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# Optimization of Clean Water Supply Fulfillment Strategies at Water Treatment Plants in Industrial Areas

**Sonia Oktariyanti*, Parwadi Moengin**
Universitas Trisakti, Indonesia
Email: oktariyantisonia@gmail.com*, parwadi@trisakti.ac.id

**Keyword**
Water Treatment Plant, operational and maintenance costs, Life Cycle Cost, cost optimization, clean water supply, industrial estates

**Abstract**
The growing demand for clean water in industrial areas requires a reliable and sustainable supply system. However, water treatment plants are operating near capacity due to tenant growth, while high energy consumption, chemical cost fluctuations, and reactive maintenance increase operational and maintenance costs. This study aims to identify optimal strategies for meeting clean water demand in industrial water treatment plant service areas by optimizing operational costs and maintaining utility networks, including operations and maintenance (O&M) improvements, small capital expenditure (CAPEX) through supply chain management (SCM) implementation, and large CAPEX such as water treatment plant expansion or new construction. The research employed financial analysis based on present value (PV) and life cycle costing (LCC) with an analysis period of 20 years and a discount rate of 8%, based on historical water treatment plant operational data and investment estimates. Scenario and sensitivity analyses were conducted to strengthen decision-making. The results show that the O&M strategy is the most optimal and highest-priority strategy, as it provides the highest cumulative cost savings without upfront investment, with PV savings on OPEX and MEX of Rp230.07–677.51 million and Rp495.26 million in the moderate scenario, respectively. The small CAPEX strategy yielded a positive net present value (NPV) saving of IDR 51.48 million but was sensitive to initial investment levels and the degree of chemical cost savings. Meanwhile, the large CAPEX strategy has a total life cycle cost of IDR 57,415.00 million and is more appropriate as a medium- to long-term solution for increasing supply capacity and reliability. This research recommends a phased strategy to ensure sustainable clean water services and improve operational cost efficiency in industrial estates.

## INTRODUCTION

Industrial estates require a reliable clean water supply system to support production processes and supporting utilities, so that the reliability of water supply is a strategic factor in maintaining the sustainability of industrial activities and minimizing the risk of operational disruptions (Ortuzar & Serrano, 2023). Currently, one of the industrial estates in Karawang operates a Water Treatment Plant (WTP) with an installed capacity of 50 L/second as a single source of clean water supply (UWT, 2019). Operational data shows that the average water production reaches 67,376 m³/month with energy consumption of around 35,686 kWh/month and operational costs of Rp 329.66 million/month, which indicates that WTP has been working at a high load level and has the potential to face capacity limitations in the future if no management intervention is carried out. In addition to capacity challenges, operational and maintenance efficiency aspects are also a concern, shown by the energy intensity of 0.53

kWh/m³ and the use of chemicals and maintenance practices that still have the potential to be optimized. This condition requires a thorough study of the WTP system from technical, operational, maintenance, and financial aspects to formulate a strategy to fulfill the optimal clean water supply. Therefore, this study uses a long-term cost analysis approach based on Life Cycle Cost (LCC) and Present Value (PV) to compare various alternative strategies, both operational performance improvement, existing WTP capacity increase, and new WTP expansion, in order to produce efficient, reliable, and sustainable strategic recommendations for industrial estate management (Boussabaine, A., & Kirkham, 2008; Sullivan et al., 2019).

An industrial estate is a planned area that integrates various manufacturing activities and supporting services in one management system (Sarjana & Khayati, 2018; Sjaifuddin, 2020). In the development of modern industrial estates, the eco-industrial park (EIP) and industrial symbiosis approach is widely discussed as an effort to improve resource efficiency, including the management of shared utilities such as water and energy, in order to improve the economic and environmental performance of the region (Nessim et al., 2024). Clean water is a critical utility because it serves as an important input in the production process and supporting utilities, so changes in industrial activities directly affect water demand. Therefore, the region's water needs to be analyzed quantitatively and projected in a measurable manner to ensure adequate supply and anticipate the risk of service shortages due to tenant growth and production (Fang et al., 2024; Vásquez-Lavín, F., 2020).

In addition to the amount of average demand, the management of the water supply system must also consider consumption fluctuations and peak demand conditions. Recent literature emphasizes that estimating peak conditions is important to improve planning reliability, as average-based analysis alone has the potential to mask risks in extreme conditions (Moretti & Guercio, 2024). The water needs of industrial estates are heterogeneous and dynamic, influenced by the type of industry, production scale, process technology, and tenant operational schedule. Therefore, the characteristics of water demand are generally identified through mapping of existing consumption, variations/fluctuations in consumption, and indications of peak demand as the basis for evaluating system capacity (Božič et al., 2025; Farooq et al., 2025; Li et al., 2020; Tolera et al., 2025).

Water demand projections are compiled based on historical data and variables driving the growth of industrial activity. Various approaches can be used, ranging from historical trend-based projections, scenario-based projections (e.g. pessimistic–moderate–optimistic) to capture growth uncertainty, to adjustment of peak conditions using peak factors to make capacity planning more reliable (Ghannam & Hussain, 2024; Moretti & Guercio, 2024). The results of these projections are the main input in the capacity gap analysis, which is a comparison between water demand (average and peak) and the effective supply capacity of the system. If capacity gaps are identified, a supply fulfillment strategy is needed that can include increasing operational and maintenance efficiency, improving the performance or capacity of existing facilities, as well as infrastructure expansion options, in line with the principles of sustainable industrial estate utility management (Crozier et al., 2024; Mallawaarachchi et al., 2023).

The Water Treatment Plant (WTP) is a raw water treatment facility through a series of integrated process units to produce clean water that meets quality standards. In surface water treatment, commonly applied conventional processes include coagulation–flocculation, solids separation (sedimentation), filtration, and disinfection, which are effective in controlling turbidity, organic matter, and microbiological risks (Łukasiewicz, 2025). Functionally, WTP aims to maintain the quality and continuity of clean water supply, but its performance is greatly influenced by raw water characteristics, process unit configuration, and operation and maintenance strategies (Maldonado et al., 2023; Murrar et al., 2025; Wang et al., 2018).

The capacity and performance of WTP is determined not only by the design discharge, but also by the variability of raw water quality, equipment conditions, and energy and chemical use efficiency. The main challenges of modern WTP include fluctuations in raw water quality, energy efficiency, process residue management, and the risk of disinfection by-products, resulting in the need for data-driven operations management and continuous performance evaluation to support system optimization (Skoczko, 2025; Swinamer et al., 2024).

The OPEX WTP fee is all routine expenses required for the water treatment plant to operate stably and meet clean water service standards. In the context of industrial estates, OPEX WTP becomes a significant component of utility costs and in many cases accounts for the largest portion of the system's lifecycle costs, with electrical energy as the dominant component. Therefore, the operational efficiency of WTP has direct implications for the financial sustainability of area management and water service tariff structure.

In general, OPEX WTP includes the cost of energy, chemicals, labor, maintenance and parts, as well as other operation-related costs such as process residue management. The magnitude of OPEX is influenced by production capacity and scale, raw water characteristics and quality, technology and process configuration, specific energy consumption and energy tariffs, and chemical dose utilization and control strategies. Thus, understanding the structure and determinants of OPEX is an important basis for optimizing operational costs and planning an efficient and sustainable WTP management strategy.

In the management of water utilities, including Water Treatment Plants (WTPs), maintenance costs are an important part of the operating and maintenance (O&M) costs that have a direct impact on service reliability and total lifecycle costs. The literature emphasizes that the analysis of maintenance costs includes not only repair costs, but also preventive inspection costs as well as reliability consequent costs arising from decreased performance or service interruptions.

Operationally, maintenance costs are defined as the routine expenses of keeping assets functioning at service capacity, and in practice O&M is treated as one of the key components in cost planning. The magnitude of this cost is greatly influenced by the maintenance strategies implemented, ranging from corrective and preventive maintenance to condition-based or data-based approaches (predictive maintenance) that aim to minimize downtime and associated costs.

For defensible estimation, maintenance costs are generally grouped into direct costs (scheduled inspections, repairs, and parts) as well as indirect costs associated with reliability consequences, such as losses due to reduced serviceability or downtime. Therefore, measurement of downtime and availability of asset data and consistent maintenance history are important prerequisites for maintenance cost analysis and Life Cycle Cost (LCC) evaluation to be technically and economically accountable.

The increasing need for clean water demands the management of Water Treatment Plants (WTPs) that are not only oriented towards capacity fulfillment, but also on operational efficiency, asset reliability, and long-term costs. The literature shows that WTP is an energy-intensive system, with performance influenced by operating characteristics, raw water source, treatment technology, and facility life. In addition, treatment process control and maintenance management play an important role in maintaining water quality stability while reducing operational costs.

Operational efficiency (OPEX) strategies are generally focused on optimizing energy and chemical consumption. Energy efficiency can be achieved through the regulation and scheduling of equipment operations, particularly pumping systems, without sacrificing supply continuity and reliability. Meanwhile, chemical optimization is carried out through process control and dose accuracy improvement that is more adaptive to changes in raw water quality, supported by adequate monitoring and control systems. In the context of capacity fulfillment, strategies can be on the spectrum from optimizing and uprating existing facilities, retrofitting or a modular approach with gradual investment, to building new WTP if the capacity gap can no longer be economically addressed. The choice of strategy is highly dependent on the level of capacity gaps, reliability needs, and long-term cost implications.

As technology develops, WTP management strategies are increasingly leading to a data-driven approach. The use of operational data and asset management supports energy and chemical optimization, preventive-predictive maintenance planning, and more structured investment decision-making. Thus, the integration of data-driven OPEX efficiency, maintenance, and capacity fulfillment strategies is key in improving the performance and sustainability of the WTP system.

Life Cycle Cost (LCC) is an economic evaluation method used to assess the total cost of a system or asset over its entire service life. This approach not only considers the initial investment costs, but also incorporates the costs of operation, maintenance, as well as other costs incurred during the analysis period into one comparable value base. Thus, LCC allows for a more comprehensive alternative comparison than an evaluation that is only based on initial cost. In the context of water infrastructure, LCC is widely used to evaluate the economic feasibility of water and wastewater treatment systems by considering the long-term costs that are repetitive. The literature shows that LCCs assist decision-makers in choosing the most cost-efficient alternatives throughout the service life of the system, especially when the cost of operation and maintenance has a significant portion of the total cost (Ilyas et al., 2021).

Based on these problems, this study aims to identify the most optimal strategy for fulfilling clean water supply needs in industrial estate WTP systems by optimizing operational costs and maintenance costs. Specifically, this study analyzes the existing condition of water demand, WTP capacity, OPEX, and MEX; evaluates alternative strategies using PV and LCC approaches; and determines priority strategies based on cost efficiency, technical feasibility, and service reliability.

This research is expected to provide both theoretical and practical benefits. Theoretically, this study contributes to the development of knowledge in water utility management, particularly in the application of PV and LCC analysis for clean water infrastructure decision-making. Practically, the findings can serve as a reference for industrial estate managers in determining phased strategies to improve WTP operational efficiency, reduce maintenance costs, and ensure sustainable clean water supply. In addition, this study can support decision-makers in prioritizing investment, whether through O&M improvements, small-scale instrumentation upgrades, or long-term WTP expansion, based on measurable financial and technical considerations.

## METHOD

This research begins with identifying the background to understand the existing conditions and urgency of the problem, then continues with the formulation of the problem which includes problem identification, goal determination, and research limitation. Furthermore, data collection was carried out consisting of primary data in the form of WTP operational observations and internal confirmations, as well as secondary data in the form of previous research studies, operational data and OPEX costs, maintenance data and MEX costs, and investment data (CAPEX). The data that has been collected is then processed to establish a baseline as the existing condition of the system, which is the basis for the formulation of alternative strategies. Each alternative strategy is analyzed technically and financially at an early stage, then further evaluated through Present Value (PV) and Life Cycle Cost (LCC) analysis to assess long-term cost efficiency. The next stage is sensitivity analysis to see the influence of changes in the main variables and determine the most optimal strategy. The research ended with the preparation of conclusions and suggestions based on the results of the analysis that had been carried out.

Primary data were obtained directly from the research site through non-intervention observation of Water Treatment Plant (WTP) operations to understand the flow of the treatment process, daily operating patterns, key points of energy consumption (such as pumps and filtration/backwash units), and chemical use practices. In addition, records of existing and maintenance conditions are collected which include identification of critical equipment, frequent outages, downtime patterns, and ongoing maintenance practices. If inconsistencies are found between data sources, internal validation is carried out through confirmation to related parties to ensure the accuracy and reliability of the data used in the analysis.

Secondary data is obtained from internal documents, operational records, as well as administrative and financial records in one of the industrial estates, and is the main source in the calculation of Present Value (PV) and Life Cycle Cost (LCC). The data used includes clean water production data, tenant water demand needs and projections, energy consumption and electricity costs, chemical consumption and costs, raw water costs, equipment maintenance and downtime data, WTP installed capacity and supporting technical information, as well as economic parameters such as analysis periods, discount rates, and CAPEX strategy estimates. All secondary data were compiled and analyzed to support the evaluation of existing conditions, analysis of water needs, and comparison of alternative strategies for fulfilling clean water supply using PV and LCC approaches consistently.

The research location includes the operational area of the water utility system in an industrial area in Karawang Regency, West Java. The areas analyzed include the Water Treatment Plant (WTP) along with the main process unit and supporting equipment, the internal supply and distribution system that delivers clean water to users, as well as data monitoring points such as records of water production, energy consumption, chemical use, and operational and maintenance costs. The scope of this location was chosen because all activities and data analyzed—including demand, capacity, OPEX, MEX, downtime, and PV and LCC-based strategy evaluation—centered on the performance of the industrial estate's clean water supply system.

The data collection technique in this study is designed to obtain accurate and measurable information related to the analysis of operational costs and maintenance of the Water Treatment Plant (WTP). Data collection was carried out through documentation studies, non-intervention observations, and internal validation. The documentation study is the main method by examining operational documents, costs, energy and chemical consumption, maintenance records, and technical specifications of the facility. Non-intervention observation is used to understand the physical conditions, process flows, and equipment without disrupting operations, while verifying the suitability of document data with actual conditions. Internal validation is carried out through cross-checking between documents, verification of data units and periods, and confirmation of historical consistency to ensure data reliability and accountability of Life Cycle Cost (LCC) calculation results.

The data analysis technique in this study was carried out quantitatively to obtain an overview of the operational cost structure and maintenance of the Water Treatment Plant (WTP) and to calculate the Present Value (PV) and Life Cycle Cost (LCC) values that can be applied to existing conditions. The analysis begins with mapping all expenses into Operating Expenditure (OPEX) and maintenance costs components to identify dominant costs, spending patterns, and costs per unit of service. Furthermore, management assumptions based on actual operating practices and literature recommendations are prepared, without subjectively changing historical data. The PV and LCC calculations are done by converting investment costs (if any), annual operating costs, and maintenance and component replacement costs into present values using a discounted rate and a specific analysis period. The results of the analysis were used to obtain an estimate of the amount of life cycle costs that are realistic and feasible to be implemented in WTP in accordance with existing technical and operational conditions, as a basis for discussion at the next stage of analysis.

## RESULTS AND DISCUSSION

### Existing Tenants' Clean Water Needs

Based on operational data for 2024–2025, the total clean water consumption of tenants served by WTP was recorded at 67,376 $m^3$/month or around 2,246 $m^3$/day, with one main tenant as the largest user. All existing water needs can still be met, indicating a safe supply condition. With a WTP design capacity of 50 L/s (±4,320 $m^3$/day), the current capacity utilization rate is in the range of 52%, so there is still an adequate capacity margin to accommodate increased consumption in the short term.

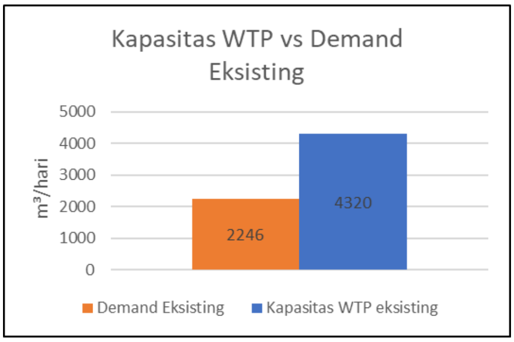


**Figure 1.** Comparison Chart of WTP Capacity vs Existing Demand

Source: WTP operational data processed by the authors (2025)

**Tenants' Upcoming Clean Water Needs**

In the next 1-2 years, industrial estates are projected to receive additional new tenants with an estimated combined clean water demand of around 3,700 $m^3$/day (±42.8 L/second). With an existing need of 2,246 $m^3$/day, the total clean water demand of the area is estimated to increase to around 5,946 $m^3$/day or equivalent to ±68.8 L/second. This increase in demand is significant and is a key factor in the formulation of WTP management strategies in the medium to long term.

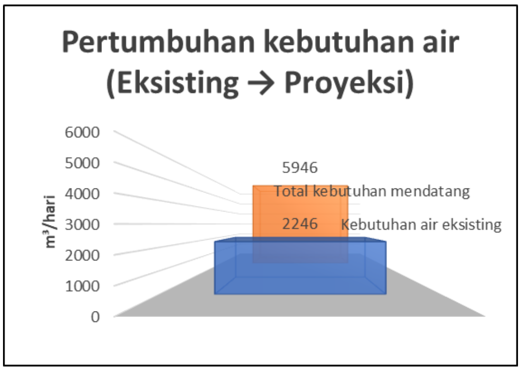


**Figure 2.** Water Demand Growth Chart

Source: Tenant water demand projection data processed by the authors (2025)

**Capacity gap analysis**

Comparison of existing WTP capacity with projected needs is shown in the following table:

**Table 1.** Needs and Capacity Gap Analysis

| Parameter | Value |
|---|---|
| Existing WTP capacity | **50 L/sec (4,320 $m^3$/day)** |
| Existing water needs | **2,246 $m^3$/day** |
| Projected *new* tenant needs | **3,700 $m^3$/day** |
| Total future needs | **5,946 $m^3$/day (68.8 L/sec)** |
| Capacity gap | **–1,626 $m^3$/day (–18.8 L/sec)** |

Source: WTP operational, maintenance, investment, and financial analysis data processed by the authors (2025)

The results of the analysis show that the existing WTP capacity is no longer sufficient to meet the clean water needs of the area after additional new tenants operate. With projected needs reaching around 68.8 L/second, there is a capacity deficit in the range of 18-20 L/second. This condition indicates that capacity building or alternative supply fulfillment needs to be seriously considered. The gap between capacity and demand has the potential to affect supply stability, especially for users with high consumption, so WTP management strategies going forward need to integrate operational efficiency (OPEX) and capacity investment (CAPEX) measures in a balanced manner.

**Analysis of WTP Existing Conditions**

**Operational Analysis and Maintenance**

Operational and maintenance analysis shows that the WTP in the industrial estate currently operates at a relatively high utilization rate, so the performance of the system is greatly influenced by the operation efficiency and reliability of the equipment. The average energy consumption was recorded at 35,132 kWh/month with a specific energy consumption of around 0.52 kWh/m³, which is above the general range of medium capacity WTP. This indicates a relatively high energy intensity and places energy efficiency as a key factor in improving operational performance.

**Table 2.** Operational Performance and Energy Consumption Indicators of WTP

| Yes | Performance Indicators | Existing Value | Units | Remarks |
|---|---|---|---|---|
| 1 | Average Energy Consumption | 35.132 | kWh/month | Relatively high energy intensity |
| 2 | Average water production | 67.376 | m³/month | 50 L/sec |
| 3 | Average energy efficiency | 0,52 | kWh/m³ | Above the *intermediate WTP* benchmark |
| 4 | Energy efficiency range | 0,43 – 0,60 | kWh/m³ | Tenants' clean water needs September – August 2025 |

Source: WTP operational, maintenance, investment, and financial analysis data processed by the authors (2025)

From the process side, the use of key chemicals (coagulants and disinfectants) shows fluctuations that are not always proportional to production volumes, so there is still potential for improved dose control to maintain process stability and cost efficiency.

**Table 3.** Indicators of the Use of Chemicals in WTP Processing

| Yes | Performance Indicators | Existing Value | Units | Remarks |
|---|---|---|---|---|
| 1 | Types of chemicals | PAC, NaOCl | – | Coagulants and disinfectants |
| 2 | Average PAC usage | 36.711,66 | ml/month | Fluctuating dosage |
| 3 | Average NaOCl usage | 18.146,16 | ml/month | Fluctuating dosage |

Source: WTP operational, maintenance, investment, and financial analysis data processed by the authors (2025)

WTP operations are carried out continuously 24 hours with a shift-based work system and supported by operational personnel as well as security and administrative functions. The source of raw water comes from surface water taken through the intake system with minimum charge provisions, making raw water management an important aspect in maintaining operational stability. Water quality control is carried out through routine laboratory testing to ensure compliance with quality standards.

**Table 4.** WTP Operational Performance and Maintenance Indicators

| Yes | Performance Indicators | Existing Value | Remarks |
|---|---|---|---|
| 1 | *Equipment downtime* | 6–8 hours/month | Routine operational disruptions |
| 2 | Maintenance patterns | *Corrective-dominant* | *Preventive* belum optimal |
| 3 | Types of maintenance | *Preventive & corrective* | Not condition-based yet |
| 4 | Frequency of interruptions | Recurring | Not condition-based yet |
| 5 | Large equipment replacement | There | Pumps and electrical panels |
| 6 | System *predictive maintenance* | Not available | Condition monitoring has not been implemented |

Source: WTP operational, maintenance, investment, and financial analysis data processed by the authors (2025)

In terms of maintenance, the pattern implemented is still dominated by corrective maintenance with an average downtime of 6-8 hours per month, and has not been supported by a condition-based maintenance system. This condition shows that the reliability of the system still depends on the response to disturbances, so there is room for improvement through improving operational efficiency, process control, and strengthening maintenance strategies as the basis for the preparation of cost analysis and clean water supply fulfillment strategies at the next stage.

Operating Cost Analysis (OPEX)

Operating Expenditure (OPEX) is a routine expenditure required to maintain the sustainability of Water Treatment Plant (WTP) operations. Based on actual data for the past year, the total OPEX of WTP was recorded at IDR 3.96 billion per year, which consisted of the cost of electrical energy, chemicals, operational and security labor, raw water extraction, water quality control, fuel, and administrative and general costs. The cost structure shows that the operational labor component, raw water harvesting, and electrical energy are the largest contributors and cumulatively account for more than two-thirds of total OPEX, reflecting the characteristics of WTP's ongoing operations.

**Table 5.** WTP Operating Costs

| Components | Percentage | Cost |
|---|---|---|
| Electrical energy | 16.19% | IDR 640,637,880 |
| Chemicals (PAC, NaOCl) | 4.20% | IDR 166,202,943 |
| Operational Workforce | 36.88% | IDR 1,458,849,895 |
| Security Workforce | 7.49% | IDR 296,280,000 |
| Raw water/water intake fee | 33.44% | IDR 1,322,762,004 |
| Laboratory & water quality control | 0.26% | IDR 10,200,000 |
| Fuel Consumption | 1.31% | IDR 52,000,000 |
| Administration & general | 0.23% | IDR 9,000,000 |
| **Total** | **100%** | **IDR 3,955,932,722** |

Source: WTP operational, maintenance, investment, and financial analysis data processed by the authors (2025)

Labor costs and raw water extraction are relatively fixed, while electrical energy and chemical costs are variable and are most sensitive to changes in operating patterns. These findings indicate that OPEX efficiency efforts are most realistically directed at controlling energy and chemical consumption without compromising continuity of service. With a significant and recurring total OPEX, operational cost management is a crucial aspect in maintaining the financial sustainability of the clean water supply system, as well as being the basis for the formulation of efficiency strategies and improving WTP performance at the next stage of analysis.

**Maintenance Cost Analysis (MEX)**

Maintenance Expenditure (MEX) is an expense intended to maintain the reliability, performance, and service life of Water Treatment Plant (WTP) equipment, and reflects the financial implications of the maintenance strategy implemented. Based on actual data for the past year, the total MEX WTP was recorded at IDR 364.13 million per year, consisting of preventive maintenance, corrective maintenance, and replacement of large equipment. The cost structure shows that preventive maintenance is the largest component, indicating that there are routine maintenance efforts to maintain the reliability of the asset.

**Table 6.** WTP Maintenance Costs (last 1 year)

| Components | Percentage | Cost |
|---|---|---|
| *Preventive maintenance* | 46.40% | IDR 168,955,701 |
| *Corrective maintenance* | 34.62% | IDR 126,061,344 |
| Large Equipment Replacement | 18.98% | IDR 69,111,621 |
| **Total** | 100% | **IDR 364,128,666** |

Source: WTP operational, maintenance, investment, and financial analysis data processed by the authors (2025)

However, the significant portion of corrective maintenance indicates that the effectiveness of preventive maintenance is not fully optimal in reducing the occurrence of equipment failures. In addition, the cost of replacing large equipment, while not routine, has a considerable financial impact and needs to be taken into account in long-term planning. With a relatively significant total MEX, maintenance is an important cost component in the evaluation of WTP management strategies and is the main input in the Life Cycle Cost (LCC) analysis at the next stage.

**Formulation of Alternative Strategies**

**Operational Strategy (OPEX)**

The operational strategy is focused on improving the operational cost efficiency of the Water Treatment Plant (WTP) based on the results of the OPEX structure analysis. Labor costs are the largest component, but they have very limited room for optimization because they are influenced by labor regulations, so they are not the focus of efficiency strategies. Therefore, the strategy is directed at cost components that are more flexible and can be optimized technically and measurably, namely the cost of raw water withdrawal, energy consumption, and the use of chemicals. Raw water cost optimization is directed at increasing volume utilization close to the minimum charge scheme as well as evaluating the suitability of contracts with actual needs. Energy optimization is carried out through pump operation settings, reservoir levels, and backwash systems to suppress specific energy consumption close to historical best performance. Meanwhile, chemical optimization is focused on more precise dose control, supported by historical analysis and potential application of process control instruments, so that efficiency can be quantitatively calculated based on the comparison of best performance and annual average.

**Maintenance Strategy (MEX)**

The maintenance strategy is focused on improving the operational reliability of the Water Treatment Plant (WTP) through reducing equipment downtime by strengthening the implementation of more structured preventive maintenance. The results of the analysis of existing conditions show an average downtime of 6–8 hours per month, mainly due to repeated disruptions to critical equipment such as pumps, electrical panels, and chemical dosing systems. Given the limitations of historical data, the evaluation of the effectiveness of maintenance strategies is focused on downtime parameters as the main indicator, as it is directly related to the frequency of interruptions and the need for corrective maintenance. The strategies formulated include assigning labor for preventive maintenance, scheduling routine inspections on main equipment, and simple recording of equipment conditions, without additional equipment investment or labor numbers. With a more planned and consistent implementation of preventive maintenance, it is hoped that equipment downtime can be reduced gradually so that the frequency of corrective maintenance and the burden of maintenance costs can be reduced.

**Existing WTP Performance & Capacity Improvement Strategy (small CAPEX)**

Increasing the capacity of a Water Treatment Plant (WTP) does not necessarily require the construction of new units or the addition of physical capacity with large investments, but can be achieved through optimizing the performance of existing process units. In the WTP of the industrial area studied, increasing operational capacity and stability is directed through optimizing the processing process with relatively small investment needs (limited CAPEX), but has a direct impact on operational efficiency, control of chemical consumption, and the ability of the system to support an increase in the volume of clean water production. One of the strategies that is considered the most relevant and applicable is the application of Streaming Current Monitor (SCM) as a real-time coagulation-flocculation control instrument. SCM allows for automatic measurement of suspended particle charge and coagulant dose setting, making the coagulation process more stable despite fluctuations in raw water quality. The selection of this strategy is supported by significant variations in the historical use of PAC chemicals, the instability of raw water quality, and the findings of the literature that show the potential for chemical savings of 10–30%. The implementation of SCM is carried out through the installation of sensors on the outlet of the rapid mix, integration with PAC dosing pumps, and set-point-based automatic control settings that are adjusted in real-time to changes in raw water quality.

**New WTP Expansion Strategy (large CAPEX)**

This strategy is a long-term solution to meet the increasing needs of clean water tenants in the industrial estates studied. Based on projections, the existing clean water demand of 2,246 $m^3$/day will increase by around 3,700 $m^3$/day as new tenants operate, so that the total demand exceeds 5,900 $m^3$/day. Meanwhile, the existing Water Treatment Plant (WTP) capacity is only around 50 liters/second or ±4,320 $m^3$/day, so it is not able to meet the total needs of the area. Therefore, the construction of a new WTP is needed as a strategy with a large investment (large CAPEX). The new WTP is planned to have a minimum capacity of 50 liters/second and is equipped with a complete process unit that is integrated with the existing WTP system. The operational integration between the existing WTP and the new WTP is expected to result in a total capacity of more than 100 liters/second, which is sufficient to support the region's clean water needs in the medium to long term (±5–10 years). The financial feasibility of this strategy is evaluated using the Life Cycle Cost (LCC) approach, taking into account the estimated construction investment cost, annual operational costs, and technical life of the facility for 20–25 years.

**Technical and Financial Analysis of Strategies**

After the formulation of four groups of clean water supply fulfillment strategies, namely operational strategy (OPEX), maintenance strategy (MEX), strategy to improve the performance and capacity of existing WTP (small CAPEX), and capacity building strategy through the development of new WTP (large CAPEX), an initial technical and financial analysis was carried out to assess the feasibility of implementing each strategy. The technical analysis focuses on the impact of the strategy on system reliability, resource requirements, operational risks, and the readiness of existing infrastructure, while the initial financial analysis aims to provide an overview of the direction and magnitude of the cost implications without making detailed lifecycle cost calculations.

The OPEX and MEX strategies are considered relatively easy to implement with low technical risk because they do not require significant physical changes and have the potential to improve operational stability and reduce downtime. A small CAPEX strategy involves limited technical intervention with the potential for improved process performance and sustainable cost efficiency, while a large CAPEX strategy has the highest technical complexity and investment needs, yet provides a guarantee of long-term water supply reliability. The initial financial analysis was carried out using a scenario approach based on historical data to identify the potential operational and maintenance cost efficiency as well as the investment implications of each strategy, so that all strategies analyzed have a rational technical and financial basis before being further evaluated using the Life Cycle Cost (LCC) method.

**Evaluation of the Strategy's Long-Term Costs**

**Evaluation of PV Operational Costs (OPEX Strategy)**

The evaluation of operational costs in this study was carried out using the Present Value (PV) approach to assess the long-term impact of the implementation of OPEX optimization strategies on the Water Treatment Plant (WTP) system of industrial estates, without involving significant new CAPEX investments. The analysis was conducted with a discount rate of 8% and a period of 20 years, using a PV annuity factor of 9.818, focusing on the OPEX components that are most likely to be technically optimized, namely electrical energy and chemicals, while the cost of raw water was not analyzed further because it is still bound by the minimum charge scheme. The efficiency potential is derived from a comparison of the best historical performance against the existing average conditions, which shows an opportunity for energy savings of up to 16.93% and chemicals of up to 14.88%.

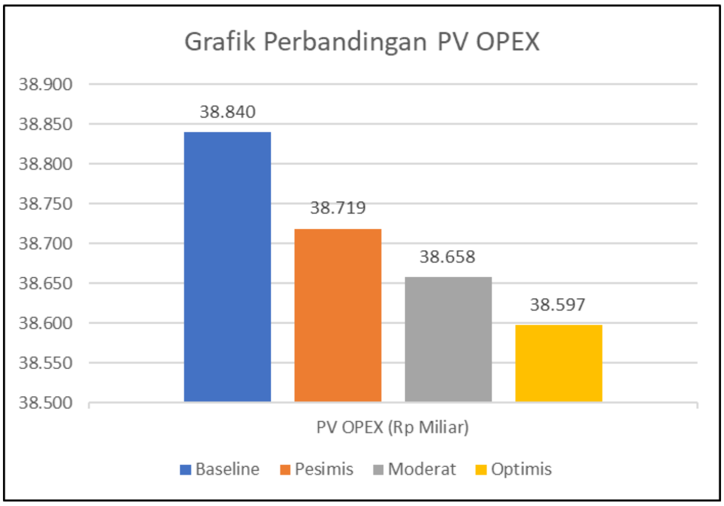


**Figure 3.** OPEX PV Value Comparison Chart
Source: OPEX calculation results processed by the authors (2025)

Based on this potential, three implementation scenarios were prepared, namely pessimistic (50%), moderate (75%), and optimistic (100%), to represent the uncertainty of implementation in the field. In baseline conditions, the value of PV OPEX for 20 years was recorded at IDR 38.84 billion, which then gradually decreased to IDR 38.72 billion in the pessimistic scenario, IDR 38.66 billion in the moderate scenario, and IDR 38.60 billion in the optimistic scenario, with cumulative PV savings of IDR 121.39 million, IDR 182.09 million, and IDR 242.78 million, respectively. These results show that the OPEX strategy is able to provide consistent long-term cost savings albeit relatively limited, so it is more appropriately positioned as an operational quick win that supports cost efficiency and stability, but has not resulted in significant structural changes to the total lifecycle costs of the WTP system.

**PV Evaluation of Maintenance Costs (MEX Strategy)**

The evaluation of maintenance costs (Maintenance Expenditure / MEX) was carried out using the Present Value (PV) approach to assess the long-term impact of the implementation of preventive maintenance strategies on the Water Treatment Plant (WTP) system of industrial estates. The analysis was carried out with a discount rate of 8% and a period of 20 years using a PVAF factor of 9,818, with a baseline maintenance cost of Rp364,128,666 per year consisting of preventive maintenance, corrective maintenance, and replacement of main equipment. The MEX strategy is formulated based on the relationship between maintenance patterns and operational downtime, with a baseline downtime of 7 hours per month.

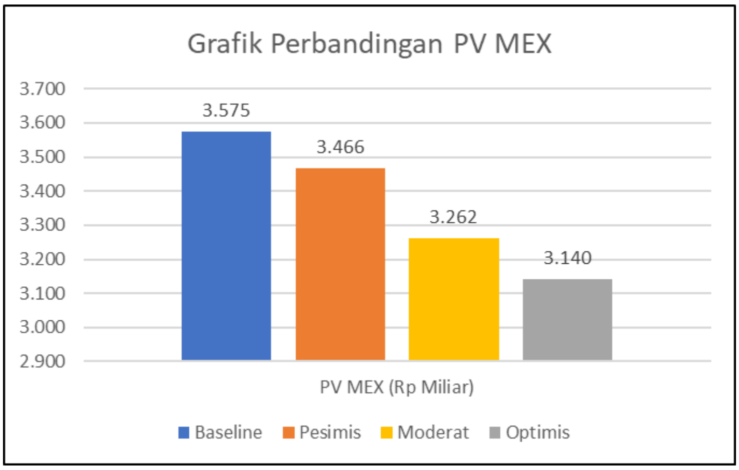

**Figure 4.** Comparison Chart of PV MEX Values
Source: MEX calculation results processed by the authors (2025)

Three scenarios were applied, namely pessimistic, moderate, and optimistic, each of which represented an increase in preventive maintenance activities and a gradual decrease in downtime. The results of the evaluation showed that the value of PV MEX at baseline conditions was IDR 3.58 billion, then decreased to IDR 3.47 billion in the pessimistic scenario, IDR 3.26 billion in the moderate scenario, and IDR 3.14 billion in the optimistic scenario, with cumulative PV savings of IDR 108.7 million, IDR 313.18 million, and IDR 434.73 million, respectively. Comparatively, the MEX strategy provides more significant PV savings than the OPEX strategy, especially in optimistic scenarios, which shows that strengthening preventive maintenance can reduce long-term maintenance costs more effectively through reduced equipment failures and downtime. Therefore, the MEX strategy is positioned as the main strategy in optimizing the life cycle costs of the WTP system that are structural and sustainable, and have the potential to be combined with other investment strategies at a later stage.

**LCC Evaluation of Small CAPEX Strategy**

The Life Cycle Cost (LCC) evaluation was conducted to assess the financial feasibility of the small CAPEX strategy as a limited investment approach in improving the stability and operational efficiency of the Industrial Estate's Water Treatment Plant (WTP) system through the installation of additional equipment, such as Streaming Current Monitor (SCM) and supporting instruments. The LCC analysis was conducted at a discount rate of 8% and a 20-year period using a PVAF factor of 9,818, which includes initial investment costs, operational costs, and maintenance costs in a single evaluation framework. The initial investment cost ($CAPEX_0$) is set at IDR 380,000,000, while the annual cost component consists of relevant OPEX of IDR 806,840,823 per year and MEX of IDR 364,128,666 per year. The implementation of a small CAPEX strategy is assumed to result in energy savings of 3% and chemical savings of 14.88% based on the best historical performance. The calculation results show a total LCC of IDR 11,445,274,151, which provides a cumulative LCC saving of IDR 51,476,902 compared to baseline conditions.

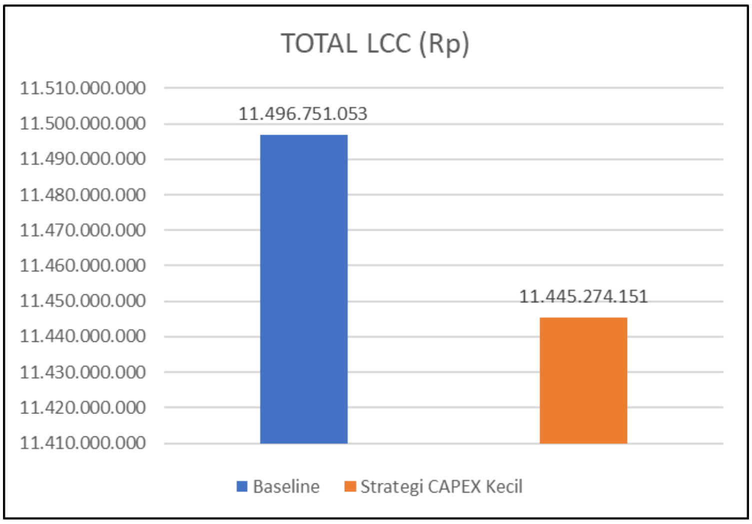


**Figure 5.** Total Value of Small CAPEX LCCs
Source: LCC calculation results processed by the authors (2025)

These findings suggest that a small CAPEX strategy is worth considering as an option for optimizing WTP operational costs and maintenance before large-scale infrastructure investments are made.

**LCC Evaluation of Large CAPEX Strategy**

As the final stage of the Life Cycle Cost (LCC) analysis, a large CAPEX strategy was evaluated to assess the financial implications of the construction of a new Water Treatment Plant (WTP) as a long-term structural solution in meeting the increasing needs of clean water supply of industrial areas. The LCC analysis was conducted with a discount rate of 8% and an analysis period of 20 years using a PVAF factor of 9,818, which includes initial investment costs, operational costs, and maintenance costs in a single evaluation framework. The initial investment cost ($CAPEX_0$) for the construction of the new WTP is set at IDR 15.00 billion, assuming annual operational costs of IDR 3.96 billion and annual maintenance costs of IDR 0.36 billion. The calculation results show that the Present Value (PV) value of operational costs is IDR 38.84 billion and PV of maintenance costs is IDR 3.58 billion, so that the total LCC of the CAPEX strategy is large reaching IDR 57.41 billion.

**Table 7.** LCC Values Large CAPEX CostslOptimal Strategy Selection

| Item | Value |
|---|---|
| Initial CAPEX (CAPEX0) | 15,000,000,000 |
| PV OPEX | 38,839,930,599 |
| PV MEX | 3,575,068,918 |
| PV Replacement | 0 |
| PV Residual | 0 |
| TOTAL LCC | 57,414,999,517 |

Source: WTP operational, maintenance, investment, and financial analysis data processed by the authors (2025)

The value of this LCC is the highest compared to other strategies, reflecting the magnitude of the financial consequences of investing in new capacity. Although less than optimal from a lifecycle cost minimization perspective, a large CAPEX strategy plays an important role in ensuring the reliability of clean water supply and the fulfillment of long-term needs, so it is more appropriately understood as a capacity fulfillment strategy than a cost-saving strategy.

**Sensitivity Analysis**

To strengthen the robustness of the decision, a single-parameter sensitivity analysis was performed to several key LCC assumptions. The results showed that the change in the discount rate affected the amount of PVAF and PV Saving. At higher discounts (10%), the PV Saving value decreases. The Operational & Maintenance strategy still delivers significant PV savings, while the small CAPEX strategy is getting closer to breaking even at higher discounts.

**Table 8.** Sensitivity to Discount Rates (r)

| r | PVAF | PV *Saving* O+M (Moderate) (Rp Million) | NPV *Saving* CAPEX Small (Rp Million) | Total LCC CAPEX Large (Rp Million) |
|---|---|---|---|---|
| 6% | 11,470 | 578,58 | 124,07 | 64.550,76 |
| **8% (Base)** | **9,818** | **495,26** | **51,48** | **57.415,00** |
| 10% | 8,514 | 429,45 | -5,86 | 51.779,12 |

Source: WTP operational, maintenance, investment, and financial analysis data processed by the authors (2025)

**Strategy Decisions**

**Table 9.** Strategy Decisions

| Strategy | Main Focus & Output | CAPEX | Financial Indicators (20-year base; r=8%) | Implementation in WTP | Priorities |
|---|---|---|---|---|---|
| **Baseline – Existing WTP (Initial Condition)** | WTP operations are running according to existing conditions, as a reference for comparing technical and financial performance. | 0 | **Financial Indicators (20-year base; r = 8%):** Baseline baseline (PV Saving = 0; NPV = 0) | WTP operations are carried out in accordance with existing practices, including pump operating patterns, chemical dosage, and routine maintenance without additional optimization or new investments. | Baseline (initial comparative conditions before strategy implementation) |
| **Operations & Maintenance (O&M)** | Lower OPEX & MEX without investment | 0 | **PV *Saving* OPEX&MEX:** Pessimistic **230.07**; Moderate **495.26**; Optimistic **677,51** (Rp Million) | Optimize pump operations, chemical dosing, and preventive maintenance based on KPIs to reduce OPEX and MEX. | **Priority 1 (optimal strategy)** |
| **Small CAPEX (SCM,** | Automatic coagulation control | 380(Rp Million) | **NPV *Saving* vs *baseline*:** | Installation of control instruments (SCM & flowmeter) | **Priority 2 (conditional):** feasible if |

| Strategy | Main Focus & Output | CAPEX | Financial Indicators (20-year base; r=8%) | Implementation in WTP | Priorities |
|---|---|---|---|---|---|
| **instrument, and installation)** | (chemical efficiency & process stability) | | **+51,48** (Rp Million) | and PLC/SCADA integration to improve process stability and chemical efficiency. | CAPEX0 ≤ 431.48 million and *chemical saving* ≥ 11.72% |
| **Large CAPEX (WTP Expansion)** | Fulfillment of capacity and reliability of supply | 15(Rp Million) | **Total LCC:57,415** (Rp Million) | WTP capacity development through the addition of process units to ensure long-term water supply reliability. | **Priority 3:** deployed when existing capacity is insufficient/supply risk is high |

Source: WTP operational, maintenance, investment, and financial analysis data processed by the authors (2025)

## CONCLUSION

Based on the analysis of Present Value (PV) and Life Cycle Cost (LCC) with an analysis period of 20 years and a discount rate of 8%, this study shows that the optimization of operational costs and maintenance of the clean water supply system in the WTP of industrial estates is most effective through a tiered approach. Operational and maintenance (O&M) strategies are a top priority as they are able to provide consistent cost savings without upfront investment, with PV savings OPEX & MEX ranging from IDR 230.07–677.51 million and IDR 495.26 million in the moderate scenario. A small CAPEX strategy is considered economically feasible because it generates positive NPV savings, but is highly dependent on the amount of initial investment and the success rate of chemical savings, thus requiring control of data-driven implementation and operations. Meanwhile, large CAPEX strategies result in high LCC values and are not prioritized in terms of cost efficiency, but are more appropriately positioned as capacity building options and increasing supply reliability when demand approaches or exceeds existing WTP safe capacity. Based on the results of the research, implementation recommendations are prepared in stages to be in line with limited data, resources, and operational needs. The top priority is the operational and maintenance (O&M) strategy through the implementation of data-driven KPIs, energy and chemical optimization, and the preparation of structured preventive maintenance on critical equipment to reduce OPEX and downtime on an ongoing basis. A small CAPEX strategy is recommended as an advanced stage with an emphasis on investment cost validation, integration of appropriate process control systems, implementation of commissioning and performance tests to ensure savings targets are achieved, and strengthening operator competencies. Meanwhile, the large CAPEX strategy is positioned as a medium-long term option implemented on a trigger-based basis, taking into account the growth in demand and reliability needs, and supported by technical-economic studies and reliability planning to ensure capacity expansion truly improves service continuity.

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