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Development of Optimized Maintenance Program for a Steam Boiler System Using Reliability-Centered Maintenance Approach

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Abstract: Reliability centered maintenance (RCM) is a new strategic framework for evaluating system maintenance requirements in its operating conditions. Some industries employ predictive maintenance strategies in addition to preventive maintenance (PM) strategies, which increase production costs. As the breakdown maintenance (BDM) technique is used, the maintenance cost increases. The RCM approach is a mixture of these maintenance strategies that can be used to optimize the maintenance costs and to ensure the availability of the system. The RCM method was applied to the steam boiler system used in the textile industries for the research work reported in this paper. The RCM methodology stated in the literature cannot be implemented, as it is in Indian textile industries due to the lack of knowledge of RCM principles, a labor-oriented nature, the use of partially computerized information systems, an inadequate maintenance database, and information about maintenance costs and production loss. To resolve these issues, a modified RCM approach involving a large number of experts is developed. To apply this RCM methodology, critical components are identified through reliability and failure mode effect and criticality analysis (FMECA). Finally, scheduled maintenance strategies and their intervals are recommended to ensure that the system continues to operate properly. According to this study, implementing the RCM technique effectively will increase boiler system reliability and availability by 28.15 percent and 0.16 percent, respectively. Additionally, up to 20.32 percent of the maintenance cost can be saved annually by applying these scheduled maintenance programs.

Keywords: reliability-centered maintenance (RCM) model; decision logic diagram; preventive maintenance; steam boiler

1. Introduction

The textile industry spins yarn from raw materials, such as cotton or wool, which is then used to make clothing. The industry involves all processes involved in converting raw material into a finished product, including textile creation, processing, manufacture and distribution. For several of these operations in the textile industry, steam is widely used as a heat transfer medium. As a result, the steam boiler is an integral part of the textile industry's operations. In order to meet this steam requirement, maintenance policies for the steam boiler system have been established.

The reliability centered maintenance (RCM) methodology was used to develop maintenance strategies that provide an appropriate level of reliability in a cost-effective manner. Reliability centered maintenance (RCM) is not a new concept, as it has been around since the 1960s. In 1978, Stanley Nowlan and Howard Heap first introduced RCM to the aviation industry [1]. Pujadas and Chen [2] developed a new simple maintenance decision framework after making some changes and incorporating the benefits of RCM and FMECA. In 1998, Nour et al. [3], emphasized the importance of cautious analysis of mechanical component reliability in order to optimize the maintenance program. Numerous studies [4–10] have identified the systematic methodology for the creation of the RCM and its successful implementation. RCM can be described as a maintenance strategy that logically integrates an optimum mix of reactive, preventive, predictive, and proactive maintenance practices.

Maintenance is characterized as a set of activities that keep equipment or systems in a state where they can perform their assigned functions. Charles et al. [11] addressed the problems of preventive maintenance (PM) strategy optimization and developed an approach with the objective of minimizing maintenance costs. Maintenance cost is an important aspect to consider while deciding the optimum maintenance intervals. Taking these maintenance costs into account, Rao et al. [12] and Santos [13] proposed a model to decide the optimum preventive maintenance interval. Similarly, Das et al. [14], Smith [15], Yun et al. [16] and Macchi et al. [17] considered the Weibull failure time dispersion parameters to decide the optimum PM intervals. Jagtap et al. also improved the maintenance schedule of the turbo-generator subsystem and boiler furnace system using particle swarm optimization [18,19].

The process industries are those in which the primary production operations are either continuous or occur on an indistinguishable batch of materials. Process industries can be found all over the world and contribute significantly to a country's economy. Many process industries rely on industrial steam boilers as a key component of their operations. As a result, the availability of the plant is dependent on the availability of the boiler. As the boiler is a complex system with various structures, there are numerous failures. In severe situations, steam boilers have been known to burst, inflicting significant damage to the plant or even the death of the operator. As a result, precise guidelines on how to clean and maintain boilers and associated systems have emerged. Furthermore, numerous failures interrupted the production process and had a financial impact. All of these problems can be avoided with inexpensive chemicals and proper maintenance.

The application of RCM in process industries enables scheduled maintenance and other steps to be done to avoid failure and the consequences of crucial components of the steam boiler system. Early detection of system failure and improving productivity of ongoing operation of the system by improving its availability is a difficult challenge. This task was taken up as a research problem and a comprehensive RCM framework is developed to detect the early failure of the steam boiler in the selected textile industries and keep the plant in healthy working condition. The availability of the critical components of the steam boiler system is improved by designing an appropriate maintenance strategy.

RCM is a logical way of defining the equipment that is expected to be maintained on a PM basis rather than on a CM basis, commonly referred to as Run-to-Failure (RTF) [20]. An effective PM policy must focus on components where failure modes will have a significant impact on safety, operations, quality, and maintenance costs. An essential issue is to reduce the maintenance costs in the direct operational costs of a process or large equipment. The main objective of this work was to develop a detailed RCM model for the steam boiler system used in textile industry (water tube boilers with capacity 03 to 05 tons), with an emphasis on maintaining system functions and system reliability. The developed reliability-centered maintenance (RCM) can be used to evaluate the optimal maintenance strategy and achieve the necessary level of reliability and availability at the lowest possible cost. The findings of this study were useful for getting a better understanding of the failure patterns that influence decision-making and system operation and maintenance planning. The paper is arranged accordingly: Section 2 developed the reliability centered maintenance (RCM) model. The results of the case study are given in Section 3. Section 4 presents results and discussions, and Section 5 eventually provides the conclusions of the study references.

2. Reliability Centered Maintenance (RCM) Model

The literature reveals that the majority of frameworks are based on qualitative analysis, with only a few frameworks based on quantitative analysis of the system. From the literature, it is observed that none of the frameworks considered both quantitative and qualitative analyses of a system; so there is a need to develop a framework that can employ both qualitative and quantitative terms. The proposed RCM model allows both qualitative and quantitative analysis and is divided into five main steps: system study preparation, critical item selection, the selection of appropriate maintenance actions, the preventive maintenance cost comparison analysis, and effective implementation of the reliability-centered maintenance program. In this section, we will provide a brief overview of these steps. The RCM's methodological definition is focused primarily by Rausand [4], Selvik and Aven [21] and Deshpande and Modak [22]. Figures 1 and 2 show the developed RCM model decision framework, respectively.

2.1. Phase I: System Study Preparation

The first phase of the developed model consists of the three main phases, i.e., selection of systems, the definition of the system boundary conditions, and system description and functional analysis. Initially, the system must be chosen taking into account the system failure frequency, preventive maintenance, corrective maintenance costs, and downtime costs incurred. Once the system has been selected for RCM analysis, the various subsystems, components and boundary conditions must be described. It is important to determine the system boundary conditions in order to maintain the RCM process under control when the system is complex. Following the selection of the boundary conditions and components/subsystems, system definition and functional analysis are needed. During the application of the RCM, the functions and their functional failures of the different components and subsystems must first be examined.

2.2. Phase II: Critical Item Selection

After selecting the system for analysis and functional failure analysis, the next phase is to identify and select the critical components and subsystems for analysis. The critical components can be identified by pareto chart analysis, FMECA, and reliability analysis. The literature-reported RCM model employs either reliability analysis or FMEA analysis. It is difficult to use a single method for criticality analysis when a system component is highly reliable, but its failure modes and effects are severe, or when the component failure does not affect system performance, but the failure frequency is high. As a result, the model presented here addresses this issue using both approaches simultaneously. Field failure data can be collected for the equipment importance analysis from maintenance history cards, life tests, and the expert opinion method. After collecting the field failure data, a reliability model can be developed and critical components identified through reliability analysis. Similarly, FMECA analysis is used to identify critical components and subsystems in terms of failure consequences. These critical components are considered to be maintenance significant items, which were later incorporated into the RCM decision logic for the planning of PM tasks.

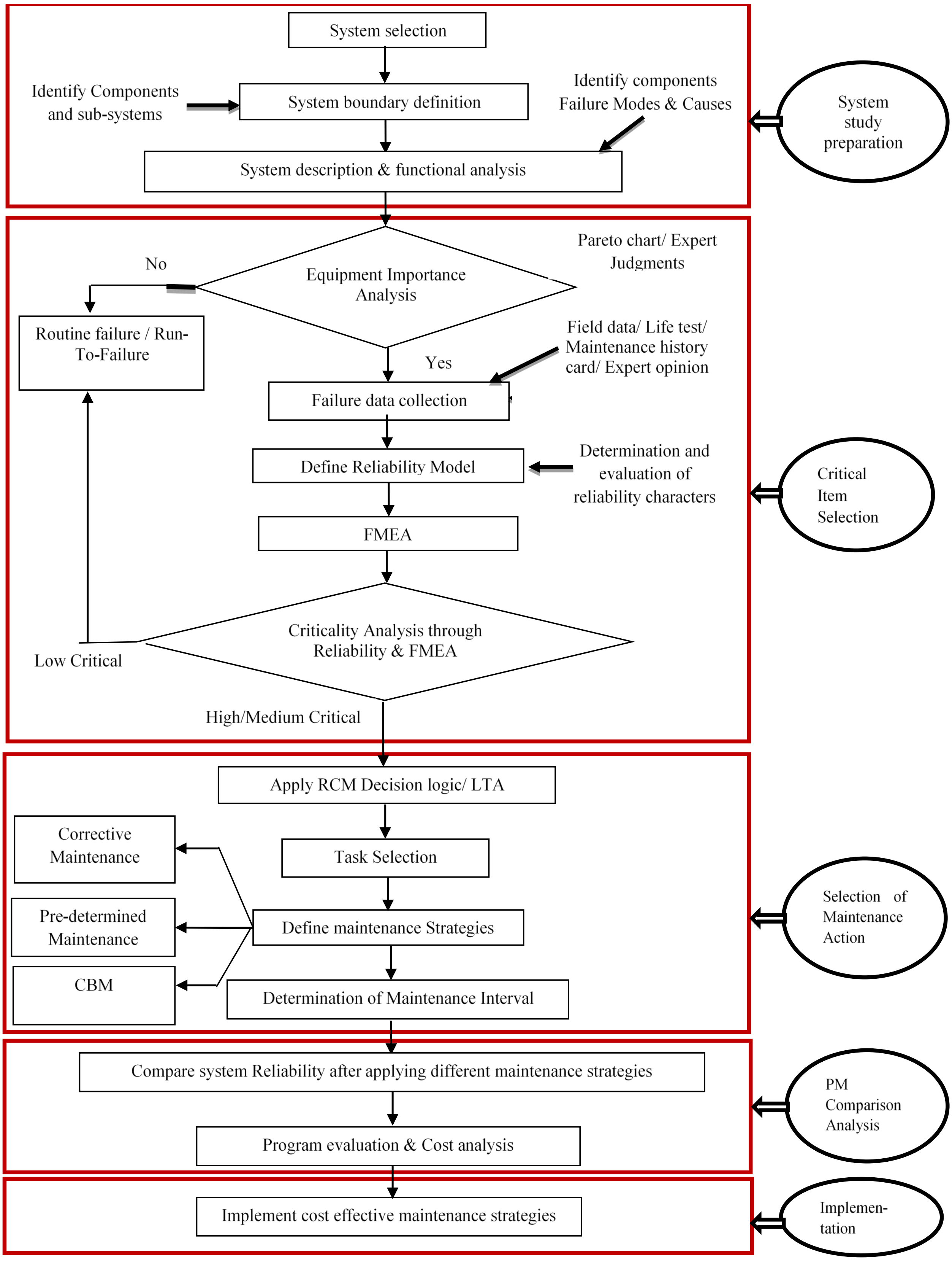

Figure 1. Modified reliability centered maintenance (RCM) model.

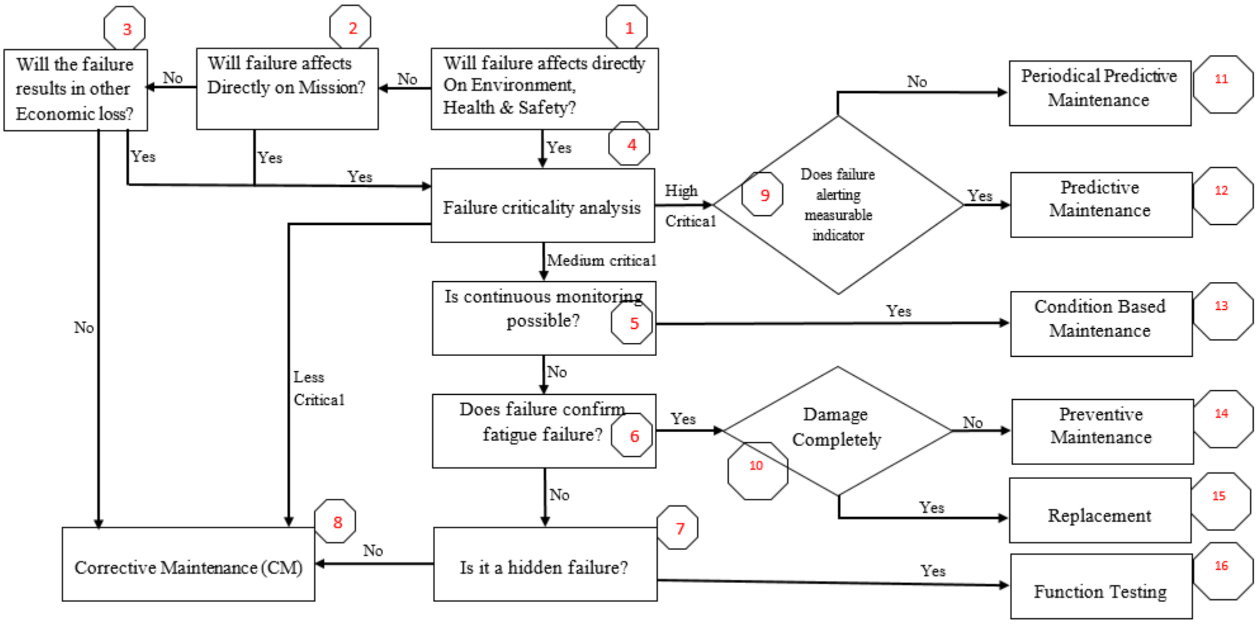

Figure 2. Modified reliability centered maintenance (RCM) decision framework.

2.3. Phase III: Selection of Maintenance Actions

The suitable PM tasks will be assigned to these maintenance significant items in this phase. This process entails applying decision logic or logic tree analysis to selected critical components, selecting the appropriate maintenance task and maintenance strategy, and determining maintenance intervals. The RCM decision logic diagram is used to evaluate the PM tasks based on the results of the reliability analysis and FMECA. This decision diagram guides the assessor in defining appropriate maintenance tasks based on a variety of YES or NO questions. After specifying the PM tasks using RCM logic, the next step is to assign maintenance intervals. The assessment of optimum maintenance intervals is a challenging task. Various mathematical models, such as Rausand and Vatn [23], Percy [24], Dekker [25], Wang and Pham [26], and Cui [27] can be used to evaluate optimum maintenance intervals. The above assessment normally results in a combination of various maintenance tasks and intervals. The PM tasks and intervals are grouped in such a way that maintenance staff can handle them effectively.

2.4. Phase IV: PM Comparison Analysis

Step IV sets out the management processes for the application of the above results. This phase involves a comparison of the reliability and maintenance costs obtained after introducing various maintenance strategies. At this point, improved system reliability following the implementation of PM tasks is compared to earlier results. Following completion of these different maintenance tasks, a cost comparison analysis must be conducted in order to reduce maintenance costs.

2.5. Phase V: Implementation of RCM

Finalize the optimum PM activities and cost-effective maintenance plans for the chosen system after a number of tests and feedback.

3. Case Study

The steam boiler is one of the most important systems in the textile industry and plays a crucial role in the production and supply of steam. Since the demand for steam is continuous, PM plays an important role in the smooth running of textile industrial operations. Maintenance costs can rise as a result of excessive PM tasks, but this can be reduced by careful task planning and scheduling. As a result, the developed RCM model is used to optimize and make cost-effective maintenance and replacement decisions for the steam boiler system used in the Indian textile industry. The main objective of the proposed model is to minimize the failure of the steam boiler subsystems and components without affecting the working environment and maintenance costs. The proposed model uses information on the failure and repair of the existing system. The following is a step-by-step description of the RCM model as applied to a steam boiler.

3.1. System Study Preperation

3.1.1. System Selection

A variety of tasks are included in the system study preparation, such as system selection, defining system boundary conditions, system description and functional failure analysis. The steam boiler system is a complex and critical system with more subsystems and components. The steam boiler ensures that the textile industry has a continuous supply of steam. Many boiler failures can interrupt the production process and create a financial impact. Therefore, a boiler system is selected for the analysis.

3.1.2. Defining System Boundary Conditions

After the selection of system, the boundary conditions were studied by defining the different subsystems and components of the system. It is important to define precise system boundaries in order to identify the major components and subsystems that lead to major failures and maintenance costs. The boiler system is therefore divided into nine separate subsystems and nearly forty-five components for study.

3.1.3. System Description and Functional Analysis

At this stage, it is important to study all the functions of the components, their operations, and all other operating and environmental conditions. The functions of all the subsystems and components of the steam boiler system have been studied. Similarly, functional failure analysis of the boiler system is carried out by identifying the failure modes and their causes.

3.2. Selection of Maintenance Significant Items/Critical Components

During this stage of maintenance, critical components are identified by criticality analysis. Criticality analysis of the boiler system is carried out using reliability analysis and FMECA.

3.2.1. Failure and Repair Data Collection

Field failure and repair data for equipment importance analysis can be collected from maintenance history cards, life tests, and by using the expert opinion method. Since many industries do not maintain maintenance history cards, real failure and repair data were not readily available. To collect the necessary information, there was continuous interaction with maintenance personnel. Finally, the expert judgment approach was used to collect as much failure data as possible.

3.2.2. Define Reliability Model

After the collection of field failure data, trend testing and goodness of fit tests were carried out [28]. Using the best-fit failure distribution parameters, a reliability analysis of the boiler system at the subsystem and components level was carried out. Finally, the critical components and subsystems of the boiler system are identified from the reliability point of view and presented in [29,30].

3.2.3. FMECA Analysis

The component failures that can weaken the main purpose of the component functions are analyzed here. The ExJ-PSI model has been developed to analyze the failure modes, causes and criticality of the components by taking into account multiple criteria. The present study takes six criteria into account: severity of the failure (SV), probability of the occurrence (O), degree of detectability (D), degree of maintainability (M), degree of safety (S), and production or quality loss (L). Critical components are identified and ranked based on the estimated criticality values. The identified critical components of the boiler system are presented in Table 1.

Table 1. Critical components of the boiler system with their criticality index.

Sr. No	Component	Overall CI of Component	Criticality Rank	Sr. No	Component	Overall CI of Component	Criticality Rank
1	Furnace	1.5559	22	14	Water level controller	1.0964	25
2	Shell	2.1224	19	15	Feed water hose	2.2889	18
3	Header	5.1139	6	16	Water softener	2.0131	20
4	Intake vent/Air vent	1.8910	21	17	Deaerator	2.4687	15
5	Combustion chamber	3.0643	10	18	Return water temperature sensor	5.2306	5
6	Water tubes	5.3936	3	19	Drain pump	2.5268	14
7	Supply water temperature sensor	5.2401	4	20	Condensate filter	1.2990	24
8	Backflow preventer valve	2.7529	12	21	Induced Draft (ID) fan	2.3364	17
9	Temperature regulator	2.7632	11	22	Forced Draft (FD) fan	4.4738	8
10	Feed water pump motor	6.5052	2	23	Mechanical dust collector (MDC)	1.3185	23
11	Feed water pump	12.2870	1	24	Burner	2.3683	16
12	Strainer	2.7128	13	25	Feed motor	5.0113	7
13	Feed water tank	4.4311	9				

3.3. *Selection of Maintenance Actions*

Using the RCM decision logic diagram, the appropriate PM tasks will be assigned to the selected maintenance significant items. After the maintenance strategies have been established, we must use various mathematical models to determine the optimum maintenance intervals.

3.3.1. Apply RCM Decision Logic

Once critical components are identified, the next step is to apply certain maintenance tasks in order to reduce the failure rate and improve the systems' reliability and performance. The RCM decision diagram or Logic Tree Analysis (LTA) may be used to select maintenance tasks. The LTA procedure is used to identify the most suitable, cost-effective PM tasks for a component. These suggested tasks are usually a function of component importance, design, use, and service setting. Without common guidance provided to different analysts, the use of LTA may result in different PM recommendations for similar components with the same criticality, environmental and component usage characteristics. Variations in the RCM analyst's experience will also influence the amount of time taken to examine suitable PM tasks for a specific component type. The RCM decision diagram developed here takes into account three major categories of consequences, i.e., "Environmental Health and safety", "Mission of the plant" and "Economic losses". It also helps to identify the most applicable and effective PM tasks and associated task frequencies when taking multiple component characteristics into account.

3.3.2. Define Maintenance Strategies

The second phase of this analysis involves the selection of particular maintenance tasks based on the consequences of failure. The binary type of decision diagram (Yes/No Answers) can be used to select various maintenance tasks such as corrective maintenance, predictive maintenance, condition-based maintenance, preventive maintenance, replacement, and run-to-failure. The maintenance strategy selected must be efficient, reliable, and most cost-effective. The overall effectiveness of the selected maintenance task should be assessed on the basis of specific criteria's such as reduction of operating irregularities, useful life, reduction of repair costs, usage of facilities, spare parts and tools, downtime maintenance, and the time required for repairs. The proposed model is used to select the appropriate maintenance tasks for the critical components and their failure modes of the steam boiler system and the results are presented in Table 2.

Table 2. Maintenance task selection.

Sr. No.	Component	Failure Mode	Criticality	Recommended Maintenance Task	Comment
1	Header	Deposition	Medium	Preventive Maintenance	Proper blow-down should be done frequently.
		Header corrosion due to Oxygen Pitting	High	Periodical Predictive Maintenance	Header surface should be checked regularly for oxygen pitting.
2	Furnace	Short term Overheating	Medium	Preventive Maintenance	Proper flow of water should be maintained.
		Layer of hardness scale over the surface	Medium	Preventive Maintenance	Water quality and pH value should be checked regularly.
3	Shell	Shell plate bulging due to scale formation	High	Predictive Maintenance	The feed water hardness should be monitored properly.
4	Intake vent/Air vent	Air vent fails to open and close	Low	Run-to-Failure	Operation of air vent must be checked frequently.
5	Combustion Chamber	Incorrect burner sequence	Medium	Corrective Maintenance	Check burner sequence and amount of fuel being fired.
		Too much fuel being fired	Medium		
		Uneven combustion	Medium	Function Testing	Check proper combustion of fuel and recondition if necessary.
		Excess air trapped	Medium		
6	Water tubes	Short term Overheating	High	Periodical Predictive Maintenance	Proper flow of water should be maintained.
		Joint Failure	High	Periodical Predictive Maintenance	Tube joints must be checked frequently.
		Tube bulging/crack/holes	High	Periodical Predictive Maintenance	Proper flow of water should be ensured and failure should be avoided as it interrupts production.
		Tube corrosion	High	Predictive Maintenance	Maintain proper pH value and hardness.
7	Supply Water temperature sensor	Fails to provide signal	Medium	Run-to-Failure	Check condition and operation of sensor and replace if needed.
		Calibration Error	Medium	Run-to-Failure	Check condition and operation of sensor and replace if needed.
8	Back flow preventer valve	Fails to open and close	Medium	Run-to-Failure	Check back flow preventer valve operating condition in preventive maintenance.
9	Temperature regulator	Fails to operate	Medium	Run-to-Failure	No preventive maintenance is recommended by manufacturer. Check temperature regulator and replace if necessary.
		Unstable response	Medium	Run-to-Failure	
10	Feed water pump	Mechanical seal failure	Low	Run-to-Failure	Replace seal when pump leaks.
		Pump impeller failure	Medium	Function Testing	Observe any cracks or pitting marks and check pump efficiency regularly.
		Pump Housing Volute damaged/Volute Erosion	Medium	Corrective Maintenance	Recondition feed water pump yearly.
		Reduction in pressure/Low efficiency	Medium	Function Testing	Check pump efficiency frequently.
11	Feed water Pump-Motor	Bearing Failure	High	Condition Based Maintenance	Bearing failure is the main cause of the feed water pump-motor failure. It can be reduced by regular checking for bearing alignment, lubrication, vibration, loose collars, fasteners, etc., and we can avoid early failure and costly replacements.
		Electrical windings short	Medium	Corrective Maintenance	Change electrical windings.
		Armature failure	Medium	Corrective Maintenance/Replacement	Repair or replace motor armature.

Table 2. *Cont.*

Sr. No.	Component	Failure Mode	Criticality	Recommended Maintenance Task	Comment
12	Feed Water tank	Oxygen Pitting	Medium	Corrective Maintenance	Repair water tank.
		Deposition/Corrosion	Medium	Corrective Maintenance	Clean tank regularly.
		Leak	Low	Run-to-Failure	Check mechanical seal conditions and avoid leakage.
13	Water Softnar	Fail to operate	Medium	Function Testing	As it affects boiler efficiency and tube failure, check the water quality daily.
		No/Excess softening	Medium	Function Testing	
14	Water level controller (Mobari)	Fails to operate	Medium	Run-to-Failure	Inspect water level controller condition regularly.
15	Feed water hose	Leakage	Low	Preventive Maintenance	Inspect water hose leakage and repair it regularly.
		Block and becomes hard	Low	Preventive Maintenance	
16	Feed check valve	Fails to operate	Medium	Preventive Maintenance	Check condition of valve and recondition it regularly.
17	Strainer	Clogging	Low	Run-to-Failure	Check condition of strainer and replace it regularly.
		Fatigue failure	Low	Run-to-Failure	
18	Deaerator	Dearator inlet pipe failure	Medium	Preventive Maintenance	Visual inspection of shell weld/DFMT test.
		Excessive dearator venting	Medium	Preventive Maintenance	Check condition of deaerator frequently.
19	Return water temperature sensor	Incorrect or loss of signal from sensor element	Medium	Function Testing	Check condition of sensor and calibrate it regularly.
		Calibration Error	Medium	Function Testing	
20	Drain pump	Drain hose leakage or blockage	Medium	Corrective Maintenance	Visual inspect drain pump and hoses.
		Drain pump gear failure	Medium	Corrective Maintenance	
21	Condensate filter	Internal Leakage	Low	Corrective Maintenance	Check condensate filter condition regularly and replace it if necessary.
		Clogging	Low		
22	Blow down valve	Valve fails to operate	Medium	Corrective Maintenance	Check blow-down connections and valve condition.
23	Induced drum (ID) fan	Motor or Contactor Failure	Medium	Condition Based Maintenance	Check vibrational, thermal, and noise parameters and decide condition of the fan. Ultrasonic analyzer and vibration analyzer are the tools can be used to diagnose fan condition.
		Fan fails to start	Medium		
		Failure due to jamming of blades	Medium		
24	Forced draft (FD) Fan	Operate with high vibration level	Medium	Condition Based Maintenance	Check vibrational, thermal, and noise parameters and decide condition of the fan. Ultrasonic analyzer and vibration analyzer are the tools can be used to diagnose fan condition.
		Failure due to foreign material entry	Medium		
		Noise in motor	Medium		
25	Mechanical dust collector (MDC)	Blockage	Low	Preventive Maintenance	Clean mechanical dust collector (MDC) regularly.
26	Coal Feed Motor	Open or shorted winding	Medium	Corrective Maintenance	Ensure proper windings of motor.
		Bearing worn	Medium	Condition Based Maintenance	Check bearing condition for proper functioning.
		Cracked/Sheared housing and armature shaft	Medium	Replacement	Replace armature shaft.
27	Safety Valve	Operation failure	Medium	Preventive Maintenance	A try lever test should be performed quarterly to check performance of safety valve.
28	Gauge Glass	Glass broken	Low	Run-to-Failure	Examine glass regularly for any signs of clouding, scratching, erosion or corrosion and replace it immediately.
29	Pressure relief valve	Fails to operate	Medium	Preventive Maintenance	A try lever test or pop test should be performed regularly to inspect operation of the valve.

The system's availability can be enhanced by making certain design improvements, reducing mean time to repair, and improving mean time to failure by proper maintenance task implementation. These steps are recommended based on design calculations, selection of components, maintenance policy, and discussion with experts. According to the failure analysis of the steam boiler system, the majority of boiler failures are caused by component failures, which are outsourced. Therefore, due to the early aging of these components, the reliability of the steam boiler system is difficult to ensure. Thus, the preferred components inventory should be re-formulated when designing the reliability improvement and standardized components with reliability guarantees should be chosen. All of this increases the time-to-failure and enhances the reliability of the steam boiler system.

In addition to these maintenance activities, some components with the higher mean time to failure values are recommended. Similarly, the maintenance time needed to repair these components, as well as the time required for fitting, are decreased. This significantly reduces downtime and improves system reliability. Table 3 shows the recommended components as well as their MTTF.

Table 3. The recommended new components with their improved MTTF.

Sr. No	Component	Recommended Components Specification	Earlier MTTF (Hours)	Improved MTTF (Hours)
01	Intake vent/Air vent	Use WJ make 1″ flat seat arrangement valve	96,024.13	120,000.00
02	Supply Water temperature sensor	Use PT100 temperature sensor	6189.33	13,000.00
03	Back flow preventer valve	Use Precision make Flanged backflow preventer BA009MC	75,522.40	90,000.00
04	Feed water Pump	Use Grandfoss make 1.5 kW Pump	50,071.74	70,000.00
05	Water level controller (Mobari)	Malhotra make 10.54 kg/cm^2 working pressure, Size 250 mm to 450 mm	99,108.20	120,000.00
06	Strainer	Use Precision make vertical mounted stainless steel body strainer	25,283.99	40,000.00
07	Coal crusher motor	Siemens 3phase 5HP motor 1LA0 107-2LA80.	100,291.77	130,000.00
08	Pressure gauge	Use Waaree SS316L Pressure Gauge	67,093.35	70,000.00
09	Pressure Relief Valve	Precision make cast steel body Flange Type Size-1″ and more	106,050.66	130,000.00
10	Pressure reducing valve (PRV) station	Precision make Carbon Steel/Alloy Steel Flanged type Size-1″ and more	80,830.56	85,000.00
11	Steam water separator	Precision make cast steel body Flanged end type Size-1″ and more	102,386.79	105,000
12	Fusible plug	Use ATAM two piece design Gun Metal Fusible Plug Size-$\frac{1}{2}$″, $\frac{3}{4}$″ and 1″	11,204.20	17,500.00
13	Globe valve	DRP make $\frac{1}{2}$″ Gun Metal Body screw end	109,447.22	130,000.00
14	Ball valve	Use LINTAS Make Stainless Steel Screwed End Ball Valve Code No.: LI-016, Size-$\frac{1}{2}$″	109,447.22	115,000.00

3.3.3. Determine Maintenance Intervals

In most situations, the methodology used to determine maintenance intervals is based primarily on the experience of the maintenance analyst [31]. Maintenance analysts are free to assign their own intervals for each maintenance tasks. Without quantitative modeling help, determining the maintenance interval is subjective and experience-based. This can result in a higher maintenance frequency, which will have an impact on system availability, performance, and economy. To improve the decision on interval selection, a mathematical model must be developed, and only a few researchers have used these models [32,33]. There is also a need for optimization-based decision support to enhance the ability to take correct and effective decisions on maintenance interval assignment, taking into account both reliability and cost parameters.

Maintenance intervals for each component of the boiler system were determined in consultation with the maintenance and operation staff. Real data on failure frequency and repair is obtained from different industries and optimum maintenance intervals are assigned. The periodic maintenance intervals are recommended to ensure a reliability level of approximately 75% [29] for each component of the boiler system. In particular, the maintenance team considers a 25% probability that the failure will occur before PM. If we consider higher reliability targets, maintenance intervals would be shorter and maintenance costs would be higher. Similarly, if we consider lower reliability targets, the preventive maintenance intervals would be higher and ultimately the failure frequencies and maintenance costs would be greater. Therefore, the reliability level of 75% is considered the optimum level. To estimate the time interval to perform periodic maintenance, a reliability equation of Weibull distribution is used by Mendes [34]. The estimated time interval to perform periodic maintenance is calculated from the reliability equation for a Weibull distribution as shown in Equation (1).

For reliability $R(t)$ = 0.75 we can calculate,

$$\text{Maintenance time } t = \theta X[-\ln(0.75)]^{\frac{1}{\beta}} \quad (1)$$

where, 't' is the maintenance time interval, θ is the Weibull scale parameter and β is the Weibull shape parameter. Periodic maintenance intervals of the boiler components were calculated using Equation (1) and the results of the same are presented in Table 4. It should be noted that PM should be carried out to inspect parts' operating condition, ensure proper lubrication, cleaning and realignment of the parts and replacement of the parts whenever necessary.

Table 4. Optimum maintenance intervals and recommended maintenance schedule.

Sr. No	Name of Component	MTTF (Hours)	Estimated Optimum Repair Time (Hours)	Recommended Maintenance Schedule
1	Header	98,553.91	3826.24	06 Months
2	Hot gas tubes	98,553.91	3826.24	06 Months
3	Furnace/shell	102,090.04	9621.16	12 Months
4	Intake vent/air vent	96,024.13	9125.04	12 Months
5	Water tubes	109,681.21	7451.50	10 Months
6	Supply water temperature sensor	6189.33	681.14	01 Month
7	Back flow preventer valve	75,522.4	1591.12	02 Months
8	Feed water pump	50,071.74	10,958.14	15 Months
9	Feed water pump-gauge	52,497.83	7564.47	10 Months
10	Softener	77,510.29	17,475.67	24 Months
11	Feed water tank	28,767.86	467.30	06 Months
12	Water level controller (Mobari)	99,108.20	4635.14	06 Months
13	Feed check valve	113,074	5879.71	08 Months
14	Feed water hose	97,120.66	8443.098	12 Months
15	Strainer	25,283.99	4621.95	06 Months
16	Deaerator	104,005.15	8105.50	12 Months
17	Return water temperature sensor	9516.97	2181.51	03 Months
18	Drain pump	43,925.53	5731.72	08 Months
19	Condensate filter	5985.82	320.66	15 Days
20	Shut-off valve	105,761.78	6177.33	08 Months

Table 4. *Cont.*

Sr. No	Name of Component	MTTF (Hours)	Estimated Optimum Repair Time (Hours)	Recommended Maintenance Schedule
21	Blow-down connections	103,704.23	5059.86	08 Months
22	Blow down valve	95,751.03	8192.44	12 Months
23	Induced drum (ID) fan	94,924.99	8420.051	12 Months
24	Forced draft (FD) Fan	102,386.79	3522.95	05 Months
25	Secondary air (SA) fan	104,256.9	6631.4	10 Months
26	Mechanical dust collector (MDC)	40,764.94	5339.81	08 Months
27	Rack and pinion coal feeding mechanism	108,341.25	11,634.34	16 Months
28	Coal crusher	22,417.63	3574.45	05 Months
29	Coal crusher motor	100,291.77	11,469.76	16 Months
30	Coal storage tank	80,199.83	9086.46	12 Months
31	Pressure gauge	67,093.35	3488.75	05 Months
32	Steam circulation pipes	105,938.83	5700.39	08 Months
33	Pressure relief valve (PRV) station	106,050.66	6702.62	10 Months
34	Pressure reducing valve	80,830.56	6623.62	10 Months
35	Strainer	65,833.27	3857.70	06 Months
36	Steam water separator	102,386.79	3522.95	05 Months
37	By-pass valve	104,256.9	6631.40	10 Months
38	Safety valves	102,228.49	10,152.84	12 Months
39	Main steam stop valve	102,228.49	10,152.84	12 Months
40	Fusible plug	11,204.2	1082.903	02 Months
41	Gate valve	109,447.22	10,319.4	15 Months
42	Globe valve	109,447.22	10,319.4	15 Months
43	Ball valve	109,447.22	10,319.4	15 Months

3.4. PM Comparison Analysis

In this step along with these recommended maintenance tasks, some improvement changes in the design stage are suggested. Following these proposed changes and the implementation of these optimal maintenance tasks, a comparison of the reliability, availability, and maintenance cost results has been carried out before and after the application of these maintenance strategies.

System Reliability after Application of These Maintenance Strategies

An effective implementation of the above suggested measures will enhance the component reliability, maintainability and LCC and, finally, system reliability. The reliability results of all the components evaluated by considering exponential distribution are presented in Table 5. The reliability of the entire steam boiler system is evaluated by using the reliability block diagram shown in Figure 3. The different codes used in this reliability block diagram are presented in Appendix A. The Equations (2) and (3) are the reliability models of the steam boiler system.

$$\therefore \mathrm{R}_{\text{Boiler System}} = \mathrm{R_A} \times \mathrm{R_B} \times \mathrm{R_C} \times \mathrm{R_D} \times \mathrm{R_E} \times \mathrm{R_F} \times \mathrm{R_G} \times \mathrm{R_H} \quad (2)$$

$$\begin{aligned} \therefore \mathrm{R}_{\text{Boiler System}} = {} & \{[1-(1-\mathrm{R_{A3}})(1-(\mathrm{R_{A1}}\times\mathrm{R_{A2}}))]\times[1-(1-\mathrm{R_{B3}})\times(1 \\ & -\mathrm{R_{B4}})\times(1-\mathrm{R_{B5}})\times(1-(\mathrm{R_{B1}}\times\mathrm{R_{B2}}\times(1 \\ & -(1-\mathrm{R_{B6}})(1-\mathrm{R_{B7}}))\times\mathrm{R_{B8}}\times\mathrm{R_{B9}}\times\mathrm{R_{B10}}\times\mathrm{R_{B11}}\times\mathrm{R_{B12}})] \\ & \times[1-(1-\mathrm{R_{C4}})\times(1-(\mathrm{R_{C1}}\times\mathrm{R_{C2}}\times\mathrm{R_{C3}}))\times(1-\mathrm{R_{C5}})\times(1 \\ & -\mathrm{R_{C6}})]\times[1-(1-\mathrm{R_{D3}})\times(1-(\mathrm{R_{D1}}\times\mathrm{R_{D2}})]\times[1-(1 \\ & -\mathrm{R_{E4}})\times(1-(\mathrm{R_{E1}}\times\mathrm{R_{E2}}\times\mathrm{R_{E3}}))]\times[1-(1 \\ & -\mathrm{R_{F5}})\times(1-(\mathrm{R_{F1}}\times\mathrm{R_{F2}}\times\mathrm{R_{F3}}\times\mathrm{R_{F4}}))\times(1-\mathrm{R_{F6}})\times(1 \\ & -\mathrm{R_{F7}})\times(1-\mathrm{R_{F8}})]\times[1-(1-\mathrm{R_{G3}})\times(1 \\ & -(\mathrm{R_{G1}}\times\mathrm{R_{G2}}))]\times[1-(1-\mathrm{R_{H1}})\times(1-\mathrm{R_{H2}})\times(1-\mathrm{R_{H3}})]\} \end{aligned} \quad (3)$$

where $\mathrm{R_A}$, $\mathrm{R_B}$, $\mathrm{R_C}$, … $\mathrm{R_H}$, are the reliabilities of the boiler subsystems.

Table 5. The earlier and improved reliability and maintenance cost results of boiler components.

Sr. No	Name of Component	Reliability		Availability		Maintenance Cost	
		Earlier R(t)	Improved R(t)	Earlier	Improved	Earlier (CM)	Improved (PM)
1	Header	0.7687	0.7873	0.999645	0.999734	85,276.66	68,228.25
2	Hot gas tubes	0.7687	0.7873	0.999621	0.999716	73,800.94	55,606.95
3	Furnace/shell	0.7758	0.7939	0.999431	0.999573	109,155.36	82,072.66
4	Intake vent/air vent	0.7634	0.8057	0.999916	0.999937	16,427.75	12,539.97
5	Water tubes	0.7895	0.8067	0.999672	0.999754	65,199.87	48,995.84
6	Supply water temperature sensor	0.0152	0.1362	0.999825	0.999868	39,552.38	31,364.39
7	Back flow preventer valve	0.7095	0.7498	0.99998	0.999985	4520.93	3557.89
8	Feed water pump	0.5959	0.6905	0.999556	0.999667	88,225.81	68,270.84
9	Feed water pump-gauge	0.6103	0.6384	0.999972	0.999979	5595.40	4236.64
10	Softener	0.7158	0.7304	0.999401	0.99955	122,886.96	93,251.27
11	Feed water tank	0.4062	0.4408	0.999771	0.999828	75,052.86	63,605.10
12	Water level controller (Mobari)	0.7699	0.8057	0.999929	0.999947	14,025.61	10,731.55
13	Feed check valve	0.7951	0.8119	0.999989	0.999992	5797.04	5278.36
14	Feed water hose	0.7658	0.7846	0.999898	0.999924	20,241.56	15,397.86
15	Strainer	0.3587	0.5231	0.999893	0.99992	21,086.67	15,981.47
16	Deaerator	0.7794	0.7973	0.999583	0.999687	81,702.50	61,479.22
17	Return water temperature sensor	0.0656	0.0841	0.999742	0.999807	61,634.49	49,542.83
18	Drain pump	0.5543	0.5848	0.99997	0.999978	10,323.87	8940.67
19	Condensate filter	0.0132	0.0195	0.999751	0.999814	51,686.67	40,522.91
20	Shut-off valve	0.7826	0.8003	0.999986	0.999989	3463.72	2796.78
21	Blow-down connections	0.7788	0.7967	0.999941	0.999956	11,570.42	8779.28
22	Blow down valve	0.7628	0.7818	0.999936	0.999952	13,410.63	10,387.66
23	Induced drum (ID) fan	0.7610	0.7802	0.999932	0.999949	31,246.63	27,869.00
24	Forced draft (FD) fan	0.7763	0.7944	0.999936	0.999952	33,080.30	29,948.83
25	Secondary air (SA) fan	0.7799	0.7977	0.999946	0.999959	22,432.75	19,852.42
26	Mechanical dust collector (MDC)	0.5295	0.5610	0.999722	0.999792	73,462.81	59,743.38
27	Rack and pinion coal feeding mechanism	0.7872	0.8045	0.999987	0.99999	6353.98	5736.72
28	Coal crusher	0.3147	0.3495	0.999592	0.999694	116,656.63	96,880.17
29	Coal crusher motor	0.7723	0.8192	0.999938	0.999953	16,034.38	13,074.97
30	Coal storage tank	0.7238	0.7454	0.999639	0.999729	84,615.36	68,709.66
31	Pressure gauge	0.6795	0.6905	0.999979	0.999984	4167.74	3144.63
32	Steam circulation pipes	0.7830	0.8006	0.999968	0.999976	8082.08	6558.19
33	Pressure relief valve	0.7832	0.8192	0.999972	0.999979	6582.75	5234.73
34	Pressure reducing valve (PRV) station	0.7257	0.7372	0.999628	0.999721	72,154.79	54,428.53
35	Strainer	0.6745	0.6991	0.999961	0.999971	7801.09	5914.75
36	Steam water separator	0.7763	0.7813	0.999972	0.999979	30,000.14	28,666.43
37	By-pass valve	0.7799	0.7977	0.999971	0.999978	21,625.04	20,255.93
38	Safety valves	0.7760	0.7941	0.99998	0.999985	5782.05	4851.19
39	Main steam stop valve	0.7760	0.7941	0.999973	0.99998	6781.50	5497.85
40	Fusible plug	0.0989	0.2274	0.999832	0.999874	35,177.06	27,321.95
41	Gate valve	0.7891	0.8063	0.999975	0.999981	5498.43	4316.11
42	Globe valve	0.7891	0.8192	0.999975	0.999981	5729.17	4546.85
43	Ball valve	0.7891	0.7982	0.999975	0.999981	5113.86	3931.54
					Total =	**Rs. 1,579,016.67**	**Rs. 1,258,052.24**

The earlier reliability of the steam boiler system after three years is calculated as follows:

$$\therefore R_{\text{Boiler System}} = R_A \times R_B \times R_C \times R_D \times R_E \times R_F \times R_G \times R_H$$

$$\therefore R_{\text{Boiler System}} = 0.7757 \times 0.8942 \times 0.9520 \times 0.8075 \times 0.7766 \times 0.9975 \times 0.6416 \times 0.9906$$

$$\therefore R_{\text{Boiler System(Earlier)}} = 0.2625$$

Similarly, the improved reliability of the steam boiler system after three years is calculated as follows:

$$\therefore R_{\text{Boiler System}} = R_A \times R_B \times R_C \times R_D \times R_E \times R_F \times R_G \times R_H$$

$$\therefore R_{\text{Boiler System}} = 0.7939 \times 0.9298 \times 0.9604 \times 0.8330 \times 0.8041 \times 0.9984 \times 0.7146 \times 0.9929$$

$$\therefore R_{\text{Boiler System(Improved)}} = 0.3364$$

Therefore, the change in system reliability = improved system reliability − earlier system reliability

$(\Delta R)3$ year = 0.3364 − 0.2625 = 0.0739 (28.15% increase)

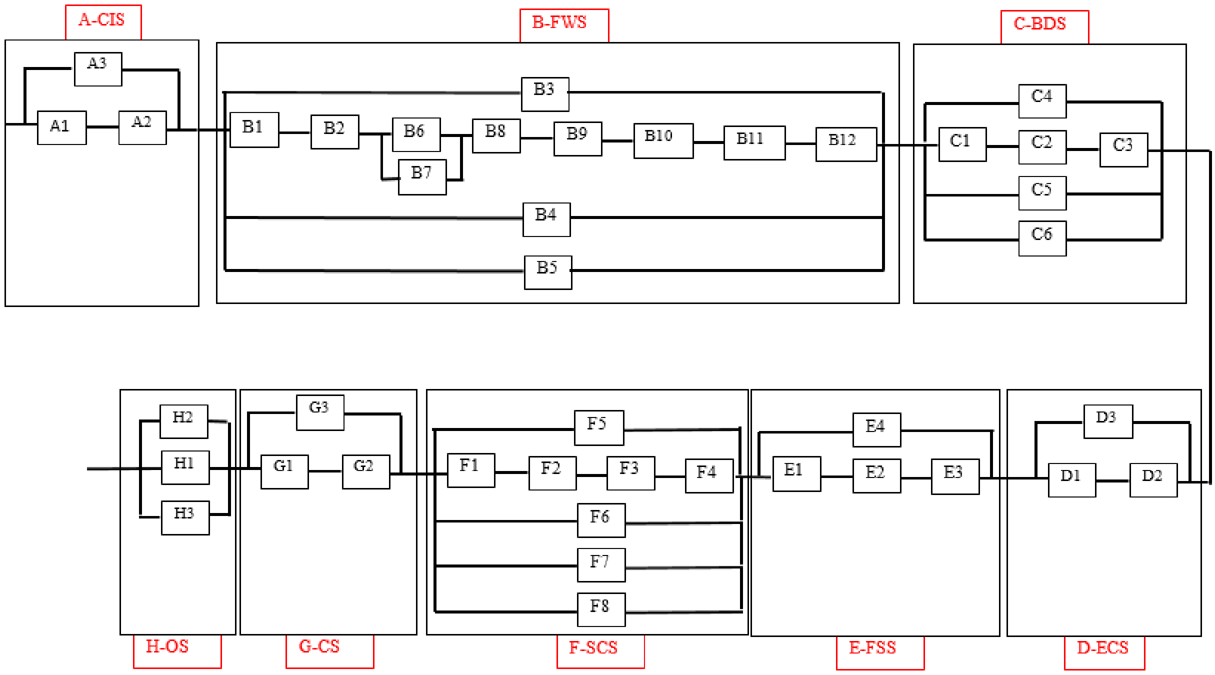

Figure 3. Reliability block diagram of the boiler system.

4. Results and Discussion

The implementation of the suggested maintenance strategies and recommended new components will enhance the reliabilities of the individual components, which ultimately improves the system reliability. The time required for scheduled maintenance of the components is also calculated by considering the mean delay time for maintenance (MDT) and mean delay for supply resources (SDT). The preventive maintenance time is estimated by using the following model.

$$T_{pm} = \text{MTTR} - \text{MDT} - \text{SDT}$$

Therefore, the time required for scheduled maintenance is less than the time required for corrective or unscheduled maintenance. Using the improved MTTF and improved MTTR for preventive maintenance, the availability of the components is therefore estimated as follows.

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

Finally, the results of the earlier availability values and the improved availability values of all the components of the boiler system are presented in Table 5.

Similarly, the purpose of this study is to investigate the optimal maintenance strategies, their frequencies, and intervals with minimal maintenance cost. The average cost of maintenance due to corrective maintenance and scheduled maintenance has been assessed. Various cost measures are considered as failure cost, part cost, logistic cost, and cost of production loss in order to estimate the maintenance costs. Additionally, in order to quantify the failure cost of the component per year, the failure rate of the components, mean time to repair, labor charges, and size of the crew are taken into account. The maintenance cost model used here is shown in Equation (4).

Cost of scheduled or unscheduled maintenance per year = failure cost per year + part cost per year + logistic cost per year + cost of production loss per year.

$$C_{\text{Maint}} = [E[N(t)]_i \times \text{MTTR}_i \times C_{L_i} \times \text{NL}] + C(\text{pci}) + C(\text{lgi}) + \text{PL} \quad (4)$$

where,

C_{Maint}: The total maintenance cost per year.
$E[N(t)]_i$: is number of failures per year.
$MTTR_i$: Mean time to repair for component i, in hours.
C_{L_i}: The labor charges in Rs/hr, for component i.
NL: The number of labors required for maintenance.
C(pci): The part cost per year for component i, in Rs.
C(lgi): Logistic cost per year for component i in Rs.
PL: The cost of production loss due to sudden breakdown for component i, in Rs.

The maintenance cost with scheduled maintenance and unscheduled maintenance are estimated and summarized in Table 5 for all the selected components of the boiler system and are also shown in Figure 4.

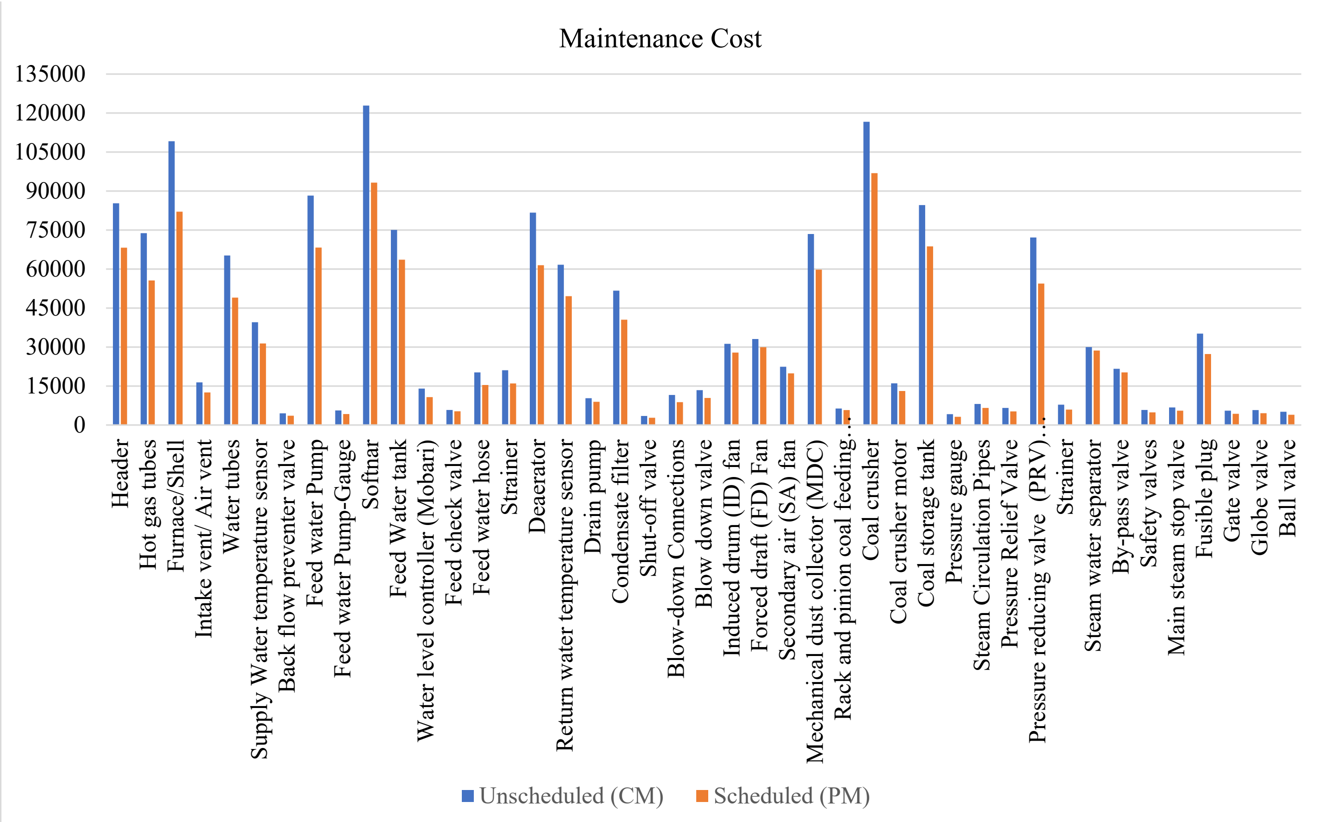

Figure 4. Cost comparison between scheduled and unscheduled maintenance of the boiler components.

The corrective maintenance cost of the header in the boiler system can be estimated as follows:

The mean time to failure of the header is estimated using best-fit distribution and is as follows:

$$MTTF_I = 95{,}714 \text{ Hours}$$

The expected number of failures per year for RP are estimated as follows:

$$E[N(t)]_I = \left(\frac{t}{MTTF_I}\right)$$

where, t is the total operating time of the component, and it is estimated by assuming 300 working days in a year. While estimating the operating time again, mean time to repair is considered.

$$\text{Operating time (t)} = 7200 - 34.005 = 7165.99 \text{ Hrs.}$$

Therefore, the expected number of failures per year of the header is as follows:

$$E[N(t)]_I = \left(\frac{t}{MTTF_I}\right) = \left(\frac{7165.99}{95{,}714}\right) = 0.07486$$

The labor charges for corrective maintenance are considered as Rs. 500 per day. The part cost per year of a component is a cost of that component per year and it can be estimated as:

$$Cp = E[N(t)]_I \times Ci$$

Therefore, the part cost of the header is

$$Cp = 0.07486 \times 200{,}000 = \text{Rs. } 14{,}854.814$$

The spare logistic cost of the component is assumed to be 15% of the part cost per year. The spare logistic cost of the header is, therefore,

$$C_{Lg_i} = 0.15 \times Cp$$

$$C_{Lg_i} = 0.15 \times 14{,}854.814 = \text{Rs.}2228.2221$$

The cost of the production loss of the component is estimated by considering the production loss of the plant as Rs. 25,000 per hour. Therefore, the cost of production loss for the component is estimated by multiplying the number of failures per year, the mean time to repair, and the production loss of the plant per hour.

$$C_{PL_i} = 25{,}000 \times Ti \times E[N(t)]_i$$

$$C_{PL_i} = 25{,}000 \times 34.005 \times 0.07486$$

$$C_{PL_i} = \text{Rs.}63{,}142.24$$

The total annual maintenance cost for the component is estimated by using Equation (4) and it is as follows:

Annual maintenance cost of the component = (the number of failures per year × mean time to repair × labor charges × no of labors) + part cost per year + logistic cost per year + cost of production loss due to that component.

$$C_{CM} = Ei[N(t)] \times Ti \times C_{L_i} \times N_p + \left[C_p + C_{Lg_i} + C_{PL_i}\right]$$

Therefore, the total annual corrective maintenance cost of the header is estimated as:

$$C_{CM} = [0.07486 \times 34.005 \times 500 \times 4] + [14{,}854.814 + 2228.2221 + 63{,}142.24]$$

$$C_{CM} = \text{Rs. } 85{,}276.66$$

Furthermore, the total annual corrective maintenance cost of the boiler system can be estimated as the sum of the corrective maintenance cost of all the components of the boiler system and is given by

$$\sum_{i=1}^{43} C_{CM} = \text{Rs. } 1{,}579{,}016.67$$

A similar calculation is carried out for all selected components of the boiler system, and the results of the corrective maintenance cost estimation are shown in Table 5.

The estimated scheduled and unscheduled maintenance costs are presented in Table 5, also it is represented graphically in Figure 4. The graphical representation aids in identifying and emphasizing the most crucial components in terms of cost, as well as focusing on components whose maintenance costs may be readily lowered.

5. Conclusions

Reliability centered maintenance (RCM) is a risk and reliability management technique that can be used to evaluate and optimize PM requirements in their working environment. The RCM approach is divided into three stages: Identification of critical components and subsystems, assessment and assignment of proper maintenance tasks, and effective implementation of the PM tasks. This paper demonstrates the successful application of the developed RCM framework on a steam boiler system. The proposed RCM model focuses on the overall maintenance of the boilers, not just cleaning schedules, by taking into account availability and reliability.

In addition to determining the proper maintenance intervals, the TTF and TTR data analysis enabled the identification of critical components from a reliability perspective and provided the information required to select the most effective action to improve their performance. We have identified the components that need additional attention at the level of system reliability. Parts with a lower MTTF need to strengthen maintenance policy, while parts with a higher MTTR need to improve training and resources for the maintenance team.

To select appropriate maintenance tasks, the developed reliability-centered maintenance model and logic decision diagrams are used. For various failure modes, various maintenance tasks such as time-directed (TD), condition-directed (CD), failure findings (FF), and run-to-fail (RTF) are proposed. After deciding the appropriate maintenance tasks, a quantitative approach to determining the maintenance interval is developed based on the system reliability and time to failure model. Assuming a failure rate of 25 percent prior to the implementation of PM, a value of 0.75 is considered to be the minimum level of reliability for calculating maintenance intervals. Along with these maintenance recommendations, some design changes are also recommended. We can increase the reliability levels of the components and system and the availability of the system by making these design improvements and conducting preventive maintenance at these intervals. From this analysis, it is observed that the reliability of the steam boiler system has improved by 28.15%.

The implementation of the proposed RCM approach demonstrates its contribution towards reducing maintenance costs and improving system availability. Up to 20.32%of the maintenance cost can be saved annually by applying these scheduled maintenance programs. Additionally, it can achieve an increase in system availability of 0.16%, i.e., from 0.993282 to 0.994957.

The proposed RCM model is able to develop a methodology to determine optimum maintenance time and maintenance costs, which can be applied to other elements of the plant. The proposed model also allows to overcome limits of the classical model, which provides quantitative analysis and precise determination of maintenance costs through crew size, logistic cost, and production loss consideration.

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Abbreviations

RCM	Reliability Centered Maintenance
PM	Preventive Maintenance
BM	Breakdown maintenance
CBM	Condition-based maintenance
CM	Corrective Maintenance
LCC	Life Cycle Cost
FMECA	Failure Mode Effect and Criticality Analysis
LTA	Logic Tree Analysis
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
MDT	Maintenance delay time
SDT	Supply delay time

Appendix A

Table A1. Boiler components and their codes used to define RBD of boiler system.

Sr. No	Component	Code
1	Furnace/Combustion Chamber	A1
2	Burner	A2
3	Temperature Regulator	A3
4	Water tubes	B1
5	Feed water Pump	B2
6	Back flow preventer valve	B3
7	Feed water Pump-Gauge	B4
8	Supply Water temperature sensor	B5
9	Softener	B6
10	Feed Water tank	B7
11	Water level controller (Mobari)	B8
12	Feed check valve	B9
13	Feed water hose	B10
14	Strainer	B11
15	Deaerator	B12
16	Drain pump	C1
17	Condensate filter	C2
18	Blow-down Connections	C3
19	Return water temperature sensor	C4
20	Shut-off valve	C5
21	Blow down valve	C6
22	Induced drum (ID) fan	D1
23	Forced draft (FD) Fan	D2
24	Mechanical dust collector (MDC)	D3
25	Rack and pinion coal feeding mechanism	E1
26	Coal crusher	E2
27	Coal crusher motor	E3
28	Coal storage tank	E4
29	Header	F1
30	Steam Circulation Pipes	F2

Table A1. *Cont.*

Sr. No	Component	Code
31	Pressure Relief Valve (PRV) station	F3
32	Pressure reducing valve	F4
33	Pressure gauge	F5
34	Steam water separator	F6
35	By-pass valve	F7
36	Intake vent/Air vent	F8
37	Safety valves	G1
38	Main steam stop valve	G2
39	Fusible plug	G3
40	Gate valve	H1
41	Globe valve	H2
42	Ball valve	H3

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