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A Multi Criteria Decision-Making for Improving Cooling Tower Reliability: An Application of Value-Focused Thinking and Analytical Hierarchy Process at PT KPI

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Abstract

This study addressed the strategic need to improve cooling tower reliability at PT KPI, where an aging timber structure had experienced progressive deterioration due to prolonged exposure to moisture, chemical effects, biological degradation, and continuous operational loading. As the cooling tower supports cooling water circulation and power generation processes, its failure could disrupt refinery operations and result in significant operational and financial impacts. The purpose of this research was to determine the most appropriate maintenance and improvement strategy by integrating stakeholder expectations with technical, operational, financial, and implementation considerations. This study employed a mixed-method approach involving semi-structured interviews, questionnaires, field observations, document reviews, Value-Focused Thinking (VFT), the Analytic Hierarchy Process (AHP), and Cost–Benefit Analysis (CBA). The results showed that operational continuity was the most important criterion, followed by technical reliability, economic performance, implementation constraints, and maintainability. Three alternatives were evaluated: constructing a new reinforced concrete cooling tower, revitalizing the existing timber structure, and replacing structural components with a Fiber-Reinforced Polymer (FRP) system. The AHP synthesis identified timber revitalization as the most preferred alternative, with the highest global priority score and the strongest cost–benefit value. Sensitivity analysis confirmed that this ranking remained stable across all evaluated scenarios. The study concluded that phased timber revitalization was the most feasible strategy for enhancing cooling tower reliability while maintaining refinery operational continuity.

INTRODUCTION

PT KPI is one of the oldest and most strategic refineries in South Sumatera, Indonesia (Mukhyi 2022; Nurcahyono and Prawiraatmadja 2025; Septian 2026; Wibowo and Hermawan 2026). Located in Palembang, South Sumatera, the refinery plays an important role in supporting national energy security, particularly by supplying fuel, special fuel products, petrochemical products, and other refinery outputs for the Southern Sumatera region. As a refinery with a long operational history, PT KPI is required to maintain reliable, safe, and efficient operations to ensure production continuity and support business profitability. In this context, utility systems serve as essential supporting facilities because they directly influence the stability of refinery processes, including power generation, steam supply, cooling water circulation, and other process support systems.

One of the most critical utility assets at PT KPI is the cooling tower system. The cooling tower supplies circulating cooling water to various process units, condensers, heat exchangers, and power generation facilities (Huang et al. 2026; Liu et al. 2023; Plata et al. 2022; Wang et al. 2023; Wang and Wang 2026). Its reliability is therefore closely associated with continuous refinery operations. Significant degradation in cooling tower performance may reduce cooling water availability, affect power generation, and potentially trigger broader operational disruptions. Since the cooling tower also supports the gas turbine system within the power plant, catastrophic structural failure could interrupt electricity production and lead to partial or complete refinery shutdowns. This condition makes the cooling tower not only a technical asset but also a strategic facility with direct implications for production reliability, operational safety, and financial performance.

The existing cooling tower structure has been operating for several decades and was originally constructed using preservative-treated timber materials (Bobadilha et al., 2022). Over time, continuous exposure to moisture, chemicals, biological degradation, and cyclic operational loading has gradually reduced the structural integrity of the timber components (Shirmohammadi et al., 2021; Uwizeyimana et al., 2021; Mendis et al., 2024). Several assessments conducted in previous years indicated progressive deterioration of both structural and non-structural elements (More et al., 2026). Based on internal inspection data from 2023, after more than 30 years of continuous operation, most of the timber structure was found to have deteriorated and required further improvement. Although sectional repairs and partial timber replacements had been periodically performed since earlier assessments in 2011 and 2014, this maintenance approach remained largely reactive and might no longer provide sufficient assurance of long-term reliability (Gahrn-Andersen & Festila, 2024; Werbinska-Wojciechowska & Rogowski, 2025).

This condition created a strategic managerial dilemma for PT KPI. Continuing the existing repair strategy could require lower short-term capital investment; however, repeated interventions could increase lifecycle costs, maintenance requirements, execution risks, and uncertainty regarding long-term structural performance (Nakazato et al., 2023; van den Boomen et al., 2020). Conversely, constructing a completely new cooling tower could provide higher reliability and improved long-term asset integrity, but it would require substantial capital expenditure, longer implementation periods, and greater project complexity (Khan et al., 2020; Sánchez-Garrido et al., 2022). Alternative structural materials could also provide modernization benefits; however, their technical suitability, maintainability, constructability, and operational impacts must be carefully evaluated before implementation (Sánchez-Garrido et al., 2022; Khan et al., 2020). Therefore, selecting the most appropriate improvement strategy could not rely solely on technical judgment or cost minimization considerations (van den Boomen et al., 2020).

The business issue became increasingly critical because cooling tower failure or severe degradation could generate significant operational and financial consequences. Failure of the cooling tower structure could interrupt cooling water distribution to the gas turbine system, disrupt power generation, and ultimately halt oil and fuel production activities. This potential impact highlighted the need for a structured and preventive decision-making approach to determine the most effective cooling tower maintenance and improvement strategy.

The complexity of this decision was also reflected in the involvement of multiple stakeholders with different concerns and priorities. PT KPI management was concerned with refinery operational availability, budget utilization, and prevention of unplanned shutdowns. Refinery unit management was responsible for determining strategic directions for maintenance and asset improvement. Engineering teams evaluated technical alternatives and design specifications, while operations teams required stable cooling water supply, safe operation, and minimal production disruption. Planning and scheduling teams focused on project execution related to scope, schedule, and budget. Equipment reliability and plant reliability teams emphasized asset integrity, maintainability, capital expenditure control, and cost–benefit considerations. These diverse expectations needed to be integrated into a transparent and systematic decision-making process.

Previous maintenance actions had helped extend the operational life of the cooling tower; however, they had not fully addressed the fundamental issue of structural deterioration and long-term reliability. This indicated a gap between routine maintenance practices and the need for strategic asset improvement planning. In this context, a multi-criteria decision-making framework was required to comprehensively evaluate available alternatives. The framework needed to balance technical requirements, operational continuity, financial feasibility, maintainability, execution complexity, and stakeholder expectations. Without a structured evaluation process, decision-making could become fragmented, biased toward short-term cost considerations, or insufficiently aligned with long-term corporate objectives.

To address this issue, this study applied an integrated decision-making approach by combining Value-Focused Thinking (VFT) and the Analytic Hierarchy Process (AHP). VFT was used to identify stakeholder values, define fundamental and means objectives, and clarify the desired outcomes of the decision beyond merely comparing available alternatives. Meanwhile, AHP was applied to systematically prioritize evaluation criteria and rank proposed maintenance and improvement alternatives through a multi-criteria assessment process. The integration of these methods enabled the translation of stakeholder expectations into measurable decision criteria and supported a more rigorous, transparent, and accountable selection process.

This study aimed to determine the most appropriate maintenance and improvement strategy for the cooling tower structure at PT KPI. Specifically, the study sought to identify stakeholder expectations related to cooling tower reliability, formulate relevant maintenance and improvement alternatives, and evaluate the alternative that best fulfilled stakeholder requirements using a multi-criteria decision analysis framework. The findings were expected to provide practical recommendations for decision-makers in selecting an effective strategy to enhance cooling tower reliability while balancing technical, financial, operational, and corporate objectives. More broadly, this research contributed to strategic asset management practices in refinery operations, particularly for aging critical utility systems requiring long-term reliability improvements.

METHOD

This study employed a mixed-method research design that integrated qualitative exploration and quantitative decision analysis to determine the most appropriate maintenance and reliability improvement strategy for the cooling tower structure at PT KPI. This approach was selected because the decision problem involved not only technical and financial considerations but also operational reliability, safety, maintainability, execution feasibility, stakeholder expectations, and corporate objectives. The research process was conducted through several sequential stages.

First, the business issue was identified by examining the declining reliability of the cooling tower structure, which had experienced significant deterioration due to aging, chemical exposure, biological degradation, and continuous operational loading. As a critical utility asset supporting cooling water circulation and power generation, the cooling tower directly affected refinery continuity, operational safety, and financial performance. This stage provided the foundation for defining the decision problem and establishing the scope of the analysis.

Second, a literature review was conducted to strengthen the conceptual foundation of the study. The review covered asset integrity management, lifecycle-based reliability, cost–benefit analysis, stakeholder expectation analysis, Value-Focused Thinking (VFT), and the Analytic Hierarchy Process (AHP). The literature review supported the selection of appropriate analytical methods and ensured that the research framework was relevant to refinery asset management and multi-criteria decision-making contexts.

Third, stakeholder mapping was performed to identify parties with authority, influence, and direct involvement in the cooling tower decision-making process. The stakeholders included corporate management, refinery management, engineering, reliability, maintenance, operations, planning, scheduling, and financial functions. This mapping ensured that the decision framework reflected organizational needs rather than solely technical considerations. The stakeholder analysis also clarified the roles, interests, and expectations of each party regarding cooling tower reliability and long-term asset performance.

Primary data were collected through semi-structured interviews, questionnaires, and field observations. Semi-structured interviews were conducted with selected subject matter experts representing process engineering, structural engineering, reliability, finance and budgeting, and project scheduling perspectives. These experts were selected through purposive sampling because they possessed direct knowledge of the cooling tower condition, maintenance practices, operational risks, and improvement alternatives. The interview questions focused on stakeholder expectations, operational constraints, key decision factors, cost considerations, maintenance strategies, and future reliability requirements.

Questionnaires were used to support the AHP analysis by collecting pairwise comparison judgments from selected management respondents. These respondents represented functions related to overhaul management, reliability, asset integrity, development, maintenance planning, and budget evaluation. In AHP-based research, the quality and relevance of expert judgment are prioritized because the method supports complex decision-making based on informed evaluation rather than statistical generalization.

Field observations were conducted to obtain direct insights into the existing cooling tower condition and operational context. The observations included assessments of structural deterioration, maintenance activities, and ongoing repair practices. This method was used to validate interview findings and provide practical context regarding the relationship between asset condition, operational risks, and maintenance requirements.

Secondary data were obtained through document reviews and data analysis. The reviewed documents included cooling tower structural inspection reports, historical maintenance and repair records, technical evaluation documents, structural modeling results, internal company guidelines, and the Asset Integrity Management System (AIMS) of PT KPI. Cost data related to maintenance, repair, replacement, and improvement alternatives were also analyzed to support the cost–benefit assessment. These secondary data provided technical, operational, and financial inputs for evaluating the available alternatives.

Data analysis was conducted using an integrated VFT–AHP framework. First, qualitative data from interviews, observations, and document reviews were analyzed using Value-Focused Thinking (VFT). VFT was applied to identify and structure stakeholder expectations into fundamental objectives and means objectives. Fundamental objectives represented desired outcomes, such as long-term reliability, operational safety, production continuity, and sustainability. Means objectives represented supporting factors required to achieve these outcomes, including improved maintainability, execution feasibility, cost control, and reduced operational disruption. The results of the VFT analysis were organized into an objective hierarchy and means–end network.

After stakeholder values and objectives were established, feasible maintenance and improvement alternatives were developed. The alternatives were formulated based on stakeholder input, field conditions, technical feasibility, operational requirements, safety considerations, environmental compliance, and financial implications. The alternatives included revitalizing existing structures, replacing structural materials or components, and constructing a new cooling tower. This process ensured that the evaluated alternatives were relevant to actual refinery conditions and aligned with stakeholder expectations.

The AHP method was subsequently applied to evaluate and prioritize the alternatives. The fundamental objectives identified through VFT were translated into the main goal of the AHP hierarchy, while the means objectives were converted into evaluation criteria. Pairwise comparisons were conducted to assess the relative importance of each criterion and the performance of each alternative against the established criteria. The comparison results were processed to calculate priority weights and overall scores for each alternative. A consistency ratio test was also performed to verify the logical consistency and reliability of expert judgments.

In addition, cost–benefit analysis was incorporated to support the financial evaluation of each alternative. This analysis assessed whether the expected benefits of each maintenance or improvement strategy were proportional to the required investment, implementation effort, and anticipated reliability improvements. By integrating VFT, AHP, and cost–benefit considerations, the study evaluated the alternatives from technical, operational, financial, and stakeholder perspectives.

The final output of the analysis was a ranked list of maintenance and improvement alternatives. The alternative with the highest priority score was selected as the recommended strategy because it best satisfied stakeholder expectations and provided the most appropriate solution for improving cooling tower operational reliability. The results of this analysis served as the basis for managerial recommendations and implementation planning at PT KPI.

RESULTS AND DISCUSSION

Analysis

The purpose of this phase is to understand the current cooling tower condition, identify the key operational and structural issues, and capture the expectations of authorized stakeholders regarding future reliability improvements. Through observations findings, existing conditions assessment, and structured stakeholders' interviews, this section provides the qualitative foundation required for the subsequent Value-Focuses Thinking (VFT) and Analytic Hierarchy Process (AHP) evaluation stages.

Current Cooling Tower Condition and Strategic Decision Context

The Cooling Tower at PT KPI is one of the critical utility assets supporting refinery operations. It provides circulating cooling water required by the heat exchanger, condensers, rotating equipment auxiliaries, and other process systems. Reliable cooling tower operations are therefore essential to maintaining refinery throughput and production continuity. The current cooling tower structure predominantly uses timber members that have operated for many years. Historical maintenance activities indicate repetitive sectional repair and member replacement caused by structural aging, wet operating conditions, biological deterioration, and long-term environmental exposure.

Although these interventions have maintained short-term operability, the current approach may no longer provide sufficient assurance of long-term structural reliability. Consequently, management requires a strategic decision regarding the most suitable maintenance or improvement alternatives.

Based on engineering assessment practices and structural evaluation references, aging industrial structures are commonly reviewed through visual inspection, dimensional verification, non-destructive testing, material checks, and engineering assessment before strategic investment decisions are made. For the cooling tower case, field observations and historical maintenance records indicate the following:

Table 1. Observations of Existing Conditions

Aspect	Existing Condition	Strategic Implication
Structural Age	Mature Timber Structure	Higher Deterioration probability
Environment	Continues wet exposure	Accelerated Degradation
Maintenance Pattern	Repetitive sectional repairs	Increasing lifecycle inefficiency
Operational Role	Critical utility support	High Consequence of Failure
Existing Configuration	Old structure design	Requires strategic improvement planning

Table 2. Analysis Observation on Existing Gap Analysis

Desired Condition	Current Condition	Gap Level
High Structural Reliability	Recurring Repairs	High
Low Maintenance Burden	Frequent Intervention	Medium
Long Term Certainty	Reactive Maintenance Approach	High
Efficient Cost Structure	Repetitive Repair Spending	Medium
Strategic Readiness	Aging Configuration	High

These findings confirm that the current situation requires strategic evaluation rather than continuation of routine reactive maintenance.

Stakeholder Expectations Analysis

Structured interviews were conducted with 5 (five) Subject Matter Experts (SME) representing Process Engineer, Structural Engineer, Reliability Engineer, Planning Constructability Engineer and Financial Budgeting Analyst. The recurring expectations identified from interviews are summarized below.

Table 3. Identified Stakeholders Expectations

Stakeholder Expertise	Main Priority
Process	Avoid production disruption
Reliability	Long-term structural integrity
Financial & Budgeting	Efficient investment utilization
Planning & Constructability	Practical execution
Maintenance	Easier inspection & repair

Consolidated stakeholder values:

a. Operational Continuity
b. Technical Reliability
c. Economic Performance
d. Implementation Constraint
e. Maintainability

Need for Multi-Criteria Decision Framework

The Cooling Tower decision involves several competing considerations:

1. Higher reliability may require higher capital investment,
2. Lower cost alternatives may provide lower longer-term reliability,
3. Faster implementation may limit technical scope,
4. Full replacement may cause greater operational disruption.

Therefore, intuitive judgement alone may be insufficient. A structured decision-making framework is required. For this reason, the study applies:

a. Value-Focused Thinking (VFT) to define stakeholders' values and generate alternatives.
b. Analytic Hierarchy Process (AHP) to prioritize alternatives quantitatively.

Structured Decision-making Framework

This Section presents the business solution stage of the study based on the analytical finding discussed in the previous section, in line with the research design, stakeholder values and identified operational issues are translated into strategic decision criteria through the Value-Focused Thinking (VFT) approach, Subsequently, feasible alternatives are evaluated using the Analytic Hierarchy Process (AHP) and supported by financial considerations to determine the most appropriate solution for improving cooling tower reliability of PT. KPI

Development of Value-Focused Thinking (VFT) Framework

Based on stakeholder interviews, field observations, and current cooling tower condition analysis. The analysis indicates that subject matter experts not only require higher structural reliability, but also expect minimal operation disruption, efficient investment utilization, practical implementation, ease of future maintenance, and safe execution. Therefore, the cooling tower decision must balance technical and business considerations simultaneously.

From these findings, the decision context of this study is defined as the selection of the most appropriate strategy to improve cooling tower structural reliability under operational, economic, engineering and implementation constraints.

The Fundamental objective identified is to ensure sustainable, safe, reliable, and economically efficient cooling tower operation while maintaining refinery continuity in long-term asset integrity.

Table 4. Summary Semi-Structure Interview Results

Topic Discussion	Guideline Question	Final Results with SME's
Identify Stakeholder Expectations	What should the cooling tower structure achieve operationally / financially?	SMEs agree the the selected strategy should ensure reliable cooling tower performance, maintain stable cooling water supply, support uninterrupted refinery operation, and provide efficient capital utilization with measurable business benefits.
	What condition should be avoided	Respondend emphasizes the need to avoid catastrophic structural failure, repetitive annual repairs, excessive CAPEX, long redesign duration, high execution complexity, and maintenance system requiring spesialized methods or unavailable spare parts.
	What are the most important expectations from your expertise discipline?	Main expectations identified include reliability, operational continuity, economic efficiency, implementation feasibility, maintainability, flexibility and schedule practicality.
Determination Decision Criteria	Why are those factors important	SME stated that cooling tower interruption can affect refinery continuity, economic efficiency, implementation feasibility, maintainability, flexibility and schedule practicality.
	What constraints must be considered	Key constraints include annual budget ceiling, capital approves process, shutdown window limitations, procurement lead time, contractor capability, manpower availability and field execution restrictions.
	Which is more important: Reliability, Cost, Continuity, Maintainability or Speed, Why?	Most respondents prioritized reliability and operational continuity, while finance respondents emphasized cost efficiency and planning respondents emphasized speed of implementation. This confirms the need of a multi-criteria decision making framework.
Generate Strategic Alternatives	What maintenance improvement strategies are realistically available	Three feasible alternatives were consistently identified; (1) Construction of a new reinforced concrete cooling tower, (2) Revitalization of the existing timber cooling tower, and (3) strucutral upgrading using FRP System.

The identified mean objectives represent the key priority areas that contribute toward achieving the fundamental objective. This includes operational excellence, technical reliability, economic performance, implementation feasibility, and maintainability. The mean objectives were later translated into decision criteria measurable and sub-criteria to be applied in the AHP-based evaluation stage. These criteria were formulated based on cross functional stakeholder's inputs and designed reflect the relevant operational, technical, financial, and execution considerations in the context of cooling tower reliability improvement. The resulting structure provides a comprehensive and consistent basis for comparing the strategic alternatives developed in this study.

Table 5. Decision Making Objectives Structure (VFT)

Level	Element	Description
Fundamental Objective	Sustainable Cooling Tower Operation	The ability of cooling tower system maintain reliable, continuous, and efficient cooling water service that supports refinery operations. The selected strategy should not only solve shor-term strucural issues, but also ensures long-term operational sustainability, asset integrity, and business continuity.
Means Objective	Operational Continuity	The ability of selected alternative to maintain stable cooling water supply, minimize shutdown exposure, and support uninterrupted refinery production during and after implementation
	Technical Reliability	The capability of structure to withstand mechanical loads, environmental exposure aging factors, and support uniterrupted refinery production during and after implementation.
	Economical Performance	The financial impact of the selected decision, including capital expenditure, maintenance & operation burden, evaluate by C/B analysis
	Implementation Constraints	The practicality of executing the project within available shutdown windows, contractor capability, procurement lead time, site constraints, and manageable execution risk.
	Maintainability	The ability of selected alternatives to support easier inspection, repair, replacement and long-term maintenance using available internal resources and practical methods.

The development of criteria in this study was also designed to ensure that conceptual stakeholder's values could be converted into observable and measurable assessments factors. Each criterion reflects a key category of the identified means objectives, that enable quantitative comparisons using the Analytical Hierarchy Process (AHP). By Applying this structure, qualitative priorities are translated into a practical evaluation framework. This is aligned with the principles of Value-Focus Thinking (VFT), which emphasizes transforming decision objectives into operational criteria for multi-criteria decision analysis.

Table 6. Final Decision Criteria

Criteria	Description
Operational Continuity	The capability of the selected strategy to maintain adequate cooling water supply during implementation and normal operation with minimum production disturbance.
Technical Reliability	The ability of structure to withstand operational loading loads, environmental exposures, and long-term service condition with predictable performance.
Economic Performance	The overall financial impact of the alternative, including CAPEX, maintenance cost, lifecycle cost, and profitability factor index by calculation of cost/benefit analysis
Implementation Constraint	The practicality of implementing the alternative considering shutdown window, procurement lead time, contractor capability, and required completion duration.

Criteria	Description
Maintainability	The ease of and inspecting and maintaining structural components throughout the asset lifecycle.

These final decision criteria pictured stakeholders' expectations for cooling tower solution to be reliable, practical, cost-efficient, maintainable and minimal disruption on operations.

Generation of Strategic Alternatives

After the decision criteria were established, the next step of the analysis was to generate feasible strategic alternatives for improving the reliability of the cooling tower structure. In accordance with VFT approach, alternatives were developed after the objective had been clearly defined, ensuring that each option was directly aligned with stakeholder expectations and decision priorities.

The generation of alternatives was based on stakeholder interviews on existing maintenance practices, engineering considerations, implementation constraints, and long-term operational requirements. Through this process, the study focused on identifying realistic options that could be implemented within the refinery environment while addressing the current structural issues of the cooling tower.

The resulting alternatives represent different strategic approaches with distinct trade-offs in terms of improvement of reliability, capital requirement, implementation complexity, execution timeline, and future maintainability; Therefore, each alternative provides a different pathway toward achieving the fundamental objective sustainable cooling tower operability.
Three strategic alternatives, were identified and considered suitable for evaluation, namely:

Table 7. Alternatives Generated

Code	Strategic Alternatives	General Description
A 1	Construction of new Reinforce concrete Cooling Tower	Development of completely new cooling tower strucutre using reinforced concrete material to provide long-term durability and modernized facility performance
A 2	Revitalization of existing cooling tower with timber structure	Rehabilitation of the current cooling tower through replacement of deteriorated timber members while maintaining the existing structural concept and phased execution approach.
A 3	Revitalization with FRP structural system	Replacement of structural members using Fiber Reinforced Plastic (FRP) materials to improve corrosion resistance and reduce maintenance burden.

Three alternatives were eventually evaluated using the Analytic Hierarchy Process (AHP) to determine which option provides the best overall with stakeholders' values, business objectives and operational requirements.

Decision Hierarchy – AHP

The next step is to construct AHP decision hierarchy. The hierarchy was developed by translating fundamental objectives, mean objectives and strategic alternatives into a structured decision model. The AHP hierarchy consists of three levels. The first level is decision goal, which is to select the most appropriate strategy for improving cooling tower structural reliability. The second level consists of five main criteria derived from VFT framework: Operational Continuity, Technical Reliability, Economic Performance, Implementation Constraint, and Maintainability. The third level consists of three strategic alternatives identified in previous section.

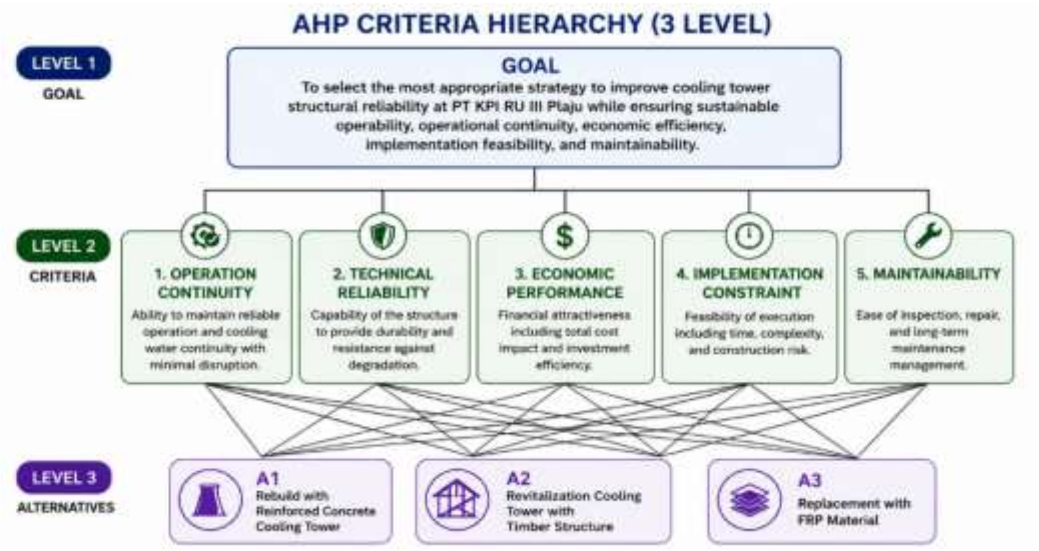

Figure 1. AHP Hierarchy Structure (Author,2026)

Pairwise Comparison of AHP model using Excell Calculation Model

The pairwise comparison in this study was performed using a structural calculation model developed in Microsoft Excell. The model was used to process experts' judgement, aggregate responses using geometric mean, and calculate priority weight for both criteria and alternatives. All respondents provide pairwise comparisons using Saaty scale. The individual judgments were then aggregated into a single matrix using geometric means to represent group consensus. The calculation results were further validated through consistency evaluation to ensure judgments are logically acceptable.

Consistency Evaluation Result

Table 8. Consistency Result

Criteria	λ max	CI	CR	Evaluation
Operational Continuity	3,0227	0,0114	0,0196	Consistent
Technical Relibility	3,0189	0,0094	0,0163	Consistent
Implement Constraint	3,0045	0,0023	0,0039	Highly Consistent
Maintainability	3,0552	0,0276	0,0476	Consistent

All consistency rate values are significantly below the acceptable threshold 0,10, indicating that the judgments are consistent and reliable.

Among criteria:

- Implementation Constraint shows the highest consistency
- Operational Continuity and Technical Reliability show strong agreement among respondents

- Maintainability, although relatively higher, remains within acceptable limits

For economic performance, consistency evaluation was not conducted because the criterion was assessed using direct normalization value of cost/benefit analysis (CBA) results rather than pairwise comparison. The pairwise comparison results are considered valid and reliable and therefore can be used as the basis for determining criteria, weights and alternatives in the AHP model.

Economic Performance Calculation using CBA

The evaluation of economic performance criterion in this study was conducted using cost/benefit analysis (CBA) approach to ensure that the assessment is based on objective financial considerations. The CBA results for each alternative are presented as follows:

Table 9. CBA Values

Alternative	Cost/Benefit Values	Evaluation
A1 – Reinforce Concrete	0,34	Low Economic Efficiency
A2 – Timber Revitalization	1,54	High Economic Efficiency
A3 – FRP Replacement	1,11	Moderate Economic Efficiency

The normalization process ensures that the total value equals 1,00, enabling direct use as a local priority weight under the economic performance criterion.

The use CBA in this study strengthens the decision-making process by incorporating quantitative financial evaluation, thereby reducing subjectivity and improving robustness of the AHP Model.

AHP Results and Decision Synthesis

The final decision was determined by synthesizing the priority weight of all criteria and alternatives obtained from the AHP analysis. This synthesis integrates expert judgments, consistency-validated pairwise comparisons, and the normalized economic evaluation.

Criteria Weight

Table 10. AHP Criteria Weights

Criteria	Weight
Operational Continuity	0,4431
Technical Reliability	0,1951
Economic Performance	0,1667
Implementation Constraint	0,1051
Maintainbility	0,0900
Total	1,0000

The results show that operational continuity is the most dominant, indicating that maintaining uninterrupted refinery operation is the primary consideration in decision-making.

Table 11. Alternative Ranking

Alternative	Global Weight	Rank
A1 – Reinforce Concrete	0,2811	3
A2 – Timber Revitalization	0,4198	1
A3 – FRP Replacement	0,2991	2

The results show that alternative 2 (timber revitalization) is the preferred option. This is driven by its strong performance across multiple criteria, particularly in:

a. Operational Continuity, due to its ability to be implemented without major shutdown.
b. Economic Performance, as it provides the highest cost-benefit value
c. Implementation constraint, due to its practical execution and lower complexity.

Although Alternative 1 offers superior structural strengths, its high cost and longer implementation duration reduce its overall attractiveness. Alternative 3 performs well in technical aspects but is less competitive in economic and implementation considerations.

The AHP synthesis confirms that the optimal decision is by balancing operational, technical, financial and implementation factors. Based on this integrated evaluation, Alternative 2 (timber revitalization) is identified as the most appropriate strategy for improving the cooling tower reliability.

Sensitivity Analysis

Sensitivity analysis was conducted to evaluate the robustness of the AHP results against potential changes in criteria weights. This analysis is important to determine whether the selected alternatives remain stable under different decision scenarios.

In this study, sensitivity testing was performed by adjusting the weight from one of the criteria by ±20%, while the remaining criteria remained.

Table 12. Sensitivity Analysis Cases

Case	Scenario
Case 1	Operational Continuity + 20%
Case 2	Operational Continuity – 20%
Case 3	Technical Reliability +20%
Case 4	Technical Reliability -20%
Case 5	Economic Performance +20%
Case 6	Economic Performance -20%
Case 7	Implement Constraint +20%
Case 8	Implement Constraint – 20%
Case 9	Maintainability + 20%
Case 10	Maintainability – 20%

The summmary of sensitivity analysis results is presented below:

Table 13. Sensitivity Analysis Cases

Scenario	Alternative 1	Alternative 2	Alternative 3	Result
Base	0,2811	0,8077	0,5608	A2
Case 1	0,2361	0,4411	0,2980	A2
Case 2	0,2084	0,3579	0,2551	A2
Case 3	0,2477	0,4092	0,2920	A2

Scenario	Alternative 1	Alternative 2	Alternative 3	Result
Case 4	0.2037	0.3985	0,2687	A2
Case 5	0,2295	0,4210	0,2928	A2
Case 6	0,2219	0,3867	0,2680	A2
Case 7	0,2278	0,4161	0,2871	A2
Case 8	0,2237	0,3916	0,2737	A2
Case 9	0,2257	0,4038	0,2804	A2
Case 10	0,2257	0,4038	0,2804	A2

The sensitivity analysis shows that the ranking of alternatives remains unchanged across all evaluated scenarios. In every case, Alternative A2 (timber revitalization) consistently achieves the highest priority value compared to the other alternatives.

This result indicates that the decision model is stable and robust against moderate changes in criteria weights. The consistent dominance of alternative 2 demonstrates that the selected strategy is not dependent on a single criterion but instead reflects balanced performance across criteria.

Although several scenarios produce changes in the magnitude of alternative scores; the overall ranking remains unchanged:

$$A2 > A3 > A1$$

The consistency strengthens the validity of the decision-making process and indicates that the selected alternative remains favourable under different evaluations conditions.

The robustness of the selected alternative directly provides the best solution to fulfil stakeholder's expectations based on a multi-criterial decision analysis framework. The consistent ranking outcome across all scenarios confirms that alternative 2 remains the most appropriate strategy for PT. KPI

Business Solution

The main problem faced by PT. KPI is determining the most appropriate maintenance and improving strategy for the aging cooling tower structure, the issue is not only related to structural deterioration but also involves broader operational and business considerations according to the stakeholders' expectations. Since the cooling tower is categorized as a critical utility asset supporting refinery operation, selecting an inappropriate strategy may increase operational risk, maintenance burden, and potential production disruption.

Based on the analysis with the structured decision framework develop in section 1 using Value-Focused Thinking (VFT), Analytic Hierarchy Process (AHP), and Cost/Benefit Analysis (CBA), the study concludes that the most appropriate solution is the revitalization of the cooling tower using preservative timber structures (Alternative 2 – 0,8077 global weight in base model). The selected alternative consistently demonstrates the best balance among the major evaluation criteria identified by stakeholders, namely Operational Continuity, Technical Reliability, Economic Performance, Implementation Constraint, and Maintainability. Compared to the other alternatives, timber revitalization provides the highest economic value, practical implementation, and lower operational disruption while still maintaining acceptable reliability performance.

The analysis results also show the Operational Continuity becomes the most important decision criterion. This finding indicates that maintaining uninterrupted refinery operation is the primary concern for stakeholders. In this context, the revitalization strategy offers significant advantages because the implementation can be conducted progressively using a cell-by-cell approach without requiring total cooling tower shutdown. This approach minimizes the risk of operational interruption and allows refinery operation to continue during execution activities. In addition, the selected strategy is more compatible with the existing operational system and maintenance practice at refinery, making the implementation process more practical and manageable.

The robustness of the selected solution is further confirmed through sensitivity analysis where alternative 2 consistently remains the highest-ranked option under all evaluated scenarios. This result indicates that the proposed business solution is not highly dependent on a single criterion or assumption but instead represents a stable and balanced strategic decision. Therefore, the revitalization of the existing cooling tower using timber structure is considered the most appropriate tower business solution for PT KPI to improve cooling tower reliability while maintaining operational sustainability, implementation practicality and investment efficiency.

Implementation Plan & Justification

Based on the results of the value-focused thinking (VFT), Analytic Hierarchy Process (AHP), Cost/benefit Analysis (CBA) and sensitivity analysis, the recommended strategy for improving the cooling water reliability at PT. KPI the revitalization of the cooling tower using timber structures (alternatives 2).

Implementation Plan

The implementation plan is therefore designed using a phased execution approach combined with operational coordination, engineering validation, and risk control measures. The proposed implementation strategy adopts a cell-by-cell revitalization method to minimize operational disruption while progressively improving the structural condition of the cooling tower.

Table 14. Implementation Plan 5W + 1H

Element	Implementation Description
What	Revitalization of the cooling tower structures through phased replacement of deteriorated timber structural members and strengthening of inspection and maintenance practices.
Why	To improve cooling tower reliability while maintaining operational continuity, minimizing operational disruption, and optimizing investment efficiency
Where	Cooling tower facility at PT. KPI
When	The implementation proposed to be executed gradually during planned maintenance windows and operationally feasible periods to minimize refinery operational impact.

Element	Implementation Description
Who	Reliability Function, Maintenance Team, Operation Team, Engineering Team (process & non process), Planning & Schedulling Team and Qualified Contractors under refinery management coordination.
How	Through phased cell-by-cell revitalization supported by detailed inspection, engineering validation, procurement planning, quality control, execution monitoring and post-implementation valuation.

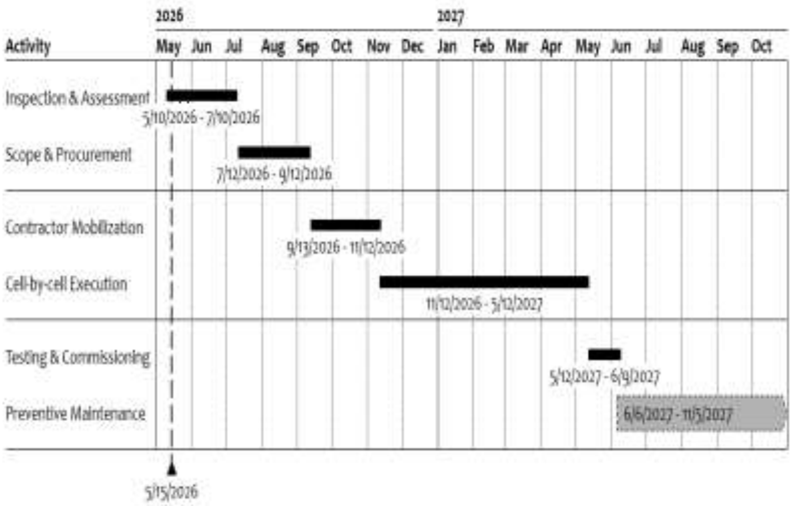

Figure 2. Implementation Schedule

Justification

The proposed implementation approach is aligned with stakeholder's expectations identified during interviews, discussions, and VFT- AHP evaluation. Stakeholders generally agreed that phased revitalization with preservative timber is the most feasible approach because it:

a. Minimizes refinery operational disruption
b. Maintains cooling water availability during execution
c. Reduces implementation complexity compared to total replacement
d. Provides practical execution flexibility
e. Support investment efficiency and manageable execution risk

The implementation plan is also supported by sensitivity analysis results, where alternative 2 consistently remain the highest-ranked solution under all evaluated scenarios. This indicates that the selected strategy is sufficiently robust and operationally justifiable.

CONCLUSION

The study was conducted to address the main research problem of determining the most appropriate strategy for improving the reliability of the cooling tower structure at PT KPI. The study applied a mixed-method approach that integrated Value-Focused Thinking (VFT), the Analytic Hierarchy Process (AHP), and Cost–Benefit Analysis (CBA) to support a structured multi-criteria decision-making process. Through this approach, the study successfully addressed the research questions and achieved the objectives formulated in Chapter 1.

The study found, through the VFT analysis, that stakeholders' expectations primarily focused on maintaining operational continuity while also considering technical reliability, economic performance, implementation feasibility, and maintainability. These findings indicated that the cooling tower issue was not solely a technical problem but also a strategic operational and managerial decision requiring balanced evaluation across multiple criteria.

Three strategic alternatives were identified through VFT: rebuilding the cooling tower using reinforced concrete, revitalizing the existing timber structure, and replacing structural components with a Fiber-Reinforced Polymer (FRP) system. Based on the integrated AHP analysis, supported by CBA evaluation, Alternative 2 was identified as the most appropriate strategy. This alternative provided the best balance among operational continuity, economic performance, implementation feasibility, and maintainability while maintaining acceptable technical reliability. The findings were further confirmed through sensitivity analysis, which demonstrated the robustness and stability of the decision model.

Therefore, this study demonstrated that the integration of VFT, AHP, and financial evaluation provided an effective and structured framework for supporting strategic asset management decision-making in refinery utility systems.

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