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Pareto Analysis of Loss Output in Geothermal Power Plant Equipment for Enhancing Operational Efficiency (Study Case: Geothermal Power Plant Salak #1)

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Abstract. This study aims to perform a Pareto analysis of output loss in Geothermal Power Plant equipment to identify priority maintenance interventions for enhancing operational efficiency. The Pareto method is used to analyze the contribution of each piece of equipment to output loss and determine which equipment should be prioritized for targeted maintenance and operational improvement. The analysis shows that 20% of equipment, such as cooling towers and pumps, contributes the most to output loss. Specifically, the DEHC Channel Malfunction resulted in a significant loss of 274,025 KWh, while Maintenance of FCT led to 180,875 KWh loss, with the total recorded loss of opportunity amounting to 929,800 KWh, equivalent to Rp883,309,991. Based on these findings, it is recommended that maintenance efforts should be focused on equipment that significantly impacts Geothermal Power Plant performance, with the goal of improving operational efficiency and reducing downtime. The Efficiency Optimization System (EOS) is used to monitor the performance of the plant in near real-time, identify inefficiencies, and provide improvement recommendations based on Pareto analysis to support decision-making in maintenance planning and operational optimization.

Keywords: *geothermal power plant, loss output, maintenance operational efficiency, Pareto analysis.*

1. Introduction

1.1 Background

Geothermal Power Plants are critical components of the renewable energy sector, playing an essential role in meeting growing global energy demands. These plants harness the Earth's internal heat to produce electricity, making them a sustainable energy source with minimal environmental impact. Despite their immense potential, Geothermal Power Plants often face operational challenges that lead to output losses, significantly affecting their efficiency and overall performance. These challenges, including equipment failures, underperfor mance of auxiliary systems, and unplanned downtime, translate directly into substantial financial losses due to ungenerated electricity and increased operational costs. Therefore, understanding and mitigating the root causes of these losses is paramount for the long-term sustainability and profitability of geothermal energy production.

Auxiliary equipment, though vital for the plant's smooth operation, often experiences issues such as wear and tear, inefficiencies, or mechanical failures, which can result in substantial energy losses. These losses can be particularly costly because auxiliary systems are necessary to maintain optimal conditions for the main generation units. Therefore, identifying and prioritizing which auxiliary equipment contributes the most to output loss is crucial for improving overall plant efficiency and reducing operational costs.

1.2 Literature Review and Research Gap

Numerous studies have explored methods for optimizing power plant operations and minimizing losses. For instance, Dani Badrazamani (2024) discusses the implementation of OEE (Overall Equipment Effectiveness) measurement standards in power plants, providing a framework for performance evaluation. Kadek Chesta Amrita (2018) focuses on thermal analysis in geothermal power plants, highlighting the importance of system-level efficiency. Zarrouk and Moon (2014) provide a thorough worldwide review on the efficiency of geothermal power plants, discussing various factors influencing conversion efficiency and the importance of optimizing these parameters for better performance. Applications of the Pareto principle in energy systems, such as advanced exergetic evaluation in geothermal district heating by Oguz Arslan (2022), underscore its utility in identifying significant contributors to inefficiency. Furthermore, PLN Nusantara Power (2023) reports on digital power plant implementation, showcasing industry efforts toward real-time monitoring and optimization, while R.S Atlason (2015) discusses innovations in geothermal turbine maintenance.

Specifically concerning the application of Pareto analysis in industrial maintenance contexts, Nwajana et al. (2024) demonstrated its effectiveness in optimizing maintenance resources for an instrumentation air compressor. Their methodology focused on identifying failure modes with the greatest cumulative effect on equipment downtime, thereby allowing for prioritized resource allocation to enhance equipment availability and reliability. This approach aligns with the core principle of this study to leverage Pareto analysis for identifying high-impact operational losses and directing maintenance efforts.

While existing literature extensively covers aspects of power plant efficiency and maintenance, there remains a gap in comprehensive studies that specifically integrate detailed, real-world operational loss data from an active geothermal power plant (quantified in KWh and monetary value) with a focused Pareto analysis to directly inform targeted, actionable maintenance recommendations. Many studies identify general problems or focus on high-level investments, but a direct linkage from granular operational incident data to prioritized maintenance interventions for enhancing overall operational efficiency is less explored. This study aims to bridge this gap by providing an actionable framework derived from real-world operational data to guide precise maintenance strategies at the equipment level.

Based on the identified research gap, this study seeks to answer the following questions:

1. What are the most significant causes of output loss (in KWh and financial terms) at the Geothermal Power Plant Salak Unit 1?
2. How can Pareto analysis effectively prioritize these loss-contributing factors to guide strategic maintenance efforts?
3. What specific and actionable maintenance recommendations can be derived from the Pareto analysis findings to enhance the operational efficiency and reliability of the Geothermal Power Plant?

Research Objectives
1. To quantify the output losses and associated financial impact due to various operational failures in the Geothermal Power Plant.
2. To apply Pareto analysis to identify and prioritize the key equipment and failure causes that contribute most significantly to total output losses.
3. To provide targeted maintenance recommendations based on the Pareto analysis findings to improve the overall operational efficiency and reliability of the Geothermal Power Plant.

This study offers practical benefits for Geothermal Power Plant operators by providing a data-driven approach to prioritize maintenance activities, optimize resource allocation, and ultimately reduce operational costs and unplanned downtime. For the broader renewable energy sector, it contributes a case study demonstrating the effective application of Pareto analysis in enhancing the sustainability and profitability of geothermal energy production.

2 Method

This study employs a quantitative descriptive research approach, focusing on a case study at Salak Unit 1 Geothermal Power Plant. The research methodology used in this study is illustrated in Figure 1.

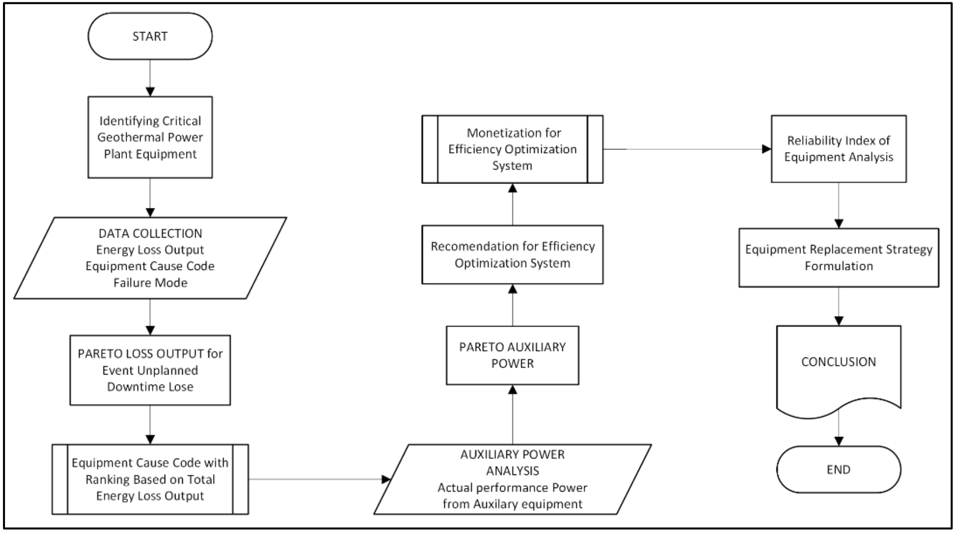

Figure 1 Research Methodology Flowchart.

2.1 Data Collection

Operational data from Salak Unit 1 Geothermal Power Plant was meticulously collected from internal plant records, including the Efficiency Optimization System (EOS) and daily operational logs, for the period of 1 January 2023 – 31 December 2023. The collected dataset specifically focuses on incidents leading to output losses and includes the following key parameters

1. ID Journal: A unique identifier for each recorded operational incident.
2. Failure Cause: A detailed description of the event or equipment malfunction that resulted in output loss
3. Respond Time: The duration (in hours) from the detection of an incident to its resolution, indicating the downtime incurred.
4. Loss of opportunity (KWH): The quantity of ungenerated electricity due to the incident. This value is calculated by multiplying the 'Respond Time' (downtime in hours) by the plant's average generation capacity of 55 MW during normal operation (in KW).
5. Benefit Losses: The monetary value of the lost opportunity, calculated by multiplying the Loss of opportunity (KWH) by the electricity selling price of Rp950/KWH.

This data provides a comprehensive overview of the plant's operational inefficiencies and their financial impact.

2.2 Pareto Loss Output Analysis

After gathering the raw data, a Pareto analysis was performed to identify and prioritize the most significant contributors to output loss. The steps involved are:

1. Aggregation of Losses: All individual incidents were grouped by their unique 'Failure Cause', and the Benefit Losses for each cause were summed to determine the total financial impact per failure type.
2. Ranking: The aggregated Failure Cause categories were then ranked in descending order based on their total Benefit Losses.
3. Cumulative Percentage Calculation: The percentage contribution of each failure cause to the total Benefit Losses was calculated, along with the cumulative percentage.
4. Pareto Chart Construction: A Pareto chart was constructed to visually represent the ranked failure causes and their cumulative contribution. This chart clearly distinguishes the vital few (the 20% of causes responsible for approximately 80% of the losses) from the trivial many.

This analysis provides a clear basis for prioritizing maintenance efforts.

2.3 Efficiency Optimization System (EOS)

The Efficiency Optimization System (EOS) is utilized to monitor and calculate the performance and efficiency of the power plant and its main components in near real-time. By leveraging operational data and historical trends, EOS identifies inefficient conditions within the plant units. It then maps these conditions through specialized analytical tools such as Pareto Heat Loss, performs evaluations, and generates actionable recommendations for addressing existing issues, improving unit efficiency, and identifying new improvement opportunities. These data-driven recommendations are crucial for guiding follow-up actions, ensuring the plant can swiftly return to and maintain optimal efficiency. The operational data utilized in the Pareto analysis within this study is directly captured and processed by this system.

2.4 Energy-loss Analysis

Energy-loss analysis is a key component of efficiency evaluation, involving the comparison of critical actual performance indicators against established reference values. Actual values are obtained from direct sensor readings or pre-calculated parameters, while reference values serve as a baseline, typically derived from commissioning documents or the latest certified Heat Rate tests. The deviation between actual and reference values is quantified using an impact factor to determine specific 'loss values'. These loss values serve as direct indicators of energy inefficiencies requiring further analysis. Performance indicators with captured loss values are then typically grouped into the top 10 and visually presented in a Pareto Heat Loss Diagram. A subsequent Gap Heat Rate analysis focuses on these top 10 performance indicators, culminating in concrete recommendations for heat rate improvement actions.

2.5 Auxiliary Equipment Analysis

Beyond the main power plant equipment, there is significant potential for Heat Rate improvement through a detailed analysis of Auxiliary Equipment. Energy loss in this context arises when auxiliary equipment operates below its optimal efficiency. By systematically tracking and quantifying losses within each auxiliary system, operators can effectively prioritize which systems demand immediate attention. This analysis helps determine whether repairs, component replacements, or strategic upgrades are necessary to restore and enhance the overall efficiency of the auxiliary fleet, thereby indirectly improving the main plant's performance.

2.6 Monetization of EOS

The analysis identifies the Potential Benefit Losses from inefficiencies in the system, calculated based on observed energy losses. These losses reflect the impact on operational costs and performance if corrective actions are not taken. Monetizing these losses helps clarify potential savings from improvements, justifying investments to optimize equipment performance and reduce energy waste. The Potential Benefit Losses are calculated by quantifying energy losses in terms of cost savings, including fuel, maintenance, and downtime costs, which aids in prioritizing corrective actions.

2.7 Reliability Index of Equipment Analysis

Based on the results of the Energy-loss Analysis and Auxiliary Power Analysis, an Equipment Reliability Index Analysis is also conducted to assess the performance and durability of equipment in the Geothermal Power Plant. The goal of this analysis is to identify equipment that frequently fails and poses a high risk of causing disruptions to plant operations. Equipment with low reliability indexes should be prioritized for maintenance or replacement to reduce downtime and improve operational efficiency. Additionally, the findings from this analysis can inform decisions related to equipment investment, as replacing unreliable or frequently failing equipment can reduce long-term operational costs and enhance the overall performance of the Geothermal Power Plant.

2.8 Equipment Replacement Strategy Formulation

Focuses on assessing the performance, reliability, and cost-effectiveness of equipment in a geothermal power plant to determine when replacement or upgrades are necessary. This strategy involves evaluating factors such as the equipment's reliability index, maintenance costs, energy losses, and the availability of spare parts. By identifying equipment that frequently fails or causes significant operational inefficiencies, the strategy prioritizes replacements that will yield the greatest improvements in plant performance and efficiency. Additionally, economic considerations, including life cycle costs and return on investment (ROI), play a key role in formulating the strategy. A well-developed replacement plan ensures the plant remains operationally reliable, cost-efficient, and capable of meeting long-term energy demands.

3 Result and Discussion

3.1 Overview of Operational Losses

Based on the data from Salak Unit 1 Geothermal Power Plant, here is the analysis of loss output (loss of opportunity) in the geothermal power plant. The data includes unplanned downtime and the failure causes for each event:

Table 1 Summary of Operational Losses at Geothermal Power Plant Salak Unit 1

NO	START		END		Duration	Failure Cause	Loss of opportunity
	Date	Time	Date	Time	Hours		
1	11-Jan-23	08:24	11-Jan-23	10:30	0.35	Maintenance of FCT Cell 3 & 4	19,950
2	20-Jun-23	08:18	20-Jun-23	11:11	0.23	Maintenance of FCT Cell 1 & 2	12,975
3	21-Jun-23	08:21	21-Jun-23	11:13	0.48	Maintenance of FCT Cell 3 & 4	27,233
4	22-Jun-23	08:13	22-Jun-23	10:31	0,39	Maintenance of FCT Cell 5	21,850
5	17-Aug-23	11:01	19-Aug-23	01:01	1.68	GRS and Steam Fluctuation Issues	95,000
6	20-Aug-23	07:30	21-Aug-23	00:17	0.74	Steam Fluctuation (GRS)	41,958
7	21-Aug-23	09:00	21-Aug-23	23:55	0.37	Steam Fluctuation (GRS)	20,883

NO	START		END		Duration	Failure Cause	Loss of opportunity
	Date	Time	Date	Time	Hours		
8	22-Aug-23	10:00	24-Aug-23	02:00	1.77	Steam Fluctuation (GRS)	100,000
9	25-Aug-23	12:05	26-Aug-23	02:30	0.89	GRS Failure	50,458
10	08-Sep-23	23:32	09-Sep-23	04:23	4.85	DEHC Channel Malfunction	274,025
11	03-Oct-23	08:15	03-Oct-23	10:35	0.27	Maintenance of FCT Cell 1 & 2	15,167
12	04-Oct-23	08:13	04-Oct-23	10:07	0.22	Maintenance of FCT cell 3 & 4	12,350
13	05-Oct-23	08:01	05-Oct-23	09:07	0.18	Maintenance of FCT Cell 5	10,450
14	01-Dec-23	09:46	01-Dec-23	12:00	2.23	Cooling Pump System Failure	126.183
15	01-Dec-23	12:00	01-Dec-23	12:50	0.72	Synchronization Test After Cooling Pump System Failure	40.417
16	12-Dec-23	08:32	12-Dec-23	10:55	0.61	Maintenance of FCT Cell No 1 & 2	34.558
17	13-Dec-23	08:04	13-Dec-23	09:53	0.47	Maintenance of FCT Cell 3 & 4	26.342
						Total Loss FOD (kwh)	**929.809**

Source: Geothermal Power Plant Salak Unit 1 Operational Data

As shown in Table 1, the total recorded loss of opportunity due to various operational incidents amounts to 929,800 KWh. Key contributors to these losses include:

1. DEHC Channel Malfunction: This single event resulted in the highest individual loss of 274,025 KWh, highlighting the critical impact of control system failures.
2. Maintenance of FCT: Scheduled or unscheduled maintenance of the Fan Cooling Tower (FCT) cells led to a loss of 180,875 KWh emphasizing the importance of optimizing maintenance windows.
3. Cooling Pump System Failure: A failure in the cooling pump system resulted in 126,183 KWh of loss output, with additional downtime for synchronization after repair.
4. Steam Fluctuations and GRS Issues: Multiple incidents related to steam fluctuations and GRS issues collectively contributed substantially to losses.

3.2 Pareto Analysis of Benefit Losses

To identify the most critical failure causes, a Pareto analysis was performed on the 'Benefit Losses (Rp)'. Table 2 presents the ranked failure causes, their individual financial loss, percentage contribution, and cumulative percentage.

Table 2 Pareto Analysis of Operational Benefit Losses

NO	ID JOURNAL	Failure Cause	Respond Time	Loss of opportunity (KWh)	Benefit Losses (Rp)
1	397086	DEHC Channel Malfunction	4.85	274,025	260,323,750
2	423992	Maintenance of FCT	3.20	180,875	171,831,250
3	422048	Cooling Pump System Failure	2.23	126,183	119,874,164
4	392095	Steam Fluctuation (GRS)	1.77	100,000	95,000,000
5	390708	GRS and Steam Fluctuation Issues	1.68	95,000	90,250,000
6	393026	GRS Failure	0.89	50,458	47,935,414
7	392335	Steam Fluctuation (GRS)	0.74	41,958	39,860,414
8	421018	Synchronization Test After Cooling Pump System Failure	0.72	40,417	38,395,837
9	391485	Steam Fluctuation (GRS)	0.37	20,883	19,839,164
Losses				**929,800**	
Benefit Losses				**Rp883,309,991**	

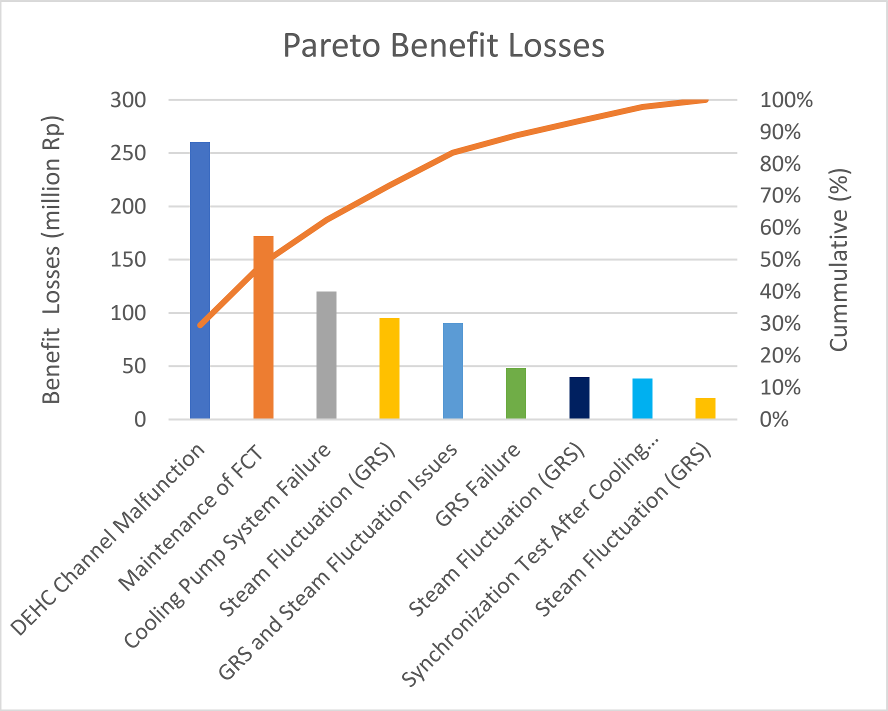

Figure 2 Pareto chart derived from Table 2, visually depicting the main contributors to financial losses and their cumulative impact

As depicted in Figure 2, the Pareto analysis clearly identifies that the top three failure causes DEHC Channel Malfunction, Maintenance of FCT, and Cooling Pump System Failure collectively account for approximately 62.49% of the total benefit losses. Expanding this to include the two largest Steam Fluctuation (GRS) related issues (ID: 392095 and 390708) brings the cumulative loss to 83.47%. This confirms the Pareto principle, where a "vital few" causes are responsible for the majority of the losses. Therefore, focusing maintenance efforts on these specific areas will yield the most significant improvements in operational efficiency and loss reduction.

3.3 Specific Pareto Analysis for Auxiliary Equipment Losses

To further refine the understanding of losses specifically within auxiliary equipment, a more granular Pareto analysis was conducted on the FCT maintenance activities, which are a recurring source of output loss. Figure 2 presents the Pareto Loss Auxiliary Equipment analysis based on KWh loss.

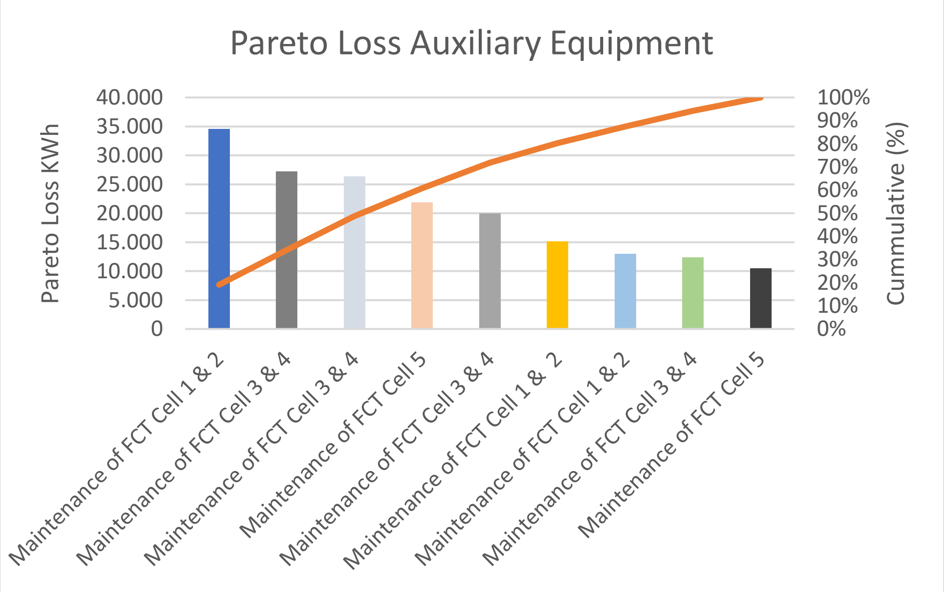

Figure 3 Pareto Loss Auxiliary Equipment

As shown in Figure 3, among the various FCT maintenance activities, Maintenance of FCT Cell 1 & 2" represents the largest individual contributor to KWh loss within the auxiliary equipment category. This is followed by Maintenance of FCT Cell 3 & 4 and Maintenance of FCT Cell 3 & 5. This granular analysis provides a clear priority for optimizing maintenance schedules and procedures specifically for these high-impact FCT cells, highlighting their critical role in overall plant output and efficiency. The cumulative line in Figure 2 further reinforces that a few specific FCT maintenance events are responsible for the majority of KWh losses within this auxiliary system.

3.4 Anomaly Detection and Frequency Analysis

Beyond quantifying losses, understanding the frequency of various operational anomalies is crucial for proactive maintenance planning. Figure 3 illustrates the frequency of detected anomalies, providing insight into which issues occur most often.

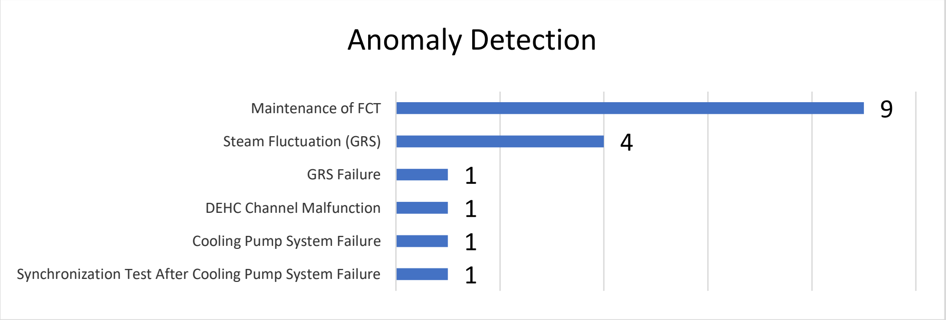

Figure 4 Anomaly Detection

Figure 4 reveals that Maintenance of FCT is the most frequently occurring anomaly, with 9 detected instances. This aligns with its significant contribution to overall KWh loss, suggesting that while individual FCT maintenance events might have shorter durations, their high frequency accumulates to substantial losses. Steam Fluctuation (GRS) is the second most frequent anomaly with 4 occurrences, indicating a recurring challenge in maintaining stable steam supply. Other issues like GRS Failure, DEHC Channel Malfunction, and Cooling Pump System Failure each occurred once, but as shown in the Pareto analysis (Table 2), single occurrences of these events can lead to very large financial losses. This frequency data complements the Pareto analysis by differentiating between high-impact, low-frequency events and lower-impact, high-frequency events, both of which require distinct maintenance approaches.

3.5 Implications for Operational Efficiency and Maintenance

The findings from the Pareto analysis provide actionable insights for enhancing operational efficiency through targeted maintenance:

1. Focus on DEHC System Reliability: The highest individual loss from DEHC Channel Malfunction indicates a critical need for rigorous preventive and predictive maintenance programs for the Digital Electro-

Hydraulic Control system, including regular calibration and sensor checks to prevent costly breakdowns.

2. Optimize FCT Maintenance Schedules: While maintenance is necessary, the significant losses from FCT maintenance suggest opportunities for optimizing scheduling, perhaps through modular FCT designs allowing partial operation during maintenance, or performing maintenance during periods of lower demand to minimize impact.
3. Strengthen Cooling Pump System Maintenance: The combined losses from Cooling Pump System Failure and subsequent Synchronization Tests underscore the need for robust preventive maintenance and redundancy in the cooling pump system. Ensuring spare parts availability and skilled personnel for rapid repair is vital.
4. Investigate Steam and GRS Stability: The recurring losses from Steam Fluctuations and GRS issues point to a broader systemic challenge. Further root cause analysis is needed to address the inherent instability, potentially involving reservoir management strategies or advanced process control optimization.
5. Role of EOS and Data-Driven Maintenance: The Efficiency Optimization System (EOS) plays a crucial role by providing real-time data to identify these inefficiencies. The data used for this Pareto analysis can be continuously fed into the EOS to monitor the effectiveness of implemented maintenance recommendations and identify emerging issues. This aligns with the principles of Energy-loss Analysis and Auxiliary Equipment Analysis, which are designed to pinpoint specific areas of inefficiency.

3.6 Reliability Index and Equipment Replacement Strategy in Maintenance Context**

While the primary focus is on maintenance interventions, the Reliability Index of Equipment Analysis and the Equipment Replacement Strategy Formulation remain integral components of a comprehensive maintenance program. Equipment with consistently low reliability indexes should not only be subject to intensified preventive maintenance but also evaluated for eventual replacement, as continuous repairs may become economically unviable in the long term. Monetizing the Potential Benefit Losses from recurrent failures justifies not only immediate maintenance actions but also strategic decisions for component upgrades or replacements that offer greater long-term cost savings and operational stability. These strategies, backed by data from Energy-loss and Auxiliary Power analyses, support decision-making for cost-effective maintenance and equipment upgrades.

4 Conclusion

4.1 Conclusion

This study successfully applied Pareto analysis to identify and quantify the most significant causes of output loss in a Geothermal Power Plant, specifically at Salak Unit 1. The comprehensive analysis revealed a total loss of opportunity amounting to 929,800 KWh, equivalent to a substantial financial loss of Rp883,309,991. Critically, the Pareto principle was strongly confirmed, as a vital few failure causes DEHC Channel Malfunction, Maintenance of FCT, and Cooling Pump System Failure were found to be collectively responsible for the predominant majority (approximately 62.49%) of these total losses. Further detailed analysis highlighted specific FCT cells (e.g., FCT Cell 1 & 2) as major contributors within auxiliary equipment losses, and frequency analysis identified FCT maintenance as the most common anomaly.

Based on these robust findings, this study strongly recommends prioritizing maintenance efforts and resource allocation on these identified high-impact equipment and recurring operational issues. By strategically focusing on targeted maintenance interventions for the DEHC system, optimizing FCT maintenance schedules and procedures, and strengthening cooling pump system maintenance, Geothermal Power Plants can significantly enhance their operational efficiency, reduce costly unplanned downtime, and improve overall reliability. Furthermore, continuous monitoring through advanced systems like EOS and detailed energy-loss analyses will serve as critical tools to support informed decision-making in proactive maintenance planning, operational optimization, and strategic equipment upgrades.

4.2 Future Works

Future research could delve deeper into the root cause analysis of the identified vital few failures (e.g., DEHC malfunctions, specific FCT issues, GRS instability) to develop more granular, specific, and sustainable long-term solutions. Investigating the correlation between response time for various failure types and their overall impact on losses, including a comprehensive cost-benefit analysis of different maintenance strategies (e.g., preventive vs. predictive), could also provide valuable insights. Additionally, a comparative study across multiple geothermal power plants using similar Pareto analysis methodologies could validate these findings and identify industry-wide best practices for maintenance optimization and asset management.

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