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Integrated CapdetWorks–BioWin modeling for energy optimization of a municipal wastewater treatment plant

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ABSTRACT

This study aims to evaluate energy reduction potential and effluent quality impacts of operational and structural optimization strategies in a full-scale municipal wastewater treatment plant in Vietnam using integrated process simulation tools. A combined modelling approach was applied using BioWin 6.1 and CapdetWorks 4.0 to simulate and compare multiple operational scenarios. The analysis focused on aeration scheduling, dissolved oxygen (DO) control, airflow regulation, and the replacement of an aerated selector with a mechanically mixed system in a sequencing batch reactor (SBR)-based configuration. Historical plant data were used for model initialization, and multiple optimization scenarios were developed to assess trade-offs between energy consumption and treatment performance under varying operational conditions. Simulation results showed that optimizing aeration duration and control parameters led to significant reductions in energy demand. The most efficient configuration achieved up to 67% reduction in energy consumption through shortened aeration cycles, while replacing aerated selectors with mechanical mixers yielded up to 50% reduction in specific operational components. The combined optimal scenario resulted in an overall energy saving of up to 83% (0.0161 kWh/m^3). Across all simulated cases, effluent quality remained within national discharge standards, with only minor variations in COD, BOD, nitrogen, and phosphorus concentrations compared to the baseline configuration. The study is limited by its reliance on simulation-based results rather than full-scale experimental validation, and uncertainties associated with model calibration and default parameter assumptions. Despite these limitations, the findings provide practical insight into cost-effective energy optimization strategies that do not require major infrastructure reconstruction. Overall, the originality of this work lies in the integrated application of BioWin and CapdetWorks for combined energy–process optimization of an SBR-based municipal WWTP in a tropical developing country context. The study highlights the critical role of aeration management and selector configuration in reducing energy demand while maintaining effluent compliance.

Keywords: wastewater plant, biological treatment, energy use, energy optimization, aeration minimization.

INTRODUCTION

Wastewater from human activities contains several organic and inorganic pollutants, some hardly biodegradable (such as grease/oil and other organic matter with large molecular weight) (Tchobanoglous et al., 2014). Wastewater treatment is performed in wastewater treatment plants through complex physicochemical and biological processes, adequately adapted to specific local conditions determined primarily by the wastewater flow and its nature and content of the impurities (Balanica et al., 2020; Mirel and Florescu 2020; Anh et al. 2024), Biological processes are decisive steps in wastewater purification. Under these conditions, the share of electricity consumption associated with biochemical processes (for aeration) frequently exceeds 60% of the wastewater treatment plant's total consumption (Guven et al., 2019, Bartha et al. 2020, Tokos et al., 2021).

Energy consumption in wastewater treatment plants (WWTPs) is primarily driven by biological processes, with aeration systems typically accounting for 50–70% of total electricity demand (Jamaludin et al., 2024; Panepinto et al., 2016). In advanced nutrient removal systems, overall energy use ranges from 0.3 to 2.1 kWh/m³ depending on process configuration and influent characteristics (Bodik and Kubaska, 2013; Hamawand, 2023; Shen et al., 2015). This makes aeration control one of the most critical targets for operational optimization. Recent studies have demonstrated that energy efficiency in WWTPs is strongly dependent on dynamic interactions between influent load, oxygen demand, and operational strategy. In particular, improper or fixed aeration control can lead to unnecessary energy consumption without improving effluent quality. Adaptive aeration strategies and process optimization have therefore been identified as key approaches for reducing operational costs while maintaining discharge compliance (Li et al., 2024; Musvoto and Ikumi, 2016). Specifically, Li et al (2024) found that when the inflow load was high and the concentration of pollutants was low, the energy efficiency of sewage treatment plants was poor. The management of WWTP should timely adjust the aeration time and coordinate the relationship between anaerobic and aerobic treatment, in order to improve the energy efficiency of WWTPs (Li et al., 2024). A range of different energy reduction strategies including implementation of more efficient air delivery systems, proper sizing and configuration and optimum process and aeration control were tried in the study of Musvoto and Ikumi (2016). They found that in the case of upgrading an already built water treatment plant, the sizing of tanks was largely set, therefore upgrading the aeration systems or implementing a better aeration control was of the priority focus.

In addition to aeration optimization, structural modifications of biological treatment units—such as selector tank configuration—have been shown to influence sludge settleability, nutrient removal efficiency, and system stability (Parker et al., 2003; Kjær Andreasen and Sigvardsen, 1996). However, the energy implications of replacing aerated selectors with mechanically mixed systems remain insufficiently quantified under full-scale operational conditions, particularly in municipal WWTPs in tropical developing regions.

Although process simulation tools such as BioWin, CapdetWorks, GPS-X, and WEST are widely used for WWTP optimization and energy assessment, most studies evaluate either process performance or energy savings independently rather than integrating both within a unified plant-scale framework (Popescu et al., 2026). Moreover, limited studies have validated combined energy–process optimization strategies under real operational constraints in Southeast Asian wastewater treatment systems. Therefore, there remains a gap in understanding how combined operational (aeration scheduling, dissolved oxygen control) and structural (selector configuration) modifications jointly influence both energy consumption and effluent quality in full-scale SBR-based WWTPs.

The aim of this study is to quantify the energy-saving potential and effluent quality impacts of alternative operational and design scenarios in a full-scale municipal wastewater treatment plant in Vietnam using integrated CapdetWorks 4.0 software (Hydromantis, Korea) combined with BioWin 6.1 (EnviroSim, Canada) modeling. The study tests the hypothesis that coordinated optimization of aeration control and selector configuration can significantly reduce energy consumption without compromising effluent compliance.

METHODOLOGY

Data collection

The historical data was collected from the wastewater treatment plant in terms of energy use (energy bills) for 02 years (2019–2020). For water quality assessment, water samples were taken from different points (influent, separator, SBR, selector and effluent) for the analysis of BOD, COD, total nitrogen, phosphate and TSS. The sample analysis was complied with the standard methods described elsewhere (APHA, 2005).

The Bac Ninh wastewater treatment plant focuses primarily on domestic wastewater with the total water processed has a capacity of 17,500 m^3/d and reaches maximum of 28,000 m^3/d during the rainy season. The flow diagram of the treatment facility is shown in the Figure 1. Table 1 presents the plant's studied units and operating conditions.

Energy optimization

Firstly, the Capdet Work software was employed to create complete replica models of wastewater plants and isolate certain processes. To determine energy saving potential of the selector and the main reactor (sequential batch reactor

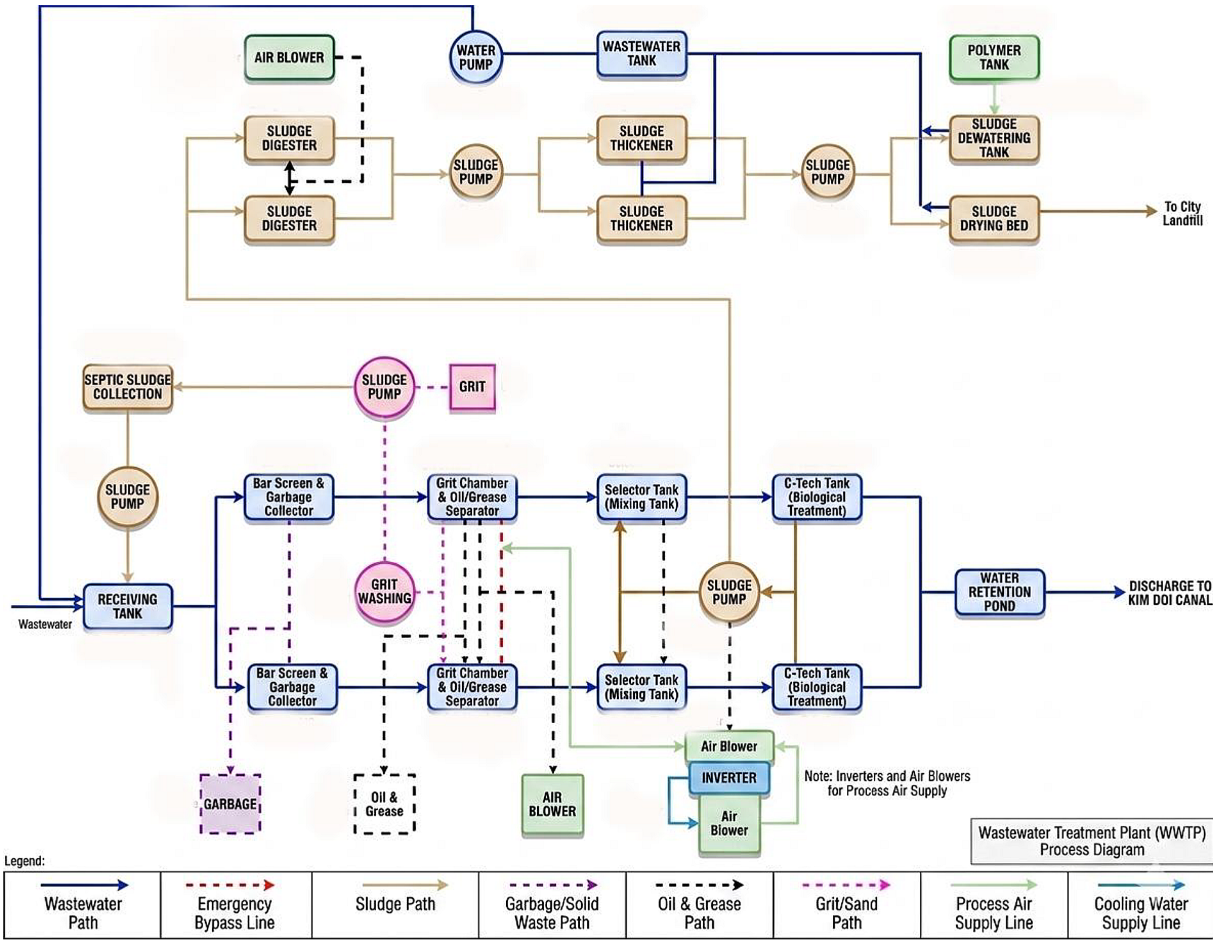

Figure 1. Flow diagram of the Bac Ninh wastewater treatment plant

– SBR), these two components were modelled in isolation**.** This process aimed to determine, irrespective of the plant conditions, what mechanisms of the plant are most capable of energy saving. Each element was modeled in isolation to best understand the energy saving potential of these two elements.

Two models were created including (1) Influent ↦ selector ↦ effluent; and (2) Influent ↦ SBR ↦ effluent as shown in Figure 2. For the selector tank modeling process, the "Predenitrification" unit were selected as the most accurate representation of the selector on site. As previously emphasized, one of this study's primary focuses is the effectiveness of substituting the blowers with a mechanical mixer in the Selector. Therefore, this modelling unit allowed for direct comparison between blowers and a mixer. For the SBR modeling, the study team used prior information provided from Bac Ninh WWTP.

Based on the findings of the Capdet works energy feasibility models, the BioWin plant-based model was adjusted to test the impact of the possible recommendations. The purpose of this process to establish the impact that these plant changes will have on effluent quality and provide assurance to the WWTP that these energy changes will not be of the detriment of the effluent quality. To simulate the wastewater treatment proccess, the Biowin model was selected to assess the feasibility of prospective plant changes that aim to reduce the plant's energy usage without being detrimental to effluent objectives (Figure 3). The historical water quality data was used as a basis for the models' influent data inputs. These values were used to calibrate the models in conjunction with water quality ratios, as outlined in Table 2. Model 1 represented the current WTTP and Model 7, a replica of the current plant except the selector was changed from an aerated selector to a mechanical mixer-based selector. Using these two base models, 9 different scenarios were run using BioWin 6.1. Five scenarios included a blower- based selector and four that included a mixer-based selector. The scenario changes were based upon the outcomes of the energy feasibility assessment conducted in Capdet

Works. The full list of 11 models is presented in Table 3. The most feasible energy-saving options identified in the CapdetWorks were:

- Replacing the blower-based selector with a mechanical mixer-based selector
- Reducing the aeration periods of both the SBR and Selector cycles.
- Implementation of a DO setpoint and thus reducing airflow rates.

These findings were further supported by current energy reduction practices identified in literature review and based on these findings, the 11 scenarios outlined in Table 2 were modelled and run using BioWin 6.1.

RESULTS AND DISCUSSIONS

Summary energy saving with different scenarios

Table 4 displays the energy outputs of the air blowers in 5 model scenarios. The models containing changes to the DO setpoint (Models 2 & 8), or the sludge recycle line flow rate (Models 6 & 11) were not previously tracked by the plant, and therefore cannot be compared to the current configurations outputs. The energy reduction of these scenarios is supported by both the Capdet Works modelling outputs.

The Table 3 demonstrates how varying operational parameters affects energy intensity (kWh/m^3) and overall energy reduction relative to a baseline. At a constant aeration time of 90 minutes (Model 1 vs. Model 7), switching from blowers to mixers reduces the required power from 72.6 kW to 36.3 kW, resulting in an immediate 50% energy reduction. In addition, reducing aeration duration has a linear effect on energy savings. For blowers, dropping from 90 to 30 minutes (Model 1 to 4) yields a 67% reduction. The most efficient configuration is Model 9 (Mixers at 30 min), which achieves an 83% reduction from the baseline, bringing energy intensity down to 0.0161 kWh/m^3. Based on the air blower flow

Table 1. Description of the studied units

Parameter		Value	Unit
General	Electricity cost	0.00012	USD/kWh
Separator	Volume	1003.68	m^3
	Depth	8.2	m
	Width	7.2	m
	Length	17	m
Selector	Length	22.9	m
	Width	6.1	m
	Depth	7.4	m
	Volume	1033.706	m^3
	Power	72.6	kW
SBR	Power	72.6	kW
	Volume	6127.2	m^3
	Depth	7.4	m
	Length	36	m
	Width	23	m
	Minimum decant level	66.7	%
	DO set point	2	Mg/L
	Cycle length	3	hours
	Aeration period	90	min
	Settling period	45	min
	Decanting period	45	min

Table 2. BioWin influent inputs

Input parameter	Value	Unit	Data source
COD	101	mg/L	Historical data
BOD	41	mg/L	COD: BOD (2.46:1)
TKN	11.4	mg/L	COD: TKN (9:1)
Total P	2.5	mg/L	Historical data
Total S	10	mg/L	BioWin default
Alkalinity	300	mg/L	BioWin default
TSS	50	mg/L	BioWin default
VSS	37.9	mg/L	TSS:VSS (1.33:1)
$COD_{Filtered}$	37.3	mg/L	COD: $COD_{Filtered}$ (2.7:1)
$COD_{Acetate}$	2.4	mg/L	COD: $COD_{Acetate}$ (41:1)
$BOD_{Filtered}$	17	mg/L	BOD: $BOD_{Filtered}$ (2.4:1)
Ammonia	7.5	mg/L	N: NH_3 (1.5:1)
Nitrate	0	mg/L	BioWin default
Soluble phosphate	1.3	mg/L	P: soluble P (1.9:1)
Soluble sulphate	8.5	mg/L	BioWin default

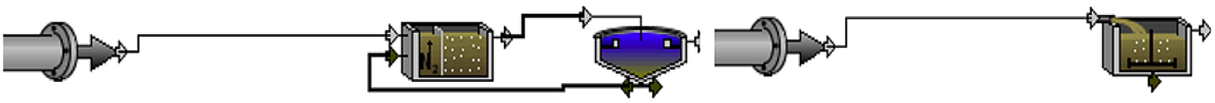
(a) (b)

Figure 2. Modeling diagram: (a) Capdet Works for selector model, (b) Capdet Works for SBR model

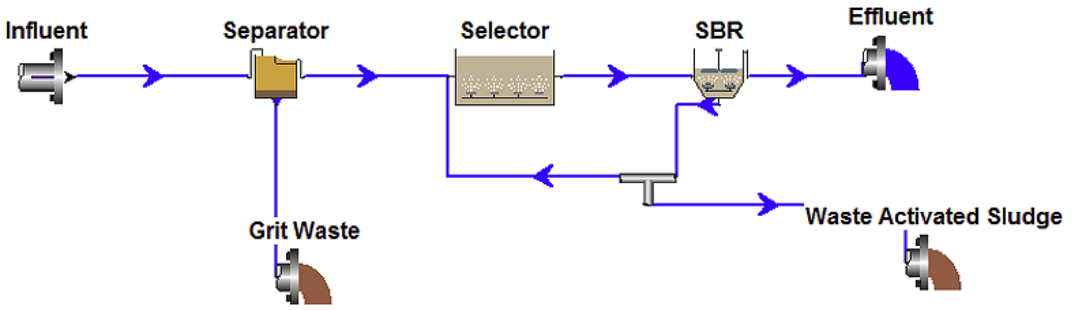

Figure 3. BioWin configuration of Model 1

Table 3. BioWin model list

No	Selector condition	Scenario
1	Model with blower-based selector	Model as per the current plant conditions
2		DO set point in selector and SBR reduced from 2 mg/l to 1 mg/l
3		Reduce the aeration period in the selector and SBR to 60 minutes
4		Reduce the aeration period in the selector and SBR to 30 minutes
5		Reduce the aeration period in the selector and SBR to 30 minutes and reduce the DO set point in the SBR to 1 mg/l
6		Increase the sludge recycle flow from SBR to selector from 100% to 200%
7	Model with mechanical mixer -based selector	Model as per the current plant condition (expect mechanical based mixer)
8		DO set point in SBR reduced from 2 mg/l to 1 mg/l
9		Reduce the aeration period in the SBR to 30 minutes
10		Reduce the aeration period in the SBR to 30 minutes and DO set point in SBR reduced from 2 mg/l to 1 mg/l
11		Increase the sludge recycle flow from SBR to selector from 100% to 200%

Table 4. Summary of energy outputs of the selected scenario

Model #	Optimized conditions	Aeration/day (min)	Aeration/day (h)	Required power (kW)	kWh/day	kWh/m^3	Energy reduction
1	Current condition, using blowers, 90 min	1440	24	72.6	1742.4	0.0964	Baseline
3	Current condition, using blowers, 60 min	960	16	72.6	1161.6	0.0643	-34%
4	Current condition, using blowers, 30 min	480	8	72.6	580.8	0.0321	-67%
7	Current condition, using mixers, 90 min	1440	24	36.3	871.2	0.0482	-50%
9	Current condition, using mixers, 30 min	480	8	36.3	290.4	0.0161	-83%

pathway provided by the treatment plant, it was assumed that for models 7–11 which run using a mixer-based selector (no aeration in the selector), the required energy of the blowers was halved from 72.6 to 36.3 kW. Previous study also confirmed the mechanical hardware choice (like the mixers in your table) was often the most stable way to ensure a baseline reduction of at least 35% in energy cost (Lozano Avilés et al., 2020). Li et al.'s result also demontrated that timely adjust the aeration time and coordinate the relationship between anaerobic and aerobic treatment, in order to improve the energy efficiency of WWTPs from 11.61% to 15.26% (Li et al., 2024). While model 9 (30 min aeration) is the most energy-efficient, excessive reduction in aeration can lead to incomplete nutrient removal (ammonia/nitrogen), potentially violating discharge permits (Jamaludin et al., 2024).

Model 3, which also has a blower-based selector, has a reduced aeration period in the SBR and selector of 60 minutes per cycle rather than 90 minutes. This shorter aeration results in the blowers running for 8 hours less per day and a 33% reduction in energy consumption of the blowers. Model 4 similarly has a blower-based selector however, the aeration period in the SBR and selector is reduced to 30 minutes per cycle. 30-minute aeration periods per cycle result in the blowers only running for 8 hours a day and a reduction of 67% in energy consumption. Henriques's study shown that regardless of WWTP scale, each station presents opportunities to improve its energy efficiency, saving 20 to 40% and, in some cases, up to 75% (Henriques and Catarino 2017). Recently, Bartha et al., (2020) found a 20–36% energy reduction via aeration optimization in the oxidation tanks managed by means of automatized control of DO and SRT. In this study, the implementation of 30-minute aeration period provides a predicated energy saving of 211,992 kWh/year. This recommendation reduces both blower cost and energy consumption by 67%.

Energy saving potential in the selector chamber

The current system at the WWTP uses a diffused aeration system in the selector to avoid settling and maintain water agitation throughout the tanks. Initial correspondence from the plant, in conjunction with recent literature identified that replacing the aeration system in the selector with a mechanical mixer could be a favorable option for energy savings. This has also been demonstrated in Miroslav's study which suggests submerged turbine could make full mixing and wide range of air flow variation which are suitable for selector tank (Stanojevic et al., 2024). Selectors require low-DO or anaerobic conditions, utilizing low-energy submersible mixers instead of high-energy blowers to manage metabolic selectors without premature aeration (Füreder et al., 2018). If the change from aerators to a mechanical mixer within the selector was enacted, the function of the selector would be altered. Currently, the selector functions with swing zones between aerobic and anoxic zones. If the aerators were replaced with a mixer, the selector would become a buffer tank for the wastewater to remain anoxic prior to aeration within the C-tech SBR tanks. Within the buffer tank, the wastewater would remain anoxic, and therefore undergo more consistent denitrification.

Table 5 displays the energy consumption of 3 different mechanical mixers in comparison to that of an aerated system. It should be noted that the SBR was set the same conditions, the only difference was the replacement of blowers with mechanical mixers. It can be seen from the results that all three mixers consumed less energy than that of the aerated system. As expected, the higher the horsepower of the mixer, the more energy required to maintain it. The largest mixer (47 kW horsepower mixer) still consumed 18% less energy than that of the aerated system. When running the model with a 27 kW mixer, there was a 56% reduction in energy usage compared to that of the aerated system. As expected, the implementation of this schedule provides a predicated energy saving of 317,842 kWh/year. This recommendation reduces both blower cost and energy consumption by 50%.

Energy saving potential in the SBR

Unlike the selector, removing aeration from the SBR is not a viable option based on the chemical processes within the reactor. The oxygenation from the blowers provides a viable environment for microorganisms to consume organic matter and allow for the process of nitrification and bod removal. Due to this inherent need for aeration within the SBR, alternative solutions to reduce its energy usage need to be assessed. Potential solutions were derived based on industry correspondence and current practice and it was determined that both the dissuade bubble size and length of aeration periods may have the greatest impact on energy consumption.

Impact of air bubble size on energy usage in SBR

Table 6 displays the energy consumption of both fine bubble and coarse bubble diffused

Table 5. Energy consumption of 4 selector methods

Mixer (kW)	Selector mixer energy consumed (kWh)	Total energy consumed (kWh)	Total energy consumed (kWh/m^3)	Energy reduction
27	383.33	1254.53	0.0494	56% decrease
37	479.16	1350.36	0.0747	45% decrease
47	714.38	1585.58	0.0877	18% decrease
Aeration (using blowers)	873.22	1938.13	0.1072	Baseline usage

aeration within an SBR. There has been previous discussion in early stages of this research that moving from fine to course bubbles in the SBR may result in a reduction in energy consumption (Füreder et al., 2018). However, modelling has indicated that the transition away from fine bubbles will have a negligible effect on the energy consumption and in turn be of little to no cost value for the treatment plant.

Impact of reduced aeration period on energy usage in SBR

An alternative method to reduce energy usage of the SBR is to lower the aeration period of each cycle, essentially decreasing the amount of time the blowers are running per day. To achieve an effective reduction in aeration time, the point where SBR effluent is still meeting requirements but the SBR is running the aeration for the shortest period needs to be identified. This process could be achieved through an automated measuring system that measures the effluent DO and when the target is met the SBR moves from the aeration phase into the settling phase. The benefit of this method is that the aeration time is tailored for every batch of water entering the SBR and allows the plant to be flexible in dealing with changing water quality. Set aeration times do risk expending too much energy on wastewater that is already close to the required parameters or not expanding enough on poor quality wastewater and not meeting required targets. An automated system mitigates this risk but comes with increases maintenance and installation costs. Alternatively, if influent data remains stable through periods of time, set aerations time can be reduced. The energy usage of that cycle was compared to a cycle with a reduced aeration time as seen in Table 4. The outputs show, as expected, that shortening the aeration period will reduce the energy consumed by the SBR by 34%. Lee's study has shown the same result when the modified activated sludge processes (ABA^2) adjusting air on/off period was fixed at 60 min/45 min with aerobic fraction being 0.57. The effluent COD, TN, N-NH$_4^+$ and TP concentrations are acceptable while reduced aeration time saves significant energy consumption (Lee et al. 2015). Muloiwa et al. (2023) also revealed that, if the aeration period was reduced by 50%, plant managers/operators would achieve low energy consumption in the biological aeration unit. As a results, a revised aeration schedule is proposed as in Table 7.

Impact of reduction in flow rate on energy consumption

Further to the change in SBR aeration periods, other factor can be altered to better optimize the SBR system and the energy consumption such as airflow rate. It was noted that the current air blower system of the entire plant runs at 65 m^3/min. CadetWorks modeling rendered that reduction of the airflow rate from 65 m^3/min down to 55 m^3/min, resulted in a 37% decrease in energy usage. Previous study by Muloiwa research group demonstraded similar observation in which an airflow rate of 5 l/min and 30 l/min resulted in an energy cónumtion of 0.087 kWh and 0.172 kWh respectively (Muloiwa et al., 2023). This implies that increasing the power demand will result in high energy consumtion in the biological aeration unit.

Water quality outputs of saving energy optimization scenarios

Water outputs of baseline model

Table 8 displays the relevant water quality parameters at each unit after the 20-day run time for the baseline model. It should be noted that the

Table 6. Impact factors on energy consumption

Parameter	Impact factors	Energy consumption (kWh/yr)
Bubble diameter	Fine bubbles	Baseline usage
	Coarse bubbles	No significant change
Cycle duration	90-minute aeration period	Baseline usage
	60-minute aeration period	34% decrease
Air flow rate	65 m^3/min	Baseline usage
	55 m^3/min	37% decrease

Table 7. Current and revised SBR aeration schedule

SBR	Current cycle			
1	Fill and aeration (90 min)		Settling (45 min)	Drain (45 min)
2	Settling (45 min)	Drain (45 min)	Fill and aeration (90 min)	
SBR	Revised cycle			
1	Fill and aeration (60 min)		Settling (75 mins)	Drain (45 min)
2	Settling (75 min)	Drain (30 min)	Fill and aeration (60 min)	

data of the influent and the effluent were the real data provided by the plant. The remaining was simulated by the software. It was found that all the influent values are relatively low when compared to typical wastewater influent. It is due to 2 main reasons: (1) The influent flow to the WWTP is from the combined sewage and drainage system; and (2) there was high rainfall in the local before the sampling times. It is worth noting that the TKN and Total N display an increase between the selector and SBR of 50.2 mg/L to 63.74 mg/L, and 50.2 mg/L to 66 mg/L, respectively. The lower TKN and TN values in the selector indicate that the anoxic zones are successfully leading to denitrification. The increase of TKN and TN in the SBR suggests that the anoxic zones within the selector are proving more effective at denitrification than those within the SBR. Whilst the selector primarily focus is denitrification, and the SBR focuses on nitrification, the model showed that both occur within each plant element. This is attributed to the blower schedule in the selector and SBR being identical. Therefore, it can be said that the physical design of the selector tank is what differentiates its treatment process from the SBR.

Water outputs of Model 7

Table 9 presents the water quality results of Model 7 for each plant component at the conclusion of 20 days of running the system. Model 7 maintains the current plant configuration and conditions, except for substituting the air blowers for a mechanical mixer in the selector. Similar to Model 1, the water quality results remain constant at the influent and separator phases of the plant. Substituting a mixer into the selector showed an overall increase in the COD, BOD, TKN, TN, VSS and TSS in both the selector and SBR. These increases are attributed to the overall reduction in treatment, as the selector is no longer aerated and acting as a buffer tank. It is worth noting that the effluent still remains comfortably within the national standard.

Comparing the effluent TKN values of Model 1 and Model 7, it is evident that without aerators in the selector, there is an overall increase of 15% in TKN compared to that of a mixer-based selector.

Comparison of effluent data

Table 10 displays the effluent water quality results for all 11 modelled energy saving scenarios. It was found that for all energy saving scenario's, the effluent results were still within the national standard. These results show that the current model configuration has ample scope for change. Due to the low nature of the influent values, there is a low degree of treatment required to meet the national regulation standard and thus dramatic changes to the plant can be made. These effluent results on models 7–11 confirm that the change from an aerated selector to a buffer tank (mechanical mixer based) will not be detrimental to the nitrification and dentification process.

Table 8. Water quality at each plant element for Model 1 (current conditions)

Plant element	COD	BOD	TKN	TN	TP	pH	VSS	TSS
Influent	101	45.84	11.4	11.4	2.6	7.3	39.96	52.66
Separator	101	45.84	11.4	11.4	2.6	7.3	39.96	52.66
Selector	811.24	194.66	50.2	50.2	17.59	7.19	544.28	694.23
SBR	1,101.57	245.54	63.74	66	24.33	7.05	750.95	965.66
Effluent	34.1	5.75	2.67	5.66	2.44	7.05	14.92	19.2
National standard (QCVN 40:2025/BYT)	60	30	NA	20	8.0	6 - 9	NA	30

Table 9. Water quality at each plant element for Model 7 (current plant condition with proposed mechanical based mixer)

Plant element	COD	BOD	TKN	TN	TP	pH	VSS	TSS
	mg/l	mg/l	mg/l	mg/l	mg/l		mg/l	mg/l
Influent	101	45.84	11.4	11.4	2.6	7.3	39.96	52.66
Separator	101	45.84	11.4	11.4	2.6	7.29	39.96	44.63
Selector	902.24	209.08	54.72	54.72	17.13	7.3	589.77	736.32
SBR	1,101.57	262.49	68.91	70.93	23.64	7.08	819.35	1030.27
Effluent	34.1	5.96	3.13	5.83	2.34	7.08	15.52	19.53
National standard (QCVN 40:2025/BYT)	60	30	NA	20	8.0	6–9	NA	30

Table 10. Effluent water quality for all 11 models

Model number	COD	BOD	TKN	TN	TP	pH	VSS	TSS
	mg/l	mg/l	mg/l	mg/l	mg/l		mg/l	mg/l
1	34.1	5.75	2.67	5.66	2.44	7.05	14.92	19.2
2	35.11	5.19	2.84	4.8	2.38	7.06	16.19	20.42
3	31.09	4.24	3.01	4.77	2.22	7.07	12.79	16.35
4	30.27	4.31	4.01	4.49	1.89	7.11	11.85	15.47
5	30.8	3.84	2.19	3.63	2.17	7.06	12.72	16.46
6	34.08	5.76	2.67	5.66	2.44	7.05	14.91	19.2
7	35.1	5.96	3.13	5.83	2.34	7.08	15.52	19.53
8	37.55	6.09	2.76	4.98	2.38	7.07	17.49	22.06
9	32.87	7.24	5.08	5.49	2.21	7.15	11.59	14.4
10	34.52	7.78	6.1	6.28	2.2	7.16	12.28	15.28
11	36.44	5.38	3.18	5.86	2.35	7.09	16.48	20.42

The energy saving scenarios that produced the best effluent results were models 4 and 5, that had a reduced aeration time of 30 mins. It is worth noting that the effluent results of these 2 models were not significantly lower than those of the other 9 scenarios and effluent data for all models can be considered comfortably meeting the objectives. This is supported by the R-test values present in Table 11. These R-tests compared the correlation between each models' effluent values to the base model of the plant (Model 1), which employed the real data of the plant under current conditions. These results found that all of the models are strongly positively related to Model 1's effluent, suggesting that changes in plant processes are not negatively impacting the overall treatment process.

Models in which the aeration schedule were reduced do pose the possible risk of reducing the potency of the microorganisms within the treatment system. Also, the longer settling period would lead to an increased time where the sludge is not in suspension, as a result, filamentous bacteria has a chance to grow (Tchobanoglous et al., 2014). This is also accentuated by the high 'settle-ability' of the sludge in the wastewater treatment plant.

Further discussion

From the above results, it can be seen that the aeration and replacement of blowers with mechanical mixers clearly had some good impacts on the energy reduction. In comparison with different optimization methods for energy saving within the plants, focusing on the biological treatment units only (Table 12), it can be seen that the most significant energy gains come from refining aeration – whether through hardware (Turbo blowers) or software (Period optimization) (Ziemba et al., 2025; Muloiwa et al., 2023) and as seen in this study. The batch nature of C-Tech SBRs (as seen in This study) allows for aggressive energy-saving cycles (up to 67%) that are harder to achieve in conventional continuous-flow municipal plants. While Intelligent PID and

Table 11. R test values for effluent water quality

Model effluent comparison	R-test value	Model effluent comparison	R-test value
1 vs 2	0.99876109	1 vs 7	0.99983904
1 vs 3	0.99764422	1 vs 8	0.99846741
1 vs 4	0.99387789	1 vs 9	0.97961725
1 vs 5	0.99722843	1 vs 10	0.97731827
1 vs 6	0.99999988	1 vs 11	0.99942371

Table 12. Comparison of energy use and energy reduction from previous studies

Optimization method	Type of wastewater	Treatment Unit	Energy use (kWh/year)	Energy reduction %	Short Reference
Aeration period and temperature optimization	Municipal	Biological aeration unit	297,900	38.4%	Muloiwa et al. (2023)
Impulse aeration/Stirring (using agitator)	Municipal	Activated sludge tank	105,120	5–20%	Füreder et al. (2017)
Microbiological activity stimulation	Municipal	Biological stage	218,160	5.57%	Bartha et al. (2020)
Aerobic/Anaerobic streamlining	Municipal	Biological treatment	214,320–280,080	N/A	Tokos et al. (2020)
Real-time electricity metering	Dairy	Biological (SBR) & DAF	341,600	N/A	Żyłka et al. (2021)
Operational variable tuning	Municipal	Activated sludge (biological)	1,450,000	15–18%	Lozano Avilés et al. (2019)
Aeration grid redesign & Pressure Opt.	Municipal	Aeration basin	1,220,000	20%	Lozano Avilés et al. (2020a)
SCADA & PLC integral control	Municipal / Industrial	MBR & activated sludge	980,000	12–25%	Lozano Avilés et al. (2020b)
Fine-bubble + Turbo blower upgrade	Municipal	Secondary treatment	2,100,000	30–35%	Ziemba et al. (2025)
Intelligent PID / Virtual power plant	Sewage-Sludge co-treatment	Aeration & pumping	3,500,000	18%	Li et al. (2026)
Algal-bacterial hybrid mixing	High-Nutrient waste	Photobioreactor / aeration	450,000	40–60%	Oruganti et al. (2022)
Low-DO nitrification stability	Municipal	Nitrification tank	850,000	8–12%	Keerio & Bae (2020)
Benchmark-driven VFD control	Municipal	Aeration & secondary lift	1,150,000	10–15%	Longo et al. (2016)
Replacement of blowers with mechanical mixers	Municipal	C-Tech SBR	317,842	18–56%	This study
Aeration period optimization	Municipal	C-Tech SBR	211,992	67%	This study

Machine Learning methods are high-tech, they were applied to massive loads (3.5M kWh). For smaller or municipal plants, fundamental operational tuning (like adjusting aeration periods or MLSS) often yields a higher energy reduction for a lower capital cost. The high success of Algal-Bacterial mixing (40–60%) suggests that biological innovation could be the next frontier for high-nutrient industrial waste (Oruganti et al., 2022).

CONCLUSIONS

Throughout the project, both energy optimization strategies and sludge recycling methods were discussed in detail. The use of computational modelling has aided the research by enabling various alternative system designs and scheduling times.

The modelling outcomes crucially highlighted that optimizing the aeration schedules is equally a viable solution as reducing the selector to act as a buffer tank in reducing energy consumption. In terms of water treatment, all modelled scenarios showed little variance to the current output. Therefore, focusing on aeration optimization will provide high level energy reductions, up to 67%, and quality effluent without significant capital investments. The addition of a mechanical mixer will also lower total energy consumption, yet requires altering the plant's configuration, which incurs high capital expenditure.

Future research shall focus on integrating Machine Learning algorithms with real-time sensors (dissolved oxygen and nutrient sensors) to develop a Predictive Dynamic Aeration System. This would allow the plant to adjust aeration intensity in real-time based on fluctuating influent loads, potentially capturing even higher energy savings during low-flow periods. Additionally, the reuse of sludge as construction materials, data statistical analysis and evaluation of the environmental footprint reduction owing to sludge usage shall be considered in detail.

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