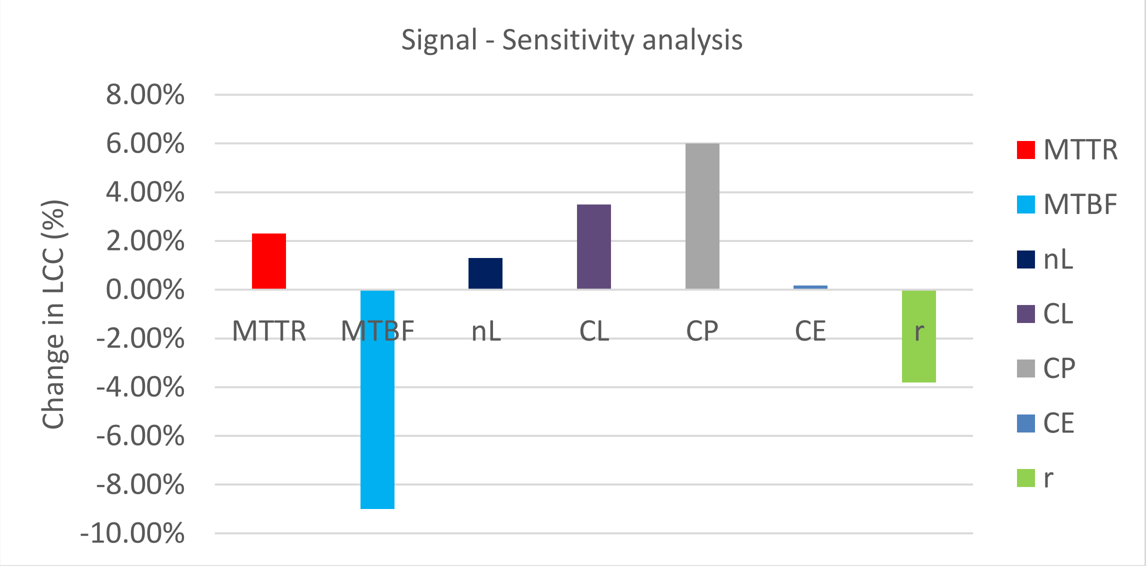


Figure 20: Sensitivity analysis for signal LCC cost

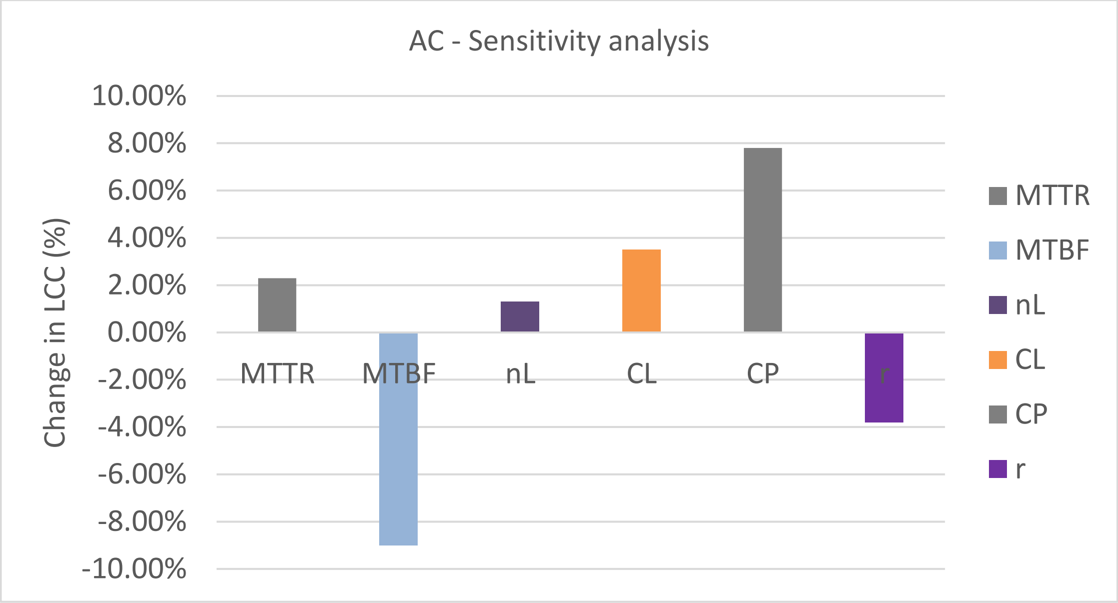


Figure 21: Sensitivity analysis for axle counter LCC cost

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the conclusions derived from the results of the analysis and provides recommendations for the AALRT maintenance performance and further research work.

This research studied an integrated RAMS and LCC analysis to optimize the maintenance of railway signaling systems. Equations were formulated for assigning costs to repair/restore asset failures, service loss, and life cycle cost during the operation and maintenance phase. Thereafter, a case study on signaling system historical corrective maintenance data was carried out.

5.1 Conclusions

Historical corrective maintenance records have been used to statistically characterize system failures in terms of RAMS. This information, together with maintenance cost figures, has been used in LCC calculations to obtain cost estimates and cost driver's dependencies. The parameters with a significant effect on the LCC value have been identified using sensitivity analysis.

The axle counter failures account for more than 80% of all signaling system failures. Preventive measures such as scheduled resets during out-of-service hours can be adopted to reduce the occurrence of failures during in-service hours. With 4.9% of the signaling failures causing traffic interruption, it is clear that the signaling system greatly contributes to SAF and therefore must be repaired or restored quickly to minimize the effect on the service. On corrective maintenance performance, repair time cost accounts for more than 50% of the corrective maintenance cost. A review of the corrective maintenance procedures is needed to minimize the time spent on maintenance as this greatly affects the costs and revenues of the operator.

Various measures can be taken to improve the RAMS performance of the signaling system: by scheduled resets to reduce failure occurrence; minimizing restoration time to improve availability; improving availability of tools to enhance maintenance performance; and ensuring safety. Although there is wide variation in maintenance practices, with some railway operators carrying out many periodic inspections than others, modern signaling equipment can easily be adapted to report the condition of components to a control center, alerting maintenance staff to impending failures and allowing timely intervention.

The results of the RAM analysis could be used as a criterion for maintenance cycle regulation. Modifying the maintenance cycle according to the MTBF can improve the reliability by processing maintenance work early. The results can also be used as a reference to determine critical areas of asset maintenance and the order of spare parts acquisition. Enhancing inter-departmental knowledge transfer can also greatly improve the maintenance performance in an organization. Better liaison with maintenance teams by management can inspire front-line signaling engineers to share best practices and reduce failure rates or improve repair rates. Their combined effort can make a tangible difference to the reliability and cost of maintaining a signaling system.

5.2 Recommendations

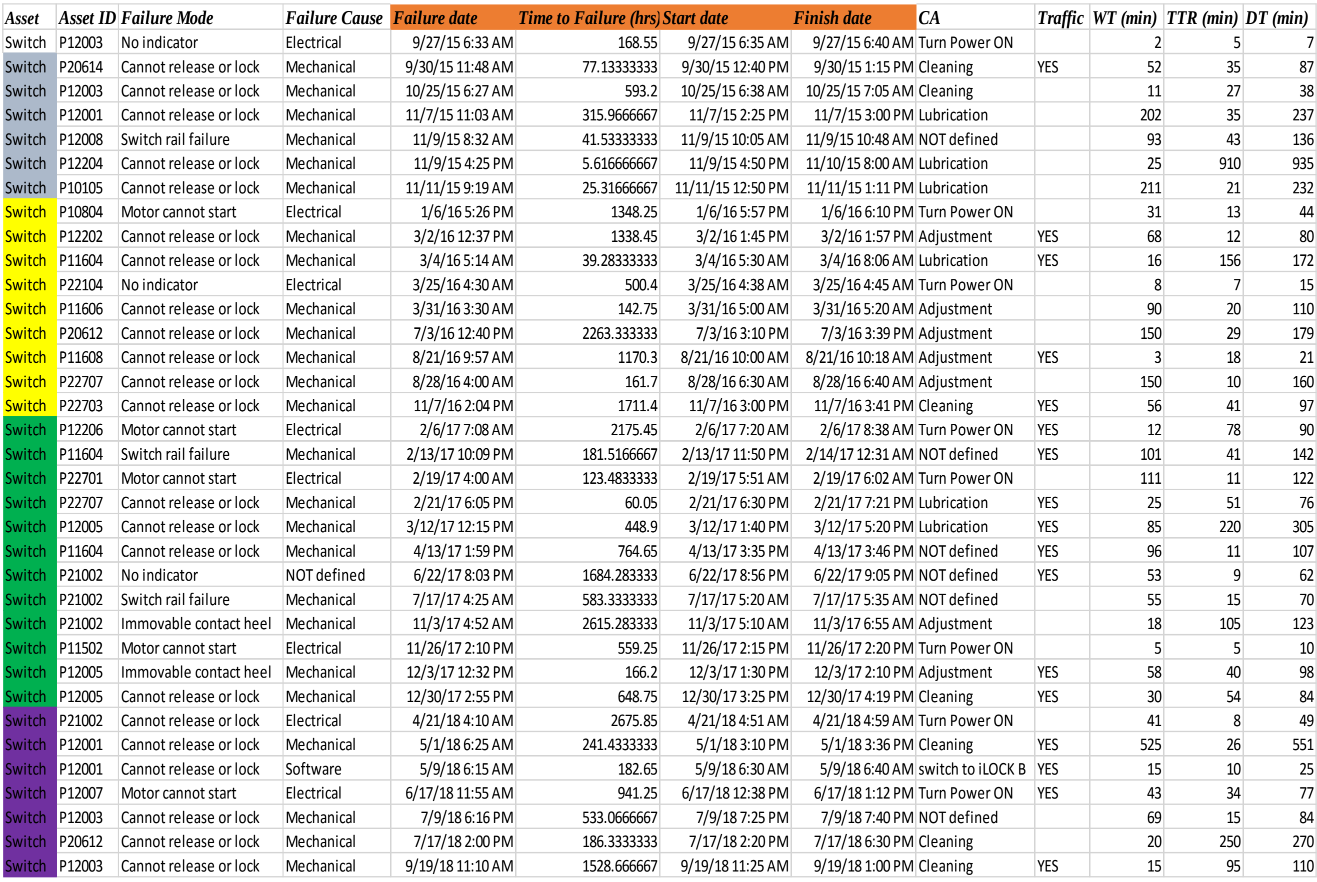
Based on the data analysis results of the case study (AALRT), the following points are recommended to improve the maintenance performance:

- Provide support for incident reporting and resolution, and failure analysis. This can be achieved by developing a Failure Reporting, Analysis and Corrective Action System (FRACAS), which incorporates a data repository of lessons learned and reliability data for further analysis.
- Improve maintenance support to ensure short restoration times. Carry out reliable maintenance actions, and adopt measures to prevent recurrence of these failures.
- Proposals for changes in the design and maintenance strategy for signaling assets must be done using quantified values of cost instead of just failure rates and the number of inspection remarks.

Arising from the results of this research, the following points can form the basis for further research:

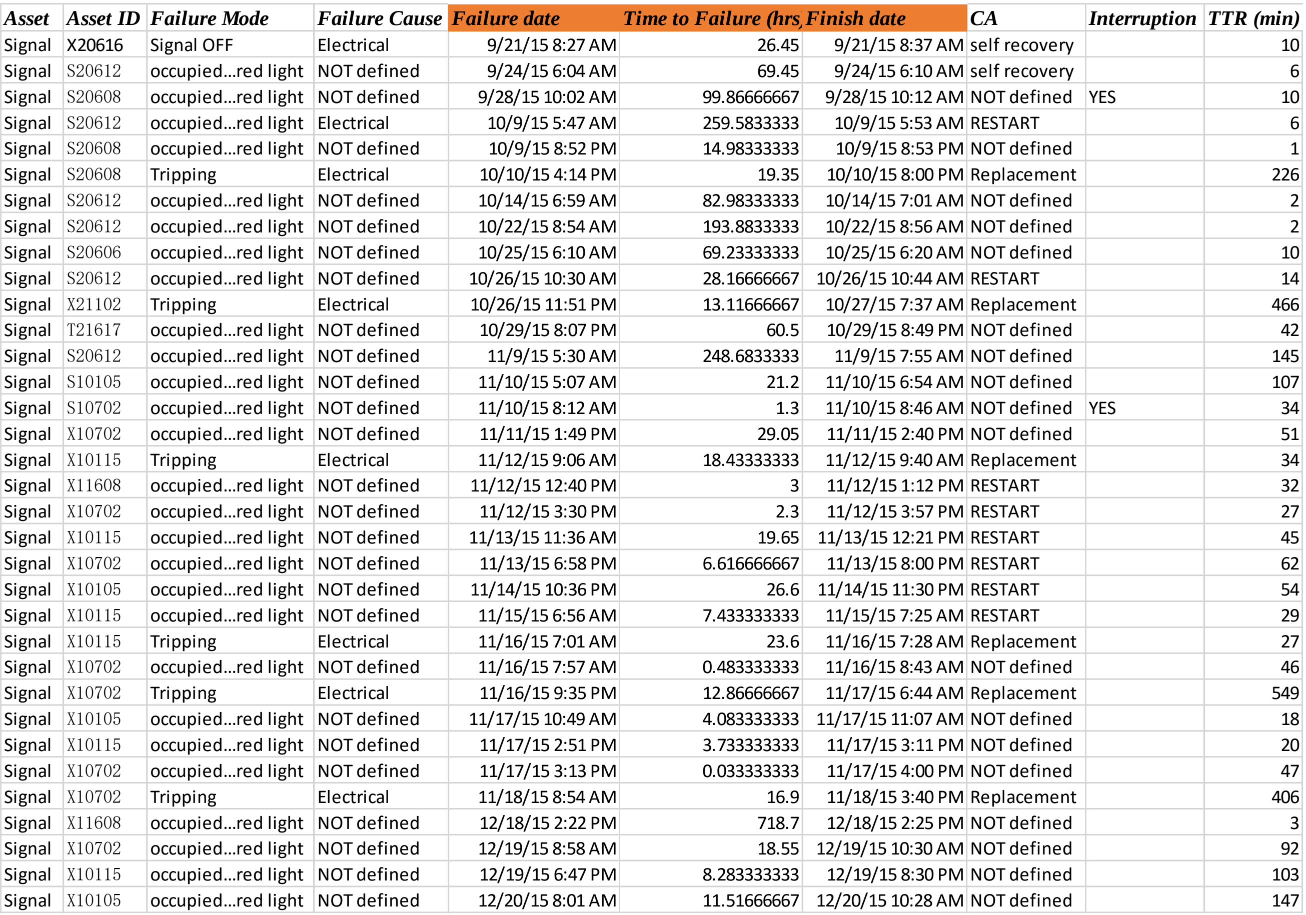
- Include preventive maintenance in the analysis.
- Evaluate RAMS and LCC on the entire signaling system during the operation and maintenance phase.
- Detailed estimation of the variable cost in LCC by performing uncertainty analysis, and considering risk analysis in the LCC calculations.

APPENDIX



Asset	*Asset ID*	*Failure Mode*	*Failure Cause*	*Failure date*	*Time to Failure (hrs)*	*Start date*	*Finish date*	*CA*	*Traffic*	*WT (min)*	*TTR (min)*	*DT (min)*
Switch	P12003	No indicator	Electrical	9/27/15 6:33 AM	168.55	9/27/15 6:35 AM	9/27/15 6:40 AM	Turn Power ON		2	5	7
Switch	P20614	Cannot release or lock	Mechanical	9/30/15 11:48 AM	77.13333333	9/30/15 12:40 PM	9/30/15 1:15 PM	Cleaning	YES	52	35	87
Switch	P12003	Cannot release or lock	Mechanical	10/25/15 6:27 AM	593.2	10/25/15 6:38 AM	10/25/15 7:05 AM	Cleaning		11	27	38
Switch	P12001	Cannot release or lock	Mechanical	11/7/15 11:03 AM	315.9666667	11/7/15 2:25 PM	11/7/15 3:00 PM	Lubrication		202	35	237
Switch	P12008	Switch rail failure	Mechanical	11/9/15 8:32 AM	41.53333333	11/9/15 10:05 AM	11/9/15 10:48 AM	NOT defined		93	43	136
Switch	P12204	Cannot release or lock	Mechanical	11/9/15 4:25 PM	5.616666667	11/9/15 4:50 PM	11/10/15 8:00 AM	Lubrication		25	910	935
Switch	P10105	Cannot release or lock	Mechanical	11/11/15 9:19 AM	25.31666667	11/11/15 12:50 PM	11/11/15 1:11 PM	Lubrication		211	21	232
Switch	P10804	Motor cannot start	Electrical	1/6/16 5:26 PM	1348.25	1/6/16 5:57 PM	1/6/16 6:10 PM	Turn Power ON		31	13	44
Switch	P12202	Cannot release or lock	Mechanical	3/2/16 12:37 PM	1338.45	3/2/16 1:45 PM	3/2/16 1:57 PM	Adjustment	YES	68	12	80
Switch	P11604	Cannot release or lock	Mechanical	3/4/16 5:14 AM	39.28333333	3/4/16 5:30 AM	3/4/16 8:06 AM	Lubrication	YES	16	156	172
Switch	P22104	No indicator	Electrical	3/25/16 4:30 AM	500.4	3/25/16 4:38 AM	3/25/16 4:45 AM	Turn Power ON		8	7	15
Switch	P11606	Cannot release or lock	Mechanical	3/31/16 3:30 AM	142.75	3/31/16 5:00 AM	3/31/16 5:20 AM	Adjustment		90	20	110
Switch	P20612	Cannot release or lock	Mechanical	7/3/16 12:40 PM	2263.333333	7/3/16 3:10 PM	7/3/16 3:39 PM	Adjustment		150	29	179
Switch	P11608	Cannot release or lock	Mechanical	8/21/16 9:57 AM	1170.3	8/21/16 10:00 AM	8/21/16 10:18 AM	Adjustment	YES	3	18	21
Switch	P22707	Cannot release or lock	Mechanical	8/28/16 4:00 AM	161.7	8/28/16 6:30 AM	8/28/16 6:40 AM	Adjustment		150	10	160
Switch	P22703	Cannot release or lock	Mechanical	11/7/16 2:04 PM	1711.4	11/7/16 3:00 PM	11/7/16 3:41 PM	Cleaning	YES	56	41	97
Switch	P12206	Motor cannot start	Electrical	2/6/17 7:08 AM	2175.45	2/6/17 7:20 AM	2/6/17 8:38 AM	Turn Power ON	YES	12	78	90
Switch	P11604	Switch rail failure	Mechanical	2/13/17 10:09 PM	181.5166667	2/13/17 11:50 PM	2/14/17 12:31 AM	NOT defined	YES	101	41	142
Switch	P22701	Motor cannot start	Electrical	2/19/17 4:00 AM	123.4833333	2/19/17 5:51 AM	2/19/17 6:02 AM	Turn Power ON		111	11	122
Switch	P22707	Cannot release or lock	Mechanical	2/21/17 6:05 PM	60.05	2/21/17 6:30 PM	2/21/17 7:21 PM	Lubrication	YES	25	51	76
Switch	P12005	Cannot release or lock	Mechanical	3/12/17 12:15 PM	448.9	3/12/17 1:40 PM	3/12/17 5:20 PM	Lubrication	YES	85	220	305
Switch	P11604	Cannot release or lock	Mechanical	4/13/17 1:59 PM	764.65	4/13/17 3:35 PM	4/13/17 3:46 PM	NOT defined	YES	96	11	107
Switch	P21002	No indicator	NOT defined	6/22/17 8:03 PM	1684.283333	6/22/17 8:56 PM	6/22/17 9:05 PM	NOT defined	YES	53	9	62
Switch	P21002	Switch rail failure	Mechanical	7/17/17 4:25 AM	583.3333333	7/17/17 5:20 AM	7/17/17 5:35 AM	NOT defined		55	15	70
Switch	P21002	Immovable contact heel	Mechanical	11/3/17 4:52 AM	2615.283333	11/3/17 5:10 AM	11/3/17 6:55 AM	Adjustment		18	105	123
Switch	P11502	Motor cannot start	Electrical	11/26/17 2:10 PM	559.25	11/26/17 2:15 PM	11/26/17 2:20 PM	Turn Power ON		5	5	10
Switch	P12005	Immovable contact heel	Mechanical	12/3/17 12:32 PM	166.2	12/3/17 1:30 PM	12/3/17 2:10 PM	Adjustment	YES	58	40	98
Switch	P12005	Cannot release or lock	Mechanical	12/30/17 2:55 PM	648.75	12/30/17 3:25 PM	12/30/17 4:19 PM	Cleaning	YES	30	54	84
Switch	P21002	Cannot release or lock	Electrical	4/21/18 4:10 AM	2675.85	4/21/18 4:51 AM	4/21/18 4:59 AM	Turn Power ON		41	8	49
Switch	P12001	Cannot release or lock	Mechanical	5/1/18 6:25 AM	241.4333333	5/1/18 3:10 PM	5/1/18 3:36 PM	Cleaning	YES	525	26	551
Switch	P12001	Cannot release or lock	Software	5/9/18 6:15 AM	182.65	5/9/18 6:30 AM	5/9/18 6:40 AM	switch to iLOCK B	YES	15	10	25
Switch	P12007	Motor cannot start	Electrical	6/17/18 11:55 AM	941.25	6/17/18 12:38 PM	6/17/18 1:12 PM	Turn Power ON	YES	43	34	77
Switch	P12003	Cannot release or lock	Mechanical	7/9/18 6:16 PM	533.0666667	7/9/18 7:25 PM	7/9/18 7:40 PM	NOT defined		69	15	84
Switch	P20612	Cannot release or lock	Mechanical	7/17/18 2:00 PM	186.3333333	7/17/18 2:20 PM	7/17/18 6:30 PM	Cleaning		20	250	270
Switch	P12003	Cannot release or lock	Mechanical	9/19/18 11:10 AM	1528.666667	9/19/18 11:25 AM	9/19/18 1:00 PM	Cleaning	YES	15	95	110

Figure 22: Sample point machine data

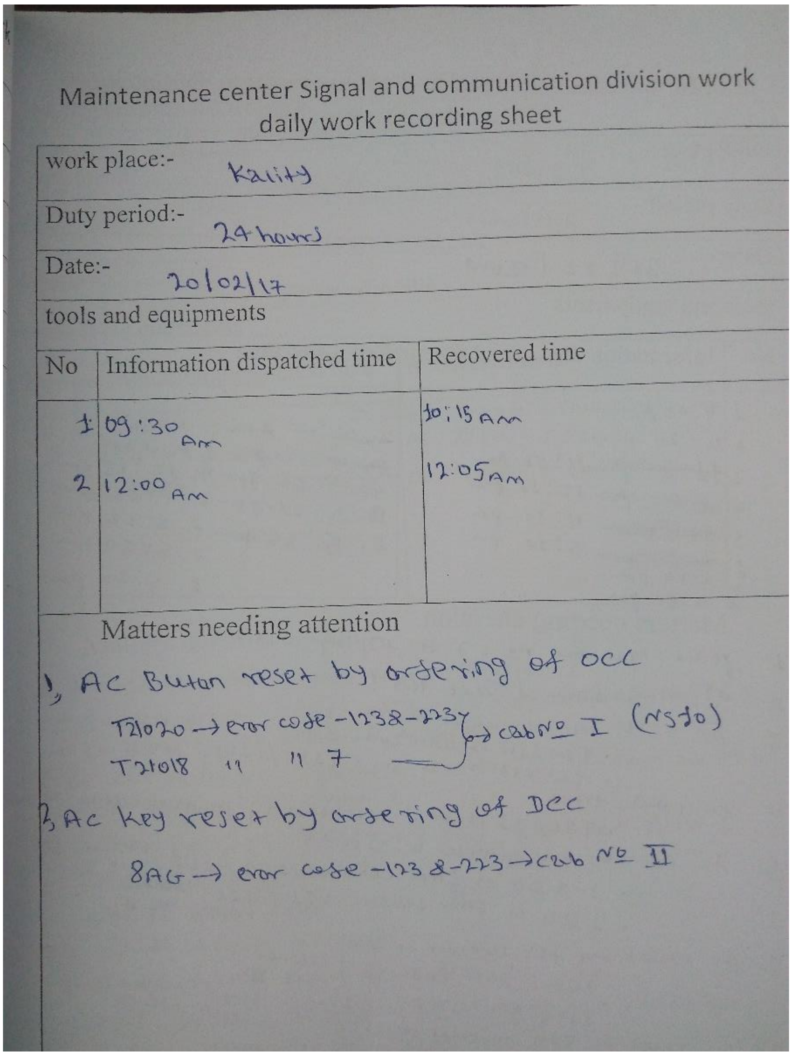


Asset	*Asset ID*	*Failure Mode*	*Failure Cause*	*Failure date*	*Time to Failure (hrs*	*Finish date*	*CA*	*Interruption*	*TTR (min)*
Signal	X20616	Signal OFF	Electrical	9/21/15 8:27 AM	26.45	9/21/15 8:37 AM	self recovery		10
Signal	S20612	occupied…red light	NOT defined	9/24/15 6:04 AM	69.45	9/24/15 6:10 AM	self recovery		6
Signal	S20608	occupied…red light	NOT defined	9/28/15 10:02 AM	99.86666667	9/28/15 10:12 AM	NOT defined	YES	10
Signal	S20612	occupied…red light	Electrical	10/9/15 5:47 AM	259.5833333	10/9/15 5:53 AM	RESTART		6
Signal	S20608	occupied…red light	NOT defined	10/9/15 8:52 PM	14.98333333	10/9/15 8:53 PM	NOT defined		1
Signal	S20608	Tripping	Electrical	10/10/15 4:14 PM	19.35	10/10/15 8:00 PM	Replacement		226
Signal	S20612	occupied…red light	NOT defined	10/14/15 6:59 AM	82.98333333	10/14/15 7:01 AM	NOT defined		2
Signal	S20612	occupied…red light	NOT defined	10/22/15 8:54 AM	193.8833333	10/22/15 8:56 AM	NOT defined		2
Signal	S20606	occupied…red light	NOT defined	10/25/15 6:10 AM	69.23333333	10/25/15 6:20 AM	NOT defined		10
Signal	S20612	occupied…red light	NOT defined	10/26/15 10:30 AM	28.16666667	10/26/15 10:44 AM	RESTART		14
Signal	X21102	Tripping	Electrical	10/26/15 11:51 PM	13.11666667	10/27/15 7:37 AM	Replacement		466
Signal	T21617	occupied…red light	NOT defined	10/29/15 8:07 PM	60.5	10/29/15 8:49 PM	NOT defined		42
Signal	S20612	occupied…red light	NOT defined	11/9/15 5:30 AM	248.6833333	11/9/15 7:55 AM	NOT defined		145
Signal	S10105	occupied…red light	NOT defined	11/10/15 5:07 AM	21.2	11/10/15 6:54 AM	NOT defined		107
Signal	S10702	occupied…red light	NOT defined	11/10/15 8:12 AM	1.3	11/10/15 8:46 AM	NOT defined	YES	34
Signal	X10702	occupied…red light	NOT defined	11/11/15 1:49 PM	29.05	11/11/15 2:40 PM	NOT defined		51
Signal	X10115	Tripping	Electrical	11/12/15 9:06 AM	18.43333333	11/12/15 9:40 AM	Replacement		34
Signal	X11608	occupied…red light	NOT defined	11/12/15 12:40 PM	3	11/12/15 1:12 PM	RESTART		32
Signal	X10702	occupied…red light	NOT defined	11/12/15 3:30 PM	2.3	11/12/15 3:57 PM	RESTART		27
Signal	X10115	occupied…red light	NOT defined	11/13/15 11:36 AM	19.65	11/13/15 12:21 PM	RESTART		45
Signal	X10702	occupied…red light	NOT defined	11/13/15 6:58 PM	6.616666667	11/13/15 8:00 PM	RESTART		62
Signal	X10105	occupied…red light	NOT defined	11/14/15 10:36 PM	26.6	11/14/15 11:30 PM	RESTART		54
Signal	X10115	occupied…red light	NOT defined	11/15/15 6:56 AM	7.433333333	11/15/15 7:25 AM	RESTART		29
Signal	X10115	Tripping	Electrical	11/16/15 7:01 AM	23.6	11/16/15 7:28 AM	Replacement		27
Signal	X10702	occupied…red light	NOT defined	11/16/15 7:57 AM	0.483333333	11/16/15 8:43 AM	NOT defined		46
Signal	X10702	Tripping	Electrical	11/16/15 9:35 PM	12.86666667	11/17/15 6:44 AM	Replacement		549
Signal	X10105	occupied…red light	NOT defined	11/17/15 10:49 AM	4.083333333	11/17/15 11:07 AM	NOT defined		18
Signal	X10115	occupied…red light	NOT defined	11/17/15 2:51 PM	3.733333333	11/17/15 3:11 PM	NOT defined		20
Signal	X10702	occupied…red light	NOT defined	11/17/15 3:13 PM	0.033333333	11/17/15 4:00 PM	NOT defined		47
Signal	X10702	Tripping	Electrical	11/18/15 8:54 AM	16.9	11/18/15 3:40 PM	Replacement		406
Signal	X11608	occupied…red light	NOT defined	12/18/15 2:22 PM	718.7	12/18/15 2:25 PM	NOT defined		3
Signal	X10702	occupied…red light	NOT defined	12/19/15 8:58 AM	18.55	12/19/15 10:30 AM	NOT defined		92
Signal	X10115	occupied…red light	NOT defined	12/19/15 6:47 PM	8.283333333	12/19/15 8:30 PM	NOT defined		103
Signal	X10105	occupied…red light	NOT defined	12/20/15 8:01 AM	11.51666667	12/20/15 10:28 AM	NOT defined		147

Figure 23: Sample signal data

Asset	Failure Mode	Failure Cause	Failure date	Time to Failure (hrs)	Finish date	CA	Interruption	TTR (min)
AC	Occupied	NOT defined	9/22/15 9:05 AM	51.08333333	9/22/15 9:40 AM	KEY RESET	YES	35
AC	Occupied	NOT defined	9/22/15 11:53 AM	2.216666667	9/22/15 12:40 PM	PUSH BUTTON RESET	YES	47
AC	Occupied	NOT defined	9/23/15 5:45 PM	29.08333333	9/23/15 5:49 PM	PUSH BUTTON RESET		4
AC	Occupied	NOT defined	9/24/15 6:15 AM	12.43333333	9/24/15 6:25 AM	PUSH BUTTON RESET		10
AC	Occupied	NOT defined	9/24/15 6:15 PM	11.83333333	9/24/15 6:23 PM	PUSH BUTTON RESET		8
AC	Occupied	NOT defined	9/29/15 7:30 PM	121.1166667	9/29/15 8:08 PM	KEY RESET		38
AC	Occupied	NOT defined	9/30/15 10:08 PM	26	9/30/15 11:13 PM	KEY RESET		65
AC	Occupied	Electrical	10/1/15 6:15 PM	19.03333333	10/1/15 6:30 PM	KEY RESET		15
AC	Occupied	NOT defined	10/2/15 5:09 AM	10.65	10/2/15 8:15 AM	KEY RESET		186
AC	Occupied	NOT defined	10/2/15 3:06 PM	6.85	10/2/15 4:00 PM	KEY RESET		54
AC	Negative axle	NOT defined	10/7/15 2:29 AM	106.4833333	10/7/15 4:03 AM	KEY RESET		94
AC	Negative axle	NOT defined	10/7/15 4:49 AM	0.766666667	10/7/15 5:36 AM	KEY RESET		47
AC	Negative axle	NOT defined	10/8/15 10:31 AM	28.91666667	10/8/15 11:45 AM	PUSH BUTTON RESET		74
AC	Negative axle	NOT defined	10/10/15 10:31 AM	46.76666667	10/10/15 12:36 PM	PUSH BUTTON RESET		125
AC	Negative axle	NOT defined	10/12/15 1:31 PM	48.91666667	10/12/15 2:31 PM	PUSH BUTTON RESET	YES	60
AC	Occupied	NOT defined	10/13/15 4:42 PM	26.18333333	10/13/15 5:21 PM	PUSH BUTTON RESET	YES	39
AC	Occupied	NOT defined	11/16/15 3:40 AM	802.3166667	11/16/15 7:28 AM	KEY RESET		228
AC	Negative axle	Unknown	11/19/15 2:38 PM	79.16666667	11/19/15 2:54 PM	KEY RESET		16
AC	Negative axle	NOT defined	12/3/15 5:05 PM	338.1833333	12/3/15 6:02 PM	KEY RESET		57
AC	Negative axle	NOT defined	12/5/15 10:05 PM	52.05	12/5/15 11:05 PM	PUSH BUTTON RESET		60
AC	Negative axle	NOT defined	12/24/15 10:11 AM	443.1	12/24/15 10:58 AM	PUSH BUTTON RESET		47
AC	Negative axle	NOT defined	12/24/15 4:54 PM	5.933333333	12/24/15 4:57 PM	PUSH BUTTON RESET		3
AC	Occupied	NOT defined	12/26/15 11:23 PM	54.43333333	12/27/15 6:40 AM	PUSH BUTTON RESET		437
AC	Occupied	NOT defined	12/28/15 7:35 AM	24.91666667	12/28/15 8:26 AM	KEY RESET		51
AC	Negative axle	NOT defined	12/29/15 12:21 PM	27.91666667	12/29/15 12:37 PM	KEY RESET		16
AC	Occupied	NOT defined	1/2/16 12:21 PM	95.73333333	1/2/16 12:51 PM	PUSH BUTTON RESET		30
AC	Occupied	NOT defined	1/2/16 1:41 PM	0.833333333	1/2/16 1:46 PM	PUSH BUTTON RESET		5
AC	Negative axle	NOT defined	1/3/16 11:36 PM	33.83333333	1/3/16 11:46 PM	PUSH BUTTON RESET		10
AC	Occupied	NOT defined	1/5/16 12:52 PM	37.1	1/5/16 3:01 PM	PUSH BUTTON RESET		129
AC	Occupied	NOT defined	1/6/16 11:20 AM	20.31666667	1/6/16 1:43 PM	KEY RESET		143
AC	Occupied	NOT defined	1/7/16 10:20 AM	20.61666667	1/7/16 12:13 PM	KEY RESET		113
AC	Occupied	NOT defined	1/8/16 12:15 PM	24.03333333	1/8/16 12:47 PM	KEY RESET		32
AC	Occupied	Electrical	1/8/16 4:55 PM	4.133333333	1/8/16 5:13 PM	KEY RESET		18
AC	Occupied	NOT defined	1/10/16 2:41 PM	45.46666667	1/10/16 2:45 PM	KEY RESET		4
AC	Occupied	NOT defined	1/11/16 11:07 AM	20.36666667	1/11/16 11:15 AM	KEY RESET		8
AC	Negative axle	NOT defined	1/14/16 12:50 PM	73.58333333	1/14/16 1:00 PM	KEY RESET		10
AC	Occupied	Electrical	1/15/16 7:55 PM	30.91666667	1/15/16 8:35 PM	KEY RESET		40
AC	Occupied	NOT defined	1/16/16 7:03 AM	10.46666667	1/16/16 7:31 AM	KEY RESET		28
AC	Occupied	NOT defined	1/16/16 5:44 PM	10.21666667	1/16/16 8:17 PM	KEY RESET		153
AC	Occupied	NOT defined	1/19/16 8:53 PM	72.6	1/19/16 9:28 PM	KEY RESET		35
AC	Negative axle	NOT defined	1/20/16 4:35 PM	19.11666667	1/20/16 4:43 PM	KEY RESET		8
AC	Occupied	NOT defined	1/20/16 4:50 PM	0.116666667	1/20/16 5:18 PM	KEY RESET		28
AC	Occupied	NOT defined	1/21/16 8:48 PM	27.5	1/22/16 7:56 AM	KEY RESET		668
AC	Occupied	NOT defined	1/23/16 10:45 AM	26.81666667	1/23/16 11:01 AM	KEY RESET		16

Figure 24: Sample axle counter data



Maintenance center Signal and communication division work daily work recording sheet

work place:- Kality

Duty period:- 24 hours

Date:- 20/02/17

tools and equipments

No	Information dispatched time	Recovered time
1	09:30 Am	10:15 Am
2	12:00 Am	12:05 Am

Matters needing attention

1, AC Buton reset by ordering of OCC

T21020 → error code -1238-223 } → cab No I (NS10)

T21018 " " 7

2, AC key reset by ordering of DCC

8AG → error code -1238-223 → cab No II

Figure 25: Sample work order

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