JURNAL LOCUS: Penelitian & Pengabdian
Volume 5 No. 8 August 2026
E-ISSN 2829-7334| P-ISSN 2829-5439
Hompage: https://locus.rivierapublishing.id/index.php/jl

A Multi-Criteria Decision-Making Framework for Selecting Reliability Improvement Strategies of an Auxiliary Boiler in a Refinery Utility System: A Case Study at PT Pertamina Patra Niaga RU IV Cilacap

Arya Bayu Wibisono
Institut Teknologi Bandung, Indonesia
Email: aryabayuwibisono@gmail.com

Keywords:
Decision-Based Strategy Selection; Analytical Hierarchy Process; Auxiliary Boiler; Reliability Improvement; Multi-Criteria Decision-Making; Refinery Utility System.

Abstract

The reliability of refinery utility systems plays a critical role in ensuring operational continuity, production efficiency, and safety in petroleum refining processes. At PT Pertamina Patra Niaga Refinery Unit (RU) IV Cilacap, the auxiliary boiler supporting the Residual Fluid Catalytic Cracking (RFCC) unit has experienced recurring reliability issues, particularly economizer tube failures, despite multiple corrective interventions. These recurring failures indicate that selecting an appropriate reliability improvement strategy is not merely a technical issue but a complex decision-making problem involving multiple conflicting criteria. Therefore, this study aims to develop a structured multi-criteria decision-making framework to identify the most appropriate reliability improvement strategy for auxiliary boiler 151B501. A case-based research design was employed using the Analytical Hierarchy Process (AHP) as the primary decision-support method. Expert judgments were collected from cross-functional stakeholders representing Engineering, Operation, Maintenance, and Management through pairwise comparison questionnaires. Five evaluation criteria Safety, Operational Reliability, Operational Flexibility, Ease of Implementation, and Cost and Risk Implications were used to assess four strategic alternatives. The results indicate that Safety and Operational Reliability are the most influential decision criteria, jointly accounting for approximately 68.9% of the overall priority weight. Comprehensive Physical Intervention emerged as the highest-ranked strategy with a global priority value of 0.427 and remained the preferred alternative under sensitivity analysis, demonstrating the robustness of the proposed framework. The study concludes that AHP provides a systematic, transparent, and accountable approach for prioritizing refinery reliability improvement strategies while integrating technical, operational, maintenance, and managerial perspectives. The proposed framework can support strategic asset management decisions and may be adapted for other critical utility systems in refinery operations.

INTRODUCTION

Energy demand, particularly for petroleum fuels, has shown an upward trend in line with economic growth, population mobility, and industrialization. In recent decades, Indonesia's oil consumption has continued to increase, reflecting growing demand pressure on the national energy supply chain (BP, 2023; CEIC Data, 2023). Under these conditions, the reliability of domestic refining operations becomes an important factor in maintaining supply continuity and managing operational disruptions within the downstream energy system.

In this context, PT Pertamina Patra Niaga through Refinery Unit (RU) IV Cilacap plays an important role as one of the backbones of national oil processing. RU IV Cilacap is recognized as one of the largest refineries in Indonesia, with a processing capacity of around 348 thousand barrels per day, and serves as an important supplier of fuel oil for Java and its surrounding regions (Pertamina, 2023). With its large facility and complex process configuration, the reliability of RU IV Cilacap operations affects not only internal operational performance but also the continuity of product supply at the regional level.

Since the operation of the Residual Fluid Catalytic Cracking (RFCC) unit at RU IV Cilacap in 2015, the reliability requirements of refinery operations have increased, given the high economic value and contribution of RFCC to overall refinery performance. RFCC was developed to increase the conversion of Low Sulfur Waxy Residue (LSWR) into higher-value products and to enhance production flexibility (Pertamina, 2016; IESR, 2022). However, the economic benefits of RFCC can only be achieved when the supporting utility systems operate reliably. Any disruption in utilities can directly affect RFCC operations, leading to operating limitations, reduced performance, or even production interruptions, which in turn reduce the overall contribution of the unit. More recently, Wang et al. (2025) combined AHP and TOPSIS to select the optimal maintenance strategy for oil and gas industry equipment based on overall equipment effectiveness, cost, safety, efficiency, and flexibility criteria, reinforcing the continued relevance of AHP-based frameworks in the petroleum sector. Within the Indonesian refining sector specifically, Afrianto and Sarjono Putro (2026) applied an integrated AHP–TOPSIS framework to support strategic pre-feasibility decisions for low-sulfur gasoline production at PT Pertamina's RU III Plaju, illustrating the growing adoption of multi-criteria decision-making in national refinery planning.

Thus, the issue of operational reliability at RU IV Cilacap does not lie solely in the performance of the main process units, but also in the reliability of support systems, particularly utility systems, that sustain the continuity of RFCC operations. Reliability management therefore needs to move beyond a narrow focus on individual main process equipment and place greater emphasis on support units that, although not directly producing products, exert an equally critical influence on overall operational reliability.

Refinery Unit (RU) IV Cilacap is one of the strategic refining facilities within PT Pertamina Patra Niaga, characterized by a high level of operational complexity. As one of the largest refineries in Indonesia, RU IV operates multiple integrated process units and supporting systems that must function in a coordinated manner to sustain daily operations. Under such conditions, the reliability of refinery performance is not determined solely by the main process units, but also by the readiness and stability of the supporting systems that connect and sustain the overall process chain. A disruption in one subsystem may propagate and create systemic impacts on overall refinery performance (Pertamina, 2023).

Following the commissioning of the Residual Fluid Catalytic Cracking (RFCC) unit in 2015, the operational dependency structure within RU IV Cilacap became more pronounced. RFCC, as a high value-added unit, requires stable and continuous support from utility systems to maintain its performance targets. Consequently, even minor disruptions in utility supply can impose operational constraints or reduce the effective contribution of RFCC to refinery output (IESR, 2022).

Within PT Pertamina Patra Niaga Refinery Unit IV Cilacap, the reliability challenge became increasingly important after the commissioning of the Residual Fluid Catalytic Cracking unit in 2015. The RFCC unit converts Low Sulfur Waxy Residue into higher-value products and contributes significantly to refinery output and production flexibility. However, its operational performance depends on the continuous availability of utility services, particularly steam, water, fuel, and electrical power. Utility equipment does not directly generate marketable petroleum products, but its failure can constrain processing capacity, destabilize operating conditions, or initiate an unplanned shutdown of connected production units. The auxiliary boiler with equipment tag 151B501 is particularly important because it supplies steam supporting RFCC-related operations. Its reliability therefore affects not only the condition of an individual boiler but also the stability of the broader utility network and the effective contribution of the RFCC unit to refinery operations.

Historical operational records described in the research manuscript indicate that auxiliary boiler 151B501 has experienced recurring reliability disturbances, especially economizer tube leakage, since the early operating period. Corrective actions have included local repairs, partial retubing, technical inspection, full economizer retubing, operational modification, enhanced monitoring, and tighter operating controls. Nevertheless, reliability concerns reappeared after several interventions, including after the major intervention undertaken during the 2023–2025 period. The recurrence of failures suggests that the problem is persistent rather than incidental and that isolated corrective actions have not eliminated the underlying reliability risk. These events may affect steam-supply stability, increase repetitive maintenance requirements, reduce operational flexibility, and elevate the possibility of localized overheating or loss of primary containment. Boiler-related safety incidents remain a recognized concern across process industries, as Ali and Habibullah (2019) reported that inadequate inspection practices and non-compliance with safety regulations continue to contribute to boiler accidents. More recently, Rahman et al. (2022) applied a neutrosophic AHP approach to prioritize the causes of boiler accidents in industrial settings, confirming that safety-related criteria are consistently regarded as dominant factors in boiler risk-management decisions. The problem must therefore be viewed as a strategic reliability decision involving technical effectiveness, safety, implementation complexity, cost exposure, production continuity, and residual risk rather than merely as a component-level repair issue.

Previous studies have demonstrated the relevance of multi-criteria methods for industrial maintenance decisions. Bevilacqua and Braglia applied the Analytical Hierarchy Process to select maintenance strategies for approximately 200 facilities in an Italian oil-refinery integrated gasification combined-cycle plant. Their framework compared preventive, predictive, condition-based, corrective, and opportunistic maintenance by considering criteria such as cost, reliability, failure consequences, applicability, and added value. The study showed that AHP can transform complex qualitative and quantitative considerations into a hierarchical structure and generate priorities through systematic pairwise comparisons. It also emphasized the importance of sensitivity analysis because maintenance decisions may change when decision-makers assign different levels of importance to safety, cost, reliability, or implementation considerations. Although this research established an important methodological foundation, it focused on broad maintenance-policy selection across groups of refinery equipment rather than on prioritizing specific physical, monitoring, repair, and operational strategies for a repeatedly failing auxiliary boiler. In a related national oil-industry context, Salmasnia et al. (2016) combined AHP with revised multi-choice goal programming to select maintenance strategies for electric motor components at the National Iranian Oil Refining and Distribution Company, underscoring the applicability of hybrid AHP-based models within state-owned refinery operations.

Bertolini and Bevilacqua subsequently integrated AHP with lexicographic goal programming to determine maintenance strategies for critical centrifugal pumps in an oil refinery. Their model incorporated failure occurrence, severity, detectability, maintenance workload, repair requirements, human resources, and budget constraints. By using maintenance and failure data covering a ten-year operating period, the study demonstrated that refinery maintenance decisions require simultaneous consideration of technical risk, resource limitations, operational consequences, and managerial priorities. Wang and colleagues also developed a fuzzy AHP-based framework for selecting an optimum maintenance strategy from corrective, time-based preventive, condition-based, and predictive alternatives, reinforcing the usefulness of multi-criteria approaches where judgments are uncertain and the evaluation factors conflict. These studies confirm that no maintenance strategy is universally superior because the preferred option depends on equipment criticality, operating context, organizational capability, failure consequences, and the relative importance assigned to each criterion. Elijah and Obaseki (2022) similarly integrated reliability-centered maintenance with AHP to prioritize maintenance actions for rotodynamic equipment in a petrochemical facility, demonstrating that AHP can be embedded within broader reliability-engineering frameworks rather than applied as a stand-alone decision tool.

Additional research has strengthened the integration of risk into maintenance-policy selection. Arunraj and Maiti combined AHP and goal programming to select maintenance policies for equipment in a benzene extraction unit, explicitly incorporating equipment-failure risk and maintenance cost. Their findings showed that condition-based maintenance could be preferable to time-based maintenance when risk-reduction capability received greater decision weight. Jagtap and Bewoor (2017) applied AHP to identify critical equipment in a thermal power plant, showing that systematic expert comparison can support equipment prioritization in complex systems where different components produce different operational consequences. In a related application, Yagmur (2016) used AHP to prioritize thermal power plant equipment for technology localization, further confirming the suitability of AHP for asset-level industrial decisions. Patil and colleagues (2022) further developed a multi-criteria failure-mode assessment for boiler systems, demonstrating that boiler criticality cannot be adequately evaluated through a single conventional risk score when multiple technical and organizational criteria are involved. Collectively, these studies demonstrate the applicability of AHP to maintenance, risk assessment, equipment criticality, and process-industry decision-making.

Despite these contributions, an important research gap remains. Most earlier studies evaluate general maintenance policies, classify equipment according to criticality, optimize inspection activities, or combine AHP with mathematical programming across many assets. Limited evidence is available regarding an AHP framework specifically designed to prioritize predefined reliability-improvement strategies for a single critical auxiliary boiler whose failures have persisted after partial and comprehensive physical interventions. Previous studies also tend to treat maintenance alternatives as mutually exclusive policies, whereas the alternatives available for boiler 151B501 may perform different but complementary roles. A comprehensive physical intervention may provide the principal long-term direction, while partial repair, enhanced monitoring, and operational control may function as interim or supporting measures. Moreover, the existing decision process at RU IV Cilacap has relied mainly on technical evaluation, expert discussion, cross-functional meetings, and managerial judgment without a formal mechanism for weighting conflicting technical, safety, operational, implementation, and business criteria.

Addressing this gap is urgent because continuing to rely primarily on repetitive corrective action may leave substantial residual risk and produce inefficient allocation of maintenance resources. The selection of an inappropriate strategy may result in repeated leakage, additional downtime, unnecessary expenditure, reduced RFCC operating stability, or greater safety exposure. Conversely, selecting a technically comprehensive strategy without considering implementation readiness, shutdown windows, material availability, vendor support, and organizational resources may create execution delays or operational disruption. The novelty of this research therefore lies in constructing a case-specific, cross-functional AHP framework that evaluates four feasible strategic alternatives comprehensive physical intervention, partial repair, enhanced monitoring and decision support, and operational control and discipline against five integrated criteria: operational reliability, safety, operational flexibility, ease of implementation, and cost and risk implications. The framework also positions AHP as a transparent prioritization instrument rather than a deterministic replacement for managerial judgment.

Accordingly, this research aims to develop and apply a multi-criteria decision-making framework for identifying the most appropriate reliability-improvement strategy for auxiliary boiler 151B501 at RU IV Cilacap. Its specific objectives are to structure the reliability problem into a clear decision hierarchy, determine the relative importance of the evaluation criteria, measure the priorities of each strategic alternative, integrate judgments from Engineering, Operation, Maintenance, and Management stakeholders, examine the logical consistency of expert assessments, and evaluate the robustness of the resulting ranking through sensitivity analysis. The research is expected to contribute theoretically by extending the application of AHP from general maintenance-policy selection to a strategic equipment-specific reliability problem and practically by providing a transparent, traceable, and accountable basis for resource allocation and implementation planning. Its broader benefits include strengthening boiler reliability, supporting RFCC continuity, reducing repetitive maintenance and residual failure risk, improving cross-functional alignment, and providing a framework that may be adapted for decision-making involving other critical utility equipment within refinery operations.

METHOD

This section described the research design, development of the AHP decision model, data collection process, and analytical procedure used to evaluate reliability improvement strategies for auxiliary boiler 151B501.

Research Design

This study was designed as a case-based decision study aimed at supporting the prioritization of reliability improvement strategies for auxiliary boiler 151B501 in the RU IV

Cilacap utility system. The study applies a qualitative decision-based approach supported by quantitative processing using the Analytical Hierarchy Process (AHP). The qualitative component was used to understand the decision context, stakeholder perspectives, operational constraints, and characteristics of available strategic alternatives. The quantitative component was used to process expert judgments systematically through pairwise comparison, consistency testing, aggregation of judgments, and calculation of global priorities. AHP remains one of the most frequently applied multi-criteria decision-making techniques in engineering decision problems because of its transparent pairwise-comparison structure and its capacity to integrate expert judgment into a hierarchical model, as noted in a recent review by Chaube et al. (2024).

In this study, AHP is positioned as a decision support tool rather than a substitute for managerial decision-making. The method provides a structured and transparent mechanism to compare alternative strategies based on multiple criteria. The output of the model is therefore interpreted as a prioritization basis, not as a final deterministic decision. This is important because the evaluated alternatives are not necessarily mutually exclusive; the highest-ranked alternative may serve as the main strategic direction, while other alternatives may function as supporting or transitional strategies.

AHP Decision Model Development

The AHP model was developed based on the decision context, stakeholder perspectives, operational experience, and historical reliability issues of auxiliary boiler 151B501. The model consists of three hierarchical levels: the decision goal, evaluation criteria, and strategic alternatives.

The decision goal is to determine the most appropriate reliability improvement strategy for auxiliary boiler 151B501. The selected strategy is expected to provide a balanced contribution to operational reliability, safety, operational flexibility, ease of implementation, and cost and risk implications within the operational context of RU IV Cilacap.

Five evaluation criteria were used in this study. Operational Reliability reflects the ability of a strategy to reduce recurring disturbances, improve steam supply stability, and support refinery utility continuity. Safety represents the ability of a strategy to control safety risks and reduce undesirable events associated with boiler failure, including escalation risks related to tube leakage and abnormal operating conditions. Operational Flexibility refers to the extent to which a strategy supports controllability and adaptability under varying operating conditions. Ease of Implementation reflects the practical feasibility of executing the strategy, including complexity, resource requirements, organizational readiness, field constraints, and coordination needs. Cost and Risk Implications represent financial exposure and residual operational, technical, and managerial risks after implementation.

Four strategic alternatives were evaluated. A1, Comprehensive Physical Intervention, refers to comprehensive repair or replacement of key boiler components to address the source of failure more fundamentally. A2, Partial Repair Strategy, focuses on targeted repair of specific critical components based on historical failure findings. A3, Enhanced Monitoring and Decision Support, strengthens condition monitoring and decision-support mechanisms to manage reliability risk proactively. A4, Operational Control and Discipline Strategy, emphasizes operating condition control, operating restrictions, and improved compliance with operating procedures.

Data Collection

The primary data were obtained through expert judgment from internal stakeholders directly involved in technical evaluation, operation, maintenance execution, and managerial decision support related to auxiliary boiler 151B501 and the refinery utility system. The respondents represented Engineering, Operation, Maintenance, and Management functions. They were selected purposively based on their functional relevance, direct involvement, and practical experience in decision-making related to boiler reliability and utility system performance.

Data were collected using a pairwise comparison questionnaire structured according to the AHP hierarchy. Respondents were asked to compare the relative importance of criteria and the relative preference of alternatives under each criterion using Saaty's 1–9 preference scale. Before completing the questionnaire, each respondent was provided with an explanation of the study objective, decision hierarchy, evaluation criteria, strategic alternatives, and interpretation of the comparison scale to reduce potential misunderstanding.

AHP Analysis Procedure

The AHP analysis was conducted in several steps. First, pairwise comparison matrices were developed for the criteria and for the alternatives under each criterion based on the judgments provided by each respondent. Second, priority weights were calculated by deriving the principal eigenvector of each pairwise comparison matrix. Third, the logical consistency of each matrix was evaluated using the Consistency Index (CI) and Consistency Ratio (CR). A CR threshold of ≤ 0.10 was used as the acceptability criterion, following common practice in AHP applications.

When a judgment matrix produced a CR value close to or above the threshold, clarification was conducted with the relevant respondent to confirm the intended comparison and ensure logical consistency. This clarification was intended to address possible misunderstanding in the pairwise comparison process, not to force a specific preference outcome. This approach is consistent with Ohta (2018), who demonstrated that clarifying or revisiting inconsistent pairwise judgments, rather than discarding them, helps preserve the validity of classical AHP applications when expert panels include participants with differing functional backgrounds.

After individual priority weights were obtained, the results were aggregated to represent group preferences. Aggregation was performed using the geometric mean, followed by normalization to obtain final group weights for both criteria and alternatives. Finally, global priority values were calculated by multiplying the weight of each criterion by the priority of each alternative under that criterion and summing the results across all criteria. The resulting global priorities were used to rank the strategic alternatives and interpret the trade-offs among them.

RESULTS AND DISCUSSION

This section presents the results of the AHP analysis and discusses their implications for selecting reliability improvement strategies for auxiliary boiler 151B501. The discussion focuses on three main aspects: the consistency of expert judgments, the priority structure of criteria and alternatives, and the strategic interpretation of the results within the operational context of RU IV Cilacap.

Decision Context and Respondent Profile

The selection of a reliability improvement strategy for auxiliary boiler 151B501 involves several internal functions with different priorities and decision perspectives. The respondents in this study represented Engineering, Operation, Maintenance, and Management functions. These functions were selected because they are directly related to technical evaluation, daily operation, maintenance execution, and managerial decision support for critical utility equipment.

Engineering focuses on equipment integrity, failure history, technical effectiveness, and long-term reliability improvement. Operation emphasizes steam supply stability, operational continuity, and flexibility under changing operating conditions. Maintenance considers implementation feasibility, resource readiness, work duration, and execution risk. Management provides a broader perspective by balancing safety, reliability, resource allocation, operational impact, and organizational priorities.

Table 1. Cross-Functional Perspectives in the Decision-Making Process

Function	Primary Focus	Key Considerations	Potential Trade-Off
Engineering	Long-term reliability and integrity	Design, failure history, technical effectiveness	Higher complexity and implementation effort
Operation	Operational continuity and stability	Steam supply, flexibility, minimal disruption	May limit the scope of physical intervention
Maintenance	Implementation feasibility	Resources, access, work duration, execution risk	Trade-off between technical effectiveness and practicality
Management	Strategic alignment and risk control	Safety, policy, resource allocation, organizational priorities	Balancing competing functional priorities

Table 1. shows that each function contributes a distinct perspective to the evaluation process. This supports the use of a multi-criteria decision-making method because the strategy selection cannot be represented adequately by a single functional viewpoint.

Consistency of Pairwise Assessments

All pairwise comparison matrices were evaluated using the Consistency Ratio (CR). The CR values for the criteria and alternative comparison matrices were below the accepted threshold of 0.10, indicating that the expert judgments were logically consistent and suitable for further AHP analysis.

Table 2. Summary of Consistency Ratio (CR)

Type of Assessment	CR Range (%)	Average CR (%)	Status
Criteria comparison	4.0 – 5.6	~4.8	Accepted
Alternative comparison under each criterion	1.1 – 8.0	~5.5	Accepted

The results in Table 2 indicate that all assessments met the consistency requirement. In cases where the initial CR values were close to or slightly above the threshold, clarification was conducted with the respective respondents to confirm their intended judgments and ensure logical consistency. This process was intended to address possible misunderstanding in the pairwise comparison process, not to force a particular preference outcome.

Patterns of Individual Expert Judgments

The individual AHP results show different preference patterns across functions. These differences reflect the distinct roles, constraints, and priorities of each function in addressing the reliability issue of auxiliary boiler 151B501.

Table 3. Summary Ranking of Alternatives

Function	1st	2nd	3rd	4th	Dominant Preference
Engineering	A1	A2	A3	A4	A1
Maintenance	A2	A1/A3	A3/A1	A4	A2
Operation	A1	A2	A3	A4	A1
Management	A1/A3	A3/A1	A2	A4	A1/A3

Note: A1 = Comprehensive Physical Intervention; A2 = Partial Repair Strategy; A3 = Enhanced Monitoring and Decision Support; A4 = Operational Control and Discipline Strategy. Combined alternatives (e.g., A1/A3) indicate comparable priority level with no clear dominance.

Engineering and Operation showed a similar preference pattern, with A1 consistently ranked as the highest-priority alternative. This indicates a reliability-driven logic that emphasizes long-term risk reduction and system stability. Maintenance placed A2 as the preferred alternative, reflecting an implementation-driven logic that considers resource readiness, execution practicality, and field constraints. Management showed a more balanced pattern between A1 and A3, indicating a trade-off perspective between fundamental reliability improvement and adaptive risk control.

These findings demonstrate that the differences in preference are not inconsistencies, but rather the result of different functional orientations. Therefore, the group AHP result is important because it integrates these perspectives into a structured and transparent decision outcome.

Group AHP Results

The group AHP results represent the aggregation of individual expert judgments. The results include criteria weights, alternative priorities under each criterion, and global priority values for each strategy.

1. Group Criteria Weights

The group criteria weights show the relative importance of the five evaluation criteria in selecting the most appropriate reliability improvement strategy.

Table 4. Group Criteria Weights

CRITERIA	NORMALIZED CRITERIA WEIGHT	PERCENTAGE	RANK
Operational Reliability	0.3017	30.17%	2
Safety	0.3871	38.71%	1
Operational Flexibility	0.0792	7.92%	5
Ease of Implementation	0.1437	14.37%	3
Cost & Risk Implications	0.0883	8.83%	4
TOTAL	**1.0000**	**100%**	

Safety and Operational Reliability were the two most dominant criteria, jointly accounting for approximately 68.9% of the total criteria weight. This indicates that the expert group placed greater emphasis on safety risk control and long-term operational reliability than on short-term implementation convenience or cost considerations. Ease of Implementation remained relevant, but it was not the primary driver of the decision. Cost and Risk Implications and Operational Flexibility had lower weights, indicating that they functioned as supporting considerations in the overall decision structure.

2. Global Priority and Ranking of Alternatives

After the criteria weights and alternative priorities were aggregated, the global priority of each strategy was calculated. The global priority represents the overall preference of each alternative by considering both the relative importance of the criteria and the performance of each alternative under each criterion.

Table 5. Global Priority and Ranking of Alternatives

Alternative	Strategy	Global Priority	Rank
A1	Comprehensive Physical Intervention	0.427	1
A2	Partial Repair Strategy	0.280	2
A3	Enhanced Monitoring and Decision Support	0.149	3
A4	Operational Control and Discipline Strategy	0.144	4

The results show that A1 – Comprehensive Physical Intervention obtained the highest global priority, followed by A2 – Partial Repair Strategy, A3 – Enhanced Monitoring and Decision Support, and A4 – Operational Control and Discipline Strategy. The dominance of A1 indicates that the group decision structure is mainly oriented toward long-term reliability improvement and safety risk control.

However, this ranking should be interpreted as a prioritization basis rather than a mutually exclusive selection. A1 can be positioned as the main strategic direction, while other alternatives may still provide supporting roles during the preparation, transition, or risk mitigation period.

3. Alternative Priorities per Criterion

The alternative priorities under each criterion provide a more detailed explanation of why A1 became the highest-ranked alternative at the global level.

Table 6. Group Alternative Priorities by Criterion

Criteria	A1	A2	A3	A4	Dominant Alternative
Operational Reliability	0.531	0.294	0.109	0.065	A1
Safety	0.529	0.291	0.110	0.070	A1
Operational Flexibility	0.333	0.329	0.221	0.117	A1
Ease of Implementation	0.060	0.141	0.244	0.554	A4
Cost and Risk Implications	0.310	0.361	0.240	0.089	A2

A1 performed strongest under Operational Reliability and Safety, which were the two highest-weighted criteria. This explains its position as the highest-ranked strategy. However, A1 did not dominate all criteria. A4 had the highest priority under Ease of Implementation, while A2 had the strongest position under Cost and Risk Implications. These results confirm that the global ranking was formed through the interaction between criteria weights and alternative performance, not through single-criterion dominance.

Interpretation, Trade-Off, and Sensitivity Analysis

1. Trade-Off Interpretation

The AHP results reveal an important trade-off between long-term reliability improvement and implementation feasibility. A1 provides the strongest contribution to Safety and Operational Reliability, but it requires greater resource readiness, more complex execution planning, and stronger cross-functional coordination. A2 represents a compromise strategy because it provides technical improvement with lower implementation complexity than A1. A3 has value as an adaptive supporting strategy because it strengthens monitoring capability and condition-based decision-making. A4 is the easiest strategy to implement and can support short-term operational control, but it has limited impact on long-term physical reliability improvement.

Table 7. Summary of Strategic Trade-Offs among Alternatives

Alternative	**Main Strength**	**Main Limitation**	**Strategic Role**
A1 – Comprehensive Physical Intervention	Strongest contribution to Safety and Operational Reliability	Higher implementation complexity and resource needs	Main strategy
A2 – Partial Repair Strategy	Stronger position in Cost and Risk Implications and competitive in Operational Flexibility	Lower contribution to Safety and Operational Reliability than A1	Compromise or interim strategy
A3 – Enhanced Monitoring and Decision Support	Supports adaptive monitoring and condition-based decision-making	Does not directly eliminate physical failure sources	Supporting strategy
A4 – Operational Control and Discipline Strategy	Highest Ease of Implementation	Limited impact on long-term physical reliability improvement	Short-term operational control strategy

Table 7 shows that the alternatives have different strategic roles. Therefore, the alternatives should not be treated as mutually exclusive. A1 can be positioned as the main strategic direction, while A3 and A4 can support risk mitigation and operating control during the preparation period before A1 is executed. A2 may also function as an interim or contingency option if the implementation of A1 requires a longer preparation period.

2. Sensitivity Analysis under Safety Weight Adjustment

A sensitivity analysis was conducted by adjusting the weight of the Safety criterion by +10% and -10%. Safety was selected because it had the highest weight in the group decision structure.

Table 8. Sensitivity Analysis of Global Priority under Safety Weight Adjustment

Alternative	Baseline	Rank	Safety +10%	Rank	Safety - 10%	Rank
A1 – Comprehensive Physical Intervention	0.427	1	0.431	1	0.423	1
A2 – Partial Repair Strategy	0.280	2	0.280	2	0.279	2
A3 – Enhanced Monitoring and Decision Support	0.149	3	0.148	3	0.151	3
A4 – Operational Control and Discipline Strategy	0.144	4	0.141	4	0.147	4

The sensitivity analysis shows that the ranking remained unchanged under the tested scenarios. A1 remained the highest-ranked strategy, followed by A2, A3, and A4. This result indicates that the decision outcome is reasonably robust within the tested Safety weight adjustment. The dominance of A1 is not driven by Safety alone, but is also supported by its strong performance under Operational Reliability. This finding is consistent with Więckowski and Sałabun (2023), who, in a systematic review of more than 250 multi-criteria decision studies, found that weight-based sensitivity testing is the most widely used approach for verifying the robustness of MCDM rankings.

However, this robustness should be interpreted proportionally. The result only confirms ranking stability under a ±10% adjustment to the Safety criterion. It does not imply that the ranking would remain unchanged under all possible changes in criteria weights or under different decision contexts.

Business Solution and Implementation Justification

The AHP results indicate that A1, Comprehensive Physical Intervention, should be prioritized as the main reliability improvement strategy for auxiliary boiler 151B501. This recommendation is justified because A1 provides the strongest contribution to the two most important criteria: Safety and Operational Reliability. In the context of a critical utility system supporting RFCC operations, a strategy that directly addresses reliability and safety risks is more defensible than a strategy selected primarily for ease of implementation.

Nevertheless, the implementation of A1 requires careful planning because it involves higher complexity, resource requirements, execution risk, material readiness, and possible coordination with vendors or OEMs. Therefore, the business solution should not be interpreted as an isolated selection of A1 alone. Instead, it should be implemented through a phased strategy.

In the short term, A3 and A4 should be used to support risk mitigation while preparation for A1 is being conducted. A3 can strengthen monitoring, condition-based evaluation, and early warning capability. A4 can strengthen compliance with operating windows, operating restrictions, and operational discipline to keep the boiler within safer operating boundaries. If required, A2 may serve as an interim repair option to manage specific critical components before the comprehensive intervention can be executed.

In the medium term, management should prepare an implementation roadmap for A1. This roadmap should include work scope definition, engineering assessment, budget preparation, material and spare part readiness, vendor or OEM support, execution schedule, shutdown or operational window alignment, and field execution risk mitigation. A cross-functional coordination forum involving Engineering, Operation, Maintenance, and Management should be established to ensure alignment between technical scope, operational readiness, safety requirements, and resource allocation.

This implementation logic confirms that the AHP ranking functions as a prioritization framework rather than a mutually exclusive selection. A1 represents the main strategic direction, while A3 and A4 provide supporting controls during the waiting and preparation period. This approach allows management to pursue long-term reliability improvement while still managing short-term operational risks.

CONCLUSION

This study demonstrates that the reliability problem of auxiliary boiler 151B501 at PT Pertamina Patra Niaga RU IV Cilacap extends beyond a purely technical equipment issue and should be addressed as a strategic decision-making problem involving multiple competing criteria. By applying the Analytical Hierarchy Process (AHP), the research systematically integrated the perspectives of Engineering, Operation, Maintenance, and Management to evaluate four feasible reliability improvement strategies based on five decision criteria: Safety, Operational Reliability, Operational Flexibility, Ease of Implementation, and Cost and Risk Implications. The findings indicate that Comprehensive Physical Intervention (A1) is the most appropriate strategy, primarily because it provides the greatest contribution to the two most influential criteria Safety and Operational Reliability which together dominate the overall decision structure. The sensitivity analysis further confirms that the ranking remains stable under moderate changes in criteria weights, indicating that the proposed decision framework is sufficiently robust for practical application. Rather than replacing managerial judgment, the developed AHP framework serves as a transparent, systematic, and accountable decision-support tool that enables refinery management to prioritize reliability improvement initiatives while balancing technical, operational, safety, and business considerations. Future research should extend the proposed decision-making framework by incorporating additional quantitative and uncertainty-based approaches to enhance the comprehensiveness of reliability strategy evaluation. Integrating methods such as Fuzzy AHP, Analytic Network Process (ANP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Life-Cycle Cost Analysis (LCCA), Cost–Benefit Analysis (CBA), Reliability-Centered Maintenance (RCM), or Risk-Based Inspection (RBI) would enable more comprehensive assessments under uncertain operational conditions and provide stronger economic justification for strategic decisions. Evidence from the power-generation sector supports this direction: Özcan et al. (2017) showed that combining AHP with goal programming and TOPSIS improved maintenance strategy selection in hydroelectric power plants, reducing equipment downtime by approximately 77% compared with unstructured decision-making, while Özcan et al. (2019) further demonstrated that AHP–TOPSIS-based maintenance prioritization produced stable, department-level maintenance plans even under varying risk conditions. Furthermore, future studies should validate the framework across different refinery utility assets, process units, or industrial sectors to examine its generalizability and adaptability. Longitudinal studies evaluating operational performance before and after strategy implementation are also recommended to quantify improvements in equipment reliability, maintenance efficiency, operational availability, safety performance, and economic outcomes. Such investigations would contribute to the development of a more integrated, evidence-based decision support framework for strategic asset management and reliability improvement in complex industrial systems.

REFERENCES

Afrianto, I., & Sarjono Putro, U. (2026). Strategic decision-making for low-sulfur gasoline production at RU III Plaju using an integrated AHP–TOPSIS framework for the pre-feasibility gate in support of Indonesia's Net Zero Emissions 2060. *Eduvest – Journal of Universal Studies, 6*(7), 8358–8377. https://doi.org/10.59188/eduvest.v6i7.53317

Ali, M. S., & Habibullah, H. (2019). A review on the current status of boiler inspection and safety issues in Bangladesh. *Energy Procedia, 160*, 614–620. https://doi.org/10.1016/j.egypro.2019.02.211

Basu, P. (2015). *Circulating fluidized bed boilers: Design, operation and maintenance*. Springer.

BP. (2023). *Statistical review of world energy 2023*. BP p.l.c.

CEIC Data. (2023). *Indonesia oil consumption data*. CEIC Data. https://www.ceicdata.com

Chaube, S., Pant, S., Kumar, A., Uniyal, S., Singh, M. K., Kotecha, K., & Kumar, A. (2024). An overview of multi-criteria decision analysis and the applications of AHP and TOPSIS methods. *International Journal of Mathematical, Engineering and Management Sciences, 9*(3), 581–615. https://doi.org/10.33889/ijmems.2024.9.3.030

Elijah, P. T., & Obaseki, M. (2022). Modeling effective maintenance strategy for rotodynamic system using RCM and AHP. In K. Geetha, F. M. Gonzalez-Longatt, & H. M. Wee (Eds.), *Recent trends in materials* (Springer Proceedings in Materials, Vol. 18). Springer. https://doi.org/10.1007/978-981-19-5395-8_36

IESR. (2022). *Indonesia energy transition outlook 2022*. Institute for Essential Services Reform.

Jagtap, H. P., & Bewoor, A. K. (2017). Use of analytic hierarchy process methodology for criticality analysis of thermal power plant equipments. *Materials Today: Proceedings, 4*(2), 1927–1936. https://doi.org/10.1016/j.matpr.2017.02.038

Ohta, R. (2018). Selection of industrial maintenance strategy: Classical AHP and fuzzy AHP applications. *International Journal of the Analytic Hierarchy Process, 10*(2). https://doi.org/10.13033/ijahp.v10i2.551

Özcan, E. C., Ünlüsoy, S., & Eren, T. (2017). A combined goal programming–AHP approach supported with TOPSIS for maintenance strategy selection in hydroelectric power plants. *Renewable and Sustainable Energy Reviews, 78*, 1410–1423. https://doi.org/10.1016/j.rser.2017.04.039

Özcan, E., Yumuşak, R., & Eren, T. (2019). Risk based maintenance in the hydroelectric power plants. *Energies, 12*(8), 1502. https://doi.org/10.3390/en12081502

Patil, S. S., Bewoor, A. K., Patil, R. B., Kumar, R., Ongar, B., Sarsenbayev, Y., PraveenKumar, S., Ibrahim, A. M. M., Alsoufi, M. S., & Elsheikh, A. (2022). A new approach for failure modes, effects, and criticality analysis using ExJ-PSI model—A case study on boiler system. *Applied Sciences, 12*(22), 11419. https://doi.org/10.3390/app122211419

Pertamina. (2016). *Residual fluid catalytic cracking unit development and operation information*. PT Pertamina.

Pertamina. (2023). *Annual report 2023*. PT Pertamina.

Rahman, M. A., Karmaker, C. L., Ahmed, T., Khan, M. I., Morshed, A. K. M., & Ali, S. M. (2022). Modelling the causes of boiler accidents: Implications for economic and social sustainability at the workplace. *Heliyon, 8*(6), e09601. https://doi.org/10.1016/j.heliyon.2022.e09601

Salmasnia, A., Ghasemi, E., & Mokhtari, H. (2016). Optimum maintenance strategy selection using a hybrid approach based on analytical hierarchy process and revised multi choice goal programming. *International Journal of Industrial Engineering & Production Research, 27*(4), 337–351.

Wang, C.-N., Hsueh, M.-H., Tran Thi, D.-O., Le, T. D.-M., & Dinh, Q.-T. (2025). Optimal maintenance strategy selection for oil and gas industry equipment using a combined Analytical Hierarchy Process–Technique for Order of Preference by Similarity to an Ideal Solution: A case study in the oil and gas industry. *Processes, 13*(5), 1389. https://doi.org/10.3390/pr13051389

Więckowski, J., & Sałabun, W. (2023). Sensitivity analysis approaches in multi-criteria decision analysis: A systematic review. *Applied Soft Computing, 148*, 110915. https://doi.org/10.1016/j.asoc.2023.110915

Yagmur, L. (2016). Multi-criteria evaluation and priority analysis for localization equipment in a thermal power plant using the AHP (analytic hierarchy process). *Energy, 94*, 476–482. https://doi.org/10.1016/j.energy.2015.11.021