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Reliability Centered Maintenance (RCM) and Preventive Maintenance (PM) Methods as a Hybrid Maintenance Model: Jordanian Electric Power Generation Company as a Case Study

Issam S. Jalham[1], Adnan Bashir[*2], Razan Yasser Zarraq[1]

[1]*University of Jordan, Industrial Engineering Dept.*
[2]*The Hashemite University, Industrial Engineering Dept.*

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Abstract

Delivering products to customers while ensuring effective and efficient asset operation is a crucial challenge that drives organizations to focus on asset preservation, extending asset lifecycles, and maintaining proper functionality. This requires maintenance organizations to select the most suitable tasks to assess the criticality of each asset within the overall system, enabling them to prioritize maintenance and allocate resources effectively. Additionally, a strategic roadmap is essential for conducting maintenance in line with best practices. The methodology employed in this article is based on asset evaluation through Asset Criticality Analysis (ACA), followed by Logic Tree Analysis (LTA) to identify the most effective maintenance tasks to implement. To obtain the proposed hybrid model, both the Reliability-Centered Model (RCM) and the Preventive Maintenance Optimization model (PMO) have been merged and utilized. The required data were extracted from reports generated by the Computerized Maintenance Management System (CMMS), which is also known as Enterprise Resource Planning (ERP). The developed model was applied, and results were analyzed, taking into consideration reliability and availability as key performance indicators. The results showed a 4.7% increase in reliability and 5% increase in availability, while a 76% improvement in the time between failures, while also reducing the number of failures. The main contribution of this paper is the integration of the Reliability-Centered Maintenance (RCM) and Preventive Maintenance (PM) methods through principles of Preventive Maintenance Optimization (PMO).

Keywords: Preventive Maintenance Optimization (PMO), Reliability Centered Maintenance (RCM), Reliability, Availability.

1. Introduction

One of the critical issues in any organization or industrial facility is to maintain assets in their normal operating conditions while ensuring availability and reliability. Unplanned equipment failures can lead to production losses, safety risks, and increased maintenance costs; therefore, preventing such failures and sustaining continuous production are essential. Preventing unintentional failures and maintaining a continuous supply of products is essential. However, industrial facilities often focus on solving arising failures rather than implementing preventive techniques, as these are perceived to be costly and require significant effort to identify the most suitable methods for preserving operating equipment, especially critical and strategic spare parts [1, 2].

Maintenance strategies have evolved over the years, with various techniques being adopted by companies. One such strategy is Reliability-Centered Maintenance (RCM), which was established in the airline industry in the 1960s as a structured procedure to determine maintenance requirements for assets throughout their life cycle. Its goal is to preserve assets by reducing the probability of failure and extending their lifespan [3].

Large industrial organizations face several maintenance challenges, including managing many assets, dealing with diverse assets (manufacturing, physical concepts, operation parameters, and conditions) across units or production lines, missing or inadequate factory documentation for many assets, and shortages in training, asset quality, employee efficiency, and tools [4].

Power plants are among the most complex industrial systems, comprising thousands of mechanical, electrical, and control assets operating under demanding conditions. Their main objective is to ensure the reliable, efficient, and sustainable supply of electricity. Maintenance plays a vital role in achieving this objective and is defined as the set of technical and administrative actions required to maintain assets in a functional state or restore them after failure, thereby ensuring continuous and reliable plant operation [5]. Given the high level of interdependence between components, failures in critical power plant assets can propagate rapidly and cause significant production losses.

* Corresponding author e-mail: abashir@hu.edu.jo.

Therefore, effective maintenance planning and prioritization of critical assets are essential for improving plant availability and reliability

This study proposes a model for maintenance planning and strategy determination using a hybrid approach that combines Reliability-Centered Maintenance (RCM) and preventive maintenance (PM) methods, with a focus on preventive maintenance optimization. The case study is conducted at an electric power plant; one of the most complex and challenging industrial facilities, which has many assets."

This model can be applied to any industrial sector, especially in organizations that contain many assets. Electricity is one of the most important sectors which is essential to deliver efficiently and sustainably by maintaining the availability of power generation units.

Using this hybrid model can help the organization plan maintenance activities by following the principles of Reliability-Centered Maintenance(RCM) strategy, where all assets throughout the plant can be evaluated and categorized according to their criticality on the system. As a result, the critical assets will be taken into consideration to guarantee a continuous supply of the intended products. This is achieved by focusing on the overall life cycle of the critical assets and exploring potential failures that may critically affect their functionality and plant operations.

The effectiveness of RCM has been demonstrated in various industrial applications. For example, Patil and Bewoor [5] applied RCM to a steam boiler in the textile industry and showed that it could successfully identify optimal maintenance strategies for aging components, leading to improved reliability and operational performance. RCM enables the selection of the most appropriate maintenance strategy for each asset or asset group, thereby enhancing reliability and reducing unnecessary maintenance activities. [6,7]

Demonstrating the practical application of Reliability-Centered Maintenance (RCM) to a steam boiler used within the textile industry; an RCM model was proposed and examined to determine the best maintenance approach for aging steam boiler components [6, 7].

RCM can help in choosing the best maintenance strategy to be followed for each asset or group of assets according to the applied results, which can help increase their reliability. The concept of Reliability-Centered Maintenance (RCM) was first used in the 1960s in the United Airlines industry. Its concept is essentially founded to be applied in the first design stages of any organization as to assess all equipment and establish a maintenance plan according to the preliminary information[8]. On the other hand, preventive maintenance methods, especially preventive maintenance optimization (PMO), are more concerned with studying and determining the best maintenance plan according to historical data after the assets are operated for a period of time. Accordingly, this study merges the advantages of the two maintenance strategies, RCM and PMO, in one model, which intensifies the benefits of both strategies and eliminates the disadvantages that affect the organization's performance.

The main objective is to propose a maintenance model that uses two maintenance techniques: Reliability-Centered Maintenance (RCM) and preventive maintenance optimization (PMO). The objectives of the study could be summarized as follows: evaluating assets, reducing time between failures, increasing life expectancy of assets, reducing repairing costs, improving availability and reliability, ensuring safety issues, preserving assets, and implementing continuous improvements.

The importance of the study is to propose a maintenance model to increase and reach high availability and reliability, maintain a continuous supply, and prevent long breakdowns. This is achieved by selecting the most effective maintenance strategies and implementing continuous improvements. This model may be applied to all industrial sectors, especially electric power plants.

The proposed model can be used not just in the first stages of the organization but also during the mid-age of the plant. So even if units have been operating for a long time, assets can still be preserved, and a well-established maintenance plan can also be achieved. The study has been conducted on a power plant during its mid-age of operating years.

2. Literature Review

2.1. Reliability-Centered Maintenance (RCM)

A new model was proposed called the Accelerated Reliability-CentredModel (Accelerated-RCM) or the A-RCM model of Petroleum refineries[8]. Petroleum refineries need the assets to be highly reliable to ensure no shutdown for the plant, or to increase the periods between shutdowns. The model is derived from RCM and another approach, which is Streamlined Reliability-Centred Model SRCM, Total Productive Maintenance (TPM), and preventive maintenance optimization methods (PMO). The currently used model has been evaluated and discussed, then alternatives have been discussed. Those alternatives are found from research and consultation perspectives

The importance of the electric power distribution system is to provide electricity to customers in a highly reliable manner at a minimum cost. Using Reliability-Centered Maintenance could reduce costs and increase the reliability of the system[8]. This study used RCM to ensure safety during the process of preventive maintenance. A logical diagram for failure modes, effects, and criticality analysis was provided to assess the related failures in the electric distribution system, where recommended actions were proposed to address the potential failures with high risk. As a result, the study gave an indication that RCM constructs a maintenance plan regarding future actions.

A study was conducted to show how to improve the availability of a thermal power plant by using multiple and integrated maintenance techniques such as Reliability-Centered Maintenance (RCM), Risk-Based Maintenance (RBM), and Condition-Based Maintenance (CBM) [4]. The methodology used is based on the results of the calculated Maintenance Priority Index (MPI) and the collected failure defines tasks. After that, the assets were prioritized in the maintenance plan by gaining data generated from the functional tree, failure mode and effects analysis, fault-tree analysis, and risk analysis. As a result, developing a maintenance plan that addresses all the predefined failure modes and monitors of the plant's conditions revealed that the availability of the thermal power plant can be increased.

A framework of Reliability-Centered Maintenance (RCM) was proposed, and a case study was applied and examined at an industrial plant for processing and producing sugar called Fayoum Sugar Works Company, located in Egypt [11]. The primary objective for studying the proposed model is to address the limitations of the currently applied RCM models throughout the companies, where classical and simple previously used models have been followed in parallel to develop efficient and effective strategies in maintenance organizations. The model tries to focus on both critical and non-critical equipment, and it focuses on the most effective procedures by deleting unwanted tasks that drain effort and cost. A criticality analysis to classify all assets into categories has been conducted as an input to the model. After that, final maintenance measurements have been checked to assess the maintenance process after applying the RCM model. The results of the study indicate that applying the model decreases the downtime of maintenance, both corrective and preventive, by an average of 53.79% in addition to reducing maintenance cost and increasing the availability of the plant.

A Reliability-Centered Maintenance study was conducted where data were collected from a manufacturing company in the Middle East. The steps of RCM regarding selection of assets, defining functions, defining failures, identifying failure consequences, and finally selecting maintenance tasks justified that the followed methodology of applying RCM can enhance assets' reliability, also the maintenance performance indicators showed improvement of results after being applied [12].

2.2. Preventive Maintenance Optimization (PMO)

A methodology called PMO2000 was developed, which is preventive maintenance optimization. This methodology has been proposed to accelerate the RCM through focusing on the failure modes from historical records without searching for all functional failures in detail [13]. Also, tasks needed for fixing those failures could be grouped and merged to address multiple failures. As a result, maintenance programs are reviewed and updated considering failure history. Many methods have been raised for this purpose, such as the US nuclear power industry, which was adopted for its considerable benefits from the North American Nuclear Regulatory Commission.

It was indicated that applying preventive maintenance optimization to observatories plays a crucial role in advancing astronomical research, maintainability, and managing the fixed budget, along with ensuring reliability, availability, and system efficiency, which directly hinges on the maintainability of this observation center[14].

A procedure was proposed to incorporate the planning of preventive interventions with Computerized Maintenance Management System (CMMS), where it has been established as a base to have a new CMMS function, which enables the act of determining the most efficient and effective frequency for preventive interventions. This maintenance optimization model forms the basis of the age replacement policy. The model helped to find the best time to conduct preventive maintenance tasks and procedures, and it uses cost as a primary factor [15].

The novelty of this paper is the combination of Reliability-Centered Maintenance (RCM) and Predictive Maintenance Optimization (PMO) into a new maintenance model designed for easy application across various companies. This specific combination has not been addressed in prior research

3. Research Methodology

To investigate the research field and prove the study results, a research methodology has been developed. The design of this methodology is based on two main maintenance strategies, which are Reliability Centered Maintenance RCM and preventive maintenance methods, where Preventive Maintenance Optimization (PMO) is being applied. The following methodology has been followed:

The process begins by selecting an actual industrial plant, specifically an Electric Power Plant located in Jordan, to serve as the application site for the proposed maintenance model. This involves preparing a comprehensive list of assets within the power plant by identifying both the main and auxiliary equipment, choosing a subset of assets that represent all asset types, including rotating, mechanical, electrical, safety and control, and utilities. Subsequently, these predetermined assets are classified into categories of high, medium, and low criticality. This categorization relies on studying several factors, such as safety, environmental impact, redundancy, production impact, non-operation costs, and maintenance costs (including manpower, repair time, and spare parts), which help determine the effect and probability of failure on the overall system. Next, Reliability-Centered Maintenance (RCM) is conducted for the high-critical assets, which involves identifying their failure modes and examining the consequences of failure through extensive study and brainstorming, utilizing Failure Modes, Effects, and Criticality Analysis (FMECA). This analysis employs manuals and historical data to document all potential failures, effects, and consequences. The failure modes for the high-critical assets are then prioritized according to their effects by calculating the Risk Priority Number (RPN), which quantifies severity, detection, and the probability of occurrence for each failure mode to ascertain its impact on the overall system. Following this, the suitable maintenance strategies are chosen for each potential failure mode using Logic Tree Analysis (LTA). For the medium-critical assets, preventive maintenance (PM) methods are conducted through Preventive Maintenance Optimization (PMO). This involves reviewing the chosen equipment, collecting historical failure data and failure modes, analyzing known or probable failure modes, and then determining the required maintenance tasks by consulting manuals, maintenance experts, and manufacturer experience. Finally, the most applicable and effective maintenance strategies are selected for all assets based on the study's results, and Key Performance Indicators (KPIs) are determined to monitor and verify the maintenance process and the proposed model's efficiency by conducting a comparison before and after its implementation. The last step involves verifying the effect of the new maintenance model on achieving the power plant's goals, such as improved availability and reliability.The study used the maintenance department database, which was extracted from reports generated by the Computerized Maintenance Management System (CMMS), which is called Enterprise Resource Planning (ERP). The assets of the power plant are extracted and listed according to the ERP system, existing manuals, and Piping and Instrumentation Diagrams (PIDs). The data was checked for its completeness and consistency. The selection for the above assets was based on their criticality and importance in the company.

4. The Proposed Maintenance Model

All companies, especially industrial sectors, are concerned about maintenance activities, where maintaining assets plays a critical part in sustaining production and achieving outstanding results by increasing availability and ensuring reliability. Many tools and techniques have been used to obtain the best maintenance practices.

The electric power plant was chosen as a case study for the proposed maintenance model, where assessing the assets and choosing the suitable maintenance strategies has been conducted by studying the historical data for corrective and preventive maintenance, identifying failure modes, and analyzing the impacts of those failures on the overall system.

The proposed maintenance model consists of hybrid strategies between Reliability-Centered Maintenance (RCM) and Preventive Maintenance methods (PM), where Preventive Maintenance Optimization (PMO) is used.

The proposed model starts with identifying assets of the plant as mentioned in paper part I, all of which are evaluated according to Asset Criticality Analysis (ACA). The highly critical assets enter the RCM strategy, where all potential failures are collected by referring to manuals, experts, and brainstorming to define all related functional failures. Those functional failures are assessed by using the RPN tool. Then, each functional failure is checked using Logic Tree Analysis (LTA) to determine the best maintenance tasks to be followed. Identifying the high ranks of Risk Priority Number RPN can help in conducting maintenance activities first, focusing on the assets that have the high ranks of RPN during the asset's life cycle, allocating resources and managing spare parts purchasing according to the failures RPN's rank/ priorities. Also, this proposed model merges two maintenance strategies, which are the Reliability-Centered Model (RCM) (Figure 1) and the preventive Maintenance Optimization Model (PMO) (Figure 2). Merging the two models gives the proposed hybrid model for this study (Figure 3).

The results of applying the model were checked according to measurements of some maintenance performance indicators, such as availability, reliability, and mean time between failures (MTBF).

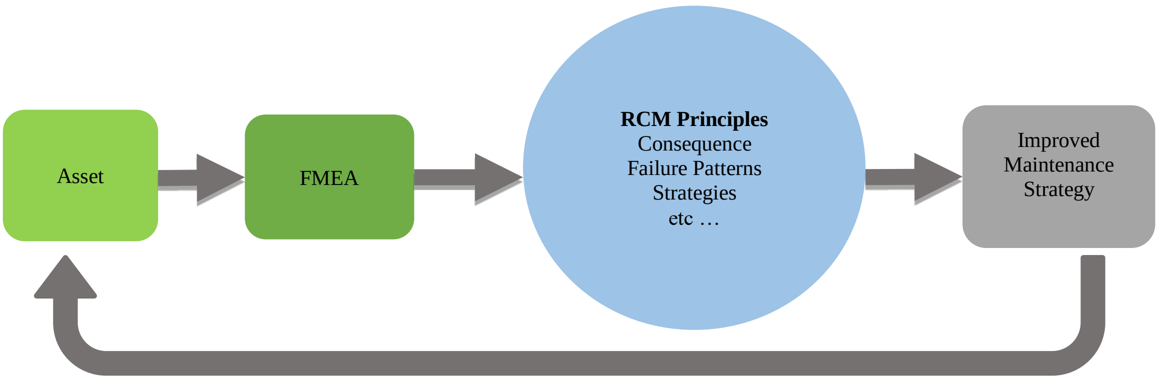

Figure 1. Reliability-Centered Maintenance (RCM) Model
(Ref. Adaptation of the proposed model by [9]

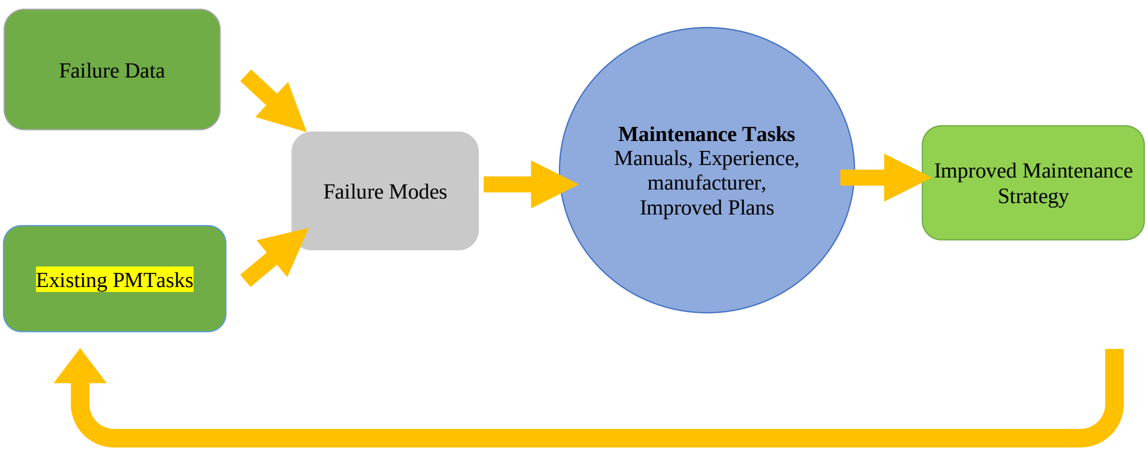

Figure 2. Preventive Maintenance Optimization (PMO) Model[14]

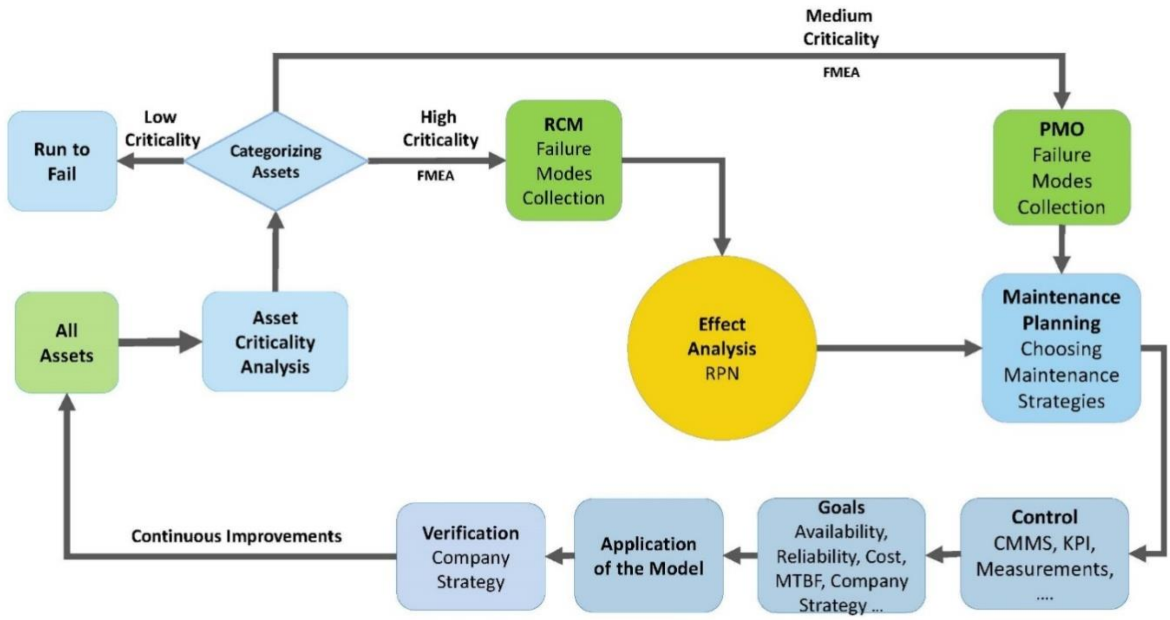

Figure 3. The Proposed Maintenance Model

As a result, the proposed maintenance model might improve the maintenance organization by benefiting from the advantages of both the RCM and PMO strategies; also, merging the two strategies can reduce the disadvantages of applying each one separately. This is achieved by focusing on the high-critical assets to identify potential failures in detail, evaluating their effects, and categorizing them to focus on high priorities that may affect the performance of the system. On the other hand, using PMO for medium-critical assets can save time spent on identifying failures in detail and trying to fix the less important failures. So, the model just focuses on the frequently appearing failures regarding the medium-critical assets.

The electric power plant, where the previous procedures were checked, was using the PMO alone from the year 2015 to 2017. After that, some other assets were considered essential pertaining to related failures, they started to use RCM by the year 2018, but it was partially implemented according to the results and historical data of failures. The percentage of applying RCM for the assets in each year was as Table 1 Shows:

Table 1. Percentage of applying PMO and RCM in the power plant

2015	2016	2017	2018	2019	2020	2021	2022
PMO	PMO	PMO	+2%RCM	+4%RCM	+6%RCM	7%RCM	+8%RCM

The categorization of assets as high, medium, and low critical can be described and dealt with based on the following criteria:

1. High-critical assets have a high and direct impact on business performance and continuity,
2. Immediate actions need to be conducted according to the RPN ranks of failure modes,
3. The medium-critical assets whose failures are not critical but may be categorized as critical with time, and actions to be taken according to predetermined tasks by the manufacturer and maintenance experts.
4. The low-critical assets have economic impacts and can be operated until they fail.

5. Analysis, Results, and Discussion

To ensure that the maintenance process is done according to the best practices, and it has a positive effect on the asset, several maintenance performance indicators could be measured to monitor the maintenance process effect.

The maintenance performance indicators for the studied assets were calculated according to the assets' performance in the power plant during the years 2015- 2022, as the company was just applying the preventive maintenance techniques during the years 2015-2017 and started to apply some RCM principles in 2018,for a percentage of assets. So, the performance indicators of assets were compared between the year 2017 and versus year 2022 to find the improvement in reliability.

Numerous performance indicators can be measured to assess how well an asset is performing and whether its performance has improved compared to past conditions. One key Maintenance performance Indicator (MPI) is reliability, which is a quality dimension defined as 'the ability of an item to perform its intended function under specified conditions for a certain period without failure' [15]. Petroleum, petrochemical, and natural gas industries — Collection and exchange of reliability and maintenance data for equipment. Enhancing asset reliability is crucial, as continuously and sustainably implementing maintenance strategies can boost an asset's performance level. [18] and [19] highlighted that Reliability-Centered Maintenance can significantly impact asset reliability.

In this study, to evaluate the model's effect on the reliability of power plant assets, the reliability of critical assets was measured

6. Reliability

6.1. Mean Time Between Failure (MTBF) and Failure Rate ($\boldsymbol{\lambda}$)

The mean time between failures is calculated according to the operating time and number of failures for each asset as the following equation [17]:

$$\mathrm{MTBF} = \frac{\text{Operating time}}{\text{Number of failures}} \tag{1}$$

The larger the value of the MTBF, the more reliable the asset.

To check the reliability of the assets, the number of failures and operating time have been checked according to the CMMS and the past historical records. Also, the failure rate, which is the inverse of the mean time between failure(Eq.2) [17], was calculated and compared for the years 2015-2022. The results are shown in Tables2, 3, 4, and5.

$$\text{Failure Rate } (\boldsymbol{\lambda}) = \frac{1}{\mathrm{MTBF}} \tag{2}$$

Table 2. Asset1 (GT Excitation System) performance indicators

Year	No. of Failures	MTBF (hr)	Failure Rate (λ)
2015	10	403.2	0.002480
2016	13	310.2	0.003224
2017	10	403.2	0.002480
2018	8	504.0	0.001984
2019	7	576.0	0.001736
2020	5	806.4	0.001240
2021	4	1008.0	0.000992
2022	3	1344.0	0.000744

Table 3. Asset2 (GT Step-up Transformer 15/132 KV) performance indicators

Year	No. of Failures	MTBF (hr)	Failure Rate (λ)
2015	9	448	0.002232
2016	8	504	0.001984
2017	6	672	0.001488
2018	4	1008	0.000992
2019	4	1008	0.000992
2020	3	1344	0.000744
2021	2	2016	0.000496
2022	1	4032	0.000248

Table 4. Asset 3 (ST Boiler Feed Water Pump) performance indicators

	For the basic asset			For the redundant asset		
Year	No. of Failures	MTBF (hr)	Failure Rate (λ)	No. of Failures	MTBF (hr)	Failure Rate (λ)
2015	12	224	0.004464	5	172.8	0.005787
2016	9	298.67	0.003348	6	144	0.006944
2017	10	268.8	0.003720	6	144	0.006944
2018	6	448	0.002232	5	172.8	0.005787
2019	5	537.6	0.001860	4	216	0.004630
2020	4	672.0	0.001488	3	288	0.003472
2021	4	672	0.001488	2	432	0.002315
2022	3	896	0.001116	2	432	0.002315

Table 5. Asset4 (GT Fuel oil control valve)performance indicators

	For the basic asset			**For the redundant asset**		
Year	**No. of Failures**	**MTBF (hr)**	**Failure Rate (λ)**	**No. of Failures**	**MTBF (hr)**	**Failure Rate (λ)**
2015	6	1344.0	0.000744	4	216	0.004630
2016	5	1612.8	0.000620	4	216	0.004630
2017	5	1612.8	0.000620	3	288	0.003472
2018	3	2688	0.000372	2	432	0.002315
2019	3	2688.0	0.000372	2	432	0.002315
2020	2	4032.0	0.000248	3	288	0.003472
2021	2	4032	0.000248	1	864	0.001157
2022	1	8064	0.000124	1	864	0.001157

6.2. Calculating reliability fora single system

Reliability was calculated according to the following equation, as it follows an exponential distribution during the asset's normal life [7] and [17].

$$R = e^{-\lambda t} \quad (3)$$

Where:
e = the base of the natural logarithm = 2.718)
λ = failure rate (which is the inverse of MTBF)
t = time (mission time)

6.2.1. Asset 1 Reliability Values:

The values of reliability for asset 1 (GT Excitation System) for the years 2015-2022, calculated for (t=50 hours),are as Table6:

Table 6. Asset 1 Reliability (2015-2022)

Year	MTBF	No. of Failures	Reliability
2015	403.2	10	88.34%
2016	310.2	13	85.11%
2017	403.2	10	88.34%
2018	504.0	8	90.56%
2019	576.0	7	91.69%
2020	806.4	5	93.99%
2021	1008.0	4	95.16%
2022	1344.0	3	96.35%

6.2.2. Asset 2 Reliability Values:

The values of reliability for asset 2 (GT Step-up Transformer 15/132 KV) for the years 2015-2022,calculated for (t=50 hours),are as Table 7:

Table 7. Asset 2 Reliability (2015-2022)

Year	MTBF	No. of Failures	Reliability
2015	448	9	89.44%
2016	504	8	90.56%
2017	672	6	92.83%
2018	1008	4	95.16%
2019	1008	4	95.16%
2020	1344	3	96.35%
2021	2016	2	97.55%
2022	4032	1	98.77%

6.3. Calculating reliability forthe parallel system

The parallel system for asset 3 and asset 4, which has redundant assets as Figure 4 shows, the reliability is calculated according to the following equation[17]:

$$R(system)xy = 1 - (1 - Rx)(1 - Ry) \quad (4)$$

Where Rx is the basic asset and Ry is the redundant asset.

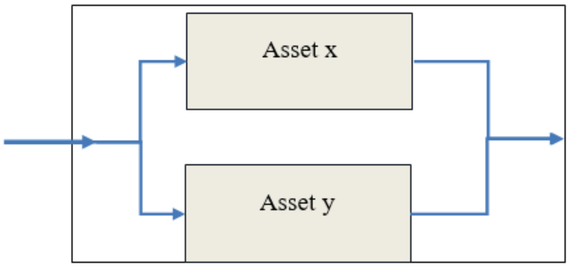

Figure 4. Parallel system of assets

6.3.1. Asset 3 Reliability Values:

The values of reliability for asset 3 (ST Boiler Feed Water Pump) for the years 2015-2022, calculated for (t=50 hours), are as shown in Table 8.

Table 8. Asset 3 Reliability (2015-2022)

Year	MTBF (Basic)	No. of Failures (Basic)	MTBF (Redundant)	No. of Failures (Redundant)	Reliability Total
2015	224	12	172.8	5	94.97%
2016	298.67	9	144	6	95.48%
2017	268.8	10	144	6	95.02%
2018	448	6	172.8	5	97.35%
2019	537.6	5	216	4	98.17%
2020	672.0	4	288	3	98.86%
2021	672	4	432	2	99.22%
2022	896	3	432	2	99.41%

6.3.2. Asset 4 Reliability Values:

The values of reliability for asset 4 (GT Fuel oil control valve) for the years 2015-2022, calculated for (t=50 hours), are as Table 9:

Table 9. Asset 4 Reliability (2015-2022)

Year	MTBF (Basic)	No. of Failures (Basic)	MTBF (Redundant)	No. of Failures (Redundant)	Reliability Total
2015	1344.0	6	216	4	99.25%
2016	1612.8	5	216	4	99.37%
2017	1612.8	5	288	3	99.51%
2018	2688	3	432	2	99.80%
2019	2688.0	3	432	2	99.80%
2020	4032.0	2	288	3	99.80%
2021	4032	2	864	1	99.93%
2022	8064	1	864	1	99.97%

6.4. Comparison ofEarlier Reliability with Improved Reliability

The Reliability-Centered Maintenance has been applied in the company since 2018, but at a specific percentage for a specific asset, where the maintenance experts focus on the failure modes for the assets that failed multiple times, and their failures affect the power plant's performance.

The improvement in reliability for the studied assets is shown in Figure 5. The earlier values indicate the reliability in 2017 before applying RCM, and the improvement value indicates the reliability for assets in 2022 after applying RCM for 8%, 6%, 4%, and 0.5% of the different assets in the plant:

6.5. Calculating the Availability of the power-generating units

Availability is a term related to two functions, which are reliability and maintainability. It is one of the most important maintenance indicators that indicates asset performance. It is calculated by finding the probability of an asset being in its operating condition once it is needed [7].

The equation to calculate the availability of an asset is as follows:[7]

$$\text{Availability} = \frac{\text{Mean Time Between Failure}}{\text{Mean time between faiure} + \text{Mean time to repair}} \qquad (5)$$

$$\text{Availability} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}}$$

This equation calculates the “Inherent Availability,” which is the availability obtained from the design. On the other hand, the “Achieved Availability” is the availability obtained from the asset after excluding the preventive or scheduled maintenance period.

Regarding critical assets, it is very important to achieve a high level of availability, as this is to preserve a continuous supply of products or electricity as well. The standard for availability is to achieve 95% or higher according to the assets' criticality and according to the company’s function [7].

Regarding the availability of assets in the power plant, which is the percentage of time that the power plant can provide electricity over a certain period. For computing the availability of the power plant, a specific phase was chosen, including steam turbine and gas turbine units; the availability for each unit alone was computed in addition to the availability of the overall phase. The results are shown in Figure 6. The y-axis presents the % of availability. It is noted that the availability of GT1, GT2, ST1, and the Phase started to increase from 2017-2022. This is due to PMO and is a part of RCM.

Table 10 clearly shows that all assets achieved **multiple-fold improvements in reliability**, with the transformer and fuel oil control valve experiencing the most significant gains.

Table 10. MTBF comparison of critical components (2017 vs 2022)

Asset	Earlier MTBF – 2017 (h)	Improved MTBF – 2022 (h)	Improvement Factor
GT Excitation System	403.2	1344	3.33
GT Step-up Transformer (15/132 kV)	672	4032	6.00
ST Boiler Feed Water Pump (Basic)	268.8	896	3.33
GT Fuel Oil Control Valve (Basic)	1612.8	8064	5.00

Table 10 presents the annual availability of GT1, GT2, ST1, and the overall plant (Phase) from 2015 to 2022. The results indicate a clear long-term improvement in availability for all major generating units and the overall plant.

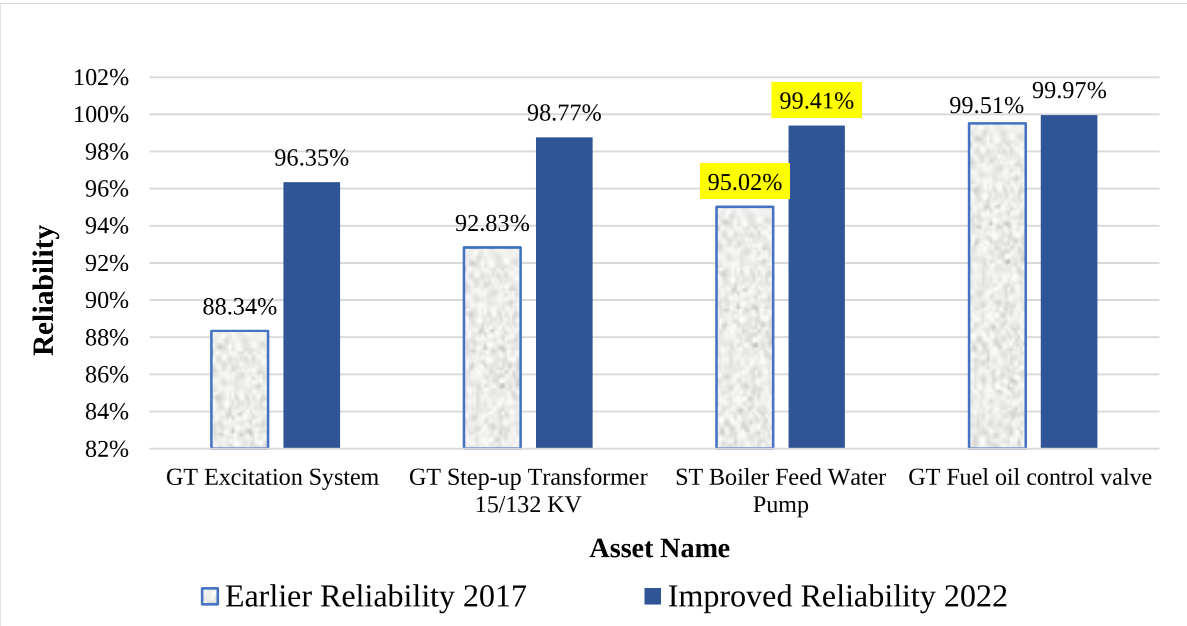

Figure 5. Comparison of earlier reliability vs. improved reliability

GT1 availability initially declined from 92% in 2015 to 90% in 2016, followed by a steady recovery and continuous improvement, reaching 96% by 2022. This reflects enhanced turbine condition monitoring, improved maintenance scheduling, and more stable operational practices.GT2 experienced greater variability during the early years, decreasing from 92% in 2016 to a low of 89% in 2017. However, a strong upward trend was observed from 2018 onward, with availability increasing to 95% by 2021 and remaining stable in 2022. This suggests that corrective maintenance actions and system upgrades were effective in stabilizing GT2 performance.ST1 shows the lowest availability among the units in the earlier years, dropping to 88% in 2017. However, a consistent year-on-year improvement is observed afterward, reaching 94% in 2022. This trend indicates progressive improvement in steam cycle reliability, likely due to better boiler feedwater control, pump reliability, and thermal system maintenance.

As a result, prioritizing assets according to their effect on the system using the approach followed during this study, making sure that focusing on high and medium critical assets to study their effects on the power plants, in addition to identifying the potential and actual failure modes, can help in establishing maintenance plans for the assets that comprise the entire system. This improvement was due to the use of the new proposed model. The overall plant (Phase) availability follows the same pattern, decreasing slightly from 91% in 2015 to approximately 89.5% in 2017, then improving steadily to 95% in 2022. The net gain of about 5.5 percentage points over the study period represents a substantial increase in plant operational readiness and reduced forced outage rates.

6.6. Comparing Performance Indicators Before and After Applying the Maintenance Model

The case study, that was conducted in an electric power plant in its mid-age time, affirmed that applying the proposed maintenance model that uses hybrid methods: the Reliability-Centered Maintenance strategy and the preventive maintenance optimization strategy makes an impact on the asset's reliability, availability, and mean time between failures as noticed in Table11 that shows the values before and after applying this model in an electric power plant.

According to Figures7 and 8, it is indicated that applying RCM with the PMO method can make an improvement in the maintenance organization, where the mean time between failures increased for the studied assets, also the number of failures decreased from the year 2017 to 2022.

Table 11. Comparing performance indicators before and after applying the maintenance model

Asset	Earlier Reliability	Improved Reliability	Earlier MTBF (hr)	Improved MTBF (hr)	Earlier # of failures	Improved # of failures
GT Excitation System	88.34%	96.35%	403.2	1344	10	3
GT Step-up transformer 15/132 KV	92.83%	98.77%	672	4032	6	1
ST Boiler Feed Water Pump (Basic)	95.02%	99.41%	268.8	896	10	3
GT Fuel oil control valve (Basic)	99.51%	99.97%	1612.8	8064	5	1

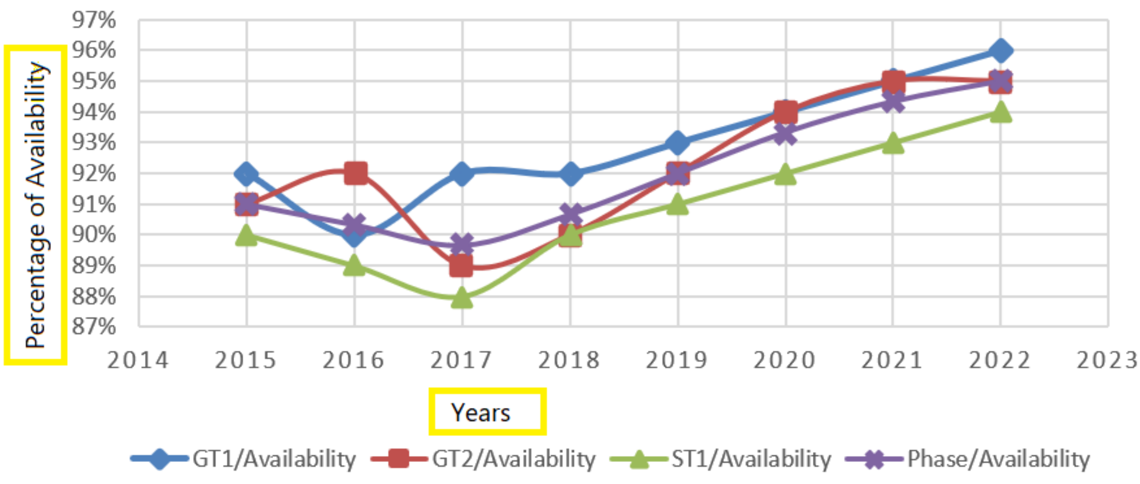

Figure 6. Availability Improvement for Power Plant Phase

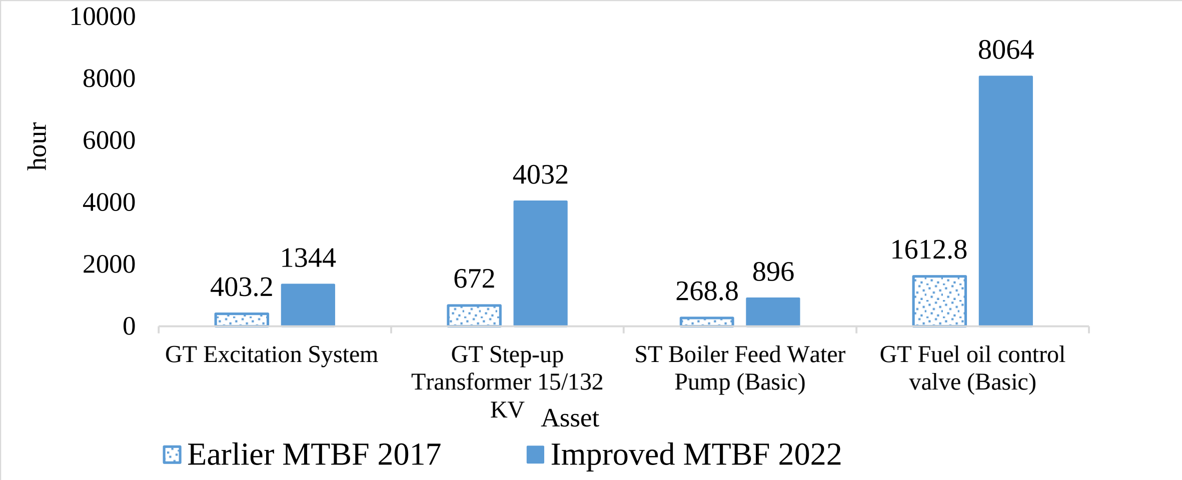

Figure 7. Comparing the Earlier MTBF and the Improved MTBF of the assets (hr)

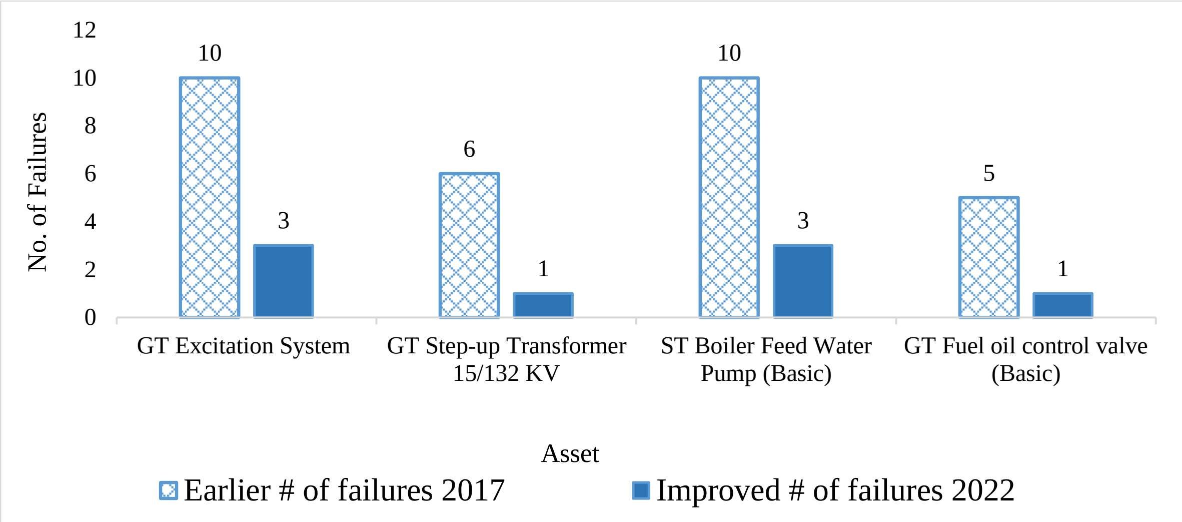

Figure 8. Comparing the Earlier No. of Failures and the Improved No. of Failures of the *assets*

According to the previous results, it was proven that using the RCM method in the power plant with a percentage of assets in accordance with PMO can make an improvement in the maintenance performance indicators. The reliability, availability, and MTBF improved, and the number of failures decreased during the years 2017-2022. The company has been using the PMO alone from the year 2015 to 2017, where the failures were determined according to the historical failures and existing maintenance plans. As a result, each failure mode can be maintained by following the maintenance tasks determined by the manufacturer's recommendations and the maintenance experts.

After that, it is found that there were some assets considered important or critical for analyzing their related failures, so it started to use RCM by the year 2018, but it was partially implemented according to the new appeared failures. Every new recorded and potential failure with the related assets are to be analyzed by referring to manuals and conducting more brainstorming.

This study showed that using the proposed maintenance model needs to have a rigid methodology to be followed in the company from the first stages of design or operations. The Reliability-Centered Maintenance strategy can determine the failure modes and related consequences for high-critical assets according to the manuals, PIDs, and brainstorming with maintenance staff experts. On the other hand, preventive maintenance optimization can identify failure modes and their consequences for the medium-critical assets by checking historical records where asset failures and root causes have been determined due to actual failures that happened in the past period of operating the power plant. Each failure mode can be maintained by following the maintenance tasks determined by the manufacturer's recommendations and the maintenance experts in the company.

7. Conclusions

This research was designed to explore and analyze related points for the improvement of maintenance activities. The following points indicate what the research concluded: what are the benefits of applying a hybrid maintenance model using RCM and PMO on large industrial facilities? and how to select effective maintenance strategies? The model merges the benefits of both Reliability-Centered Maintenance and preventive maintenance optimization. On the other hand, it diminishes the disadvantages of each maintenance strategy arising from being conducted separately. Prioritizing power plant assets to determine the important assets that need comprehensive monitoring and maintaining is considered a vital point, which results in helping maintenance staff categorizing the best maintenance time, in addition to choosing the best maintenance strategy as to decrease cost, sustain operations, enhance reliability and availability, and prioritize procurement. It will also help identify optimum number of spare parts needed for critical assets, and finally build an effective maintenance program based on the condition of assets. Applying this model provides evidence to affect the performance of the power plants or any organization by increasing the availability and reliability of the overall system. It increases the availability of the generating unit by 5% and it increases the reliability by 7% of the high-critical assets and by 2.4% of the medium-critical assets. The model also improves the mean time between failures and hence decreases the number of failures by 76%. This is concluded by comparing the performance indicators before and after applying the maintenance model. Thus, it is an important method to enhance system reliability by choosing adequate maintenance strategies for every asset in the system, especially the critical ones that greatly affect the overall system. The proposed maintenance model can help the maintenance staff and power plant owners to develop effective maintenance plans for the assets to ensure preserving the system's availability and enhancing reliability over time. It is recommended to establish a maintenance model, especially in complex systems, to follow the suitable maintenance tasks required for each failure mode of the related assets. The proposed maintenance model in this study is an effective way to enhance maintenance performance indicators. The model could be applied in any industrial facility, where it could be adjusted by choosing suitable categories and ranges to study the factors and the categories regarding asset assessment and failure modes evaluation.

Future Research

It is recommended for future research to increase the number of experts for studying the factors of the asset criticality assessment and the analysis of the failure modes and failure consequences. Also, it is recommended to establish maintenance plans with a specific time frame for the studied assets and related failure modes.

Declaration

All the authors in this document declare that there is no conflict of interest with any entities mentioned herein that could influence the content or create a conflict of interest.

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Limitations: The study was limited to the period of 2017-2022, and four main critical assets were chosen according to the critical asset number.

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