Optimization of Aeration Diffuser System Design: A Simulation Study

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Abstract: The influence of aeration diffuser system design on electricity usage, effluent water quality, and life-cycle cost in biological wastewater treatment was investigated. A plant-wide model was implemented, and simulations were carried out with different process configurations and aeration systems. Model-aided design of new aeration diffuser systems could significantly decrease electricity usage and life-cycle cost while at the same time avoiding negative effects on the treatment performance. The optimum distribution of diffuser systems in tanks in series was found to be influenced by process configuration, volumetric loading rate, temperature, and the internal recirculation flow rate. Compared with a conventional design approach, increasing the number of diffusers, up to a critical point, led to higher energy efficiency and lower life-cycle cost. This was despite an increasing limitation of the minimum airflow rate, leading to dissolved oxygen levels significantly exceeding control targets. Aeration systems optimized by simulations were found to, independently of process configuration, exhibit 20% lower electricity usage and 16%–18% lower life-cycle costs compared with systems designed based on a more conventional approach typically applied in practice. **DOI: 10.1061/JOEEDU.EEENG-7047.** *© 2023 American Society of Civil Engineers.*

Author keywords: Activated sludge; Aeration efficiency; Energy; Diffuser system design; Benchmark simulation model.

Introduction

Most water resource recovery facilities (WRRFs) contain aerobic biological treatment equipped with fine-bubble diffusers made of porous solid material or perforated flexible membranes (Rosso et al. 2008). Aeration contributes significantly to the electricity usage at municipal WRRFs, and typically makes up 30%–75% of the total electricity usage (Guo et al. 2016; Rosso 2018; WEF 2010). The relatively low solubility of oxygen in water, interference of wastewater contaminants on the oxygen mass transfer as indicated by the α factor (Gillot et al. 2000; Gillot and Heduit 2008; Iranpour et al. 2000a; Stenstrom and Gilbert 1981), and the low oxygen content of air contributes to a high energy demand.

Energy conservation of WRRFs is an active field within research and engineering practice. The control of dissolved oxygen (DO) concentrations is commonly applied and has been further developed by, for instance, ammonia feedback control (Åmand et al. 2013; Rieger et al. 2014) and combined ammonia feedback and solids retention time (SRT) control (Schraa et al. 2019). Such control strategies can be adapted to the treatment targets and help to avoid unnecessary energy usage for aeration at periods with low loading to the WRRF.

Fine-bubble diffusers are occasionally prone to aging and clogging that lead to larger bubbles with lower oxygen transfer efficiency (Garrido-Baserba et al. 2016; Krampe 2011; Noble et al. 2016). Therefore, methods to diagnose diffuser conditions (Rosso et al. 2012), restore the performance by cleaning (Hung and Boyle 2001), and reverse flexing (Odize et al. 2017) have been researched and put into practice at WRRFs.

The mentioned approaches focus on the operation and control for minimized energy usage with already-existing aeration systems. However, the design of a new aeration system may also have a significant impact on the overall energy efficiency. High energy efficiency and low costs are common targets for the engineering design practice of new aeration systems. But this aspect has not been thoroughly and systematically addressed in the research literature. A diffuser system with higher oxygen transfer efficiency will lead to a lower airflow requirement and thereby a lower blower energy usage. At the same time, the design of a diffuser system may affect the control window for the concentration of DO. This may influence the performance of the biological treatment and thus the ability to reach the treatment targets.

Diffuser systems have well-defined operating ranges that are determined by the type and number of diffuser elements in the system (Drewnowski et al. 2019). The commonly used membrane diffusers have a minimum airflow rate per unit, below which operation is not recommended because the diffusers do not create uniform bubble patterns. There is also a minimum airflow rate to each tank to provide sufficient mixing. The maximum airflow rate per diffuser is determined by the durability of the membrane. The oxygen transfer efficiency is higher at lower airflow rates per diffuser (Leu et al. 2009; Rosso et al. 2005) because low airflow rates lead to less expansion of the membranes and therefore smaller bubbles with higher specific surface area (Baquero-Rodríguez et al. 2018). A higher diffuser density leads to higher oxygen transfer efficiency (Schraa et al. 2017) because of fewer opportunities for vertical water circulation that reduce the retention time of the rising air bubbles in the tank. A higher number of diffusers will generally lead to lower airflow rate per diffuser and therefore higher oxygen transfer efficiency. At the same time, the minimum airflow rate to the tank will increase. Thus, the design of a diffuser system is a balance between energy efficiency, investment cost, and the level of controllability for the DO concentration.

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The interdependent relations between the aeration diffuser system and the biological treatment process can be investigated with existing models, combining models such as Activated Sludge Model No. 1 (ASM1) (Henze et al. 2000) with oxygen transfer models (Amaral et al. 2017; Arnell 2016; Juan-Garcia et al. 2018; Schraa et al. 2017). In this way, the link between the electricity usage and the effluent water quality can be systematically evaluated. Such relations should preferably be assessed on a plant-wide level over the long term and with realistic variations in influent composition and flow rate. To this end, the Benchmark Simulation Model No. 2 (BSM2) provides a well-established framework for plant-wide evaluations including a 609-day phenomenological influent generator with daily variations as well as rain and stormwater events (Gernaey et al. 2014).

In this paper, the aeration electricity usage and treatment performance were investigated as a function of the aeration diffuser system design. Optimization of diffuser system design has not been previously addressed in the research literature even though it may have significant potential impact on the system and energy performance. A model was implemented on the basis of the BSM2 framework and its reactor configuration as a starting point. Electricity usage, effluent water quality, and life-cycle cost (LCC) were investigated as a function of process configuration (nitrogen removal, nitrification, or high-loaded activated sludge), number and distribution of diffusers, and other factors such as volumetric loading rate, temperature, and the internal recirculation flow rate. The benefits of using aeration modeling for diffuser system design are illustrated and guidance provided for design for minimized life-cycle cost with maintained effluent water quality.

Materials and Methods

Process Models

A process model based on BSM2 was implemented in Simba# (version 4.3.4) in accordance with Gernaey et al. (2014). A process scheme is depicted in Fig. 1. BSM2 contains a typical WRRF treating on average 20,648 $m^3\,day^{-1}$. The water line is comprised of a primary clarifier (area of 300 m^2), two anoxic tanks (each of 1,500 m^3), three aerated tanks (Ox1–Ox3, each of 3,000 m^3), followed by a secondary clarifier (area of 1,500 m^2). Return activated sludge (20,648 $m^3\,day^{-1}$), internal recirculation from Ox2 to the first anoxic tank (61,944 $m^3\,day^{-1}$), and addition of external carbon source to the first anoxic tank (400,000 $g\,m^{-3}$, 2 $m^3\,day^{-1}$) are also included in the BSM2 setup. The sludge line is comprised of thickening, anaerobic digestion, dewatering, and buffering of the reject water. Further details of BSM2 are given in the Supplemental Materials of this paper and elsewhere (Gernaey et al. 2014). This process represented the nitrification and denitrification (NDN) alternative. In addition, two alternative process configurations were modeled treating the same influent wastewater, namely, a nitrification alternative (N) without anoxic tanks, internal recirculation, and addition of external carbon source, and an alternative with only carbon removal (C) with smaller aerated tanks and higher flow rate of surplus sludge withdrawal. The details of the three process configurations are given in Table 1. These alternatives were included because they represent common WRRF process options in relation to different treatment objectives or different post-treatment steps such as post-nitrification and -denitrification.

For conditions that would not influence the quantity or composition of the sludge produced in the water line, routine simulations were simplified by excluding the sludge treatment and instead adding the reject water as an additional dynamic influent to the water line upstream of the primary clarifier. The dynamic reject water influent data file for each process alternative was created by a simulation of the complete process model including the sludge treatment (Arnell 2016). The present model was confirmed to yield the results expected for BSM2 in its standard configuration (Gernaey et al. 2014) with less than 1% deviation.

A water depth of 4 m was assumed in the aerated tanks. The aeration diffusers were assumed to be installed 0.3 m above the tank floor and thus the immersion depth of the aeration systems was 3.7 m.

Aeration Model and Aeration System Performance Data

The consumption of oxygen in the bioprocess, represented by the actual oxygen requirement (AOR) ($kg\,day^{-1}$), was derived from the ASM1 stoichiometry (Henze et al. 2000) and equals the oxygen transfer rate (OTR) ($kg\,day^{-1}$). OTR was adjusted for standard conditions in clean water (SOTR) [101,325 Pa (1 atm), 20°C, and DO 0 $mg\,L^{-1}$] and used to simulate the airflow rate [Q_{air} in cubic meter at normal conditions $(Nm^3)\,h^{-1}$, defined at 101,325 Pa, 0°C and 0% humidity] based on diffuser system performance data in terms of standard oxygen transfer efficiency [(SOTE) in $g\,Nm^{-3}\,m^{-1}$] as detailed in the Supplemental Materials.

Diffuser system performance data were obtained from commercial suppliers of disc diffusers with membranes of ethylene propylene diene monomer rubber. Representative data on SOTE for the current immersion depth (3.7 m) versus airflow rate per diffuser (q_{diff} in $Nm^3\,h^{-1}$) were fitted by the least-squares method to the expression

$$\mathrm{SOTE} = A \cdot q_{\mathrm{diff}}^{m}$$

where A and m = constants. The thus fitted SOTE data were used, as part of the simulations, to calculate the airflow rate into each aerated tank as a function of the oxygen demand determined in the process model as otherwise described elsewhere (Supplemental Materials; Schraa et al. 2017). Each tank was considered with a specific number of uniformly distributed diffusers in it, with an oxygen transfer performance according to the input SOTE profile. Aeration system performance data were collected over a wide range of diffuser densities (0.03–0.25 m^2 diffuser area per square meter tank area) and found to be well described by the expression

$$\mathrm{SOTE}_i = B - D \cdot E^{dd}$$

where SOTE_i ($g\,Nm^{-3}\,m^{-1}$) = SOTE at a q_{diff} of $i\,Nm^3\,h^{-1}$; dd = diffuser density ($m^2\,m^{-2}$); and B, D, and E = fitting constants. Thus, the influence of water depth and dd on SOTE was based on real supplier data and not extrapolated using the internal methods in Simba# (Schraa et al. 2017).

Examples of SOTE data obtained in the present study are depicted in Fig. 2. As expected, SOTE increase with decreasing q_{diff}. In addition, SOTE increase with dd. However, this effect was observed to diminish at high diffuser densities. Above around 0.15 $m^2\,m^{-2}$, SOTE did not increase further with increased density.

The active area of each disc diffuser was 0.038253 m^2 and the q_{diff} operating range was 0.85–17 $Nm^3\,h^{-1}$. The α factor for the process alternative NDN was set to 0.6, 0.8, and 0.9 in the first second, and third aerated tank, respectively. For alternatives N and C, lower α factors were assumed, as expected because of the absence of pre-denitrification and/or a lower SRT. The α factors are given in Table 1. These levels of α and the increasing values in subsequent tanks are in line with experimental observations from full-scale activated sludge plants with nitrogen removal, nitrification, or only carbon removal, respectively, and are also assumed to include typical levels of diffuser aging and fouling (Iranpour et al. 2000b; Jiang et al. 2017; Leu et al. 2009; Mueller et al. 2001; Rosso et al. 2008).

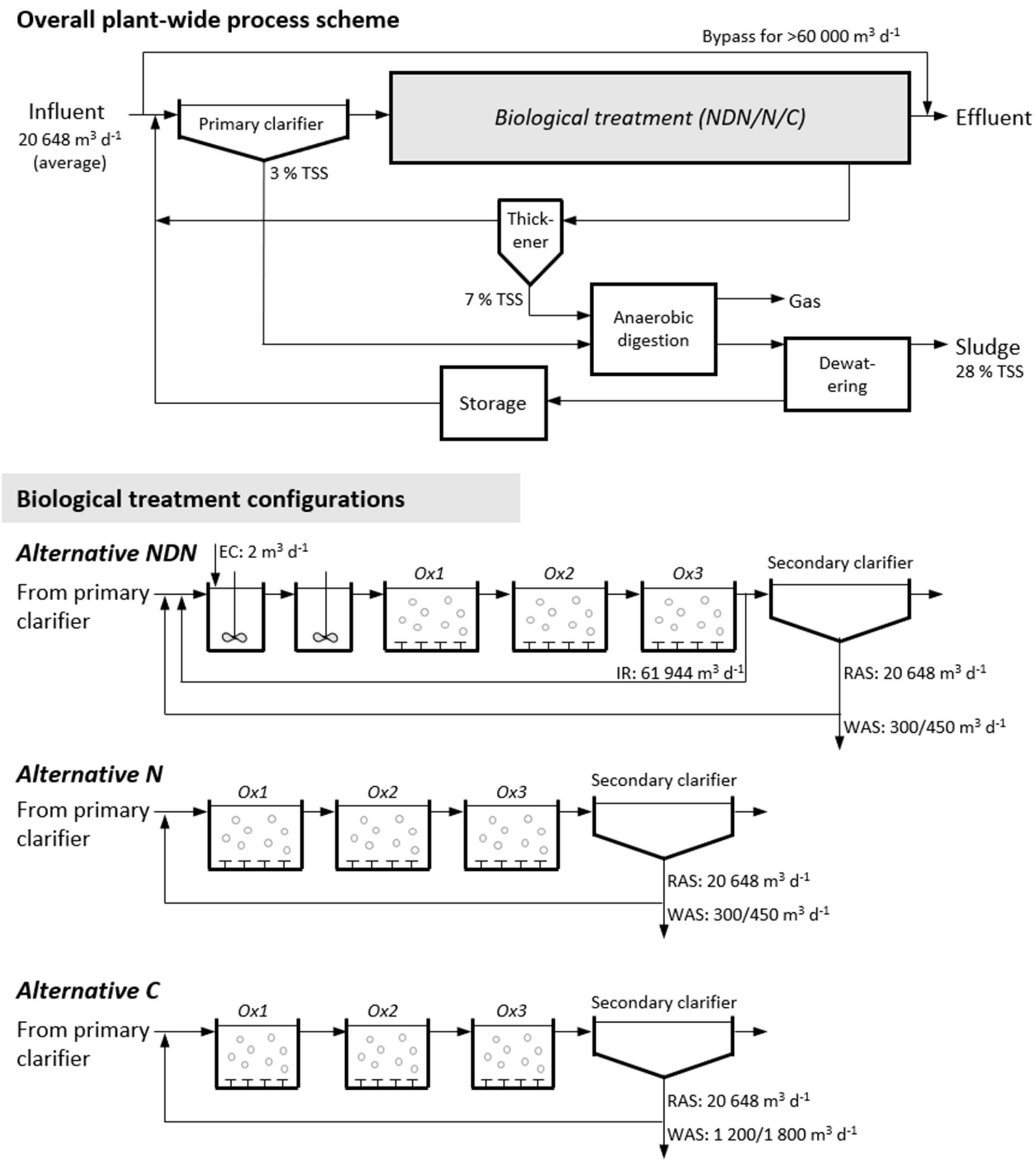

Fig. 1. Process schemes of the modeled configurations. Three alternative biological treatment configurations were integrated into an overall plant-wide model. The two waste activated sludge (WAS) flow rates represent winter and summer operation, respectively. EC = external carbon source; IR = internal recirculation; and RAS = return activated sludge.

Independent proportional integral (PI) controllers for the DO concentration in each aerated tank were included. The DO set points of these controllers for the NDN alternative were 2.0, 2.0, and 1.0 mg L^{-1} in the first, second, and third aerated tank, respectively. Such DO profile is common in practical application and the lower DO level in the last aerated tank aims to decrease the negative influence of oxygen on denitrification when recirculated to the first anoxic tank. The same DO profile was used for the N process. For the C process, a DO set point of 1.0 mg L^{-1} was applied in all three tanks because such lower DO levels is typical for removal of only organic matter without nitrification (Tchobanoglous et al. 2014).

Simulation and Evaluation

The simulations were performed according to the BSM2 guidelines (Gernaey et al. 2014) including model initialization at steady-state conditions followed by simulation of 609 days with dynamic influent data for flow rate and concentrations. The last 364 days of the dynamic simulations were used for evaluation.

The electricity usage was calculated based on a fixed ratio to make the evaluations general and independent of blower setup. A ratio of 0.0175 kWh Nm^{-3} was applied as a realistic number based on the average system pressure that can be expected with the assumed immersion depth and typical levels of other system pressure losses (Jenkins 2014).

The LCC of each aeration system was calculated as the sum of investment, electricity cost, and maintenance cost over the 15 years of expected technical lifetime. The present value of the LCC was calculated with a discount rate of 3% based on guidelines for water and wastewater infrastructure investments in Sweden (Swedish Water 2017). The maintenance requirement was defined as one replacement of diffuser membranes after half the technical lifetime (7.5 years). Such frequency of replacement is reasonable based on literature data on aging and clogging (Garrido-Baserba et al. 2016;

Table 1. Characteristics of the three modelled process alternatives

Process alternative	Unit	NDN (BSM2)	N	C
Anoxic volumes	m^3	$2 \times 1{,}500$	0	0
Aerated volumes (Ox1–Ox3)	m^3	$3 \times 3{,}000$	$3 \times 3{,}000$	$3 \times 1{,}000$
Return sludge flow rate	$m^3\ day^{-1}$	20,648	20,648	20,648
Internal recirculation flow rate	$m^3\ day^{-1}$	61,944	0	0
External carbon source	$m^3\ day^{-1}$	2	0	0
Waste activated sludge flow rate (winter/summer)	$m^3\ day^{-1}$	300/450	300/450	1,200/1,800
DO set points in Ox1/Ox2/Ox3	$mg\ L^{-1}$	2.0/2.0/1.0	2.0/2.0/1.0	1.0/1.0/1.0
α in Ox1/Ox2/Ox3	—	0.6/0.8/0.9	0.5/0.7/0.8	0.4/0.6/0.7
SRT (summer)	day	14	11	0,9
SRT (winter)	day	20	15	1,3

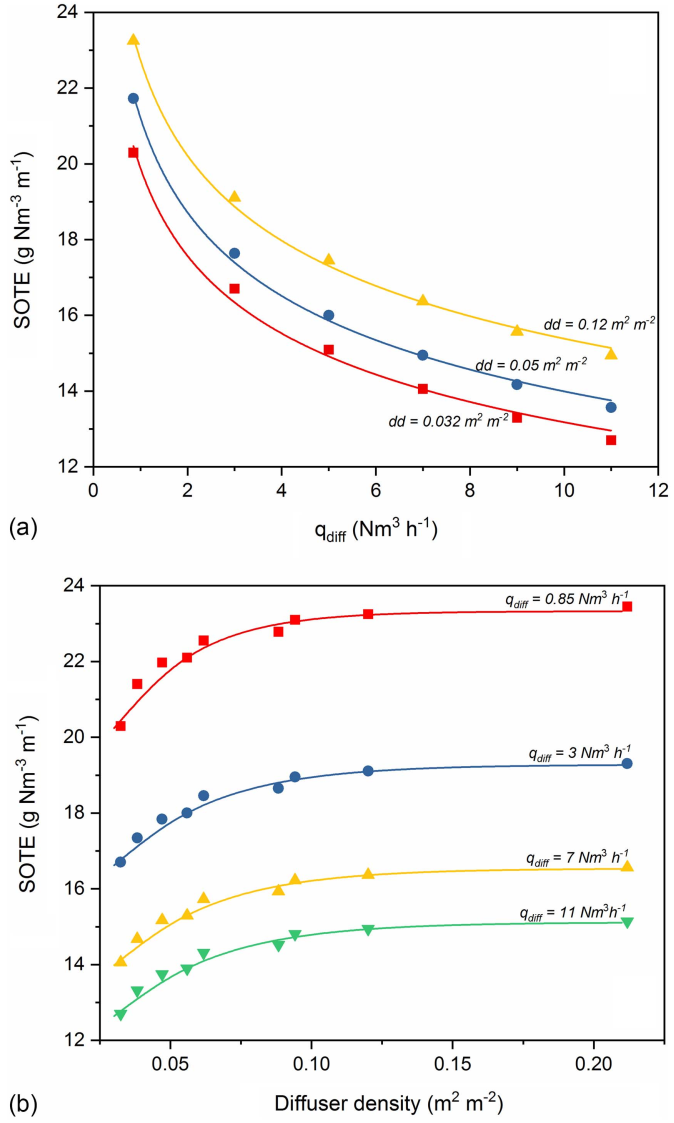

Fig. 2. Diffuser system performance: standard oxygen transfer efficiency (a) as a function of airflow rate per diffuser; and (b) as a function of diffuser density.

Krampe 2011; Noble et al. 2016) and furthermore in line with typical manufacturer recommendations. Price data for aeration systems and spare parts (membranes) were obtained from manufacturers. Labor costs for installation and maintenance were not included because they will vary strongly with local factors. The electricity cost was based on the present and past average price, corrected for inflation, for industry clients in Europe. It was €0.116 kWh^{-1} the first year (2021) followed by an annual increase by 1.4% in accordance with the price development during the last 15 years (Eurostat 2021).

Results and Discussion

The aeration electricity usage and treatment performance were investigated as a function of the aeration diffuser system design. An optimum balance was sought between energy efficiency, investment cost, and the level of controllability for the DO concentration. Outcomes were compared for the three commonly used process configurations NDN, N, and C (high-loaded activated sludge with only carbon removal).

Tapering

Aeration systems are typically designed with a tapered layout to meet the spatial variation in oxygen demand in the plant. A higher diffuser density in the first aerated zone and successively lower densities in the following zones allow optimum control range and operation efficiency in each zone. However, the distribution of oxygen demand is often unknown in a design situation, and therefore rules of thumb are applied. According to the widely applied USEPA guidelines, airflow rate can be assumed to be distributed by 45%–55% to the first, 25%–35% to the second, and 15%–25% to the third zone (USEPA 1989). According to an alternative source, around 50% of the oxygen demand can be expected to occur in the first 20% of the aeration volume (Jenkins 2014).

Simulations were executed with an aeration system design according to the USEPA guidelines for each process alternative. Thus, the diffusers were distributed by 50%/30%/20% in the three tanks and the total number of diffusers was adjusted to obtain minimum total airflow rates while at the same time respecting the target DO levels (Table 1) throughout the 1-year evaluation period. It was observed that with this tapering, the total number of diffusers was determined by the maximum number in the third zone and the period with lowest loading.

For comparison, a simulation was performed with an aeration system design that was directly optimized for the observed oxygen demand for the respective process alternative. The number of diffusers was individually determined for each zone by maximizing the number without exceeding the target DO levels. For NDN, the optimum tapering was found to be 61% in the first, 24% in the second, and 15% in the third zone. Alternative N had a very similar optimum tapering of 62%/23%/15%, whereas alternative C had an optimum tapering of 53%/28%/20%. Thus, for the NDN and N processes, the optimum tapering had significantly stronger

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Table 2. Summary of key characteristics for selected aeration systems

Process and diffuser system	Diffuser density (m^2 m^{-2})			Average airflow rate per diffuser (Nm^3 h^{-1})			Electricity usage (MWh $year^{-1}$)	LCC (k€)
	Ox1	Ox2	Ox3	Ox1	Ox2	Ox3		
NDN								
Conventional tapering	0.056	0.034	0.022	4.19	3.12	1.99	1,153	1,849
Optimized tapering	0.094	0.037	0.022	2.11	2.76	1.99	1,035	1,682
Minimized electricity	0.160	0.062	0.038	1.13	1.36	1.03	918	1,545
Minimized LCC	0.151	0.059	0.036	1.21	1.46	1.08	920	1,542
N								
Conventional tapering	0.064	0.038	0.026	6.00	2.94	1.69	1,613	2,573
Optimized tapering	0.107	0.039	0.026	3.06	2.83	1.69	1,443	2,327
Minimized electricity	0.204	0.075	0.048	1.41	1.27	0.89	1,272	2,127
Minimized LCC	0.182	0.067	0.043	1.60	1.42	0.92	1,276	2,118
C								
Conventional tapering	0.065	0.039	0.026	3.57	2.76	3.24	424	681
Optimized tapering	0.070	0.037	0.026	3.21	3.01	3.24	420	676
Minimized electricity	0.162	0.084	0.060	1.16	1.03	1.06	338	572
Minimized LCC	0.155	0.081	0.057	1.21	1.08	1.11	338	571

inclinations than suggested by the USEPA guidelines, but for C it was similar to the USEPA guidelines.

For alternatives NDN and N, the optimized designs led to 119,000 and 170,000 kWh lower electricity usage, respectively, for 1 year of operation than the 50%/30%/20% designs (Table 2). This corresponded to 10%–11% less electricity. For C, the optimized design only led to 3,000 kWh $year^{-1}$ or 1% lower electricity usage because the optimized design was already close to the 50%/30%/20% distribution. The significant differences in electricity usage in case of NDN and N highlights the potential saving when using the true oxygen demand distribution as a design basis rather a general guideline. No differences with respect to treatment performance were observed.

The spatial distribution of the oxygen demand was examined in further detail. The distribution of the AOR, which occurred in the processes due to carbon and nitrogen removal and endogenous respiration, and the distribution of standard oxygen requirement (SOR) (clean water, 1 atm, 20°C, and DO 0 mg L^{-1}) was according to Fig. 3 with respect to average values over the year.

In accordance with the optimum tapering, the NDN and N alternatives had distributions with stronger inclinations than the C alternative. This was related to nitrification activity that predominantly took place in the first aerated tank for NDN and N. It was also observed that increased rate of internal recirculation led to smaller differences between the tanks if nitrification was occurring (data not shown). Thus, the N alternative exhibited stronger tapering than NDN (Fig. 3).

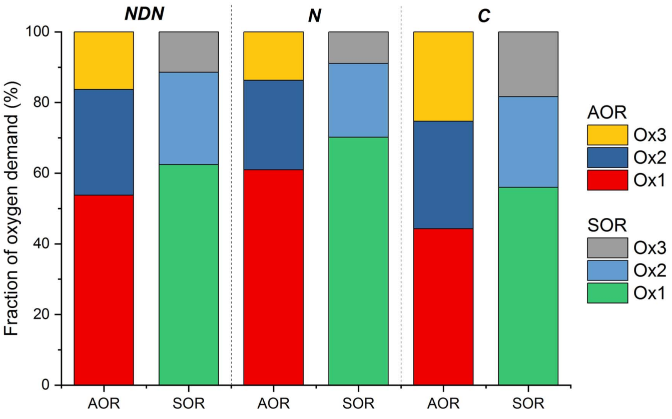

Fig. 3. Average distrbution of AOR and SOR in the process alternatives with NDN, N, and C configurations.

For the NDN alternative, the AOR was distributed by 54%/30%/16% in Ox1/Ox2/Ox3 on average over the year. Given a unified α value and DO level across the plant, this AOR distribution would lead to the same SOR distribution and consequently the same distribution in diffuser number. In practice, such unified α value is often applied and it is noteworthy that under those circumstances this approach is relatively close to the USEPA guideline of 50%/30%/20% distribution of airflow rate (USEPA 1989). However, as detailed previously, it has been repeatedly observed that the α value increase spatially over a plant and thus SOR and the optimum number of diffusers will have a stronger inclination in case of NDN and N processes, as confirmed by the simulations.

At higher temperature and/or lower loadings, a higher fraction of AOR occurred in the first tank (Fig. 4). Correspondingly, at lower temperature and/or higher loadings, relatively less of the AOR occurred in the first tank and a higher fraction was passed on the second and third tanks. This implies that besides process configuration, the volumetric loading rate and the wastewater

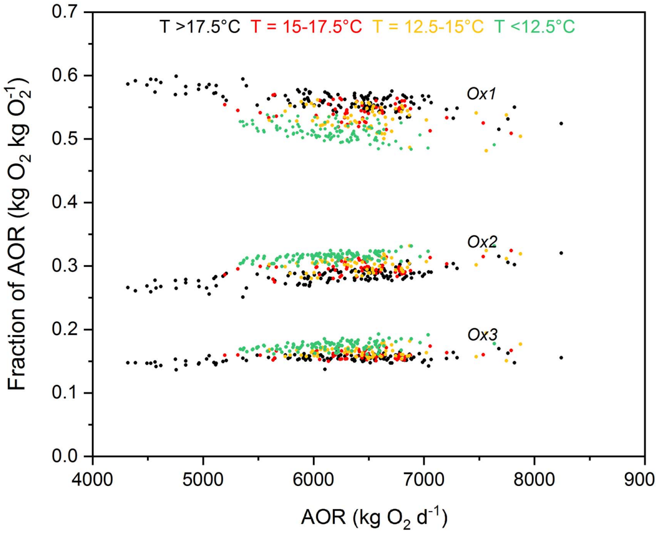

Fig. 4. Fraction of the AOR in each of the three aerated tanks Ox1–Ox3 as a function of the total AOR in alternative NDN. Daily average values.

temperature have implications for the diffuser system design. It is commonly known that aeration is influenced by temperature through the effects on the oxygen diffusion rate (Drewnowski et al. 2019), the DO saturation level (Baquero-Rodríguez et al. 2018), and the biochemical reaction rates (Henze et al. 2000). Furthermore, higher ambient temperatures lead to lower oxygen concentration in the influent air that increase blower energy usage (Jenkins 2014). In addition to these effects, it is clear that temperature also has an effect on the optimal diffuser tapering.

Our results show that modeling a case-specific situation is strongly beneficial to reach the most efficient diffuser system design. As an alternative, the results presented herein can be used as guidance for how factors such as process configuration (NDN, N, and C), internal recirculation flow rate, volumetric loading rate, and temperature influence the optimum tapering.

Diffuser Density

The influence of diffuser density on electricity usage and effluent quality was investigated. The optimized tapering design was used as a reference for each process alternative from which the number of disc diffusers was varied proportionally in the three aerated tanks.

It was found that a system with a diffuser density corresponding to 70% of the reference case would lead to 12%–15% higher electricity usage. This was because fewer diffusers led to higher airflow rate per diffuser (for instance, 3.4 compared to 2.1 $\mathrm{Nm^3\,h^{-1}}$ in Ox1 of NDN) and consequently lower oxygen transfer efficiency.

Higher diffuser densities than the reference cases led to lower average airflow rates per diffuser and thus higher oxygen transfer efficiency and lower electricity usage. For NDN, the average q_{diff} decreased from 2.1 to 1.0 $\mathrm{Nm^3\,h^{-1}}$ as the number of diffusers in Ox1 doubled (Table 2). However, because the reference cases were based on the maximum number of diffusers that would allow maintaining target DO levels, increasing the diffuser density led to periods of elevated DO levels. This was because, when the number of

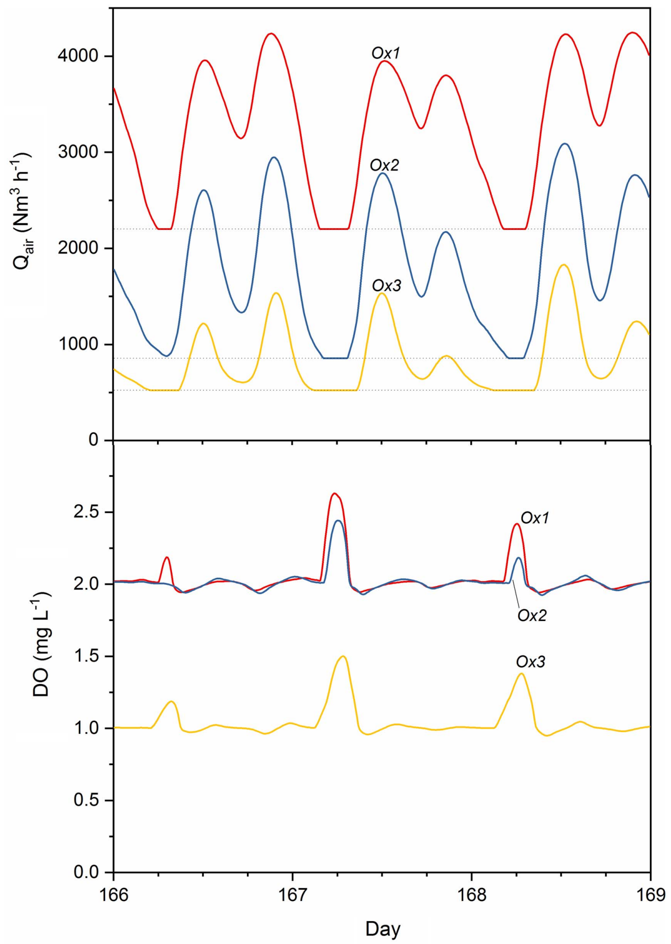

Fig. 5. Periods with overaeration (dissolved oxygen levels above set points) due to limitation of the minimum airflow rate. The dotted lines represent minimum airflow rates for the three aerated tanks.

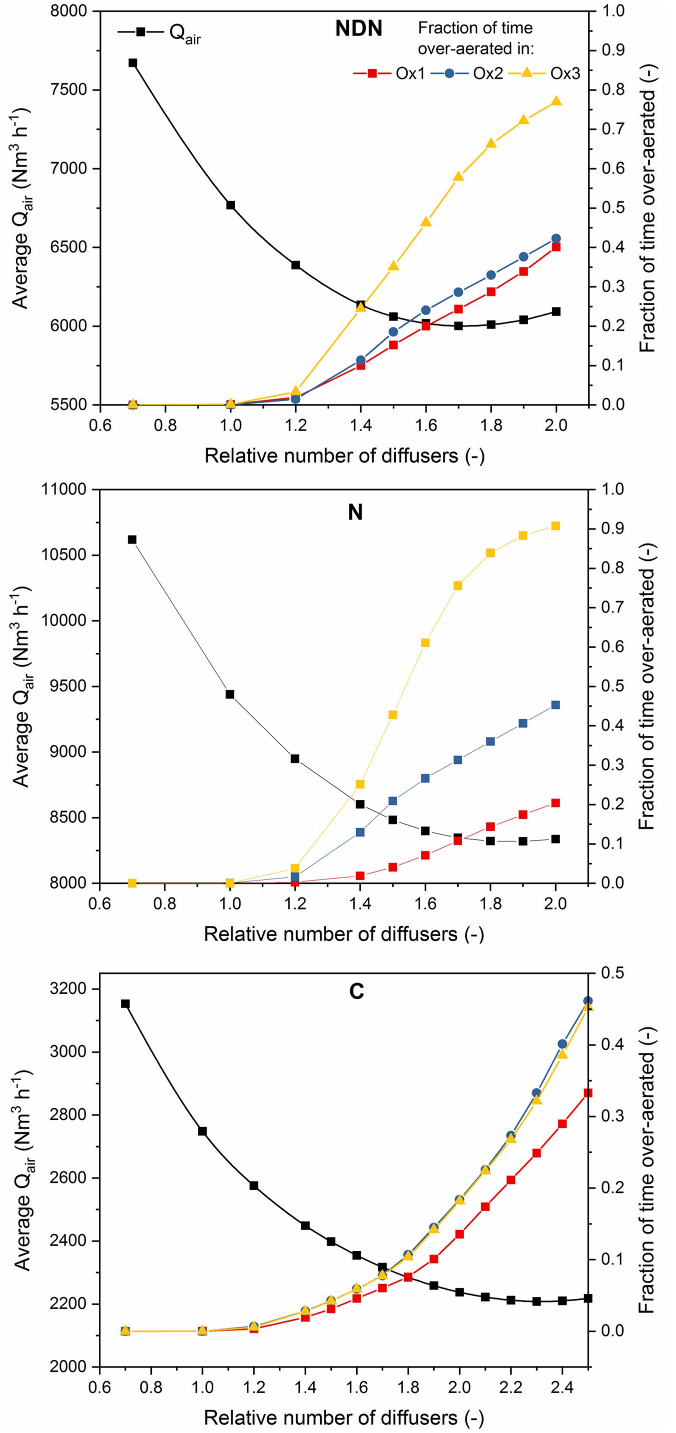

Fig. 6. Average airflow rate (Q_{air}) and fraction of overaerated time as a function of the relative number of diffusers.

Table 3. Average dissolved oxygen concentrations in aerated tanks and effluent concentrations of nitrogen and chemical oxygen demand

	Average dissolved oxygen			Ammonia nitrogen	NO_x nitrogen	Total nitrogen	Chemical oxygen demand
Process and diffuser system	Ox1	Ox2	Ox3	Effluent	Effluent	Effluent	Effluent
NDN							
Conventional tapering	2.00	2.00	1.00	0.3	12.0	14.2	47.6
Optimized tapering	2.00	2.00	1.00	0.3	12.0	14.2	47.6
Minimized electricity	2.27	2.36	1.57	0.3	12.7	14.9	47.6
Minimized LCC	2.18	2.24	1.38	0.3	12.5	14.7	47.6
N							
Conventional tapering	2.00	2.00	1.00	0.2	38.1	40.1	47.6
Optimized tapering	2.00	2.00	1.00	0.2	38.1	40.1	47.6
Minimized electricity	2.21	2.64	2.38	0.1	39.1	41.1	47.5
Minimized LCC	2.09	2.37	1.75	0.2	38.7	40.7	47.5
C							
Conventional tapering	1.00	1.00	1.00	40.5	0	43.1	46.1
Optimized tapering	1.00	1.00	1.00	40.5	0	43.1	46.1
Minimized electricity	1.25	1.40	1.46	40.5	0	43.1	46.0
Minimized LCC	1.19	1.32	1.36	40.5	0	43.1	46.1

Note: All concentrations in $mg\,L^{-1}$.

diffusers increased, the minimum airflow rate to the tank increased correspondingly. When the systems were limited by the minimum airflow rate, the DO levels increased beyond the set points. One such period is depicted in Fig. 5.

In Fig. 6, the electricity usage is shown as a function of the relative number of diffusers. The fraction of time that each of the aerated tanks (Ox1–Ox3) were overaerated, i.e., limited by the minimum airflow rate to the tank, is shown in the same graph. The more diffusers in the system, the higher the fraction of time with elevated DO levels due to loss of down-regulation ability.

For the NDN process, an optimum number of diffusers, in terms of electricity usage, was found to occur with 170% diffusers relative to the reference case. This is a considerably higher number of diffusers than would have been installed based on a conventional aeration system design approach, constrained by the target DO levels. With this design, DO levels above the respective set points occurred 24%, 29%, and 58% of the time in the first, second, and third aerated tanks, respectively. The estimated electricity usage for one year was 233,000 kWh lower than with the aeration system designed by the conventional approach, corresponding to savings of 20%. Increasing the number of diffusers beyond this number was found to increase the electricity usage by leading to too long periods with overaeration (Fig. 6).

The N and C alternatives were also found to have the lowest energy usage with considerably higher number of diffusers than a conventional design approach would suggest. The optimum number of diffusers for the N process was at 190% relative to the reference case, and for the C process it was 230%. The higher optimum relative number of diffusers in the C process was clearly related to the lower oxygen requirement in the absence of nitrification. The potential savings were 20% for the N and C processes as well, although the absolute energy savings were higher for N (329,000 kWh) and lower for C (86,000 kWh) due to higher and lower oxygen requirements, respectively, in these processes. The magnitude of the energy savings were similar or larger than what is typically achieved when implementing more advanced control strategies such as ammonia feedback (Åmand et al. 2013; Åmand and Carlsson 2013; Li et al. 2022).

An optimization of the energy usage will not be accepted if it leads to undue reduction in effluent water quality. For the N and C alternatives, negligible negative effects were observed while increasing the number of diffusers (Table 3). For the NDN process, excessive DO levels may lead to insufficient denitrification because more oxygen is recirculated back to the first anoxic zone. The simulations in the present study suggest that with 170% diffusers and long periods with overaeration up to DO levels of almost 6 $mg\,L^{-1}$, the effluent total nitrogen was only 0.74 $mg\,L^{-1}$ higher than in the reference case operated at the target DO set points (Table 3). This led to an average effluent total nitrogen concentration of 14.9 compared with 14.2 $mg\,L^{-1}$ in the reference case. The reason for this relatively small increase in effluent nitrate was that DO levels increased during periods with low loading (e.g., nighttime, holiday seasons), and these periods also thus exhibited lower demand for denitrification. At higher loading when more nitrate was available for denitrification, such as at typical daytime peaks, the DO levels were controlled at the set points and less oxygen was recirculated to the anoxic tank. Hence, there was ample room to optimize energy usage by increasing the diffuser density without compromising the effluent quality. Furthermore, a spacious design has advantages in improved robustness and resilience toward disturbances and peak loadings as well as future increase in loadings due to population growth.

The potential to counteract the negative impact on nitrogen removal of overaeration was investigated by including a small unaerated zone (DeOx) as an additional volume after the last aerated tank (Ox3). In a set of simulations with varying DeOx volumes, it was found that a DeOx of 500 m^3, corresponding to 4% of the total activated sludge reactor volume, would suffice to reduce the effluent total nitrogen to 14.2 $mg\,L^{-1}$, the same level as without overaeration (Fig. 7). At this volume, the DeOx volume served to reduce the DO concentration recirculated back to the anoxic tank from, on average, 1.6 to 0.6 $mg\,L^{-1}$. Such a volume of a DeOx zone relative to the total activated sludge reactor volume is similar to what is already applied at some nutrient removal WRRFs (Andersson et al. 2016; Ostgaard et al. 1997).

Life-Cycle Cost

While a higher number of diffusers often leads to lower electricity usage and thus lower operating cost, it will at the same time increase the investment costs. To this end, the life-cycle cost for 15 years of operation was assessed (Fig. 8). It was found that the operating costs due to electricity dominated the LCC by 92%–98% independent of process alternative. This was even higher than the 85%–90% that is typical for LCCs of blower investments (Rosso 2018). Thus, the increased investment associated with a higher number of diffusers exhibited a minor influence on the

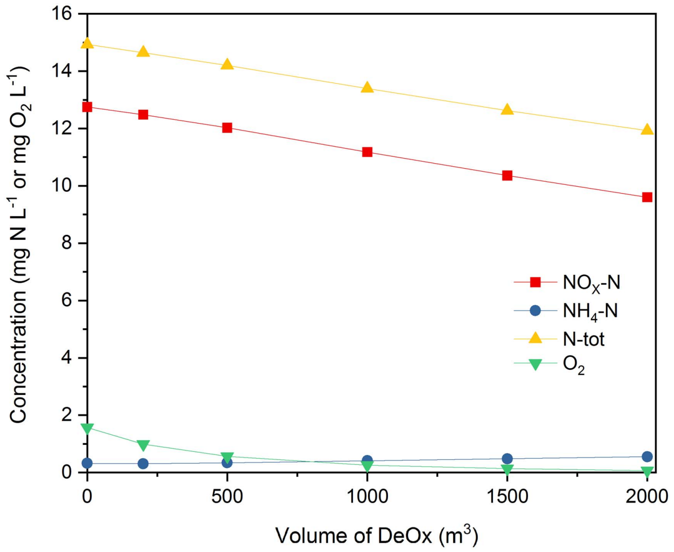

Fig. 7. Influence of a DeOx zone on dissolved oxygen level in the last reactor and on nitrogen effluent concentrations.

optimum diffuser density. Whereas minimum electricity usage occurred at 170% relative number of diffusers for the NDN process, the minimum LCC occurred at 160% diffusers. Similarly for the N and C alternatives, minimum LCC was obtained at slightly lower diffuser densities than minimum electricity usage, namely, 170% and 220%, respectively. Thus, the investment cost of an aeration system has a small impact on the overall economics of aeration because it is overshadowed by the energy cost.

By increasing the number of diffusers relative to the reference cases, the maximum airflow was reduced by around 15%. This would lead to decreased investment costs for blowers and piping systems that were not taken into account in the LCC presented herein but would further enhance the incentive to install a higher number of diffusers. Increased labor costs for installation and maintenance associated with higher number of diffusers were not taken into account, but this effect was expected to be minor. Thus, there can also be clear incentives to retrofit existing aeration tanks for an increased number of diffusers.

Implications and Outlook

The control of DO levels to 1–2 mg L^{-1} in municipal wastewater treatment is widely applied and well established. But according to the results in the present study, the design of an aeration system should allow operation at higher DO levels at low-loaded periods because this could lead to overall lower LCC. This may also require a shift in mindset among WRRF operators, away from a strict focus on minimized DO levels. To the best of our knowledge, this is the first time a systematic evaluation of the influence of diffuser system design on energy efficiency, effluent quality, and life-cycle cost is reported.

These findings also suggest that procurement procedures should be differently set up than what is commonly the case. Rather than specifying a minimum SOR (or minimum AOR with a DO level), procurement would often better be based on minimizing overall LCC. This may lead to periods of elevated DO (at low loading) if this allows an overall better energy efficiency through higher oxygen transfer efficiency.

The oxygen transfer models (Arnell 2016; Juan-Garcia et al. 2018; Schraa et al. 2017) were found to be very useul for the purpose of aiding the design of new aeration systems, resulting in significant energy savings. The aeration model should preferably be formulated such that performance data from suppliers can easily be incorporated into the model. The model presented herein

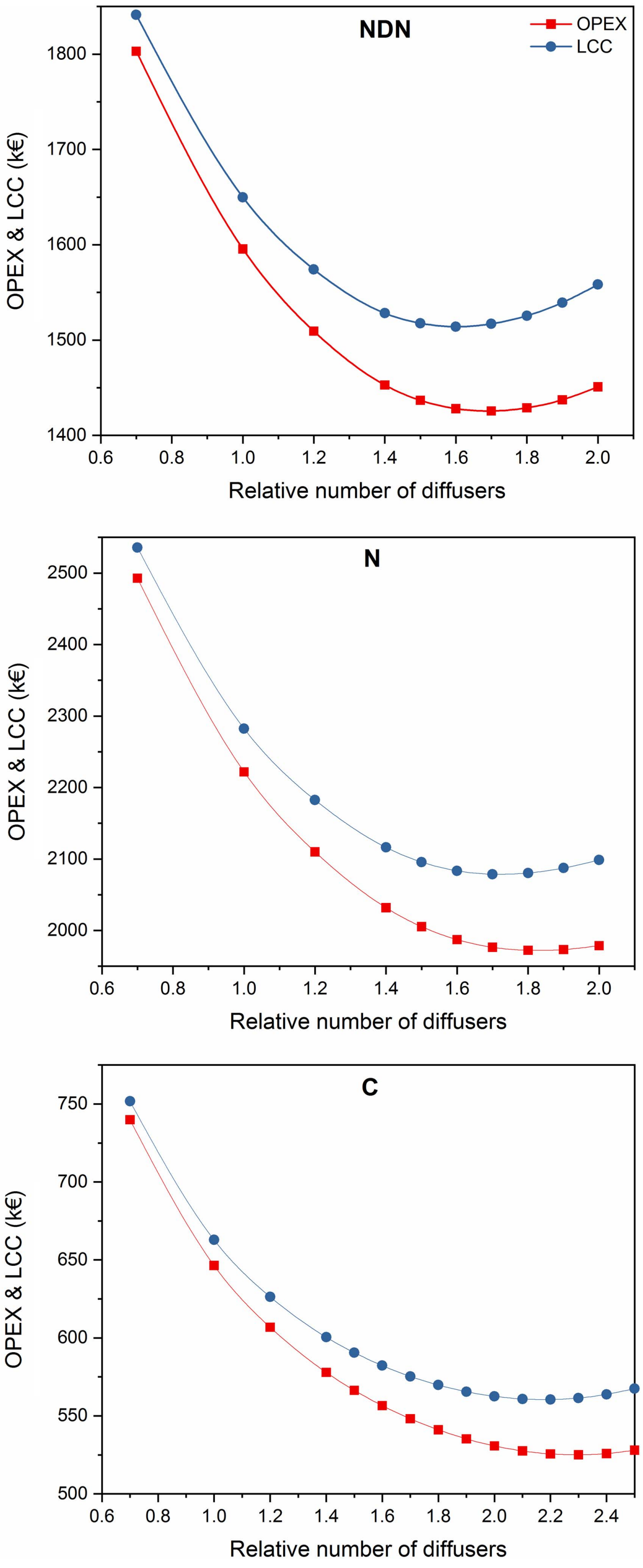

Fig. 8. LCC and operating expenditures of aeration systems as a function of the relative number of diffusers. LCC includes capital and operating expenditures for 15 years of operation.

can easily be adapted for aeration systems containing other types of diffusers such as other disc diffusers, panels, strips, or tubes. This would be done by incorporating the performance data in terms of the corresponding SOTE profile. The model can also be readily adapted for other process configurations such as other tanks in series designs and step feed.

In the present study, a constant specific energy usage was applied for the blowers. This approach was considered sufficient for the current scope and facilitated a general comparison. However, when modeling an existing WRRF, it could be preferrable to include the dynamics of blowers and piping systems (Amaral et al. 2017; Juan-Garcia et al. 2018; Schraa et al. 2017) to improve the realism and the accuracy of electricity usage estimations. Additionally, the dynamics of electricity cost should be considered because it has been shown that reductions in power use does not always lead to lower cost (Aymerich et al. 2015). Time-varying power tariffs can be included in modeling for comprehensive evaluation in specific cases.

An alternative to operating the system at elevated DO levels would be to operate with intermittent aeration (Balku 2007; Dotro et al. 2011; Hanhan et al. 2011). In this way, aeration can be turned off during low-loaded periods. However, the possibility of operating the aeration intermittently depends on several features of the aeration system such as number of zones, number and types of blowers, and mixing.

Conclusions

The use of modeling in the design of new aeration diffuser systems has a great potential to contribute to decreased electricity usage and life-cycle cost. Interactions between aeration design and treatment process performance can be evaluated to reach an overall optimization of energy, effluent quality, and cost. It was demonstrated that increasing the number of diffusers significantly beyond the numbers required to maintain target DO levels leads to higher energy efficiency and lower life-cycle cost. Even though with such a high number of diffusers, the system was limited by the minimum airflow rate (leading to elevated DO levels) around 30% of the time, the lower average airflow rate per diffuser was an advantage because of higher oxygen transfer efficiency. For processes with nitrification, an optimized tapering of the diffuser system was found to be steeper than suggested by rules of thumb commonly applied in practice. An aeration system optimized by simulations was found to, independently of process configuration, exhibit 20% lower electricity usage and 16%–18% lower life-cycle cost compared with a system designed based on a conventional approach.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

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Notation

The following symbols are used in this paper:

A = dimensionless constant;
B = dimensionless constant;
D = dimensionless constant;
dd = diffuser density ($\mathrm{m^2\,m^{-2}}$);
E = dimensionless constant;
m = dimensionless constant;
Q_{air} = airflow rate ($\mathrm{Nm^3\,h^{-1}}$);
q_{diff} = airflow rate per diffuser ($\mathrm{Nm^3\,h^{-1}}$);
SOTE_i = SOTE at $q_{\mathrm{diff}} = i\,\mathrm{Nm^3\,h^{-1}}$ ($\mathrm{gNm^{-3}\,m^{-1}}$); and
α = correction factor for oxygen transfer in process water (dimensionless).

Supplemental Materials

Figs. S1–S4, Table S1, and additional text are available online in the ASCE Library (www.ascelibrary.org).

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