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Model-based optimisation of the biological performance of a sidestream MBR

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Abstract A model-based optimisation of the operation in view of the biological performance in terms of nitrogen (N) and phosphorus (P) removal of a pilot-scale side-stream MBR has been performed by means of a two-tier scenario analysis. The methodology uses two different scenario analyses to simulate the effect of three degrees of freedom in the MBR system: (1) DO set-point in the aerobic reactor, (2) sludge residence time and (3) internal recirculation rate. The scenarios are simulated using a calibrated ASM2d MBR model. Effluent quality, in terms of nitrate, ammonia and phosphate, is used to select the best scenario. It proved to be a compromise between nitrogen and phosphorus removal as these are linked. A 42% reduction in ammonium and a 32% reduction in nitrate concentration were achieved. Phosphate removal is partly sacrificed (39% increase) compared to the standard operation.

Keywords ASM2d; modelling; MBR; nutrient removal; optimisation; scenario analysis

Introduction

Constraints on the effluent quality demanded from wastewater treatment plants (WWTPs) are becoming more stringent in view of the implementation of the EU Water Framework Directive. To meet these constraints, the performance of the currently used biological nutrient removing technologies needs to be improved considerably. In the case of membrane bioreactors (MBR), the effluent suspended solids criterion is not an issue as it is removed to a great extent by the membrane. However, the effluent nitrogen and phosphorus criteria are usually the most challenging to comply with. These criteria are mostly met by developing an optimal configuration and operational strategy for the MBR system under study.

The objective of this study is to improve the MBR performance in terms of effluent quality using a systematic approach relying on a model-based optimization methodology. During the last two decades mathematical models have been developed for the conventional activated sludge process, resulting in a suite of models known as the Activated Sludge Models (ASM) (Henze *et al.*, 2000). These models have been successfully applied for various purposes ranging from capacity evaluation to optimization of operation and controller development for activated sludge systems (Demuynck *et al.*, 1994; Hvala *et al.*, 2001; Artan *et al.*, 2002; Sin *et al.*, 2004; Corominas *et al.*, 2006). These models can also be applied for the description of the biological processes in MBR systems, since the underlying biological processes are similar (Jiang *et al.*, 2005; Jiang, 2007). One advantage of using a model-based approach is that the number of scenarios that can be evaluated increases considerably, e.g. from 5–6 scenarios typically tested in experimental approaches to thousands as tested using models (e.g. Sin *et al.*, 2004).

The model-based optimization methodology used in this study is adopted from Sin *et al.* (2004) and is shown in Figure 1. In this contribution, we evaluate the methodology for improving the effluent quality of a pilot-scale side stream MBR performing COD, N and P

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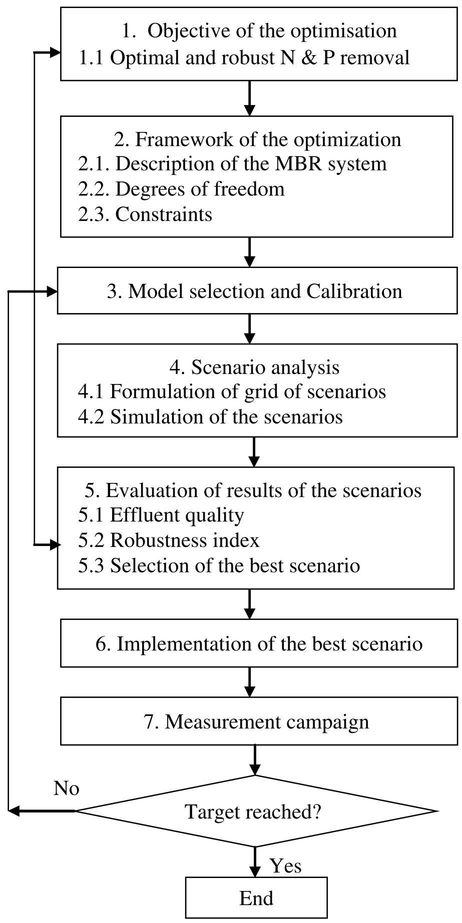

Figure 1 A systematic methodology for the model-based optimisation of MBR systems (after Sin *et al.*, 2004)

removal. The methodology is based on running a multitude of scenarios to simulate the effect of different operational parameters (in the jargon of optimization, *degrees of freedom*) on the MBR performance. In this optimization study, we focused on the following operational parameters: DO set-point (DOsp) in the aerobic phase, the sludge residence time (SRT) and the internal recirculation rate (Qint) of sludge from the aerobic/anoxic to the anaerobic compartment. The ASM2d model was chosen to describe the biological processes occurring in the pilot-scale MBR. In what follows, the pilot-scale MBR system under study is described, the calibrated model is introduced and the optimisation methodology is illustrated. Subsequently, the results of the optimisation exercise are shown and discussed.

Materials and methods

Pilot-scale MBR

The pilot-scale MBR consists of an anaerobic compartment (8 l), an aerobic/anoxic compartment (17 l) and a membrane loop (3.8 l) and is operated following a UCT type configuration treating a synthetic influent with a composition mimicking a domestic wastewater. The MBR, automated for data acquisition and control, is operated in a 40 min aerobic/anoxic cycle mode. Each cycle consists of 17 min aerobic and 23 min anoxic conditions. During the first 11 minutes of the anoxic phase, the sludge is mixed within the aerobic/anoxic compartment. During the last 12 minutes of the anoxic phase, the sludge from the aerobic/anoxic compartment is recycled to the anaerobic compartment since it then contains the lowest concentration of nitrate. Biomass separation is achieved by a tubular PVDF membrane module with a surface area of 0.17 m^2 (Norit, XF, The Netherlands) and the fouling is controlled by a periodical backwash operating at a 475 seconds cycle mode. Each cycle, consisting of 450 seconds of filtration and 18 seconds of backwashing, is followed by a short 7 seconds relaxation period during which the permeate pump is stopped. A detailed description of the MBR is given in Jiang *et al.* (2007).

ASM2d MBR model

The lab-scale MBR was modelled using ASM2d (Henze *et al.*, 2000). All modelling and simulations were performed using WEST® (MOSTforWater, NV, Kortrijk, Belgium) a powerful modelling and simulation software platform designed for the modelling of WWTP (Vanhooren *et al.*, 2003).

The ASM2d MBR model was calibrated using averaged long-term (3 months) daily monitoring data (NH_4, NO_3, PO_4 and TSS) and data of a detailed measurement campaign (NH_4-N, NO_3-N and PO_4-P measurements in the anaerobic and aerobic/anoxic compartments) of one cycle (40'). The discussion of this calibration is beyond the scope of this contribution. Results of the calibrated model are shown in Figure 2, merely for the reader to asses the model quality. For details on the entire calibration process, the reader is referred to Jiang *et al.* (2007).

Optimization methodology

The optimization methodology is shown in Figure 1. The first step is the definition of the objective of the optimisation study that will serve as the main criterion in selecting the optimal operational strategy for the system. The second step defines the framework of the optimisation and included the description of the system, and the definition of the degrees of freedom and constraints of the system. This is followed by the model selection and calibration step to obtain a realistic model of the MBR system. In the fourth step, different levels of scenarios based on the above degrees of freedom and constraints are formulated and simulated using the calibrated model. In the following step (5), all simulated scenarios are thoroughly evaluated using effluent quality. A best (or optimal) scenario is selected that meets the defined objective(s). This scenario is then to be implemented in the system (step 6) and evaluated after three sludge ages (for the changes to take effect and a transient to fade out) by both monitoring the effluent quality of the lab-scale MBR on a daily basis and also by performing a detailed measurement campaign, i.e. step 7. The methodology can be repeated if the target has not been reached, starting from step 3.

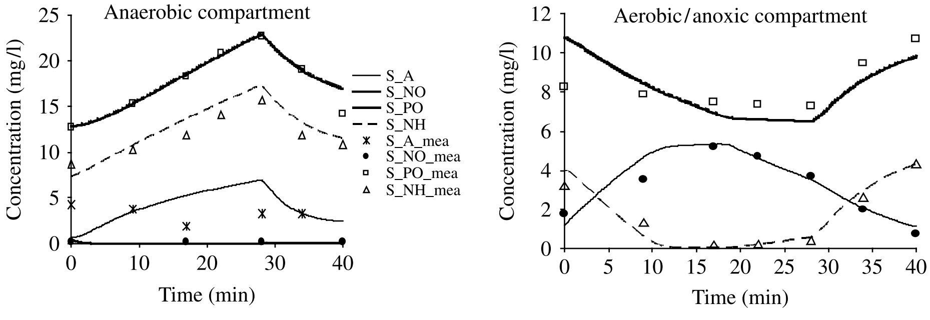

Figure 2 Results of the calibration with the comparison of the simulation and measurements in the anaerobic and aerobic/anoxic compartment during 1 cycle (Jiang *et al.*, 2007)

Scenario analysis

The calibrated model is used in a scenario analysis to evaluate the effect of the three chosen operational parameters of the MBR: the DOsp in the aerobic phase, the sludge residence time (SRT) and the internal recirculation rate (Qint) (see Table 1). For a thorough analysis of individual and combined effects of parameters on the performance of the MBR, three levels of scenario analysis can be adopted: (1) one parameter is varied, while the other two parameters are fixed to the reference values (2) two parameters are co-varied, while one parameter is fixed, and (3) all three parameters are co-varied at the same time (grid design). So far, only the first 2 levels have been applied in this work. The considered parameter ranges are shown in Table 1. All scenarios are simulated for three times the corresponding SRT. This is needed to ensure stable operation and, hence, a reliable comparison between different scenarios.

The simulation results from the scenarios were evaluated using the effluent quality for COD, N and P removal. The parameter range considered in the second level of scenarios was decided based on the interpretation of the first level results (see below). The modelling and simulation platform WEST® that was used provides a scenario analysis module.

Results

First level of scenario analysis

The results of the first level scenario analysis are shown in Figures 2–4. In total 36 scenarios were simulated.

Increasing the internal recirculation rate (Qint) results in a decrease of the effluent nitrate concentration. However, this happens at the expense of phosphorus removal, which deteriorates slightly. It is important to note that beyond a certain point (i.e. 1.728 m^3/l) further increasing of Qint did not result in a further improvement of nitrate removal. This may be due to a limited amount of readily biodegradable COD which is not sufficient to denitrify the remaining nitrate in the anaerobic tank. Increasing Qint did not have a significant effect on the COD and ammonia removal efficiency.

Figure 4 reveals that an increasing DOsp slightly increases the effluent concentrations of nitrate and phosphorus, whereas the efficiency of COD and ammonia removal remain almost unchanged at a satisfactory level. A DOsp below 0.5 causes a large increase particularly in the effluent concentration for ammonia, indicating washout of nitrifiers. This is not surprising since it is known that the affinity constant of nitrifiers for oxygen is quite high, meaning that lower oxygen levels will decrease the observed growth rate of nitrifiers.

The DOsp is observed to affect the phosphorus removal in two distinctive ways. First, when DO is too low (e.g. 0.25 mg/l), biological phosphorus removal collapses because

Table 1 Levels of scenarios to simulate the single and simultaneous effect of three degrees freedom on the MBR performance

Levels	SRT (days)	DOsp (mg/l)	Qint (m^3/d)	Total no. scenarios
1	[5, 10, 15, 17.55(1), 20, 25, 30, 45, 60]	[0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75, 2(1), 2.25, 2.5, 2.75, 3, 3.25, 3.5, 3.75, 4, 4.25, 4.5, 4.75, 5]	[0.264, 0.423, 0.864(1), 1.728, 2.592, 3.456, 4.32]	36
2	[7.5, 10, 12.5, 15, 17.55(1), 20, 22.5, 25]	[0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75, 2(1)]	[0.264, 0.523, 0.781, 1.040, 1.229, 1.557, 1.816, 2.075, 2.333, 2.592]	224

(1) Reference values

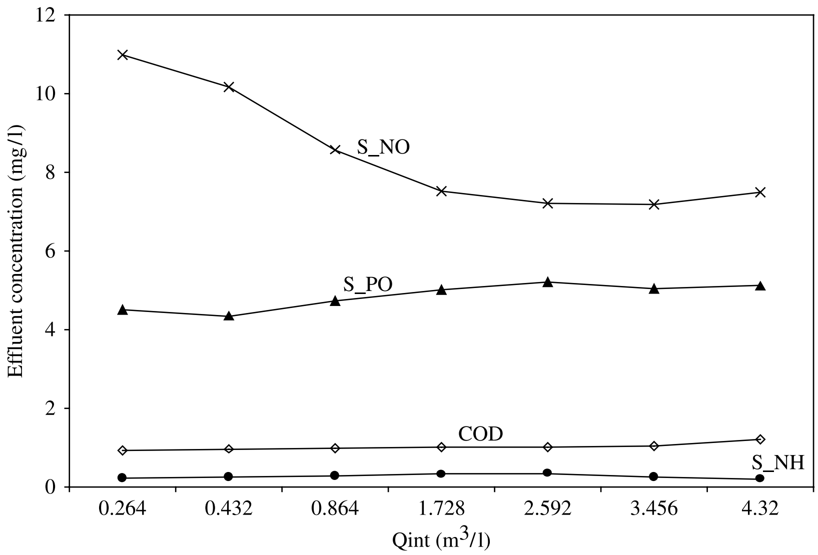

Figure 3 Effluent phosphorus, nitrate, ammonia and COD concentrations for level 1 scenario analysis with varying Qint (SRT = 17.5d and DOsp = 2 mg/l)

polyphosphate accumulating organisms (PAOs) are unable to fully take up the released phosphorus in the aerobic phase, since the oxygen level is controlled below or close to the oxygen affinity constant of PAOs (leading to almost 50% decrease in the P-uptake rate and washout of PAOs). Second, the optimal P-removal is achieved at a DOsp equal to 0.5 mg/l, which also corresponds to the minimum nitrate concentration achieved in the MBR. Higher DOsp values lead to a gradual decrease in P-removal caused by the well known nitrate effect. Also nitrate levels gradually increase as increased oxygen hampers the extent of simultaneous nitrification and denitrification (SND) in the system. Overall, the extent of phosphorus removal depends on the level of nitrate in the MBR (see Figure 4).

Figure 5 shows that increased SRTs result in a decreased P- and COD-removal. However, both ammonia and nitrate removal improved. The latter is understandable since

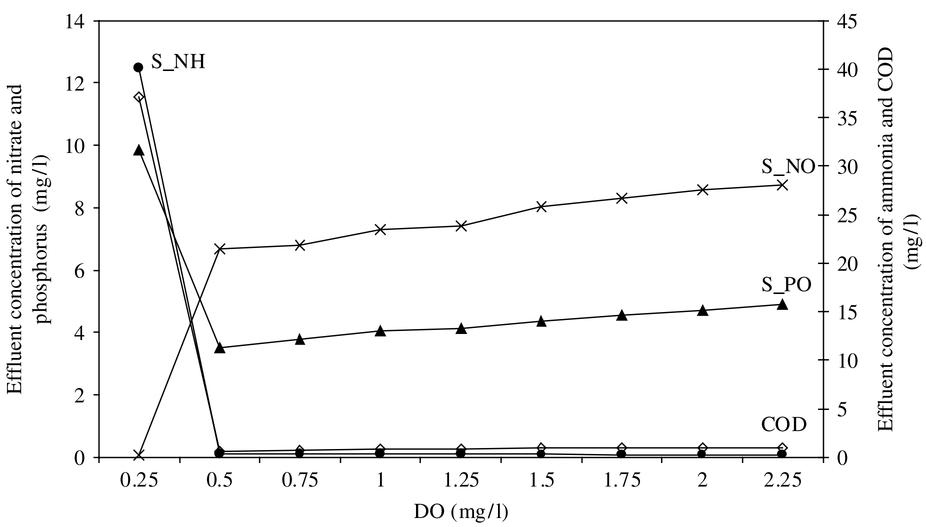

Figure 4 Effluent phosphorus, nitrate, ammonia and COD concentrations for level 1 scenario analysis with varying DOsp (SRT = 17.5d and Qint = 0.864m^3/d)

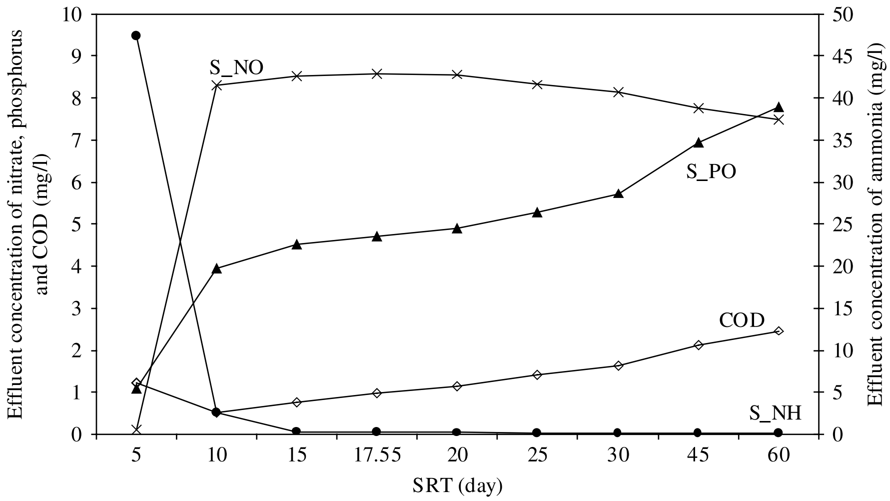

Figure 5 Effluent phosphorus, nitrate, ammonia and COD concentrations for level 1 scenario analysis with varying SRT (DO = 2 mg/l and Qint = 0.864m^3/d)

an increasing SRT leads to a higher biomass concentration in the system. This eventually leads to a higher anoxic endogenous respiration and, hence, more nitrate removal.

Concerning the SRT effect on P-removal, one also notices that increasing SRT beyond 25d has a strong negative effect (note the increase in slope beyond 25d). This negative effect of high SRTs stems from the P-release and P-uptake mechanism, which depends in a non-linear way on the concentration of the intracellular storage products, polyphosphate and PHA in PAOs. Under fixed influent organic loading, an increase in the SRT has a dilution effect on the intracellular products. Subsequently, this leads to a reduction in the P-release and P-uptake rates of PAOs, with as a result bad P-removal (Smolders *et al.*, 1995). Finally, it should be noted that the SRT of 10d is a point of minimum and maximum for COD and nitrate concentration respectively. Ammonia and nitrate concentrations largely increase and decrease respectively with SRT values lower than 10d mainly due to wash-out effects on the nitrifiers and PAOs.

Second level of scenario analysis

The results of the second level scenario analysis are shown in Figure 6. In total 224 scenarios were simulated. The advantage of the second level scenario analysis is that these trends can be evaluated quantitatively at different settings of another degree of freedom. Based on the fact that most of the scenarios analysed resulted in high COD and ammonia removal efficiencies, the discussion is limited to the phosphorus and nitrate effluent concentration plots only. The same trends as in the first level scenario analysis can be observed.

Discussion

Some general elements are observed from the detailed analysis of the two levels of scenario analysis.

- *Qint:* Increasing the recirculation flow rate decreases the effluent concentration of nitrate. This is because a high internal recirculation recycles more nitrate back to the anaerobic tank from the aerobic/anoxic tank, which in turn enhances overall nitrate removal. As mentioned above, this enhanced nitrate removal happens at the expense of phosphorus removal, due to the increased consumption of influent VFAs by the denitrifying heterotrophs.

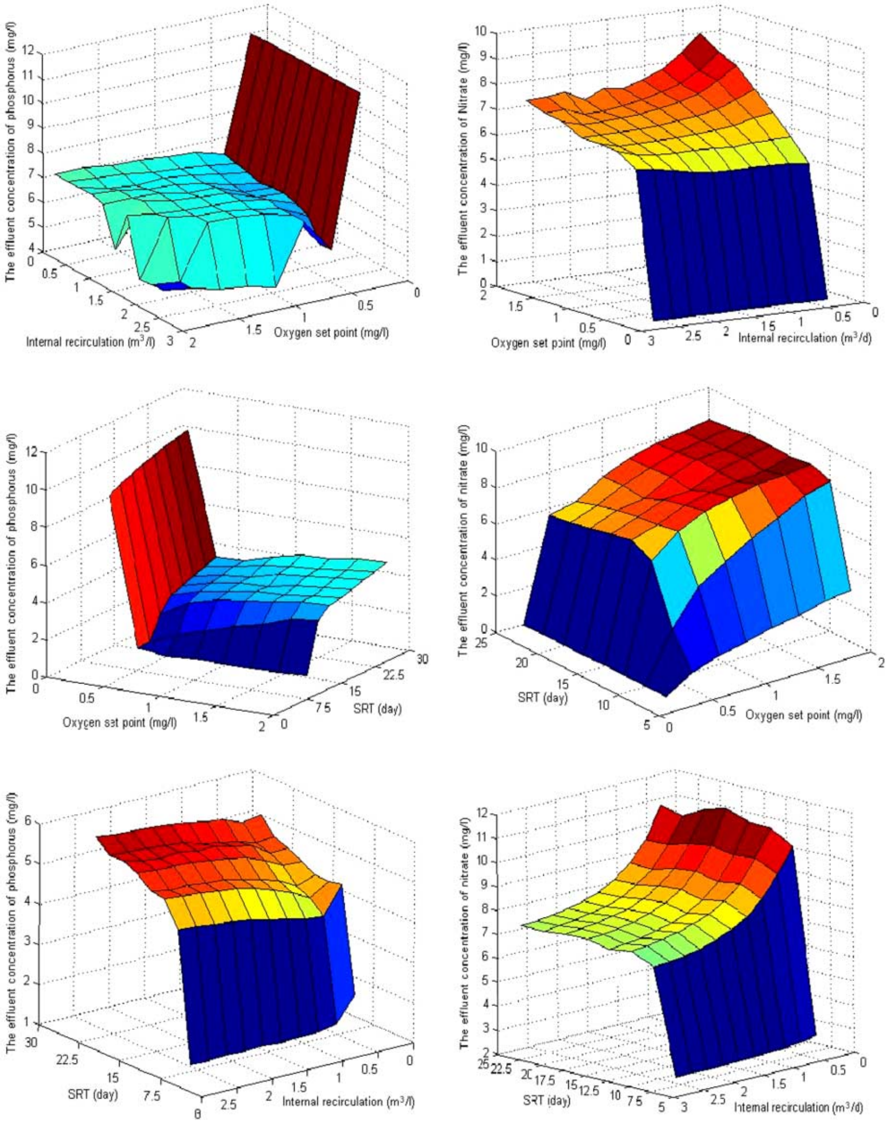

Figure 6 Effluent phosphorous (left) and nitrate (right) concentration for the second level scenario analysis: fuxed SRT (top), fixed Qint (middle), fixed DOsp (bottom)

- *DOsp:* Increasing the DOsp is only efficient for ammonia removal, while it has a negative effect on both phosphorus and nitrate removal because the simultaneous nitrification and denitrification decreases in the aerobic tank.
- *SRT*: Too low SRTs are bad for P and N removal as it causes washout of nitrifiers and PAOs from the system. High SRTs are good for the ammonium removal efficiency up to a certain point (15 days in this study) where ammonia removal efficiency is no longer affected by an increased SRT. A high SRT is observed to elevate the COD effluent concentration, probably due to an increased decay of biomass (as SRT increases) and the increased level of hydrolysis products being produced and can end up in the effluent. As mentioned earlier, too high SRTs cause a decrease in the efficiency of phosphorus removal, mainly because of the inverse relationship between SRT and the dynamics of P-storage and P-release (Smolders *et al.*, 1995).

Table 2 Optimal operational strategy obtained from the model-based optimisation methodology

	SRT d	Qint m^3/d	DO mg/l	Nitrate mg/l	Phosphate mg/l	Ammonia mg/l	COD mg/l
Reference	17.55	0.864	2.00	8.57	4.72	0.28	0.98
Best scenario	17.55	1.04	0.75	5.84	6.58	0.16	2.20

Determining the optimal scenario for nutrient removal

Based on the previous discussion, it can be concluded that (1) DOsp should be kept low, (2) SRT should be intermediate and (3) Qint should be intermediate as well. Under given conditions and constraints (e.g. fixed organic loading), it seems impossible to find a scenario (among 260) that provides a phosphorus removal comparable to the reference case without drastically sacrificing on the N removal. Having this in mind, the best scenario was chosen as the one providing the following criteria: (i) complete nitrification ($NH_4 < 0.2$ mgN/l) and (ii) optimal denitrification and P-removal (equal weight for the effluent nitrate and phosphate). This led to the selection of the scenario given in Table 2. It results in a 42% decrease in ammonium and a 32% reduction in nitrate concentration. However, P-removal is partly sacrificed (39% increase).

The optimisation suggests to maximise simultaneous nitrification and denitrification (SND) in the system as a means to optimise P and N removal. For our particular system, lowering the oxygen set-point appears to provide this objective (under the optimal SRT and Qint). This observation is very similar to the conclusions of the model-based optimisation of other systems, particularly with low organic COD/P ratios (Sin *et al.*, 2004, Corominas *et al.*, 2006). However, in traditional activated sludge systems with gravity settling, low oxygen is known to be a common cause of filamentous bulking and bad settling (among many other factors), and hence it is often avoided (Sin *et al.*, 2006; Comas *et al.*, 2006). For the MBR systems, we anticipate that this should not be a concern since the solid-liquid separation is performed with ultrafiltration. Another drawback of low DOsp is possible accumulation of nitrite. This was not included in the model and can not be verified at this point. It will be ignored at this stage. The obtained optimal scenario will now be implemented and tested in the pilot scale MBR and evaluated.

Conclusions

The improvement of nutrient removal of a side stream MBR was investigated using a model-based approach. Individual as well as combined impacts of three degrees of freedom (DOsp in aerobic reactor, Qint and SRT) were investigated using scenario analysis. It was found that:

- too low DO causes washout of nitrifiers and PAOs, while increasing DOsp too much negatively influenced both nitrate and phosphate removal;
- low SRTs result in washout of nitrifiers whereas too high values had a negative effect on phosphate removal;
- high Qint has a positive effect on nitrate removal, but deteriorates P-removal. However, too high values do not have a significant effect on N and P removal.

The optimal scenario was found as a compromise between N and P removal, which suggested a 32% decrease in nitrate concentration and a 42% decrease in ammonia concentration. Phosphate, however, had to be sacrificed to achieve this high nitrogen removal performance (39% increase).

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