

Analysis of boiler efficiency using the direct method and an integrated FMEA–fishbone approach: A case study at an automotive manufacturing plant

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ABSTRACT

Frequent boiler failures interrupt the steam supply to the paint-shop pretreatment line of an automotive plant and degrade its energy performance. This study evaluated the efficiency of the most critical boiler at an automotive manufacturing plant and identified the failure modes and root causes behind its decline. A descriptive quantitative case study was carried out on five water-tube boilers from July to August 2024. Boiler No. 1, which accounted for 43.5% of the total downtime (990 min), was selected as the critical unit. Its daily efficiency over 28 operating days was calculated with the direct (input–output) method from log sheet data, steam-table enthalpies, and a natural-gas heating value of 39,120.46 kJ/m³. Failure risks were prioritized with Failure Mode and Effect Analysis (FMEA) using ratings from eight boiler personnel, and the dominant failure was traced with a fishbone diagram. Daily efficiency ranged from 63.3% to 98.4% (mean 87.6%); six days fell below 75%, four of which coincided with misfire interventions. Misfire had the highest risk priority number (RPN = 245), followed by boiler tube leakage and brittle strainer filters (RPN = 96 each). Its causes were distributed across man, method, machine, environment, and system factors. An integrated preventive, corrective, and predictive maintenance strategy is proposed, focusing on gas flushing, air–fuel ratio control, sensor calibration, combustion monitoring, and condition-based maintenance.

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1. Introduction

Steam remains one of the most widely used energy carriers in manufacturing. Products such as textiles, food, pharmaceuticals, electricity, and vehicles all rely on process steam at some stage of production, and this steam is generated in boilers, closed pressure vessels in which the chemical energy of a fuel is released by combustion and transferred to water until it evaporates [1], [2]. Because boilers are among the largest single energy consumers in a plant, even a small loss of efficiency translates into substantial fuel cost and emissions, and industrial energy audits consistently identify boilers as a priority area for energy saving [3]. As operating hours accumulate, wear, scale formation on tube surfaces, combustion instability, and pressure fluctuations gradually reduce boiler performance, lower plant productivity, and threaten operational continuity. A comprehensive review of industrial boilers likewise identifies combustion control, heat recovery, and improved operating practice as major routes to lower fuel use and emissions [4].

An automotive manufacturing plant manufactures commercial vehicles. Its boilers supply steam that heats the hot-water tanks of the paint-shop pretreatment line, particularly the phosphating stage, where car bodies are immersed in a phosphate solution to improve paint adhesion and corrosion resistance.



Phosphating requires a stable bath temperature and therefore a continuous steam supply. However, maintenance records for July–August 2024 show that the boilers repeatedly suffered technical disturbances, most notably combustion misfires, a leaking boiler tube, and a brittle strainer filter. These events interrupted steam production and indicated that the current maintenance system has not yet delivered optimal results.

Measuring boiler efficiency periodically is the first step towards addressing such problems, because it shows whether a unit is still operating within an acceptable range [5]. The direct, or input–output, method determines efficiency by comparing the useful energy carried by the steam with the energy supplied by the fuel. Djafar [6] showed that thermal efficiency can be evaluated realistically from routine daily operating data—temperature, pressure, steam flow, and fuel consumption—without laboratory flue-gas analysis and reported an efficiency of 80.3% for a power-plant boiler, about 5% below its design value. Aprilia [7] applied the same method in a sugar factory and highlighted the importance of reliable steam-flow instrumentation. The method follows the input–output approach of ASME PTC 4 [8]. Mathematical modelling of a steam-boiler room further demonstrates that operating measurements can be used to evaluate thermal performance and energy-saving opportunities at system level [9].

Efficiency figures alone, however, do not explain why performance deteriorates. Failure Mode and Effect Analysis (FMEA) is a structured technique that identifies potential failure modes, rates their severity (S), occurrence (O), and detection (D), and ranks them by the risk priority number $RPN = S \times O \times D$ so that corrective resources can be focused where the risk is highest [10]. Although the RPN has known limitations, such as equal weighting of the three factors and non-unique products [11], it remains the most widely used prioritization tool in maintenance practice. The fishbone (Ishikawa) diagram complements FMEA by organizing the possible causes of a selected problem into categories such as man, machine, method, material, and environment, which makes root-cause discussion systematic [12]. Juanda et al. [13] combined FMEA and the fishbone diagram to analyze boiler damage and found that tube leakage and the associated downtime were driven mainly by human and maintenance factors, while Narto et al. [14] traced combustion failure in a ship boiler to contaminated burner components, irregular planned maintenance, and poor fuel quality. A broader review of FMEA/FMECA research confirms both the method's wide industrial use and the continuing development of alternatives intended to overcome conventional RPN weaknesses [15].

Previous studies have typically applied either efficiency evaluation or risk analysis in isolation. Few have linked the measured day-to-day efficiency of an industrial boiler directly with its failure history and then used that link to prioritize maintenance actions. This study addresses that gap for a gas-fired water-tube boiler in an automotive plant. Its objectives are to determine the efficiency of the critical boiler using the direct method, identify and prioritize the failure modes that contribute to efficiency decline using FMEA, and formulate improvement and maintenance strategies based on a fishbone analysis of the highest-priority failure mode.

2. Method

2.1 Research Design and Object

This descriptive quantitative case study was conducted at an automotive manufacturing plant which is in Karawang, West Java, Indonesia, between July and September 2024. Data covered the period 1 July–31 August 2024. The plant operates five boiler units, of which one critical unit was selected for detailed analysis. The boilers are Miura E1-2000GU gas-fired water-tube boilers made in Japan, with a rated steam capacity of 2,000 kg/h and a design pressure of 0.98 MPa, fueled by natural gas. The analysis

proceeded in four stages: selection of the critical boiler, calculation of its efficiency by the direct method, FMEA of its recorded failure modes, and a fishbone analysis of the highest-priority failure mode, followed by the formulation of a maintenance strategy.

2.2 Data Collection

Both primary and secondary data were used. Secondary data comprised the daily boiler log sheets (steam pressure, steam temperature, steam flow, feedwater temperature, and fuel-gas consumption), maintenance history records, and boiler specifications. Steam temperature, pressure, and flow were read directly from the flowmeter installed on the steam line. Primary data were collected in two ways. First, an FMEA questionnaire distributed via Google Forms asked eight boiler-station personnel (six operators, one utility-maintenance operator, and one utility-maintenance team leader) to describe the effects, causes, and controls of each failure mode and to rate its S, O, and D on a 1–10 scale. Second, semi-structured interviews with maintenance technicians explored the human, method, machine, system, and environmental factors behind the dominant failure and supplied the input for the fishbone diagram.

2.3 Critical Boiler Selection

The critical boiler was defined as the unit whose failures had the greatest effect on operation, measured by its share of the total downtime of all units:

$$\%DT_i = \frac{DT_i}{\Sigma DT} \times 100\% \quad (1)$$

where DT_i is the total downtime of boiler i (min) and ΣDT is the total downtime of all boilers over the observation period (min). Downtime per event was taken as the difference between the start and end times recorded in the maintenance log.

2.4 Direct-Method Efficiency

The daily efficiency of the critical boiler was calculated as the ratio of the heat absorbed by the steam to the heat supplied by the fuel [6]:

$$\eta = \frac{\dot{m}_s (h_s - h_{fw})}{V_f \times \text{LHV}} \times 100\% \quad (2)$$

where $\dot{m}_s$ is the daily steam production (kg/day), h_s is the specific enthalpy of the steam leaving the boiler (kJ/kg), h_{fw} is the specific enthalpy of the feedwater (kJ/kg), V_f is the daily fuel-gas consumption (m³/day), and LHV is the heating value of the fuel (kJ/m³). Enthalpies were obtained from the SteamTab Companion software (ChemicalLogic) using the measured steam pressure and temperature and the feedwater temperature. The heating value of the natural gas, 1,038.27 Btu/scf according to the gas composition used by the plant, was converted to 39,120.46 kJ/m³. Daily results were compared across the 28 operating days to identify periods of abnormal performance.

2.5 Failure Mode and Effect Analysis

The failure modes recorded in the maintenance history of the critical boiler were analyzed with FMEA [10]. Severity was rated from 1 (no effect) to 10 (hazardous failure without warning), occurrence from 1 (almost never) to 10 (very frequent), and detection from 1 (almost certain to be detected) to 10 (practically undetectable). For each failure mode, the ratings of the eight respondents were averaged and rounded to the nearest integer, and the risk priority number was calculated as:

$$\text{RPN} = S \times O \times D \quad (3)$$

The failure mode with the highest RPN was taken as the first priority for root-cause analysis and corrective action.

2.6 Fishbone Diagram and Strategy Formulation

A fishbone diagram was constructed for the highest-priority failure mode. The problem was placed at the head of the diagram, and the causes obtained from the FMEA questionnaire, the interviews, and the literature were grouped under five categories: man, method, machine, environment, and system [12]. Improvement actions addressing these causes were then organized into preventive, corrective, and predictive maintenance categories.

3. Results and Discussion

3.1 Selection of the Critical Boiler

Table 1 summarizes the operating time and downtime of the five boilers during July–August 2024. Boiler No. 1 was the most heavily used unit, with 148 operating hours over 28 operating days, and also recorded the largest downtime, 990 min or 43.5% of the total. Its downtime was dominated by a single long event on 3 July 2024 (720 min), when a leaking water tube had to be replaced. Boiler No. 5 ranked second (630 min, 27.7%) because of relatively frequent failures, whereas Boilers No. 3 and No. 4 showed short, sporadic interruptions (13.8% and 14.9%). Boiler No. 2 was not operated during the period and could not be evaluated. Boiler No. 1 was therefore selected as the critical unit.

Table 1. Operating time and downtime of the five boilers, July–August 2024

Boiler	Operating days	Operating time (h)	Downtime (min)	Share of downtime (%)
No. 1	28	148	990	43.5
No. 2	0	0	0	0.0 (standby)
No. 3	23	72	315	13.8
No. 4	30	103	340	14.9
No. 5	19	78	630	27.7
Total			2,275	100.0

The failure history of Boiler No. 1 (Table 2) contains three failure modes. Misfire occurred most often (six events), each corrected by readjusting the fuel–air mixture ratio within about 15 min. Boiler tube leakage and a brittle strainer filter occurred once each but caused much longer stoppages. High-frequency, short-duration combustion faults and low-frequency, long-duration mechanical failures thus coexist in the same unit, which matters for how maintenance resources should be allocated.

Table 2. Failure history of Boiler No. 1, July–August 2024

Failure mode	Events	Dates	Downtime (min)	Corrective action
Misfire	6	8, 17, 22 Jul; 7, 12, 24 Aug	90 (6 × 15)	Adjust fuel–air mixture ratio
Boiler tube leakage	1	3 Jul	720	Replace leaking water tube
Brittle strainer filter	1	19 Jul	180	Replace filter strainer
Total	8		990	

3.2 Performance Efficiency of Boiler No. 1

Table 3 lists the log sheet data, the corresponding enthalpies, and the calculated efficiency for each of the 28 operating days. For day 1, for example, Eq. (2) gives $\eta = [12,897 \times (2,754 - 440)] / (786.2 \times 39,120.46) \times 100\% = 97.0\%$. The steam pressure ranged from 4.66 to 6.25 bar and the steam temperature from 148.6 to 160.9 °C, close to saturation, so the steam enthalpy varied only between 2,744 and 2,757 kJ/kg. Day-to-day variation in efficiency was therefore driven mainly by the ratio of steam produced to fuel consumed rather than by the steam condition.

Table 3. Daily operating data, enthalpies, and direct-method efficiency of Boiler No. 1

Day	Date	<i>P</i> (bar)	<i>T_s</i> (°C)	<i>m_s</i> (kg/day)	<i>T_{fw}</i> (°C)	<i>V_f</i> (m ³ /day)	<i>h_s</i> (kJ/kg)	<i>h_{fw}</i> (kJ/kg)	η (%)
1	01 Jul	5.73	156.6	12,897	105	786.2	2,754	440	97.0
2	03 Jul	4.92	151.1	3,564	101	221.4	2,747	423	95.6
3	05 Jul	5.12	153.3	10,889	102	752.0	2,749	427	85.9
4	08 Jul ^a	5.22	154.7	2,835	104	170.4	2,750	436	98.4
5	10 Jul	5.39	155.2	4,886	101	324.8	2,751	423	89.5
6	12 Jul	6.25	156.2	7,432	102	458.9	2,757	427	96.5
7	15 Jul	5.88	157.8	6,640	105	620.5	2,755	440	63.3
8	17 Jul ^a	5.98	155.1	3,280	103	285.8	2,756	432	68.2
9	19 Jul	6.09	158.7	8,768	105	607.2	2,756	440	85.5
10	22 Jul ^a	5.93	158.0	7,220	100	590.2	2,755	419	73.0
11	24 Jul	4.66	148.6	8,221	104	512.8	2,744	436	94.6
12	26 Jul	5.14	151.7	7,387	103	455.4	2,749	432	96.1
13	29 Jul	5.27	153.7	12,346	101	819.6	2,750	423	89.6
14	31 Jul	5.11	152.7	4,405	100	266.9	2,749	419	98.3
15	02 Aug	4.99	151.2	8,273	103	557.6	2,748	432	87.8
16	05 Aug	5.91	160.9	8,289	105	528.7	2,755	440	92.8
17	07 Aug ^a	5.06	153.7	4,506	103	360.7	2,748	432	74.0
18	09 Aug	5.89	157.4	7,430	100	497.5	2,755	419	89.2
19	12 Aug ^a	6.01	158.7	5,758	100	512.4	2,756	419	67.1
20	14 Aug	5.58	158.3	3,942	102	283.7	2,752	427	82.6
21	16 Aug	5.92	157.8	8,986	105	583.4	2,755	440	91.1
22	19 Aug	5.73	156.3	8,045	102	547.5	2,754	427	87.4
23	21 Aug	5.65	156.7	10,980	105	664.9	2,753	440	97.6
24	23 Aug	5.92	155.6	10,224	100	622.7	2,755	419	98.0
25	25 Aug	5.12	152.3	3,720	104	310.1	2,749	436	70.9
26	26 Aug	5.97	157.7	8,946	103	542.5	2,755	432	97.9
27	28 Aug	5.88	157.4	5,430	101	337.9	2,755	423	95.8
28	30 Aug	5.46	155.4	13,191	100	889.2	2,752	419	88.5
Mean									87.6

^a Date with a recorded misfire intervention. Values in bold are below 75%. LHV = 39,120.46 kJ/m³.

Fig. 1 shows the daily efficiency profile. Efficiency ranged from 63.3% (day 7) to 98.4% (day 4), with a mean of 87.6% and a standard deviation of 10.7 percentage points. On 13 of the 28 days, efficiency exceeded 90%, but on six days it fell below 75%: days 7 (63.3%), 8 (68.2%), 10 (73.0%), 17 (74.0%), 19 (67.1%), and 25 (70.9%). The period-aggregated efficiency, obtained by dividing the total useful heat by the total fuel energy over the 28 days, was 87.7%, which is close to the arithmetic mean.

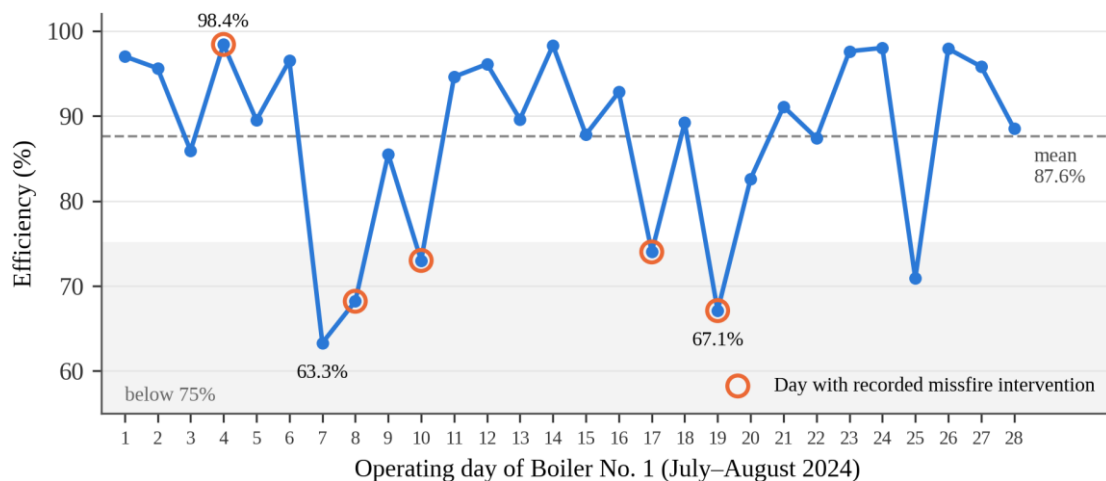


Fig. 1. Daily performance efficiency of Boiler No. 1, July–August 2024

Matching the log sheet days to the calendar dates of the maintenance records (Table 3) shows that four of the six low-efficiency days—17 July, 22 July, 7 August, and 12 August—coincided with recorded misfire interventions. The mean efficiency on days with a misfire intervention was 76.2%, compared with 90.1% on the remaining days. This agrees with the mechanism of misfire: when ignition is unstable, or the flame is lost, unburned gas passes through or accumulates in the furnace, the burner cycles through purge and re-ignition, and the fuel consumed is not fully converted into useful heat [14], [16]. The two other low days (15 July and 25 August) did not coincide with a logged intervention, which suggests either unrecorded combustion disturbances or operation at low, intermittent load. Conversely, day 4 (8 July) reached 98.4% despite a misfire record, presumably because the fault was corrected early in the shift. The recurrence of low-efficiency days throughout the period indicates a systemic rather than a one-off problem.

Two limitations should be noted. First, several daily values approach 98%, which is near the upper limit for a non-condensing gas-fired boiler. Single-day results are sensitive to the resolution of the steam-flow and gas meters and to the heating-value basis, so the period-aggregated efficiency is the more robust indicator of overall performance, and the daily series is best interpreted in relative terms. Second, the direct method does not separate individual losses. An indirect (heat-loss) analysis with flue-gas measurement would be needed to quantify stack, radiation, and blowdown losses [3], [8].

3.3 Failure Mode and Effect Analysis

Fig. 2 compares the averaged S, O, and D ratings of the three failure modes. Boiler tube leakage received the highest severity ($S = 8$) because a ruptured tube interrupts steam and water supply and forces a long shutdown. Misfire had the highest occurrence ($O = 7$), consistent with its six recorded events, and the highest detection rating ($D = 5$), which reflects the respondents' view that incipient combustion faults are difficult to recognize before the burner trips. The brittle filter received moderate ratings on all three criteria.

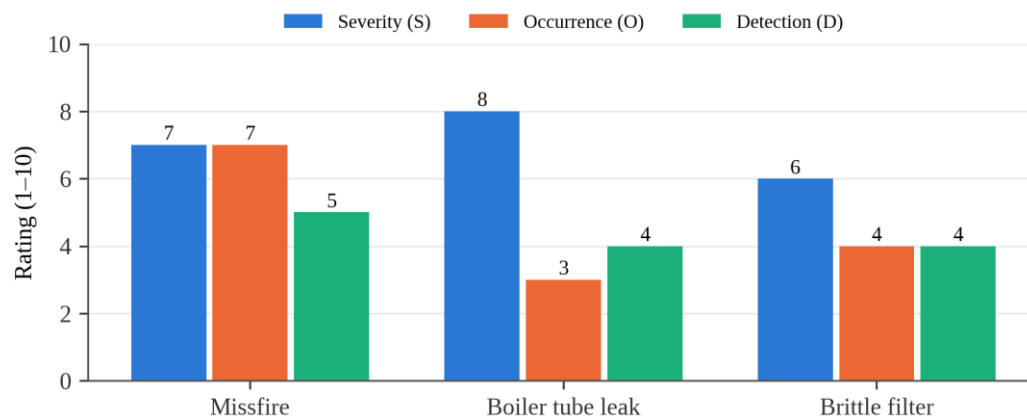


Fig. 2. Average severity, occurrence, and detection ratings of the failure modes of Boiler No. 1 (n = 8 respondents)

The resulting FMEA worksheet is shown in Table 4. Misfire had by far the highest risk (RPN = 245), about 2.5 times that of boiler tube leakage and the brittle filter (RPN = 96 each). Besides reducing efficiency, misfire is a safety hazard: if unburned gas accumulates in the combustion chamber and meets an ignition source, a furnace explosion can occur. The respondents attributed misfire to an unbalanced air–fuel ratio and to gas that had not been properly flushed before entering the burner, so that contaminated gas reached the combustion chamber. Tube leakage and filter brittleness were both linked to poor feedwater quality, which promotes scale and corrosion on the tube walls and in the drum, and, for the filter, to the use of filter elements of inadequate quality. To test the sensitivity of the ranking to rounding, the RPNs were recalculated from the unrounded mean ratings, giving 222.0 for misfire, 89.3 for the brittle filter, and 87.7 for tube leakage. Misfire remains the clear first priority, whereas the two lower-ranked modes are practically tied, which is consistent with the known sensitivity of the RPN to small rating differences [11]. The tube-leakage finding is also consistent with international failure studies showing that overheating, oxidation, flow-accelerated corrosion, scale deposition, and locally high heat flux can progressively thin or rupture boiler tubes [17]–[20].

Table 4. FMEA worksheet for Boiler No. 1

Failure mode	Effect	Cause	Current control	S	O	D	RPN
Misfire	Unburned gas accumulates in the furnace; explosion risk if an ignition source is present; lost heat output	Unbalanced air–fuel ratio; gas not flushed, so contaminated gas enters the combustion chamber	Gas flushing on the supply valve; monitoring of sensors and control system	7	7	5	245
Boiler tube leakage	Disturbed steam/water supply; reduced efficiency; long shutdown	Poor feedwater quality causing corrosion and erosion	Periodic inspection and cleaning of boiler tubes	8	3	4	96
Brittle strainer filter	Higher risk of scale and corrosion in tubes and drum	Poorly maintained feedwater quality; filter of inadequate quality	Routine maintenance and scheduled filter replacement	6	4	4	96

3.4 Root Causes of Misfire

Because misfire had the highest RPN, the fishbone analysis focused on this failure mode (Fig. 3). The causes identified from the questionnaire and interviews were grouped into five categories.

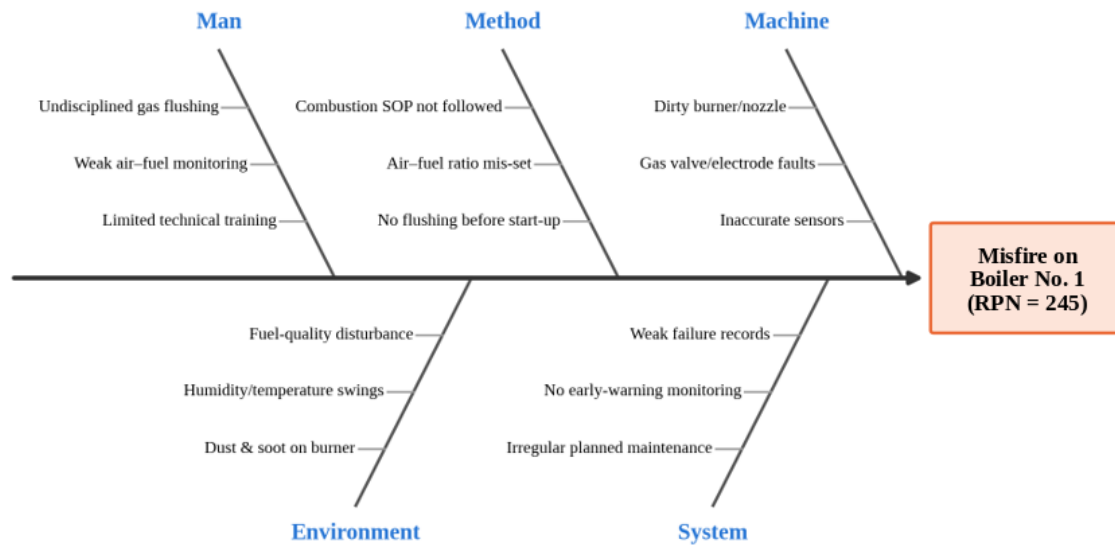


Fig. 3. Fishbone diagram of the causes of misfire in Boiler No. 1

Man. Human factors were the main contributors. Operators did not consistently flush the gas line before start-up or monitor the air-fuel ratio closely, and technical training on the combustion system was limited. Narto et al. [14] similarly found that poor maintenance practice and contaminated burner components were direct causes of combustion failure in a ship boiler, and Nugraha et al. [16] reported that uncontrolled air-fuel ratios and dirty or incorrectly set nozzles led to burner failure.

Method. Combustion procedures were not always performed according to the standard operating procedure (SOP). An improperly set air-fuel ratio and skipped or incomplete gas flushing produce an unbalanced mixture at ignition, making the flame unstable and increasing the likelihood of misfire.

Machine. Misfire depends strongly on the condition of the gas valve, ignition electrode, flame sensor, automatic control system, and burner nozzle. Contamination of the burner, electrode, or solenoid valve disturbs the fuel supply [14], and an inaccurate sensor prevents the controller from correcting the air-fuel ratio.

Environment. Dust, soot deposits, humidity, and temperature fluctuations in the boiler room contaminate combustion components and impair ignition, especially when cleaning is infrequent. Disturbances in fuel quality further destabilize combustion.

System. At the organizational level, planned maintenance was implemented irregularly, early-warning monitoring was lacking, and failure events were poorly documented, so recurring misfires were not analyzed or prevented in time. Integrating early detection with systematic failure records is therefore essential [21], [22]. Condition-based maintenance literature emphasizes that reliable diagnostics, health indicators, and remaining-useful-life estimation are central to converting monitoring data into timely maintenance decisions [23], [24].

3.5 Proposed Maintenance Strategy

The consequences of misfires extend beyond lower efficiency. They include interrupted production, fewer effective operating hours, higher operating costs due to unplanned downtime, and an elevated risk of workplace accidents. On the basis of the FMEA and fishbone results, a combined preventive, corrective, and predictive maintenance strategy was formulated (Table 5).

Table 5. Proposed maintenance strategy for preventing misfire

Maintenance category	Proposed actions
Preventive	Flush the gas line before boiler start-up; set the air–fuel ratio according to the SOP; clean the burner routinely; check the gas valve and ignition system; calibrate gas-pressure and gas-flow sensors; perform daily visual inspection of the combustion system; keep a daily combustion log sheet; train operators on the combustion system
Corrective	Stop operation when a misfire occurs; purge residual fuel from the combustion chamber; repair or replace a damaged burner; replace a faulty gas valve or igniter; retune the combustion system; carry out a minor overhaul, or a major overhaul if misfire recurs; test function after repair
Predictive	Monitor the air–fuel ratio, gas pressure, and gas flow; monitor vibration of combustion components; apply acoustic-emission monitoring for gas leaks; analyze trends in combustion and daily efficiency data; evaluate combustion-sensor performance; schedule condition-based component replacement

Preventive maintenance forms the core of the strategy because it acts directly on the two causes named in the FMEA. Routine gas flushing on the supply valve before start-up removes contaminants, moisture, and stale gas from the line, and setting the air–fuel ratio according to the SOP stabilizes ignition. Periodic calibration of the gas-pressure, gas-flow, and flame sensors prevents the control system from treating a deviating supply as normal, since inaccurate operating data are a major reason for late fault detection in boilers [22]. Structured daily, weekly, monthly, and annual maintenance schedules supported by systematic failure records also improve maintenance decision-making and reliability [25]. This combination of scheduled tasks and condition evidence is consistent with the complementary roles of time-based and condition-based maintenance in industrial systems [26].

Corrective maintenance defines the response once a misfire has occurred: shutting down safely, purging residual fuel from the furnace, repairing or replacing the faulty burner, gas valve, or igniter, retuning the combustion system, and testing its function before restart. Minor and major overhauls of the combustion system should be scheduled when misfires recur, because combustion failures often result from accumulated component degradation [27].

Predictive maintenance is proposed as the long-term measure. Continuous monitoring of the air–fuel ratio, gas pressure, and gas flow, together with vibration monitoring of the combustion blower and acoustic-emission monitoring for gas leaks, allows abnormalities to be detected before they cause a trip. Trend analysis of combustion data can also support condition-based replacement of components. Predictive, data-driven approaches have been shown to increase boiler availability, reduce unexpected shutdowns, and avoid excessive spare-part inventories [21], [22]. The daily efficiency calculated in this study can itself serve as a simple, low-cost condition indicator. Since low-efficiency days tended to coincide with misfires, a sudden drop in the daily steam-to-fuel ratio can alert operators to inspect the combustion system. Recent systematic reviews show that machine-learning-based predictive maintenance can support fault diagnosis and maintenance planning when adequate historical and sensor data are available [28], [29].

4. Conclusion

Boiler No. 1 was the critical unit among the five boilers at the automotive manufacturing plant being studied, contributing 43.5% (990 min) of the total downtime in July–August 2024. Its daily efficiency by the direct method ranged from 63.3% to 98.4%, with a mean of 87.6% over 28 operating days. Six days fell below 75%, four of which coincided with misfire interventions. FMEA identified misfire as the highest-priority failure mode (RPN = 245), followed by boiler tube leakage and brittle strainer filters (RPN = 96 each), and the fishbone analysis showed that misfire results from combined man, method,

machine, environment, and system factors, particularly inconsistent gas flushing, improper air–fuel ratio setting, and weak monitoring.

An integrated preventive, corrective, and predictive maintenance strategy focused on gas flushing, air–fuel ratio control, sensor calibration, combustion monitoring, and data-based condition maintenance is recommended to improve both the efficiency and the reliability of the boiler. Future work should add indirect-method heat-loss analysis and continuous metering to strengthen the efficiency assessment, evaluate early-warning combustion sensors, and use Overall Equipment Effectiveness (OEE) to quantify the effect of the proposed strategy.

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