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Evaluation of Different Nitrogen Control Strategies for a Combined Pre- and Post-Denitrification Plant

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Abstract: In the paper different nitrogen control strategies are proposed and tested on a simulation model of a combined pre- and post-denitrification plant. The plant configuration corresponds to the Domžale-Kamnik wastewater treatment plant that will be upgraded for nitrogen removal using MBBR (moving bed biofilm reactor) technology. The aim of the study is to find an optimal control strategy in terms of required effluent quality and operating (i.e. carbon and aeration) costs. The tested control strategies address aeration control, internal recirculation control, and external carbon dosage control, and are based on PI and feedforward control algorithms. Simulation results indicate that the nitrate PI controller that manipulates external carbon flow-rate and the ammonia PI controller that manipulates oxygen concentration in the aerobic reactors give the best performance with respect to the effluent quality and operating costs. In addition, it was shown that the control authority of the internal recirculation flow-rate was rather limited as the internal recycle flow-rate on the real plant can be increased only up to 200% of the average influent flow-rate. Hence, no improvement of effluent quality could be achieved with internal recycle control. While the improvement of effluent quality with the proposed overall control scheme is small if compared to the basic control scheme with optimal set-points, the energy savings are quite significant reaching up to 40%.

1. INTRODUCTION

Because of the introduction of stricter legislation for nitrogen removal many wastewater treatment plants (WWTPs), which were primarily built to remove organic matter, need to be upgraded to remove also nitrogen and phosphorus compounds from wastewater. This is also the case in Domžale-Kamnik WWTP, Slovenia. Based on an extensive set of real-plant experiments and a simulation study (Hvala *et al.*, 2002) the moving bed biofilm reactor (MBBR) technology was chosen for plant upgrading rather than a conventional activated sludge process. Because there is a very strict total nitrogen requirement in the effluent, a combined pre- and post-denitrification plant was proposed.

The aim of this paper is to propose the control system for the upgraded plant so that not only effluent requirements are met but also the operating costs are minimised. The control strategies considered are based on on-line nutrient (ammonia, nitrate) measurements, which are planned to be installed on the upgraded plant for monitoring and control purposes to improve the dynamic operation of nitrification and denitrification processes. The control loops considered address aeration control, nitrate recirculation control and external carbon dosage control that have been already extensively studied in other papers (Yuan *et al.*, 2002; Stare *et al.*, 2007). As the more advanced model-based predictive control concepts did not prove to give a significant improvement of plant operation (Stare *et al.*, 2007), only more simple feedforward and PI control algorithms were considered in the study. The main contribution of the paper is the evaluation of the control system as a whole with respect to both quality and energy costs while considering different alternatives of the chosen control variables and the chosen control algorithm.

This paper is organized as follows. In the following section, the process configuration is presented. Then, the applied control strategies are described. Next, the simulation analyses are shown. At the end some conclusions are drawn.

2. PROCESS CONFIGURATION

The upgraded plant will be built for nitrogen removal and consists of three identical parallel lines with seven reactors in each line (Fig. 1). A combination of pre- and post-denitrification is used because of strict effluent requirement on nitrogen removal. The effluent total nitrogen (*TN*) and ammonia nitrogen (S_{NH}) concentration should be below 10mg/l and 3mg/l, respectively. The chosen technology is MBBR, i.e. reactors filled with small free floating plastic carriers on which a fixed biofilm is formed.

From Fig. 1 it can be seen that the first two reactors are anoxic reactors where nitrate is converted to atmospheric nitrogen with the organic matter in the influent as a carbon source. Nitrification takes place in aerobic reactors 3 and 4. The 5th reactor can be also aerated, but its main purpose is to reduce the dissolved oxygen concentration in the water that is recycled back to the inlet or flows forward to the post-denitrification reactor. The post-denitrification takes place in the 6th reactor where an external carbon source (in our case methanol) can be added to reduce the nitrate concentration.

The external carbon that is not removed in the 6th reactor is degraded in the last aerobic reactor. After the biological stage the water enters the separation stage, where flocculation and flotation are used for particle separation.

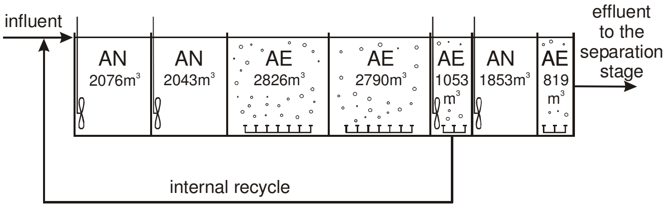

Fig. 1. Scheme of the MBBR plant – one line.

2.1 Simulation model

The performance of the control strategies was examined by GPS-X simulation software (Hydromantis, 2001). To simulate the MBBR process a Hybrid-System model was used, which combines standard plug-flow tank configuration with suspended growth biomass, and the biofilm model representing fixed film growth on the media inserted into the tank. In the model, the reactor contents is represented by 6 layers, the first layer representing the bulk liquid, while the remaining five layers represent the biofilm formed on the carriers. In each layer, all the process components are subject to biological reactions and are modelled with the Mantis model, which is similar to the well known Activated sludge model no. 1 (ASM1) (Henze *et al.*, 2000), except with some minor modifications (Hydromantis, 2001). The default kinetic and stoichiometric GPS-X parameters were used in our study, providing a satisfactory agreement between simulated and real plant dynamic data as measured on the MBBR pilot plant.

2.2 Influent data

Simulation analyses were performed based on real plant influent data as measured in the plant from 14.10.-24.10.2006. In these analyses only influent flow-rate (Fig. 2), ammonia concentration (Fig. 3) and readily biodegradable substrate concentration (Fig. 4) where changing dynamically. All other components were set constant and defined according to prior wastewater characterization (Hvala *et al.*, 2002).

For influent flow-rate (Q_{in}) the actual measurements were used, only the average flow-rate was increased from approximately 6000 (as measured in the plant) to 8333m^3/day, which was the value used in plant design for one line. The influent ammonia concentration was measured, while influent readily biodegradable substrate concentration was computed from influent total organic carbon measurements.

The given data is a good representative of real plant influent conditions with typical daily ammonia variations, and periods of variable influent carbon source that are typical for the plant (low from day 0-4, higher from day 5-10 in Fig. 4). Simulated at different temperatures, the data is a good representative for the whole year operation. In our case, the analyses were performed at 15°C, which is approximately the average temperature of the wastewater over the year.

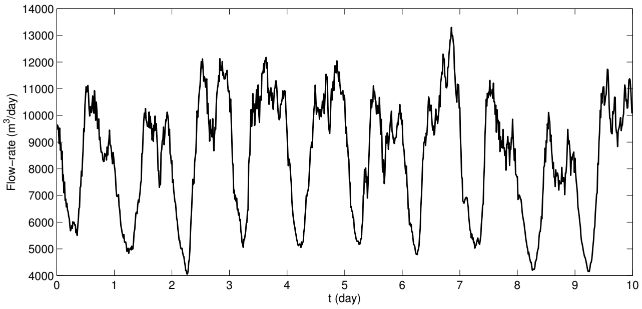

Fig. 2. Influent flow-rate.

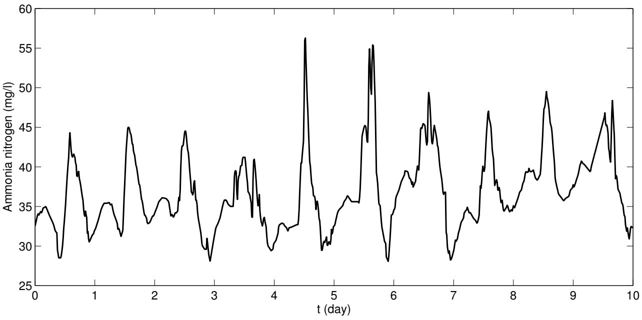

Fig. 3. Influent ammonia nitrogen.

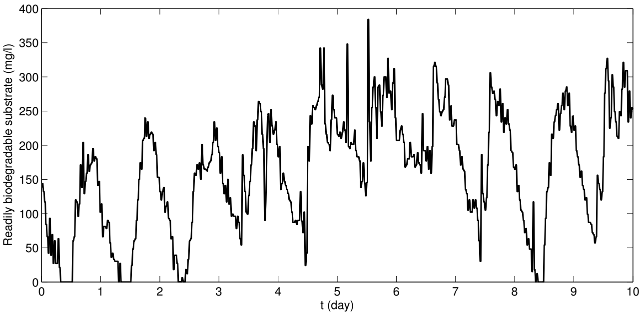

Fig. 4. Influent readily biodegradable substrate.

2.3 Evaluation criteria

In this study, average energy costs (i.e. aeration) and external carbon dosage costs were used to evaluate the control strategies. The operating costs (*OC*) were defined as follows:

$$OC = AC + CC \ , \tag{1}$$

where *AC* means average aeration costs (€/day), while *CC* means average external carbon costs (€/day).

The electric energy (€/day) required for aeration of aerobic reactors is calculated using a pre-defined formula inside the GPS-X simulation software (Hydromantis, 2001):

$$AC = \frac{E_{price}}{T_p} \int_{t=0}^{t=T_p} \frac{Q_{air}(t) \cdot head \cdot \rho_{H2O}}{86.4 \cdot 10^7 \cdot \eta_{pump}} dt, \tag{2}$$

where E_{price} is the electricity price, T_p is the simulation period, Q_{air} is the airflow rate, head is the hydraulic head, ρ_{H2O} is the density of wastewater and η_{pump} is the pumping efficiency. In our case the following values of parameters were used: head = 4.5 m, ρ_{H2O} around 1000 kg/m^3 (depends on the temperature) and $\eta_{pump} = 0.7$. For the E_{price}, an average electricity price in Slovenia (0.1 €/kWh) was used.

The average external carbon costs (€/day) are calculated as the average external carbon mass flow (kg/day) multiplied by the price of the carbon source (€/kg):

$$CC = \frac{C_{price} \cdot COD_S}{1000 \cdot T_p} \int_{t=0}^{t=T_p} Q_{carb}(t)dt, \tag{3}$$

where COD_S is the carbon source concentration ($1.186 \cdot 10^6$ mg/l), Q_{carb} is the carbon flow-rate, T_p is the simulation period, while C_{price} is the price of carbon (methanol) source. The price of the methanol solution that was used in our case was set to 0.7 €/kg, which is an estimate of the methanol price in Slovenia.

Additionally, the effluent quality was also considered for the evaluation of control performance. Effluent requirements for this plant are to achieve effluent TN and chemical oxygen demand (COD) below 10mg/l and 70mg/l, respectively. However, as the separation stage (flocculation and flotation) was not modelled, only the soluble total nitrogen (TN_S) concentration (i.e. the sum of ammonia, nitrate, and soluble organic nitrogen concentration) in the last reactor was used to evaluate control strategies. Beside this also ammonia nitrogen and readily biodegradable substrate concentrations in the last reactor were considered in the evaluation of control strategies.

3. CONTROL STRATEGIES

Different aeration, internal recirculation flow-rate, and external carbon dosage control strategies were proposed and compared on the simulated upgraded MBBR plant. For the internal recirculation flow-rate control, a nitrate PI controller can be used. In this strategy, the nitrate concentration in the 2nd reactor is controlled at a desired set-point by manipulating the internal recycle flow-rate (Yuan *et al.*, 2002). This control strategy maximises the usage of influent organic matter for denitrification, but has a limited effect on effluent nitrate concentration, as the effluent nitrate concentration will vary with the influent flow-rate and composition, in particular with the influent carbon to nitrogen ratio (C/N). Because the internal recycle flow-rate on the real plant can be increased only up to the double value of the average influent flow-rate, the control authority of the internal recirculation flow-rate was limited. In fact, no improvements of nitrogen removal could be gained by using a PI nitrate controller as the internal recycle flow-rate is most of the time at its maximum value (17000m^3/day). Therefore, a constant (maximum) internal recycle flow rate was applied in all control strategies.

The following control strategies were tested:

(I) The ***basic control strategy***. In this case, a constant internal recycle flow-rate, a constant carbon dosing in the 6th reactor and PI oxygen control were used. In the latter case, the oxygen concentrations in the aerobic reactors are controlled at desired set-points by manipulating the air flow-rates. The oxygen set-point values for the 3rd, 4th, 5th, and 7th reactor were set to 2mg/l, 3mg/l, 0mg/l, and 3mg/l, respectively. It had previously been determined that satisfactory ammonia nitrogen removal could be achieved even in the case when reactor 5 was not aerated. The chosen carbon flow-rate was 0.1m^3/day.

(II) ***External carbon dosage control***. In this strategy the carbon dosing is performed in one of the two ways described below, while the internal recirculation flow-rate and oxygen control are the same as in the basic control strategy. The two different control strategies for carbon dosing are:

(a) *Feedforward (FF) control* of the external carbon flow-rate in the 6th reactor, where carbon flow is proportional to the influent flow-rate Q_{in}:

$$Q_{carb} = k_1 Q_{in} - n_1, \tag{4}$$

The feedforward controller parameters k_1 and n_1 were determined by trial and error. Proportional factor k_1 was set to 10^{-4} and n_1 was set to 0.8m^3/day. To prevent external carbon from being unnecessarily dosed during high influent flow-rates, the Q_{carb} was limited between 0 and 0.7m^3/day.

(b) *PI control* of the nitrate concentration in the 6th reactor by manipulating external carbon addition in the 6th reactor (Fig. 5). A natural strategy is to control the nitrate concentration at the end of the anoxic reactor at a low set-point (Yuan and Keller, 2003). In our study, the nitrate-set point was set to 3mg/l, while Q_{carb} was limited between 0 and 0.7m^3/day.

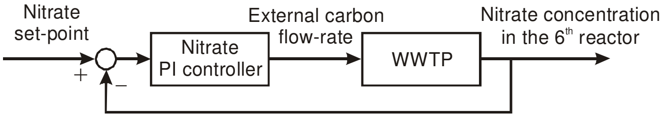

Fig. 5. Control scheme for nitrate PI control.

(III) ***Ammonia control***. In this strategy, the S_{NH} concentration in the 5th reactor was controlled with a cascade PI controller (Lindberg and Carlsson, 1996). In the cascade control (Fig. 6), the outer (ammonia) controller adjusts the oxygen set-point values in the 3rd and 4th reactor based on desired and actual S_{NH} value, and the two inner (oxygen) controllers manipulate the air flow-rate values based on desired and actual dissolved oxygen concentrations (Stare *et al.*, 2007). The ammonia set-point for the 5th reactor was set to 1mg/l. The oxygen concentrations in the 5th and 7th reactor were controlled as in the basic control strategy with DO set-points set to 0mg/l and 3mg/l, respectively. Internal recycle flow-rate and carbon dosing were the same as in the basic control strategy.

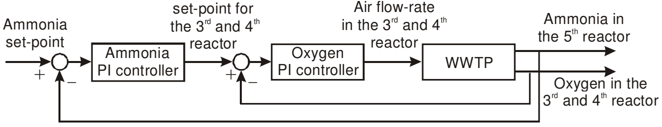

Fig. 6. Control scheme for ammonia PI control.

4. EVALUATION OF CONTROL ALGORITHMS

4.1 External carbon dosage control

Simulation results of the external carbon control strategies are shown in Fig. 7 and Fig. 8. From Fig. 8 it can be seen that with FF flow-rate control better (soluble) total nitrogen removal was achieved in the period from day 3 to 8 compared to the basic control strategy, while the average (soluble) total nitrogen removal over the whole period was similar (Table 1). In addition, more external carbon was dosed in FF control (Table 2). Besides, the parameters of the FF controller (4) have to be modified with changing operating conditions. For example, at higher temperatures (20°C) a satisfactory removal of the nitrate can be achieved without using external carbon dosage. This means that if the parameters of the FF controller are not changed during higher temperatures the carbon would be unnecessarily dosed, while at lower temperatures (e.g. 10°C) too little carbon would be dosed.

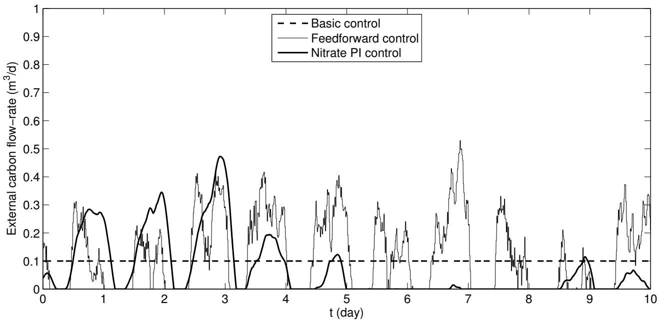

Fig. 7. External carbon flow-rate for different control strategies.

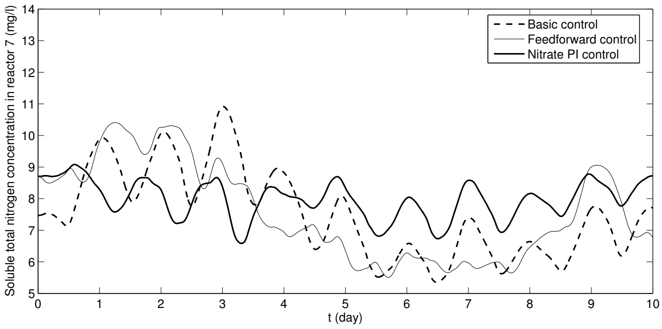

Fig. 8. Soluble total nitrogen concentration in the 7th reactor for different control strategies.

This problem can be solved by using the nitrate PI controller, which adds carbon only when the nitrate concentration in the 6th reactor is high. When the nitrate concentration is low, the external carbon is not added. From Fig. 8 it can be seen that by using the nitrate PI controller a better removal of (soluble) total nitrogen is achieved in the period from day 0 to 4. In fact, over the entire simulation period the soluble total nitrogen concentration was kept below 9mg/l. However, the average (soluble) total nitrogen concentration was a little higher when using the nitrate PI controller (Table 1) as less carbon was dosed (Table 2).

Table 1. Average concentrations in the last reactor

	S_{NH} (mg/l)	S_{NO} (mg/l)	S_S (mg/l)	TN_S (mg/l)
Basic control	0.36	3.37	4.60	7.50
FF control	0.34	3.42	5.49	7.51
Nitrate PI control	0.39	3.81	4.04	7.99

Table 2. Carbon and aeration costs

	CC (€/day)	*AC* (€/day)
Basic control	83.0	355.7
Feedforward control	99.3	355.6
Nitrate PI control	59.0	355.4

4.2 Ammonia control

In Fig. 9, Fig. 10, and Fig. 11 the ammonia control strategy results are compared with the basic control strategy. It can be seen that the ammonia controller increases DO concentrations during high load periods (see Fig. 9) to enhance nitrification and to successfully remove ammonia nitrogen (Fig. 11), while during low loads it decreases the DO concentrations to save aeration energy. With the introduction of the ammonia controller a considerable reduction (about 30%) in aeration costs was achieved (Table 4) because of variable DO set-point.

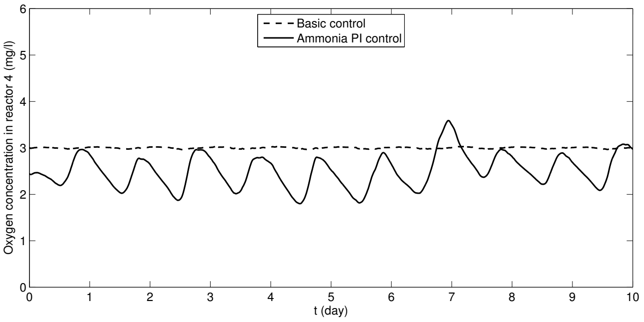

Fig. 9. Oxygen concentration in the 4th reactor.

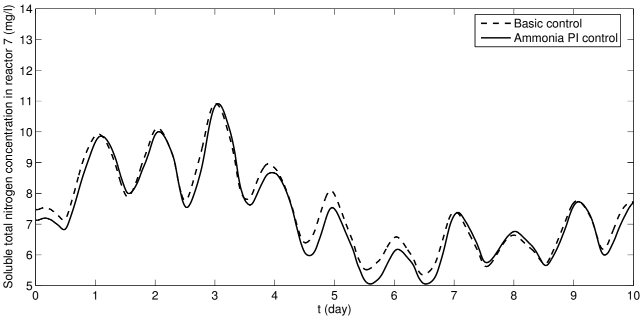

Fig. 10. Soluble total nitrogen concentration in the 7th reactor.

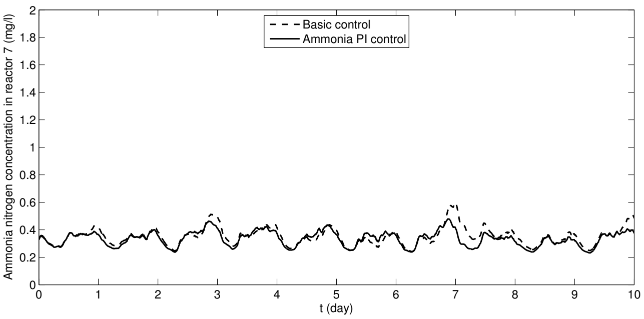

Fig. 11. Ammonia nitrogen concentration in the 7th reactor.

In Fig. 11 and Table 3 it can be seen that the ammonia controller does not remove more nitrogen than in the basic approach. This happens because the DO set-points in the basic control strategy were set relatively high. With lower

DO set-points in the basic control strategy (e.g. 2,5mg/l, which is the average of ammonia controller) the energy consumption in both cases would be similar, but with considerably higher effluent ammonia peaks and higher average ammonia concentration in the basic control strategy.

Table 3. Average concentrations in the last reactor

	S_{NH} (mg/l)	S_{NO} (mg/l)	S_S (mg/l)	TN_S (mg/l)
Basic control	0.36	3.37	4.60	7.50
Ammonia control	0.35	3.17	4.79	7.27

Table 4. Carbon and aeration costs

	CC (€/day)	*AC* (€/day)
Basic control	83.0	355.7
Ammonia control	83.0	245.7

4.3 Overall control

In Figures 12 to 14, the performance of the basic control is compared with the overall control strategy. For the overall control strategy, the PI ammonia controller and the nitrate PI controller were used. As seen in Fig. 13, a better removal of TN_S was achieved with the overall control in the period from day 1 to 4, while in the period from day 5-10 a poorer removal was achieved as no external carbon was added (Fig. 12). Ammonia removal in Fig. 14 was slightly better in overall control during the whole simulated period. From Table 5 it can be seen that similar effluent quality was obtained in both cases, but with considerable reduction of external carbon dosage costs and aeration costs in the overall control (Table 6). In fact, the operating costs (the sum of *CC* and *AC*) decreased by around 40% in the overall control.

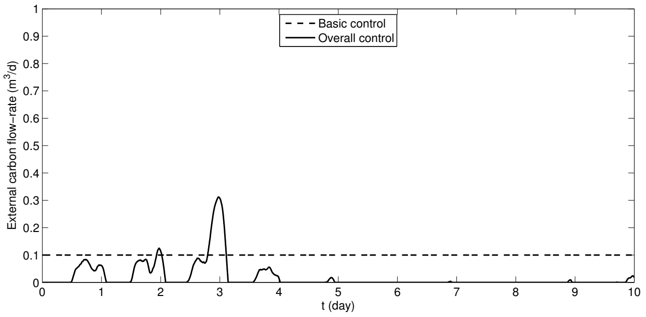

Fig. 12. External carbon flow-rate for different control strategies.

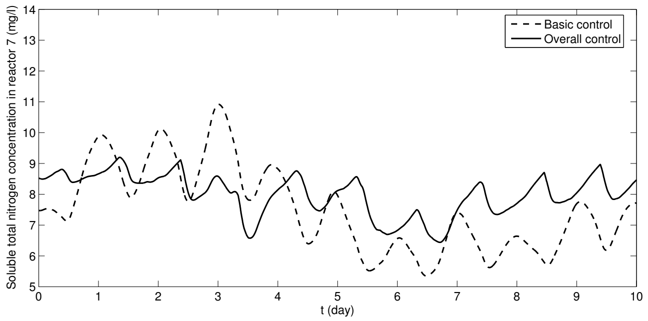

Fig. 13. Soluble total nitrogen concentration in the 7th reactor for different control strategies.

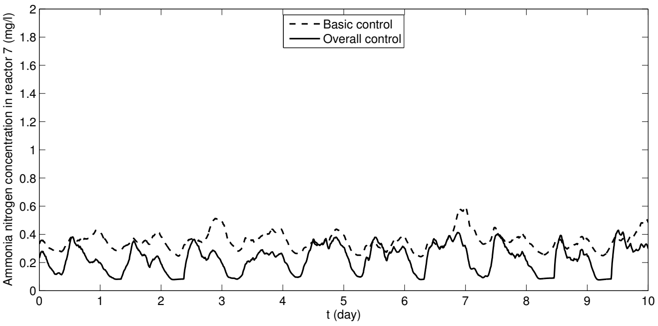

Fig. 14. Ammonia nitrogen concentration in the 7th reactor for different control strategies.

Table 5. Average concentrations in the last reactor

	S_{NH} (mg/l)	S_{NO} (mg/l)	S_S (mg/l)	TN_S (mg/l)
Basic control	0.36	3.37	4.60	7.50
Overall control	0.28	3.81	3.02	7.79

Table 6. Carbon and aeration costs

	CC (€/day)	*AC* (€/day)
Basic control	83.0	355.7
Overall control	15.9	221.7

4.4 Evaluation of control strategies at low temperatures

The basic and overall control strategies were also evaluated at a wastewater temperature of 10°C, which is the lowest temperature at which the required effluent quality should be met but is most difficult to achieve. Due to a lower wastewater temperature the oxygen set-point values for the 3rd, 4th, 5th, and 7th reactor were set to 3mg/l, 4mg/l, 0mg/l, and 3mg/l, respectively. The chosen carbon flow-rate was increased to 0.3m^3/day, while the ammonia and nitrate nitrogen set-points were set to 2mg/l and 3mg/l, respectively.

The simulation results indicate that problems related to nitrate removal can be expected during low influent COD concentration and low temperature. Namely, during such periods the nitrate removal in the pre-denitrification reactors (1st and 2nd reactor) is limited. For this reason, the denitrification process is active only in the post-denitrification reactor (6th reactor) where the readily biodegradable substrate from the external carbon source is available. However, in post-denitrification not all the nitrate could be removed because the 6th reactor is too small. Hence, the PI nitrate controller increases external carbon flow-rate to its maximum value (Fig. 15) because of high nitrate concentration, but this consequently leads to a high readily biodegradable substrate concentration in the effluent (Fig. 16).

It has turned out that overall effluent quality results can be improved by using a PI controller that adds carbon to the 5th reactor. In this way, readily biodegradable substrate in all anoxic reactors is available, which improves the removal of nitrate and total nitrogen. From Table 7 it can be seen that the nitrate, readily biodegradable substrate, and (soluble) total nitrogen removal were improved in spite of lower external carbon addition (Table 8). It should be mentioned, however, that this control strategy can be applied only in the case when the oxygen concentration in the 5th reactor is low or zero, otherwise oxygen is used for carbon removal, which leads to considerably higher operating costs. To solve this problem, carbon should be added separately to the 1st and 6th reactor.

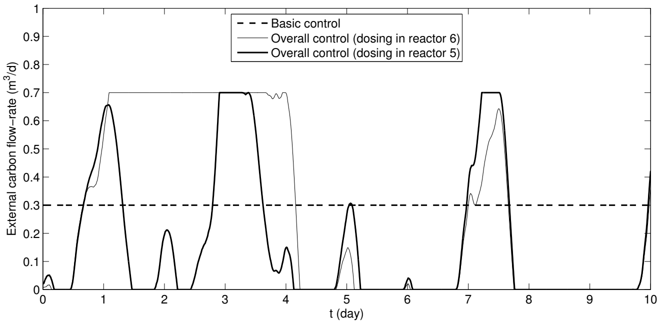

Fig. 15. External carbon flow-rate for different control strategy.

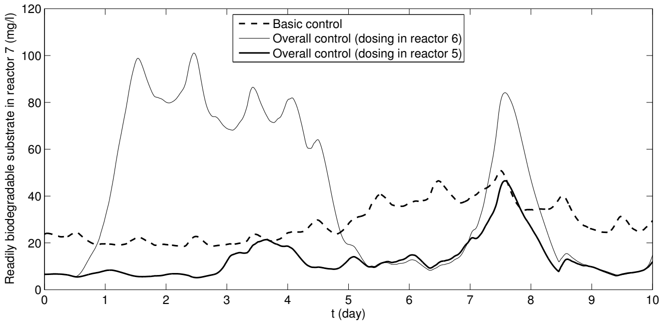

Fig. 16. Soluble total nitrogen concentration in the 7th reactor for different control strategies.

Table 7. Average concentrations in the last reactor

	S_{NH} (mg/l)	S_{NO} (mg/l)	S_S (mg/l)	TN_S (mg/l)
Basic control	0.56	5.07	28.8	9.39
Overall control*	0.51	4.92	51.42	9.21
Overall control**	0.54	4.48	14.31	8.77

*Carbon is dosed in the 6th reactor, ** Carbon is dosed in the 5th reactor

Table 8. Carbon and aeration costs

	CC (€/day)	AC (€/day)
Basic control	249.2	435.5
Overall control*	228.6	259.9
Overall control**	134.3	255.3

*Carbon is dosed in the 6th reactor, ** Carbon is dosed in the 5th reactor

5. CONCLUSIONS

In this paper, several control alternatives addressing nitrogen removal in a combined pre- and post-denitrification plant were evaluated using a simulation model. Control strategies for external carbon dosing, internal recycle control and the ammonia control were proposed and compared with respect to effluent quality and operating (i.e. carbon and aeration) costs. The presented simulations clearly indicate that the nitrate PI controller that manipulates external carbon flow-rate in the 6th reactor and ammonia PI controller that manipulates oxygen concentration in the aerobic reactors give only slightly better effluent quality if compared to the basic control scheme with optimally selected set-points, while the energy savings are quite significant reaching around 40%. It was also shown that the control authority of the internal recirculation flow-rate was rather limited as the internal recycle flow-rate on the real plant could be increased only up to 200% of the average influent flow-rate. Hence, no improvements of effluent quality could be achieved with internal recycle control.

The simulation results also indicate that problems related to nitrate removal can be expected during low influent COD concentration and low wastewater temperature. In this case, the nitrate removal in the anoxic reactors of the pre-denitrification stage is limited. Consequently, the denitrification process is active only in the anoxic reactor of the post-denitrification stage, which is too small for all nitrate to be removed. For this reason, the external carbon should be dosed in the 5th instead in the 6th reactor so that readily biodegradable substrate is available in all anoxic reactors (i.e. in the pre- and post-denitrification stages). In this way, the removal of nitrate and total nitrogen can be improved, while also reducing the operating costs considerably.

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