DECISION-MAKING CRITERIA FOR BOILER MAINTENANCE: AN EMPIRICAL STUDY

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Abstract. Accurate decision-making in boiler maintenance is essential to ensuring efficiency, reliability and cost-effectiveness, especially in low-tech integrated buildings where manual data collection is prevalent. This study identifies key criteria for boiler maintenance decision-making to support structured and data-driven maintenance. A comprehensive literature survey was conducted to identify the key boiler maintenance activities which had been studied by different scholars. In addition to that, a qualitative research approach was adopted, including expert interviews and the Delphi technique, to develop the criteria based on practical understanding. Findings highlight critical factors such as equipment-specific parameters, resource allocation, and operational impact, influencing effective maintenance decisions. The proposed criteria provide a structured basis for improving boiler maintenance practices in low-tech environments. This research contributes to developing a systematic software-based decision-making model that enhances maintenance efficiency, minimizes downtime, and optimizes operational performance.

Keywords. Boiler Maintenance, Decision-Making Criteria, Low-Technology Buildings, Manual Data Collection, Preventive Maintenance, Predictive Maintenance, Delphi Technique

1. Introduction

Building service systems deteriorate with time due to operational usage and environmental factors, which produce system failures that affect safety levels, operational quality and system availability (Alaswad & Xiang, 2017). Traditional methods of maintenance include performing maintenance only after failures which complicates maintenance management activities within organizations (Jonge & Scarf, 2020). In contrast, modern maintenance aims to achieve occupant satisfaction alongside safety and regulatory compliance standards through data-driven decision-making (Mydin, 2015).

Maintenance decision-making heavily depends on data collection of building systems and their maintenance activities. Despite the availability of advanced technologies such as IoT, smart sensors, and BIM, most organizations continue to use manual data collection methods. (Mahlamaki & Nieminen, 2020). Higher implementation costs for sensor networks and analytics platforms (Senthilkumar et al., 2023), institutional resistance to digitization in traditionally manual workflows (Pasi & Muller, 2007), and skill gaps in interpreting IoT-generated data among maintenance staff (Agarwal & Suhane, 2017) have hindered the adaptation of digital technologies in building maintenance.

Boilers are one of the critical building systems in buildings where building heating and hot water or steam facilities are available (Patil et al., 2022). In manual operations and maintenance, boilers are considered a critical component, particularly in low-tech integrated buildings which are defined as facilities that rely on manual or semi-automated systems due to budget constraints or lack of technical infrastructure such as old industrial plants in developing economies (Khalil et al., 2021). Rodrigues et al. (2023) demonstrated how maintenance decisions play a vital role in cost-effective operations, as studies reveal that maintenance costs account for between 2-20% of operating costs in various building sectors. Furthermore, in terms of the health and safety of the building occupants, data-driven decision-making in boiler maintenance provides a secured workplace for the occupants, by predicting associated risk based on the prevailing data (Patil et al., 2022). Existing research highlighted the relevance of reactive maintenance strategies in such environments, where manual inspections and logbooks relied. For instance, Yang et al. (2020) demonstrated the potential of IoT to reduce downtime by 30%

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through predictive analytics, but these technologies are rarely applied in resource-constrained settings. Similarly, Triantaphyllou et al. (1997) established frameworks for multi-criteria decision-making but did not address manual data handling limitations. This exacerbates the gap in boilers where maintenance decisions often prioritize short-term cost savings over long-term efficiency. In addition to that, Widyanto (2025) introduced a decision support model for determining fuel in boilers, but a comprehensive study of decision-making in boiler maintenance is still lacking.

Therefore, there is a need to develop a multi-criteria maintenance decision-making model using manually collected data to achieve operational efficiencies. This research aims to identify boiler maintenance decision-making criteria to develop a software-based multi-criteria maintenance decision-making model using manually collected data for low-tech integrated buildings. The objectives include reviewing existing boiler maintenance activities and identifying boiler maintenance criteria. Limiting to oiled fired firetube boilers with capacities ranging from 1000kg/hr. to 1800kg/hr.

2. Literature Review

This review explores existing boiler maintenance activities and identifies the criteria that have been studied by other scholars in the field. Modern industries depend heavily on boilers to generate steam and hot water throughout their operation. Other applications include power production, oil extraction, food processing and heat-based sterilization (Bhatt et al., 2023). Hotels and healthcare facilities depend on boilers because these supply heat and offer both laundry and medical sterilization functions (Favero, 2007). Greenhouse heating and crop processing in agriculture also utilize boilers (Reinoso et al., 2021). Moreover, high-capacity boilers serve district heating systems as well as support domestic water heating and space heating applications according to Bennett et al. (2019).

Boilers are generally classified based on fuel type, design and application. Design types include water tubes, fire tubes, packed, fluidized beds and pulverized fuel boilers (Singh et al., 2018) Boiler maintenance relies on three maintenance approaches including corrective, preventive and predictive methods to extend operational life and improve performance. Preventive maintenance requires regular inspections along with cleaning and stopping system failures (ER-Ratby & Mabrouki, 2018). The combination of analytics in predictive maintenance allows organizations to optimize resource use by monitoring both temperature variations and vibrational signals (Moleda et al., 2020). The procedures of corrective maintenance involve repairing broken device components and fixing leaking areas (Arno et al., 2015).

2.1 KEY MAINTENANCE ACTIVATES IN BOILERS

Maintenance is a set of activities that are organized to keep the operation condition of an asset at its expected level with minimum cost. Those are activities which aim either to prevent failures or rectify existing issues. Therefore maintenance is a combination of financial and engineering activities that are coupled and suitable for the convenience of its users throughout its life cycle by restoring, configuring, commissioning, parameterizing, diagnosing, repairing, managing assets and auditing (Agarwal & Suhane, 2017). Maintenance activities for critical components in boilers are synthesized in Table 1.

Table 1: Key maintenance carried out on boiler key components

Key Component	Key Maintenance Activities	Source
Feed Pump	• Replace worn seals to prevent leaks and maintain operating pressure.	(Leishear et al., 2007)
	• Replace damaged impellers to maintain efficient water flow.	

	• Realign the motor shaft with pump coupling to reduce vibration and wear.	
	• Lubricate and clean bearings to reduce friction and extend life.	
	• Replace worn or damaged couplings to ensure smooth power transmission.	
Economizer	• Remove soot and ash deposits to restore heat transfer efficiency.	(Arifin & Herlina, 2022)
	• Replace corroded or eroded pipes to prevent leaks.	
	• Apply protective coatings to reduce corrosion caused by acidic flue gases.	
	• Replace loose economizer fittings and supports.	
Feed Water Tank	• Remove sediment and sludge from the bottom of the tank to maintain water quality.	(Rahmania et al., 2020) (Johnston, 2020)
	• Replace worn or damaged inlet and outlet valves to ensure proper flow control.	
	• Apply anti-corrosion coatings or paints to prevent internal rust.	
	• Replace damaged or deteriorated insulation to maintain consistent water temperatures.	
	• Clear clogged drainpipes to ensure proper drainage.	
Heat Exchanger	• Use chemical stripping agents to remove mineral buildup.	(Kuchař et al., 2018)
	• Replace cracked heat exchanger tubes.	
	• Reinforce tube sheets to maintain structural integrity.	
	• Clean internal and external surfaces to improve heat transfer.	
Combustion Chamber	• Remove ash and slag deposits to maintain proper combustion airflow.	(Singh et al., 2018)
	• Replace or patch cracked reflector linings to effectively contain heat.	
	• Replace defective igniters.	
	• Resurface-worn chamber interior to maintain thermal efficiency.	
	• Cracks in combustion chamber welds.	
Burner	• Replace worn or clogged nozzles to maintain efficient fuel spray patterns.	(Sarofim, 2001)
	• Clean or replace damaged burner electrodes for proper ignition.	
	• Calibrate air dampers to ensure the correct air-fuel mixture.	
	• Tighten or replace burner flanges to prevent instability during operation.	
Exhaust Stack	• Apply coatings to protect the stock from high temperatures.	(Elkelawy, 2019)
	• Replace or patch corroded parts.	
	• Clean accumulated soot or carbon deposits to ensure unobstructed airflow.	
	• Replace defective draft regulators to ensure proper exhaust.	
Safety Valve	• Replace worn springs to maintain pressure relief function.	
	• Polish valve seats to ensure a tight seal.	
	• Replace corroded or damaged discs for effective pressure regulation.	
	• Replace worn gaskets to prevent leaks.	
Pressure Gauge	• Replace damaged internal mechanisms for accurate pressure readings.	
	• Clean the measurement ports to ensure unobstructed pressure transmission.	

	• Replace or tighten loose fittings to prevent leakage at measurement connections.	

According to Table 1, 9 key components were identified which require thorough attention in maintenance. Several key maintenance activities were identified under each key component. Among them, the feed pump requires replacing worn seals, replacing damaged impellers, realigning the motor shaft with coupling, lubricating and cleaning bearings, and replacing worn or damaged couplings. The key maintenance activities of the economizer are removing soot and ash deposits, replacing corroded or eroded pipes, applying protective coatings, and replacing loose economizer fittings and supports. Furthermore, the feed water tank requires removing sediment and sludge, replacing worn or damaged inlet and outlet valves, applying anti-corrosion coatings or paints to prevent internal rust, replacing damaged or deteriorated insulation, and clearing clogged drainpipes. The key maintenance activities of heat exchangers are removing mineral buildup, replacing cracked heat exchanger tubes, reinforcing tube sheets, and cleaning internal and external surfaces. The combustion chamber requires removing ash and slag deposits, replacing or patching cracked reflector linings, replacing defective igniters, resurfacing worn chamber interiors and fixing cracks in combustion chamber welds.

In addition, replacing worn or clogged nozzles, cleaning or replacing damaged burner electrodes, calibrating air dampers, and tightening or replacing burner flanges are key maintenance activities of the burner. Exhaust stack requires applying coatings, replacing or patching corroded parts, cleaning accumulated soot or carbon deposits, and replacing defective draft regulators. Key maintenance activities of the safety valve are replacing worn springs, polishing valve seats, replacing corroded or damaged discs, and replacing worn gaskets. Pressure gauge requires replacing damaged internal mechanisms, cleaning the measurement ports, and replacing or tightening loose fittings as key maintenance activities.

2.2 REVIEW OF MAINTENANCE DECISION-MAKING CRITERIA

Several scholars have studied the decision-making criteas related to different aspects of boilers. Widyanto (2025) introduced a decision support model for determining fuel in boilers. Patil et al. (2022) developed an optimized maintenance program for boiler systems using a reliability-centered maintenance approach. Demirel et al. (2021), developed a PROMETHEE decision model to prioritize energy efficiency practices for industrial steam boilers. According to Ahmad & Kamaruddin (2012), condition-based maintenance decision-making involves assessing the current condition of the equipment and conducting maintenance activities based on the findings of the assessment to enhance the performance or restore the standard performance levels. Effective boiler maintenance in resource-limited environments requires structured decision-making frameworks to prioritize actions among competing operational demands. Traditional approaches often rely on reactive strategies but recent research suggests that multi-criteria models can balance various factors. (Disegna, 2018). Estimate equipment-specific parameters used, include the reliability, repairability and total lifecycle of machinery (Hassanain et al., 2015). Resource allocation includes trained labour, spare parts, and financial capacity, which affect maintenance feasibility (Poppe et al., 2017). The operational impact is managed by scheduling maintenance during periods of low demand to minimize disruptions (Bangari et al., 2019). Technological advances such as predictive analytics, IoT, and condition monitoring have transformed maintenance into a proactive task, reducing unplanned downtime and improving reliability (Green et al., 2022).

Triantaphyllou et al. (1997) showed that criteria such as "steam pressure deviation" and "flue gas temperature differences" are very important for fire tube boilers, and when integrated into preventive schedules, they reduce downtime by 25%. Similarly, ResQ's guidelines highlighted the role of feedwater flow rates (<4 bar) and sediment levels in determining maintenance urgency. This shows weighted decision models for assessing these criteria, including AHP as well as WSM, and demonstrates their importance for low-tech implementations where IoT/BIM integration is limited.

3. Methodology

This section discusses the research methodology used to identify boiler maintenance decision-making criteria for the Sri Lankan context. The Delphi method was used to identify boiler maintenance criteria, which was carried out by iterative expert consensus, and included three rounds of testing. Semi-structured interviews identified 38 initial criteria across boiler components (Table 3). Experts provided open-ended feedback on operational thresholds. Then, assessed agreements on criteria (Criteria retained only if supported by ≥4 experts' practical logs). Finally, revised criteria which analysed and summarized were redistributed with experts to obtain feedback (35/38 criteria reached 90% agreement: Table 4).

Interviews with five boiler maintenance experts (Table 2) with extensive experience were conducted using a semi-structured format. After conducting the first interview with an expert, a second interview was structured including the main findings of the first interview. This process was repeated throughout all 5 interviews to collect more insightful findings due to the limitation of the literature in this area. This method enabled in-depth investigation into maintenance decision-making criteria while collecting both theoretical understanding and practical knowledge from the experts. Additional data sources maintenance logs, visual inspection reports, and feedback from technicians on the effectiveness of various maintenance tasks were used for the data collection.

Manual qualitative content analysis is used for data analysis. Systematically coded to identify recurring themes, patterns, and criteria relevant to boiler maintenance. The analysis followed a stepwise process: organizing data, coding for key concepts, grouping codes into broader themes, and synthesizing insights for decision-making. Especially, findings obtained from interviews, log analysis, and literature review were cross-validated to ensure the reliability and robustness of the identified criteria.

Table 2: Profiles of Experts

Expert Name	Organization	Experience Level	Role
E1	Steam engineering company	34 years	Regional Site Manager in boiler maintenance
E2	Hotel	35 years	Chief Engineer specializing in steam engineering.
E3	Hotel	32 years	12 years experience as a shift engineer in boilers
E4	Outsourcing	18 years	Site Executive in boiler maintenance.
E5	Hotel	52 years	Experienced boiler operator (50+ years).

4. Findings and Discussion

While the literature emphasizes theoretical best practices, expert insights are based on practical, experiential knowledge. Appropriate criteria were obtained by majority agreement of the experts or by considering the common suggestions provided. The summary of the expert interviews is shown in Table 3.

Table 3: Findings of expert interviews

Key Component	**Key Maintenance Activities**	**Input Data (From Expert Interviews)**	**Experts' Opinion on Maintenance Criteria**					**Suitable Criterion**
			E1	**E2**	**E3**	**E4**	**E5**	
Feed Pump	FPMA 1	Pump Operating Hrs	12,000hrs	10,000hrs	12,000hrs	12,000hrs	-	**12,000hrs**
	FPMA 2	Feed Water Flow Rate	4 -6 bars	Below 4 bars	Below 4 bars	Below 4 bars	Below 4 bars	**Below 4 bars**
	FPMA 3	Operating Temp	85-110°C	90°C	90°C	110°C	90°C	**Above 90°C**
	FPMA 4	Ampere Logs	Increase	Increase	Annually	Increase	Annually	**Increase**
Economizer	EMA 1	Flue Gas Temp	190-220°C	Above 190 °C	190-200°C	Above 190°C	Above 200°C	**Above 190°C**
Feed Water Tank	FWTMA 1	Sediment Levels	Annually	Annually	Annually	Annually	Annually	**Annually**
		Return Hot Water Temp	Below 90°C	Below 85°C	Below 90°C	Below 90°C	Below 90°C	**Below 90°C**
	FWTMA 2	Return Hot Water Temp	Above 90°C	Above 95°C	Above 90°C	Above 90°C	Above 90°C	**Above 90°C**
	FWTMA 3	FW Temp	Below 85-90°C	Below 90°C	Below 90°C	Below 80°C	Below 85°C	**Below 90°C**
	FWTMA 4	FW Flow Rates	Below Operating	Below 4 bars	Below 4 bars	Below Operating	Below Operating	**Below Operating**
	FWTMA 5	Boiler Water Level	Above Baseline	Above Baseline	Above Baseline	Above Baseline	Above Baseline	**Above Baseline**
	FWTMA 6	FWT Water Level	Above Baseline	Above Baseline	Above Baseline	Above Baseline	Above Baseline	**Above Baseline**
Heat Exchanger	HEMA 1	Steam Production Rate	Below Daily Requirement	Below 1800 kg/hr	Below 1200 kg/hr	Below Daily Requirement	Below 1100 kg/hr	**Below daily requirement**
	HEMA 2	Hydro Test	Water leak	-	-	Water leak	Water leak	**Water leak**
	HEMA 3	Flue Gas Temp	190-220°C	Above 190 °C	190-200°C	Above 190°C	Above 200°C	**Above 190°C**
Combustion Chamber	CCMA 1	Steam Pressure	Pressure Drop	Below 9 bars	Below 8 bars	Pressure Drop	Below 9 bars	**Below 9 bars**
	CCMA 2	Physically	Break Down	Break Down	Break Down	Break Down	Break Down	**Break Down**
	CCMA 3	Steam Temp	Above 160-170°C	Above 160°C	Above 170°C	Above 160-180°C	Above 170°C	**Above 170°C**

Burner	BMA 1	Flue Gas Temp	190-220°C	Above 190 °C	190-200°C	Above 190°C	Above 200°C	**Above 190°C**
		Operating Hrs	2000-3000hrs	2000hrs	1500hrs	2000hrs	-	**2000hrs**
	BMA 2	Visual	Poor Spark	Poor Spark	Poor Spark	Poor Spark	Poor Spark	**Poor Spark**
	BMA 3	O_2 Level at Exhaust	Increase	Increase	Increase	Increase	-	**Increase**
	BMA 4	Fuel Readings	Overconsumption	-	Overconsumption.	Overconsumption	-	**Overconsumption**
	BMA 5	Steam Productivity	Below Daily Requirement	Below 1800 kg/hr	Below 1200 kg/hr	Below Daily Requirement	Below 1100 kg/hr	**Below daily requirement**
		Steam Temp	Below 160-170°C	Below 160°C	Below 170°C	Below 160-180°C	Below 170°C	**Below 170°C**
	BMA 6	Fuel Readings	Overconsumption	Overconsumption	Overconsumption	Overconsumption	Overconsumption	**Overconsumption**
	BMA 7	Visual	Poor Spark	Poor Spark	No Spark	Poor Spark	No Spark	**Poor Spark**
Exhaust Stack	ESMA 1	Flue Gas Temp	Below 190°C	Below 190°C	Below 190°C	Below 190°C	Below 200°C	**Below 190°C**
	ESMA 2	CO Readings	100 – 200 ppm	200 ppm	300 ppm	100 – 200 ppm	-	**Above 200 ppm**
Safety Valve	SVMA 1	Valve Popping Pressure	8-10 bars	9 bars	8 bars	8-10 bars	9 bars	**Deviation**
	SVMA 2	Steam Pressure	Pressure Drop	Below 9 bars	Below 8 bars	Pressure Drop	Below 9 bars	**Below 9 bars**
	SVMA 3	Steam Leak	Break Down	Break Down	Break Down	Break Down	Break Down	**Break Down**
	SVMA 4	Steam Leak	Break Down	Break Down	Break Down	Break Down	Break Down	**Break Down**
Pressure Gauge	PGMA 1	Steam Pressure Readings	Break Down	Break Down	Break Down	Break Down	Break Down	**Break Down**
	PGMA 2	Steam Pressure Readings	Break Down	Break Down	Break Down	Break Down	Break Down	**Break Down**
	PGMA 3	Steam Pressure Readings	Break Down	Break Down	Break Down	Break Down	Break Down	**Break Down**
Boiler Shell	BSMA 1	Blowdown	Break Down	Break Down	Break Down	Break Down	Break Down	**Break Down**

	BSMA 2	Steam Pressure	Above 9 bars	Above 9 bars	Above 8 bars	Above 9 bars	Above 9 bars	**Above 9 bars**

Combining all the findings of the literature review and expert interviews, a decision-making criterion for boiler maintenance was developed. The developed boiler maintenance decision-making criteria are shown I Table 4.

Table 4: Decision-making criteria for boiler maintenance

Key Component	**Key Maintenance Activities**	**Input Data**	**Criteria**
Feed Pump	• Replace worn seals	• Pump Operating Hrs	12,000hrs
	• Replace damaged impellers	• Feed Water Flow Rate	Below 4 bars
	• Lubricate and clean bearings	• Operating Temp	Above 90°C
	• Motor Megger testing	• Ampere Logs	Increase
Economizer	• Remove soot and ash deposits	• Flue Gas Temp	Above 190°C
Feed Water Tank	• Remove sediment and sludge from the bottom	• Return Hot Water Temp	Below 90°C
	• Whole Trap System Clean	• Return Hot Water Temp	Above 90°C
	• Replace damaged or deteriorated insulation	• Feed Water Temp	Below 90°C
	• Clear clogged drainpipes	• Feed Water Flow Rates	Below Operating
	• Water Level Cutoff valve replacement/repair	• Boiler Water Level	Above Baseline
	• Non-return valve replacement/repair	• Feed Water Tank Water Level	Above Baseline
Heat Exchanger	• De-Scaling / remove COCO3.	• Steam Production Rate	Below daily requirement
	• Replace cracked heat exchanger tubes.	• Hydro Test	Water leak
	• Clean internal and external surfaces	• Flue Gas Temp	Above 190°C
Combustion Chamber	• Remove ash and slag deposits	• Steam Pressure	Below 9 bars
	• Rebe tray Repair	• Physically	Break Down
	• Resurface worn chamber interior	• Steam Temp	Above 170°C
Burner	• Replace worn or clogged nozzles	• Flue Gas Temp	Above 190°C
	• Replace defective igniters.	• Visual	Poor Spark
	• Calibrate air dampers	• O_2 Level at Exhaust	Increase
	• Photocell cleaning	• Fuel Readings	Overconsumption
	• Fuel Pressure Pump filter cleaning	• Steam Productivity	Below daily requirement
	• Solenoid Valve Replace	• Fuel Readings	Overconsumption
	• Atomizer Replace	• Visual	Poor Spark

Exhaust Stack	• Clean accumulated soot or carbon deposits	• Flue Gas Temp	Below 190°C
	• Replace defective draft regulators	• CO Readings	Above 200 ppm
Safety Valve	• Replace worn springs	• Valve Popping Pressure	Deviation
	• Polish valve seats	• Steam Pressure	Below 9 bars
	• Replace corroded or damaged discs	• Steam Leak	Break Down
	• Replace worn gaskets	• Steam Leak	Break Down
Pressure Gauge	• Replace damaged internal mechanisms	• Steam Pressure Readings	Break Down
	• Clean the measurement ports	• Steam Pressure Readings	Break Down
	• Replace or tighten loose fittings	• Steam Pressure Readings	Break Down
Boiler Shell	• Blowdown Valve repair	• Blowdown	Break Down
	• Pressure switches replace	• Steam Pressure	Above 9 bars

These criteria provide guidelines to support preventive and predictive maintenance approaches in resource-constrained settings, reducing downtime and optimizing maintenance plans. This research bridges the gap between theoretical best practices and real-world constraints by providing practical insights from industry experts. However, the study is limited to oil-fired fire tube boilers within a specific capacity range. Future research could explore the integration of emerging technologies such as IoT and AI to overcome the issues in manual data collection. Implementing the proposed criteria in real-world settings will further validate the effectiveness of optimizing maintenance decision-making for low-tech buildings.

5. Conclusion

This research identifies key decision-making criteria for boiler maintenance in low-tech integrated buildings, where manual data collection remains the standard. Effective maintenance decision-making is critical to ensuring operational efficiency, reducing downtime, and optimizing resource allocation. By analysing equipment-specific parameters, resource constraints, and operational impact, this research provides a structured framework to support maintenance planning. Unlike traditional reactive approaches, the proposed criteria emphasize preventive and predictive strategies, enabling maintenance teams to make informed decisions despite technical limitations. The findings highlight the importance of aligning maintenance actions with practical constraints, ensuring that even buildings without advanced monitoring tools can adopt systematic maintenance practices. Ultimately, this research will be used to develop a software-based maintenance decision-making model for low-tech integrated buildings, which will improve maintenance practices.

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