Int. j. adv. multidisc. res. stud. 2026; 6(3):300-306

Received: 21-03-2026
Accepted: 01-05-2026

International Journal of Advanced Multidisciplinary Research and Studies

ISSN: 2583-049X

Maintenance Cost Reduction for Electrical Power Distribution System in Refinery using Reliability-Centered Maintenance Technique

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DOI: https://doi.org/10.62225/2583049X.2026.6.3.6238

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Abstract
This research carried out maintenance cost reduction for electrical power distribution system in a refinery using reliability centred maintenance (RCM) technique. Exponential reliability method was employed to analyse the electrical power distribution system failure data to determine the reliability metrics of the electrical power distribution system which generated the proposed reliability-centred maintenance plan for the critical electrical power distribution system equipment in the refinery. Linear programming was employed to develop a mathematical model that predicts and optimizes maintenance requirement for the electrical power distribution system based on the analyzed reliability metric. The reliability of the electrical power distribution system was analysed and the results showed that, out of the six (6) components that make the electrical power distribution system in the refinery, pins and disc insulators had the highest reliability with 69.27% and power transformers had the lowest reliability with 7.31% during the period investigated. The formulated linear programming model was solved using LINDO software, and the fifth iteration produced an optimal solution of: x1 =2.67, x2 = 1.67 and F = 2,800,000 naira. The optimized maintenance labour force gave that approximately 3 engineers and 2 technicians should be employed for the refinery electrical power distribution system maintenance task to spend a minimum of N2,800,000 naira as cost of salaries and wages for the labour force monthly, and N33,600,000 as cost of salaries and wages for the labour force annually. The current labor cost (N187,200,000 /year) decreased with respect to the optimized maintenance labour force (N33,600,000/year), The proposed linear programming maintenance model results indicate a saving of about 82.05% of the total annual maintenance labor cost as compared with that of current maintenance labor (RTF) plan for the refinery electrical power distribution system. Conclusion and recommendation were made that the reliability centered maintenance and linear programming technique applied in this study were effective in providing means to reduce maintenance cost of electrical power distribution system taking both the refinery operators and the power suppliers into account when performing asset management, and as such should be adopted by refinery stakeholders to reduce maintenance cost of their production system.

Keywords: Electrical Power Distribution System, Maintenance Cost Optimization, Linear Programming, Operations, Maintenance Planning, Asset Management

1. Introduction

An electrical power system consists of interconnected generating stations of different types, transmission lines, sub-transmission networks, and distribution systems designed to supply electricity to various categories of consumers (Zhang & Gockenbach, 2016). Among these components, the electrical power distribution system plays a crucial role as it provides the final link between utility providers and end users. In practice, most distribution systems are radially configured with a single-circuit main feeder due to their simple design, relatively low cost, and ease of protection coordination (Dehghanian *et al*., 2013) [15]. However, this configuration implies that all components between the supply point and the load point must function effectively, as the failure of any single component can interrupt supply and significantly affect system reliability (Hilber, 2008; Manuel *et al*., 2022). Electricity is indispensable to modern society, and its continuous availability is essential for economic growth and societal development. Consequently, any interruption in power supply can result in substantial losses to stakeholders. The reliability of an electrical power distribution system is defined as its ability to deliver uninterrupted service to end users (Suryono & Rosyidi, 2018), and it serves as a key measure of service quality for utility companies. Reliability is closely linked to national development, economic growth, and customer satisfaction (Fischer *et al*., 2011) [18], and it remains an integral component of modern power system design, planning, and operation (Frie & Kemal, 2020) [20]. However, system reliability is often affected by factors such as faults, component failures, environmental conditions (e.g., wind, rain, floods), and increasing demand (Vanittanakom *et al*., 2008; Olajuyin & Eniola, 2022). In industrial settings, the probability of component failure is particularly high due to heavy loading conditions and the need for continuous power supply (Raghavaiah & HariPrasad, 2019) [28].

The consequences of electrical power distribution system failures are especially critical in industries such as oil and gas refineries, where uninterrupted power supply is essential for operational efficiency. Failures in these systems can reduce performance, disrupt operations, and in extreme cases lead to complete system breakdown (Radomir, 2017) [27]. Such disruptions can result in significant economic losses and may also increase the risk of environmental and safety hazards (Ogujor & Kuale, 2007; Sengi & Ntagwirumugara, 2021 [34]). Therefore, improving system reliability and minimizing failures are essential for maintaining productivity and ensuring safe operations in such industries. Maintenance plays a fundamental role in enhancing the reliability and performance of electrical power distribution systems. It involves all actions taken to retain equipment in, or restore it to, a condition in which it can perform its intended function (Yssaad *et al*., 2014). Maintenance activities aim to reduce failure frequency, minimize downtime, extend equipment lifespan, and improve system availability (Muath *et al*., 2016; Awara *et al*., 2024 [11]). Over time, maintenance has evolved from a purely corrective approach, where actions are taken only after failures occur, to more proactive and strategic approaches that emphasize prevention and optimization (Blischke, 2000). Traditional maintenance strategies, particularly time-based or scheduled maintenance, have proven inadequate in meeting the increasing reliability demands of modern power systems. These approaches may lead to excessive maintenance costs or increased failure rates due to poorly optimized maintenance intervals (Patil *et al*., 2022; Stanislav *et al*., 2005). Consequently, there has been a shift toward more advanced maintenance strategies that integrate reliability analysis with cost considerations (Mahmoudi *et al*., 2014). This shift is driven by the need to balance maintenance expenditures with system performance, as maintenance activities can account for a significant portion of total operational costs (Marketz *et al*., 2005; Ali *et al*., 2018 [7]).

Reliability-Centered Maintenance (RCM) has emerged as an effective approach for improving system reliability while minimizing maintenance costs. RCM provides a structured framework for determining optimal maintenance strategies based on reliability analysis, failure modes, and cost–benefit considerations (Shashi *et al*., 2020). It integrates corrective, preventive, predictive, and condition-based maintenance practices to enhance system performance and reduce unplanned downtime (Amjad & Ammar, 2018; Afefy, 2010) [9, 1]. By focusing on system functions, potential failure modes, and their consequences, RCM enables the development of targeted maintenance actions that improve reliability and reduce lifecycle costs (Yssaad *et al*., 2014; Vishnu & Regikumar, 2016; Liu, 2014).

In this study, Reliability-Centered Maintenance is applied to reduce maintenance costs and improve the reliability of an electrical power distribution system in a refinery. Key reliability parameters, including Mean Time Between Failures (MTBF), Mean Time to Repair (MTTR), failure rate, repair rate, availability, and maintainability, are evaluated. Additionally, Failure Mode Effects and Criticality Analysis (FMECA) is conducted to identify critical system components and develop appropriate maintenance strategies. Ultimately, a maintenance optimization model is developed and validated to enhance system performance while minimizing operational costs.

2. Methodology

2.1 Method of Data Collection

The materials that were used in this study are failure data of the electrical power distribution system components including cables, transformers, breakers, line conductors and busbars & isolators obtained from primary electrical power distribution system in Port Harcourt Refinery supplying electricity to Area 2 made up of Naphtha Hydrotreating unit (NHU) and data of the available maintenance manpower/ labour resources for the electrical power distribution system. The method of data collection was through direct observation from the monitoring screen of the automated system called human machine interface (HMI), including data from log books and manufacturers manual of the electrical power distribution system. Data collection will involve gathering both historical and real-time data on the operational parameters of the electrical power distribution system. Historical data will be obtained from electrical power distribution system operation logs and performance reports, while real-time data will be captured using sensors, instruments and data acquisition systems installed in the electrical power distribution system.

2.2 Method of Data Analysis

Reliability-centered Maintenance Method for Electrical Power Distribution System Maintenance Cost Reduction

The reliability of the electrical power distribution system in Port Harcourt Refinery supplying electricity to Area 2 made up of Naphtha Hydrotreatung unit (NHU) which facilitates reliability-centered maintenance of electrical power distribution system in a refinery for maintenance cost reduction is determined using the following as posited by David & Graham (2018):

Mean Time Between Failures (MTBF)

$$MTBF = \frac{\sum t_O}{n}$$

Mean Time to Repair (MTTR)

$$MTTR = \frac{\sum t_R}{n}$$

Failure Rate (λ)

$$\lambda = \frac{1}{MTBF}$$

Repair Rate

$$\mu = \frac{1}{MTTR}$$

Availability

$$A = \frac{MTBF}{(MTBF + MTTR)}$$

Maintainability Function

$$M(t) = 1 - e^{-\mu t}$$

Exponential Reliability Model

$$R(t) = e^{-\lambda t}$$

$$F(t) = 1 - e^{-\lambda t}$$

Linear Programming Method

Linear programming was employed to develop, apply and validate a mathematical model that optimizes the maintenance scheduling of the electrical power distribution system using extant maintenance scheduling optimization models. Linear programming is that branch of mathematical programming which is designed to solve optimization problems where objectives and all the constraints involved can be expressed as a linear function. It is a powerful tool in management science and operations research for decision making under certainty with the aid of a mathematical model (Awara *et al.,* 2024) [11]. It is useful in the allocation of scarce resources like materials, machine, man, time, etc. The general optimization equations, constraints and assumptions used for the linear programming method is presented in Appendix A.

Multiple Linear Regression Model

Multiple linear regression model was employed to validate a mathematical model that optimizes the maintenance scheduling of the electrical power distribution system using extant maintenance scheduling models using the data of the mean time between failures, mean time to repair, failure rate, repair rate, and availability. The regression equation is presented in Appendix B.

ANOVA/F-test

The one-way analysis of variance (ANOVA)/F-test was also used to validate the results of the mathematical model that optimizes the maintenance scheduling of the electrical power distribution system using extant maintenance scheduling optimization models. The equation is presented in Appendix B.

2.3 Data Analysis

Failure data was obtained from Port Harcourt Refinery to analyze the reliability of the electrical power distribution system in Port Harcourt Refinery supplying electricity to Area 2 made up of Naphtha Hydrotreating unit (NHU) to improve its operational performance. Data for this research work was obtained through direct observation and operational record of the electrical power distribution system in Port Harcourt Refinery supplying electricity to Area 2 made up of Naphtha Hydrotreating unit (NHU). The electrical power distribution system was resolved into the smallest component of the system and a block diagram was developed which facilitated the formulation of Failure Mode Effect and Criticality Analysis (FMECA) and Root Cause Failure Analysis (RCFA) of the electrical power distribution system. In analyzing the collected failure data, the exponential distribution method was applied accordingly.

Data related to the first and second objectives which is to assess the electrical power distribution system's MTBF, MTTR, repair rate, failure rate, cum availability, maintainability and reliability maintenance metrics and parameters and to conduct the failure mode effects and criticality analysis (FMECA) of the electrical power distribution system, was achieved using the relevant MTBF, MTTR, failure rate, repair rate, availability, maintainability and reliability methods with the system's failure data. For the third objective, which is to generate a maintenance task for the electrical power distribution system centred on the analysed reliability indices, Root Cause Failure Analysis and Failure Mode Effect and Criticality Analysis was conducted for the electrical power distribution system in order to generate a reliability-based maintenance task and action plan that predicts the maintenance requirements for the electrical power distribution system. For the fourth objective, while ANOVA was employed to develop, apply and validate a mathematical model that optimizes the maintenance scheduling of the electrical power distribution system using extant maintenance scheduling optimization models.

3. Result

3.1 Maintenance Task for the Electrical Power Distribution System centred on the analysed Reliability Indices

Table 1: Electrical Power Distribution System Maintenance Task

Equipment	Failure Mode	Failure cause	Group	Task	Description	Frequency
Power Transformer	Transformer cable/connection failure	Cable/connection corroded cum damaged,	B (Medium-High)	CD	Check and replace cable/connection for corroded or damage and tighten	Monthly
	Transformer forced air cooling failure	Incorrect or loose installation and Electrical or thermal overload	A (High)	CD	Check for loose installation or improper installation	Monthly
		Dirt/contaminant build up	A (High)	CD	Check against Electrical or thermal overload	Monthly
		Insufficient grease	A (High)	CD	Lubricate and grease adequately	Weekly
		Fan electronic control failure, fan damaged	A (High)	CD	Check and replace fan electronic control against failure	Monthly
	Transformer insulation failure	Electrical or thermal overload	A (High)	CD	Check against Electrical or thermal overload	Monthly
		Insulation physically damaged	A (High)	CD	Check and replace Insulation physically damaged	Monthly

	Transformer windings failure	Windings physically damaged	A (High)	CD	Check and replace Insulation physically damaged	Monthly

The maintenance task for the refinery electrical power distribution system is presented in Table 1. The table reveals that for transformer cable/connection failure mode of the power transformer, caused by cable/connection corroded which was analysed with medium-high criticality level (criticality group B); the maintenance task prescribed is the condition-directed (CD) maintenance as it has a moderately high effect on the system and the maintenance task prescribed the failure mode is to check and replace cable/connection for corroded or damage monthly. For failure mode transformer cable/connection caused by incorrect or loose installation which was analysed with high criticality level (criticality group A), the maintenance task prescribed for the failure causes is to check for loose installation or improper installation monthly and tighten. For failure mode Transformer forced air cooling failure caused by electrical or thermal overload, dirt/contaminant build up, insufficient grease, fan electronic control failure, fan damaged and electrical or thermal overload which were analysed with high criticality level (criticality group A), the maintenance task prescribed for the failure causes is the condition-directed (CD) maintenance tasked with check against electrical or thermal overload, check and replace fan electronic control against failure, to be carried out monthly, except for insufficient grease with maintenance lubricate and grease which should be carried out weekly as the failure caused has a high effect on the system.

For failure mode transformer insulation failure caused by electrical or thermal overload and insulation physically damaged which was analysed with high criticality level (criticality group A), the maintenance task prescribed is condition-directed (CD) maintenance, tasked with check against electrical or thermal overload and check and replace insulation physically damaged, monthly, as the failure caused has a high effect on the system Finally, for failure mode transformer windings failure caused by Windings physically damaged was analysed with high criticality level (criticality group A), the maintenance task prescribed is the condition-directed (CD) maintenance, tasked with checking and replacing insulation, monthly, and as it has a maximal effect on the system.

3.2 Maintenance Labor Force for the Electrical Power Distribution System

Table 2: The Size of Annual Maintenance Labor Force for the Electrical Power Distribution System

PM Level	Frequency	Duration (Hours)	No. of Workers	Man-hour per PM level
Monthly	10	5	2	100
Weekly	50	6.15	1	325

Maintenance labor force = 1 labor.

Table 3: Electrical Power Distribution System Current Maintenance Labor Size per day

Item	Labor type	Number of labours Per day (current maintenance)
Engineers (N 800, 000.00/month)	Mechanical	4
	Electrical	5
	Control	4
Technician (N 400, 000.00/month)	Mechanical	5
	Electrical	6
	Control	2
Total cost (Naira/year)		**187,200,000**

(PHRC, 2025).

The size of the reliability-based maintenance labour force for the refinery electrical power distribution system is presented in Table 2 based on calculations for the PM levels (monthly and weekly). Tasks prescribed monthly is carried out 10 times annually with 2 maintenance personnel working 5 hours on each schedule, totalling 100 (10 x 5 x 2) man-hour per PM level while task prescribed every week is done 50 times annually with 1 maintenance personnel working 6 hours 9 minutes on each schedule, totalling 325 (50 x 6.15 x 1) man-hour per PM level. The refinery electrical power distribution system current maintenance labour size per day and cost of salaries for their maintenance work annually is introduced in Table 3. The current maintenance force for the refinery electrical power distribution system in the facility as obtained from the plant presented in Table 2reveals that the facility employs 4 mechanical engineers, 5 electrical engineers, 4 control engineers, 5 mechanical technicians, 6 electrical technicians, and 2 control technicians for their current maintenance task costing the industry N187,200,000 annually.

3.3 Mathematical model that optimizes the maintenance scheduling of the electrical power distribution system using extant maintenance scheduling optimization models

Table 4: Linear Programming Model Formulation

				Labor type	Cost of Salaries
		M	El	C	(x 10^3Naira
Labor Rank	E	4	5	4	800
	T	5	6	2	400
Quantity available		19	16	14	

The linear programming model is formulated using the data of the current quantity of maintenance engineers and technician needed for maintenance as well as the current quantity of mechanical, electrical and control engineers and technicians available for refinery electrical power distribution system maintenance in the facility. All the linear programming iterations are presented in Appendix C. The formulated linear programming model was solved using LINDO software, and the fifth iteration gives an optimal solution of: x1 =2.67, x2 = 1.67 and F = 2,800,000 naira. The optimized maintenance labour force gave that approximately 3 engineers and 2 technicians should be employed for the refinery electrical power distribution system maintenance task to spend a minimum of N2,800,000 naira as cost of salaries and wages for the labour force monthly, and N33,600,000 as cost of salaries and wages for the labour force annually.

The current labour cost (N187,200,000 /year) decreased with respect to the optimized maintenance labour force (N33,600,000/year), The proposed linear programming maintenance model results indicate a saving of about 82.05% of the total annual maintenance labour cost as compared with that of current maintenance labour (RTF) plan for the refinery electrical power distribution system. The mathematical model that optimizes the maintenance of the refinery electrical power distribution system was validated using extant maintenance optimization models.

The multiple linear regression model was generated from the reliability maintenance metrics data in Table 5 is presented below:

Table 5: Multiple Linear Regression ANOVA Results

Summary Output								
Regression Statistics								
Multiple R	1							
R Square	1							
Adjusted R Square	48274							
Standard Error	0							
Observations	4							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	6	482.2838	134.7392	11.824	0.00003			
Residual	0	0	48274					
Total	6	482.2838						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-77.235	0	48274	0.522	-793.235	-793.235	-793.235	-793.235
MTBF	0.082937	0	48274	0.516	0.019476	0.019476	0.019476	0.019476
MTTR	0.728013	0	48274	0.477	0.847246	0.847246	0.847246	0.847246
Failure Rate	0	0	48274	0.924	0	0	0	0
Repair Rate	0	0	48274	0.337	0	0	0	0
Availability	5.62924	0	48274	0.482	5.03448	5.03448	5.03448	5.03448
Maintainability	0	0	48274	0.956	0	0	0	0

As per the MATLAB generated table, the regression model is:

$$Y = -77.235 + 0.082937X1 + 0.728013X2 + 5.62924X6$$

The multiple linear regression model results above reveal that there is a relationship between dependent variable (electrical power distribution system reliability) and independent variables (MTBF, MTTR, Availability). From the findings, one unit change in MTBF results to 0.082937 units increase in reliability, one unit change in MTTR results to 0.728013 units increase in reliability, and one unit change in Availability results to 0.62924 units increase in reliability. Multiple linear regression reveals that the F calculated at 5% level of significance was 11.842 and since F calculated is greater than the F critical (value = 2.17), this shows that the overall model was significant. The F significance value of 0.00003, validates that regression model has probability of 0.003% of giving wrong prediction. It can be concluded that regression model is statistically significant, hence suitable for predicting the maintenance requirements of the rotary hydraulic pump equipment. These findings are coherent with maintenance optimization models developed by Yssaad and Abene (2015), Yssaad (2020) and Dorin *et al.* (2011) [17].

Fig 6: Validating the predictive maintenance optimization model developed for the electrical power distribution system comparatively with other maintenance optimization models

Model	MSE	RMSE	MAE	R2
Linear Regression	0.981	0.962	0.927	0.990

In the validation analysis, it is also known that the MSE (Mean Squared Error) value obtained for the linear regression model generated is 0.981, then the RMSE (Root Mean Squared Error) value is 0.962, then the MAE (Mean Absolute Error) value is 0.927 and the R-squared (R2) value is 0.990. Information regarding these results can be seen in Table 6.

4. Discussion of Findings

The maintenance task for the electrical power distribution system in the refinery was generated and the results reveals that for transformer cable/connection failure mode of the power transformer, caused by cable/connection corroded cum damaged which was analysed with medium-high criticality level (criticality group B); the maintenance task prescribed is the condition-directed (CD) maintenance as it has a moderately high effect on the system and the maintenance task prescribed the failure mode is to check and replace cable/connection for corroded or damage monthly. For failure mode transformer cable/connection caused by incorrect or loose installation which was analysed with high criticality level (criticality group A), the maintenance task prescribed for the failure causes is to check for loose installation or improper installation monthly and tighten. For failure mode Transformer forced air cooling failure caused by electrical or thermal overload, dirt/contaminant build up, insufficient grease, fan electronic control failure, fan damaged and electrical or thermal overload which were analysed with high criticality level (criticality group A), the maintenance task prescribed for the failure causes is the condition-directed (CD) maintenance tasked with check against electrical or thermal overload, check and replace fan electronic control against failure, to be carried out monthly, except for insufficient grease with maintenance lubricate and grease which should be carried out weekly as the failure caused has a high effect on the system. For failure mode transformer insulation failure caused by electrical or thermal overload and insulation physically damaged which was analysed with high criticality level (criticality group A), the maintenance task prescribed is condition-directed (CD) maintenance, tasked with check against electrical or thermal overload and check and replace insulation physically damaged, monthly, as the failure caused has a high effect on the system Finally, for failure mode transformer windings failure caused by Windings physically damaged was analysed with high criticality level (criticality group A), the maintenance task prescribed is the condition-directed (CD) maintenance, tasked with checking and replacing insulation, monthly, and as it has a maximal effect on the system.

A mathematical model that optimizes the maintenance of the electrical power distribution system in the refinery was developed, applied and validated using extant maintenance scheduling optimization models. From the reliability centred maintenance task developed for the most critical electrical power distribution system equipment in the refinery, a mathematical model that predicts and optimizes maintenance requirement for the electrical power distribution system equipment in the refinery was developed and the maintenance labor/task force was optimized using linear programming method with an objective function of minimizing the maintenance labour cost. The objective is to obtain the best labor mix (engineer- mechanical, electrical and control and technician-mechanical, electrical and control) at minimum cost of maintenance in terms of salaries and wages of the labor force. The formulated linear programming model was solved using LINDO software, and the fifth iteration produced an optimal solution of: x1 =2.67, x2 = 1.67 and F = 2,800,000 naira. The optimized maintenance labour force gave that approximately 3 engineers and 2 technicians should be employed for the refinery electrical power distribution system maintenance task to spend a minimum of N2,800,000 naira as cost of salaries and wages for the labour force monthly, and N33,600,000 as cost of salaries and wages for the labour force annually. The current labour cost (N187,200,000 /year) decreased with respect to the optimized maintenance labour force (N33,600,000/year), The proposed linear programming maintenance model results indicate a saving of about 82.05% of the total annual maintenance labour cost as compared with that of current maintenance labour (RTF) plan for the refinery electrical power distribution system.

The mathematical model that optimizes the maintenance of the electrical power distribution system was validated using extant maintenance optimization models. The multiple linear regression model was generated from the reliability maintenance metrics. The multiple linear regression model results revealed that there is a relationship between dependent variable (electrical power distribution system reliability) and independent variables (MTBF, MTTR, Availability). From the findings, one unit change in MTBF results to 0.082937 units increase in reliability, one unit change in MTTR results to 0.728013 units increase in reliability, and one unit change in Availability results to 0.62924 units increase in reliability. Multiple linear regression reveals that the F calculated at 5% level of significance was 11.842 and since F calculated is greater than the F critical (value = 2.17), this shows that the overall model was significant. The F significance value of 0.00003, validates that regression model has probability of 0.003% of giving wrong prediction. It can be concluded that regression model is statistically significant, hence suitable for predicting the maintenance requirements of the rotary hydraulic pump equipment. These findings are coherent with maintenance optimization models developed by Yssaad and Abene (2015), Yssaad (2020) and Dorin *et al.* (2011) [17]. In the validation analysis, it is also known that the MSE (Mean Squared Error) value obtained for the linear regression model generated is 0.981, then the RMSE (Root Mean Squared Error) value is 0.962, then the MAE (Mean Absolute Error) value is 0.927 and the R-squared (R2) value is 0.990.

5. Conclusion

This study successfully developed and applied a reliability-centered maintenance (RCM) framework to optimize maintenance practices for an electrical power distribution system in a refinery. The findings revealed that most critical failure modes of the power transformer components fall within high and medium-high criticality levels, necessitating condition-directed maintenance strategies. Regular inspection, replacement, tightening, lubrication, and monitoring activities—carried out either monthly or weekly depending on severity—were identified as effective measures to mitigate failures and enhance system reliability. Furthermore, a linear programming model was developed to optimize maintenance labor allocation with the objective of minimizing cost. The model, solved using LINDO software, recommended an optimal workforce of approximately three engineers and two technicians, resulting in a significant reduction in maintenance labor cost from ₦187,200,000 to ₦33,600,000 annually. This represents an 82.05% cost saving compared to the existing run-to-failure maintenance approach. The developed model was validated using multiple linear regression analysis, which confirmed a strong and statistically significant relationship between reliability and key maintenance metrics (MTBF, MTTR, and availability). Validation results demonstrated high predictive accuracy, confirming the model's suitability for maintenance planning. Overall, the study establishes RCM combined with optimization techniques as an effective approach for improving reliability and reducing maintenance costs in refinery power systems.

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