Supplementary Material

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

1. NOTATIONS

MTTF: Mean Time to Failure (hours)

RWN: Risk Weighting Number (dimensionless)

a_{ji}: Lower Triangular matrix values (dimensionless)

S: Severity (dimensionless)

F: Failure Frequency (dimensionless)

D: Detectability (dimensionless)

IR: Inconsistency Ratio (dimensionless)

CI: Consistency Index (dimensionless)

λmax: Maximum eigenvalue of the matrix (dimensionless)

R: Average random value of CI for an n x n matrix. (dimensionless)

R(t): Reliability (dimensionless)

t: maintenance time interval (hours)

θ: Weibull scale parameter (dimensionless)

β: Weibull shape parameter (dimensionless)

$R_{Boiler\ System}$: Boiler System reliability (dimensionless)

$A_{failure}$: availability to failure (dimensionless)

FF_i: Failure frequency per component (failure /year)

$MTTR_i$: average repair time per component I (hours)

C_{li}: Direct costs of correction for labor faults per component i ($ / hours)

N: Number of people required for the repair (dimensionless)

C_{pci}: Cost of the component per year ($)

C_{logi}: Cost of logistics per year per component i ($)

C_{pp}: Cost of production loss per component i ($)

2. Analysis of the articles selected following the PRISMA guidelines.

Patil and Bewoor [1] proposed an approach to analyze the reliability of steam boiler systems in the textile industry using the expert judgment method. The aim was to assess system reliability and compare the results with another failure modeling method. Critical components with low reliability, such as the feedwater tank and feedwater pump, were identified. The authors emphasized the significance of reliability analysis for enhancing boiler system performance, highlighting the value of expert judgment in the absence of sufficient failure data.

On the other hand, Patil, Bewoor, Kumar, *et al.* [2] conducted a study based on the application of Reliability-Centered Maintenance (RCM) methodology to enhance maintenance programs in the textile industry. They utilized a five-phase model that spanned from system study preparation to RCM implementation. It was applied to water tube boilers with a capacity of 3 to 5 tons. The primary objective of the proposed model was to minimize the failure of subsystems and components of the steam boiler without affecting the work environment or maintenance costs. The main conclusions of the article were that the implementation of the proposed RCM approach improved the reliability of the steam boiler system by 28.15% and allowed for savings of up to 20.32% in annual maintenance costs. The study underscored the importance of integrating qualitative and quantitative analyses in the RCM process for effective maintenance planning and cost savings in the textile industry.

In 2022, the same authors conducted a study that focused on applying RCM methodology to optimize maintenance programs in the textile industry. They utilized a five-phase model, from system study preparation to RCM implementation, applied to water tube boilers with a capacity of 3 to 5 tons [2]. The main objective of the model was to minimize the failure of subsystems and components of the steam boiler without affecting the work environment or maintenance costs. Conclusions of the article indicated that the application of the RCM approach improved the reliability of the steam boiler system by 28.15% and allowed for savings of up to 20.32% in annual maintenance costs. The importance of integrating qualitative and quantitative analyses in the RCM process for effective maintenance planning and cost savings in the textile industry was highlighted.

Another study focused on the reliability, availability, and maintainability (RAM) analysis of the boiler system, identifying critical subsystems for optimization [3]. They presented a comprehensive framework for system reliability data analysis and maintenance modeling, including the selection of appropriate models based on Time-to-Failure (TTF) and Time-to-Repair (TTR) data. The implications of the study include a better understanding of reliability and maintenance aspects of boiler systems in the textile industry, as well as improvements in methodologies for trend testing, goodness of fit tests, and RAM analysis in industrial systems. It is worth mentioning that the type of steam boiler used by the authors is not explicitly stated in the article.

A different study introduced the ExJ-PSI model as an innovation in Failure Modes, Effects, and Criticality Analysis (FMECA), aiming to enhance traditional limitations by integrating expert judgments and multicriteria decision-making methods [4]. Applied to a boiler system in the textile industry, this model was compared with conventional FMECA and the normalized median method. It was highlighted that the ExJ-PSI improved risk assessment accuracy by involving multiple experts, considering additional criteria such as operational and maintenance time, and using a statistical approach for decision-making in conflicting situations. Furthermore, its effectiveness was demonstrated in identifying critical components and prioritizing failure modes in complex systems like boilers. The study emphasized the importance of considering various risk factors and enhanced FMECA methods for decision-making in critical industrial systems.

In another study conducted by [5], the implementation of RCM in a steam boiler within the textile industry was demonstrated to improve system reliability and availability. The importance of efficient preventive maintenance (PM) to reduce associated downtime was emphasized. Additionally, it was observed that several maintenance programs labeled as proactive turned out to be reactive, highlighting the versatility of RCM across various systems. In a subsequent investigation by [6], common failures and human errors in industrial boilers were addressed, despite established maintenance protocols. The reliability block diagram (RBD) technique was employed to evaluate the reliability of boilers in the Indian textile industry, both before and after the implementation of preventive maintenance.

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 [1]	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.* [2]	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.* [3]	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.* [4]	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 [5]	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.* [6]	Springer Series in Reliability Engineering	1

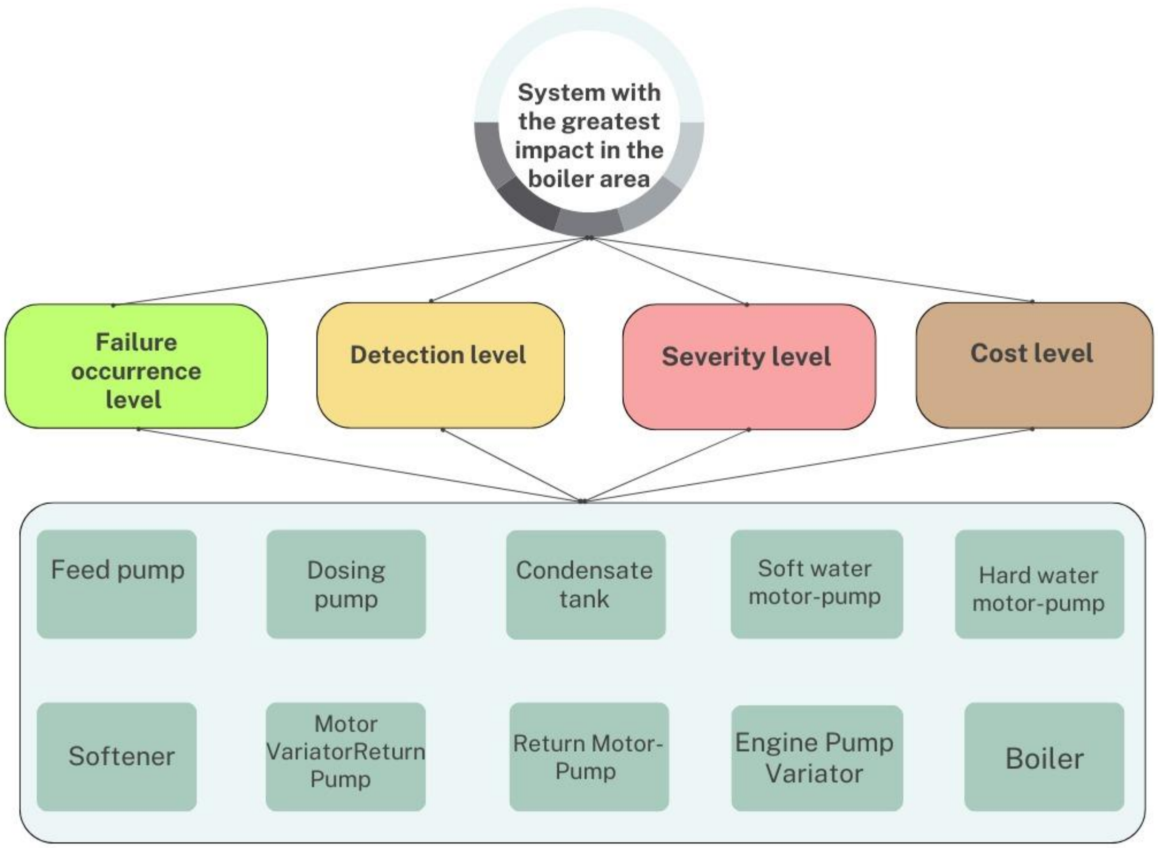
[1] S. S. Patil and A. K. Bewoor, "Reliability analysis of a steam boiler system by expert judgment method and best-fit failure model method: a new approach," *Int. J. Qual. Reliab. Manag.*, vol. 38, no. 1, pp. 389–409, 2020, doi: 10.1108/IJQRM-01-2020-0023.

[2] S. S. Patil, A. K. Bewoor, R. Kumar, M. H. Ahmadi, M. Sharifpur, and S. PraveenKumar, "Development of Optimized Maintenance Program for a Steam Boiler System Using Reliability-Centered Maintenance Approach," *Sustainability*, vol. 14, no. 16, p. 10073, Aug. 2022, doi: 10.3390/su141610073.

[3] S. S. Patil, A. K. Bewoor, and R. B. Patil, "Availability analysis of a steam boiler in textile process industries using failure and repair data: A case study," *ASCE-ASME J. Risk Uncertain. Eng. Syst. Part B Mech. Eng.*, vol. 7, no. 2, 2021, doi: 10.1115/1.4049007.

[4] S. S. Patil *et al.*, "A New Approach for Failure Modes, Effects, and Criticality Analysis Using ExJ-PSI Model—A Case Study on Boiler System," *Appl. Sci. Switz.*, vol. 12, no. 22, 2022, doi: 10.3390/app122211419.
[5] S. S. Patil and A. K. Bewoor, "Optimization of maintenance strategies for steam boiler system using reliability-centered maintenance (RCM) model – A case study from Indian textile industries," *Int. J. Qual. Reliab. Manag.*, vol. 39, no. 7, pp. 1745–1765, Jan. 2022, doi: 10.1108/IJQRM-07-2021-0216.
[6] S. S. Patil, A. K. Bewoor, R. Kumar, and I. K. Iliev, "Development of Reliability Block Diagram (RBD) Model for Reliability Analysis of a Steam Boiler System," *Springer Ser. Reliab. Eng.*, pp. 137–148, 2023, doi: 10.1007/978-3-031-05347-4_9.

3. AHP model designed to prioritize systems in the Boiler Area of the textile company



4. Recommended Maintenance Intervals.

Item	Component	MTTF (Hours)	Recommended Maintenance Time
1	Body	157,445.75	12 Months
2	Gasket	33,845.75	6 Months
3	Steam control valve	37,649.92	Daily / 12 Months

4	External body	148,537.29	12 Months
5	Condensate water supply pipes	28,901.75	Daily / Monthly
6	Blowdown Pipe	11,597.75	Daily / Monthly
7	Bracket	149,723.98	12 Months
8	Safety valves	50,843.98	Monthly
9	Internal body	149,723.98	12 Months
10	Burner	30,804.21	Monthly / 12 Months
11	Smoke tubes	104,964.21	Daily / Weekly / Biannual
12	Combustion chamber	49,657.29	12 Months
13	Electrodes	2,689.29	Weekly
14	Ignition transformer	16,235.98	Monthly
15	Contactor	50,843.98	Monthly
16	Control panel	50,843.98	Monthly
17	Breakers	50,843.98	Monthly
18	Burner controller	50,843.98	Daily
19	Flame controller	26,123.98	Daily
20	Internal power supply	26,123.98	12 Months
21	Operating Pressuretrol	51,721.54	Monthly
22	Pressure gauge	12,169.54	6 Months
23	Temperature gauge	12,169.54	6 Months
24	Gas control valve	26,123.98	Monthly
25	Air regulating valve	26,123.98	Monthly
26	McDonnell	150,601.54	Monthly
27	Motor fan	26,123.98	Daily / Monthly
28	Gate seals	14,069.75	6 Months
29	Flame viewer	12,169.54	Monthly
30	Burner gaskets	33,845.75	6 Months
31	Water level indicator	7,225.54	Monthly

5. Values of θ and β for critical components.

Component	θ	β	t (time interval)
Blowdown Pipe	4374.71	0.80	Daily/Monthly
Burner	4,136	0.29	Weekly/Monthly/Annual
Smoke tubes	1713.77	0.49	Daily/Semi-annual
McDonnell	6411.24	0.42	Monthly

6. **Results of the improved MTTF calculation for each component.**

Ítem	Component	OREDA Failure Mode	OREDA μ	OREDA σ	T	r	Improved FF	Improved MTTF
1	Body	External leakage	0.00005479	0.00005479	296,640.00	1	0.000006351	157,445.75
2	Gasket	External leakage	0.00005479	0.00005479	49,440.00	1	0.000029546	33,845.75
3	Steam control valve	Other	0.00016437	0.00016437	69,216.00	1	0.000026560	37,649.92
4	External body	Insufficient heat tranfer	0.00230112	0.00230112	296,640.00	1	0.000006732	148,537.29
5	Condensate water supply	External leakage	0.00005479	0.00005479	39,552.00	1	0.000034600	28,901.75
6	pipes	External leakage	0.00005479	0.00005479	4,944.00	1	0.000086224	11,597.75
7	Blowdown Pipe	Minor in service problems	0.00035613	0.00035613	296,640.00	1	0.000006679	149,723.98
8	Bracket	Minor in service problems	0.00035613	0.00035613	98,880.00	1	0.000019668	50,843.98
9	Safety valves	Minor in service problems	0.00035613	0.00035613	296,640.00	1	0.000006679	149,723.98
10	Internal body	Insufficient heat tranfer	0.00008218	0.00008218	49,440.00	1	0.000032463	30,804.21
11	Burner	Insufficient heat tranfer	0.00008218	0.00008218	197,760.00	1	0.000009527	104,964.21
12	Smoke tubes	Insufficient heat tranfer	0.00230112	0.00230112	98,880.00	1	0.000020138	49,657.29
13	Combustion chamber	Insufficient heat tranfer	0.00230112	0.00230112	4,944.00	1	0.000371846	2,689.29
14	Electrodes	Minor in service problems	0.00035613	0.00035613	29,664.00	1	0.000061592	16,235.98
15	Ignition transformer	Minor in service problems	0.00035613	0.00035613	98,880.00	1	0.000019668	50,843.98
16	Contactor	Minor in service problems	0.00035613	0.00035613	98,880.00	1	0.000019668	50,843.98
17	Control panel	Minor in service problems	0.00035613	0.00035613	98,880.00	1	0.000019668	50,843.98
18	Breakers	Minor in service problems	0.00035613	0.00035613	98,880.00	1	0.000019668	50,843.98
19	Burner controller	Minor in service problems	0.00035613	0.00035613	49,440.00	1	0.000038279	26,123.98
20	Flame controller	Minor in service problems	0.00035613	0.00035613	49,440.00	1	0.000038279	26,123.98
21	Internal power supply	Abnormal instrument reading	0.00021915	0.00021915	98,880.00	1	0.000019334	51,721.54

22	Operating Pressuretrol	Abnormal instrument reading	0.00021915	0.00021915	19,776.00	1	0.000082172	12,169.54
23	Pressure gauge	Abnormal instrument reading	0.00021915	0.00021915	19,776.00	1	0.000082172	12,169.54
24	Temperature gauge	Minor in service problems	0.00035613	0.00035613	49,440.00	1	0.000038279	26,123.98
25	Gas control valve	Minor in service problems	0.00035613	0.00035613	49,440.00	1	0.000038279	26,123.98
26	Air regulating valve	Abnormal instrument reading	0.00021915	0.00021915	296,640.00	1	0.000006640	150,601.54
27	McDonnell	Minor in service problems	0.00035613	0.00035613	49,440.00	1	0.000038279	26,123.98
28	Motor fan	External leakage	0.00005479	0.00005479	9,888.00	1	0.000071074	14,069.75
29	Gate seals	Abnormal instrument reading	0.00021915	0.00021915	19,776.00	1	0.000082172	12,169.54
30	Flame viewer	External leakage	0.00005479	0.00005479	49,440.00	1	0.000029546	33,845.75
31	Burner gaskets	Abnormal instrument reading	0.00021915	0.00021915	9,888.00	1	0.000138398	7,225.54

7. Considering the exponential distribution, the reliability results for all evaluated components.

Item	**Name of Component**	**Current R (t)**	**Proposed R (t)**	**Current A(t)**	**Proposed A(t)**	**Maintenance Cost (Earlier)**	**Maintenance Cost (Improved)**
1	Body	0.9672	0.9694	0.999676	0.999695	$1,271.67	$1,128.27
2	Gasket	0.8187	0.8643	0.999676	0.999764	$1,281.26	$889.69
3	Steam control valve	0.8669	0.8772	0.999653	0.999681	$1,285.50	$1,118.25
4	External body	0.9672	0.9680	0.999192	0.999193	$2,975.54	$2,747.41
5	Condensate water supply pipes	0.7788	0.8430	0.999596	0.999723	$1,493.76	$968.40
6	Blowdown Pipe	0.1353	0.6534	0.996774	0.999311	$11,648.19	$2,353.25
7	Bracket	0.9672	0.9678	0.999676	0.999680	$1,161.47	$1,078.35
8	Safety valves	0.9048	0.9075	0.999838	0.999843	$690.94	$640.91
9	Internal body	0.9672	0.9691	0.998384	0.998400	$5,831.28	$5,202.71
10	Burner	0.8187	0.8530	0.998062	0.998444	$9,786.29	$7,481.15
11	Smoke tubes	0.9512	0.9562	0.997579	0.997719	$10,076.61	$8,613.13
12	Combustion chamber	0.9048	0.9061	0.999030	0.999034	$3,513.15	$3,279.97
13	Electrodes	0.1353	0.1593	0.998384	0.998515	$5,903.16	$5,267.14

14	Ignition transformer	0.7165	0.7377	0.999730	0.999754	$998.23	$867.40
15	Contactor	0.9048	0.9074	0.999919	0.999921	$297.31	$274.11
16	Control panel	0.9048	0.9074	0.999939	0.999941	$219.57	$202.40
17	Breakers	0.9048	0.9074	0.999919	0.999921	$305.22	$281.79
18	Burner controller	0.9048	0.9074	0.999899	0.999902	$489.34	$456.81
19	Flame controller	0.8187	0.8277	0.999838	0.999847	$597.50	$536.88
20	Internal power supply	0.8187	0.8277	0.999879	0.999885	$460.71	$414.99
21	Operating Pressuretrol	0.9048	0.9089	0.999919	0.999923	$377.81	$346.34
22	Pressure gauge	0.6065	0.6664	0.999596	0.999671	$1,461.41	$1,129.68
23	Temperature gauge	0.6065	0.6664	0.999596	0.999671	$1,465.01	$1,132.59
24	Gas control valve	0.8187	0.8299	0.997096	0.997251	$10,453.19	$9,226.02
25	Air regulating valve	0.8187	0.8276	0.999919	0.999923	$331.10	$299.84
26	McDonnell	0.9672	0.9679	0.999757	0.999761	$983.70	$916.12
27	Motor fan	0.8187	0.8278	0.999676	0.999694	$1,209.38	$1,085.08
28	Gate seals	0.3679	0.7042	0.997981	0.999290	$7,716.76	$2,574.40
29	Flame viewer	0.6065	0.6664	0.999495	0.999589	$1,821.38	$1,405.83
30	Burner gaskets	0.8187	0.8653	0.998062	0.998584	$6,928.54	$4,741.81
31	Water level indicator	0.3679	0.5046	0.999596	0.999723	$1,468.60	$969.43
					Total=	$94,503.59	$67,630.15

8. The projected reduction in maintenance costs over the next five years, averaging 27.54%,

The calculation of current maintenance costs and the estimated cost of the proposed plan was carried out using Equation 11 from the article. This equation calculates maintenance costs based on the direct and indirect expenses related to repairs, considering the selection and definition of a system over a specific period.

Annual costs for both plans were calculated over a 5-year period, with the average serving as the projected savings. The results are shown in the table below. All calculations were performed using Excel.

Year	Current Plan	Proposed Plan	Savings	Difference
1	$ 94,503.59	104,103.59	9,600.00	-9.22%
2	$ 97,338.70	74,459.06	-22,879.64	30.73%
3	$ 100,258.86	74,459.06	-25,799.81	34.65%
4	$ 103,266.63	74,459.06	-28,807.57	38.69%
5	$ 106,364.63	74,459.06	-31,905.57	42.85%
Total	**$ 501,732.41**	**$401,939.81**	**-$99,792.59**	**27.54%**

* In the "Savings" column, the symbol (-) indicates savings.

In the first year, it is important to highlight that the cost of the proposed maintenance plan is higher due to the expenses associated with its implementation. This is illustrated in the following table.

Administrative costs of RCM Plan design	**$ 2,800.00**	**Only the first year**
Training costs	$ 2,000.00	Only the first year
Maintenance Software Costs	$ 4,800.00	$/Year

To demonstrate the impact on costs associated with implementing the maintenance plan, a minimum period of 5 years is proposed. It is worth noting that a 3% inflation rate was used for this evaluation, as the average inflation in El Salvador ranged between -0.37% and 1.09% during the 2015–2020 period. From 2021, inflation has shown an upward trend, reaching 1.23% in 2023.