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Cost-performance analysis of nutrient removal in a full-scale oxidation ditch process based on kinetic modeling

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Abstract

A full-scale oxidation ditch process for treating sewage was simulated with the ASM2d model and optimized for minimal cost with acceptable performance in terms of ammonium and phosphorus removal. A unified index was introduced by integrating operational costs (aeration energy and sludge production) with effluent violations for performance evaluation. Scenario analysis showed that, in comparison with the baseline (all of the 9 aerators activated), the strategy of activating 5 aerators could save aeration energy significantly with an ammonium violation below 10%. Sludge discharge scenario analysis showed that a sludge discharge flow of 250–300 m^3/day (solid retention time (SRT), 13–15 days) was appropriate for the enhancement of phosphorus removal without excessive sludge production. The proposed optimal control strategy was: activating 5 rotating disks operated with a mode of “111100100” (“1” represents activation and “0” represents inactivation) for aeration and sludge discharge flow of 200 m^3/day (SRT, 19 days). Compared with the baseline, this strategy could achieve ammonium violation below 10% and TP violation below 30% with substantial reduction of aeration energy cost (46%) and minimal increment of sludge production (< 2%). This study provides a useful approach for the optimization of process operation and control.

Key words: activated sludge model; cost-performance analysis; oxidation ditch; nutrient removal

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Introduction

Nowadays, environmental deterioration and energy shortage have become two major challenges. Biological wastewater treatment has been considered as the most important technology for water pollution control. However, its high energy input, which contributes significantly to operational costs, has become a big concern (Wesner, 1978). Environmental engineers and plant managers have been pursuing a plant design and operational strategy permitting efficient pollutant removal with minimal cost (Middleton and Lawrence, 1974). In the past decades, model-based optimization has been employed as an important approach to improve the process performance (Alex et al., 1999; Vanhooren et al., 2002; Gernaey et al., 2002; Abusam et al., 2002, 2004; Gernaey and Jørgensen, 2004; Benedetti et al., 2005, 2006). Process models, such as the activated sludge model (ASM) developed by the task group of the International Water Association (IWA) (Henze et al., 2000), have provided a promising tool for process analysis and decision making. Since the 1990s, a series of benchmark simulation models (BSM) including BSM1, BSM1_LT and BSM2 (Copp, 2002; Rosen et al., 2004; Jeppsson et al., 2006, 2007) have been proposed and applied for the evaluation and optimization of operational strategies for various biological wastewater treatment processes (Ghermandi et al., 2005; Devisscher et al., 2006; Yamanaka et al., 2006; Holenda et al., 2008; Machado et al., 2009; Benedetti et al., 2010; Guerrero et al., 2011).

The BSM series models have adopted several key criteria to evaluate the operational strategies, which include performance indicators such as effluent quality and violation, and economic ones such as aeration energy, pumping energy and sludge production (Copp, 2002). To evaluate the performance and economic criteria at the same scale, previous studies have proposed to convert the effluent quality into monetary units in terms of fines (Vanrolleghem et al., 1996; Steffens and Lant, 1999; Copp, 2002; Vanrolleghem and Gillot, 2002; Stare et al., 2007; Volcke et al., 2007). However, another important performance indicator, effluent violation, which is considered with a top priority

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for the plant operators, remains difficult to integrate into operational costs.

In this study, the economic indicators including aeration energy and sludge production were first normalized based on their maximum values, and then combined with the effluent violations to generate a unified non-dimensional cost index (CI), as the criterion for the evaluation of biological wastewater treatment processes. The ASM2d model developed by the IWA (Henze et al., 2000) was used to simulate the ammonium and phosphorus removal in a full-scale oxidation ditch process for treating sewage. The aeration energy cost, effluent violation and sludge production of the process were evaluated by scenario analysis based on the long-term dynamic simulations to produce an optimal operational strategy. The proposed approach, which integrates the performance and economic indicators, will be useful for process optimization.

1 Materials and methods

1.1 Process layout of the plant

The full-scale sewage treatment plant studied consists of one cyclone grit chamber, one anaerobic tank, one oxidation ditch, and one sedimentation tank as illustrated in **Fig. 1**. The capacity of the entire plant is 15000 m^3/day, and the ditch has an effective volume of 7500 m^3 with separated anoxic and aerated zones. The ditch is equipped with rotating disks for aeration and underwater propellers for driving the flow in the channel. The pH, dissolved oxygen (DO) and oxidation-reduction potential (ORP) in the effluent are monitored online. During the study period, all of the 9 rotating disks were activated, and the DO in the ditch effluent varied over a range of 0.3–1 mg/L. Daily operational data from April to November 2010 were used for modeling. Detailed operational data are shown in **Table 1**. The discharge standards of ammonium (NH_4^+-N) and total phosphorus (TP) required for the plant were 5 mg/L and 1 mg/L, respectively.

Table 1 Operational data of the oxidation ditch process

Parameter	Value		Parameter	Value
	Influent	Effluent		
COD (mg/L)	154 ± 41	35 ± 12	Temp. (°C)	20 ± 4
SS (mg/L)	116 ± 70	8.1 ± 5.3	MLSS (g/L)	4.7 ± 1.4
NH_4^+-N (mg/L)	34 ± 12	1.9 ± 3.0	MLVSS (g/L)	1.3 ± 0.5
TP (mg/L)	2.8 ± 0.9	1.2 ± 0.6	HRT_{OD} (hr)	11.0 ± 8.6
pH	7.4 ± 0.1	7.2 ± 0.1	SRT (day)	24 ± 11

HRT_{OD}: hydraulic retention time of the ditch, SRT: solid retention time. Data are expressed as mean ± SD.

1.2 Simulation model

The oxidation ditch evaluated in this study was modeled as a combination of an aerated and non-aerated compartment. It is important to set up an appropriate hydraulic model for the simulation of oxidation ditch processes. The tank-in-series approach is one of the prevailing hydraulic models to simulate the plug-flow behavior of oxidation ditch processes (Abusam and Kessman, 1999; De Clerq et al., 1999; Glover et al., 2006). In this study, the non-aerated compartment of the ditch was modeled as a continuous stirred tank reactor (CSTR), and the aerated one was modeled as 12 CSTR units in series to represent the plug-flow hydraulics. Considering that there is actually bacterial activity in the sludge layer of the sedimentation tank, we split the sedimentation tank into two compartments. The settling compartment was set as a location for solid-liquid separation, while the sludge zone compartment was set as a virtual CSTR reactor to account for the possible biological processes.

The ASM2d model developed by the IWA (Henze et al., 2000), without the chemical precipitation of phosphorus, was employed to simulate the biochemical reactions in the process. The effluent from the grit chamber was analyzed and fractionated into model components according to the physical-chemical method suggested by Stichting Toegepast Onderzoek Waterbeheer (STOWA) (Roeleveld and van Loosdrecht, 2002). The dynamic simulation was performed using AQUASIM (Reichert, 1994, 1998) and the model parameters were calibrated to fit the ammonium and TP in the effluent. The dataset of 2010.4–2010.8 was used for calibration and the dataset of 2010.9–2010.11 for

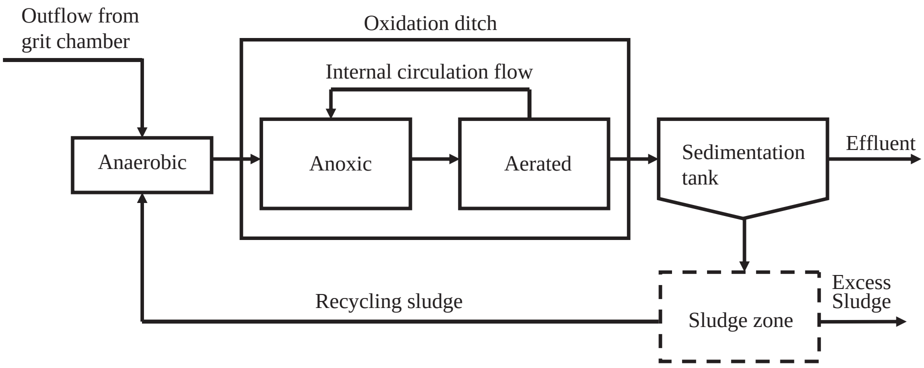

Fig. 1 Layout of the oxidation ditch process.

validation of the model. Finally the calibrated model was used for the evaluation of different operational strategies. The simulation results of the calibrated model for ammonium and phosphorus are shown in **Fig. 2**. The calibrated model was able to fit the measured data well (**Fig. S1**).

1.3 Evaluation criteria

1.3.1 Performance and economical indicators

Indicators used for the evaluation of the oxidation ditch process were selected by referring to the COST Simulation Benchmark (Copp, 2002), which included aeration energy, sludge production, and effluent violations of ammonium and phosphorus. The effluent violations of ammonium and phosphorus (EVN, % and EVP, %) were defined as the percentage of the time that the effluent ammonium and total phosphorus were above the discharge limits (5 mg/L and 1 mg/L respectively). The sludge production (SP, kg/day) was defined to reflect the total sludge produced for disposal:

$$\mathrm{SP} = [\Delta M(\mathrm{TSS\ system}) + M(\mathrm{TSSw})]/T \tag{1}$$

where, ΔM (TSS system) is the change of sludge mass in the reactors and settler during the evaluation period and M(TSSw) is the discharged excess sludge mass and T is the evaluation period (3 months):

$$\Delta M(\mathrm{TSS\ system}) = M(\mathrm{TSS\ system})_{t0+T} - M(\mathrm{TSS\ system})_{t0} \tag{2}$$

$$M(\mathrm{TSS\ system}) = M(\mathrm{TSS\ reactors}) + M(\mathrm{TSS\ settler}) \tag{3}$$

$$M(\mathrm{TSSw}) = \int_{t_0}^{t_0+T} X_{\mathrm{TSSw}}(t)Q_{\mathrm{w}}(t)\mathrm{d}t \tag{4}$$

where, X_{TSSw} (g/L) is the concentration of total suspended solid in the excess sludge, and Q_{w} ($\mathrm{m^3}$/day) is the discharge flow.

The aeration energy cost (AE, kWh/day) in the BSM models was calculated for air diffusers (Copp, 2002; Jeppsson, 2005). In present work, the oxidation ditch adopted mechanical aerators for aeration instead. Therefore, the equation suggested by Abusam et al. (2001) was used for the calculation of aeration energy as follows:

$$\mathrm{AE} = \frac{1}{TN}\int_{t_0}^{t_0+T}\sum_{i} F_i k_i (C_{\mathrm{S}}^{*} - C_{\mathrm{L},i})\mathrm{d}t \tag{5}$$

where, F is the average daily aeration capacity relative to the aerator full capacity (F = 1 in this study). k ($\mathrm{m^3}$/day) is the aeration constant, $k = K_{\mathrm{L}}a \times V$, and V ($\mathrm{m^3}$) is the aeration volume. $K_{\mathrm{L}}a$ ($\mathrm{day^{-1}}$) is the coefficient of overall oxygen transfer rate. C_{S}^{*} (mg/L) is the oxygen saturation concentration. C_{L} (mg/L) is the oxygen concentration. i is the number of the aerated compartment. N ($\mathrm{kgO_2}$/kWh) is the efficiency of the aerator.

1.3.2 Unified index

Effluent quality and operational costs are the key factors to evaluate the efficiency of wastewater treatment processes. To develop a unified index involving the operational costs and effluent violation, the aeration energy and sludge production indicators were normalized based on their maximum values, respectively, and then integrated into the non-dimensional CI. With the weighted sum of the effluent violations of nitrogen and phosphorus, the CI index can be calculated as Eq. (6):

$$\begin{aligned}\mathrm{CI} = {} & 2 \times \mathrm{AE}/(\mathrm{AE_{max}} + \mathrm{AE}) \times \\ & 2 \times \mathrm{SP}/(\mathrm{SP_{max}} + \mathrm{SP}) \times \\ & (\alpha \times \mathrm{EVN} + \beta \times \mathrm{EVP})\end{aligned} \tag{6}$$

where, α and β are the weight factors subject to $\alpha \geq 0$, $\beta \geq 0$, $\alpha + \beta = 1$. In this study, we defined $\alpha = \beta = 0.5$ to use the

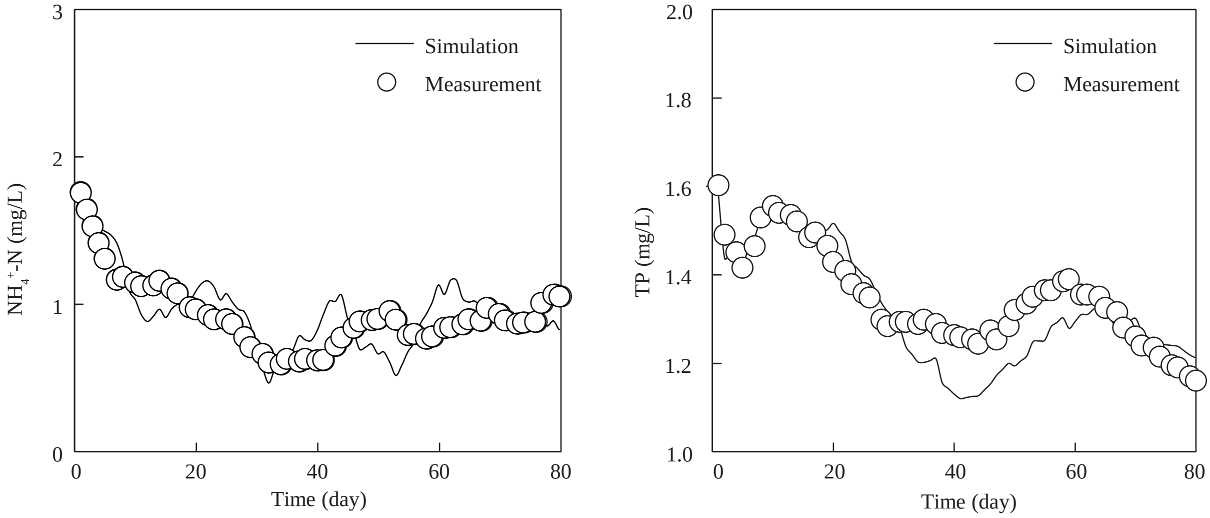

Fig. 2 Simulation results of $\mathrm{NH_4^+}$-N and TP by the calibrated model for the period of 80 days.

average effluent violation of ammonium and phosphorus. The AE_{max} and SP_{max} are the maximum capacity of the aeration energy and sludge production, respectively.

The unified CI index was used to assess the cost of different operational strategies for the process.

1.4 Scenario analysis

The cost-performance analysis and optimization of the operational strategies based on the five evaluation criteria were performed for the evaluation period of three months, which included different aeration and sludge discharge strategies (**Table S1**). The evaluated aeration strategies are shown in **Table 2**, which consisted of the number of activated aerators and their combination modes. The distribution between the anoxic and aerobic volumes in the ditch will vary with the change in the number of activated aerators, and hence affect the performance of nitrogen and phosphorus removal. Furthermore, different combinations of aerators lead to spatial differences in the oxygen supply, and thus influence the aerobic biochemical conversions. In addition, different sludge discharge flows from 100 to 400 m^3/day were evaluated based on the proposed criteria (**Table S2**).

Table 2 Scenario settings of different aeration strategies

ID	N_{ae}	Mode	V_{ax}/V_{ae}
a0	9	111111111	1:2.3
a1	7	111111100	1:1.2
a2	5	111110000	1.7:1
a3	5	111101000	1.7:1
a4	5	111100100	1.7:1
a5	4	011100100	2.1:1
a6	4	111000100	2.1:1
a7	3	010100100	3.0:1
a8	3	101000100	3.0:1

N_{ae}: the number of activated aerators. Mode: “1” represents the activation of aerators and “0” represents the inactivation of aerators. V_{ax}/V_{ae}: the ratio of unaerated to aerated volume in the ditch.

2 Results and discussion

2.1 Optimization of aeration strategy

Aeration strategies are crucial to the treatment efficiency and operational cost. In the present study, the effect of the number of activated aerators on the performance of ammonium and phosphorus removal was investigated as shown in **Fig. 3**. It was found that extensive aeration (baseline, a0) could ensure a low ammonium violation (EVN < 2%), but was detrimental for biological phosphorus removal (EVP > 40%). Decreasing the number of running aerators leads to the improvement of phosphorus removal performance due to the reduced interference from nitrate on phosphorus release (Henze et al., 2008), with the sacrifice of ammonium removal due to the reduction of oxygen supply. Consequently, proper aeration strategies are required to maintain a good balance between nitrification and phosphorus removal. In addition, the number of activated aerators determines the aeration energy input. Compared with the baseline (all of the 9 aerators activated), up to 67.6% of aeration energy could be saved by activating only 3 rotating disks.

Variation of the unified index CI under different aeration strategies is also presented in **Fig. 3**. The optimal CI can be identified with the aeration strategies a4–a6, which required activation of 4–5 aerators. It is interesting that for a given number of activated aerators, the locations of activated aerators could affect the performance significantly. For example, aeration strategies a2–a4, which employed 5 aerators in different modes, were remarkably different in effluent violations and CI values. This result was due to the DO distribution along the channel in the ditch resulting from the different locations of the activated aerators, which affected the spatial distribution of hydrolysis, nitrification and denitrification kinetics, and hence had a significant effect on the ammonium and phosphorus removal performance. The effect of aeration mode on the performance of an oxidation ditch was reported previously

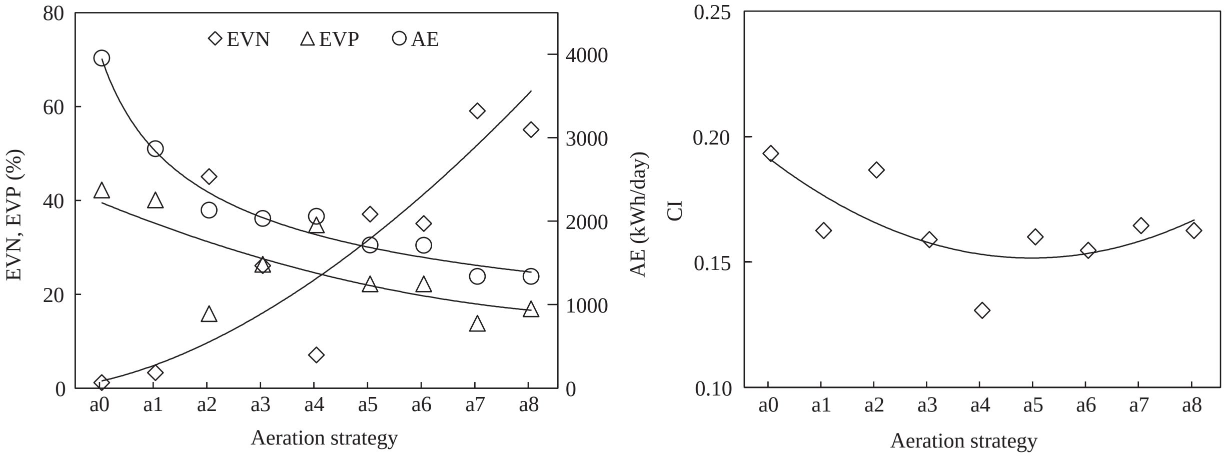

Fig. 3 Effect of aeration strategies on effluent violation (EVN, EVP), aeration energy (AE) and unified index CI under solid retention time of (24 ± 11) days.

(Liu et al., 2007, 2008; Guo et al., 2012a, 2012b). Strategy a4 appeared to be the most suitable option in terms of minimal CI (0.131) with a violation of effluent ammonium below 10%.

2.2 Optimization of sludge discharge strategy

It is known that the sludge discharge strategy, which is directly related with the SRT, could affect not only the ammonium and phosphorus removal but also the costs for sludge treatment. The effect of different sludge discharge strategies on process performance is shown in **Fig. 4**. With the increase of sludge discharge flow from 100 to 400 m^3/day, EVN increased from 0 to 24.2%, while EVP decreased from 49.5% to 22.1%. A sludge discharge flow of 300 m^3/day (SRT of 13 day) permitted an effluent TP violation of 27% while keeping a relatively low EVN (below 10%). Further increasing the excess sludge flow to 350 m^3/day (SRT < 11 day), however, could not improve the phosphorus removal much, but lead to the deterioration of nitrification performance (EVN > 10%) due to the wash-out of biomass from the system (Henze et al., 2008) (MLVSS < 1000 mg/L). Since phosphorus could be further removed through subsequent chemical precipitation, it is more important to control ammonium violation to a low level. From the viewpoint of controlling ammonium violation, the sludge discharge flow should be below 300 m^3/day. As for the sludge production, in spite of the greatly increased sludge discharge flow compared to the baseline (189 ± 78 m^3/day), the amount of sludge production had no significant increment (< 5%) (**Table S2**).

The unified index CI for different sludge discharge strategies is also shown in **Fig. 4**. The minimal CI (0.16) was achieved at a sludge discharge flow of 250–300 m^3/day (SRT of 13–15 days).

2.3 Optimization of the integrated control strategy

On the basis of scenario analysis, operational maps were drawn (**Fig. 5**) to determine optimal operating points with respect to the effluent violation and the unified index for each combination of the aeration and sludge discharge strategies. For strategies with an activated aerator number of 3–5, those with the lowest CI values (a4, a6 and a8) were selected for the analysis.

The effects of activated aerator number and sludge discharge flow on the effluent ammonium and phosphorus violations are shown in **Fig. 5**. At a fixed number of activated aerators, it is necessary to decrease the sludge discharge flow in order to prevent the ammonium violation from rising (**Fig. 5a**). When running 5 aerators, for example, the sludge discharge flow should be below 200 m^3/day to keep the EVN below 10%. Conversely, increasing sludge discharge flow was required to keep a low EVP for a given number of activated aerators (**Fig. 5b**). Take 5 activated aerators for example, the sludge discharge flow must be over 250 m^3/day to keep the EVP below 20%. Therefore, a compromise must be made to ensure that both

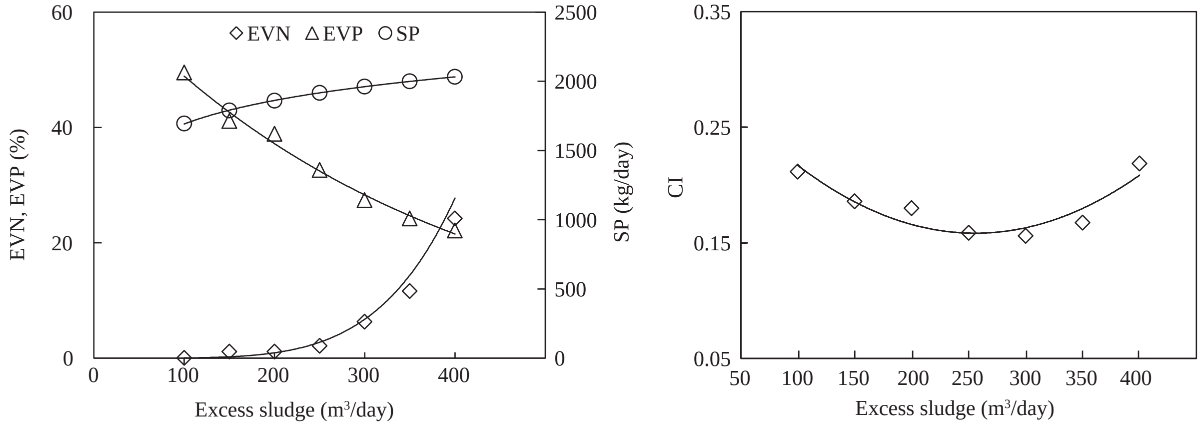

Fig. 4 Effect of sludge discharge strategies on effluent violation, sludge production (SP) and unified index CI with 9 activated aerators.

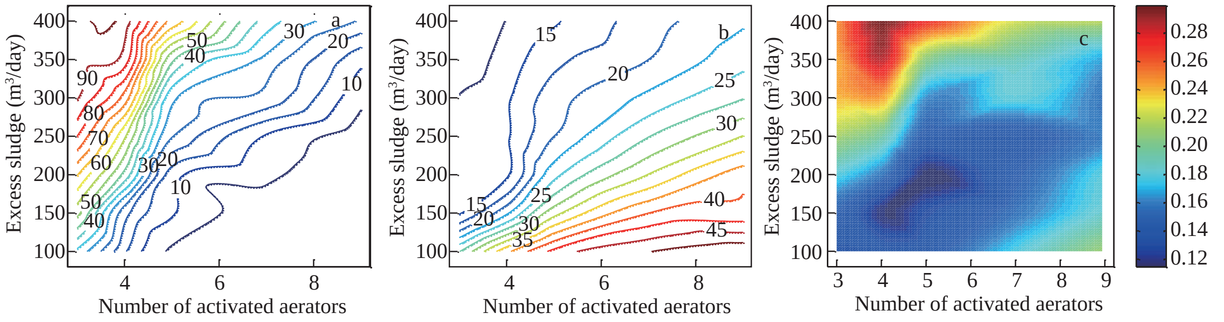

Fig. 5 Operational maps for the effluent violations of ammonium (a), phosphorus (b) and unified index CI (c).

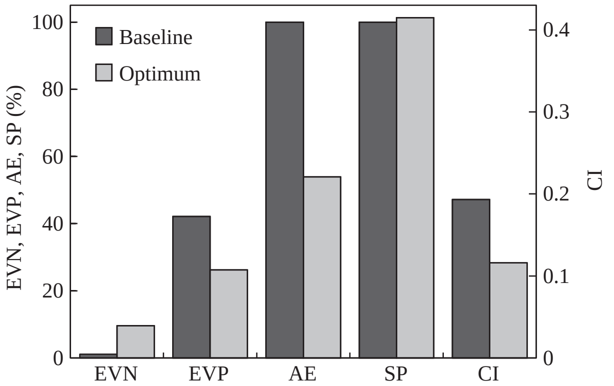

Fig. 6 Operating costs and performance of optimized operational strategy.

the requirements for ammonium and phosphorus removal are considered.

The operational map for CI is illustrated in **Fig. 5c**. It is clear that the minimal CI (< 0.12) could be identified at the activated aerator number of 4–5 and sludge discharge flow of 150–200 m^3/day. Since phosphorus could be further removed by subsequent chemical precipitation, it is more important to suppress effluent violation of ammonium at a reasonable cost. Therefore, the optimal operational strategy should be a combination of 5 activated aerators with a sludge discharge flow of 200 m^3/day, which permits an EVN below 10% and EVP below 30%.

The performance of the proposed optimal strategy is shown in **Fig. 6** and **Table S3**, which employs 5 rotating disks operated with the mode "111100100" for aeration (a4) and the sludge discharge flow of 200 m^3/day. Compared with the current status (baseline), this strategy could achieve effluent violation of ammonium and TP below 10% and 30%, respectively, with substantial reduction of aeration energy cost (46%) and minimal increment of sludge production (<2%). The unified index CI was also improved. The main reason for the effluent ammonium violations was the sudden increase of ammonium load as shown in **Fig. S2**. Thus the effluent ammonium violation could be reduced effectively by increasing the number of activated aerators temporarily to cope with the increased load.

3 Conclusions

A unified index was introduced by integrating operational costs (aeration energy and sludge production) with effluent violations as the criteria for the evaluation of the process performance of a full-scale oxidation ditch process treating sewage. Scenario analysis based on the ASM2d model showed that a strategy employing 5 rotating disks operated with the mode "111100100" and a sludge discharge flow of 200 m^3/day was optimal. Compared with the current status, this strategy could achieve ammonium violation below 10% and TP violation below 30% with substantial reduction of aeration energy cost (46%) and minimal increment of sludge production (<2%).

Acknowledgments

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Supporting materials

Supplementary data associated with this article can be found in the online version.

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Supplementary material

Table S1 Performance and economical indicators with different aeration strategies

ID	EVN	EVP	SP (kg/day)	AE (kWh/day)*
a0	1.1%	42.1%	1839.9	3954.3
a1	3.2%	40.0%	1843.3	2868.8
a2	45%	15.8%	1854.6	2057.6
a3	26%	26.3%	1850.5	2030.3
a4	7.0%	34.7%	1846.4	2130.9
a5	37%	22.1%	1852.1	1711.6
a6	35%	22.1%	1851.3	1713.5
a7	59%	13.7%	1855.4	1335.8
a8	55%	16.8%	1854.4	1337.2

EVN: effluent ammonium violation; EVP: effluent phosphorous violation; SP: sludge production; AE aeration energy cost. * Average value for the evaluation period of three months.

Table S2 Performance and economical indicators with different sludge discharge strategies (s1-s7)

ID	Q_{es} ($\mathrm{m^3}$/day)	SRT (day)*	$\mathrm{VSS_{OD}}$ (mg/L)*	EVN	EVP	SP (kg/day)	AE (kWh/day)*
Baseline	189*	24	1489	1.1%	42.1%	1839.9	3954.3
s1	100	38	1946	0%	49.5%	1694.1	3954.7
s2	150	25	1594	1.1%	41.1%	1789.4	3954.4
s3	200	19	1351	1.1%	38.9%	1859.8	3954.2
s4	250	15	1176	2.1%	32.6%	1915.6	3953.9
s5	300	13	1044	6.3%	27.4%	1961.1	3953.5
s6	350	11	941	11.6%	24.2%	2000.1	3953.1
s7	400	10	858	24.2%	22.1%	2033.1	3952.8

Q_{es}: excess sludge discharge. * Average value for the evaluation period of three months.

Table S3 Comparison of different operational strategies

	Baseline	Optimum
Number of activated aerators	9	5
SRT (day)	24 ± 11	19 ± 3
Q_{es} ($\mathrm{m^3}$/day)	189*	200
$\mathrm{NH_4}^+$-N (mg/L)*	1.24	2.96
EVN	1.1%	9.5%
TP (mg/L)*	1.13	0.85
EVP	42.1%	26.2%
SP (kg/day)	1839.9	1864.7
AE (kWh/day)*	3954.3	2130.5
CI	0.193	0.116

* Average value for the evaluation period of three months.

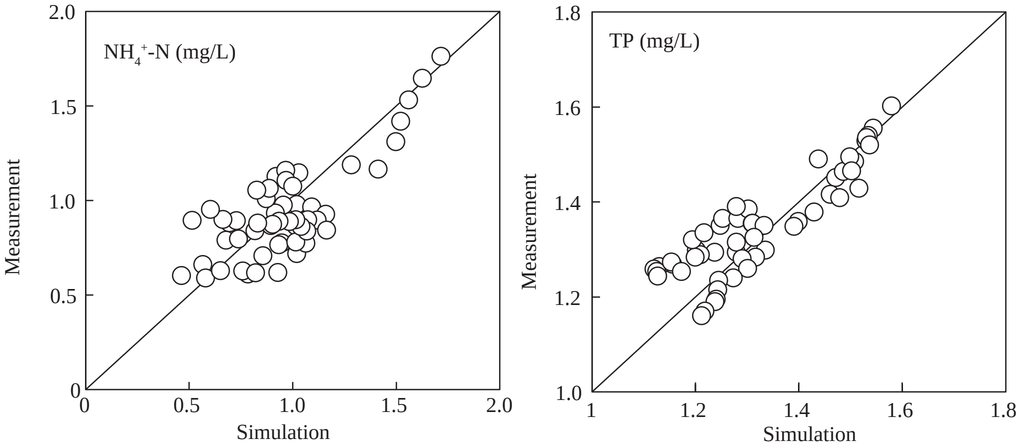

Fig. S1 Measurements vs. simulation results of ammonium and phosphorus. The correlation coefficients between simulation and measured data are: ammonium: R^2 = 0.7778, phosphorus: R^2 = 0.8765.

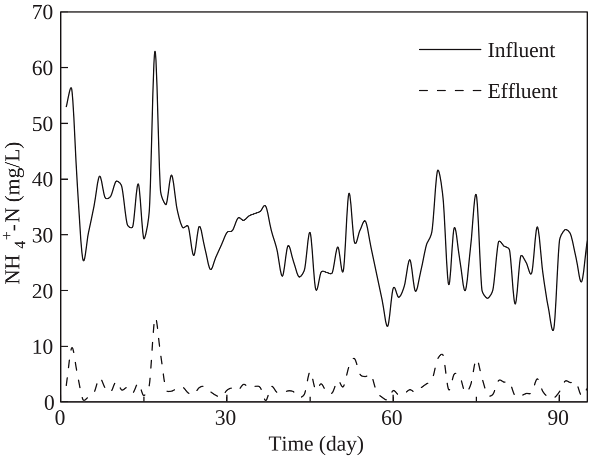

Fig. S2 Performance of ammonium removal for the optimal strategy.

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