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

MAINTENANCE INTERVAL DETERMINATION FOR DIESEL ELECTRIC LOCOMOTIVES

A CASE STUDY OF UGANDA RAILWAYS CORPORATION

A Thesis in Railway Engineering (Traction and Train Control)

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A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Railway Engineering (Traction and Train Control)

June 2019 Addis Ababa

APPROVAL

The undersigned have examined the thesis entitled “Maintenance Interval Determination for Diesel Electric Locomotives” presented by Morris Mugyema a candidate for the degree of Master of Science in Railway Engineering (Traction and Train Control), African Railway Centre of Excellency, Addis Ababa Institute of Technology, and hereby certify that it is worthy of acceptance.

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UNDERTAKING

I certify that the research work “Maintenance Interval Determination for Diesel Electric Locomotives” is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources, it has been properly acknowledged/referred.

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ABSTRACT

Uganda Railways Corporation (URC) operates and maintains the railway line from Kampala to Malaba (single line of 251km) that is currently active. URC uses diesel-electric locomotives as mainline locomotives. Nalukolongo Railway Workshop (NRW) is the main workshop which does maintenance of locomotives and wagons. Proper maintenance system will ensure high availability of the railway network.

The maintenance concepts and intervals for all locomotives are, of course, dependent on the type of locomotive and what the Original Equipment Manufacturer (OEM) has prescribed for it. URC is therefore generally reluctant in determining its own maintenance strategies that would provide more efficient or effective use of maintenance resources and higher availability for the entire fleet.

OEM's prescribe inspection and replacement moments dependent on time, cycles or working hours and they consider a certain usage pattern that is not necessarily applicable for URC. Moreover, inspection and maintenance periods also vary with the operating environment.

Maintenance interval based on OEM is not reliable since actual operating conditions can differ thus need to adjust maintenance interval for a specific operating environment. Also, the application of preventive maintenance through experience is a conventional preventive maintenance practice. Through experience, no standard procedures are followed, thus it's not effective.

In this thesis, a step by step model for the "in house locomotive maintenance interval determination" is developed and tested. The model utilizes the cost per unit time function. The minimization of the total cost per unit time $C(t)$ allows obtaining the optimal replacement interval. By using a graphical method on the cost per unit time function the optimal replacement time is obtained and the maintenance schedule is modified accordingly. The model is applied to improve the maintenance performance and hence increase the availability of the locomotives.

Keywords: *railway, locomotive, maintenance, availability, reliability, optimization*

ACKNOWLEDGMENTS

I offer my sincere gratitude to my advisor Dr. Yalemzewd Negash (Ph.D.) for giving me the opportunity to do my master’s research with him and for the invaluable guidance, support, and encouragement. During my master’s research with him, he gave me consideration and support which enabled me to overcome all challenges faced and I can say I am fortunate to have him.

I am grateful to a great group of friends and colleagues at the African Railway Centre of Excellence for their assistance, comments, and friendship during this journey at Addis Ababa University.

I am grateful to Uganda Railways Corporation who provided me with data for my research. Further gratitude goes to all the URC employees, in particular, those in the maintenance department that were helpful in providing all the necessary information that has been used in this research.

Last but not least I would like to express my deepest gratitude to my family and my parents who always believed in me and encouraged me during these two years. Special thanks go to my mother whose encouragement has always been a source of inspiration. I am fortunate to have my lovely family and parents and would like to share this moment of joy with them.

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LIST OF ABBREVIATIONS

Term	Explanation / Meaning / Definition
CBM	Condition Based Maintenance
CDF	Cumulative Distribution Function
CM	Corrective Maintenance
CMMS	Computer Maintenance Management System
CPUT	Cost Per Unit Time
EARC	East African Railways Corporation
FMEA	Failure Mode Effect Analysis
MSc	Master of Science
MTBF	Mean Time Between Failure
MTTF	Mean Time to Failure
NRW	Nalukolongo Railway Workshop
OEM	Original Equipment Manufacturer
PDF	Probability Density Function
PM	Preventive Maintenance
RCM	Reliability Centered Maintenance
TBM	Time-Based Maintenance
TPM	Total Productive Maintenance
URC	Uganda Railways Corporation
USD	United States Dollar
WOs	Work Orders

1. INTRODUCTION

Traction in railway engineering means locomotion in which the driving force is obtained from electric motors. Electric traction systems involve the use of electric energy at some stage. The traction system is further subdivided into two groups.

1. Self-contained locomotives, for example, diesel-electric locomotives
2. Vehicles that receive power from a distributed network or suitably spaced sub stations e.g. railway electric locomotive fed from overhead ac supply [1].

The Uganda Railways Corporation (URC) is the parastatal railway of Uganda. It was formed after the breakup of the East African Railways Corporation (EARC) in 1977 when it took over the Ugandan part of the East African railways. URC’s system is rooted in the British colonial 1,000 mm (3 ft. 3 3⁄8 in) meter gauge Uganda Railways that was transformed after World War 1 into the EARC [2].

Uganda Railways Corporation runs and maintains the railway line from Malaba to Kampala (single line of 251km) that is currently active. URC uses diesel-electric locomotives as mainline locomotives. Nalukolongo Railway Workshop (NRW) is the main workshop which does maintenance of locomotives and wagons. Proper maintenance systems will ensure high dependability and availability of the railway network. The maintenance concepts and intervals for all locomotives are, of course, dependent on the type of locomotive and what the Original Equipment Manufacturer (OEM) has prescribed for it. URC is therefore generally reluctant in determining its own maintenance strategies that would provide more efficient or effective use of maintenance resources and higher availability for the entire fleet.

OEM’s prescribe inspection and replacement moments dependent on time, cycles or working hours and they consider a certain usage pattern that is not necessarily applicable for URC. Moreover, inspection and maintenance periods also vary with the operating environment.

Therefore, there is a need for URC to adapt to a given maintenance program of its locomotives while retaining a certain reliability level. In order to do so, a model needs to be created and tested where all factors, such as reliability and necessity are considered.

1.1 Statement of the Problem

Locomotives ensure availability of the railway transport network and their reliability affect the capacity and availability of the railway transport network. The function of the locomotives is to provide motive power for hauling of trains. Ensuring good maintenance practices will increase the availability of these locomotives during operation thus increasing the efficiency of the railway network.

Some of the major expenses incurred by the railway industry relate to the replacements and repairs of locomotives. Condition monitoring and preventive maintenance are the main approaches adopted to reduce these costs. However, most companies devote insufficient effort to modeling their systems and optimizing their maintenance strategies, to benefit fully from the advantages that they offer.

Maintaining of the locomotives requires multidisciplinary skills including mechanical, electrical, electronic and software skills. Hence improved efficiency in maintenance can be achieved by taking a number of different perspectives.

Through OEM recommendations, preventive maintenance is carried out at a fixed interval of time. However, this is not practical for specific operating environments. As such, actual outcomes may not satisfy company requirements.

Currently, there is no systematic evaluation of the maintenance program. The historical data has not been used for any analysis including reliability. Hence there is a need to analyze the failure data and to use the results to improve the maintenance program.

To the best of the researcher's knowledge, a lot of work has been done on locomotive maintenance approaches but there is no holistic approach to improve the maintenance system through a scientific approach to enhancing their dependability in general for a specific operating environment using historical data.

1.2 Objective of the Study

1.2.1 General Objective

The objective of this thesis is to study and explore the areas that could improve the maintenance performance of locomotives during the operating life cycle. The improvement of the locomotive performance will lead to an increase in the reliability of the railway transport network.

1.2.2 Specific Objectives

The specific objectives of this thesis are;

- Study the maintenance practices of the locomotives.
- Study and analyze the reliability characteristics of locomotives.
- Improve the reliability performance of the locomotives through the optimization of maintenance interval.
- Develop a step by step model for the "in house locomotive maintenance interval determination" based on a scientific approach.

1.3 Research Question

The proposition is transformed into a research question:

"How can historical maintenance data be used to determine a proper maintenance interval that leads to improved reliability of locomotives?"

1.4 Scope

The scope of research is to perform an analysis which will provide insight on the best way to improve the reliability of locomotives. The research will be limited to mainline diesel locomotives and data is based on URC's operations from Kampala to Malaba.

The research is made up of failure data, not failure modes.

1.5 Thesis Structure

This thesis is divided into 5 chapters

In Chapter 1, a detailed introduction which discusses the problem statement, objectives and research question is presented.

In Chapter 2, a detailed review of the literature on maintenance strategies focusing on the reliability of locomotives is presented. The different maintenance strategies are reviewed, a model for determining failure rate discussed and lastly maintenance optimization systems reviewed.

In Chapter, 3 the methodology that has been used in this research is described. The research process requires a sequence of steps which are discussed in this chapter. The framework is discussed and selected model for determining failure times is described.

In this chapter, the equation for optimization of maintenance interval is formulated and this is applied in chapter 4 to determine the optimal maintenance replacement/repair interval.

In Chapter 4, the discussed models in chapter 3 are used to present case studies for Uganda Railways Corporation (URC). Analysis of specific components is done, the failure parameters are obtained and used in the optimization model to determine the optimal maintenance interval. The reliability of the components is also obtained and a discussion is made in regards to reliability and cost per unit time for each item. A shape parameter sensitivity analysis for the different components is also carried out.

In Chapter 5, conclusions are made that offer some guidelines for future research and recommendations for URC.

2. LITERATURE REVIEW

2.1 Current State of Maintenance Practices in Railways

2.1.1 Overview of Maintenance Practices in Railways

Since the beginning of time, humans have always felt the need for the maintenance of their equipment, machine, even the most rudimentary tools. Most of the failures experienced have been a result of abuse, as it sometimes still happens. First, they would do maintenance only when it was no longer possible to run it. That was called “Breakdown or Reactive Maintenance”. It was until 1950’s that some groups of Japanese engineers started a new concept in maintenance that consisted on following the manufacturer's recommendations about the care that should be taken in the operation and maintenance of the machines and devices. That is called “Preventive Maintenance”. To make it more effective proper scheduling can be done on the basis of the history sheet of the system and past experience [3].

This can be achieved by identifying the most critical components in the various systems of the locomotive. Present practices of maintenance schedule, past failure data, and their experiences can be taken into consideration for identifying the critical components.

Over the last few decades, maintenance functions have drastically evolved with the growth of technology. Maintenance is defined as a set of activities or tasks used to restore an item to a state in which it can perform its designated functions [4] [5]. Maintenance strategies can be broadly classified into Corrective Maintenance (CM) and Preventive Maintenance (PM) strategies [6].

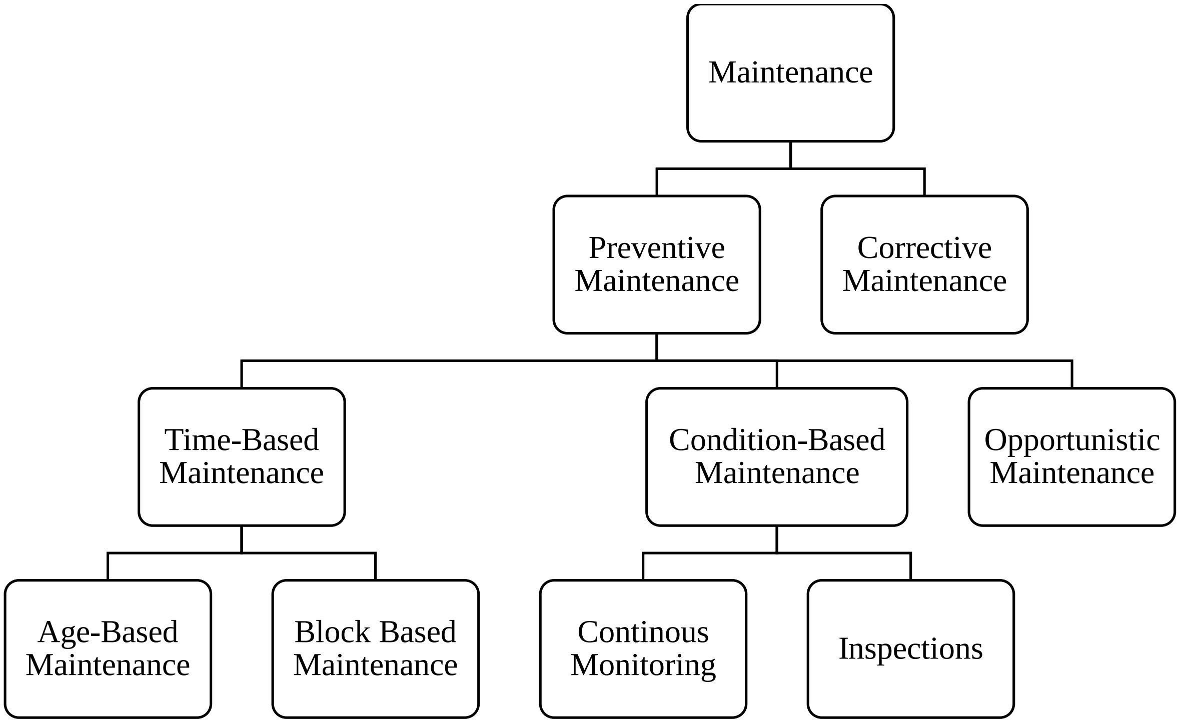

Figure 1. Schematic Overview of Maintenance Policies [6]

Corrective maintenance, also known as run-to-failure or reactive maintenance, is a strategy that is used to restore (repair or replace) some equipment to its required function after it has failed [7]. This strategy leads to high levels of machine downtime (production loss) and maintenance (repair or replacement) costs due to sudden failure [8].

An alternative to the corrective maintenance strategy is the preventive maintenance strategy. The concept of preventive maintenance involves the performance of maintenance activities prior to the failure of equipment [9]. Maintenance is the keyword in today’s corporate strategy for survival in the global market. With a scheduled and cost-effective maintenance of the facility, an organization can ensure its competitive edge in the market. A good preventive maintenance schedule is essential to perform an efficient shutdown. One of the main objectives of preventive maintenance is to reduce the failure rate or failure frequency of the equipment. This strategy contributes to minimizing failures and machine (equipment) downtime and increasing product reliability. In the industry, the application of the PM strategy can be generally performed through either experience or Original Equipment Manufacturer (OEM) recommendation.

The application of preventive maintenance through experience is a conventional preventive maintenance practice. In most cases, it is performed at regular time intervals [10]. Through experience, no standard procedures are followed, thus knowledge from technicians and engineers for maintenance purposes is an asset to the company. Technicians and engineers in this setting learn from previous mistakes and, based on their experience, can detect the abnormal conditions of a machine by sense. They can then decide the appropriate preventive maintenance actions to apply in order to avoid machine breakdown. The main drawback of preventive maintenance through experience, however, is that the company may face difficulties when the experienced person leaves the company. Moreover, such persons may not be present in production lines round-the-clock to solve maintenance problems.

Through OEM recommendations, preventive maintenance is carried out at a fixed time, for example, every 15 days, based on recommendations. However, this preventive maintenance practice is not usually applicable when attempting to maximize machine reliability performance. First, each machine works in a different environment and would, therefore, need different preventive maintenance schedules because actual operating conditions may be very different from those considered by the OEM. Second, machine designers often do not experience machine failures and have less knowledge of their prevention compared to those who operate and maintain such machines. Finally, OEM companies may have hidden agendas, that is, maximizing spare parts replacement through frequent PMs. This is supported by [11] Tam et al, who stated that PM intervals based on OEM recommendations may not be optimal because actual operating conditions may be very different from those considered by the OEM. As such, actual outcomes may not satisfy company requirements.

The operating environment of system/machine has considerable influence in system performance and its technical characteristics such as reliability and maintainability. The area of operational research introduced the application of PM based on a scientific approach in 1950. The scientific approach involves specific processes and principles that employ various analytical techniques, such as statistics, mathematical programming, artificial intelligence, etc. The main advantage of preventive maintenance practice based on the scientific approach is that decision making is based on facts acquired through real data analysis. In the literature, PM based on the scientific approach can be classified into two techniques: comprehensive-based and specific-based techniques. The comprehensive-based technique also known as maintenance concept development, which can be defined as a set of various maintenance interventions (experience-based, time-based, condition-based, etc.) and the general structure in which these interventions are foreseen [12]. The maintenance concept development forms the framework from which installation-specific maintenance techniques are developed and is the embodiment of the way a company thinks about the role of maintenance as an operational function.

Some examples of maintenance concepts are reliability-centered maintenance (RCM), business-centered maintenance, risk-based maintenance, total productive maintenance (TPM), and the center for industrial management maintenance concept development framework. The specific-based technique, as its name implies, is a specific maintenance technique that has unique principles for solving maintenance problems. Examples of the specific-based technique are time-based maintenance (TBM) and condition-based maintenance (CBM) [13].

In providing maintenance programs, the OEMs typically do not consider owner and stakeholder requirements and often focus solely on managing their risk. This is often achieved through a mix of usually ‘mandatory’ requirements during a warranty period and ‘recommended’ requirements after.

Product warranties provide assurance that production defects will be remedied by the supplier. Mandatory maintenance tasks during warranty protect the supplier’s warranty risk. Such programs are usually conservative, and often consider a worst-case scenario for operating environment and usage. These programs are unlikely to produce a balanced outcome (cost, risk, and performance) for the asset owner in the long term [14].

In [15] Charles et al, a periodic PM policy is described in which degraded machines are maintained in fixed time intervals, independent of machine failures. However, this is not practical as failure rates vary with age of equipment and also type of operating environment and have an adverse effect on reliability. The time interval should be obtained scientifically over time for a specific route to ensure dependability.

In [16] David et al, an overview of several models have been proposed for scheduling the preventive maintenance (PM) of complex repairable systems in the industry. These are often application-specific, and some make unrealistic assumptions about the stationarity of the process and quality of repairs. However, with the dynamic systems involved in a locomotive, a more holistic approach is required.

The main goal of preventive maintenance is to extend the useful life of an asset and prevent breakdowns from occurring.

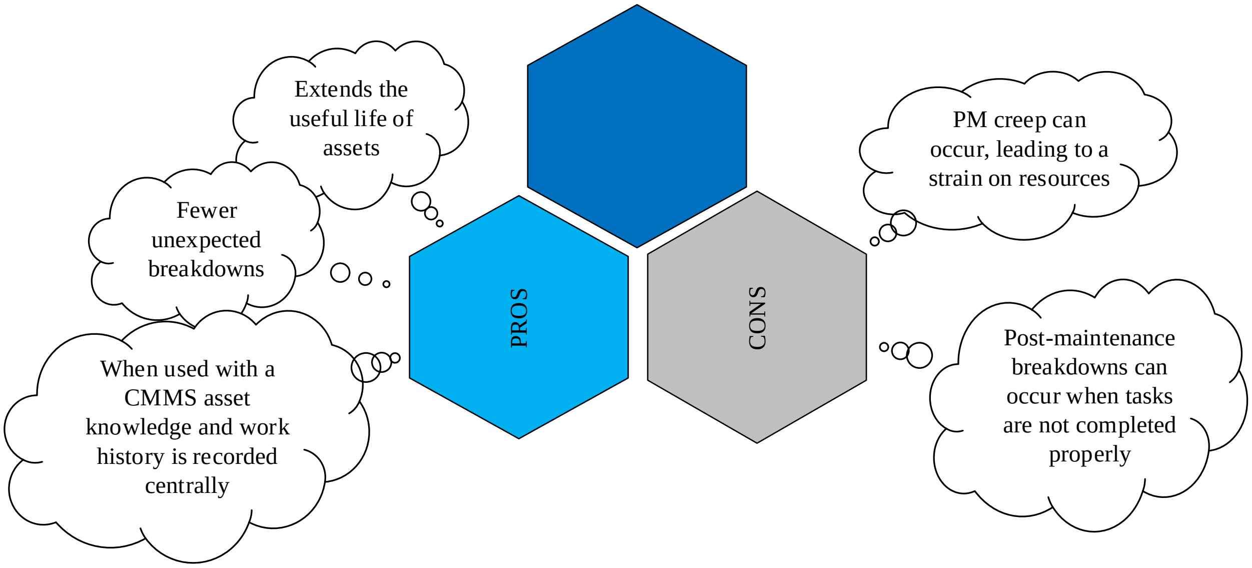

Figure 2. Pros and Cons of Preventive Maintenance

Computer Maintenance Management System (CMMS) software can be used to trigger Work Orders (WOs) when a PM is due. This allows a facility to automate much of its scheduling efforts, which is a key ingredient of this preventive approach. Because planning is done in advance, it’s much easier to have the right parts and resources on hand to complete each task.

As with all maintenance types, there are potential drawbacks to relying solely on preventive maintenance. If the PM schedule isn’t regularly monitored, audited, and improved, “PM creep” can occur. This is when technicians get bogged down by unnecessary tasks and cost the organization time and money.

Similarly, performing too many PMs can open the door for post-PM breakdowns. There are a number of ways to prevent this, but the risk gets higher as PMs get more frequent. The bottom line is, if a PM program is used, it should go hand in hand with PM optimization.

There are seven elements of PM. Each element is discussed below.

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

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

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

Testing: Periodically testing or checking out to determine serviceability and detect electrical/mechanical related degradation.

Alignment: Making changes to an item’s specified variable elements for the purpose of achieving optimum performance.

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

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

Currently, in Uganda Railways Corporation, the periodicity of preventive maintenance interventions is defined based on information from equipment suppliers. However, this technique presents some fragilities and it is intended that the periodicity of the interventions be determined more objectively, i.e., using a scientific approach.

In this thesis, the researcher has developed a step by step procedure to identify the optimal preventive interventions periodicity to suite URC's operating environment based on the available historical maintenance data. The procedures developed to this end consider two crucial processes: reliability study and determination of failure rate based on historical maintenance data for the specific operating environment.

2.2 Concept of Reliability

2.2.1 Reliability

Reliability is a characteristic of an item, expressed by the probability that the item will perform its required function under given conditions for a stated time interval. Reliability, failure rate and Mean Time Between Failure (MTBF) or Mean Time to Failure (MTTF) for non-repairable components are related.

$$R(t) = e^{-\int_0^t \lambda(t)dt} \qquad (1)$$

Where $R(t)$ is reliability, $\lambda(t)$ is failure rate, t is the time interval.

From a qualitative point of view, reliability can be defined as the ability of the item to remain functional. Quantitatively, reliability specifies the probability that no operational interruptions will occur during a stated time interval. This does not mean that redundant parts may not fail, such parts can fail and be repaired (without operational interruption at item (system) level) [17].

2.2.2 Failure Analysis and Failure Rate

A failure is defined as an event in which the ability of an item to perform a required function ends [18]. Failure Rate $\lambda(t)$: It is the probability of occurrence of a failure at a specific component age. The functional failures identification is followed by the identification of failure modes (which are the events that cause a functional failure) and the determination of the associated failure effects, that can be understood as what happens when a failure mode occurs. This is done by performing a failure mode and effect analysis (FMEA) for each function item. FMEA is a structured, bottom-up approach that starts with known potential failure modes at one subsystem level and investigates the effect on the next subsystem level. FMEA may be the source for virtually all subsequent reliability analyses and assessments because it forces an organization to systematically evaluate equipment and systems weaknesses, and their interrelationships that can lead to product unreliability [19].

When a system or component is unable to deliver its satisfactory function, the undesirable situation is defined as a failure [20]. In practice, two types of failures can be recognized: hard failure and soft failure. When a component stops functioning or the system breaks down, such a failure is a hard failure. For example, power outage due to a short circuit can lead to a complete shutdown of a production system. When a system or component can continue its operation with lower performance compared with its normal standard, such a failure is a soft failure. For example, a worn bearing connecting to the main shaft in a wind turbine will reduce the efficiency of energy generation, while the wind turbine is still operating. This lower performance results in a loss in terms of revenue generation, which we may also see as quality loss costs.

Item’s reliability is one of the inputs for the application of maintenance optimization models. So, failure analysis through component reliability study must be performed to this end. It can be carried out using various statistical tools and, the most common is the Weibull distribution [21]. This probability distribution has been widely used to model the times to failure of components due to its ability to model various lifetime distributions, including increasing, decreasing, or constant hazard rates. Data are essential inputs for building decision models that support evidence-based physical asset management. It must be recognized that mathematical models by themselves do not guarantee that the right decisions will be made if the data used does not have the required quality.

The reliability for Weibull distribution is formulated as

$$R(t) = e^{-\left(\frac{t}{\beta}\right)^{\alpha}} \qquad (2)$$

The value of the MTTF can then be determined using

$$MTTF = \beta\Gamma\left(1 + \frac{1}{\alpha}\right) \qquad (3),\ \ \Gamma(x) \text{ is the gamma function}$$

In the Weibull distribution model, β is the scale parameter and α is the shape parameter. The scale parameter shows the lifetime (age) of the component, while the shape parameter presents the characteristics of the component lifetime, whether with a decreasing, constant, or increasing failure rate. The types of failure rates based on the Weibull distribution model can be presented by α, as shown below:

$\alpha < 1$, represents a decreasing failure rate

$\alpha = 1$, represents a constant failure rate

$\alpha > 1$, represents an increasing failure rate

Weibull distribution fits a large number of failure characteristics of the equipment. The optimization of TBM decisions requires good quality and timely obtained data. Consequently, it is crucial that failure records, typically maintained in a database of CMMS, are properly treated and organized.

TBM assumes that the failure behavior (characteristic) of the equipment is predictable. This assumption is based on hazards or failure rate trends, known as bathtub curves, as shown in Figure 3.

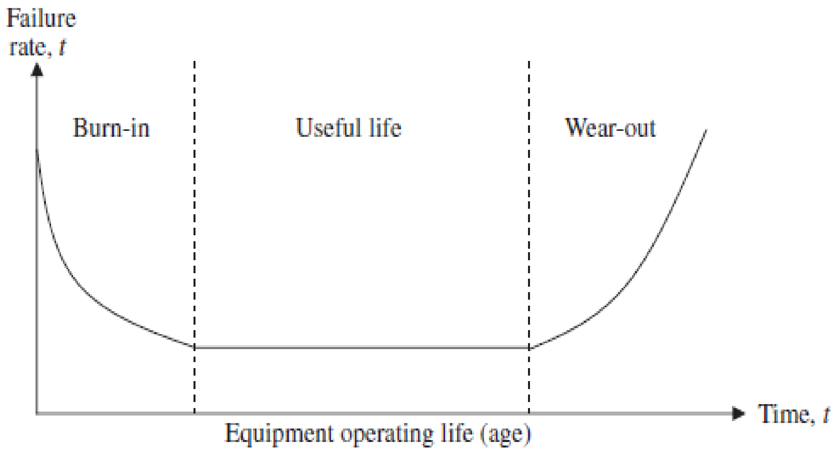

Figure 3. Bathtub Curves [21]

Failure rate trends can be divided into three phases: burn-in, useful life, and wear-out [21]. The TBM technique assumes that the equipment experiences decreasing failure rates early in its life cycle (burn-in), followed by a near constant failure rate (useful life). At the end of its life cycle (wear-out), equipment experiences increasing failure rates. Alessandro Birolini also states that the failure rate strongly depends upon the item's operating conditions thus the need to determine maintenance periodicity based on maintenance data for a specific operating environment [17].

2.3 Maintenance Optimization Models

In [22] Dekker defines a maintenance optimization model as a mathematical model in which the costs and benefits of maintenance are quantified in order to obtain an optimal balance between them. Maintenance optimization models aim to evaluate and compare maintenance policies, to determine how often to inspect or to maintain an item and to help to determine effective and efficient schedules and plans. In [22] Dekker, he concluded that there are several case studies published which show that mathematical models are a good way to achieve both effective and efficient maintenance. However, the author identifies several factors which may hamper the application of optimization models. The usual problems presented are data problems (e.g. analyzing data without knowing the underlying failure mechanisms can lead to wrong results) and the gap between theory and practice (e.g. many maintenance models have a stochastic nature which is not only difficult to grasp but also difficult to interpret) [20].

As the PM effort increases, the PM cost increases and the CM cost decreases. Since the total cost of PM and CM actions together first decreases and then increases with increasing PM effort, there is an optimal level of PM effort that will minimize the total maintenance cost. Minimization of the total cost is one approach to determining the optimal maintenance actions.

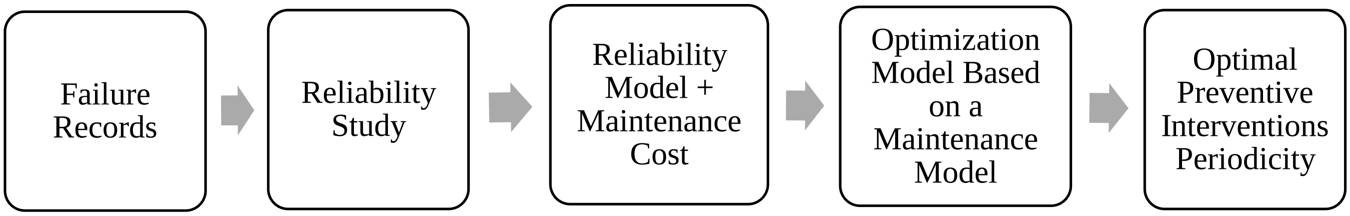

Figure 4. Step by Step Process of Obtaining Optimal Preventive Intervention Periodicity

The major merit of PM is its ability to increase the average life of equipment items and to reduce the risk of catastrophic failure [23]. However, despite the numerous benefits of PM, the major limitation is the difficulty in evaluating the optimum interval of performing the maintenance task as this may take years of data collection and analysis to be able to get the best interval for maintenance [24].

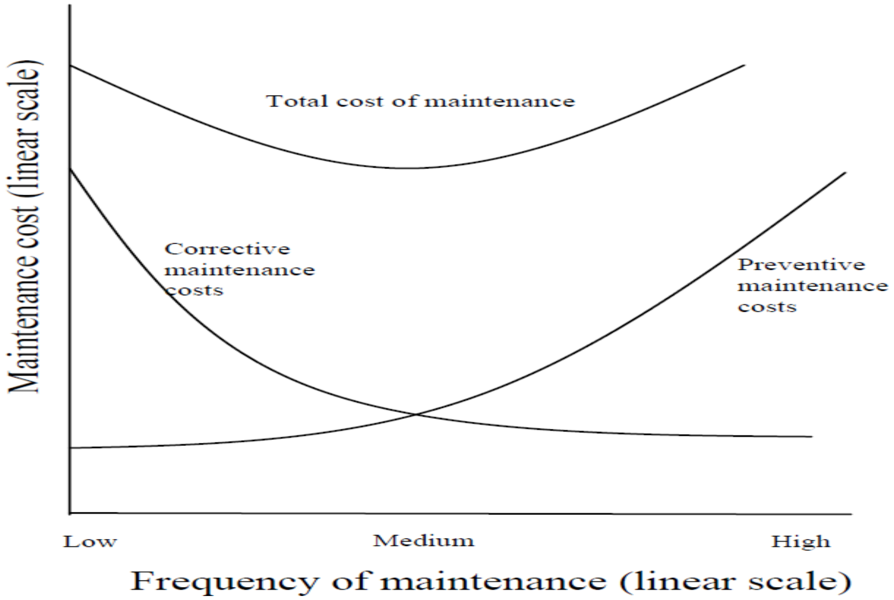

Figure 5. Indication of how Maintenance Performance should be Optimized [20]

2.4 Weibull Model

Engineering systems typically degrade over time and thus more likely to exhibit a failure distribution characterized by a strictly increasing hazard function. The Weibull distribution is considered to be the most widely used distribution for modeling failure in reliability applications because of its substantial flexibility. Weibull distribution function provides sometimes good service but it does always work. Weibull analysis is particularly emphasized for failure analysis.

The Weibull analysis includes:

- Plotting the data and interpreting the plot
- Failure forecasting and prediction
- Evaluating corrective action plans
- Maintenance planning and cost-effective replacement strategies
- Spare parts forecasting

- Warranty analysis and support cost predictions
- Recommendations to management in response to service problems

Advantages of Weibull

The primary advantage of Weibull analysis is the ability to provide reasonably accurate failure analysis and failure forecasts with extremely small samples. Solutions are possible at the earliest indications of a problem without having to "crash a few more". Small samples also allow for cost-effective component testing. For example, "sudden death" Weibull tests are completed when the first failure occurs in each group of components, (say, groups of four bearings). If all the bearings are tested to failure, the cost and time required are much greater. Another advantage of Weibull analysis is that it provides a simple and useful graphical plot of the failure data. The data plot is extremely important to the engineer and to the manager. The Weibull data plot is particularly informative [25].

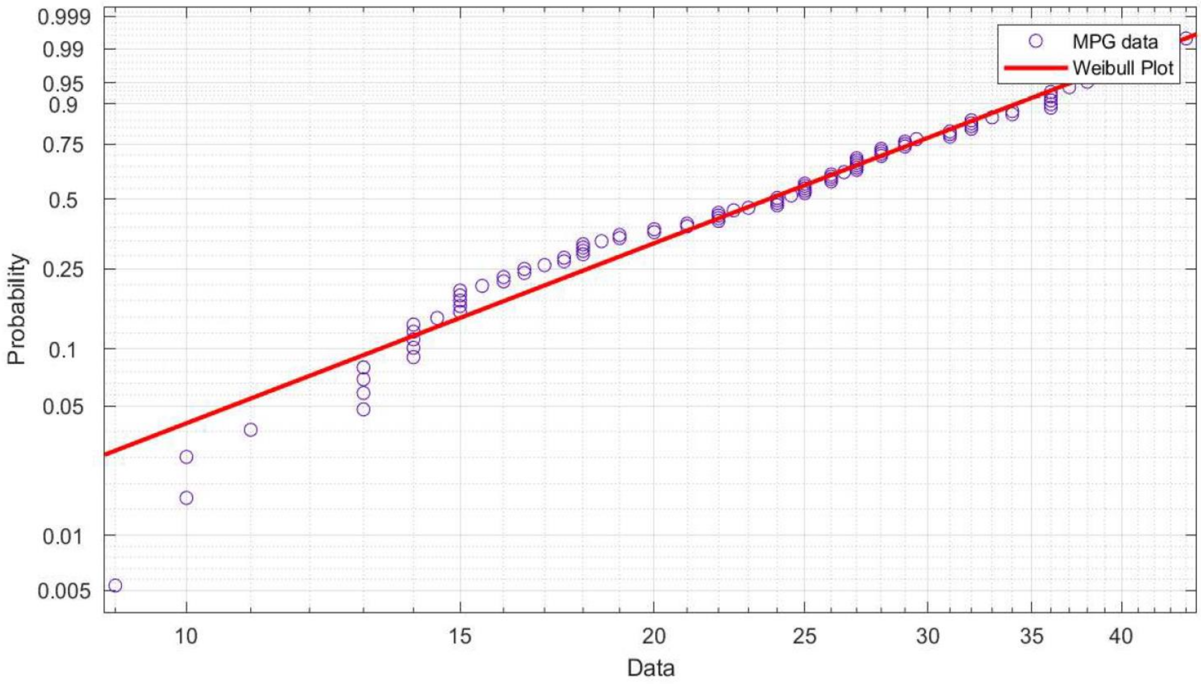

Figure 6. Typical Weibull Plot [25]

The horizontal scale is a measure of life or aging. Start/stop cycles, mileage, operating time, landings or mission cycles are examples of aging parameters. The vertical scale is the cumulative percentage failed. The two defining parameters of the Weibull line are the slope (shape parameter) α, and the Scale parameter, β. The slope of the line, α, is particularly significant and may provide a clue to the physics of the failure. The scale parameter, β, is the typical time to failure in Weibull analysis. It is related to the MTTF.

2.5 Trend and Direction

It is clear that the main trends in maintenance are the use of a combination of several maintenance policies to achieve an organization's requirements. Also, the assessment of risk after failure is often performed through a FMEA method. Engineering knowledge is used to find the cause and eliminate this cause by changing its maintenance policy however no emphasis is put in adjusting the maintenance interval to obtain the optimal time.

There is no clear approach defined to obtain a maintenance interval based on historical maintenance data. Manufacturer's model-based wear calculations are very elaborate and are in principle performed by the manufacturer during the design process in order to determine the periodicity of maintenance. However, this does not necessarily fit in a given operating environment since the manufacturer doesn't get the feel of the equipment during operation. In this thesis, a maintenance interval for diesel locomotives is determined based on the historical maintenance data using a scientific approach.

3. METHODOLOGY

3.1 Research Design

Six dimensions of research are discussed in this section, namely how research is used, the purpose of research studies, the research approach, the research strategy, the technique for data collection and data analysis. These have been used in this thesis to perform the research.

3.1.1 The Use of Research

Considering the essence of the present research, it is to be classified in the applied research group. Applied research conducts a study to address a specific concern or to offer solutions to a problem. Applied research usually means a study that provides practical results that people can use [26]. This is motivated by the fact that it uses fundamental and other related practical knowledge and provides practical solutions and results. In this thesis, optimal maintenance interval is determined and maintenance is carried out at specified periodicity thereby by improving the reliability of the locomotives. The failure time of the system is determined based on maintenance data and a schedule for the maintenance is made to ensure that the failure rate is minimized while the system is in use. The railway industry, in general, faces downtime of machines when failures occur thus it’s important to plan and schedule maintenance to avoid failures.

However, the maintenance practice used by URC is through OEM where maintenance is carried out at a fixed interval of time and is not usually applicable when attempting to maximize machine reliability performance or minimize maintenance costs. First, each machine works in a different environment and would, therefore, need different (preventive) maintenance schedules because actual operating conditions may be very different from those considered by the OEM. Second, machine designers often do not experience machine failures and have less knowledge of their prevention compared to those who operate and maintain such machines. As such, actual outcomes may not satisfy company requirements. This thesis provides a scientific approach to determine the periodicity of maintenance based on historical maintenance data.

3.1.2 The Purpose of Research Studies

The purpose of research may be classified into three groups based on what the research is trying to accomplish: exploring a new topic, describing a phenomenon, or explaining why something occurs [27]. The present study tries to answer the following question: "How can historical maintenance data be used to determine a proper maintenance interval that leads to improved reliability of locomotives?"

It can, therefore, be concluded that this research is to be grouped in the exploratory (looking at the current problems and challenges of the locomotives from a reliability point of view) and descriptive (defining the effect of the operating environment on the failure rate and maintenance periodicity estimation) classes. In fact, the present research can be classified as a prescriptive research category as well, which indicates how to determine the periodicity of maintenance in order to increase reliability by reducing the system downtime. This study also attempts to find out the risk of using the OEM maintenance schedule. Locomotive dependability and availability can be improved through minimization of downtime by increasing reliability through timely maintenance and decreasing the repair/replacement time (mean time to repair/replace).

3.1.3 Research Approach

The research approach, in fact, involves building and testing theory. According to the essence of abduction research where "the researcher can start with a deductive approach and make an empirical collection of data based on a theoretical framework, and then continue with the inductive approach to develop theories based on the previously collected empirical data, and during the research process, an understanding of the phenomenon is developed and the theory is adjusted with respect to the new empirical findings", the present study coincides with this type of research, because it starts with a literature review in order to identify the need for further investigation of locomotive reliability characteristics related to failure rate which are then used to determine the periodicity of maintenance. Some statistical models are adapted from the literature for analyzing the collected data.

3.1.4 Qualitative and Quantitative Research

The methods applied in the present research can be classified as quantitative methods, because the data used is mostly statistical data collected from databases and reports. Moreover, the outcomes are used to recommend a final decision (maintenance periodicity) to implement.

3.1.5 Research Strategy

The selection of a research strategy mostly depends on which kind of information the researcher is looking for due to the purpose of the study and the research questions.

With reference to the different forms of research strategy presented in [28] and considering the goal, approach and the questions of the present research, this study can be classified into both archival analysis and case study research strategy group. The researcher has done a case study at URC over a given period of time and studied it analytically in detail to find out some further features. The research also uses historical data to determine outcomes.

3.1.6 Data Collection Techniques Used

The quantitative techniques have been used in this research. Archival records, company reports are the quantitative data collection methods used in this research. The data has been organized in new ways to address the research question.

3.1.7 Data Analysis and Research Quality

Data Analysis

Data analysis consists of examining, categorizing, tabulating, or otherwise recombining the evidence to address the initial propositions of a study.

The analytical method has used in the present research to find out the periodicity of maintenance based on the locomotive reliability characteristics (mean time to failure and mean time between failures). Weibull technique has been used as it provides reasonably accurate failure analysis and failure forecasts with extremely small samples. It also provides a simple and useful graphical plot of the failure data.

Figure 7 describes the process of obtaining the failure distribution parameters that are then later used to determine the maintenance interval from the cost function.

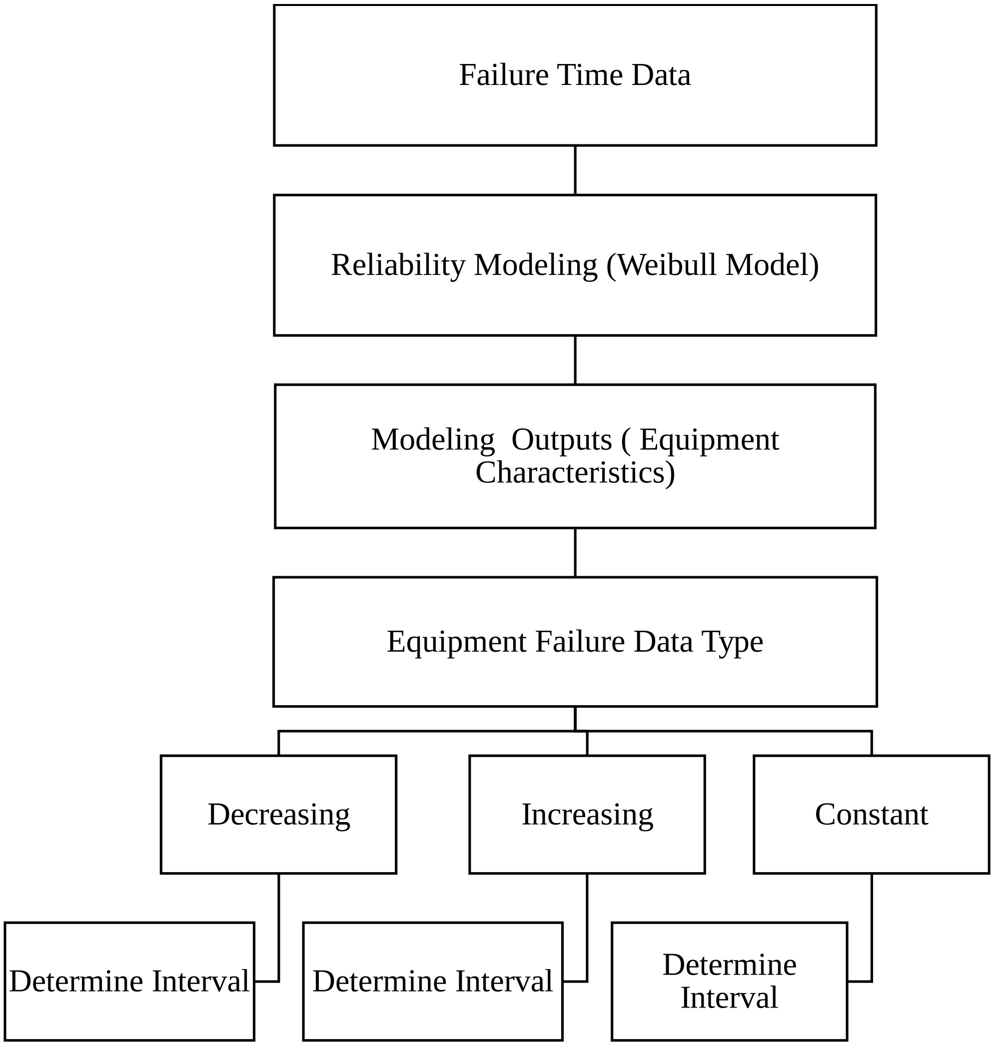

Figure 7. Process of Obtaining Failure Distribution Parameters Used in Determining Maintenance Interval

Research Quality

In order to achieve reliability, a case study protocol and case study database have been constructed. The researcher has defined the type of data acquired, how it was obtained to ensure that an acceptable level of reliability is achieved in this research.

Validity. With regard to the validity of the research, the step by step model has been used on a given case study. The maintenance data was derived from the maintenance database to reflect actual conditions.

3.2 Steps of the Research Process

The research process requires a sequence of steps. The present research went through the process shown in Figure 9.

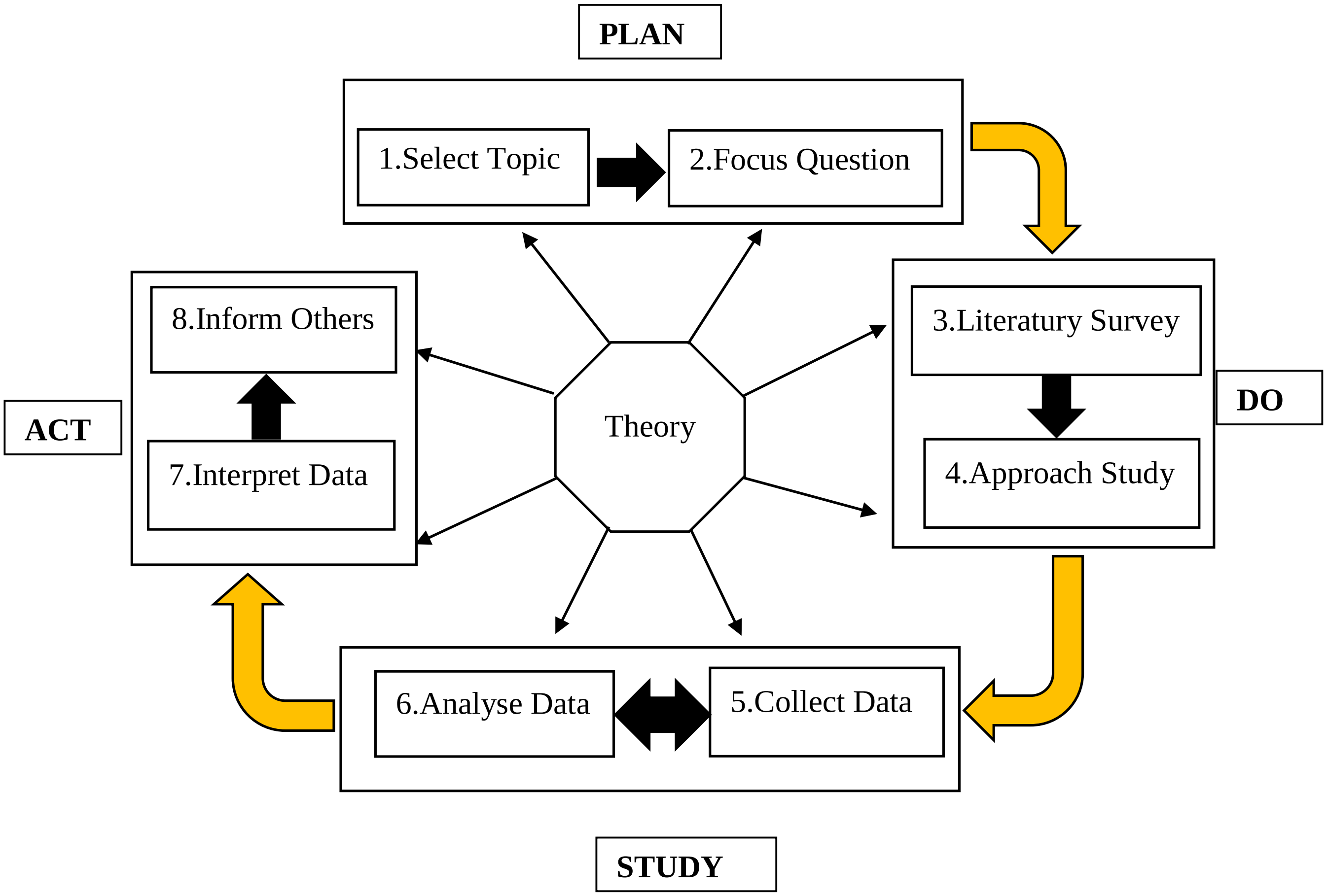

Figure 8. Steps in the Research Process

In the present study, the topic was narrowed down into the following question: "How can historical maintenance data be used to determine a proper maintenance interval that leads to improved dependability and availability of the diesel-electric locomotives?"

A detailed literature survey was done from which an approach was determined to answer the research question. Data was collected and analyzed using Weibull model and parameters used to determine optimal maintenance interval. From the analysis of the data and based on the output it is decided whether to proceed to the interpretation or carry out more data collection.

Finally, the researcher interpreted the data and provided a detailed report. The theory, which is revised and renewed constantly, supports all the steps continuously. It helps researchers to be on the right track and improves the accuracy and the robustness of the study.

3.3 Framework

In order to create a method that can be used by the maintenance department, general steps are established and explained so that optimal interval calculations can be applied. The steps and methods for determining optimal maintenance interval are explained in chapter 3 and validated in chapter 4.

3.3.1 Research Approach

The following are steps needed to arrive at the optimal maintenance interval

1. Acquire failure data of the specific component
2. Choose specific solution directly from the literature that can be applied within URC
3. Create a maintenance model /method to be used by the maintenance engineers
4. Validate the method and determine optimal maintenance interval.
5. Give recommendations for future research.

3.3.2 Proposed Procedure for Interval Determination

1. Give an overview of the component or system that is under research. What are the main components that are inspected and what are the functions of the components in the locomotive? Is there a time interval for removal scheduled for these components and are they discarded or repaired?
2. Collect all data including failure data inspection data. See also data requirements.
3. Perform a Weibull analysis where all failure data are analyzed. Run calculations to determine the mean time to failure or mean time between failure. Analyze the failure pattern and relate the failures that occur between intervals and those that are found through inspection at the actual interval.
4. Use engineering judgment from the maintenance team to ensure that the part itself is not maintained from another unregistered method.

5. The optimal maintenance interval is calculated and a new maintenance plan is generated to be followed to ensure increased reliability and minimum maintenance cost.
6. Depending on the values of optimization obtained, the advice can be to stretch the interval to a convenient new interval or reduce to a convenient new interval.

The system selected in this research was the compressor and specific items described in the following chapter together with analysis of the failures for each item. The failure data was collected for selected components that were analyzed as presented in the next chapter.

3.3.3 Determining Optimal Maintenance Interval.

Two objectives are usually considered when determining an optimal maintenance interval. They are: 1) improve the system availability, and 2) minimize the maintenance cost. In this thesis, the purpose is to minimize the maintenance cost. The following assumptions are used:

- Maintenance intervals are based on system (or component) age (hours of operation), not calendar time.
- Failure time is a random variable following a cumulative distribution function $F(t)$.
- A failure will be noticed right away when it occurs.
- The system is replaced either at failure or at inspection.
- An inspection will not affect the age of the system.
- A new cycle starts (the system is renewed) when the system is replaced.
- Inspections do not introduce failures.

In this thesis, MINITAB software is used for Weibull analysis to produce the graphs and also to obtain values of the scale and shape parameters for the specific data set as will be shown in the next chapter. MINITAB automates calculations and the creation of graphs, allowing the user to focus more on the analysis of data and the interpretation of results.

The values of scale and shape parameters are then used in MATLAB to determine the optimal preventive maintenance time. Below is the formulation of the equations used in MATLAB.

For the component under study, the age replacement model to obtain optimal preventive replacement age was considered. It is necessary to note that preventive replacement actions require two necessary conditions. First, the cost of corrective maintenance must be greater than the cost of preventive maintenance. Secondly, the component hazard rate must be increasing [20]. The minimization of the total cost per unit time $C(t)$ allows obtaining the optimal replacement interval.

Definition of variables;

- C_p the total cost of preventive maintenance.
- C_f the total cost of corrective maintenance (when a failure occurs).
- $f(t)$ the probability density function of the failure times of the system.
- t the specified age at which a preventive maintenance is done
- α the shape parameter.
- β the scale parameter.
- α, β are positive integers.

The main objective is to find the optimal maintenance interval in order to minimize $C(t)$. The function $C(t)$is the cost per unit time for the age replacement model as a function of t, where t is the predetermined time interval for each maintenance.

$$C(t) = \frac{C_p * [1 - F(t)] + C_f * F(t)}{\int_0^t [1 - F(u)]du} \quad [20] \qquad (4)$$

The first step in determining the optimal maintenance time interval t is to take the derivative of the cost function $C(t)$ and set it to zero.

$$C'(t) = \frac{-\left[C_p * [1-F(t)] + C_f * F(t)\right] * [1-F(t)] + \left[-C_p f(t) + C_f f(t)\right] * \int_0^t [1-F(u)]du}{\left(\int_0^t [1-F(u)]du\right)^2} = 0 \qquad (5)$$

Setting the nominator equal to zero

$$-\left[C_p * [1 - F(t)] + C_f * F(t)\right] * [1 - F(t)] + \left[-C_p f(t) + C_f f(t)\right] * \int_0^t [1 - F(u)]du = 0 \quad (6)$$

Equation (6) is reduced to

$$-\left[C_p * [1-F(t)] + C_f * F(t)\right] * [1-F(t)] + \left[-C_p f(t) + C_f f(t)\right] * \int_0^t [1-F(u)]du = 0 \quad (7)$$

$$-C_p * [1-F(t)]^2 - C_f * F(t) * [1-F(t)] + \left[-f(t) * \left(C_p - C_f\right)\right] * \int_0^t [1-F(u)]du = 0 \quad (8)$$

$$\frac{-C_p*[1-F(t)]^2 - C_f*F(t)*[1-F(t)] + \left[-f(t)*\left(C_p-C_f\right)\right]*\int_0^t [1-F(u)]du}{1-F(t)} = 0 \quad (9)$$

$$-C_p * [1-F(t)] - C_f * F(t) + \frac{\left[-f(t)*\left(C_p-C_f\right)\right]*\int_0^t [1-F(u)]du}{1-F(t)} = 0 \quad (10)$$

$$F(t)\left(C_p - C_f\right) - C_p + \frac{\left[-f(t)*\left(C_p-C_f\right)\right]*\int_0^t [1-F(u)]du}{1-F(t)} = 0 \quad (11)$$

$$\frac{F(t)\left(C_p-C_f\right)-C_p+\frac{\left[-f(t)*\left(C_p-C_f\right)\right]*\int_0^t [1-F(u)]du}{1-F(t)}}{C_p-C_f} = 0 \quad (12)$$

$$F(t) - \frac{C_p}{\left(C_p-C_f\right)} - \frac{f(t)}{1-F(t)} * \int_0^t [1-F(u)]du = 0 \quad (13)$$

The failure rate function $r(t)$ is defined as $r(t) = \frac{f(t)}{1-F(t)}$, therefore equation (13) can be written as

$$r(t) * \int_0^t [1-F(u)]du - F(t) = \frac{C_p}{\left(C_f-C_p\right)} \quad (14)$$

The probability density function (PDF) and the cumulative distribution function (CDF) of the Weibull distribution are as follows;

PDF: $f(t) = \frac{\alpha}{\beta^{\alpha}} * t^{(\alpha-1)} * e^{-(\frac{t}{\beta})^{\alpha}}$ (15)

CDF: $F(t) = 1 - e^{-(\frac{t}{\beta})^{\alpha}}$ (16)

Then equation (14) can be written and expanded to obtain the equation below

$$\frac{\frac{\alpha}{\beta^{\alpha}} * t^{(\alpha-1)} * e^{-(\frac{t}{\beta})^{\alpha}}}{1-(\,1-e^{-\left(\frac{t}{\beta}\right)^{\alpha}})} * \int_0^t e^{-(\frac{u}{\beta})^{\alpha}} du - (1 - e^{-\left(\frac{t}{\beta}\right)^{\alpha}}) = \frac{C_p}{(C_f - C_p)} \quad (17)$$

$$\frac{\alpha}{\beta^{\alpha}} * t^{(\alpha-1)} * \int_0^t e^{-(\frac{u}{\beta})^{\alpha}} du + e^{-\left(\frac{t}{\beta}\right)^{\alpha}} - 1 = \frac{C_p}{(C_f - C_p)} \quad (18)$$

Equation (18) will be used to find the value of t that will minimize the cost of the age replacement model.

Since it's difficult to evaluate $\int_0^t e^{-(\frac{u}{\beta})^{\alpha}} du$ explicitly, the integral can be transformed into a more solvable form.

Assume the integral $\int_0^t R(u)du$ needs to be evaluated.

Where $R(u) = \exp(-\left(\frac{u}{\beta}\right)^{\alpha})$ stands for the reliability function

Let $y = (\frac{u}{\beta})^{\alpha}$ $so\ that\ u = \beta y^{\frac{1}{\alpha}}$ and $du = \frac{\beta}{\alpha} y^{\frac{1}{\alpha}-1} dy$ the integral can be written as follows

$$\int_0^t R(u)du = \int_0^w e^{-y} \frac{\beta}{\alpha} y^{\frac{1}{\alpha}-1} dy \quad \text{where } w = (\frac{t}{\beta})^{\alpha}$$

$\int_0^t R(u)du$ can be represented by the incomplete gamma function

$\frac{\beta}{\alpha}\int_0^w e^{-y}\, y^{\frac{1}{\alpha}-1}dy = \frac{\beta}{\alpha}*\Gamma\left(\frac{1}{\alpha}, w\right)$; Incomplete gamma function from 0 to w

To evaluate this function, a built-in command in MATLAB is used. The command is written as "gammainc ((t/β) ^α,1/α) *gamma(1/α) *(β/α)". It evaluates the integral

$\int_0^t e^{-(\frac{u}{\beta})^{\alpha}} du$ from 0 to t.

After determining the optimal time then the maintenance schedule is adjusted accordingly to be able to maintain a certain level of availability of the locomotives.

It is critical to note that without quality data of the failures as well as to have the fault time recorded treated and organized properly, very poor and insignificant results can be obtained.

4. ANALYSIS RESULTS AND DISCUSSIONS

The analysis is based on a fully operative railway line where diesel-electric locomotives are used on the network. The line has been operative with no major changes for many years; hence, It is assumed that the Work Orders (WOs) represent maintenance and not design changes. The data covers the work orders from January 2013 until December 2017 on a 251 km long line in Uganda.

More specifically, over 1,000 WOs were registered during that period, of which 455 were associated with compressors. Due to the number of WOs directly related to compressors, the focus was on this system even though the methodology can be extrapolated to the whole locomotive.

Data were obtained from the files provided by URC about the failure of the locomotives. Since there is no automated software for capturing data, the data provided was in the form of reports and this was extracted manually into excel and analyzed.

Figure 10 below is a hierarchy block showing the selection of the method for analysis based on the available data extracted from the WOs.

Selected failures for analysis where 23 in number and these were later broken down into specific components and analyzed individually to obtain a clear picture of maintenance action required for each component.

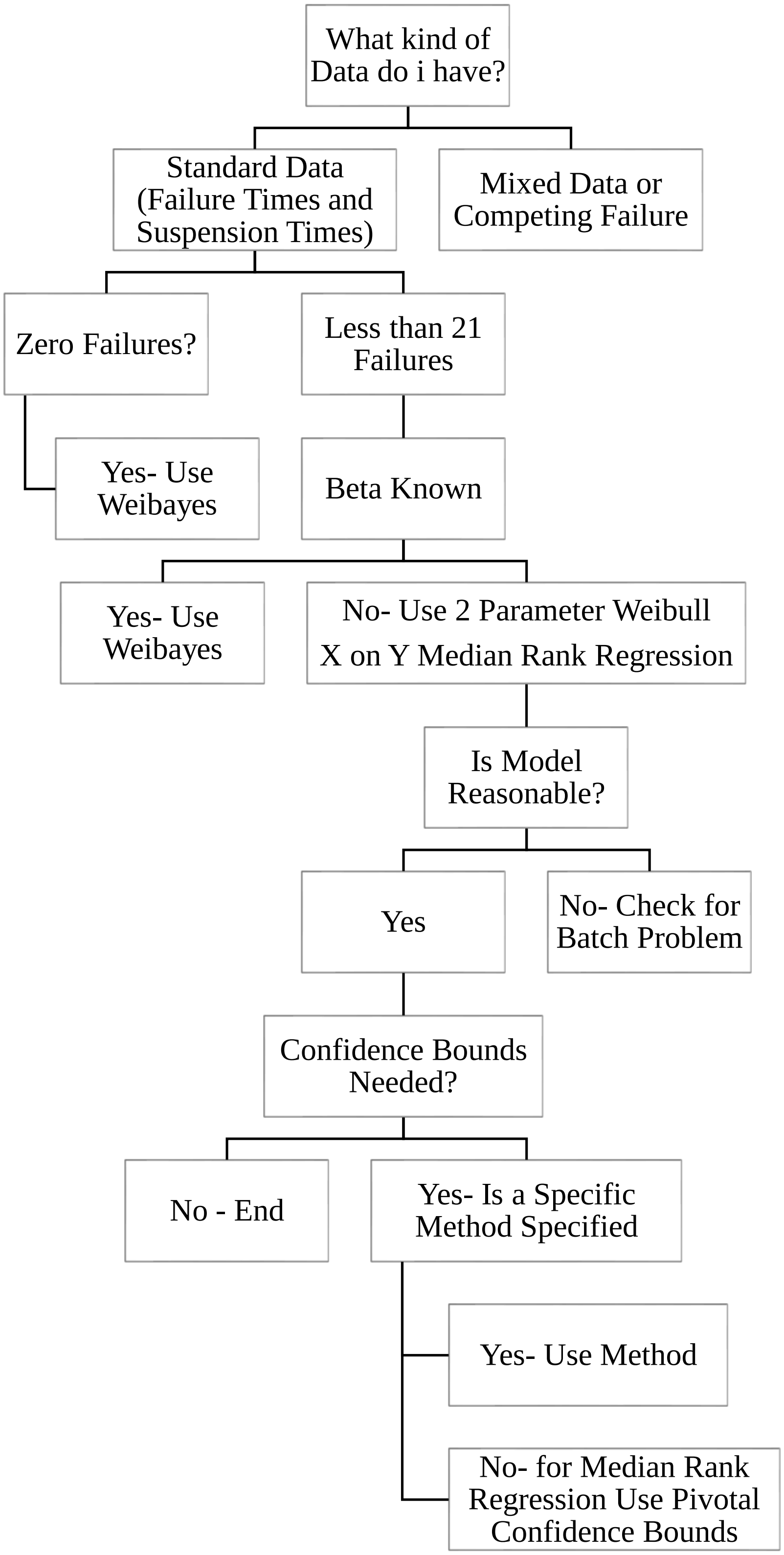

Figure 9. Overview of Steps Followed in Weibull Analysis Based on Available Maintenance Data

The greatest benefit of the Weibull method is that it can be useful for engineering with extremely small samples of data sets that have major deficiencies which we call “dirty data”. Every industry has dirty data.

In the railway industry suspensions are very common. Weibull distribution handles suspensions well.

4.1 Case Study of Compressor

The air compressor is required to provide a constant supply of compressed air for the locomotive and train brakes. With the Ugandan locomotives, it is standard practice to drive the compressor off the diesel engine drive shaft.

Compressed air is almost always used for brakes and sometimes for powering train doors. Also popular for powering traction power switches or contactors.

Compressed air needs drying after compression to avoid moisture from condensation getting into valves. On the diesel locomotives, the compressor is driven directly from the diesel engine by way of a connecting shaft.

4.1.1 Flange Gaskets for Compressor

The flange gaskets are located on the cylinder heads and their main use is to prevent leakage of compressed air.

Table 1. Failure Times for Flange Gaskets I and II

Batch I	**Failure Times for Flange Gaskets I (Engine Hours)**
1	1551
2	1556
3	1231
4	1225
5	16709
Batch II	**Failure Times for Flange Gaskets II (Engine Hours)**
1	1550
2	414
3	1370
4	1443
5	1342

The data in Table 1 is separated into 2 batches. The different batches are due to missing data for maintenance between the 57049 engine hour mark and 40340 engine hour mark.

With both data plotted together, it shows that the failure rate is increasing based on the shape parameter which is 1.62307. The mean time between failure is 1965.66 engine hours.

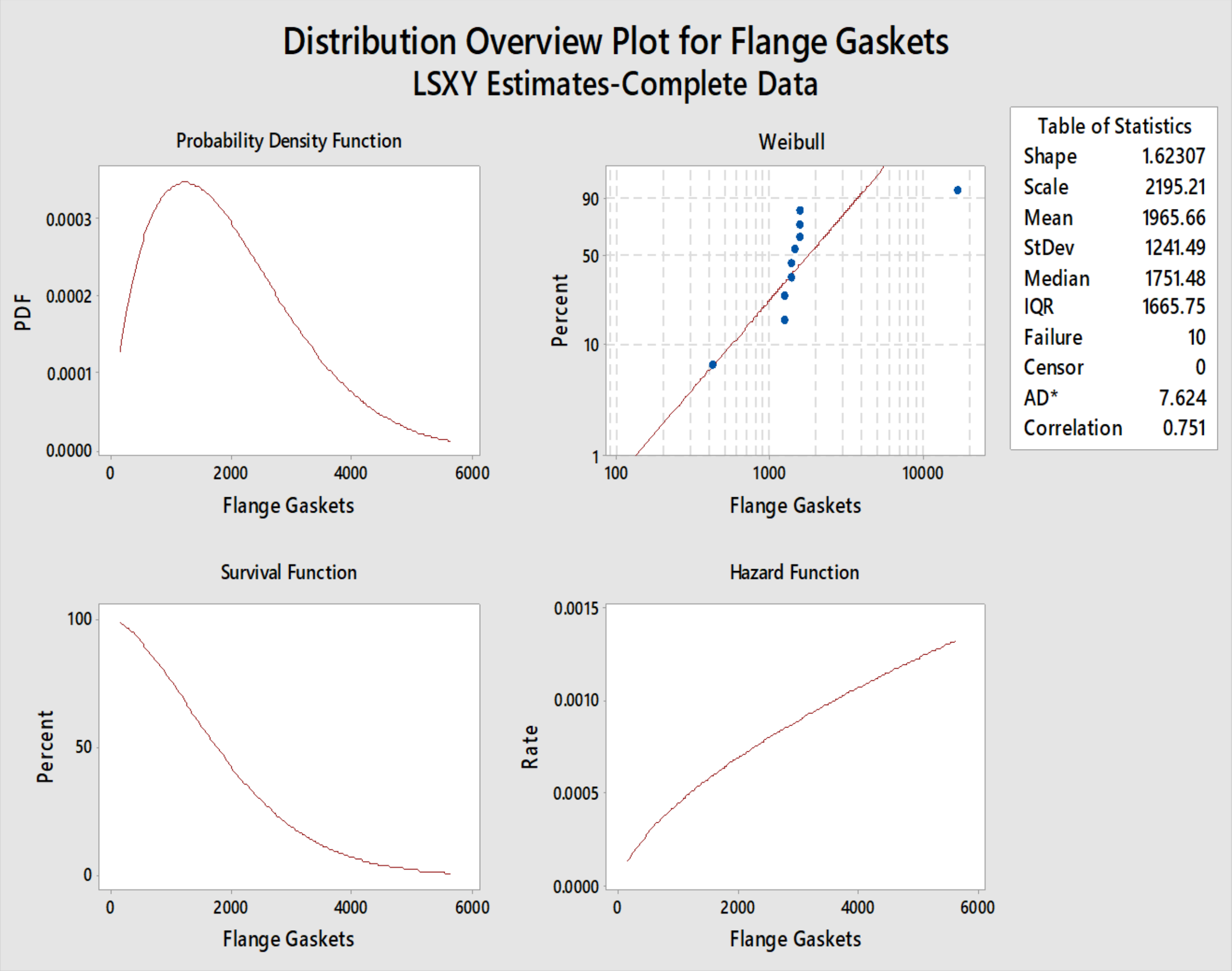

Figure 10. Distribution Overview Plot for Flange Gaskets

A step curve is a sign of a batch problem. The Weibull graph in Figure 11 clearly shows the need to separate the batches. The result of mixing the two batches can lead to false information about the mean time to failure.

Figure 12 is the probability plot with a confidence interval of 95%.

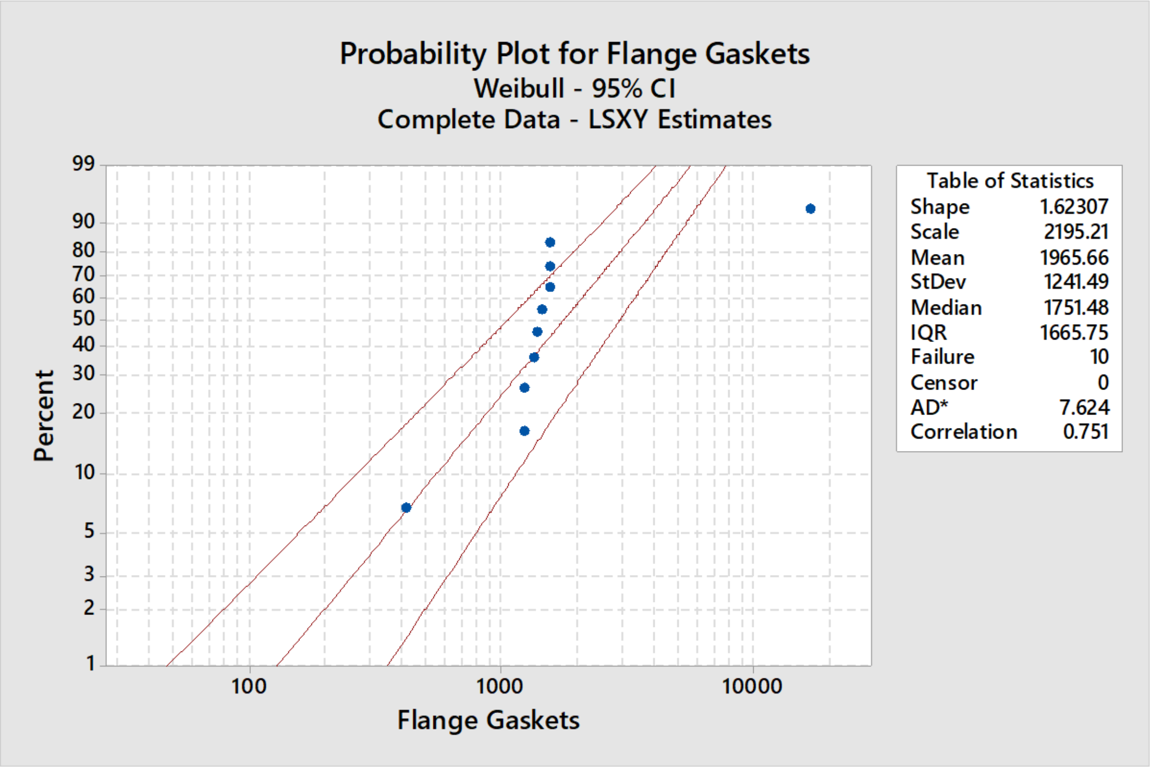

Figure 11. Probability Plot for Flange Gaskets

From the details of the maintenance report, it indicated that the 414 engine hour replacement of gasket was done when the locomotive was involved in an accident. Although the replacement of the gasket was done it was a precaution since the locomotive had been involved in an accident.

Also, the shape of the Weibull plot shows that there are batches in data. However, to be able to obtain clear information, the 2 batches of data are separated to be able to get more informative graphs from an engineering perspective.

Table 2. Failure Time for Flange Gaskets Batch I

Batch I	Failure Times for Flange Gaskets (Engine Hours)	Description
1	1551	Failure
2	1556	Failure
3	1231	Failure
4	1225	Failure

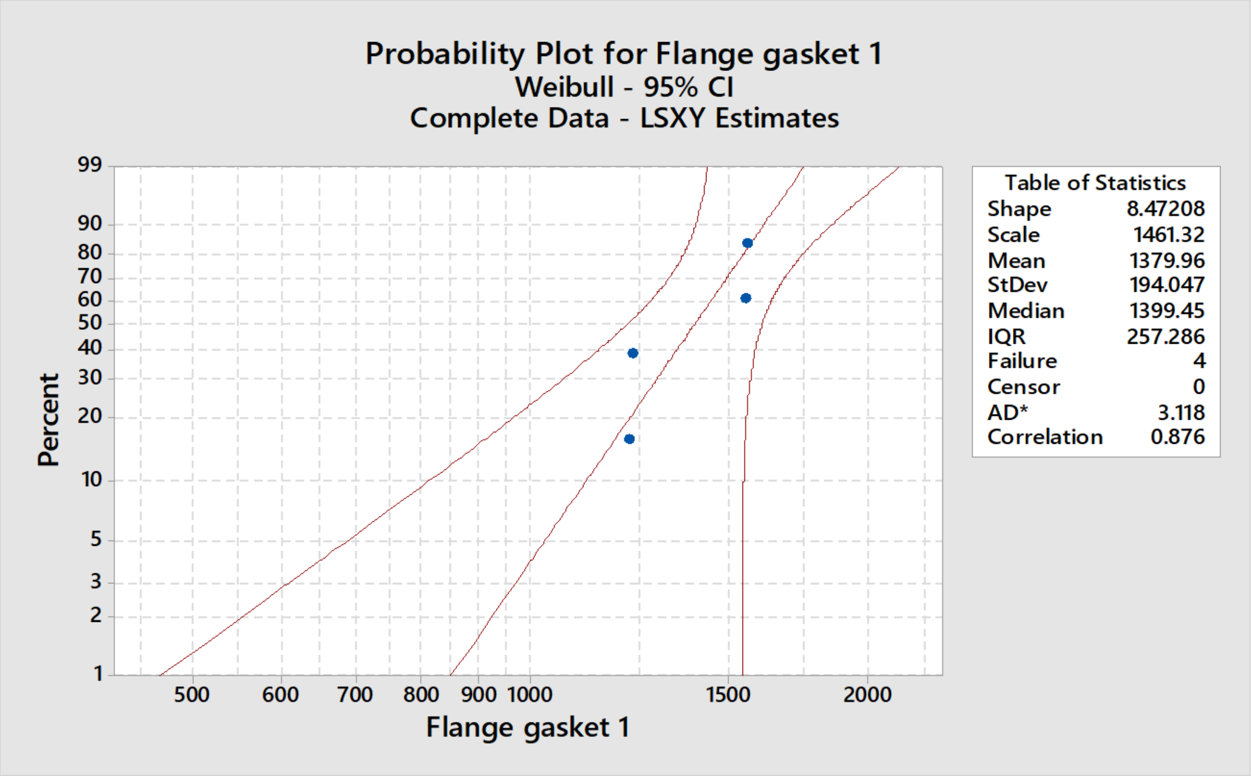

Figure 12. Probability Plot for Flange Gaskets Batch I

The probability graph in Figure 13 provides a clearer and more informative plot with all data points falling within the 95% confidence interval. The mean time to failure is 1379.96 engine hours. More specifically, expect a failure every 1379.96 engine hours of operation.

Table 3. Failure Times for Flange Gaskets Batch II

Batch II	Failure Times for Flange Gaskets (Engine Hours)	Description
1	1550	Failure
2	1370	Failure
3	1443	Failure
4	1342	Failure

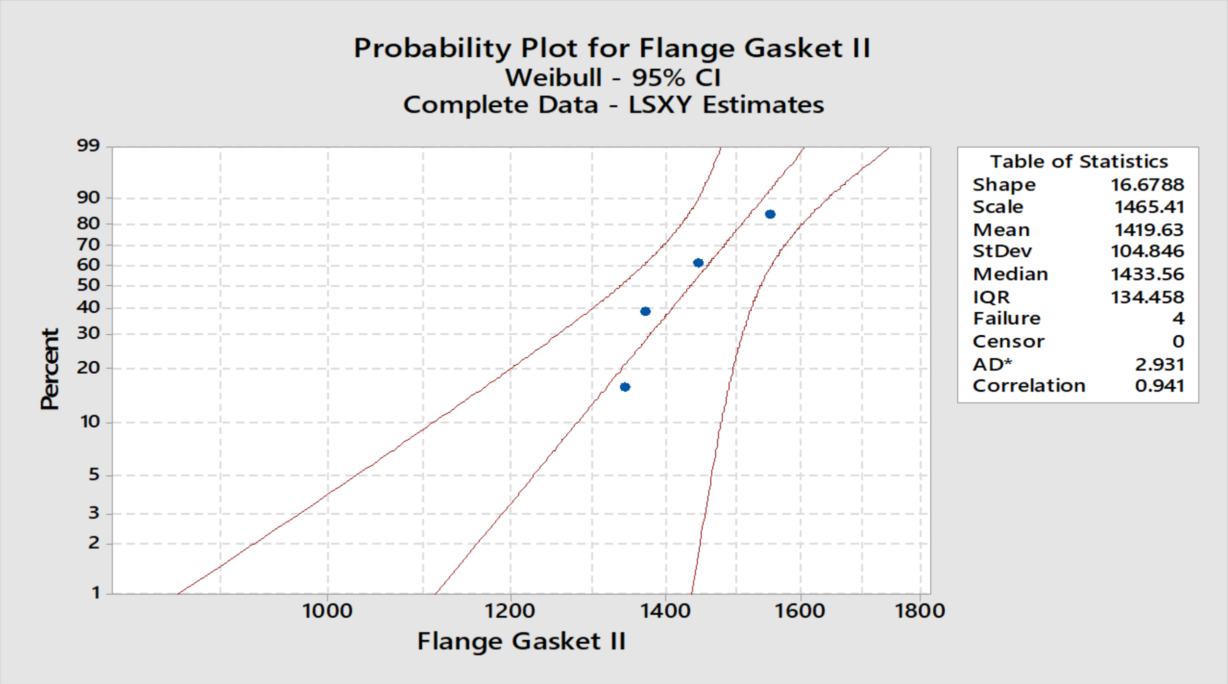

Figure 13. Probability Plot for Flange Gaskets Batch II

Figure 14 shows the probability plot with the mean time to failure being 1419.63. This is for the batch data from engine hour 35563 to engine hour 40340.

The most current data from engine hour 57049 to engine hour 62612 has a mean time to failure of 1379.96 engine hours.

This shows that the failure rate has been increasing. The latter mean time to failure of 1379.96 engine hours will be considered since it is obtained using the most recent batch of data.

Optimization of the Maintenance Interval for Flange Gaskets

In order to determine the value of the initial estimate, a graphical method is used where the derivative of equation (14) (in section 3.3.3) is equated to zero. The plot of the function in MATLAB is shown in Figure 15.

$$dc(t) = F(t) - \frac{C_p}{(C_p - C_f)} - \frac{f(t)}{1-F(t)} * \int_0^t [1 - F(u)]du = 0 \quad (19)$$

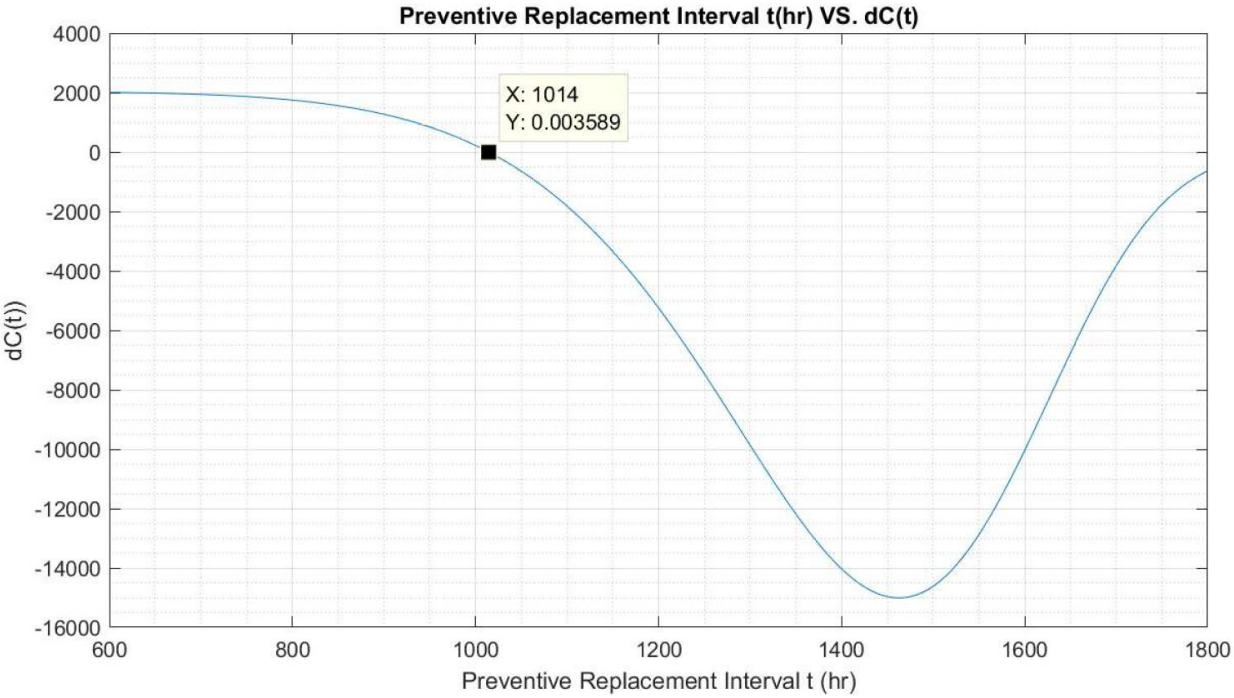

Figure 14. Preventive Replacement Interval Vs. The Derivative of the Cost Function (Flange Gaskets)

Figure 15 graph shows that the approximate maintenance interval for the flange gaskets is 1014 engine hours.

To confirm the accuracy of this estimation, the relationship between preventive replacement interval and the corresponding cost per unit time is examined. As mentioned above, the main goal is to find the replacement interval that gives minimal cost per unit time.

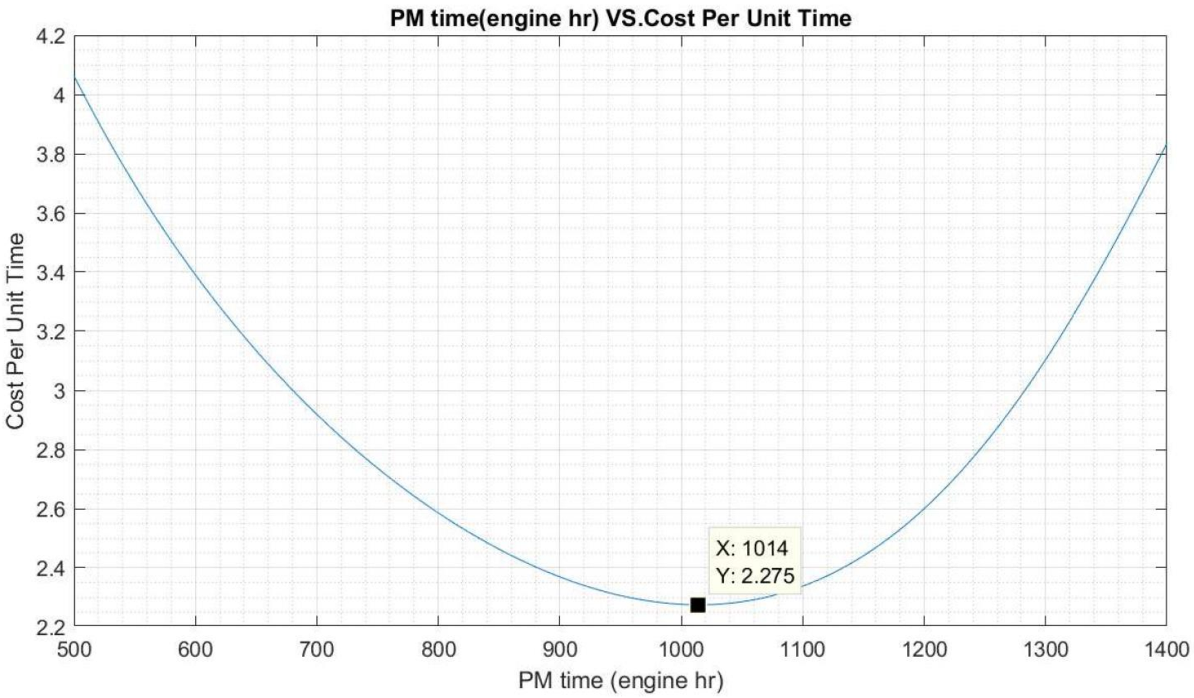

Figure 15. Preventive Maintenance Interval Vs. Cost Per Unit Time (Flange Gaskets)

The plot of Figure 16 shows that the minimum cost occurs when the replacement interval is approximately 1014 engine hours which is consistent with the result obtained in Figure 15.

To obtain an accurate value, a function in MATLAB for obtaining minimum value is used. The value of maintenance interval is 1014.5 engine hours corresponding to a cost per unit time of 2.2752.

Assuming a failure of a component can be detected any time after 70% of its life span has been consumed. Inspection/ replacement are scheduled at 1014.5 engine hours which is the optimal replacing period obtained after analysis in MATLAB. Considering that MTTF is 1379.96, 70% of its life is 965.972 engine hours. Since the scheduled inspection/replacement is at 1014.5 engine hours which is between 965.972 and 1379.96 engine hours, the failure will be noticed before it occurs.

From the optimization, the gaskets will be replaced every 1014.5 engine hours to avoid high costs that will result from doing corrective maintenance in case a failure occurs. The cost per unit time of this inspection/ replacement is 2.2752 and the length is 1014.5 engine hours.

4.1.2 Seals

Prevent the lubricating oil used in the cooling of the reduction gears from leaking.

Table 4. Failure Times for Seals

	Failure Times for Seals (Engine Hours)	**Description**
1	1370	Failure
2	3279	Failure
3	4033	Failure
4	4964	Failure
5	5160	Failure

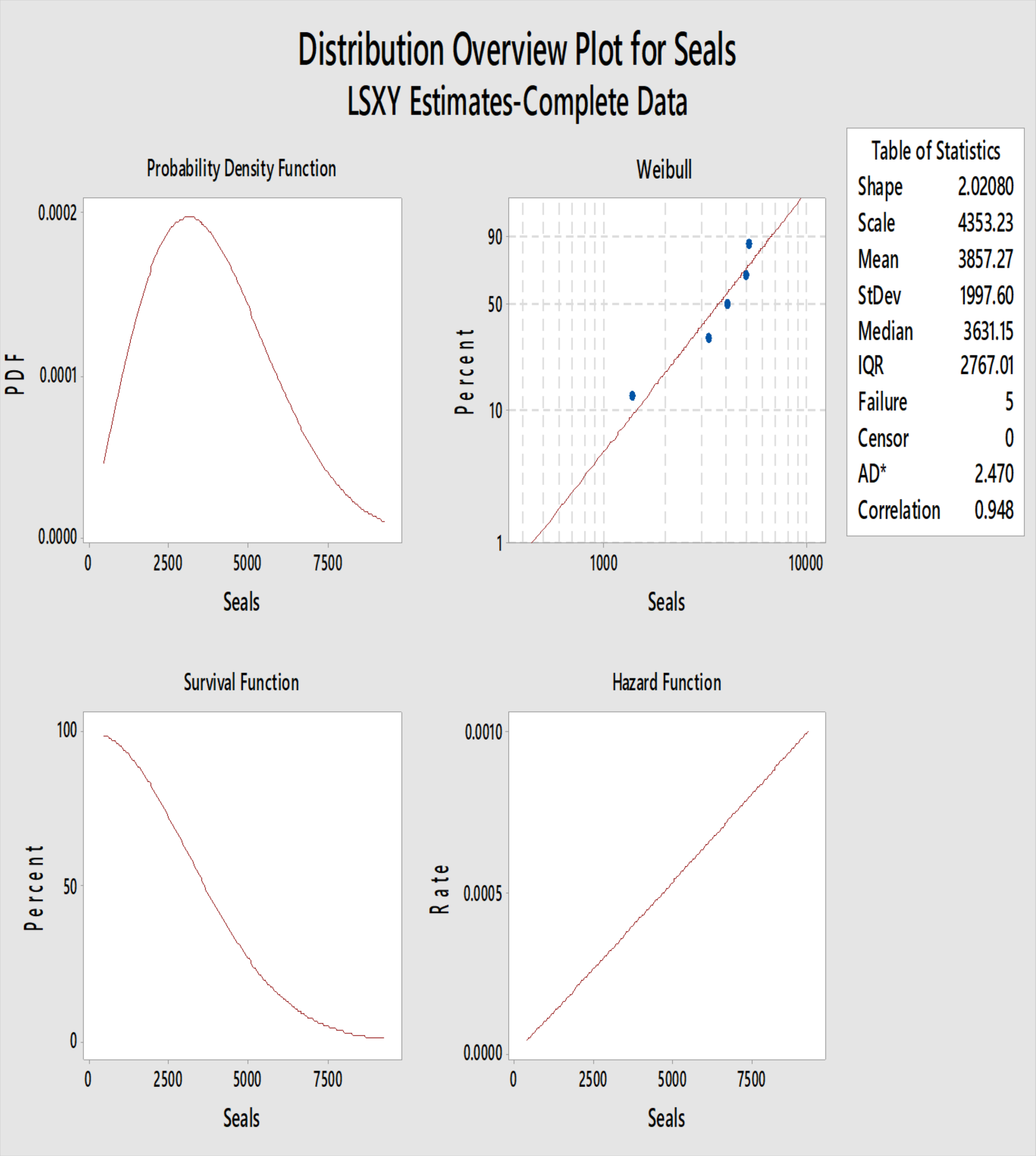

Figure 16. Distribution Overview Plot for Seals

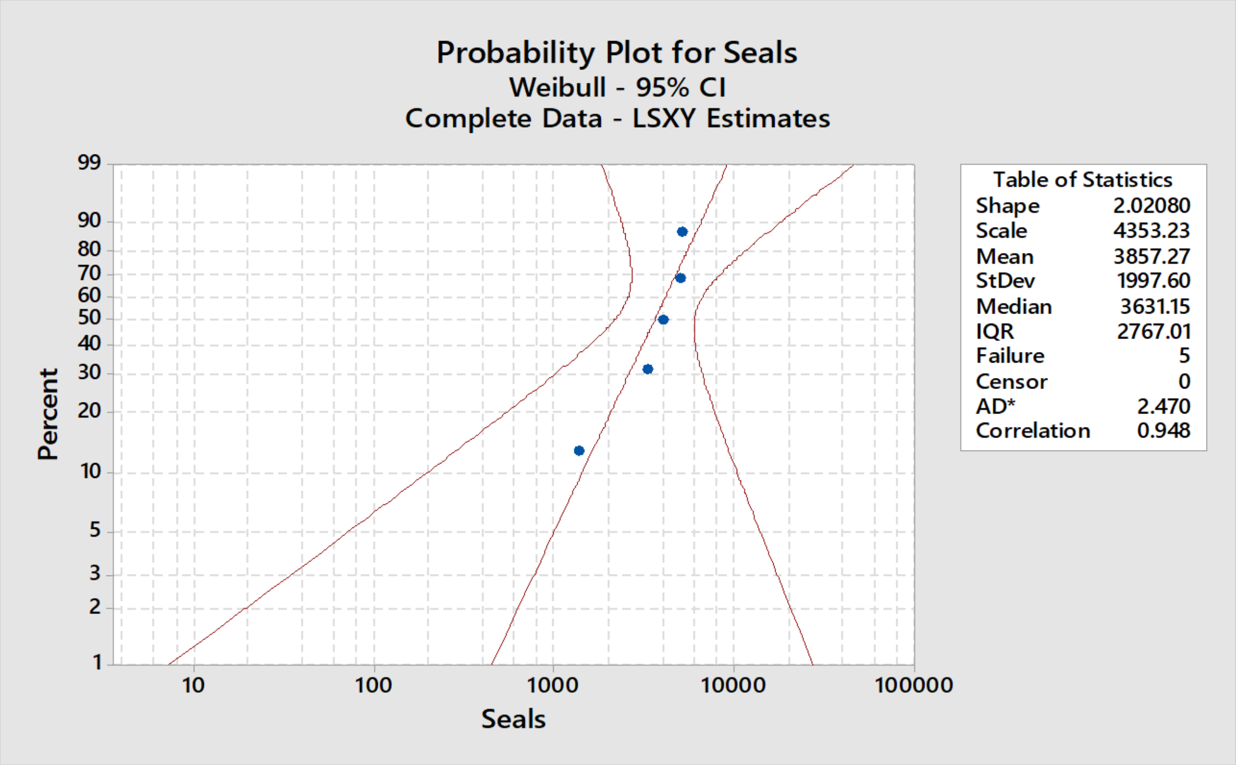

Figure 17. Probability Plot for Seals

The points all lie within the 95% confidence interval. From the graph, the mean time to failure of the seals is 3857.27 engine hours.

The shape parameter is 2.02080 which is greater than 1 implying an increasing failure rate hence the preventive maintenance interval needs to be adjusted to cab failures and reduce unscheduled downtime of the compressor.

It must be highlighted that the set of failure times is smaller than an ideal situation and a larger set of values will always allow the best estimate of the Weibull parameters.

Optimization of the Maintenance Interval for Seals

In order to determine the value of the initial estimate, a graphical method is used where the derivative of equation (14) is equated to zero. The plot of the function in MATLAB is shown in Figure 19.

$$dc(t) = F(t) - \frac{C_p}{(C_p - C_f)} - \frac{f(t)}{1-F(t)} * \int_0^t [1 - F(u)]du = 0 \quad (19)$$

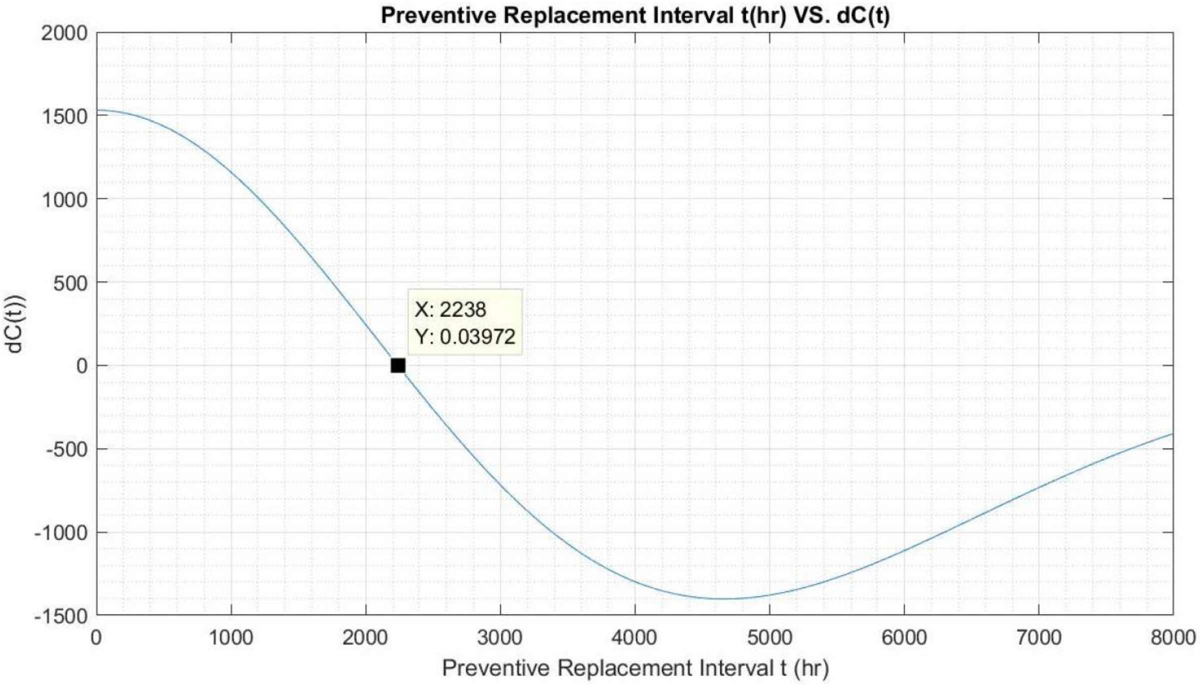

Figure 18. Preventive Replacement Interval Vs. The Derivative of the Cost Function (Seals)

Figure 19 shows that the approximate maintenance interval for the seals is 2238 engine hours.

To confirm the accuracy of this estimation, the relationship between preventive replacement interval and the corresponding cost per unit time is examined. As mentioned above, the main goal is to find the replacement interval that gives minimal cost per unit time.

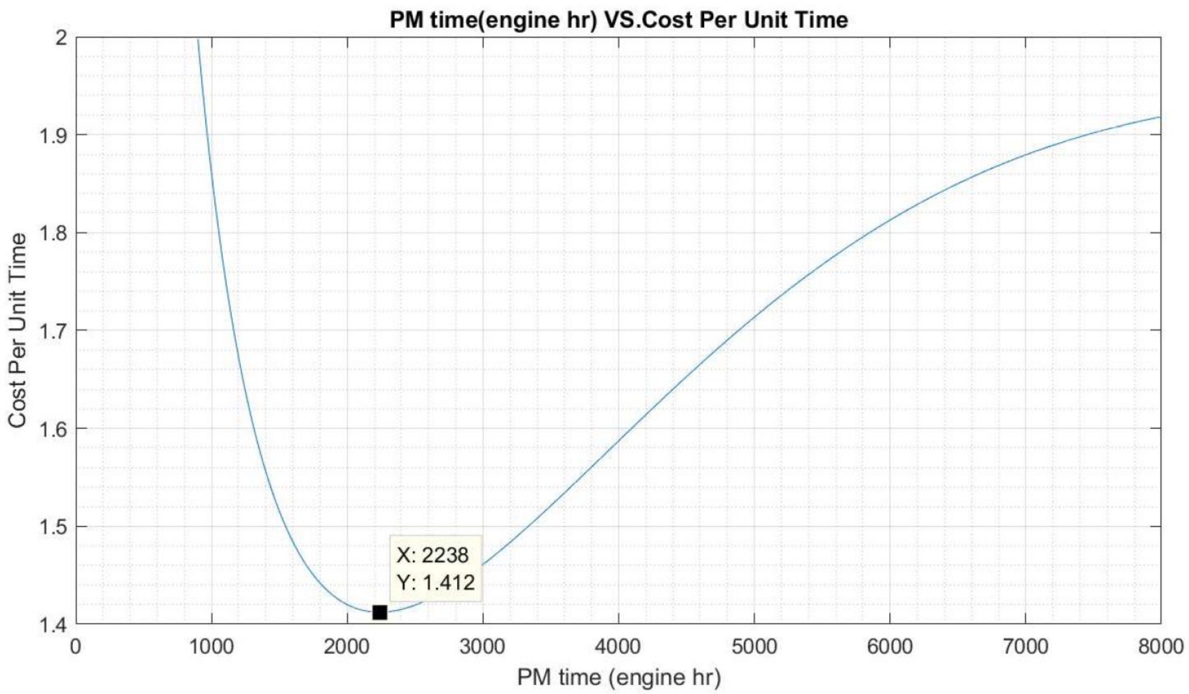

Figure 19. Preventive Maintenance Interval Vs. Cost Per Unit Time (Seals)

Figure 20 shows that the minimum cost occurs when the replacement interval is approximately 2238 engine hours which is consistent with the result obtained in Figure 19.

To obtain an accurate value, a function for finding minimum value in MATLAB is used. The value of maintenance interval is 2238.0 engine hours corresponding to a cost per unit time of 1.4122

Assuming a failure of a component can be detected any time after 70% of its life span has been consumed. Inspection/ replacement are scheduled at 2238 engine hours which is the optimal replacing period obtained after analysis in MATLAB. Considering that MTTF is 3857.27, 70% of its life is 2700.089 engine hours. Since the scheduled inspection/replacement is at 2238 engine hours which is less than 2700.089, the failure may not have started to occur. However, 2238 is the optimal time for replacing the seals in order to avoid high costs related to corrective maintenance as a result of sudden failures.

From the optimization process, the seals should be changed after 2238.0 hours to avoid high costs that will result from corrective/breakdown maintenance.

4.1.3 Compressor Valves

Compressor valves are valves used within a compressor to allow gas flow to and from the cylinder area. They operate based on pressure difference: if the pressure below the valve is greater than the pressure above plus the spring force, it opens. The valves function as spring-loaded non-return valves, with the gas only being able to flow in one direction.

Features

Compressor valves are circular and consist of a series of plates or rings sandwiched between the valve seat and cover. When a pressure difference occurs, the rings or plates are pulled toward the area of greater pressure and use springs to return to their closed position when pressure normalizes.

Table 5. Failure Time for Compressor Valves

	Failure Times for Compressor Valves (Engine Hours)	Description
1	5629	Suspension- loose valve
2	7312	Failure
3	7779	Failure
4	8160	Failure
5	8729	Failure

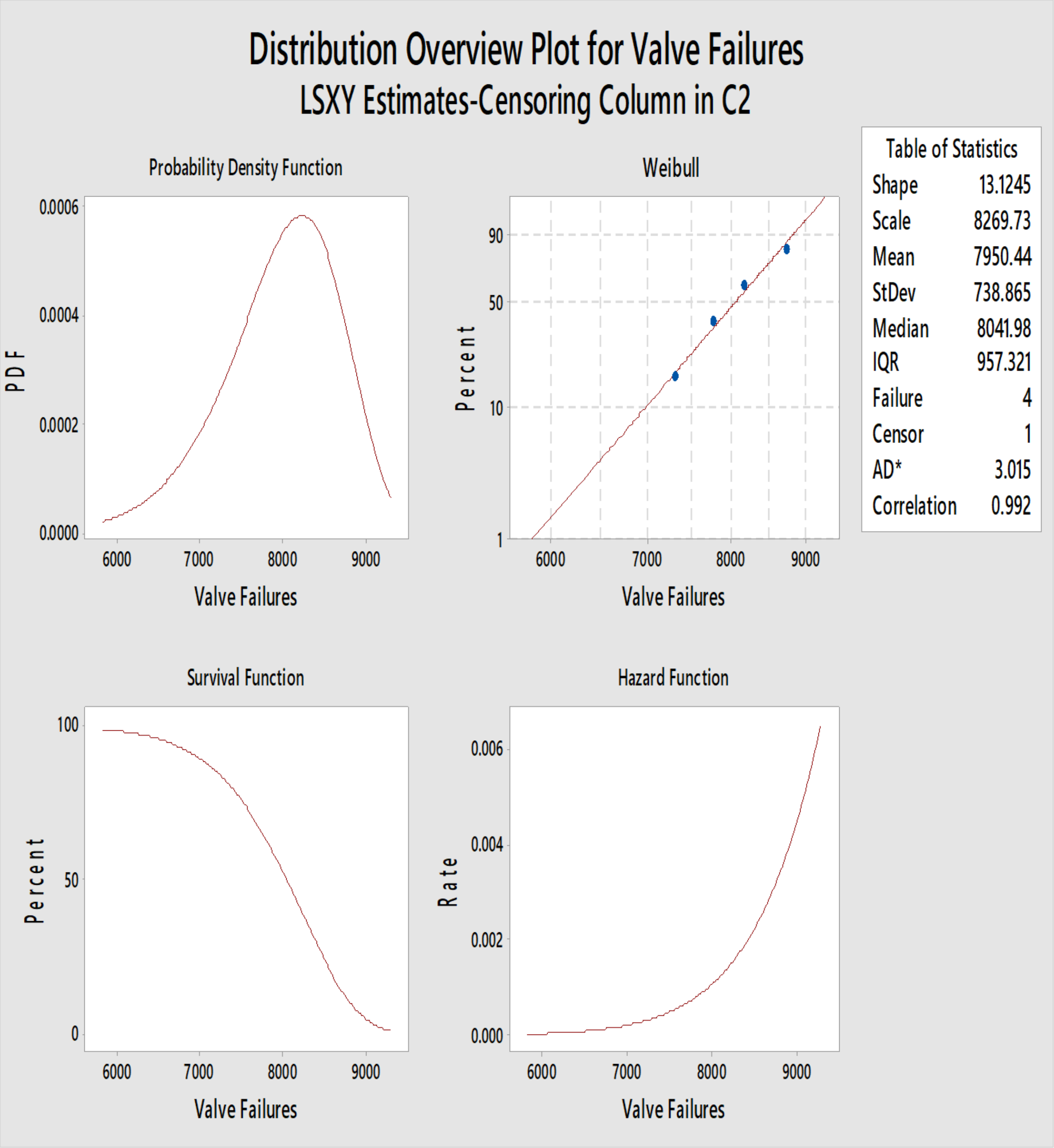

Table of Statistics	
Shape	13.1245
Scale	8269.73
Mean	7950.44
StDev	738.865
Median	8041.98
IQR	957.321
Failure	4
Censor	1
AD*	3.015
Correlation	0.992

Figure 20. Distribution Overview Plot for Compressor Valves

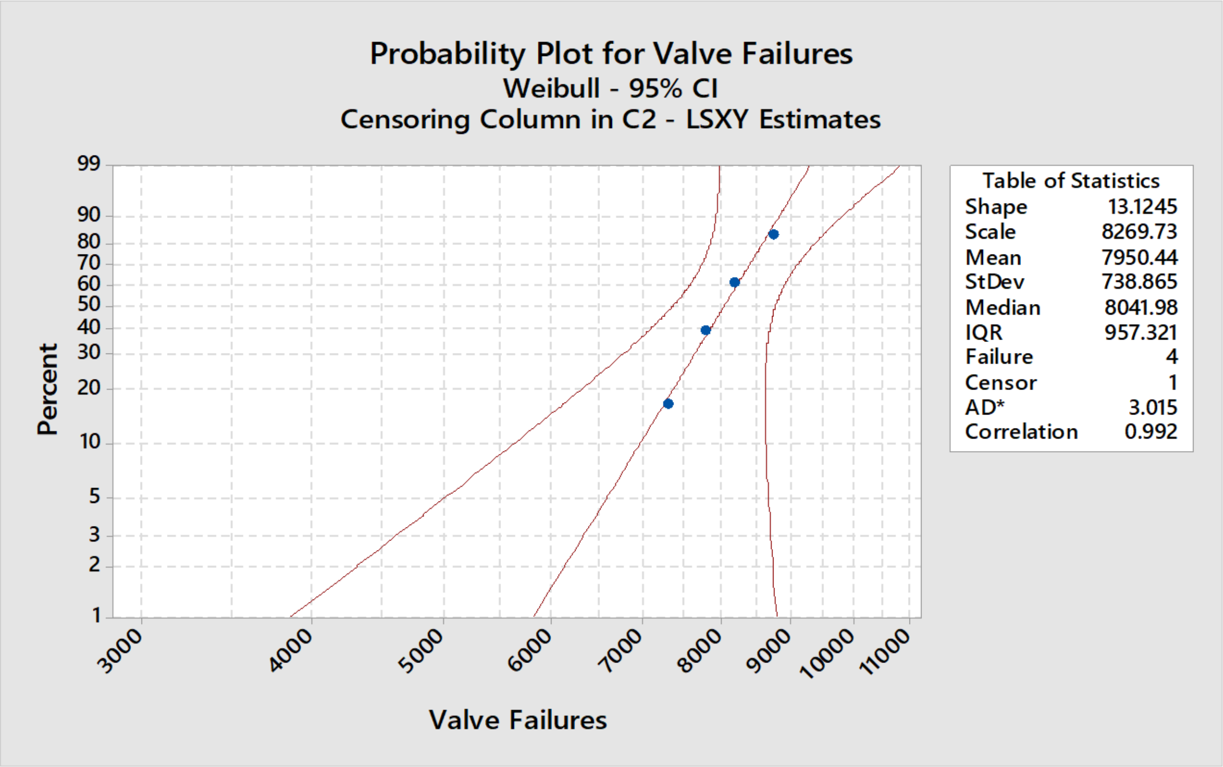

Figure 21. Probability Plot for Valves

One valve was suspended as it was recorded as a loose valve, not a failed valve. Suspensions are always included as they affect the scale parameter. It is wrong to ignore suspensions.

From the analysis shown in Figure 22, it is seen that the mean time to failure is 7950.44 engine hours.

Optimization of the Maintenance Interval for Compressor Valves

In order to determine the value of the initial estimate, a graphical method is used where the derivative of equation (14) is equated to zero. The plot of the function in MATLAB is shown in Figure 23.

$$dc(t) = F(t) - \frac{C_p}{(C_p - C_f)} - \frac{f(t)}{1-F(t)} * \int_0^t [1 - F(u)]du = 0 \quad (19)$$

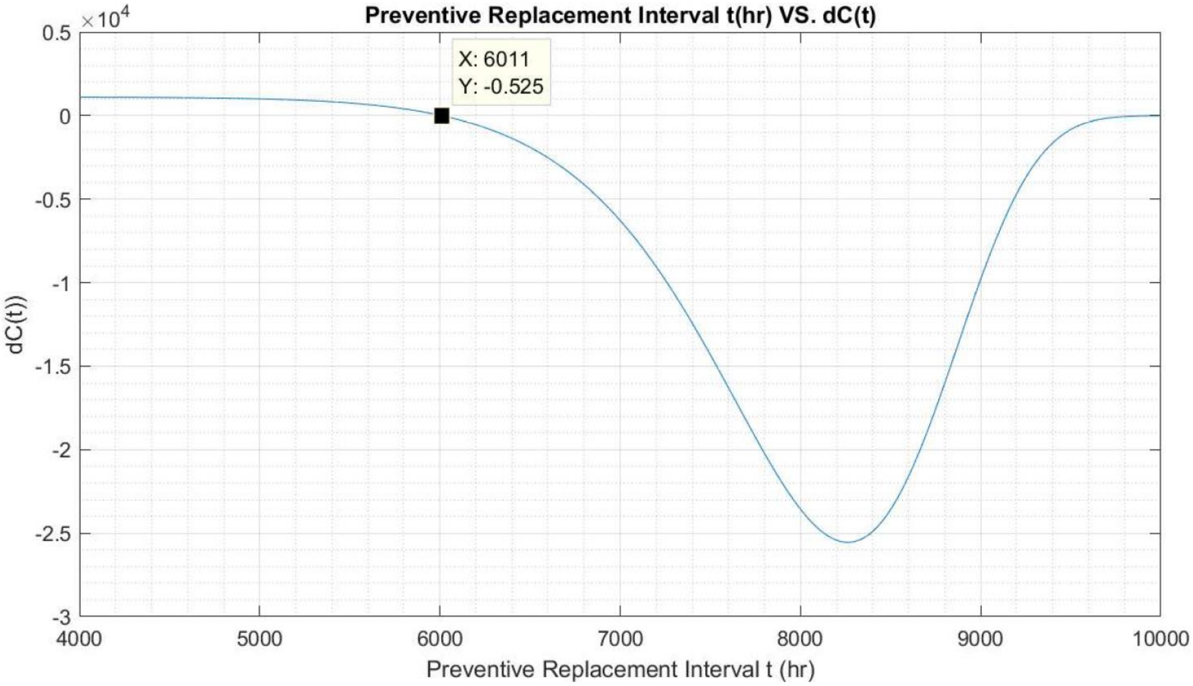

Figure 22. Preventive Replacement Interval Vs. The Derivative of the Cost Function (Compressor Valves)

Figure 23 shows that the approximate maintenance interval for the compressor valves is 6011 engine hours.

To confirm the accuracy of this estimation, the relationship between preventive replacement interval and the corresponding cost per unit time is examined. As mentioned above, the main goal is to find the replacement interval that gives minimal cost per unit time.

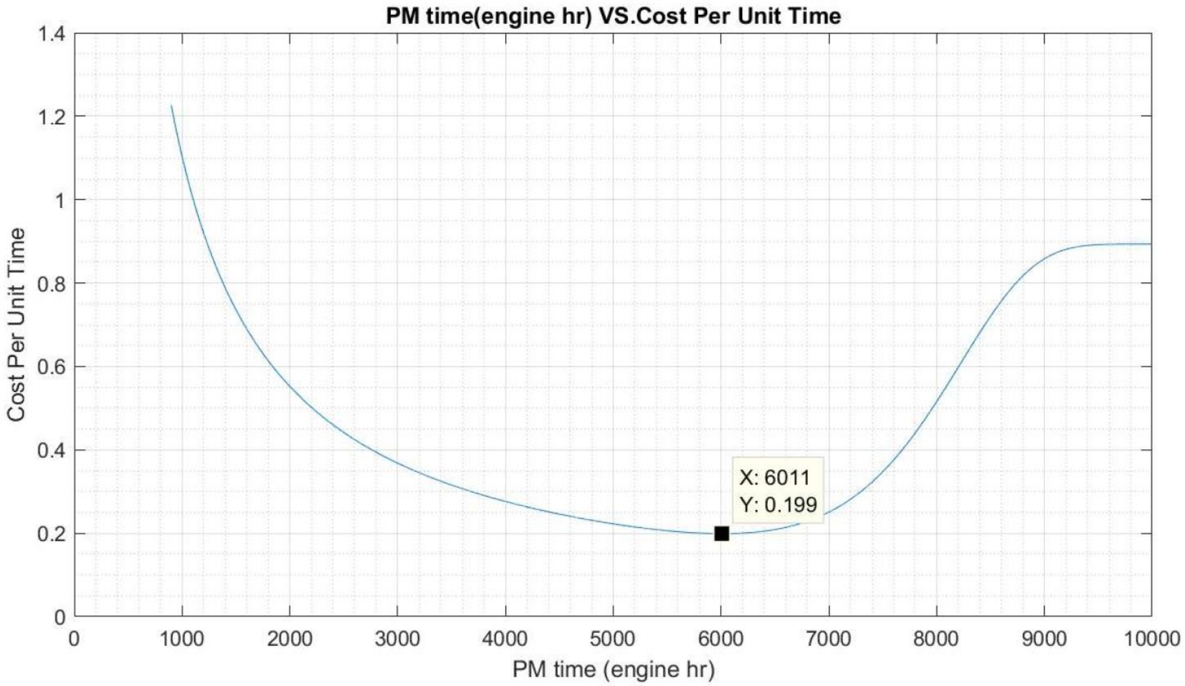

Figure 23. Preventive Maintenance Interval Vs. Cost Per Unit Time (Compressor Valves)

Figure 24 shows that the minimum cost occurs when the replacement interval is approximately 6011 engine hours which is consistent with the result obtained in Figure 23.

To obtain an accurate value, a function for obtaining minimum value in MATLAB is used. The value of maintenance interval is 6010.8 engine hours corresponding to a cost per unit time of 0.1990.

Assuming a failure of a component can be detected any time after 70% of its life span has been consumed. Inspection/ replacement are scheduled at 6010.8 engine hours which is the optimal replacing period obtained after analysis in MATLAB. Considering that MTTF is 7950.44, 70% of its life is 5565.308 engine hours. Since the scheduled inspection/replacement is at 6010.8 engine hours which is between 5565.308 and 7950.44 engine hours, the failure will be noticed before it occurs.

From the optimization, the gaskets will be replaced every 6010.8 engine hours to avoid high costs that will result from doing corrective maintenance in case a failure occurs. The cost per unit time of this inspection/ replacement is 0.1990 and the length is 6010.8 engine hours.

4.1.4 Housing Studs

Table 6. Failure Time for Housing Studs

	Failure Times for Housing Studs(Engine Hours)	Description
1	440	Failure
2	451	Failure
3	483	Failure

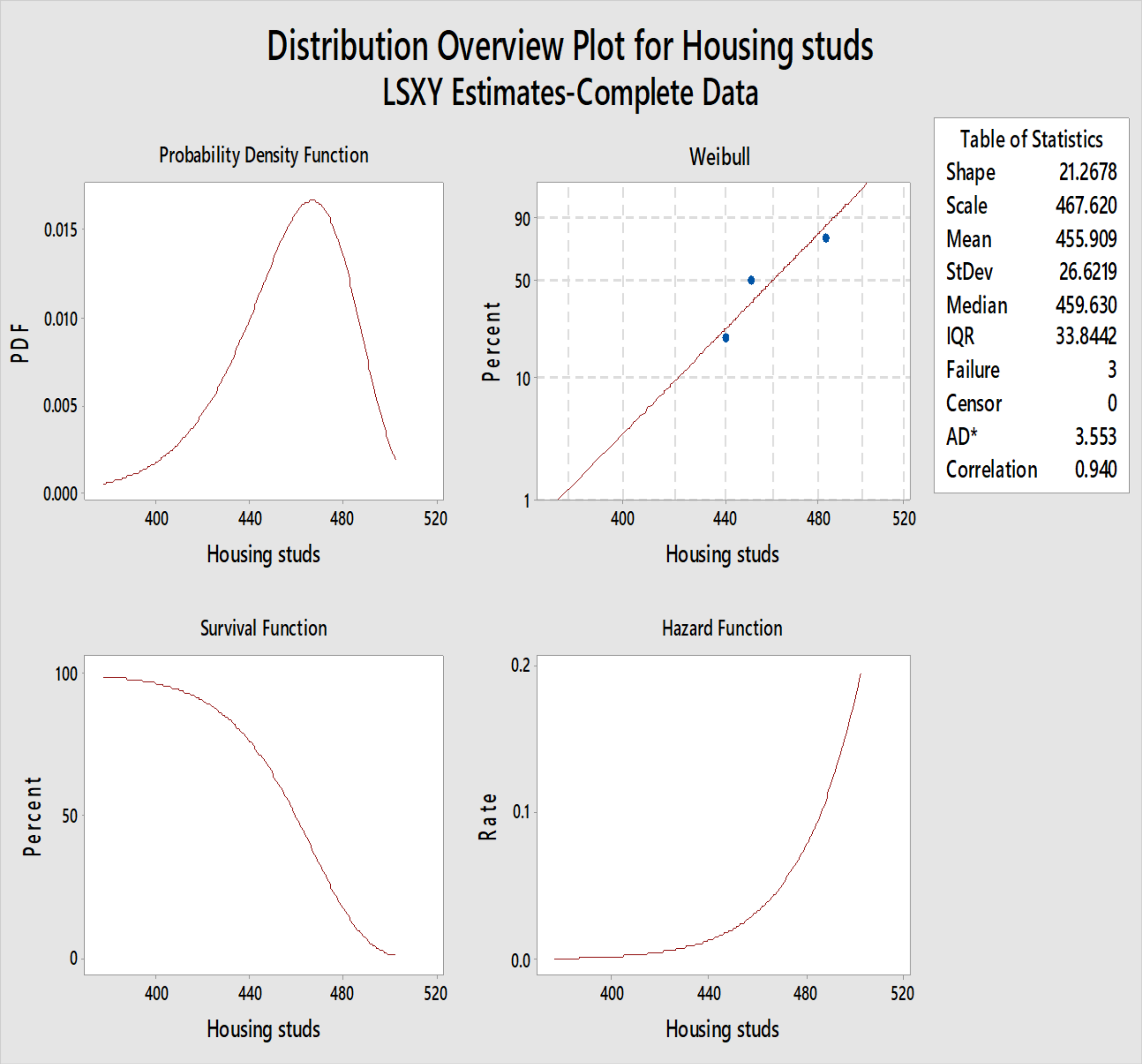

Figure 24. Distribution Overview Plot for Housing Studs

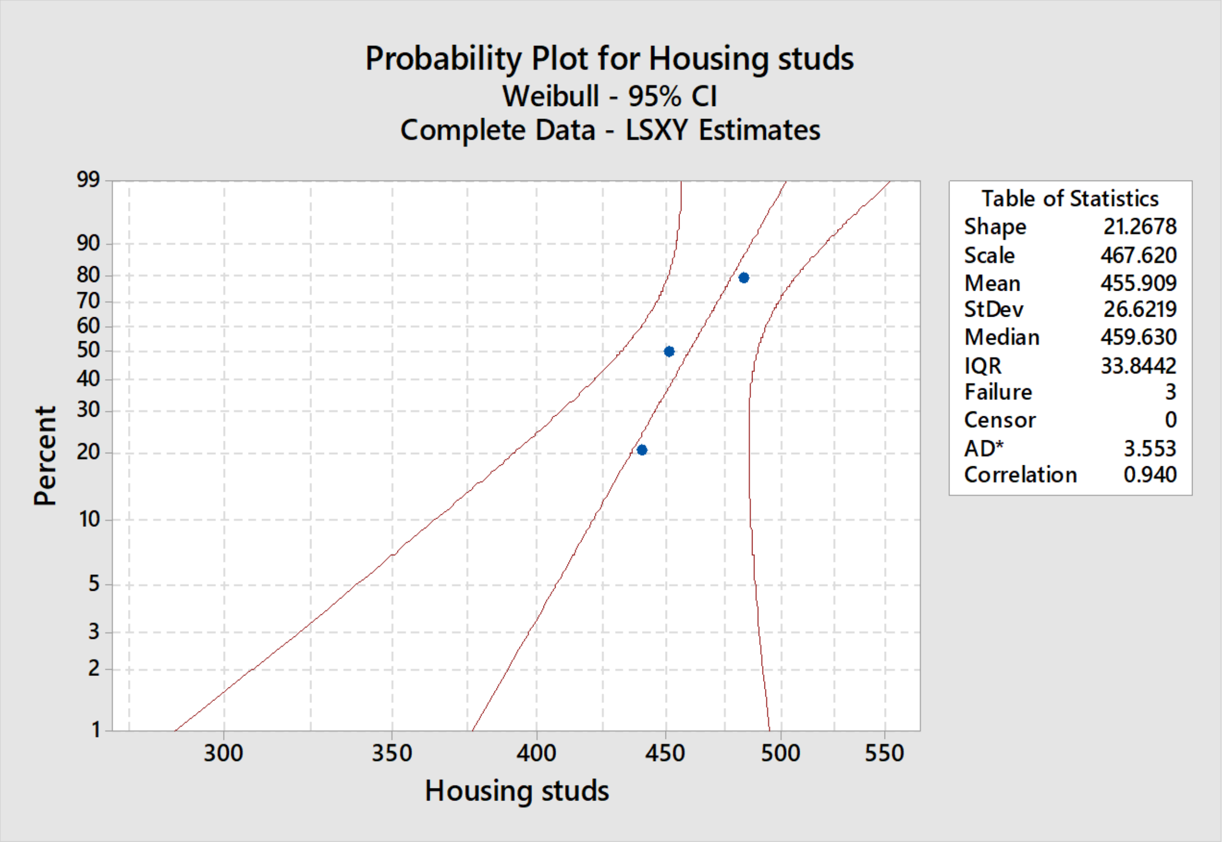

Figure 25. Probability Plot for Housing Studs

From the analysis, as shown in Figure 26, it shows that the mean time to failure of the studs is 455.909 engine hours. The studs being the weakest point from the connection of the shaft from the engine to compressor they are affected most by the vibrations generated.

Optimization of the Maintenance Interval for the Housing Studs

In order to determine the value of the initial estimate, a graphical method is used where the derivative of equation (14) is equated to zero. The plot of the function is shown in Figure 27.

$$dc(t) = F(t) - \frac{C_p}{(C_p - C_f)} - \frac{f(t)}{1 - F(t)} * \int_0^t [1 - F(u)]du = 0 \quad (19)$$

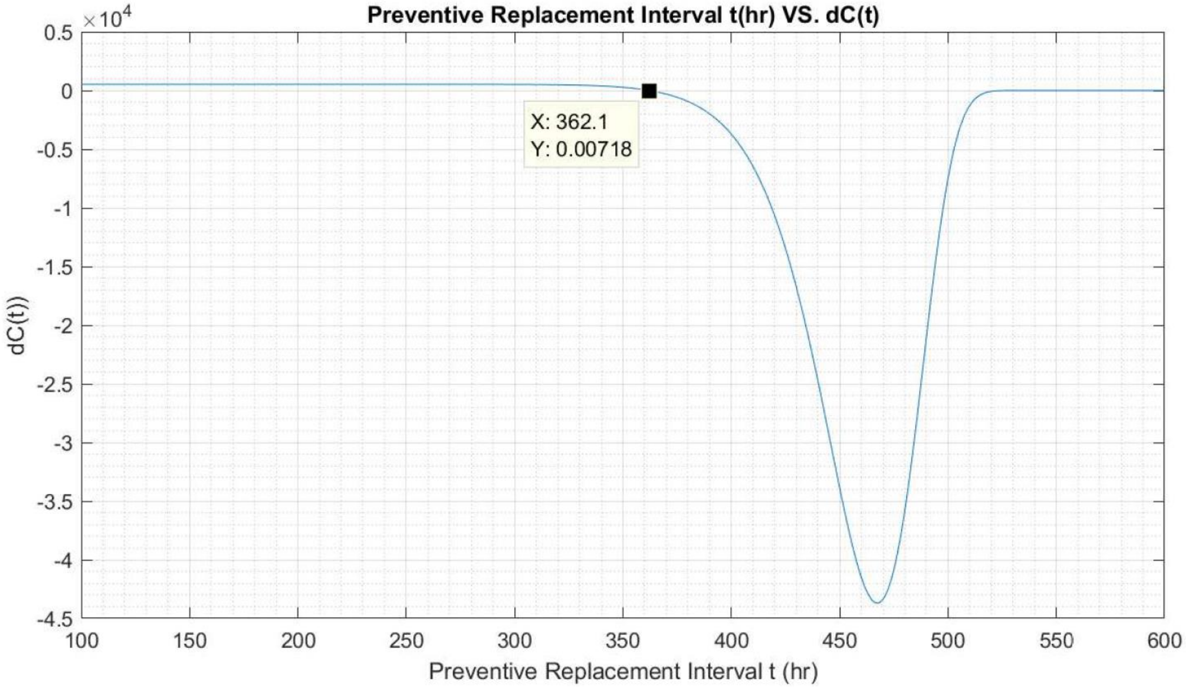

Figure 26. Preventive Replacement Interval Vs. The Derivative of the Cost Function (Housing Studs)

Figure 27 shows that the approximate maintenance interval for the housing studs is 362.1 engine hours.

To confirm the accuracy of this estimation, the relationship between preventive replacement interval and the corresponding cost per unit time is examined. As mentioned above, the main goal is to find the replacement interval that gives minimal cost per unit time.

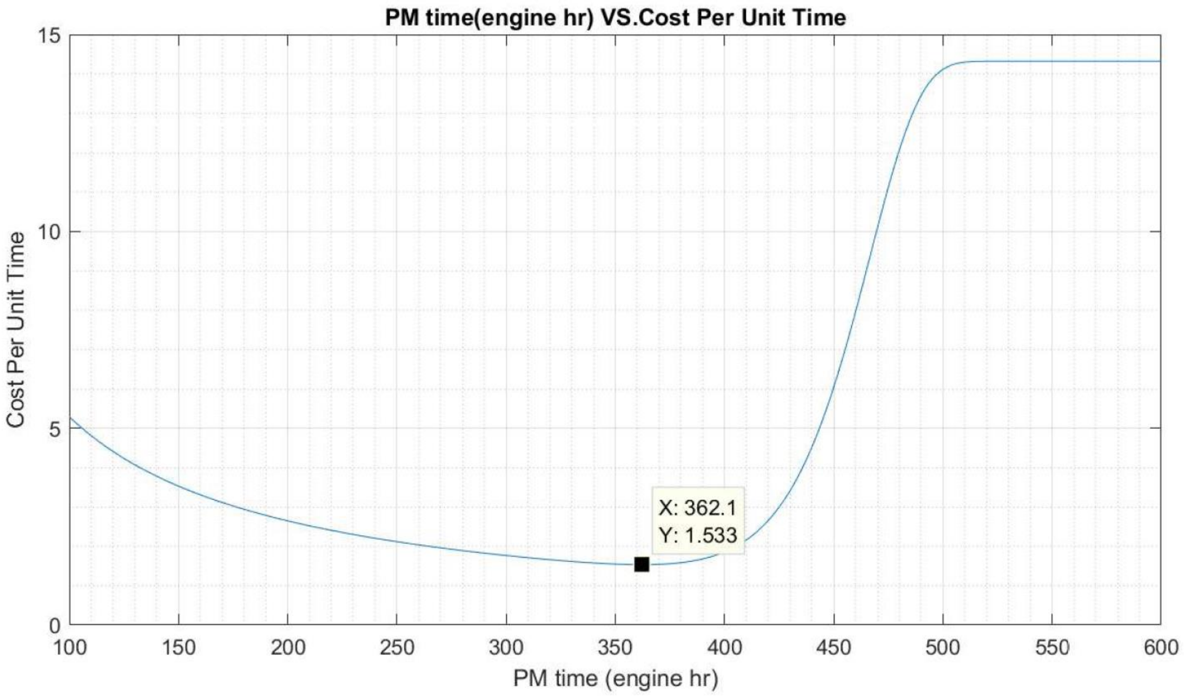

Figure 27. Preventive Maintenance Interval Vs. Cost Per Unit Time (Housing Studs)

Figure 28 shows that the minimum cost occurs when the replacement interval is approximately 362.1 engine hours which is consistent with the result obtained in Figure 27.

To obtain an accurate value, a function for obtaining minimum value in MATLAB is used. The value of maintenance interval is 362.1292 engine hours corresponding to a cost per unit time of 1.5334.

Assuming a failure of a component can be detected any time after 70% of its life span has been consumed. Inspection/ replacement are scheduled at 362.1292 engine hours which is the optimal replacing period obtained after analysis in MATLAB. Considering that MTTF is 455.909, 70% of its life is 319.1363 engine hours. Since the scheduled inspection/replacement is at 362.1292 engine hours which is between 319.1363 and 455.909 engine hours, the failure will be noticed before it occurs.

From the optimization, the gaskets will be replaced every 362.1292 engine hours to avoid high costs that will result from doing corrective maintenance in case a failure occurs. The cost per unit time of this inspection/ replacement is 1.5334 and the length is 362.1292 engine hours.

4.2 Preventive Maintenance/Replacement Interval Variation Analysis

The purpose of this analysis is to determine if variations in the shape parameter result in significant changes in the outcome of the optimization model.

This analysis examines the difference in the resulting cost per unit time when the shape parameter is varied.

Flange Gaskets

Table 7. Shape Parameter Sensitivity Analysis for Flange Gaskets

α=2 to10

Shape Parameter	Cost per unit time $C(t)$ when t =1014.5	Cost per unit time associated with optimal replacement time	Cost difference
2	4.9568	4.9163	0.0405
3	3.9876	3.8221	0.1655
4	3.3749	3.2242	0.1507
5	2.9587	2.8627	0.0960
6	2.6696	2.6227	0.0469
7	2.4675	2.4522	0.0153
8	2.3262	2.3247	0.0015
9	2.2275	2.2259	0.0016
10	2.1587	2.1469	0.0118

From Table 7 it can be noticed that there is a very small cost difference when there is a variation in the shape parameter. The 4.15% (highest) increase in cost per unit time is not very significant. This implies that the cost per unit time will be less affected by a change in shape parameter and use of the optimal time 1014.5 engine hours with changes in the behavior of the flange gaskets in the short run is good because the cost per unit time is not affected greatly hence maintenance costs are still low.

Seals

Table 8. Shape Parameter Sensitivity Analysis for Seals

α=2 to 7

Shape Parameter	Cost per unit time $C(t)$ when t =2238	Cost per unit time associated with optimal replacement time	Cost difference
2	1.4228	1.4228	0.0000
3	1.0594	1.0592	0.0002
4	0.8771	0.8739	0.0032
5	0.7834	0.7656	0.0178
6	0.7351	0.6951	0.0400
7	0.7103	0.6457	0.0646

From Table 8 it can be noticed that there is a very small cost difference when there is a variation in the shape parameter. The 9.09% increase in cost per unit time is not very significant. This implies that the cost per unit time will be less affected by a change in shape parameter and use of the optimal time 2238.0 with changes in the behavior of the seals is good because the cost per unit time is not affected greatly hence maintenance costs are still low.

Compressor Valves

Table 9. Shape Parameter Sensitivity Analysis for Compressor Valves

α=8 to 16

Shape Parameter	Cost Per Unit Time $C(t)$ when t =6010.8	Cost per unit time associated with optimal replacement time	Cost difference
8	0.2607	0.2408	0.0199
9	0.2400	0.2286	0.0114
10	0.2248	0.2191	0.0057
11	0.2136	0.2113	0.0023
12	0.2055	0.2049	0.0006
13	0.1996	0.1996	0.0000
14	0.1952	0.1950	0.0002
15	0.1921	0.1910	0.0011
16	0.1898	0.1876	0.0022

It can be noticed that there is a very small variation in cost when there is a variation in the shape parameter. The 7.63% increase in cost per unit time is not very significant. This implies that the cost per unit time will be less affected by a change in shape parameter and use of the optimal time 6010.8 engine hours with short-run changes in the behavior of the seals is good because the cost per unit time is not affected greatly hence maintenance costs are still low.

Housing Studs

Table 10. Shape Parameter Sensitivity Analysis for Housing Studs

α=18 to 26

Shape Parameter	Cost per unit time $C(t)$ when t =362.1292	Cost per unit time associated with optimal replacement time	Cost difference
18	1.6274	1.6051	0.0223
19	1.5900	1.5804	0.0096
20	1.5610	1.5583	0.0027
21	1.5385	1.5384	0.0001
22	1.5211	1.5204	0.0007
23	1.5076	1.5039	0.0037
24	1.4971	1.4889	0.0082
25	1.4890	1.4751	0.0139
26	1.4827	1.4624	0.0203

It can be noticed that there is a very small variation in cost when there is a change in the shape parameter. The 1.37% increase in cost per unit time is not very significant. This implies that the cost per unit time will be less affected by a change in shape parameter and use of the optimal time 362.1292 engine hours with short-run changes in the behavior of the housing studs is good because the cost per unit time is not affected greatly hence maintenance costs are still low

Table 11. Comparison of Reliability Levels for Current Maintenance Interval and Optimized Maintenance Interval

Equipment	Component	Current maintenance interval (hour)	Optimal maintenance interval (hour)	Current reliability level	Reliability level with an optimal maintenance interval
Compressor	Flange Gasket	1379.96	1014.5	0.5404	0.9556
	Seals	3857.27	2238	0.4570	0.7705
	Valves	7950.44	6010.8	0.5508	0.9849
	Housing Studs	455.909	362.1292	0.5582	0.9957

Based on the reliability equation (2) in section 2.2.2, the current and optimal reliability levels are calculated and on average the reliability of every component is improved by 43%.

Considering a reliability level of 0.95 (the average reliability of some major European railroad operators is around 95 percent [29]), in Table 11 there is a 3% average increase in reliability level for flange gaskets, valves, and housing studs. One thing to notice is that the reliability of the seals has increased but still below 0.95. This brings out the fact that optimal preventive maintenance does not guarantee maximum reliability hence at times a compromise has to be made between reliability and minimum cost while planning for maintenance.

Table 12. Comparison of Cost Per Unit Time for Current Maintenance Interval and Optimized Maintenance Interval

Equipment	Component	Current maintenance interval (hour)	Optimal maintenance interval (hour)	Current Cost Per Unit Time	Cost Per Unit Time with optimal maintenance interval
Compressor	Flange Gasket	1379.96	1014.5	3.6749	2.2752
	Seals	3857.27	2238	1.5682	1.4122
	Valves	7950.44	6010.8	0.496	0.199
	Housing Studs	455.909	362.1292	7.1376	1.5334

It is clear from Table 12 that the optimal maintenance interval is sooner than the URC’s policy of maintenance replacement however on average for all components, the reduction of the total cost per unit time is 47% by implementing optimal maintenance interval.

4.3 Model Validation

The proposed maintenance decision model has been applied on locomotives at Uganda Railways Corporation (URC). The subject (a critical component) used in this case study is the compressor which has contributed to a high rate of locomotive failures. Failure data from the already existing WOs were used and optimal maintenance interval obtained.

Currently, the company implements the PM program (preventive replacement) that is provided by OEM, however, it hasn’t helped much in reducing the rate of unplanned maintenance (failures). Therefore, the proposed model has been used to revise its PM program by considering the current locomotive state and operating environment. The sources of the data used in the analysis are maintenance records obtained at Nalukolongo Railway Workshop (NRW).

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Instead of running a system to failure, one can arrange a preventive replacement at a high-risk situation to avoid costly failure. Also one has the opportunity at the failure to decide whether to repair the system or to replace it by a new one. The objective is to optimize the system based on a given criterion. This thesis presents an overview of preventive maintenance and corrective maintenance and how maintenance optimization is used to achieve better dependability and availability of locomotives that have increasing hazard rate.

From the concept/ principle point of view, the application of maintenance interval determination from a scientific approach is realistic. This is based on the fact that operating environments vary and the nature of failure varies and is difficult to predict before equipment is put into operation.

The procedure for determining the optimal periodicity of preventive maintenance interventions was presented. The step by step procedure was applied to a specific component in order to analyze and evaluate the difficulties associated with its use. With the evaluation, some problems that maintenance engineers may face in maintenance optimization application were identified.

The major problems are a lack of required records in proper organization for procedure application. The research highlights the following limitations: lack of data based on failure modes; no standardization of failure data; incomplete calculation of the costs associated with corrective and preventive maintenance interventions for each component.

5.2 Recommendations for URC

In order to improve the maintenance performance at URC, the following solutions are recommended.

- Develop a computerized maintenance management system that will be integrated with the planning of preventive interventions. The CMMS should not only be considered for storing data but mainly for supporting the processing and analysis of all data. This can efficiently improve the optimal periodicity definition of preventive interventions while considering cost and reliability.
- Have properly standardized complete and organized data to assist in failure analysis and reliability study. One of the problems identified was a generic listing of failures. Also, different maintenance technicians list same failures using different terminologies due to lack of standardization.
- Failure events records should be supported by a failure tree structure. Failure mode effect analysis should be carried out to establish a clear structure that is to be used in the CMMS.

5.3 Recommendations for Future Research

- The effect of inspections is not considered in this research. Further research should be carried out to investigate the effect of inspections on the MTTF of the components.
- Further research can be done on the development of a computer application based on the method described in this thesis and its integration with a CMMS.
- Development of a failure diagnosis system that will help maintenance technicians to identify failure modes, maintenance tasks, and spare parts thus improving the efficiency of carrying out maintenance in general.
- Further research should be carried out to determine the time interval between preventive maintenance where predetermined reliability is guaranteed while incurring minimum maintenance cost.

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APPENDICES

Appendix A

Corrective and Preventive maintenance costs

(in section 3)

Flange Gaskets

Corrective Maintenance.

Task Duration			Cost per Incident		
Delay -wait for labor	2.5		Material cost	24.03	
Delay-wait for material	3.5		Downtime Cost(1000/hr.)	8000.00	
Task duration	2.0		Miscellaneous Cost	0.00	
Others	0.0		Time-based labor cost	6.76	
Total Time per Incident	8.0	Hours	Total Cost per Incident	8030.79	USD

Preventive Maintenance

Task Duration			Cost per Incident		
Delay -wait for labor	0.0		Material cost	24.03	
Delay-wait for material	0.0		Downtime Cost(1000/hr.)	2000.0	
Task duration	2.0		Miscellaneous Cost	0.00	
Others	0.0		Time-based labor cost	6.76	
Total Time per Incident	2.0	Hours	Total Cost per Incident	2030.79	USD

Seals

Corrective Maintenance.

Task Duration		
Delay -wait for labor	2.5	
Delay-wait for material	3.5	
Task duration	1.5	
Others	0.0	
Total Time per Incident	7.5	Hours

Cost per Incident		
Material cost	26.06	
Downtime Cost (1000/hr.)	7500.00	
Miscellaneous Cost	0.00	
Time-based labor cost	5.07	
Total Cost per Incident	7531.13	USD

Preventive Maintenance

Task Duration		
Delay -wait for labor	0.0	
Delay-wait for material	0.0	
Task duration	1.5	
Others	0.0	Hours
Total Time per Incident	1.5	

Cost per Incident		
Material cost	26.06	
Downtime Cost (1000/hr.)	1500.0	
Miscellaneous Cost	0.00	
Time-based labor cost	5.07	
Total Cost per Incident	1531.13	USD

Valves

Corrective Maintenance.

Task Duration		
Delay -wait for labor	2.5	
Delay-wait for material	3.5	
Task duration	1.0	
Others	0.0	
Total Time per Incident	7.0	Hours

Cost per Incident		
Material cost	100.81	
Downtime Cost (1000/hr.)	7000.00	
Miscellaneous Cost	0.00	
Time-based labor cost	3.38	
Total Cost per Incident	7104.19	USD

Preventive Maintenance

Task Duration		
Delay -wait for labor	0.0	
Delay-wait for material	0.0	
Task duration	1.0	
Others	0.0	
Total Time per Incident	1.0	Hour

Cost per Incident		
Material cost	100.81	
Downtime Cost (1000/hr.)	1000.0	
Miscellaneous Cost	0.00	
Time-based labor cost	3.38	
Total Cost per Incident	1104.19	USD

Housing Studs

Corrective Maintenance.

Task Duration		
Delay -wait for labor	2.5	
Delay-wait for material	3.5	
Task duration	0.5	
Others	0.0	
Total Time per Incident	6.5	Hours

Cost per Incident		
Material cost	27.44	
Downtime Cost (1000/hr.)	6500.00	
Miscellaneous Cost	0.00	
Time-based labor cost	1.69	
Total Cost per Incident	6529.13	USD

Preventive Maintenance

Task Duration		
Delay -wait for labor	0.0	
Delay-wait for material	0.0	
Task duration	0.5	
Others	0.0	
Total Time per Incident	0.5	Hour

Cost per Incident		
Material cost	27.44	
Downtime Cost (1000/hr.)	500.0	
Miscellaneous Cost	0.00	
Time-based labor cost	1.69	
Total Cost per Incident	529.13	USD

Appendix B

Source code

MATLAB program for determining the optimal preventive maintenance period

(in Section 3)

Function to obtain the graph of preventive maintenance time vs derivative of cost per unit time function.

```
function Optimum_preventive_maintenance (al, b, cp, cf, t)

%Constants
al=2.02080;
b= 4353.23;
cp= 1531.13;
cf= 7531.13;

%t=376.3276;
%c=(cf*(1-exp(-(t/b) ^al)) +cp*exp(-(t/b) ^al))/(gammainc((t/b)
^al,1/al) *gamma(1/al) *(b/al))
%Initial values
x=1; pt= [];
%Determining pt (derivative of the cost function)
while(x<=8000)

x=x+0.5;
pt=[pt;(cp*(exp(-(x/b) ^al)) +cf*(1-exp(-(x/b) ^al))) *(exp(-
(x/b) ^al)) -(cp*(-al*x^(al-1)/b^al*exp(-(x/b) ^al))
+cf*(al*x^(al-1)/b^al*exp(-(x/b) ^al))) *(gammainc((x/b)
^al,1/al) *gamma(1/al) *(b/al))];

end
xa=1:0.5:8000;

plot (xa, pt);
xlabel ('Preventive Replacement Interval t (hr)');
ylabel('dC(t))');
title ('Preventive Replacement Interval t(hr) VS. dC(t)');
```

Function to obtain a graph of preventive maintenance time vs cost per unit time function

```
function cost_per_unit_time (al, b, cp, cf)

%Constants
al=2.02080;
b= 4353.23;
cp= 1531.13;
cf= 7531.13;

t=2238.0
c=(cf*(1-exp(-(t/b) ^al)) +cp*exp(-(t/b) ^al))/(gammainc((t/b)
^al,1/al) *gamma(1/al) *(b/al))

%Initial values
x=900;
cput= [];
%Determining cput (the cost per unit time function)
while(x<=8000)
x=x+0.5;
cput=[cput;((cf*(1-exp(-(x/b) ^al)) + cp*exp(-(x/b)
^al))/(gammainc((x/b) ^al,1/al) *gamma(1/al) *(b/al)))];

end
xa=900:0.5:8000;

plot (xa, cput);
xlabel ('PM time (engine hr)');
ylabel ('Cost Per Unit Time');
title ('PM time (engine hr) VS. Cost Per Unit Time');
```

Function for obtaining minimum valve for preventive maintenance interval

```
[xmin, fval] =fminbnd (@function, x1, x2)

%Minimum cost per unit time (MCPUT) equation

MCPUT=@(x)(cf*(1-exp(-(x/b) ^al)) + cp*exp(-(x/b)
^al))/(gammainc((x/b) ^al,1/al) *gamma(1/al) *(b/al));

fminbnd(MCPUT,1000,3000)
```