Effectiveness of Reliability and Asset Lifecycle Management Practices in Railway Traction Substations

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Abstract

The South African rail network is under increasing pressure to transport commodities reliably, but poor substation performance makes it difficult for the system to meet its mandate. The primary goal of this study was to provide the engineering communities with the factors affecting the reliability of traction substations. The bathtub curve theory was used in the study, along with Weibull analysis, to assess the lifecycle phase of the substations. A questionnaire and the operational data of the 3kV DC section were used to collect a mix of qualitative and quantitative data. Using the Weibull distribution model, the study discovered that the substation equipment was in the wear-out phase in terms of the bathtub curve. Most failure causes are due to protection equipment, circuit breakers, and telecontrol. According to the financial data, most of the maintenance cost is attributed to corrective maintenance. The study suggested that the organization look into implementing predictive maintenance and training maintenance personnel in order to improve plant performance.

Keywords
Bathtub Curve, Corrective Maintenance, Predictive Maintenance, Reliability and Weibull.

1. Introduction
The South African rail network is under increasing pressure to transport commodities reliably, but poor substation performance makes it difficult for the system to meet its mandate. It is critical to manage, upgrade, and maintain these networks to achieve economic growth. Because of its complexity, the rail transportation system must operate under adverse weather conditions and meet stringent client requirements. The study focused on the reliability of traction substations owned by a national South African railway company. The majority of existing substation equipment has outlived its design life of a traction substation (40 years) and has reached obsolescence. South Africa is experiencing increased commodity demand, which means increased demand for freight logistics. To ensure that the country and company meet demand and remain competitive, reliability and asset lifecycle management practices must be effective. Previous studies into the reliability of railway infrastructure have investigated the factors that influence, and affect reliability (Mukwena 2018; Shihlomule 2019). There are existing reliability and asset lifecycle management practices such as corrective and routine maintenance (Sprong 2008). However, the South African railway systems still experience outages due to asset failures. This necessitates research to establish the effectiveness of the existing reliability and asset lifecycle management practices. This will present an opportunity to identify the gap in the current practice and opportunities for improvement (Nichols and Matusheski 2000).

1.1 Objectives
This study was aimed at providing the engineering community with information on the factors that influence the reliability of South African railway traction substations. The goal is to 1) examine where South Africa's traction substations are on the bathtub curve, 2) compare the reliability and asset lifecycle management practices used to world best practices, and 3) identify the causes of substation failures. This will be accomplished by analyzing substation performance data, maintenance policies in place, maintaining financial records, and seeking expert advice.

2. Literature Review

2.1 Traction system overview

There are mainly three different traction systems in South Africa, namely 3 kV DC, 25 kV AC and 50 kV AC and they differ in their feeding arrangement. These substations receive their supply from Power Utilities in the range of 22 kV to 220 kV. The 3 kV DC traction system is connected to the overheard track equipment in a parallel feeding arrangement where all 3kV DC traction substations feed the complete 3kV DC traction system. The 3 kV DC traction system has high substation construction costs resulting from its short substation intervals (10-15 km) and complex equipment for the conversion of AC to DC. A unit of 25 kV AC traction substation is connected to the overhead track equipment in a series feeding arrangement and only uses two phases from the utility supply and has a substation interval of 25 – 30 km (Sharma 2019). The traction substation equipment goes through the planning, design, construction, testing, operating, maintenance and renewal or disposal phases (Hinow and Mevissen 2011). The typical design life of overhead traction equipment is 30 years for coastal and 50 years for inland areas. Every phase of the life cycle has a cost attached to it, classified as explicit and implicit. Authors (Hinow and Mevissen 2011) indicate the possibility of reducing the operation cost by cutting down on maintenance activities running at a risk of increased probability of failure which may invoke higher replacement and penalty costs.

2.2 Reliability Engineering

Reliability is defined as “the probability that an item will perform a required function without failure under stated conditions for a stated period” (O’Connor and Kleyner 2011). Authors classify (O’Connor and Kleyner 2011) the goal of reliability engineering in the order of importance 1) the use of specialist knowledge to prevent or reduce failure frequency and occurrence, 2) the identification and correction of the causes of failures experienced, 3) development of coping mechanisms if failure causes haven’t been corrected, and 4) application of methods to estimate the reliability of new designs and analyse reliability data. Authors (Nichols and Matusheski 2000) present the best practice for the development and implementation of reliability programs as a three-step process starting by developing a reliability strategy with the involvement of both employees and management to increase the chances of success. Followed by a gap analysis that will drive an understanding of what pushes reliability task selection. Lastly, the selection of the appropriate reliability tool to meet the organization's reliability strategy objectives (Nichols and Matusheski 2000).

2.3 Asset Management

Asset Management is more focused on the operation of a group of assets through the assets' entire lifecycle to guarantee a good return on investment, good service, and security (Schneider et al. 2006). To address the question of determining the condition of equipment, there are existing methods to determine the remaining time to failure of equipment using approximations and statistical methods. Technically, online monitoring of substation components such as transformer oil and SF6 pressure in circuit breakers can be used to determine or approximate the time to failure. In addition, offline measurements and visual inspections during maintenance can be used to estimate (Schneider et al. 2006). The ISO 55000 standard for asset management is more generic and can be used in all types of assets (Okoh et al. 2016). Maintenance management is a part of asset management whereas asset management forms a whole of the asset life (Okoh 2016). Benefits that can be realized from maintenance-based physical asset management include 1) sustained physical asset reliability, 2) improved physical asset and production availability, 3) reduced maintenance cost, 4) improved product quality, 5) reduced safety and environmental impact, 6) improved product compliance, 7) enhanced potential for life extension, 8) improved lifecycle cost, and 9) increased return on investment.

2.4 Traction Substation Reliability

The application of different maintenance strategies impacts the system's reliability differently. In the business of today, businesses and sectors of the economy need to develop suitable maintenance and reliability strategies to remain competitive and meet customer expectations by delivering high-quality and reliable services. In this case, the rail sector is competing with the road sector considering the advantages the rail transport sector has over the road, it still must compete for its place. Authors (Endrenyi et al. 2001) mention the key fundamentals of maintenance which include the following 1) Extending the life of equipment 2) Extending mean time to failure which may prove costly and 3) Reduction in frequency of service interruptions. Three maintenance policies are common in maintenance strategies, and they are namely reactive, preventive, and proactive maintenance. Existing maintenance strategies include corrective, time-based, condition-based and reliability-centred maintenance. The authors (Endrenyi et al. 2001)also surveyed to study the present maintenance policies used in electric utilities. As much as railway traction substations are not utilities, similar equipment used gives insight into substations in general. The study indicated that most utilities use the scheduled maintenance technique or a modified form of this technique as a result of inspections carried out on equipment. The study also found that there are only a few utilities that use predictive maintenance (Endrenyi et al. 2001). Feinstein and Morris (2007) investigate the life of transformers and conclude that the bathtub curve may represent the transformer failure mode with varying lifetimes. In addition, it cites that accelerated life testing has also demonstrated that fact. This implies that the life of the transformer can be divided into three failure modes namely (Feinstein and Morris 2007) Early Failure occurs in the first year of energizing because of manufacturing defects resulting from poor workmanship or materials, followed by Random Failures that are not linked to the above early failures but occur as a result of operating conditions such as switching and lightning surges, operating faults. This is a phase where the failure rate is almost constant and is also known as the useful lifetime phase. Lastly, Wear-Out Failure as a result of ageing equipment. This is mostly after 20 years of operation followed by an increasing failure rate. In addition to the bathtub curve, there exist mathematical models that can be utilized to model different failure modes. This can be very useful in the random failure mode. Key to the reliability study is the probability distribution function (PDF) representing the operating time in the random failure mode (Feinstein and Morris 2007).

3. Methods

This research is both exploratory and descriptive, it seeks to investigate the causes of failure in traction substations and failure trends. This research followed the research onion (Saunders and Brist 2012) approach and adopted the inductive approach. The study used both quantitative and qualitative methods using the case study strategy to 1) establish the existing conditions 2) study the failure trends and establish failure causes and 3) understand the practices currently used against world best practices. The case study required analysis of the technical performance of substations to gain insight into the age of the infrastructure and the reliability and asset lifecycle management practices used in South African traction substations. In addition, a questionnaire was sent to qualifying participants in railway and infrastructure maintenance to get their opinion on the subject matter.

4. Data Collection

The research used multiple sources of data namely, operational data, financial data, and a questionnaire to answer the research question. This process requires accurate data collection to maintain the integrity of the research (Muhammad and Kabir 2016). To establish where in the bathtub curve are the traction substation, the process started with a planning phase where the type of data required was established, data sources identified, and important stakeholders notified of the study. This was followed by the data collection phase where primary and secondary data was sourced from the asset management system and through a documentation review process. The data includes both qualitative and quantitative data. The qualitative data is made up of asset management data indicating the age of existing equipment and its remaining useful life and condition assessment forms from substation technical audits. The quantitative is from the substation performance data from the asset management system. Data description and grouping was used to clean and identify the most relevant data to be used to answer the research question. To understand the reliability and asset lifecycle management practices that can be used to optimize South African traction substations the research had planning, followed by data collection from existing literature to compile a list of the reliability and asset life cycle management best practices across the world. Also, data gathering of the reliability and asset life cycle management practices used in South African railway traction substations.

The research identified maintenance cost, substation failure data and questionnaire data as three elements to investigate and help understand the causes of substation failures that affect the implementation of reliability and Asset Life Cycle Management practices by making use of the triangulation method (Green et al. 2002;Wang and Duffy 2009). The substation failure data were collected to understand the causes of failure and to also determine the equipment and components with the highest failure rates. The financial data was used to establish which maintenance activities are more costly in comparison to other activities. The questionnaire data provided information on the specialists' opinions on the existing reliability management and asset lifecycle management practices that are used in South African railways. The questionnaire design entailed the concept development of questions, the sample frame and size and the delivery platform. The sample frame was selected from both employees in the organization as well as employees who have left the organization. Google forms were used as a data collection instrument and a quantitative questionnaire approach was used in combination with an open-ended question. The form was pre-tested before it was sent to participants to improve questionnaire quality.

5. Results and Discussion

This section describes the results from the operational data, maintenance standards, financial data and questionnaire data aimed at answering the research questions.

5.1 Numerical results

The participant that met the criteria were invited to participate in the research through an email that had a link to the questionnaire. The questionnaire had demographical questions and research-based questions. The demographical questions were aimed at understanding the age, highest qualification, and years of experience of the participants in the railway maintenance industry and the results are presented in Table 1.

Table 1. Demographical information

Items	Participants	% Contribution
Age of the Participants		
>50	1	3,33%
26-30 years	4	13,33%
31-35 years	19	63,33%
36-40 years	6	20,00%
Qualification		
BTech, BSc, BEng	24	80,00%
Masters, PhD	5	16,67%
National Diploma	1	3,33%
A number of years in the railway infrastructure maintenance industry?		
0-2 years	1	3,33%
11-15 years	4	13,33%
16-20 years	1	3,33%
3-6 years	8	26,67%
7-10 years	15	50,00%
Above 20 years	1	3,33%

5.2 Effectiveness of The Asset Management System

The research-based questions used Likert scale items as well as open-ended questions. The Likert scale items questions asked participants to rate their level of agreement or disagreement where a score of 5 was assigned to strongly agree, 4 to agree, 3 to neutral, 2 to disagree and a score of 1 assigned to strongly disagree. The analysis was done using weighted averages. Results of the Likert items aimed at understanding the participants' opinions regarding the effectiveness of the asset management system in railway traction substations are presented in Table 2.

Table 2. Effectiveness of The Asset Management System

Items	Strongly Agree	Agree	Neutral	Disagree	Strongly disagree	Weighted Average
The asset management system can detect age-related failures.	6,00	14,00	4,00	6,00	1,00	3,6
The substation failure rate is increasing with time.	10,00	12,00	7,00	2,00	0,00	4,0
The substation failure rate is decreasing with time.	0,00	5,00	5,00	14,00	7,00	2,3
The substation failure rate is random with time, it doesn't follow any specific pattern.	1,00	11,00	6,00	8,00	5,00	2,8

Items	Strongly Agree	Agree	Neutral	Disagree	Strongly disagree	Weighted Average
The substation replacement parts are still obtainable.	4,00	12,00	6,00	7,00	2,00	3,3

The items measure of internal consistency in terms of Cronbach's alpha was 0,696. On the item that tests the asset management system's ability to detect age-related failures, the calculated weighted average was 3,6 indicating that the asset management system can detect age-related failures. The Likert items testing if the failure rate is increasing with time highlights that the participants agree that the substation failure rate is increasing with time which indicates that in terms of the bathtub curve principle, the substations are in their wear-out stage. The last item of the section aimed at understanding the opinion of participants on the availability of replacement parts to assist in understanding whether the substations have reached a stage of obsolescence. The majority of the participants agreed that spares are still obtainable, the overall weighted score was 3,3.

5.3 Strategies to improve the effectiveness of the asset management system

The second question was aimed at understanding the participants' opinions on what strategies can be used to improve the effectiveness of the asset management system to manage the reliability of the substation.

Table 3. Strategies to improve the effectiveness of the asset management system

Items	Strongly Agree	Agree	Neutral	Disagree	Strongly disagree	Weighted Average
The maintenance strategy links with the organization's vision and mission statement.	6	12	7	4	2	3,5
The maintenance strategy is designed to reduce reoccurring failures.	8	15	3	4	1	3,8
The strategy increases the life expectancy of substations.	7	19	3	1	1	4,0
It is in line with the business performance.	6	13	6	5	1	3,6
It improves infrastructure availability.	7	17	4	2	1	3,9
The maintenance performance indicators assist in identifying reliability challenges.	4	18	3	4	2	3,6

In this case, the first part was Likert scale items, the second part was open-ended questions. The items measure of internal consistency in terms of Cronbach's alpha was 0,963. The majority of the participants agreed to the items tested indicating that the strategy is linked to the organization's vision and mission statement, designed to reduce reoccurring failures, and improves infrastructure availability as shown in Table 3.

5.4 Improving maintenance

An open-ended question was posed to participants and their responses were grouped into common concepts identified in the literature, results are shown in Figure 1. The top two group items identified for improvement are 1) maintenance strategy and 2) skills both accounting for 53 percent of the suggested improvements. The improvements suggested for the maintenance strategy include a shift from corrective and preventive maintenance to a predictive maintenance strategy. The skills improvements include training of maintenance staff to improve productivity. These two are followed by budget prioritizing, change of technology and adherence to and conformance to maintenance schedule and standards all at 11 percent.

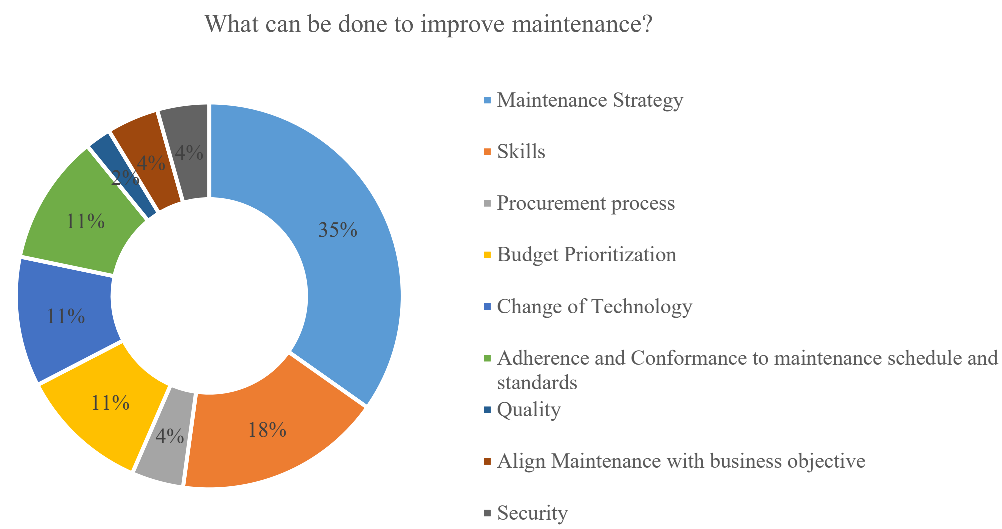

Figure 1. Participant opinion on what can be done to improve maintenance

The participant felt that if more budget can be allocated to maintenance activities, the reliability of traction substations can be improved. Also, participants suggested a shift to an online real-time conditioning monitoring system to give a better indication of how the system is performing. Lastly, both operations and maintenance personnel should allow maintenance to be performed as scheduled, and more time allocated to maintenance. Worthy of note is the issue of theft and its impact on the maintenance of substations. Participants suggested that the security of the traction substation be improved to assist maintenance personnel to focus on their maintenance activities as opposed to attending to theft-related incidents.

5.5 Ability of asset management to improve the reliability and availability of substations

The items of the questionnaire in Table 4 aimed at assessing the participants' opinion on the ability of asset management to improve the reliability and availability of substations measured an internal consistency in terms of Cronbach's alpha of 0,914.

Table 4. Ability of asset management to improve the reliability and availability

Items	**Strongly Agree**	**Agree**	**Neutral**	**Disagree**	**Strongly disagree**	**Weighted Average**
Potential failures are detected before the failure occurs	4	10	5	9	3	3,1
Potential failures are detected during maintenance	1	16	10	4	0	3,5
Potential failures are detected during operations	5	13	7	5	1	3,5
Is the asset failure rate regularly assessed	1	16	7	3	4	3,2
The asset management system can predict the remaining life of equipment and components based on the failure rate	5	14	6	3	3	3,5
The asset management system is used to plan future replacements	12	15	2	1	1	4,2

The result in Table 4 indicates that most of the potential failures are detected during both maintenance and operations. Furthermore, the participants were asked if the asset failure rate is regularly assessed. A weighted score of 3,2 was recorded for this item. The participants agree that the asset management system can predict the remaining life of equipment and components based on failure rate and is used to plan future replacements.

5.6 Stability of substation failures

Operational data from reported failure incidents, maintenance policies, and maintain financial records obtained from the South African Railway Company for thirty-six months was used in this study. The failure incidents data were first tested for stability to understand whether there are special causes. The stability was tested for four hypotheses using a run chart and the study found that there was a special cause, clustering, and presence of a trend (Figure 2). The data was further tested for normality, the first assumption is that the data is normally distributed. Minitab software was used in this research to test normality.

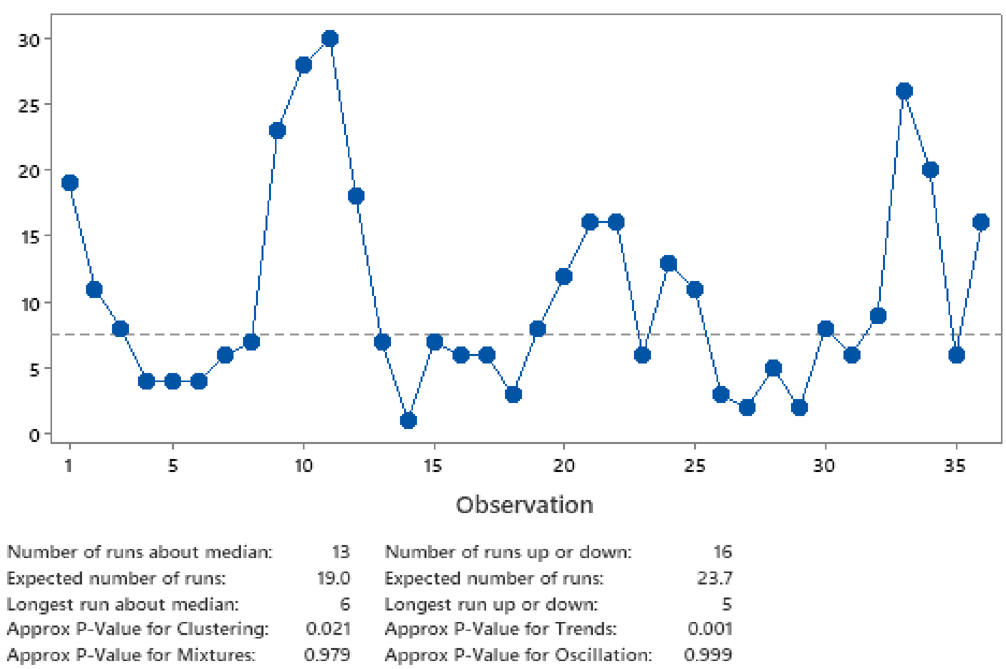

Figure 2. Stability of substation failures

Figure 3 (M= 10.5, STD = 7.718) shows that there was a big variation in the failure data. The KS test result (D (36) =0.209, p <0.01) shows that the data is not normally distributed which also confirms the run chart results that indicated that there was a special cause. For normally distributed data the p-value should be greater than or equal to 0.05 (Ghasemi and Zahediasl 2012).

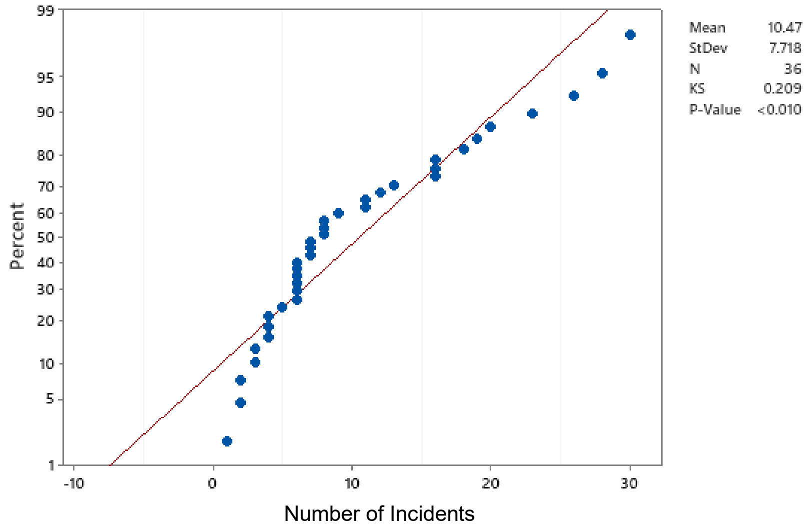

Figure 3. Normality Test

5.7 Goodness of fit test

The goodness of fit test was conducted on the traction substation failures to determine which distribution model will best fit the data using the Minitab software.

Table 5. Goodness of fit test results

Distribution	Anderson-Darling (adj)
Weibull	**0.846**
Lognormal	0.663
Exponential	1.918
Loglogistic	0.642
3-Parameter Weibull	0.716
3-Parameter Lognormal	0.669
2-Parameter Exponential	1.323
3-Parameter Loglogistic	0.641
Smallest Extreme Value	2.702
Normal	1.936
Logistic	1.847

The result in Table 5 presents the distribution model and the Anderson-Darling (AD) values obtained from the Minitab software. The AD values are used to select the distribution model to be used. The smaller the AD the more fit the distribution model. The Weibull, Lognormal, Loglogistic, 3-parameter Weibull, 3 parameters, Lognormal and 3-parameter Loglogistic all have AD values less than 1. This indicates that all these distribution models can be used. However, the Weibull distribution model was selected as it is the most common model used by researchers (Hallinan, 1993; Li, 2004; Lai, Murthy and Xie, 2011; Melchor-Hernández et al., 2015; Lin and Miyauchi, 2017; Agarwal et al., 2020).

5.8 Weibull distribution plot analysis

The Weibull distribution model was used to understand where in the bathtub curve the South African Railway traction substations.

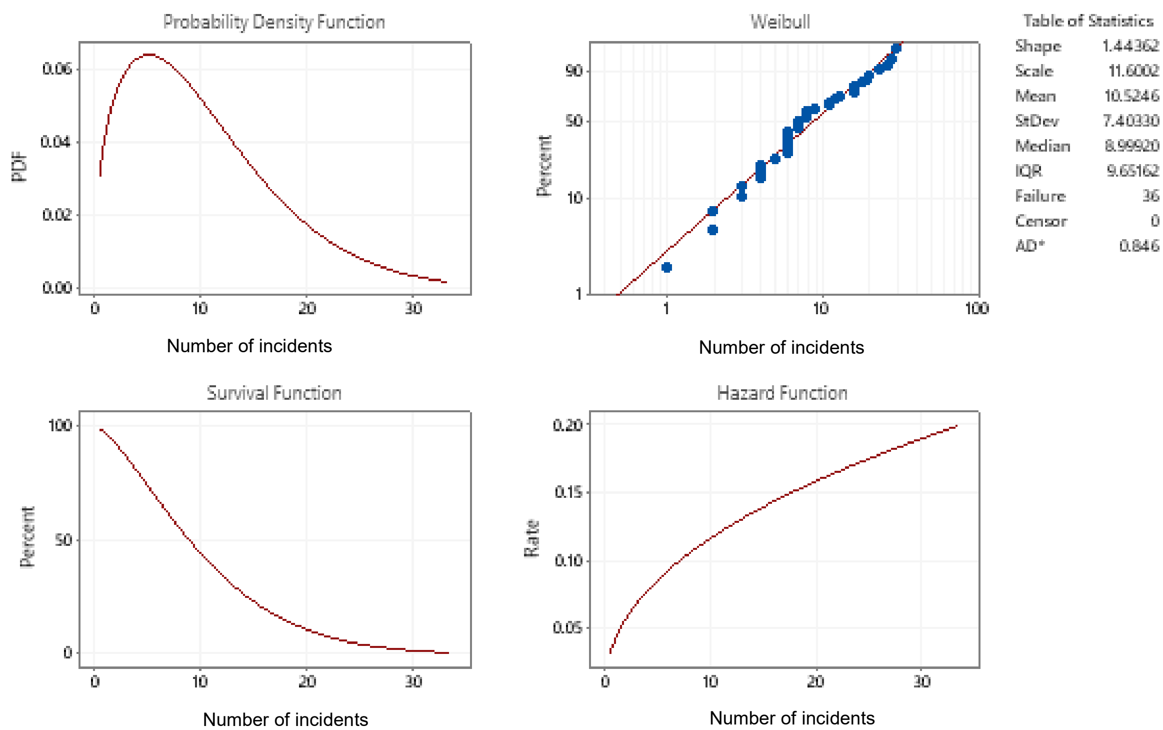

Figure 4. Distribution plots and survival and hazard function

Figure 4 above presents the Weibull distribution of traction substation failures per month for three years. Also, the Probability Distribution Function, Survival and Hazard function. The shape parameter is used to describe the traction substation condition in terms of the bathtub curve. A shape parameter of 1.44 was obtained for the traction substation which indicates that the traction substation of the section under investigation is in the ageing phase. Figure 4 above also indicates a scale parameter of 11.6 faults per month for the traction substations under investigation. The results (mean=10.5, STD=7.403, IQR =9.651), also indicated that there was a big variation in the substation failures which could be due to the wear-out phase of the system.

5.10 Financial Data Analysis

The objective of this analysis is to uncover which type of maintenance accounts for most of the total maintenance cost. The figure below will define the maintenance activities that account for the maintenance cost.

Table 6. Distribution of Maintenance Cost

Maintenance Activity	**% Cumulative**	**%Contribution**
Corrective Maintenance	44,60%	44,60%
Routine Maintenance	71,30%	26,70%
Refurbishment	83,96%	12,66%
Minor Breakdown	95,17%	11,21%
Major Breakdown	100,00%	4,83%
Grand Total		**100,00%**

Table 6 above presents the distribution of the maintenance cost per maintenance activity. Refurbishment items in terms of budget classification cover replacement and refurbishment of existing assets. A Minor Breakdown has a project lifecycle that is less than a year, Major Breakdown has a project lifecycle of more than a year. Table 6 indicates that corrective maintenance accounts for 44.6 percent of the total maintenance cost. This was followed by preventive maintenance, accounting for 26.7 percent of the total cost. In third place is Refurbishment at 12.66 percent. The minor and major breakdowns together account for 16.04 percent of the total maintenance cost. In terms of the Pareto principles, the top twenty percent accounting for eighty percent of maintenance activities are mainly Corrective Maintenance, Routine Maintenance and Refurbishments. The bottom eighty percent are both minor and major breakdowns.

5.9 Pareto Analysis of Equipment failures

A Pareto chart for traction substation failures was done to determine the causes of substation equipment failures. Figure 5 presents the Pareto chart of traction substations failures by equipment classification. The Pareto principle is important in this case as it indicates that eighty percent of the problems come from twenty percent of the causes (Singh Bhangu and Singh 2018). In Figure 5, the protection equipment (37%), circuit breaker (28%) and telecontrol (10%) form the top twenty percent of the causes. The indoor equipment (7.1%), outdoor equipment (3.4%), transformer (1.13%), LT panel Indoor (0.85%), battery charger (0.85%), tie station (0.57%), AC disconnects (0.57%) and current transformer (0.28%) form part of the bottom eighty percent of failure causes. This assisted the researcher in understanding the type of defects the substation is subjected to and the scale of the problems.

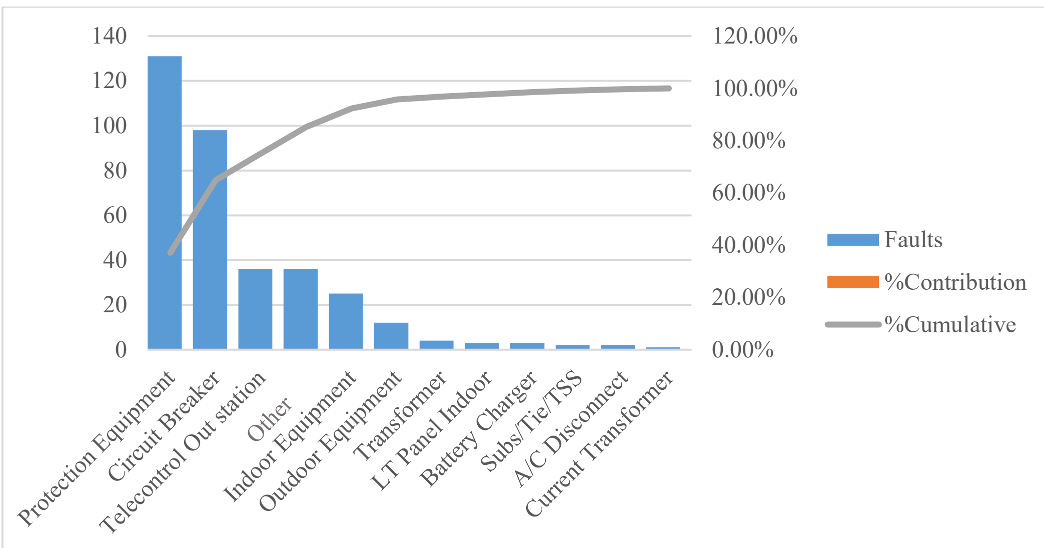

Figure 5. Pareto chart of substation failures by equipment classification

5.12 Validation

This research ensured reliability by using data from reliable data from the case study organization as well as using reliable databases to conduct a literature review. The research used construct validity by using multiple sources of data and triangulation. Also, internal validity by finding matching patterns and providing explanations for opposing patterns (Runeson and Höst 2009). The link between the substation failure data, financial data and questionnaire was studied by making use of the triangulation method to understand the causes of substation failures. The substation failure data indicated that the substations are in their wear-out phase, this agreed with the maintenance cost as the majority of the maintenance cost went towards corrective maintenance. Furthermore, the participants indicated that the failures are increasing with time. This indicates that the common cause of the substation failures is that the substations are in the wear-out phase in terms of the bathtub curve. The Likert items had an acceptable internal consistency between 0,696 and 0.963.

6. Recommendations

According to (Mitsuhiro et al. 2020), organizations face challenges when they must replace ageing equipment as a result of cost, construction and network operational constraints. This is because a lot of equipment must be replaced in a short period. It is recommended that the organization adopts and formalizes a replacement approach based on the equipment 1) technical 2) operational and 3) economic efficiency evaluation with consideration to equipment age such that a proper replacement plan is established and that not all replacement happens at once. The organization should consider the formalization of a lifecycle management plan (Chilwane 2011) to provide an effective long-term planning tool aimed at minimizing unplanned losses and optimizing maintenance programs and capital investment. The plan will incorporate all phases of the product lifecycle where maintenance, replacement or redesign issues will be addressed. This way the organization will manage ageing, obsolescence, and system maintenance. The company is recommended to investigate the application of artificial intelligence in the lifecycle management of substation equipment (Khalyasmaa et al. 2020). Also, it is recommended that the organization consider the involvement of maintenance in all phases of the product lifecycle (Okoh, Schjølberg and Wilson 2016).

The organization makes use of traditional corrective and predictive policies in the form of routine and corrective maintenance. It is therefore recommended that the organization investigate introducing predictive maintenance as a proactive approach considering these research findings. Furthermore, the organization should investigate the introduction of Time-Based Maintenance (TBM), Condition Based Maintenance (CBM) and Reliability Centered Maintenance (RCM) to extend the equipment life and reduce the frequency of service interruptions. The recommendations towards the best practice of reliability and asset lifecycle management include but are not limited to 1) systematic management 2) staff development and 3) technology advancement (Dzulkifli et al. 2021). Security to curb the rate of theft and vandalism so that resources are focused on maintenance activities thus adhering to the maintenance schedule is recommended. The organization should investigate the use of IoT and AI in the condition monitoring of substation equipment (Khalyasmaa et al. 2020; Mitsuhiro et al. 2020).

7. Conclusion

The traction substations of the South African rail network are in their wear-out phase and require intervention in the form of a change of maintenance and replacement of aged equipment. The reliability and asset management lifecycle practices should be updated to include predictive maintenance to improve the reliability of assets. The causes of failure were identified as main equipment failure due to the age of the equipment. This research will assist the south African railway company and engineering community with identifying the phase of the existing fleet, factors that affect reliability and the effective implementation of reliability and asset lifecycle management practices.

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