Optimal but robust N and P removal in SBRs: a model-based systematic study of operation scenarios

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Abstract A systematic approach to determine the optimal operation strategy for nitrogen (N) and phosphorus (P) removal of sequencing batch reactors (SBRs) has been developed and applied successfully to a lab-scale SBR. The methodology developed is based on using a grid of possible scenarios to simulate the effect of the key degrees of freedom in the SBR system. The grid of scenarios is simulated using a calibrated ASM2dN model developed and calibrated in a previous study. Effluent quality in combination with a robustness index for each of the scenarios is used to select the best scenario. With the best scenario, it is possible to improve/increase the current performance of the SBR system by around 54% and 74% for N and P removal respectively.

Keywords Models; nutrient removal; optimisation; SBR; sensitivity analysis

Introduction

Sequencing batch reactor (SBR) technology for nutrient removal has received worldwide attention from the wastewater treatment community in view of the ever-stricter demands on effluent discharge quality (Wilderer *et al*., 2001). Both nitrogen and phosphorus removal from wastewaters have been demonstrated successfully at lab-scale and full-scale installations (Manning and Irvin, 1985; Furumai *et al*., 1999; Keller *et al*., 2001; Wilderer *et al*., 2001; Demoulin *et al*., 2001).

Being flexible to operate, a myriad of operation strategies have been developed to optimise nutrient removal performance in SBRs (Wilderer *et al*., 2001). The operational strategies have usually been tested experimentally at lab-scale (Manning and Irving, 1985; Lin and Jing, 2001; Hvala *et al*., 2001). Increasingly, mathematical models (e.g. ASM1 for N-removal and ASM2d for N and P-removal) have been used for developing and testing optimal operation strategies for biological N and P removal (Demuynck *et al*., 1994; Hvala *et al*., 2001; Artan *et al*., 2002). The main parameters that have been demonstrated in the above-mentioned studies to impose a major effect on the N- and P-removal capacity of the SBRs until now are the step-feed of the influent (Hvala *et al*., 2001; Lin and Jing, 2001), intermittent aeration (Demuynck *et al*., 1994; Demoulin *et al*., 2001), oxygen set-point in the aerobic react-phase to regulate the extent of simultaneous nitrification and denitrification in the SBR (Munch *et al*., 1996; Artan *et al*., 2002) and length of anaerobic, aerobic and anoxic phases (Wilderer *et al*., 2001; Artan *et al*., 2002).

The objective of this study is to develop a systematic approach to determine the best operational strategy for the optimisation of the N- and P-removal performance of the SBR technology. The methodology is based on using a grid of scenarios to simulate the effect of different degrees of freedom on the SBR system. The scenarios, i.e. the operating strategies, formulated using realistic combinations of the significant degrees of freedom tested so far elsewhere, are simulated using the ASM2dN model developed and calibrated in a previous study (Insel *et al*., 2003). Criteria for the selection of the best scenario are proposed based not only on the effluent quality but also the robustness against deviations of the

modelled reality (Vanrolleghem and Gillot, 2002). Finally, the systematic approach has been applied to a lab-scale SBR. Particular attention is given to the oxygen set-point in the aerobic react phase on the overall performance of the SBR system.

Material and methods

A lab-scale sequencing batch reactor (SBR) with a working volume of 80 L was seeded with sludge from the Ossemeersen WWTP (Ghent, Belgium). It is operated in a 6 h cycle mode, each cycle consisting of 60 min fill/anaerobic, 150 min aerobic, 60 min anoxic, 30 min aerobic and 60 settling/draw phases. A synthetic sewage is used as SBR influent, which was shown to mimic a real pre-settled domestic wastewater. The detailed description of the SBR is given in Insel *et al.* (2003). Simulations were performed using WEST® (Hemmis, Belgium) a dedicated software for the modelling of WWTP that contains a scenario analysis module (Vanhooren *et al.*, 2003).

A systematic methodology for the optimisation of SBR systems

The model-based optimisation of the lab-scale SBR is performed following the methodology described in Figure 1.
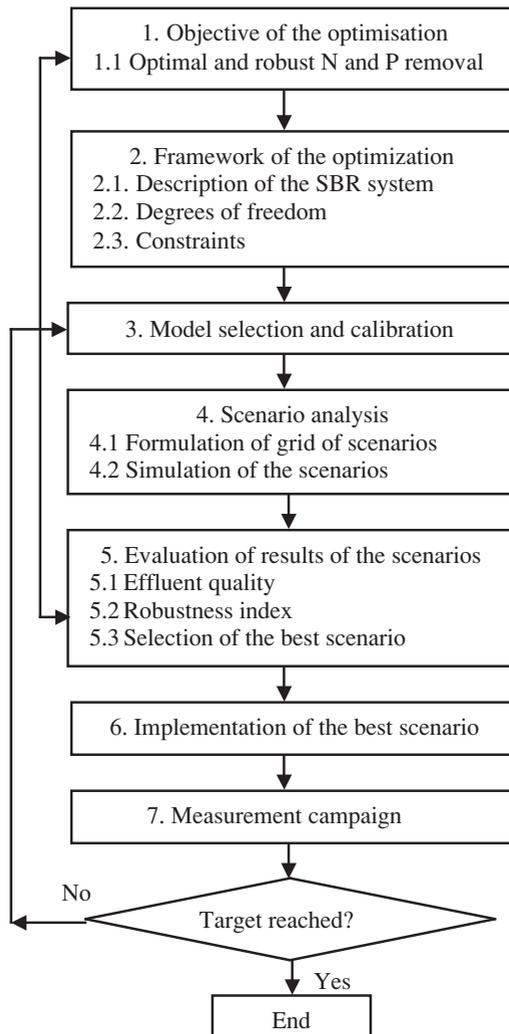
Figure 1 A systematic methodology for the model-based optimisation of SBR systems

The first step is the definition of the objective of the optimisation study. This will determine the required calibration accuracy and serve as the main criterion in selecting the optimal operation strategy for the system. The second step is the description of the system including the definition of the degrees of freedom and constraints of the system, which will determine the framework of the optimisation. This is followed by the model selection and calibration step to obtain a realistic model-based description of the SBR system. Following this step, i.e. step 4, a grid of scenarios based on the above degrees of freedom and constraints is formulated and simulated using the calibrated model. The results of the scenarios are evaluated in the following step, i.e. step 5. The analysis of the results is expected to provide in-depth insight into the operating scheme of the SBR system. In this step, the optimal scenario is chosen considering the objective of the optimisation. Two criteria are proposed for this purpose: the effluent quality and the robustness of the system to deviations of the modelled system (Vanrolleghem and Gillot, 2002). Afterwards, the best scenario should be implemented to the SBR system. The last step, i.e. step 7, is to check if the objective of the optimisation is reached. To this aim, a measurement campaign should be carried out after the SBR system reaches a new steady state. If the SBR performance under the newly implemented operation conditions is not satisfactory, the procedure should be iterated starting from step 3.

Results and discussion: application of the systematic methodology to a lab-scale SBR

1. Objective of the optimisation

In this study, the objective of the optimisation is to find an optimal and robust SBR operation scenario that achieves the best possible effluent quality with respect to N and P removal under given physical boundary and influent characteristics.

2. The framework for the SBR optimisation: degrees of freedom and constraint

Being flexible systems to operate, SBR systems offer a large number of operating variables to be optimised. Ideally, all possible operating variables should be used in the optimisation of the SBR system. However, the number of the degrees of freedom that can be selected must be limited due to the resulting overhigh computational demand (in this study, simulation of one scenario takes on average 25 min with a 1 GHz Pentium III processor). In this study, based on a survey of the relevant literature (see the introduction) and a preliminary model-based analysis of the system (see Insel et $al.$, 2003), the following degrees of freedom were identified and used for the SBR optimisation: (1) oxygen set-point (S_O-sp) in the aerobic react phase, (2) length of the anaerobic phase (T_{ANB}), (3) length of the reaction (aerobic and anoxic) phase (T_R i.e. $T_{AER} + T_{ANX}$), (4) step-feed of the influent organic load ($V_{step-feed}$) and (5) intermittent aeration frequency (IAF) which is explained below.

The constraints of the optimisation study stem from several reasons including the lower and upper boundaries of the degrees of freedom, the physical boundary of the SBR (e.g. maximum volume of the SBR, influent pump capacity etc.), and the priorities of the objective of the optimisation. In this study, the solids retention time (SRT) (10 d), hydraulic retention time (HRT) (12 h), the volumetric exchange ratio, i.e. the ratio of the fill volume to the maximum volume of the reactor (0.5), and the total cycle time (360 min) are fixed. Further, the mass transfer coefficient for oxygen (K_La) is fixed to a sufficiently high value (500 d^{-1}) to ensure the oxygen set-point can be maintained effectively with on/off control. The last aerobic react phase is fixed to 30 min to strip the nitrogen gas entrapped in the flocs and to polish the effluent prior to discharge to the receiving water. The minimum anaerobic time is set to 60 min based on preliminary simulation results with the SBR model. The length of the settling/draw phase is also fixed to its design value (60 min) as this incorporates a safety margin to provide sufficient settling time in case of a sludge bulking event.

3. Model selection and calibration

From the dynamic ammonium and nitrate trends in the SBR, it was observed that the degradation of organic nitrogen (i.e. hydrolysis and ammonification) is the rate limiting-step in the overall nitrogen turnover in the SBR (Insel *et al.*, 2003). This was probably due to the high fraction of organic nitrogen present in the influent (ca. 95%), which is not typical for domestic wastewaters for which ASM2d is valid. As a result, the ASM2d model had to be extended with a hydrolysis process for the entrapped organic nitrogen (ASM1) to adequately describe the dynamic N and P trends in the SBR. The calibration of the so-called ASM2dN model is given in Insel *et al.* (2003).

4. Scenario analysis: formulation and simulation of grid of scenarios

A grid of scenarios considering the degrees of freedom and the constraints of the system mentioned above was formulated as a full-factorial experimental design (Table 1). The IAF (Table 1) refers to the number of aerobic and anoxic sequences/sub-phases during the reaction phase excluding the last aerobic period. For instance, IAF 2 means that there are 2 aerobic and 2 anoxic (in total 4) sub-phases in the react phase (see Figure 2B). In the implementation of the intermittent aeration for the SBR model (see Figure 2), the length of the total aerobic react phase (T_{AER}) is divided equally by the number of aeration sub-phases, i.e. 1, 2, 4 and 8. For instance, when the aeration frequency is equal to 2, the length of each aerobic sequence is equal to the length of the total aerobic react phase divided by 2, i.e. $T_{AER}/2$. In the same way, the length of the anoxic sequence is equal to the total length of the anoxic-react phase (T_{ANX}) by 2, i.e. $T_{ANX}/2$. Further, the step-feed volume is partitioned equally between the anoxic sequences except for the IAF 8 where some of the sub-phases do not receive any influent COD.

The amount of influent fed to the anaerobic phase is calculated straightforwardly by subtracting the step-feed volume from the total fill volume ($V_{fill} - V_{step-feed}$). Moreover, the filling time of the SBR cycle depends on the influent feed volume (the influent pump flowrate is fixed to 0.96 m³/d). Therefore the filling time is 60 min, 52.5 min and 45 min for 40 L, 35 L and 30 L influent volumes, respectively. The length of the anaerobic phase (T_{ANB}) is chosen to range between 60 and 80 min. The aerobic period of the reaction phase (T_{AER}) (excluding the last aerobic phase) ranges from 130 to 150 min. Note that the sum of the lengths of anaerobic (T_{ANB}), aerobic (T_{AER}) and the anoxic (T_{ANX}) phases is constrained to 270 min which means that the length of the anoxic phase (T_{ANX}) is also varying for each combination of aerobic and anaerobic durations. The combination of these degrees of freedom under the above-mentioned constraints results in 648 scenarios, which is expected to be sufficient to provide significant insight into the optimal operational scheme for the SBR system. In this way, the optimal scenario of the SBR operation can be searched using the predefined criteria.
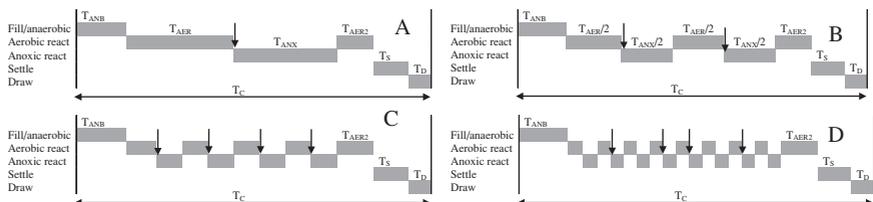
Figure 2 Implementation of IAF with step-feed options to anoxic sub-phases. The arrow indicates the step feed instants. SBR with IAF 1 (A), IAF 2 (B), IAF 4 (C) and IAF 8 (D)

Table 1 Grid of scenarios to simulate the effect of key degrees of freedom on the SBR system

Scenario ID IAF	S_O-sp (mgO$_2$/l)	Degrees of freedom (d.f.) $V_{step-feed}$ (L)	T_{ANB} (min)	T_{AER} (min)	Total no. scenarios
1	[0.2, 0.4, 0.6, 0.8, 1,2]	[0,5,10]	[60,70,80]	[130,140,150]	162
2	[0.2, 0.4, 0.6, 0.8, 1,2]	[0,5,10]	[60,70,80]	[130,140,150]	162
4	[0.2, 0.4, 0.6, 0.8, 1,2]	[0,5,10]	[60,70,80]	[130,140,150]	162
8	[0.2, 0.4, 0.6, 0.8, 1,2]	[0,5,10]	[60,70,80]	[130,140,150]	162

5. Evaluation of the scenario analysis results

5.1 Effluent quality. The grid of scenarios presented in Table 1 is simulated for 30 days, equal to three times the system SRT. The steady-state results of the SBR system in each scenario are then recorded, resulting in a huge amount of data. The scenarios are compared in order to find the best scenario according to the predefined criteria, which are the minimum concentrations of NH_4, NO_3 and PO_4 in the effluent (Table 2). Note that total nitrogen (TN) is the sum of NH_4 and NO_3 in the effluent.

The scenario analysis results (SCA) indicate that the best system performance for either N- or P-removal is obtained under different operating conditions. The best system performance for N can provide additional 10.62 mg N/l removal (see Table 2 with IAF 8) which means a 57% improvement compared to the existing performance. On the other hand, the best P-removal performance is obtained under IAF1 providing additional 4.73 mgP/l removal, which means an 83% improvement in the existing P-removal performance. Moreover, in all the best scenarios the effluent total nitrogen contains not only nitrate but also ammonium nitrogen. In this regard, the correct definition of the objective function is crucial. In this study, the objective was set to improve the N removal defined as the sum of NH_4 and NO_3 in the effluent.

The scenario analysis results (Table 2) are the result of the sum-up effect of all the evaluated degrees of freedom on the system. Since the number of degrees of freedom is relatively high (i.e. 5), it becomes difficult to distinguish exclusively and quantitatively the effect of each degree of freedom on the overall system performance. The following general remarks are observed from the detailed analysis of the scenario analysis data (unpublished):

- Increasing the T_{ANB} improves the P-removal efficiency, however, the N-removal performance decreases. Obviously, this favours conditions for phosphorus accumulating organisms (PAOs) to effectively utilise the VFA generated during the anaerobic phase (Wilderer *et al.*, 2001).
- Increasing the T_{AER} slightly improves the performance of the nitrification process. However, this parameter has a negative effect on the denitrification process (Artan *et al.*, 2002).
- The S_O-sp appeared to be the most critical parameter in determining the overall behaviour of the system. A detailed discussion is provided below.

Table 2 Summary of the scenario analysis results: the best scenario in each category

Scenarios ID	T_{ANB} (min)	T_{AER} (min)	T_{ANX} (min)	$V_{Step-feed}$ (L)	S_O-sp (mgO$_2$/l)	NH_4 (mgN/l)	NO_3 (mgN/l)	PO_4 (mgP/l)	TN (mgN/l)
Reference	60	150	60	0	2	0.73	17.10	5.7	17.83
IAF 1	60	130	80	10	0.4	2.50	8.26	0.97	10.76
IAF 2	60	130	80	10	0.4	2.04	7.88	1.04	9.93
IAF 4	60	130	80	10	0.4	1.70	6.67	1.47	8.38
IAF 8	60	130	80	10	0.4	1.88	5.84	1.03	7.72

- The step-feed option has a considerable positive effect on the denitrification process. This parameter is essential in improving the denitrification capacity of the system (Hvala *et al*., 2001; Lin and Jing, 2001).
- Increasing the intermittent aeration frequency in general has a positive effect on the nutrient (N and P) removal capacity of the system (Demuynck *et al*., 1994).

In general, the results of the optimisation study (Table 2) demonstrate that during the filling phase there is a strong competition between PAOs and denitrifiers for the influent COD (particularly VFA), which is in agreement with several studies (Manning and Irvin, 1985; Wilderer *et al*., 2001; Hvala *et al*., 2001; Lin *et al*., 2001; etc.). To improve P removal in SBRs, the fraction of influent COD utilised by PAOs should be increased during the filling phase. This can be achieved by providing sufficient anaerobic time and decreasing the initial NO_3 concentration present at the beginning of the filling phase. Hence, improving N removal in the SBR is not only useful in itself but also enhances P-removal. In this respect the following actions are useful to consider: (1) step-feed of the influent, (2) maintain oxygen limited conditions during the aerobic react phase to increase simultaneous nitrification and denitrification (SND) capacity of the system (see below), (3) high intermittent aeration frequency during react phase and (4) optimise the length of aerobic and anoxic sub-phases during the react phase. The systematic methodology presented here significantly facilitates the efforts to find the optimal combination of the above-mentioned parameters to achieve both optimal N and P removal in SBR systems.

5.2 Robustness analysis of the best scenarios. The robustness index (RI) introduced by Vanrolleghem and Gillot (2002) is used to assess/measure the robustness of each scenario against a change in the system operation conditions. The sensitivity of the SBR under different scenarios was determined by applying the following manipulations: (1) 10% decrease in the sludge age (SRT), (2) 10% increase in the hydraulic loading rate, (3) 10% decrease in the organic (COD) loading rate and (4) 33% decrease in the temperature (from 15 to 10°C). The temperature effect on the system performance was modelled using the Arrhenius equation.

Table 3 provides the relative sensitivities S_i (calculation, see Table 3 footnote) of the effluent TN and PO_4 concentration with respect to a change in each operating condition parameter (defined in the parameter column). The magnitude of the relative sensitivity indicates how strong the resulting effect of a change in a parameter on the SBR system is. The sensitivity analysis of the SBR showed that decreasing the SRT of the system has a negative (although only small) effect, while increasing the hydraulic loading rate has mainly a dilution effect on the effluent N and P concentrations. Further, decreasing the influent COD load resulted in higher concentrations of N and P in the effluent. On the other hand,

Table 3 Sensitivity analysis and robustness index of the best scenarios (see text for explanation)

Parameters (±)	Reference		IAF1		IAF2		IAF4		IAF8	
	TN	PO$_4$	TN	PO$_4$	TN	PO$_4$	TN	PO$_4$	TN	PO$_4$
1. SRT (−10%)	0.11	0.56	−0.10	0.56	0.00	−0.07	0.05	0.18	0.05	−0.02
2. HRT (+10%)	−0.04	−0.37	−0.07	0.47	−0.08	−0.01	−0.06	0.26	−0.10	0.02
3. COD load (−10%)	0.09	0.79	0.03	0.53	0.22	0.32	0.40	0.81	0.46	0.82
4. Temp. (−33%)	0.13	0.67	2.45	12.10	3.33	7.07	1.22	−0.31	4.17	5.99
Robustness index (RI)*	**9.52**	**1.36**	**0.81**	**0.16**	**0.60**	**0.28**	**1.48**	**1.62**	**0.47**	**0.33**

$$* \quad RI = \left(\sqrt{\frac{1}{p} \sum_{i=1}^{p} S_i^2} \right)^{-1} \quad \text{where} \quad S_i = \frac{\partial Cost}{\partial \theta_i} \cdot \frac{\Delta \theta_i}{Cost} \quad i = 1...p \text{ and } Cost = \left[TN, PO_4 \right]$$

the temperature induced a sharp decrease in the performance of the SBR, almost leading to system failure.

Based on the comparison of the RI (Table 3), the reference system appeared to be the most robust with respect to N-removal, followed by the best scenario under IAF4. From a P-removal point of view, however, the SBR system is most robust under the best IAF4 scenario followed by the reference system. However, the robustness index does not indicate the goodness of a scenario with respect to effluent quality, it only indicates how stable the (good or bad) performance is under process changes (Vanrolleghem and Gillot, 2002). The robustness of the system is particularly low when the system delivers its best effluent quality, see IAF1, IAF2 and IAF8 in Table 3. This implies that the optimised SBR is forced to operate close to its limit under the above-mentioned scenarios. Hence, a small deviation in the input to the system leads to drastic deviations in the performance of the system, even up to system failure where biological N and P removal is no longer achieved. From this perspective, it can be said that the RI of a scenario indicates how the SBR system is forced to operate close to its limits/edge and therefore how fragile it becomes against a deviation in the input to the system. This provides significant information, particularly for wastewater treatment plants operated under dynamic input conditions, since the effluent quality should be ensured not for short-term (optimal) but for long-term (variable) operation.

5.3 Selection of the best scenario for implementation. The objective of the optimisation study is to optimise the operation of the SBR in such a way that the best effluent quality can be obtained. Obviously, one of the criteria to decide for the best scenario is the effluent quality in each scenario. However, the effluent quality standards (e.g. EC Directives, 91/271/EEC) usually require the treatment plant to deliver the effluent quality over a certain period of the operational time (e.g. 95%). From this perspective, the stability of the system becomes significant and should be considered equally in the final decision.

Based on the effluent quality (Table 2) and RI of the best scenarios (Table 3), the SBR operation under IAF4 appeared to be the best scenario to provide effluent quality below discharge standards accompanied with good system stability. Under this scenario, the existing SBR performance for the N and P removal is improved by 54% and 74%, respectively. The best scenario is to be implemented soon in the BIOMATH laboratory.

Effect of the oxygen set-point and length of the aerobic react phase
An important outcome of the scenario analysis is the fact that the system delivers the best
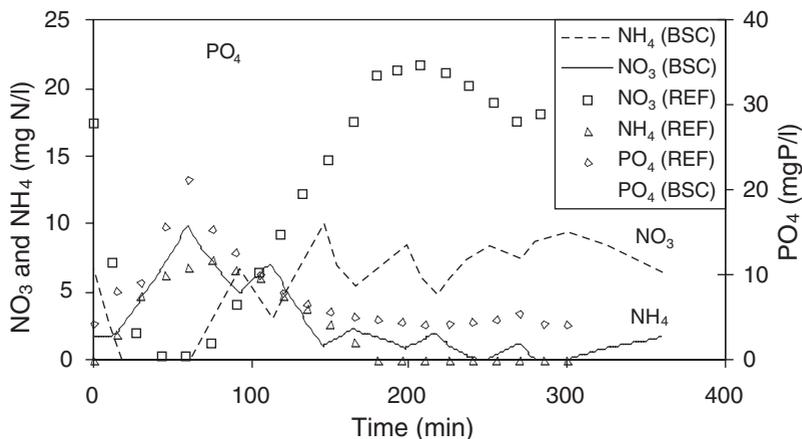
Figure 3 N- and P-removal dynamics under the best scenario (BSC) obtained in IAF4 in comparison with the reference (REF) system
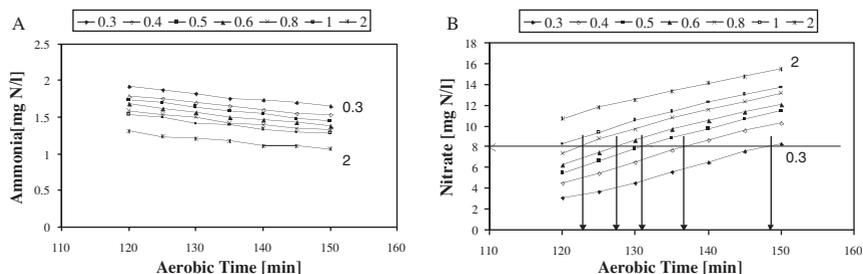
Figure 4 Trend of ammonium (A) and nitrate (B) as function of oxygen set-point under different lengths of aerobic react phase for the SBR operation with IAF4. Arrows indicate combinations of oxygen set-points and aerobic-time corresponding to 8-mgN/l nitrate in the effluent (B)

effluent quality (both for N and P criteria) under oxygen-limited conditions (see Table 2). A set of simulations (224 in total) were carried out to understand the effect of the oxygen set-point on the nitrification and denitrification processes in the SBR system. A grid of scenarios was constructed around a vector of oxygen set-points and a vector of aerobic react phase times. The simulation results obtained under the best IAF4 scenario are shown in Figure 4. Similar trends are observed in the ammonium and nitrate profiles obtained under the best scenarios with IAF1, IAF2 and IAF8 (Mura, 2003).

The simulation results demonstrated that a linear relationship exists between the oxygen set-point or the length of the aerobic react phase (i.e. aerobic SRT) and the effluent nitrogen concentrations (see Figure 4). A certain nitrate concentration (8 mgN/l) can be obtained under different oxygen set-points and aerobic react time (see Figure 4B). This linear relationship can be explained by the changing extent of simultaneous nitrification and denitrification (SND) occurring during the reaction phase of the SBR (Munch *et al.*, 1996). Based on the simulation results, it is strongly advised to consider the oxygen set-point in the design of SBRs and probably also for other types of wastewater treatment plants.

In this optimisation study, a fixed length of aerobic and anoxic sequences is assumed to reduce the number of scenarios required for the optimisation. It is clear that the optimisation of the SBR should also consider the variable length of the aerobic/anoxic sequences, particularly for SBRs subjected to dynamic input conditions. Moreover, the settling properties of activated sludge are not incorporated in the state-of-the-art activated sludge models such as ASM2dN (Insel *et al.*, 2003). Hence, it is not possible to predict the behaviour of activated sludge during the settling phase under different operating conditions. Ideally, this should be a third criterion to consider during the selection of the best scenario.

Conclusions

A systematic approach (methodology) for the optimisation of SBRs using mechanistic models is developed and evaluated at a lab-scale SBR in view of an improvement of effluent N and P discharges. Based on a compromise between the effluent quality and the robustness of the operation, the best scenario for SBR optimisation is found out to be a step-feed with four intermittent aeration sub-phases during the react phase. Under this scenario, it is possible to improve the current N- and P-removal performance of the SBR by 54% and 74%, respectively.

Acknowledgements

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