



Factors Causing Ineffectiveness of Capex-Opex Management on the Reliability of Coal-Fired Power Plants

Mohammad Anang Fachrudin^{1*}, I Ketut Gunarta²

^{1,2}Departemen Teknik Sistem dan Industri, Institut Teknologi Sepuluh Nopember, Indonesia

E-Mail: ¹anangfachrudin.its@gmail.com, ²ik.gunarta@gmail.com

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Corresponding Author: Mohammad Anang Fachrudin

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Abstract

This study examines the ineffectiveness of Capital Expenditure (Capex) and Operational Expenditure (Opex) management in improving the reliability of coal-fired power plants in isolated electricity systems, using PLTU Bolok and PLTU Ropa in East Nusa Tenggara as case study units. The study is motivated by fluctuations in Equivalent Availability Factor (EAF) and Equivalent Forced Outage Rate (EFOR) during 2019-2024, despite recurring maintenance and investment expenditures. A descriptive case-study design was applied, combining reliability and maintenance performance analysis with Root Cause Analysis (RCA) using a Fishbone Diagram, Pareto Analysis, and Five Whys. The dataset includes Capex and Opex realization, FOH, POH, downtime, maintenance backlog, and the composition of preventive and corrective maintenance. The findings show that ineffective Capex-Opex management is primarily driven by equipment degradation, maintenance delays, high backlog levels, delays in spare-part procurement, delayed critical investments, and the dominance of corrective maintenance. The novelty of this study lies in integrating cost-allocation evaluation, reliability indicators, and root-cause diagnosis into a single analytical framework for isolated coal-fired power plant systems. In practice, the results imply that reliability improvement should prioritize reliability-based maintenance planning, backlog reduction, control of critical-spare procurement, and Capex prioritization based on asset criticality rather than budget magnitude alone.

Keywords: Capex, EAF, EFOR, Opex, RCA

1. INTRODUCTION

The reliability of steam power plants (PLTU) is a fundamental aspect in ensuring the continuity and stability of electrical energy supply, especially in isolated electricity systems such as in East Nusa Tenggara (NTT). In this system, the coal-fired power plant serves as a base load, supporting frequency stability and power availability. The reliability level of a plant is generally measured using indicators such as the Equivalent Availability Factor (EAF) and the Equivalent Forced Outage Rate (EFOR), which reflect the level of operational readiness and frequency of unplanned outages [1].

In operational practice, the management of plant maintenance is highly dependent on the allocation of Capital Expenditure (Capex) and Operational Expenditure (Opex) [2]. Capex is used for long-term investments such as overhaul, rehabilitation, replacement of critical components, and asset modernization, whereas Opex is allocated for daily operation, routine maintenance, spare parts, and corrective activities [3]. Theoretically, increased investment in these two components should improve plant reliability by decreasing failure rates and increasing availability [4, 5]. The urgency of this study arises because an increase in expenditure does not automatically improve reliability when investment timing, procurement readiness, work prioritization, and maintenance execution are not aligned with the actual condition of critical assets. Therefore, ineffective Capex-Opex management may create a cost-performance gap: resources are spent, but the expected improvement in plant availability is not fully achieved.

Nevertheless, empirical phenomena show that the relationship between maintenance costs and reliability is not always linear. In the case of PLTU Bolok and PLTU Ropa, the increase in Capex and Opex allocation in recent years has not been accompanied by a proportionate improvement in reliability performance, as indicated by stagnation and even a decrease in EAF value, as well as fluctuations in EFOR. This phenomenon is also found in various other plant studies, where increased maintenance costs do not necessarily result in improved system performance due to time delays, system complexity, and inaccuracies in investment decision-making [6, 7].

This condition indicates that the ineffectiveness of Capex and Opex management is not only influenced by the size of the budget, but also by systemic factors such as maintenance delays, work backlogs, asset degradation, limited human resources, and weak organizational coordination [8]. Thus, an analytical approach is needed to comprehensively identify the main causative factors to formulate a more effective and sustainable reliability improvement strategy.

Previous studies have examined the relationship between maintenance strategies, expenditure control, and generating-system reliability from different perspectives. Do et al. demonstrated that condition-based maintenance can reduce equipment degradation and optimize lifecycle costs when maintenance actions are triggered by asset condition rather than fixed intervals [4]. Alvarez-Alvarado et al. explained that power-system maintenance has evolved from run-to-failure practices toward predictive and preventive strategies that integrate reliability, cost, and risk considerations [9]. In a broader maintenance optimization context, Sharma et al. emphasized that optimization models are useful for balancing maintenance cost and performance, but their effectiveness depends on the suitability of the model to operational constraints and data availability [10].

Nevertheless, the relationship among Capex, Opex, and reliability is complex because plant maintenance is influenced by feedback loops, time delays, resource constraints, and prioritization decisions. Manenzhe et al. explain that maintenance work management has dynamic characteristics, so improper investment decisions can generate inefficiency and reduce system performance [6]. Basirat et al. also show that increasing maintenance frequency without a suitable strategy can increase cost without producing a significant reliability improvement [7]. Similarly, Ding and Kamaruddin show that maintenance policy selection must consider certainty, risk, and uncertainty conditions, which means that expenditure decisions should be connected to asset condition and failure consequences rather than treated as routine budget absorption [10].

From a reliability perspective, parameters such as Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR), EAF, and EFOR are closely related to the quality of maintenance planning and execution. Griparić et al. show that increasing MTBF and reducing MTTR can significantly increase system availability [11]. George-Williams and Patelli found that delays in maintenance implementation can increase EFOR because postponed work allows degradation to accumulate [12]. In line with this view, Jardine et al. argue that diagnostics and prognostics can strengthen condition-based maintenance by allowing organizations to detect degradation earlier and plan maintenance before failure occurs [13].

In the context of identifying failure causes, Root Cause Analysis (RCA) is widely used to trace the underlying technical and managerial factors that cause system ineffectiveness [14]. Yuniarto and Lawlor-Wright emphasized that failures in generating systems are frequently associated with systemic factors such as weak coordination, delayed decision-making, and inadequate feedback mechanisms [15]. Susendi et al. also explain that combining Fishbone Diagram, Five Whys, and Pareto Analysis can improve the accuracy of root-cause identification because each method has a different analytical role: Fishbone maps possible causes, Five Whys traces causal depth, and Pareto prioritizes dominant contributors [16]. However, most previous studies still focus on technical failure, maintenance scheduling, or cost optimization separately, while fewer studies explicitly examine why integrated Capex-Opex management becomes ineffective in isolated coal-fired power plant systems.

The critical comparison of previous studies shows three important limitations. First, condition-based and predictive maintenance studies generally emphasize component-level decisions, while the linkage to annual Capex-Opex budgeting is rarely discussed in detail [4], [13]. Second, maintenance optimization studies tend to use mathematical or simulation models that require extensive data, but they do not always explain the managerial causes behind the failure of implementation [8], [10], [17]. Third, studies on power-plant reliability often analyze EAF, EFOR, MTBF, or MTTR, but they seldom integrate these indicators with backlog, spare-part procurement, and investment-priority issues in a single cause-based framework [11], [12]. These limitations indicate the need for a study that connects reliability performance, expenditure management, and root-cause identification in one integrated analysis.

Based on the literature review, there is a significant research gap between increased maintenance expenditure and the reliability results achieved. Prior studies have generally emphasized the quantitative relationship between cost and performance, technical optimization of maintenance policies, or general reliability improvement, without identifying in depth the managerial and operational factors that cause Capex and Opex implementation to become ineffective in specific plant contexts.

Within the scope of PLTU Bolok and PLTU Ropa, the phenomenon of increasing or relatively stable budgets that are not followed by consistent reliability improvement indicates systemic and multidimensional problems. The distinction of this study from previous research lies in its focus on two coal-fired power plants operating in isolated electricity systems, its use of 2019-2024 operational and maintenance data, and its integration of Capex-Opex evaluation with RCA to identify the dominant causes of ineffectiveness. This problem cannot be explained solely through statistical or econometric approaches; it requires a cause-based analysis that explores how technical degradation, work backlog, spare-part procurement, and investment delays interact with maintenance performance.

In addition, the characteristics of isolated electricity systems, such as those in NTT, which have limited resources and high dependence on selected generating units, make the effectiveness of maintenance management a critical operational issue. Therefore, this study fills the gap by identifying the main causative factors of ineffective Capex and Opex management using the RCA approach. The expected contribution is twofold: scientifically, it provides an integrated framework linking cost policy, reliability indicators, and root-cause diagnosis; practically, it provides evidence for performance-based maintenance policies and for more accurate resource allocation to support the generation system's reliability.

Based on the background, literature review, and research gaps described above, the research question in this study is formulated as follows: What are the main causative factors that affect the ineffectiveness of Capex and Opex management on the reliability of coal-fired power plants in the case of PLTU Bolok and PLTU Ropa?

The objectives of this study are: (1) to analyze the trend of Capex, Opex, EAF, EFOR, downtime, and maintenance performance during 2019-2024; (2) to identify the dominant technical, operational, and managerial factors that cause ineffective Capex-Opex management; and (3) to formulate practical implications for improving reliability-based maintenance and investment prioritization in isolated coal-fired power plant systems

2. MATERIALS AND METHOD

Before entering the methodology stage in detail, this research begins by preparing a research flowchart that outlines the systematic process from problem identification to conclusion formulation. As illustrated in Figure 1, the study starts by identifying the mismatch between Capex-Opex allocation and reliability performance at PLTU Bolok and PLTU Ropa. The next stage is data collection, covering annual budget realization, FOH, POH, downtime, EAF, EFOR, and maintenance backlog for the 2019-2024 period. The collected data are then processed and classified according to reliability indicators and RCA categories. After that, RCA is conducted through three complementary tools: Fishbone Diagram to map possible causes, Five Whys to trace the causal chain of selected cases, and Pareto Analysis to prioritize dominant root causes. The results are validated by checking consistency across historical operational data and maintenance performance patterns. Finally, the validated causes are interpreted to formulate conclusions, practical implications, and future research directions. This flow ensures that the analysis is not limited to descriptive trends but proceeds toward systematic root-cause identification

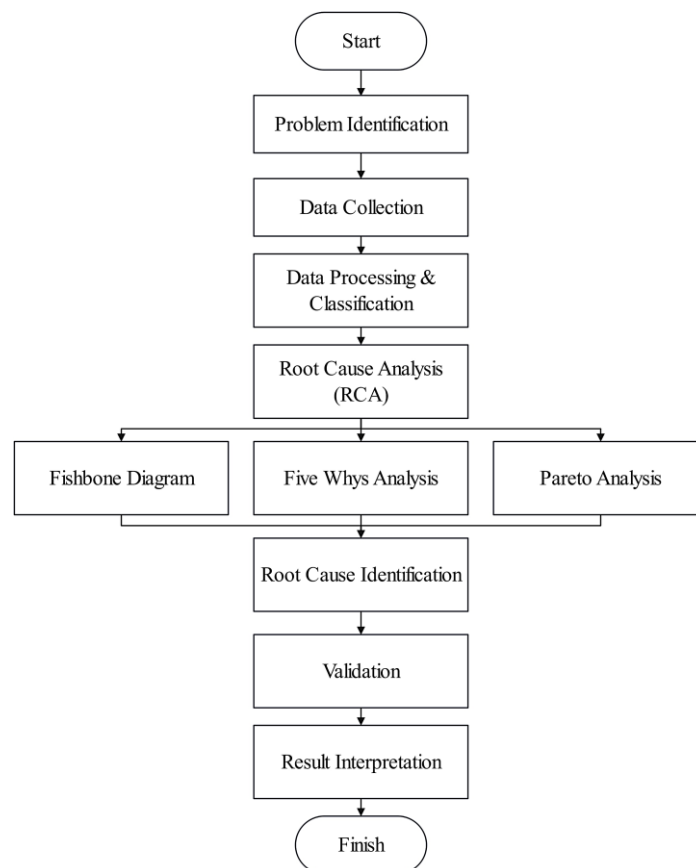


Figure 1. Research Methodology

2.1. Research Design

This study uses a quantitative-descriptive approach supported by qualitative analysis, which aims to identify the main factors causing the ineffectiveness of Capital Expenditure (Capex) and Operational Expenditure (Opex) management on the reliability of coal-fired power plants. The descriptive quantitative analysis is used to examine trends in cost allocation and reliability indicators, while qualitative RCA is used to interpret the underlying technical, operational, and managerial causes. RCA was selected because it can systematically trace both direct and indirect causes of failures and performance degradation in complex engineering systems [14], [15].

The combination of Fishbone Diagram, Pareto Analysis, and Five Whys is academically justified because the three tools address different but complementary analytical needs. Fishbone Diagram provides a structured cause-and-effect map by grouping possible causes into Man, Machine, Method, Material, and Environment categories [16]. Pareto Analysis supports prioritization by identifying the small number of causes that contribute the largest proportion of disturbance cases, consistent with the 80/20 principle. Five Whys then deepens the analysis by tracing the causal chain from observed reliability problems to the underlying managerial or system-level cause. Therefore, the combined use of these tools strengthens the validity of RCA by covering cause mapping, cause prioritization, and causal-depth exploration rather than relying on a single diagnostic method.

2.2. Research Object and Scope

The object of this research is two units of steam power plants (PLTU) in the PLN UIW East Nusa Tenggara environment, namely:

1. PLTU Bolok with a capacity of 2×16.5 MW (Timor System)
2. PLTU Ropa with a capacity of 2×7 MW (Flores System)

The research focused on the operational period of 2019–2024, which was selected based on the availability of historical data related to the realization of Capex (AI) and Opex (ABOP) budgets, as well as plant reliability indicators such as Equivalent Availability Factor (EAF) and Equivalent Forced Outage Rate (EFOR). The scope of the research is limited to the analysis of the relationship between:

1. Opex budget (routine operation and maintenance),
2. Capex budget (maintenance investment),
3. Reliability indicators (EAF and EFOR),
4. Factors that cause ineffective management.

2.3. Data and Materials

The data used in this study consisted of:

1. Data Seconds
 - a. Opex (ABOP) and Capex (AI) budget realization report
 - b. Generator reliability data (EAF and EFOR)
 - c. Data operational unit (downtime, forced outage, maintenance schedule)
 - d. PLN internal report documents and power plant performance reports
2. Supporting Data
 - a. Scientific literature related to plant maintenance and system reliability
 - b. Reliability standard (IEEE Std 762)
 - c. RCA method reference and maintenance management

Data were collected as an annual time series over 6 years (2019–2024) for each generation unit.

2.4. Variables and Measurement

The variables used in this study include:

Table 1. Research Variables [1]

Variable	Type	Indicator
Capex (AI)	Independent	Maintenance investment value (Rp/year)
Opex (ABOP)	Independent	Operation and maintenance costs (Rp/year)
Reliability	Dependent	EAF (%) and EFOR (%)
Causal Factors	Qualitative	RCA results (technical, managerial, operational)

2.5. Root Cause Analysis Procedure

The main method in this study is Root Cause Analysis (RCA) which is carried out in stages to identify the root causes of ineffective Capex–Opex management. The stages of RCA in this study are as follows:

1. **Problem Identification**
Identify the main phenomenon: the mismatch between the increase in the maintenance budget and the plant's reliability performance.
2. **Data Collection and Classification**
Group data on disruptions and operational factors by category:
 - a. Man (HR)
 - b. Machine (tools)
 - c. Method (Working Methods)
 - d. Material (parts/materials)
 - e. Environment (Operating environment)
3. **Fishbone Diagram Analysis**
It is used to systematically map all possible causes of disorders [16].
4. **Five Whys Analysis**
It is carried out in stages to trace the main cause until the problem's deepest root is identified.
5. **Pareto Analysis**
It is used to determine the dominant factors contributing most to the system's ineffectiveness, based on the 80/20 principle.
6. **Root Cause Validation**
The identification results were verified using historical data and by assessing consistency across disturbance events.

2.6. Data Analysis Technique

Data analysis is carried out through two main approaches:

1. **Quantitative Descriptive Analysis**
 - a. Analyze Capex, Opex, EAF, and EFOR trends
 - b. Identify patterns of mismatches between cost and reliability
2. **Qualitative Analysis (RCA)**
 - a. Identifying cause-and-effect relationships
 - b. Determining the dominant factors causing ineffectiveness

The analysis results were synthesized to produce a mapping of the main factors affecting the effectiveness of plant maintenance management.

2.7. Research Reproducibility

The methodology used in this study is replicative and can be applied to other power generation systems with the following steps:

1. Collect Capex, Opex, and reliability data for at least 3–5 years,
2. Classify interference data by RCA category,
3. Applying Fishbone, Five Whys, and Pareto Analysis,
4. Identifying and validating root causes,
5. Determine the dominant factors affecting reliability.

This approach has been widely used in the analysis of generation systems and has proven to be effective in improving the quality of maintenance decision-making [13, 14].

3. RESULTS AND DISCUSSION

3.1. Results

3.1.1. Trend of Capex–Opex and Reliability Performance

Analysis of Capex, Opex, and reliability performance trends was conducted to identify the pattern of relationship between investment and operational cost allocation and power plant performance. The reliability indicators used in this study are Equivalent Availability Factor (EAF) and Equivalent Forced Outage Rate (EFOR), which are derived from the distribution of plant operating time, including period hours, forced outage hours (FOH), and planned outage hours (POH). This analysis aims to describe the dynamics of plant reliability performance in relation to changes in Capex and Opex allocations during the period 2019–2024

Table 2. Trend Capex–Opex and Reliability Performance PLTU Bolok

Year	Opex (Billion Rp)	Capex (Billion Rp)	EAF (%)	EFOR (%)
2019	53	73	84.1	3.7
2020	40	72	84.0	3.0
2021	49	65	85.4	3.1
2022	57	72	81.4	5.6
2023	55	74	87.9	4.5
2024	54	65	84.3	5.1

Table 3. Trend Capex–Opex and Reliability Performance PLTU Ropa

Year	Opex (Billion Rp)	Capex (Billion Rp)	EAF (%)	EFOR (%)
2019	56	61	78.6	6.5
2020	50	58	83.2	5.8
2021	42	59	74.7	6.6
2022	47	62	82.7	5.3
2023	59	61	79.8	5.6
2024	52	60	77.8	3.7

Based on Tables 2 and 3, the Capex and Opex trends in both generating units show fluctuations during the observation period, but these changes are not always accompanied by improved reliability performance. At PLTU Bolok, the increase in Opex from 49 billion in 2021 to 57 billion in 2022, accompanied by Capex of 72 billion, was followed by increases in FOH from 239 hours to 423 hours and in POH to 1206 hours. This condition decreased EAF from 85.40% to 81.40% and increased EFOR from 3.10% to 5.60%.

In 2023, although Opex (55 billion) and Capex (74 billion) did not increase significantly, POH decreased to 697 hours and FOH decreased to 363 hours. This contributed to the EAF rising to 87.90%, the highest value during the observation period. However, in 2024, the re-increase of FOH to 397 hours and POH to 978 hours led to a decrease in EAF to 84.30% and an increase in EFOR to 5.10%.

Meanwhile, at PLTU Ropa, Capex and Opex fluctuations also show an inconsistent relationship with reliability performance. In 2020, with Opex of 50 billion and Capex of 58 billion, the value of EAF increased to 83.20% with FOH of 449 hours and POH of 1023 hours. However, in 2021, although Capex increased to 59 billion, FOH remained high by 462 hours, and POH increased significantly to 1754 hours, which led to a decrease in EAF to 74.70% as well as an increase in EFOR to 6.59%.

In 2022, performance improved, with FOH decreasing to 405 hours and POH to 1110 hours, resulting in an EAF of 82.71%. However, this trend did not continue in the following years. In 2023 and 2024, although Capex and Opex are relatively stable, the POH value remains high and causes the EAF value to be in the range of 77–80%.

Overall, these results show that changes in Capex and Opex allocation are not necessarily directly proportional to the increase in plant reliability. The variation in EAF and EFOR values is more influenced by the dynamics of FOH and POH which reflect operational disruptions and the effectiveness of maintenance implementation.

3.1.2. Downtime and Operational Disruption Analysis

Downtime is an important operational indicator that directly reflects the level of disruption and availability of the generating unit. Downtime analysis was carried out to identify operational disruption patterns and their relationship with plant reliability performance represented through Equivalent Availability Factor (EAF) and Equivalent Forced Outage Rate (EFOR) values. By analyzing changes in downtime over time, it can be observed the dynamics of operational disruptions that occur in each generating unit.

Table 4. Downtime Analysis of PLTU Bolok

Year	FOH (Hours)	POH (Hours)	Downtime (Hours)
2019	283	1110	1390
2020	228	1174	1400
2021	239	1040	1280
2022	423	1206	1630
2023	363	697	1050
2024	397	978	1370

Table 5. Downtime Analysis of PLTU Ropa

Year	FOH (Hours)	POH (Hours)	Downtime (Hours)
2019	479	1396	1880
2020	449	1023	1470

Year	FOH (Hours)	POH (Hours)	Downtime (Hours)
2021	462	1754	2210
2022	405	1110	1510
2023	415	1355	1760
2024	262	1683	1940

Based on Tables 4 and 5, the total downtime for both generating units shows a fluctuating pattern during the 2019–2024 period. At PLTU Bolok, downtime was relatively stable in 2019 and 2020, namely 1393 hours and 1402 hours, respectively. In 2021, downtime decreased to 1279 hours, but increased significantly in 2022 to 1629 hours due to increased FOH and POH. In 2023, downtime decreased to 1060 hours, the lowest value during the observation period, before increasing again in 2024 to 1375 hours.

At PLTU Ropa, downtime was higher than at PLTU Bolok throughout the observation period. In 2019, downtime was recorded at 1875 hours and decreased to 1472 hours in 2020. However, in 2021 there was a significant increase to 2216 hours, which was the highest value during the study period. In 2022, downtime decreased again to 1515 hours, but increased in 2023 and 2024 to 1770 hours and 1945 hours, respectively. This pattern indicates that planned outage duration and forced outage events jointly contributed to the lower availability of PLTU Ropa.

In general, the variation in downtime at both plants is affected by a combination of planned and unplanned disruptions, where the increase in FOH reflects an increase in sudden operational disruptions, while the variation in POH indicates a change in the intensity of planned maintenance activities that directly impacts unit availability.

3.1.3. Maintenance Performance Analysis

Maintenance performance analysis is conducted to evaluate the effectiveness of implementing operational and maintenance activities in supporting the plant's reliability. The indicators used include the number of work-order backlogs and the proportions of preventive and corrective maintenance, which reflect the maintenance workload and the balance between proactive and reactive maintenance approaches. Changes to these indicators reflect the dynamics of maintenance implementation and may affect operational disruption levels and unit availability.

Table 6. Maintenance Performance Indicators

Year	Backlog Work Order	Preventive Maintenance (%)	Corrective Maintenance (%)
2019	120	65	35
2020	140	60	40
2021	160	55	45
2022	210	48	52
2023	180	52	48
2024	220	45	55

Based on Table 6, the number of maintenance work backlogs shows an increasing trend over the period 2019–2024, from 120 jobs in 2019 to 220 jobs in 2024. This increase in backlog indicates an accumulation of maintenance work that has not been optimally completed, potentially increasing the risk of operational disruption. At the same time, the proportion of preventive maintenance has decreased from 65% in 2019 to 45% in 2024. In contrast, corrective maintenance increased from 35% to 55% in the same period. This change shows a shift in the maintenance approach from proactive to reactive.

In 2022, when the backlog reached 210 jobs and the proportion of corrective maintenance increased to 52%, operational disruptions increased, reflected in higher FOH and total downtime in the same period. Despite a temporary improvement in 2023, with the backlog decreasing to 180 jobs and preventive maintenance increasing to 52%, the condition will decline again in 2024, marked by an increase in the backlog to 220 jobs and a dominance of corrective maintenance at 55%. Overall, these results indicate a decrease in the effectiveness of maintenance implementation, characterized by an increasing backlog of work and a dominance of corrective maintenance over preventive maintenance during the observation period.

3.1.4. Root Cause Analysis Results

Root cause analysis was conducted to identify the main factors that contribute to the ineffectiveness of Capex and Opex management in supporting plant reliability. The approach includes causal classification using the Fishbone Diagram framework, identification of dominant factors through Pareto Analysis, and systematic tracing of the problem's root using the Five Whys method. The analysis process is based on operational data and maintenance performance during the period 2019–2024, as well as disruption patterns reflected through indicators of downtime, forced outage hours (FOH), and maintenance work backlogs.

1. Fishbone Classification Result

The results of the causal classification indicate that the factors of operational disruption can be grouped into five main categories: Man, Machine, Method, Material, and Environment. This classification is based on the relationships among increases in FOH, downtime, and maintenance backlog across the two generating units.

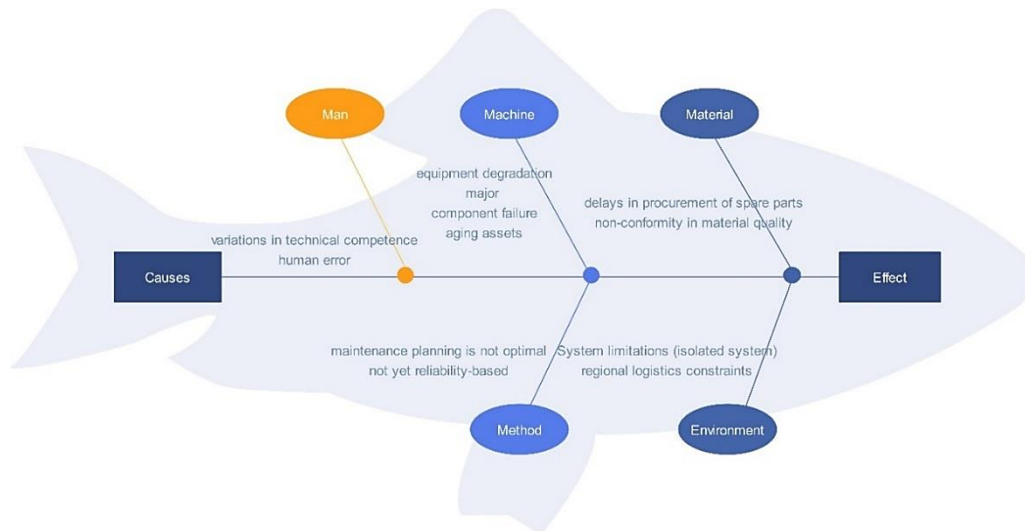


Figure 2. Fishbone Classification

2. Pareto Analysis Result

The results of the causal classification show that the factors of operational disruption can be grouped into five main categories, namely Man, Machine, Method, Material, and Environment. This classification is based on the relationships among increases in FOH, downtime, and maintenance backlog across the two generating units.

Table 7. Pareto Analysis of Root Causes

Category	Number of Cases	Percentage (%)	Cumulative (%)
Machine	42	32%	32%
Maintenance Delay	28	21%	53%
Human Error	18	14%	67%
Spare Part Delay	16	12%	79%
Operational Error	14	11%	90%
Material/Fuel	9	7%	97%
Environment	5	3%	100%

Table 7 shows that Machine is the largest root-cause category, with 42 cases (32% of total cases). Maintenance Delay accounts for 28 cases (21%), so the cumulative contribution of these two categories reaches 53%. When Human Error, Spare Part Delay, and Operational Error are added, the cumulative contribution reaches 90%. This means that most reliability disturbances are concentrated in equipment condition, maintenance execution, human factors, spare-part readiness, and operational discipline. Therefore, improvement programs should first focus on critical equipment rehabilitation, reducing the maintenance backlog, strengthening maintenance planning, and accelerating the procurement of critical spares.

3. Five Whys Analysis Result

To identify the dominant factors, a Five Whys analysis was conducted based on the frequency of disturbance events indicated by increases in FOH and the maintenance backlog during the observation period.

Table 8. Case 1 PLTU Ropa (2021)

Step	Analysis
Problem	High EFOR (6.59%)
Why 1	High forced outage (FOH)
Why 2	Equipment disruption increases

Step	Analysis
Why 3	Maintenance is not carried out on time
Why 4	Backlog of maintenance work increases
Why 5	Delays in the procurement of spare parts and maintenance priorities are not optimal
Root Cause	Maintenance management systems are not yet reliability-based

Table 8 explains the causal chain for PLTU Ropa in 2021, when EFOR reached 6.59%. The immediate cause was high forced outage hours, which were associated with increasing equipment disturbances. The deeper causes indicate that maintenance was not performed on time because the maintenance backlog increased and spare-part procurement was delayed. The final root cause is that the maintenance management system was not yet fully reliability-based. This finding shows that the problem was not merely technical failure, but a combination of asset degradation, delayed execution, spare-part constraints, and weak prioritization based on asset criticality.

Table 9. Case 2 PLTU Bolok (2022)

Step	Analysis
Problem	EAF decreased (81.40%)
Why 1	Total downtime increased
Why 2	Increased FOH and POH
Why 3	The frequency of disruptions and planned maintenance is increasing
Why 4	
Why 5	
Root Cause	Maintenance strategies tend to be reactive

Table 9 presents the Five Whys analysis for PLTU Bolok in 2022, when EAF decreased to 81.40%. The decrease was caused by higher total downtime, driven by increases in both FOH and POH. Further tracing shows that the frequency of disturbances and planned maintenance increased while the proportion of preventive maintenance declined. The root cause is that maintenance planning and execution were suboptimal, leading the strategy to become more reactive. This means that budget allocation alone was insufficient because reliability improvement also required timely planning, adequate work preparation, and a stronger preventive maintenance orientation. The results of the analysis integration showed that the main factors causing the ineffectiveness of Capex-Opex management were focused on several aspects, namely equipment degradation (machine factor), maintenance that experienced implementation delays (maintenance delays), limited procurement of spare parts (material factors), and imbalances between preventive and corrective maintenance (method factors). These factors appeared consistently in both generating units and were associated with increased FOH, downtime, as well as maintenance backlogs during the observation period.

3.2. Discussion

The results showed that increased Capex and Opex allocation did not consistently improve the plant's reliability, as indicated by fluctuations in EAF and EFOR values during the observation period. This condition indicates that the relationship between cost and reliability is non-linear, where effectiveness is determined not only by the budget amount but also by the accuracy of maintenance allocation and implementation.

These findings are in line with the research of Do et al., which showed that optimization of maintenance costs is only effective when combined with the right maintenance strategy [4]. However, the research still focuses on the technical optimization of components and has not considered the interaction between Capex and Opex in the broader system. In the context of this study, the ineffectiveness observed indicates a gap between cost allocation and the implementation of maintenance policies at the system level.

The shift in maintenance composition from preventive to corrective indicates a strategy that increases operational disruptions. The dominance of corrective maintenance, as shown by the increase in backlog and FOH, indicates that the maintenance system tends to be reactive. These findings support the concept of Reliability-Centered Maintenance (RCM) proposed by Moubray, where prevention-based maintenance is more effective in maintaining system reliability [18]. In addition, Akhsani and Yuniarto show that the integration of RCA in the maintenance system is able to reduce the failure rate through the feedback mechanism [19]. However, the study remains limited to the operational level and has not explicitly linked the RCA results to the Capex-Opex allocation policy.

The analysis showed that maintenance delays and work backlogs were the dominant factors driving increases in FOH and downtime. This condition shows an imbalance between maintenance needs and the capacity to implement them. Research by George-Williams and Patelli shows that a 20% reduction in maintenance delays can significantly lower EFOR [12]. These findings are consistent with this study's results,

which show that increased backlogs are directly associated with greater operational disruptions. However, previous research has still focused on scheduling and has not integrated systemic causal factors or their relationships with cost policy. Delays in Capex investment, particularly in the rehabilitation of key equipment, contribute to increased asset degradation and a higher failure frequency. This can be seen from the increase in FOH in a period where investment is not followed by an improvement in operating conditions.

These findings relate to the concept of asset lifecycle management which emphasizes the importance of timely investments to maintain asset performance [20]. In addition, Chumai shows that improper investments, such as an overhaul that is too frequent or not on target, does not provide a significant increase in reliability [21]. This reinforces that the effectiveness of CapEx is highly dependent on the accuracy of investment priorities.

The results show that Capex–Opex management ineffectiveness is systemic, involving interactions among technical, operational, and managerial factors. The RCA results show that most disruptions are caused not only by technical factors but also by systemic factors such as planning, coordination, and decision-making. This finding is in line with Yuniarto and Lawlor-Wright, who stated that about 68% of failures in the generation system are caused by systemic factors [15]. In addition, the System Dynamics approach proposed by Sterman emphasizes that complex systems have interrelated cause-and-effect relationships and form feedback loops [22]. In the context of this study, maintenance delays, work backlogs, and investment delays form a cycle that repeatedly undermines the plant's reliability. Basirat et al.'s research also showed that there is a feedback relationship between maintenance levels and failure rates, but it has not included cost policy variables such as Capex and Opex in its model [7]. Thus, this research fills a gap by integrating technical, operational, and cost policy factors into a single analytical framework.

Compared to previous research, this study contributes to integrating operational indicator-based reliability analysis (EAF, EFOR), root cause identification using the RCA approach, and Capex and Opex policy evaluation in the context of maintenance systems [1]. Previous research has tended to be partial, such as a focus on technical optimization, static reliability models, or technology-based approaches [4, 6, 10]. However, there has been little research integrating these three aspects within a single analytical framework that considers system dynamics and cost policies.

The practical implementation of these findings requires several managerial actions. First, annual CapEx planning should be linked to an asset-criticality matrix so that rehabilitation and replacement are directed to components with the highest effect on FOH and EFOR. Second, Opex planning should reserve sufficient resources for preventive maintenance and critical-spare procurement to prevent corrective work from dominating the maintenance portfolio. Third, backlog monitoring should be used as an early warning indicator because a rising backlog signals that maintenance demand exceeds execution capacity. Fourth, RCA results should be incorporated into periodic maintenance review meetings so that recurring problems are translated into actionable improvement programs.

Based on the results of the analysis, the main factors that affect the ineffectiveness of Capex and Opex management on plant reliability include equipment degradation that is not balanced with preventive maintenance, maintenance delays, high backlog of maintenance work, delays in procurement of spare parts, critical investment delays (Capex delays), and the dominance of reactive maintenance approaches

4. CONCLUSION

This study concludes that Capex and Opex management in coal-fired power plants does not directly determine plant reliability when expenditure is not supported by accurate prioritization, timely execution, and reliability-based maintenance strategies. The trend analysis of PLTU Bolok and PLTU Ropa during 2019-2024 shows that fluctuations and increases in cost allocation were not always followed by consistent improvement in EAF or reduction in EFOR. This indicates that reliability improvement is more strongly influenced by the effectiveness of maintenance implementation than by the budget alone.

The main factors causing ineffective Capex-Opex management include equipment degradation that is not offset by preventive maintenance, delays in maintenance implementation, a high maintenance backlog, delays in spare-part procurement, and delays in critical investments. The dominance of corrective maintenance further indicates that the maintenance system is reactive, contributing to increased unplanned outages and downtime. Therefore, Capex should be prioritized for critical asset rehabilitation and modernization, while Opex should strengthen preventive maintenance, routine inspections, and spare-part readiness.

The strength of this study is its integrated analytical framework, which combines reliability and maintenance performance indicators with RCA tools to identify the dominant causes of ineffectiveness. This approach enables the study to explain not only what happened to EAF and EFOR, but also why the cost allocation did not produce proportional reliability improvement. The practical contribution is the recommendation that Capex-Opex decisions should be aligned with asset criticality, backlog control, procurement lead time, and the balance between preventive and corrective maintenance.

However, this study also has limitations. The analysis is limited to two PLTU units in East Nusa Tenggara and uses annual historical data for the 2019-2024 period. In addition, the RCA results are based on

available operational records and maintenance performance indicators, so they may not fully capture daily execution constraints, detailed component-level failure modes, or differences in human resource capabilities. These limitations should be considered when generalizing the findings to other generating units or interconnected electricity systems.

Further research is recommended to develop a quantitative dynamic model that can comprehensively map the relationships among Capex, Opex, asset condition, maintenance backlog, FOH, EAF, and EFOR. A system dynamics approach, a predictive maintenance model, or a component-level reliability analysis can be used to simulate the effects of different investment and maintenance scenarios. Future studies may also expand the research object to other types of power plants or compare isolated and interconnected systems to strengthen the generalizability of the findings.

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