Efficiency Analysis of Coagulant and Energy Consumption of Surabaya Water Treatment Plant using Data Envelopment Analysis Method

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Abstract. The high demand for clean water in Surabaya has driven the optimisation of the water treatment process at three water treatment plants (WTPs). The primary challenge is determining the optimal dosage for coagulation and flocculation, which play a crucial role. DEA was used to assess the optimum coagulant dosage. The DEA calculates the coagulant dosage efficiency score and energy consumption in every WTP unit, with a threshold score of 1. The DEAP 2.1 software performs the assessment simulation. When the WTP score is 1, it is considered efficient in saving coagulants, and an energy A score below 1 indicates inefficiency in conserving those resources. The inputs are energy requirements and coagulant doses between 2018 and 2022. The outputs are water quality parameters such as turbidity, total dissolved solids (TDS), and colour. The highest efficiency performance was obtained by WTP 2 (46%), followed by WTP 3 (43%) and WTP 1 (29%). Overall, the recommendations for energy efficiency and coagulant dosage efficiency vary. The energy efficiency improvement recommendations are pump monitoring, maintenance of the electromotor, and supervision of the main assets. On the other hand, maintaining optimal coagulant requirements, selecting the right coagulant, and administering flocculants effectively are key.

1 Introduction

The essential resources for socioeconomic development in urban areas are water and energy. The water resources in urban environments require energy to supply, treat, and distribute. The availability of drinking water, which is affected by water scarcity, population growth, and urbanisation, will become a challenge for water utilities in the upcoming years [1].

Coagulants play an essential role in water treatment processes, particularly in the energy consumption during the coagulation process. The energy consumption efficiency in the coagulation process can be affected by several factors, such as fractal dimensions, floc growth models, floc strength, and floc settling velocity [2]. A practical method for improving coagulant dosing efficiency and energy requirements in water treatment utilities is benchmarking. Evaluating the WTP performance using various metrics and procedures has been done by several studies [1]. Life Cycle Assessment (LCA) is the most common method used to measure the energy intensity of WTP. However, this method has limitations. It focused on the energy consumption by the WTP without considering the effect of raw water quality on the quality of the product [3].

The Surabaya Municipal Water Company operates three major water treatment facilities that consume around 30–40% to the total energy utilisation in process operations. Therefore, drinking water processes contribute to more than 45 million tons of greenhouse gases annually [6]. As much as 40% of the operational costs for drinking water systems are used for energy costs [8]. This study addresses the knowledge gap of the Data Envelopment Analysis (DEA) Common Sets of Weights (CSW) approach to score coagulant dosage and energy requirements efficiency at WTPs 1, 2, and 3. Multiple inputs and outputs for each WTP unit are utilised by using the DEA method, resulting in multi-criteria analysis without requiring assumptions.

2 Methodology

This study required a field research method, collecting both primary and secondary data from WTPs 1, 2, and 3. The research framework involved several systematic stages, including problem formulation, literature review, data collection, data processing and analysis, and formulation of conclusions and recommendations. This study utilised the DEA-CSW method to overcome the limitations of previous DEA-FSW (Flexible Sets of Weights) approaches, which often resulted in multiple facilities being identified as equally efficient, thus limiting their discriminatory power [4]. The DEA-CSW approach allocates common weights to variables (inputs and outputs) for all assessed units, enabling all units to be fully discriminated and ranked in a specific sequence.

Primary data were collected through field surveys examining the condition of production pumps and equipment at all three facilities. The secondary data is using the data series between 2018 and 2022, including water quality parameters (Turbidity, Total Dissolved Solids, and Colour), coagulant dosage, and energy consumption. The input variables consisted of energy requirements and coagulant doses, whereas the output variables included turbidity, TDS, and colour measurements [5]. The efficiency maximum score (EEo) is 1. A score of 1 indicated efficient operation in saving coagulant and energy, whereas scores below 1 indicated inefficiency.

The research methodology also included calculating the optimal coagulant dosage using artificial neural network methods with a 3-4-1 network architecture and evaluating pump efficiency based on pump and electromotor specifications. Field research was conducted to identify the actual conditions of the main assets, including pumps, electromotors, and other processing equipment, at each facility. The correlation between water tariffs and pump efficiency was also analysed to understand the economic implications of the operational efficiency.

3 Result

The analysis of 1,747 data points WTP 1, 2, and 3 during 2018-2022 revealed significant differences in operational efficiency among the three facilities. Using the DEA-CSW method, WTP 2 achieved the highest average efficiency score of 46%, followed by WTP 3 at 43%, and WTP 1 at 29%. This contrasts with the DEA-FSW results, where 55 calculations achieved perfect efficiency scores of 1.0, demonstrating the limited discriminatory power of the FSW approach [7]. The DEA-CSW method successfully identified only one calculation (number 14 from WTP 2) as having the highest efficiency score of 0.994, representing the most energy-efficient coagulant dosage and energy usage among all the evaluated data.

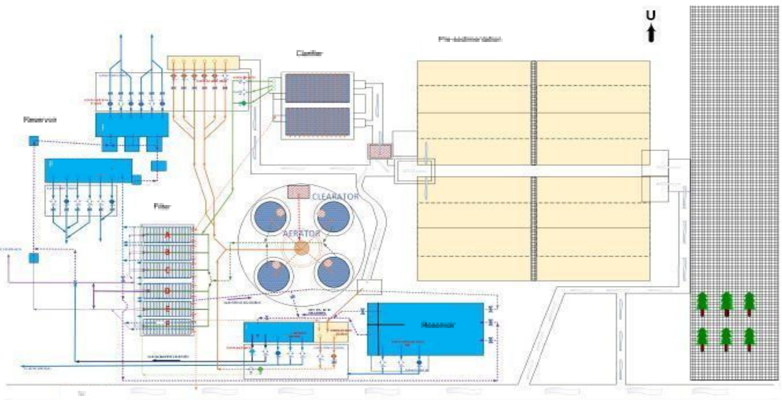

Fig. 1. Water Treatment Scheme Process

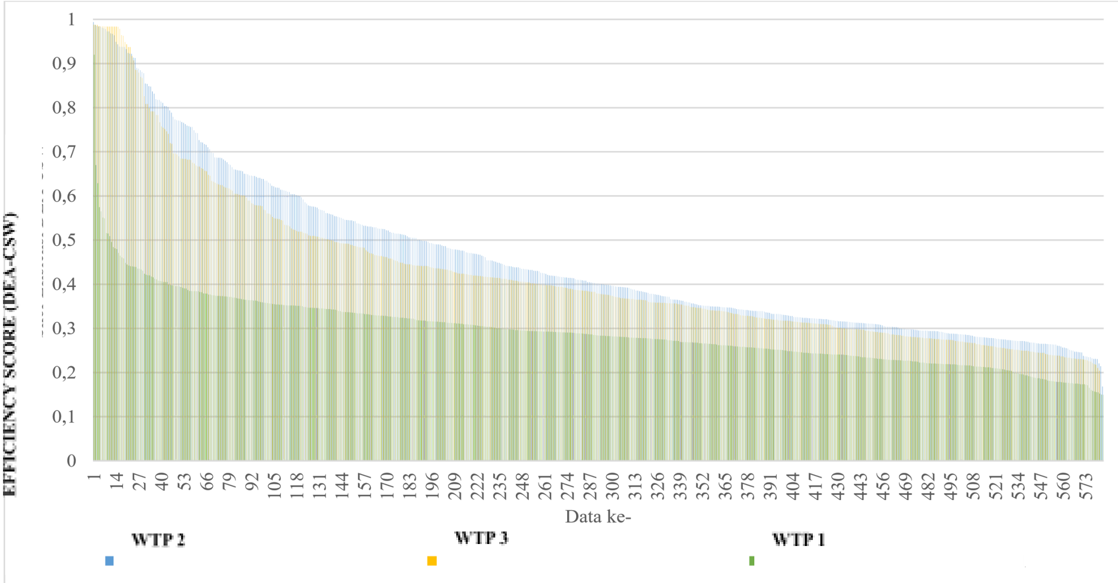

Fig. 2. DEA-CSW calculation chart based on highest to lowest scores

The superior performance of WTP 2 can be attributed to several factors identified through field studies. The facility features four pre-sedimentation basins with a gravity-based overflow settling velocity of 8.3 m/s. A primary clarifier with a 19-meter diameter for initial sedimentation by adding aluminum sulphate and an upflow accelerator clarifier also with 19-meter diameter for continued sedimentation. Additionally, WTP 2 employs 32 rapid sand filter units with dual media layers consisting of 60 cm of silica sand and 30 cm of anthracite, utilizing both air and water backwashing. Overall, WTP 2 has maintained a consistent coagulant dosage and appropriate energy.

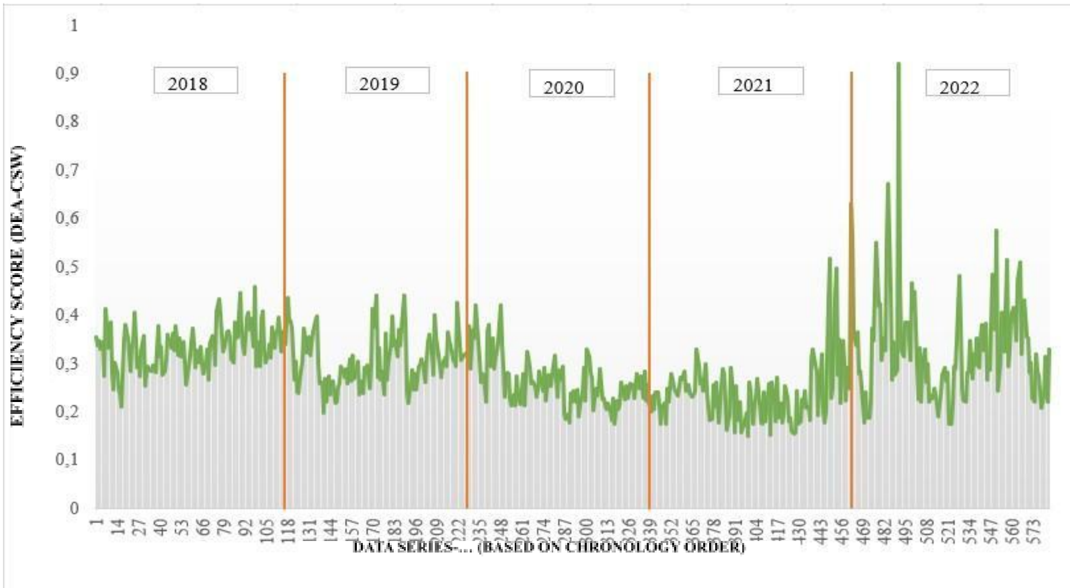

Fig. 3. DEA-CSW WTP 1 calculation chart based on chronological order

Figure 3 illustrates the DEA-CSW efficiency scores for WTP 1 from 2018 to 2022, showing moderate performance with values generally ranging between 0.25 and 0.50 during the first four years. Efficiency levels remain relatively stable but do not show significant improvement from 2018 through 2021, indicating consistent yet modest operational effectiveness. Several notable peaks emerged above 0.70 and approached 0.90, showing an impressive change in operational control, coagulant dosing optimisation, and energy management during 2022. This upward shift implies that corrective actions or process enhancements implemented at WTP 1 were successful, resulting in its strongest performance in the final year of observation.

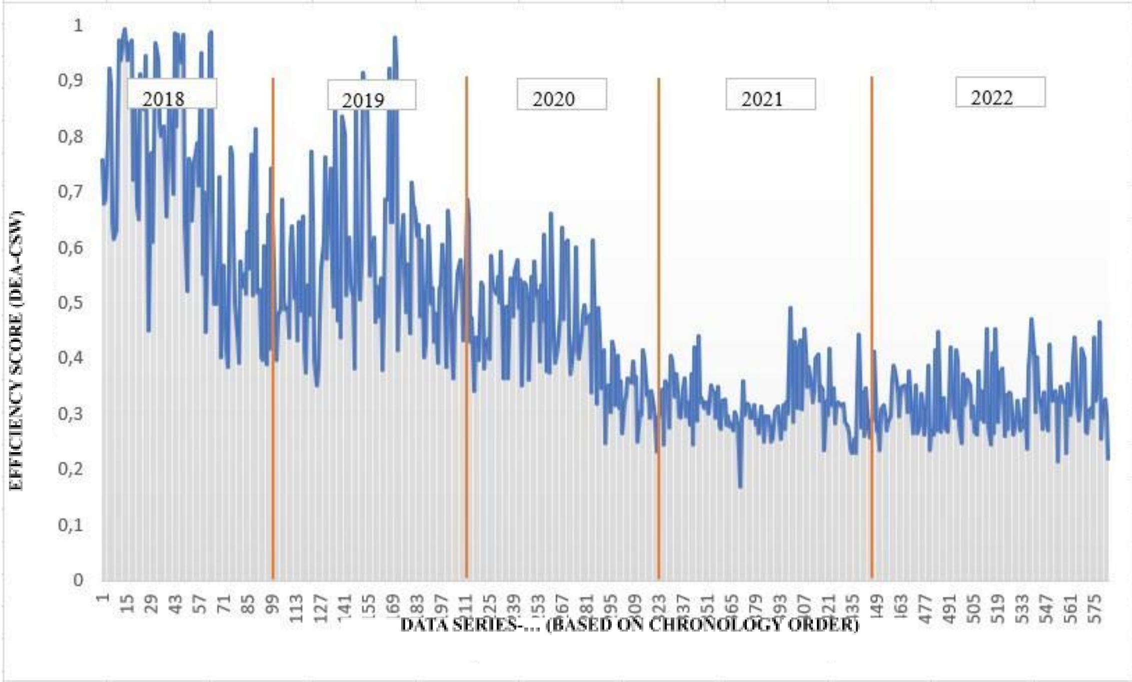

Fig. 4. DEA-CSW WTP 2 calculation chart based on chronological order

Figure 4 illustrates the efficiency trend of WTP 2. Started with the highest performance among the three plants in 2018, with many data points reaching between 0.70 and 0.95. However, a steady downward trend emerges beginning in 2019, indicating progressive declines in efficiency. This situation is related to aging infrastructure, raw water variability, or an imbalance in coagulant and energy usage. By 2020 and continuing through 2021 and 2022, the scores stabilize at significantly lower levels, generally between 0.20 and 0.40, with very few high-efficiency peaks. This sustained decline highlights deterioration in operational consistency and suggests that WTP 2 requires targeted improvements, equipment rehabilitation, and better optimisation strategies to recover its earlier high performance.

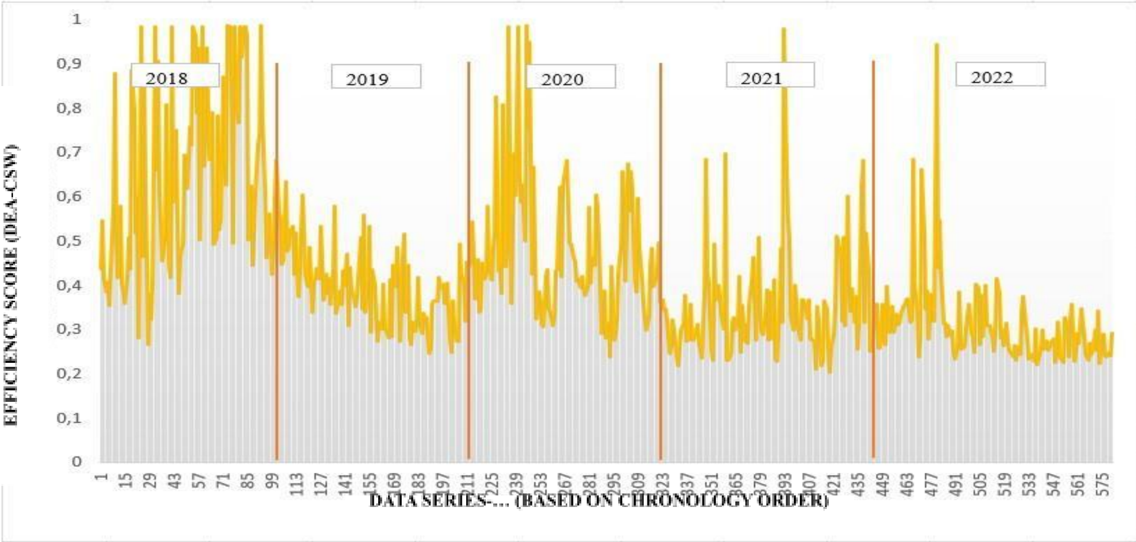

Fig. 5. DEA-CSW WTP 3 calculation chart based on chronological order

Figure 5 presents the efficiency profile of WTP 3, which exhibits extreme volatility in 2018 and 2019, with frequent spikes approaching or exceeding 0.90, indicating periods of very high performance mixed with sharp declines. This instability suggests inconsistent process conditions or fluctuating raw water quality. Beginning in 2020, the efficiency values show a pronounced downward shift, with fewer high peaks and greater clustering around lower scores. By 2021 and 2022, the efficiency stabilises in the range of 0.20 to 0.35, indicating a sustained decline in operational effectiveness. This pattern reflects deterioration in process reliability, potential equipment wear, or the need for improved coagulant dosing and energy management. Overall, WTP 3 transitions from high performance to consistently low efficiency over time.

The energy optimisation potential across all three facilities was substantial. Based on the DEA-CSW analysis, the cumulative energy that could be optimised reached 16,038,796.76 kWh/year, compared to 11,739,038.89 kWh/year using the DEA-FSW method. This energy savings potential could reduce greenhouse gas emissions by 6,704,217.05 kg CO_2 eq/year (DEA-CSW) or 4,906,918.26 kg CO_2 eq/year (DEA-FSW), equivalent to the annual emissions from 1,457 or 1,067 typical passenger vehicles, respectively. For coagulant optimisation, the cumulative potential savings reached 2,927,710 kg/year using DEA-CSW compared to 2,115,895 kg/year using DEA-FSW, representing significant operational cost reduction opportunities for WTP.

Pump efficiency analysis revealed considerable variations across facilities. Sample calculations from WTP 1 showed that southern water pumps no. 1 and 2 achieved 72.21% efficiency, while pump no. 6 achieved only 27.69% efficiency. At WTP 2, water pump no. 5 demonstrated 55.6% efficiency, whereas water pump No. 1 showed 45.5% efficiency. Primary water pumps no. 7 and 8 of WTP 3 exhibited efficiencies of 34.4% and 43.8% respectively. These findings indicate that several pumps, particularly those over 15-20 years old with efficiency scores below 50%, require replacement with high-efficiency models to optimise energy consumption.

The relationship between operational efficiency and water tariffs was analysed using data from 2016 to 2020. The average water tariff in 2020 was IDR 3,087.06 per m³, while operational production costs showed relatively stable increases over the period, reaching IDR 842 per m³ in 2020, representing a 3.59% increase from the previous year. The ratio of operational production costs to the average water selling price was 27.27% in 2020, up from 25.88% in 2019. This indicates that efficiency improvements in coagulant dosage, main assets, processing units, and pump operations directly impact operational production costs, ultimately affecting consumer tariffs and service quality.

4 Conclusions

This study presents a robust analysis using the DEA-CSW method to measure the energy and coagulant efficiency at three WTPs. Shortly, the potential savings in energy (16,038,796.76 kWh/year) and coagulant (2,927,710 kg/year) are significant results.

The efficiency ranking showed WTP 2 achieving the highest score of 46%, followed by WTP 3 at 43%, and WTP 1 at 29%. The superior performance of WTP 2 was attributed to its consistent operational capacity of 1,000 litres per second (lps). A comprehensive treatment process design, including four pre-sedimentation basins and dual-media rapid sand filters, followed by systematic operational practices enabling consistent coagulant dosing and appropriate energy management.

Significant optimisation potential was identified across all facilities, with a cumulative energy savings potential of 16,038,796.76 kWh/year and coagulant savings of 2,927,710 kg/year using the DEA-CSW method. These savings translate to substantial environmental benefits, equivalent to removing 1,457 passenger vehicles. Pump efficiency analysis revealed considerable variation, with some units, particularly those over 15-20 years old, achieving efficiency scores below 50%, indicating an urgent need for replacement with high-efficiency models.

Comprehensive recommendations were formulated to address both coagulant and energy efficiency through a detailed evaluation of coagulant requirements, optimal dosage determination, systematic maintenance programs, proper asset management, and strategic replacement of aging equipment. The correlation analysis between operational efficiency and water tariffs demonstrated that efficiency improvements directly impact operational production costs and consumer tariffs, emphasising the economic importance of optimisation. The implementation of these recommendations will enable the WTP facilities to achieve substantial improvements in operational efficiency, cost reduction, and environmental performance while maintaining high-quality drinking water production for the residents.

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