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Root Cause Analysis of Performance Degradation for an XYZ Thermal Power Plant in Tanzania

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ABSTRACT

Thermal power plants in Tanzania have been experiencing performance degradation, typically arising from component and subsystem failures, which contribute to power system instability and unreliability. This paper presents a case study of the root causes of performance degradation of an XYZ thermal power plant. The study was conducted by reviewing plant documentations, including maintenance and operational data logbooks, and by standardising the approach through the adoption of ISO 14224:2016 for maintenance and reliability data exchange. Data evaluation was carried out using principal component analysis and scree plot analytical techniques to enhance the depth and accuracy of root cause identification. Additionally, Pareto analysis was employed to determine the extent of the degradation. The findings revealed that plant performance degradation was primarily caused by local environmental factors (i.e. dust and air salinity) and operational practices at the plant level, including skills gap and non-adherence to recommended maintenance schedules. With regard to component and subsystem failure incidents, the majority were valve and ignition system failures, accounting for 11.5% and 10.9%, respectively. The main failure modes were external utility fluid leakage (ELU) and overheating (OHE), which accounted for 23.32% and 18.78%, respectively. Moreover, instead of the 34,848 hours planned for proactive maintenance activities based on Original Equipment Manufacturer (OEM) recommendations, the plant consumed 127,392 hours, with over 80% dedicated to reactive maintenance. In conclusion, timely and proactive maintenance, supported by knowledgeable and skilled personnel, is crucial in ensuring stability, reliability, and longevity of the XYZ thermal power plant.

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INTRODUCTION

Power generation system comprises of complex interlink of components, subsystems and systems that have to meet certain level of robustness to demonstrate effective performance. Eti *et al.*, (2005), assert that availability of any power generation facility is influenced by established proper maintenance scheme as well as adherence to Original Equipment Manufacturer (OEM) recommended operations. Deterioration of one component within a system, might propagate and manifest into the degradation of the entire system (Fu *et al*., 2016). According to the Tanzania's National Power System Master Plan 2020, the average peak demand is projected to reach 17,611 MW by 2044 from 1,120 MW of 2019. In 2025 and 2030, the peak demand is anticipated to reach 2,677 MW and 4,878 MW, respectively, reflecting an average annual growth rate of 11.7 percent (Kihwele *et al.*, 2012). Currently, Tanzania has a total installed capacity of 2,308 MW which encompasses both grids connected and off-grid systems. To ensure that the nation's energy security aligns with society's evolving needs and effectively supports sustained economic growth, it is essential to optimize the availability and reliability of power infrastructure (Ibekwe *et al.*, 2024; Nyanda *et al*., 2022). In this context, a Root Cause Analysis (RCA) was conducted to investigate performance degradations of thermal power plants in Tanzania focusing on an XYZ plant as a case study. The study aimed to identify the causes of the performance degradation and quantify the extent of the degradation in the representative thermal power plant.

METHODOLOGY

This case study aims to identify the underlying issues causing performance degradation in the XYZ thermal plant. Ethical considerations have necessitated referring the case study as the XYZ thermal power plant. Data collection process involved both quantitative and qualitative methods. Procedures included brainstorming, interviews, and a review of plant maintenance and operational data. Data from maintenance and operations logbooks were in free-text form, thus requiring data cleaning before processing. This entailed adoption of ISO 14224:2016 vocabulary to enhance data coherence. Therefore, ELU is external utility fluid, OHE is overheating, PDE is parameter deviation, LOO is low output, ELF is external fuel leakage, INL is internal leakage. BRD is unexpected breakdown, VIB is abnormal vibration and ERO is erratic output. The analysis focused on ranking the frequency of component's and subsystem's failures causing engine breakdowns. Criticality ranking and prioritisation for enabling root cause analysis were adopted, as advocated by Reid and Smyth (2012) and Guerin (2015). The ranking was followed by the causal mapping process. This process interpreted recorded failure events from an operational viewpoint and sought to link failure associations, using them as inputs for the causal mapping initiatives (Chemweno *et al.*, 2016). Through this process, initial rational cause-and-effect associations were drawn. Furthermore, root cause analysis was conducted by incorporating traditional methods (i.e. the 5-Why technique) and advanced analytical techniques (i.e. principal component analysis and scree plot) to enhance the depth and accuracy of root cause identification. Finally, the Pareto analysis tool was employed to gain insight into the production loss incurred due to the time spent on maintenance activities aimed at rectifying or restoring the operation of the faulted components and subsystems. The process enabled quantification of the extent of performance degradation. The revelation of the factors contributing to plant performance degradation and the degree of performance degradation were then followed by the development of mitigation strategies to reduce the degradation.

RESULTS AND DISCUSSION

Results of the RCA tool are presented in Table 1. It can be revealed that majority of the component failures were primarily associated with four items: engine valve (11.5%), plugs and coils for ignition system (10.9%), gas throttle (10%), and lubricating pipes (10%). Notably, valves failures were prominent in engine number 9 (14 out of 103 failures) and engine number 10 (13 out of 103 failures), collectively constituting 26.2% of all valve's failures (27 out of 103 failures). Plug and coils for ignition system failures were prevalent in engines number 10 (14 out of 98) and engine number 9 (13 out 98), collectively accounting for 27.6% of all plug and ignition coils related component failures. Gas throttle failures were prevalent in engines number 2 (19 out of 90) and engine number 4 (13 out 90), accounting for 35.6% of all gas throttle related component failures. Lube oil pipe and accessories failures were prevalent in engines number 2 (13 out of 90) and engine number 9 (11 out 90), accounting for 26.7% of all Lube oil pipe and accessories related component failures. At the subsystem level, the highest prevalence of failures was observed in the combustion unit, collectively representing 64.7% of all failures. This was followed by component failures in the lubrication, cooling and control systems which contributed to 17%, 13.6% and 5.3 % consecutively.

Table 1: Failure distribution per type of component and subsystem based on ISO 14224:2016

Engine sub system and component		Number of failure of components per each engine												Total component failure and percentage
Sub system	Component													
Engine number		1	2	3	4	5	6	7	8	9	10	11	12	
Combustion	Engine valves	12	8	11	6	6	5	4	6	14	13	12	6	103(11.5)
	Plugs and Coils for ignitions	7	7	6	9	7	2	7	12	13	14	7	7	98(10.9)
	Gas Throttle	10	19	4	13	9	2	5	5	2	2	10	9	90(10)
	Turbocharger	7	12	5	5	3	10	8	5	4	1	7	3	70(7.8)
	Fuel piping (Gas distributors)	4	7	2	8	5	2	3	4	5	8	4	5	57(6.4)
	Exhaust bellow	3	5	1	4	2	8	2	9	5	1	3	2	45(5.0)
	Camshaft	5	5	2	2	7	3	3	4	2	3	5	7	48(5.4)
	Cylinders	1	6	3	7	2	2	3	4	2	3	1	2	36(4.0)
	Conrods	1	0	1	0	1	0	0	1	0	0	1	0	5(0.6)
	Piston	2	0	1	0	0	0	0	0	0	0	3	0	6(0.7)
	Air filters	2	3	1	1	2	2	1	1	4	1	2	2	22(2.5)
Lubrication	Lubricant pipes	5	13	5	10	4	9	10	7	11	7	5	4	90(10.0)
	Lubricant pump	2	4	1	3	1	5	2	2	4	2	2	1	29 (3.2)
	Centrifugal Filter	1	2	2	2	1	1	1	1	7	7	1	1	27 (3.8)
Cooling	Radiator	5	10	3	5	3	2	2	5	11	2	5	3	56 (6.3)
	Coolant piping	3	3	6	5	2	1	2	8	3	4	3	2	42(4.7)
	Coolant pump	2	5	1	1	2	1	4	3	1	1	2	2	25(2.5)
Control	WECs Control unit.	8	3	7	3	2	1	3	6	2	2	8	2	47(5.2)
	Totals	80	112	62	84	59	56	60	83	90	71	81	58	896 (100)

Failure Distribution as per the Type of Failure Mode (FMEA)

Table 2 presents the failure's distribution as per type of failure modes. A total of 772 mechanical failures of engine components were recorded originating from mainly nine failure modes.

Table 2: Mechanical Equipment Failure mode distribution based on ISO 14224:2016

Failure mode & Description		Number of modes of failures per each engine												Total failure mode and percentage
Engine number		1	2	3	4	5	6	7	8	9	10	11	12	
Mode	Description													
ELU	External utility fluid leakage	12	23	11	14	8	15	11	20	33	17	9	7	180 (23.32)
PDE	Parameter deviation	4	3	3	8	2	4	3	5	51	44	3	2	132 (17.1)
OHE	Overheating	10	30	6	14	17	7	11	13	7	9	6	15	145 (18.78)
LOO	Low Output	15	13	14	16	5	4	4	9	12	12	11	5	120 (15.54)
ELF	External fuel leakage	10	13	6	15	4	11	9	4	11	5	7	4	99 (12.82)
INL	Internal leakage	4	7	1	7	9	2	6	7	0	0	1	9	53 (6.87)
BRD	Unexpected breakdown	2	1	2	2	4	0	0	7	1	0	2	3	24(3.11)
VIB	Abnormal vibration	1	0	2	1	2	0	0	2	0	0	0	0	8(1.04)
ERO	Erratic output	2	0	1	0	0	0	0	5	0	0	2	1	11(1.4)
Total		60	90	46	77	51	43	44	72	115	87	41	46	772(100)

The results provided in Table 2 indicate a notable prevalence of the major five failure modes which are external utility fluid leakage (ELU) with 23.32%, overheating (OHE) 18.78%, parameter deviation (PDE) with 17.1%, system low output (LOO) with 15.54%. and external fuel leakage (ELF) with 12.82%. Evaluation of the distribution of the failure modes revealed that ELU failures were significantly prevalent in engines number 9, 2, 8, and 10 accounting to 51.7% of all ELU related failures. OHE failures were significantly prevalent in engines number 2, 5, 12, and 4 accounting to 52.41% of all OHE related failures while PDE failures were predominant in engines number 9, 10, 4 and 8, collectively accounting to 81.82% of all PDE related failures. Ranked seventh in terms of failure code frequent, BRD failure mode was experienced in engine number 9. The insights gathered from Tables 1 and 2 were then utilized as input data for the subsequent Principal Component Analysis (PCA) and Scree plot leading to the derivation of failure associations.

Table 3 presents findings of the plant maintenance activities conducted in the span of two years. The maintenance activities comprise of two categories. First category represents scheduled maintenance as per original equipment manufacturer (OEM) recommendations also known as proactive maintenance. Second category are breakdown maintenances due to unexpected engine failures, also known as reactive maintenances. As per the engine maintenance manuals, recommended maintenances comprise major overhaul carried after every 16,000 hours operations, inspections carried out after every 8,000 hours operations, checks carried out after every 4,000 hours operations and services carried out after every 2,000 hours operations. Each category has its own scopes of which if well followed, needs a downtime duration of 30 days, 15 days, 5 days and 4 days consecutively assuming working duration of 10 hour per day. Analysis of the maintenance activities is presented in Figure 1 to Figure 4 and Table 4.

Table 3: Plant maintenance activities distribution

Two Years Engine Maintenance Downtime Data					
Type of Maintenance	OEM Recommended Schedule	Maintenance Strategy	Number of Unit involved	Planned hours	Actual hours
Major Overhaul	16,000 hours Maintenances	Proactive	5	7200	2,880
Inspections	8000 hours Maintenances		12	8064	6,240
Checks	4000 hours Maintenances		12	9216	6,912
Services	2000 hours Maintenances		12	10368	7,680
Minor Repair		Reactive	12	0	10,430
Refit			12	0	34,130
Corrective Replacements			12	0	59,120
Total Operation Hours			12	207,360	79,968

Figure 1 presents analysis on maintenance activities based on the repair hours, focusing on the twelve thermal engines at a span of two years operations equivalent to a total of 207,360 cumulative hours for all twelve engines. Accordingly, the analysis shows that during the same operation interval, there was recommended proactive maintenance schedule that could have lasted for 34,848 hours of which its respective scope covers major overhaul, inspections, checks, and services. If the activities were done properly, the proactive maintenance program recommended by the original equipment manufacturer (OEM) would enable the engines to evade surprise failures that lead into unplanned downtimes. Conversely, the study revealed that plant maintenance activities during this particular time constituted 127,392 cumulative hours of which only 23,712 hours equivalent to 18.61% were planned maintenances and the remained 103,680 hours equivalent to 81.39% involved reactive maintenances activities that cover minor repair, refit as well as corrective and replacements.

Likewise, the analysis revealed that maintenance activities at the power plant were predominantly reactive, with 46.41% of the activities involving corrective component replacement, 26.79% involving refit and 8% involving minor repair strategy. As per the ISO 14224:2016 standard, refit strategy entails minor maintenance actions aimed at restoring equipment to an acceptable performance post-failure. Conversely, proactive maintenance activities such as service, check, or major overhaul constituted only 11.13% of the total maintenance activities conducted at the power plant. Table 4 presents findings of the downtime losses for both individual and cumulative maintenance hours to enable establishing a level of percentage production losses due to maintenance downtime.

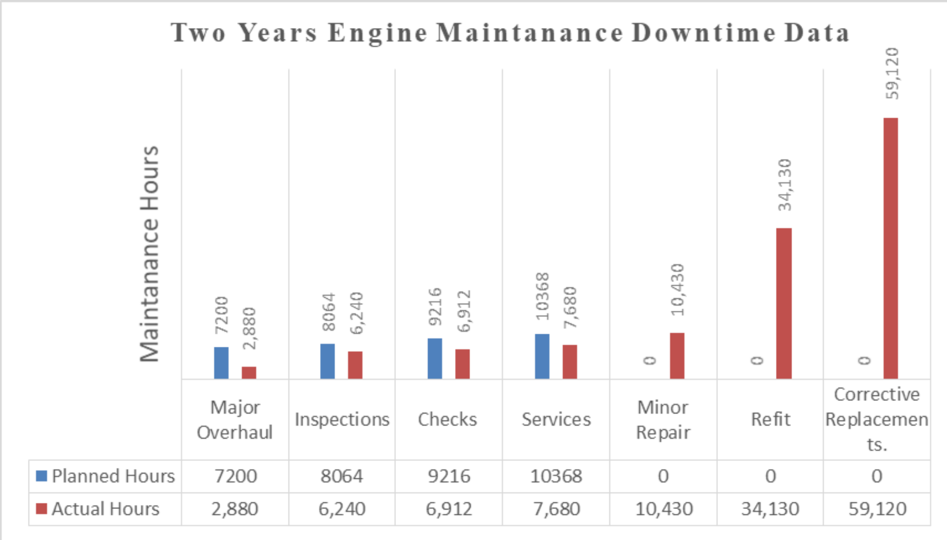

Figure 1: Time consumed on maintenance activities

Table 4: Plant engine downtime data

Type of Maintenance downtime losses	Total loss (Hours)	Cumulative Loss (Hours)	Individual loss percentage	Cumulative loss Percentage
Corrective Replacements	59,120	59,120	46.41	46.41
Refit	34,130	93,250	27.12	73.52
Minor Repair	10,430	103,680	8.1	81.62
Services	7,680	111,360	6.0	87.62
Checks	6,912	118,272	5.4	93.02
Inspection	6,240	124,512	4.8	97.81
Major Overhaul	2,880	127,392	2.2	100

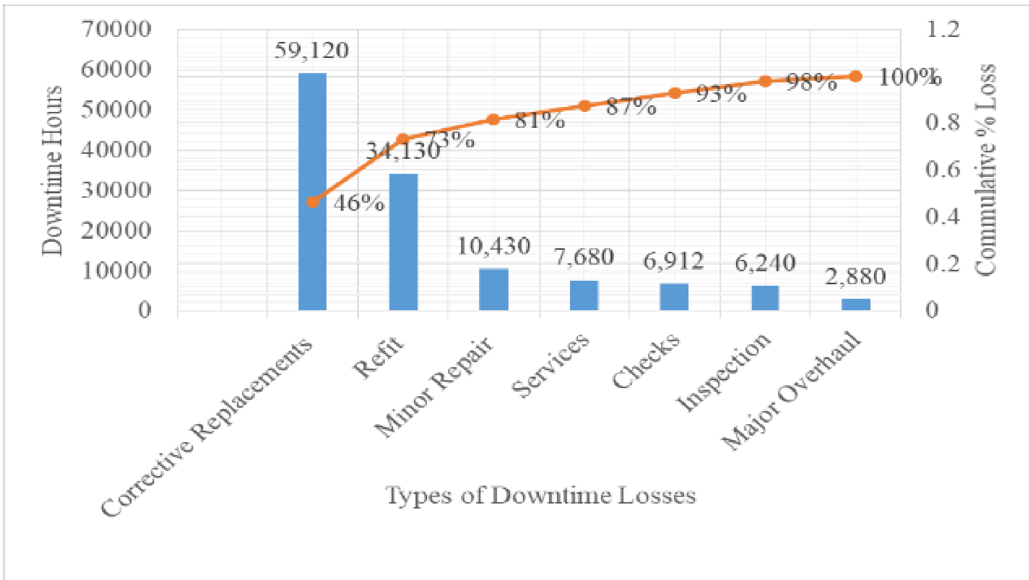

Figure 2: Pareto chart on downtime maintenance losses.

Pareto analysis on maintenance down losses

Figure 2 shows Pareto analysis regarding the maintenance downtime losses. Various downtime losses were drawn alongside primary horizontal axis. Individual downtime maintenance hours plotted alongside primary vertical axis as well as cumulative downtime maintenance percentage loss. The figure reveals factors contributing 80% towards maintenance downtime were corrective component replacement which accounts for 46.41%, refit which accounts for 26%, and minor repair strategy accounting for 8%.

Furthermore, out of 34,848 hours of planned maintenance activities only 23,712 hours equivalent to 68% were utilized as intended whereby 11,136 hours, equivalent to 32 % were not utilized. On the other hand, majority of the unattended works involved major overhaul activities which covers a wide scope of inspections and replacements of worn out engine components. Non-replacement of worn out engine components results into suboptimal maintenance which manifest into jeopardizing availability and reliability of the thermal generating units. Together with this, issues relating to suboptimal knowledge and skills were identified as amongst factors contributing to repetitive repair works. This deduces to the reason why maintenance activities were predominantly reactive.

Principal Component Analysis (PCA)

Figure 3 provides results derived from the PCA. In the loading plot, vectors representing failures modes with their respective correlated component have been shown. The correlation is attributed by their comparable vector magnitudes and minimal angular separation between the vectors. From the plot, overheating (OHE) failure mode including engine valves, turbocharger and coolant pump are aligned and strongly correlated to the first component. Abnormal vibration (VIB) failure mode is correlated by cylinders (plug and coils). Similarly, on the same first component strong correlation is seen between low output (LOO) failure mode, lubricating piping, lubricating pump, fuel filters and heat exchanger. Parameter deviation (PDE) failure mode, which demonstrates statistical correlation with the fuel injector (throttle), fuel piping (distributor) and fuel filters is well noted in Figure 3. Correlation is also seen on erratic output (ERO) and breakdown (BRD) failures modes with the control unit and coolant piping. The correlation demonstrated in Figure 3 entails a linkage between system failure modes and their respective component failures.

Figure 4 depicts a scree plot relating to Figure 3 PCA loading plot. Usually eigenvalues larger than 1 are regarded as being stable and therefore retained (Pérez and Medrano 2014).

From the Scree plot in Figure 4, a total of six factors are found to have Eigen values larger than 1 and are therefore retained. The values were 6.7, 6.3, 3.8, 2.5, 2.1, and 1.6 each representing percentage data variability of 26.80%, 24.71%, 14.90%, 9.80%, 8.24%, 6.27%. Together, they account for 90.72 % of the variation on the data set. Referring to the correlations depicted in Figure 3, the scree plot provides that, 26.80% variance explained by component failures correlated to overheating (OHE) failure mode, 24.71% variance explained by component failures correlated to abnormal vibration (VIB) failure mode, 14.90% variance explained by component failures correlated to low output (LOO) failure mode, 9.80% variance explained by component failures correlated to parameter deviation (PDE) failure modes, 8.24% variance was correlated to erratic output (ERO) failure mode and 6.27% variance was correlated to unexpected breakdown (BRD) failure mode. Thus, targeting efforts on mitigating component failures will result into reducing failure modes incident as well.

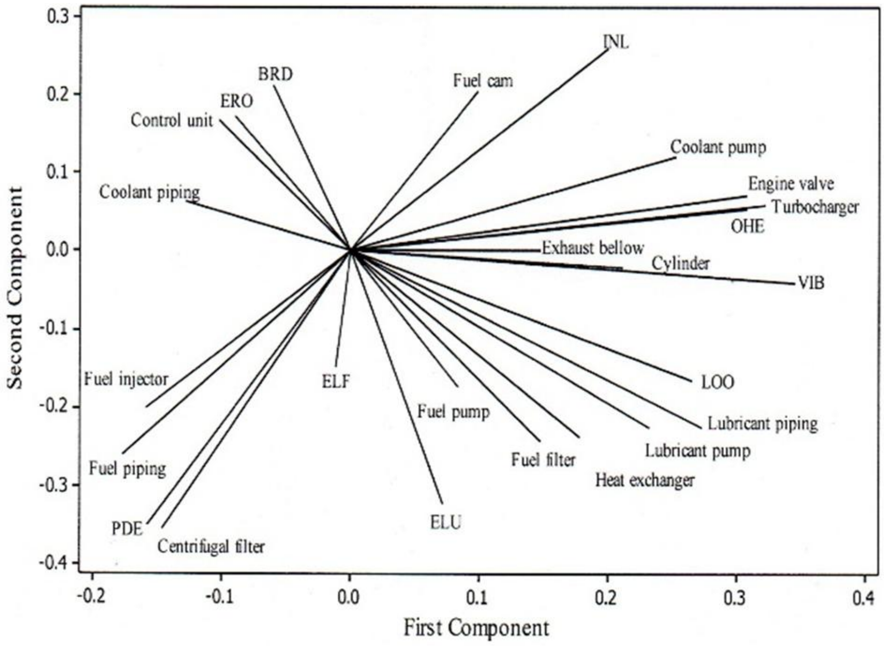

Figure 3 : PCA loading plot for failures modes and component failures.

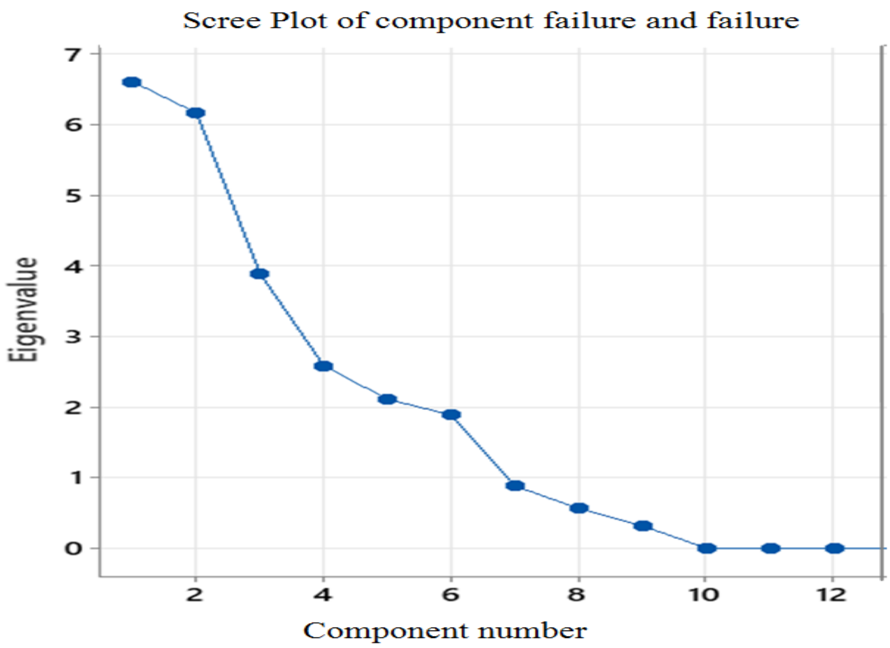

Figure 4: Scree plot.

CONCLUSIONS

The findings have revealed that the contributing factors to performance degradation at the XYZ thermal power plant are mechanical failures in engine components and subsystems, correlating with six failure modes, of which the main three are overheating (OHE), abnormal vibration (VIB), and low output (LOO). It is also established that, instead of the planned 34,848 maintenance hours recommended by the OEM in proactive maintenance, the plant's maintenance activities consumed 127,392 hours, of which 103,680 hours, equivalent to 81.39%, were spent on reactive maintenance activities. It is also deduced that the plant performance degradation was also affected by environmental factors (e.g. dust and air salinity which impaired cooling system due to clogged heat exchangers and corrosion). In addition, other factors include skills gaps, non-adherence to OEM-recommended maintenance schedules, and deferred system upgrades. Therefore, there is a need for timely and proactive maintenance, adherence to OEM maintenance strategies, knowledgeable and skilled personnel to support the maintenance activities in order to ensure stability, reliability, and longevity of the XYZ thermal power plant.

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