Implementation of a Reliability-Centered Maintenance Plan for Fire-Tube Boilers: A Case Study in the Textile Industry

Erick Mejia-Portillo, Sofia Guevara-Barrera, Juan Aguilar-Rosa, and Yakdiel Rodriguez-Gallo

***Abstract*—Reliability-Centered Maintenance (RCM) application in steam systems aims to prevent potential failures by understanding their causes and consequences and determining necessary actions to preserve physical assets. The textile company frequently experiences unplanned stoppages due to steam boiler failures. This study proposes implementing an RCM plan to optimize the maintenance program for fire-tube boilers. A criticality analysis of boiler area equipment was conducted using the Analytical Hierarchy Process (AHP). Failure modes and effects were assessed, and the Risk Weighting Number (RWN) was calculated. Maintenance tasks were assigned using the RCM diagram based on the RWN value. The reliability block diagram of the boiler system was designed, and optimal time intervals were determined using the Weibull distribution for critical components. The literature review found no prior studies applying RCM to fire-tube boilers in the textile industry. The proposed maintenance plan's reliability, availability, and economic viability were assessed in a case study, showing a 16.15% increase in reliability and a 0.004% increase in availability. Additionally, annual maintenance cost savings of up to 27.54% could be achieved. This novel RCM methodology optimizes fire-tube boiler maintenance plans, overcomes classical model limitations, and underscores the importance of reliability analysis for effective preventive maintenance, with potential applications to other systems in the textile industry.**

Link to graphical and video abstracts, and to code: https://latamt.ieeer9.org/index.php/transactions/article/view/9225

***Index Terms*—Maintenance Plan, RCM, Reliability, Fire-Tube Boilers, Textile Industry.**

I. Introduction

STEAM systems play a critical role in most current industrial processes. In key industrial sectors, a significant portion of fossil fuel consumption is allocated to steam generation [1]. Its function is of vital importance in multiple sectors and applications, providing heat and energy for industrial processes, power generation, and heating systems [2].

Steam boilers are widely used in the textile industry for various processes such as chemical fixation, washing, dyeing, finishing, and drying of textile materials [3]. The demand for steam in processing industries, including textiles, is rapidly increasing, leading to the need for greater utilization of steam boiler capacity. It is crucial to highlight that proper maintenance and precise operation are essential aspects to ensure both safety and efficiency in boiler performance in this industry [4].

There are three fundamental techniques to optimize system maintenance strategies: Condition-Based Maintenance (CBM), Total Productive Maintenance (TPM), and Reliability Centered Maintenance (RCM) [5], [6]. Implementing a predominantly corrective and unplanned maintenance policy entails significant costs, as the impacts of failures, whether catastrophic or not, are only realized post-occurrence. Conversely, adopting a planned, proactive maintenance program based on condition monitoring enables operation and maintenance teams to detect, analyze, and diagnose failures in their nascent stages, leading to heightened operational reliability of systems and equipment, thus reducing maintenance expenses [7].

RCM stands out as one of the most well-known and utilized methodologies for maintaining operational efficiency in steam systems. It operates by balancing the significant costs of corrective maintenance (CM) with the costs of scheduled policies (preventive or predictive), all while considering the potential reduction in the assessed element's 'useful life' [8].

The application of RCM aims to anticipate potential failures, understand their causes, and assess their consequences, all to prevent them and determine the actions needed to preserve physical assets while maintaining operational availability [9]. It is a methodology that enables resource optimization in maintenance, cost efficiency, and system maintenance effectiveness improvement [10]. RCM is capable of minimizing maintenance activities and associated costs related to failure repairs without affecting production performance, product quality, and safety. It is also utilized as a procedure for identifying steps for preventive maintenance (PM) of complex systems. The success of RCM is not only reflected in equipment reliability but also in the principles and the proper understanding and application of its concept. RCM allows for the establishment of an appropriate maintenance strategy for each type of potential failure, serving as the basis for creating a new maintenance program. It also aids in deciding whether the equipment is suitable for the process, determining design changes in equipment needs for new investments, and assessing the feasibility of the process [11].

In this study, RCM is the primary focus, as none of the other approaches can fully address the following four points: 1 - Preserve the functionality of a machinery system consistently throughout its lifecycle; 2 - Identify failure modes

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that could compromise functions; 3 - Prioritize the necessity of the function; and 4 - Select only applicable and effective preventive maintenance tasks [11].

A contribution of this work is that the review conducted revealed no published study applying RCM to a fire-tube boiler in the textile industry. Patil et al. [12] conducted a case study on water-tube boilers. In the case of fire-tube boilers, no similar case studies have been published. Hence, the novelty of the methodology presented in this work lies in its potential to serve as a basis for optimizing maintenance plans for fire-tube boilers, overcoming the limitations of the classical model, and providing a precise analysis of costs and maintenance activities.

This article follows the following structure: In Section II, a literature review is presented. Subsequently, the implementation of the RCM methodology is detailed in Section III. Following that, the case study is presented, addressing criticality analysis, boundary definition, failure mode and effects analysis in the critical system, maintenance plan, and reliability comparison. In Section IV, the obtained results are presented, accompanied by a discussion. Conclusions and future research directions are provided in Section V.

II. Literature Review

The review was conducted using the Web of Science (WoS) and Scopus databases. The search criteria included keywords always combined with the term "maintenance", such as steam, boiler, and textile industry. These searches were performed on June 24, 2024. The data collection methodology is described in Table I. The inclusion criteria were implemented by first selecting papers with relevant titles, then evaluating their abstracts, and finally reviewing the full texts (Fig. 1). The collected data were organized into a standardized spreadsheet format, such as MS Excel. Throughout the data extraction process, transparency was maintained to prevent heterogeneity in data documentation, and all review steps were documented using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) checklist.

TABLE I
The Data Collection Methodology for Boiler Maintenance in the Textile Industry

Databases	Web of Science (WoS) and Scopus
Keywords	Maintenance, steam, boiler, textile industry
Document type	No date filtered
Date	No date filtered
Language	No date filtered
Search query	TITLE-ABS-KEY (maintenance) AND (ABS (textile AND industry) OR ABS (textile AND industries) OR ABS (textile AND sector) OR ABS (textile)) AND (ABS (steam) OR ABS (boiler))
Initial search	49
Provisional collection	45
Selected articles	6

In the conducted review, it was noted that articles related to the topic have been published in recent years, indicating an increasing interest in the subject. Research in the papers included in this review was predominantly from India. A total of 6 peer-reviewed research articles that specifically discussed boiler maintenance in the textile industry were fully examined. These papers were published in 5 different journals (Table II), with the majority in the International Journal of Quality and Reliability Management (2 articles). The articles selected according to the PRISMA guidelines are analyzed in depth in the supplementary material.

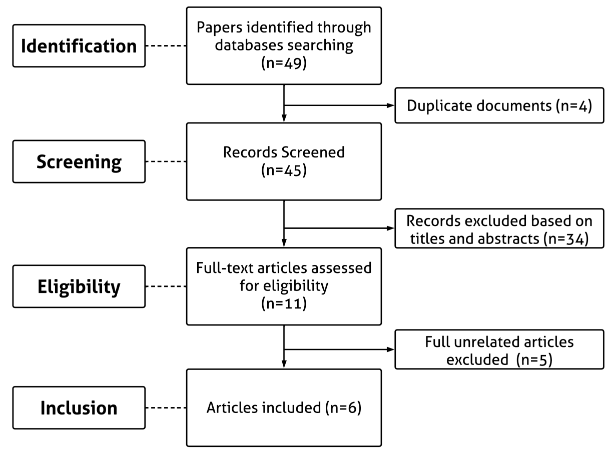

Fig. 1. Flow diagram depicting the systematic review process following the PRISMA guidelines.

III. Materials and Methods

A. Implementation of the RCM Methodology

The process begins by selecting the system and conducting a criticality analysis using the Analytical Hierarchy Process (AHP) technique for the systems that make up the boiler area. This method assesses multicriteria decision-making and is used in problems where it is necessary to evaluate both qualitative and quantitative aspects. The AHP technique helps organize critical aspects of a problem into a hierarchical structure similar to a family tree, simplifying complex decisions into a series of comparisons that enable the prioritization of different evaluated aspects with a matrix of judgments and a calculated priority vector used for comparing elements within a matrix [17].

Before initiating the RCM methodology analysis, it is essential to gather the necessary information about the assets, which will serve as input. This information includes blueprints, diagrams, manuals, operation/maintenance logs, and other relevant documents, such as the operational context (if available). Additionally, surveys of operation, production, and maintenance personnel, as well as interviews with boiler experts, are considered necessary to obtain information about desired performance requirements and current issues that may be arising. This data collection is crucial to ensure an effective RCM process analysis and to address the seven basic questions for RCM implementation [9].

The next step will involve identifying the equipment or components belonging to the system and defining the boundary conditions according to ISO 14224:2016, which provides a

TABLE II
SCIENTIFIC PUBLICATIONS ON BOILER MAINTENANCE IN THE TEXTILE INDUSTRY, RANKED BY CITATION NUMBER

R	Title	Authors	Journal	NC
1	Reliability analysis of a steam boiler system by expert judgment method and best-fit failure model method: a new approach.	Patil and Bewoor [13]	International Journal of Quality and Reliability Management	10
2	Development of Optimized Maintenance Program for a Steam Boiler System Using Reliability-Centered Maintenance Approach.	Patil, Bewoor, Kumar, *et al.* [12]	Sustainability (Switzerland)	9
3	Availability Analysis of a Steam Boiler in Textile Process Industries Using Failure and Repair Data: A Case Study.	Patil *et al.* [4]	ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering	9
4	A New Approach for Failure Modes, Effects, and Criticality Analysis Using ExJ-PSI Model—A Case Study on Boiler System.	Patil, Bewoor, *et al.* [14]	Applied Sciences (Switzerland)	3
5	Optimization of maintenance strategies for steam boiler system using reliability-centered maintenance (RCM) model – A case study from Indian textile industries.	Patil and Bewoor [15]	International Journal of Quality and Reliability Management	2
6	Development of Reliability Block Diagram (RBD) Model for Reliability Analysis of a Steam Boiler System.	Patil *et al.* [16]	Springer Series in Reliability Engineering	1

R: Ranking; **NC**: Number of citations.

foundation for collecting and organizing reliability and maintenance data for assets installed in industries [18]. Next, the necessary calculations are performed to develop a maintenance plan for the fire-tube boiler, focusing on RCM. To do this, the current operating parameters of the system in the textile company are defined, serving as input data for calculating the variables involved. In this way, a complete operational context of the system is obtained. Based on these conditions, the Functional Analysis, Failure Mode, Effects of Failure, and Consequence of Failure (Safety and hygiene impact, environmental impact, production, and maintenance costs) are carried out for each subsystem. For this, historical data and operational records of the boiler are considered, and evaluation criteria based on Severity, Failure Frequency, and Detectability indices are applied for Risk Weighting Number (RWN) calculation (RWN= S x F x D) [9]. To facilitate understanding, a section on notations has been included in the supplementary material, covering all the nomenclatures used in the article.

Maintenance tasks are logically assigned by utilizing the logical decision diagram of the RCM approach, which is crucial for improving the reliability and availability of systems and equipment in the field of study. The logical decision diagram for maintenance tasks used is the one developed by [12].

Subsequently, optimal maintenance intervals are established based on the previously calculated RWN. These intervals are grouped according to the type of maintenance (application frequency). To perform these calculations, the Weibull distribution is employed [17]. This distribution enables the visualization of times from the first and second failure in equipment. The AHP method was used to prioritize systems within the Boiler Area, while the RWN method was specifically applied to prioritize components of a fire-tube boiler, as suggested by Patil et al. [12] for elements that need improvements.

The Mean Time to Failure (MTTF) in hours is calculated by updating the failure frequency distribution using Bayes' Theorem [19]. Next, the reliability of the proposed maintenance plan is assessed compared to the current plan, and finally, the evaluation of the plan and its cost analysis are conducted. The flowchart of the methodology to be followed according to the RCM model is illustrated by Patil et al. [12].

IV. CASE STUDY

A. Criticality Analysis AHP

Criticality analysis is a tool that allows for the prioritization of systems and the eventual selection of those to be prioritized. The application of the AHP technique is crucial, as it contributes to identifying the specific level of criticality of systems and equipment [20].

This, in turn, optimizes the allocation of maintenance resources according to importance, i.e., the criticality each system or equipment holds in the production process. The method will generate a list based on the fundamental risk factors to be evaluated: Failure Frequency criterion (FF), Failure Detection levels (DF), Failure Severity levels (SF), and Failure Costs (FC) within the operational context [20]. The AHP model designed to prioritize systems in the Boiler Area of the textile company is presented in the supplementary material.

The evaluation, or weighting, of the various criteria, subcriteria, and alternatives is carried out considering their relative importance at each level. Both qualitative and quantitative criteria can be compared through informal judgments to determine weights and priorities [21].

Next, in a judgment matrix, a priority vector is calculated and used to weigh and compare the elements of the matrix. The lower triangular matrix is filled using the following equation:

$$a_{ij} = \frac{1}{a_{ji}} \tag{1}$$

The FF criterion is evaluated based on the number of failures per time period. The DF criterion is related to the protection, control, and alert systems available to safely detect the occurrence of failure events. The SF criterion is related to the impact of failures on safety, the environment, and operations. For defining the SF criterion, it is necessary to understand the effects that failures can bring within a specific operational context. The FC criterion is related to the potential economic consequences of failures in safety, the environment, and operations. To define the SF criterion, it is necessary to estimate the costs that failures can bring within a specific operational context. The criteria FF, DF, SF, and FC are calculated according to [22].

Subsequently, the estimation of the Inconsistency Ratio (IR) and the prioritization of criteria are calculated. Before determining inconsistency, it is necessary to estimate the Consistency Index (CI) of an n x n matrix of judgments, where CI is defined by the equation:

$$CI = \frac{\lambda_{\max - n}}{n - 1} \tag{2}$$

where $\lambda_{\max}$ is the maximum eigenvalue of the matrix. Thus, IR is defined by the equation:

$$IR = \frac{CI}{R} \tag{3}$$

Results are ranked by level of importance from highest to lowest, and the final criticality analysis ranking obtained is shown in Table III. According to the results of the criticality analysis, it was identified that the fire-tube boiler is the most critical component, representing an index of 15.6% of the systems involved.

TABLE III
FINAL RANKING OF CRITICALITY ANALYSIS

Systems	Final Prioritization	Ranking
Boiler	0.156	1
Water softener	0.113	2
Boiler Condensate Water Feed Pump	0.103	3
Boiler Chemical Dosing Pump	0.102	4
Hard Water Pump Motor	0.102	5
Soft Water Pump Motor	0.102	6
Soft Water Pump Motor Variable Speed Drive	0.084	7
Hot Water Return Pump Motor	0.084	8
Hot Water Return Pump Motor Variable Speed Drive	0.084	9
Condensate Tank	0.069	10

B. Boundary Delimitation

The ISO 14224:2016 standard [18] allows for the disaggregation of the equipment under study into subsystems, classifying components in each subsystem in a way that makes it easy to obtain useful data about their operation for subsequent application of appropriate maintenance strategies. Based on this classification, the functional analysis will proceed for each subsystem, where its criticality risk value will be weighted and established. This analysis is a tool that identifies and classifies subsystems according to their criticality within the process from different perspectives, adjusting resources accordingly.

C. Analysis of Failure Modes and Effects for Critical System

The Analysis of Failure Modes, Effects, and Criticality (FMECA) was applied to the previously identified subsystems. It relied on historical data and operational records of the fire-tube boiler to identify potential failure modes that could lead to malfunctions and, simultaneously, determine the adverse effects associated with each of these failure modes.

The Severity Index (G) plays a fundamental role in assigning appropriate criticality to each component. The Likert scale [23] was used to classify this severity. The Failure Frequency Index (F) is defined as the number of failure events experienced by a component in a specific period. Intervals were assigned to this frequency using a Likert scale [23] covering values from 1 to 10, and the failure frequency was determined based on historical data.

The Detectability Index (D) refers to the difficulty of associating a failure mode in a component. It was also evaluated using intervals classified on a Likert scale [23] covering values from 1 to 10 and determined based on the location and context in which the failure occurred.

The RWN is used to quantify the risk associated with a failure in a specific equipment or component and to prioritize its treatment within the analysis. This value is determined by multiplying the Severity, Failure Frequency, and Detectability indices. RWN values are classified on a scale ranging from 0 to 1000, following the methodology proposed by Moubray. A range below 75 is considered Low. A range from 75 to 200 is considered Medium. A range from 200 to 1000 is considered high.

In relation to functions and functional failures, three categories of failure modes were established, and the corresponding effects were assigned to each of them. Subsequently, the consequences of each failure effect were evaluated. Table IV presents the result of the risk weighting for all components. After the analysis, the following components were identified as the most critical, due to the RWN indicator: Smoke Tubes with RWN = 490, Burner with RWN = 240, Blowdown Pipe with RWN = 200, and McDonnell with RWN = 140.

D. Proposed Maintenance Plan

Based on the logical decision tree of ISO 14224:2016, questions are posed for each failure mode of the critical components, suggesting the application of maintenance tasks to reduce the failure rate and improve reliability. This involves selecting specific maintenance tasks based on the consequences of the failure. The binary type of decision tree (Yes/No answers) can be used to choose various maintenance tasks, such as CM, PdM, CBM, PM, RTF. The overall effectiveness of the selected maintenance task must be evaluated based on specific criteria such as the reduction of operational irregularities, lifespan, reduction in repair costs, spare parts and tools, downtime, and the time required for repairs. The proposed model is used to identify and select the most suitable maintenance tasks for critical components and their failure modes in the steam boiler system. The results obtained through this process are detailed in the supplementary material.

TABLE IV
RISK WEIGHTING FOR ALL COMPONENTS OF THE FIRE-TUBE BOILER

No.	Component	RWN	Ranking	No.	Component	RWN	Ranking
1	Body	9	30	17	Breakers	10	20
2	Packing	56	8	18	Burner controller	10	21
3	Steam control valve	20	13	19	Flame controller	10	22
4	External body	5	31	20	Internal power supply	10	23
5	Condensate water supply pipes	37	9	21	Operating pressuretrol	10	24
6	Blowdown Pipe	200	4	22	Pressure gauge	10	25
7	Bracket	10	28	23	Temperature gauge	10	26
8	Safety valves	10	29	24	Gas control valve	15	16
9	Internal body	63	7	25	Air regulating valve	15	17
10	Burner	240	3	26	McDonnell	140	5
11	Smoke tubes	490	1	27	Motor fan	10	27
12	Combustion chamber	63	6	28	Gate seals	15	15
13	Electrodes	350	2	29	Flame viewer	35	10
14	Ignition transformer	21	12	30	Burner gaskets	20	14
15	Contactor	10	18	31	Water level indicator	35	11
16	Control panel	10	19				

The proposed maintenance plan is presented as an initial guide and not as a final version. Its purpose is to establish a preliminary structure that can be adapted according to the specific needs of the company, with the expectation that it will evolve as its implementation progresses. This dynamic evolution process includes adjustments based not only on feedback from operational and maintenance personnel but also on information collected through maintenance records.

It is crucial to consider that the current data records include some non-recurrent failures that may be attributed to the poor execution of a specific maintenance. These specific cases require special consideration when assessing the plan's effectiveness. Continuous review of the records will facilitate the identification of patterns, trends, and specific situations, allowing adjustments to the plan to address the needs and challenges of the company more effectively.

For the plan, maintenance intervals will be assigned based on the previously calculated RWN. Reliability calculations were performed for critical components using the Weibull distribution [24]. In the context of reliability, a value of R(t) = 0.75 is recommended, as suggested in the study by [13]. A reliability value of 0.75 is recommended because periodic maintenance intervals aim to ensure an approximately 75% reliability level for each boiler system component. Specifically, the maintenance team considers a 25% probability that a failure will occur before PM. If higher reliability targets are set, maintenance intervals would be shorter, resulting in higher maintenance costs. Conversely, if lower reliability targets are set, preventive maintenance intervals would be longer, ultimately leading to increased failure frequencies and maintenance costs. With this value as a reference, the maintenance time for each task corresponding to the critical components of the boiler can be calculated using the following equation:

$$t = \theta \times [-\ln(0.75)]^{1/\beta} \tag{4}$$

where t is the maintenance time interval, θ is the Weibull scale parameter, and β is the Weibull shape parameter [25].

To carry out these calculations, data such as the Operating Time (TO) and Downtime (TFS) of these components collected over a period of 3 years are used. Subsequently, the values of θ, β and t were calculated for each critical component. The results are detailed in the supplementary material. The remaining components had their intervals indicated based on the maintenance manual, expert criteria, and legal framework.

The MTTF in hours was calculated based on the determination of the updated distribution of the failure frequency, supported by Bayes' Theorem. This is because it allows combining this information with the corresponding data on failure frequencies from information banks like OREDA [26], facilitating the obtaining of more robust and realistic estimates of the failure frequency. Results of the improved MTTF calculation for each component are detailed in the supplementary material.

E. Reliability Comparison

To assess the reliability of the steam boiler system, a comparison was made between the reliability results of the current maintenance plan and the proposed plan. The reliability of the entire system was evaluated using the developed reliability block diagram (RBD), illustrated in Fig. 2. Additionally, the different codes used in the reliability block diagram are indicated in Table V.

The RBD model assumes a specific configuration of the system, such as series, parallel, or combinations of both, which determines how the overall system reliability is calculated. It is assumed that the failures of the system components are independent, meaning that the failure of one component does not affect the probability of failure of others. This assumption simplifies the analysis and is common in reliability studies. Equations (5) to (8) assume that the failure times of the components follow exponential distributions, selected based on historical data to accurately represent the behavior of the components. To simplify the model, it is assumed that the failure rates of the components are constant during the analysis

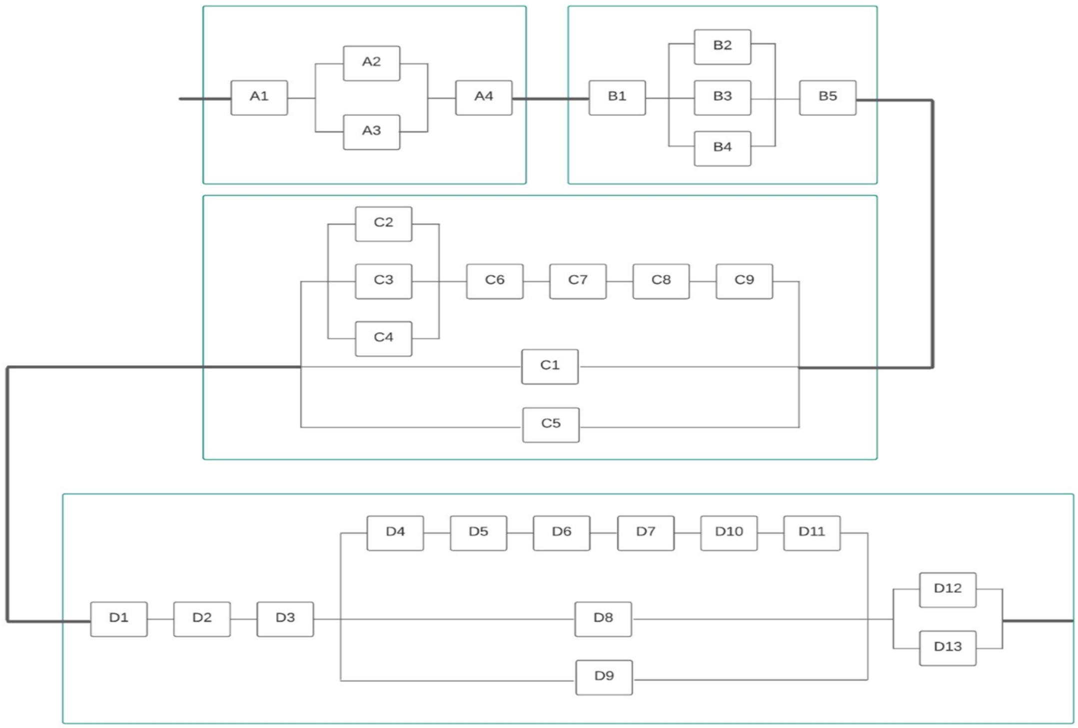

Fig. 2. Component codes for the reliability block diagram.

period, implying that the probability of failure within any time interval is constant, a suitable assumption for components with exponential distributions of time between failures.

Equations 5 and 6 are the reliability models developed for the calculation in the steam boiler system.

$$R_{\text{Boiler System}} = R_A \cdot R_B \cdot R_C \cdot R_D \tag{6}$$

where $R_A, R_B, \ldots, R_D$ are the reliabilities of the subsystems of the fire-tube boiler.

The current reliability of the steam boiler system is calculated as follows:

$$R_{\text{Boiler System (Current)}} = R_A \cdot R_B \cdot R_C \cdot R_D \tag{7}$$

Substituting the values:

$$\begin{aligned} R_{\text{Boiler System (Current)}} &= 0.7424 \times 0.8697 \times 0.9945 \times 0.6545 \\ &= 0.4202 \end{aligned}$$

Similarly, the reliability of the proposed steam boiler system is calculated as follows:

$$R_{\text{Boiler System (Proposed)}} = R_A \cdot R_B \cdot R_C \cdot R_D \tag{8}$$

Substituting the values:

$$\begin{aligned} R_{\text{Boiler System (Proposed)}} &= 0.8162 \times 0.8769 \times 0.9952 \times 0.6852 \\ &= 0.4881 \end{aligned}$$

Therefore, the change in system reliability is equal to the proposed system reliability minus the current system reliability:

$$\begin{aligned} &R_{\text{Boiler System (Proposed)}} - R_{\text{Boiler System (Current)}} \\ &= 0.4881 - 0.4202 \\ &= 0.0679 \quad (16.15\% \text{ increment}) \end{aligned}$$

The reliability results for all evaluated components, considering the exponential distribution according to the following equation, are detailed in the supplementary material.

$$R(t) = e^{-FF \cdot t} \tag{9}$$

Also, using the improved MTTF and MTTR for preventive maintenance, the failure availability(A_{failure}, Availability) of the components is estimated as follows:

$$A_{\text{failure}} = \frac{\text{MTTF}}{\text{MTTF} + \text{MTTR}} \tag{10}$$

V. RESULTS AND DISCUSSION

The obtained result indicates that the probability of the system functioning correctly has improved by 16.15%; however, there is a need to work on improving individual components with lower reliability. Regarding availability, a very slight increase of 0.004% is observed, changing from 0.997174 to 0.997211.

In Fig. 3, the "attainable operational reliability versus time" graph is presented, constructed using equations 5 and 6 for the two scenarios: current and proposed. The reliability over time in the graph has the expected trend level: two negative exponentials with different slopes due to different failure frequencies. Significant differences exist, emphasizing that from approximately 1000 hours of usage, the improvement becomes noticeable, and particularly at 5000 hours (one year

$$\begin{aligned}R_{\text{Boiler System}} = &\Big[R_{A1}\cdot(1-(1-R_{A2})\cdot(1-R_{A3}))\cdot R_{A4}\Big]\\ &\cdot\Big[R_{B1}\cdot(1-(1-R_{B2})\cdot(1-R_{B3})\cdot(1-R_{B4}))\cdot R_{B5}\Big]\\ &\cdot\Big[1-(1-(1-R_{C2})\cdot(1-R_{C3})\cdot(1-R_{C4}))\cdot R_{C6}\cdot R_{C7}\cdot R_{C8}\cdot R_{C9}\Big]\\ &\cdot\Big[R_{D1}\cdot R_{D2}\cdot R_{D3}\cdot(1-(1-(R_{D4}\cdot R_{D5}\cdot R_{D6}\cdot R_{D7}\cdot R_{D10}\cdot R_{D11}))\cdot(1-R_{D8})\cdot(1-R_{D9}))\\ &\cdot(1-(1-R_{D12})\cdot(1-R_{D13}))\Big]\end{aligned} \quad (5)$$

TABLE V
COMPONENT CODES FOR RELIABILITY BLOCK DIAGRAM

Component	Code	Component	Code	Component	Code	Component	Code
Body	A1	Internal body	C1	Contactor	D1	Gas control valve	D10
Gasket	A2	Burner	C2	Control panel	D2	Air regulating valve	D11
Gate seals	A3	Flame viewer	C3	Breakers	D3	Water level indicator	D12
Steam control valve	A4	Burner gaskets	C4	Burner controller	D4	McDonnell	D13
External body	B1	Motor fan	C5	Flame controller	D5		
Condensate water supply pipes	B2	Smoke tubes	C6	Internal power supply	D6		
Blowdown Pipe	B3	Combustion chamber	C7	Operating Pressuretrol	D7		
Support	B4	Electrodes	C8	Pressure gauge	D8		
Safety valves	B5	Ignition transformer	C9	Temperature gauge	D9		

of operation), the increased reliability achieved by the proposed configuration is approximately 16%. Additionally, after 20,000 hours (4 years), the behavior of the curves tends to be similar due to the natural wear of the boiler.

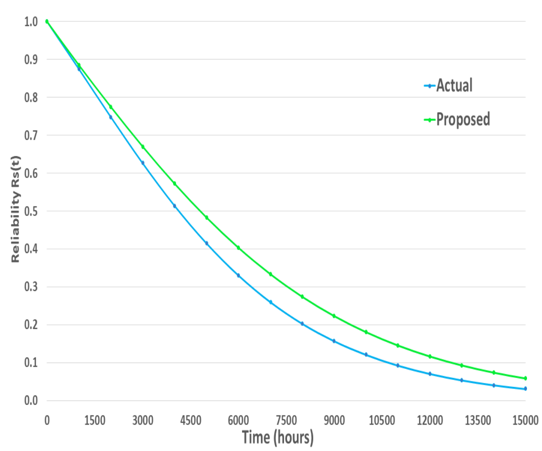

Fig. 3. Graph of reliability versus operating time in hours for the boiler system.

The maintenance cost due to corrective and preventive maintenance has been evaluated. Various costs such as failure cost, part cost, logistics cost, and production loss cost are considered to estimate maintenance costs. Additionally, to quantify the component's failure cost per year, the component failure rate, mean repair time, labor costs, and the number of people involved in activities are considered. The maintenance cost model used is shown in the following equation:

$$\begin{aligned}\text{Maintenance cost} = &(\text{FF}_i \times \text{MTTR}_i \times C_{li} \times N)\\ &+ C_{pci} + C_{logi} + C_{pp}\end{aligned} \quad (11)$$

Where:

$$\begin{aligned}\text{FF}_i &= \text{Failure frequency per component per year.}\\ \text{MTTR}_i &= \text{average repair time per component } i,\\ &\quad\text{measured in hours.}\\ C_{li} &= \text{Direct costs of correction for labor faults}\\ &\quad\text{per component } i,\ \text{in \$ / hours.}\\ N &= \text{Number of people required for the repair.}\\ C_{pci} &= \text{Cost of the component per year, in \$.}\\ C_{logi} &= \text{Cost of logistics per year per component } i,\ \text{in \$}\\ C_{pp} &= \text{Cost of production loss per component } i,\ \text{en \$}\end{aligned}$$

It should be noted that C_{pci}, C_{logi}, and C_{pp} are calculated by multiplying them by FF_i. A similar calculation is performed for all components, both for the current and proposed scenarios. The difference in maintenance costs, calculated as Current Maintenance Cost minus Proposed Maintenance Cost, is \$26,873.44, representing savings (average savings of 27.54%). The results of the earlier availability values and the improved availability values of all the components of the boiler system are presented in the supplementary material. Fig. 4 presents the costs per component, both current and proposed. This representation helps identify and highlight the most crucial components in terms of cost, as well as focus on those whose maintenance costs can be easily reduced.

With the current and proposed costs, a difference of \$26,873.44 is observed; however, it is necessary to add the administrative costs of RCM plan design, training costs, and maintenance software costs. The projected reduction in maintenance costs over the next five years, averaging 27.54%, is detailed in the supplementary material. With the development for the implementation of the proposed RCM plan in the boiler,

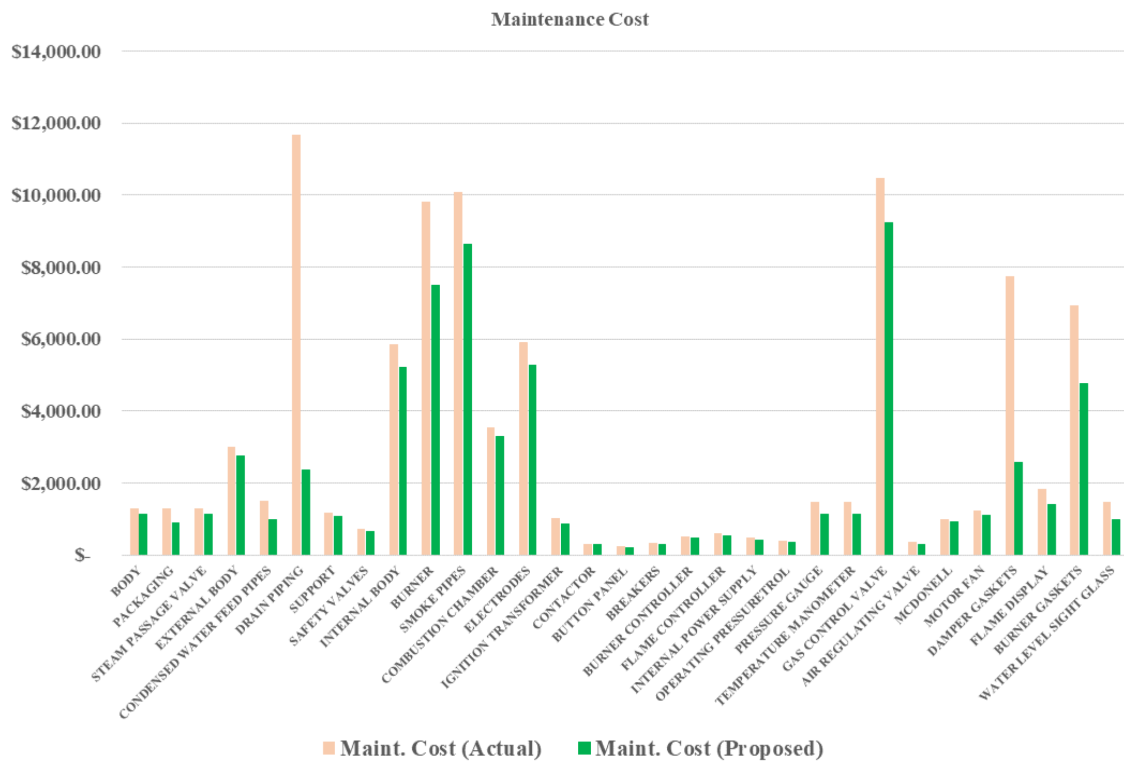

Fig. 4. Comparison of current costs and proposed Maintenance costs.

it is anticipated that the savings will be noticeable within approximately 12 months, considering that the production process is continuous during that timeframe.

This study highlights the application of RCM in fire-tube boilers in the textile sector, addressing a gap identified through a systematic literature review using the PRISMA guideline. Previous research focused on water-tube boilers [4], [12], [14], [16]. Unlike these studies, which reported reliability improvements of 28.28% and savings of 20.25% [12], this analysis achieved a 16.15% increase in system reliability and an average savings of 27.54% in maintenance costs. The calculation method is explained in the supplementary material. The results emphasize the effectiveness of RCM in optimizing resources, reducing failures, and prioritizing critical components, significantly contributing to the economic and operational improvement of maintenance in this type of boiler, which has been underexplored in the existing literature [3], [4].

VI. Conclusions

The RCM methodology allows for the optimization of available resources in the maintenance department through a reliability analysis. This methodology is geared towards preserving the functionality of boilers, which play a crucial role in production, occupational safety, health, and environmental protection.

Given the crucial function of the boiler in production and its potential impact on the plant, the conducted analysis proposes a solid foundation for prioritizing maintenance and operation activities. The employed RCM methodology has proven effective in assigning specific tasks to reduce failures and enhance reliability, with recommended intervals for preventive maintenance. The comparison between the current and proposed plans reveals a 16.15% increase in reliability, highlighting the effectiveness of maintenance tasks on critical components. The use of the methodology presented in this study will enhance equipment availability, reducing events that jeopardize a company's integrity and interests.

The proposed maintenance plan emphasizes its economic viability by achieving an average savings of 27.54%, compared to the costs associated with the current maintenance plan in the case study. Additionally, the applied methodology results in an increased reliability of the system by emphasizing the importance of reliability analysis. These approaches can be extrapolated and applied to other systems within the textile industry.

In the future, the possibility of implementing the concept of smart RCM in the textile industry is envisaged. This innovative combination of Industry 4.0 technologies, such as the Internet of Things (IoT), Cyber-Physical Systems (CPS), and cloud computing, promises to revolutionize maintenance practices in this sector. Although currently facing challenges related to workforce adaptation and resistance to change, smart RCM offers significant benefits, such as performance optimization and cost reduction. Furthermore, the potential integration of emerging technologies, such as artificial intelligence and augmented reality, could take maintenance management to a new level of efficiency and precision in the industry.

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