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IMPROVED DESIGN AND CONTROL OF INDUSTRIAL AND MUNICIPAL NUTRIENT REMOVAL PLANTS USING DYNAMIC MODELS

F. Coen*, B. Vanderhaegen**, I. Boonen***, P. A. Vanrolleghem* and P. Van Meenen**

** BIOMATH, University of Gent, Coupure Links 653, B-9000 Gent, Belgium*
*** EPAS NV, Technologiepark 3, B-9052 Gent-Zwijnaarde, Belgium*
**** AQUAFIN NV, Dijkstraat 8, B-2630 Aartselaar, Belgium*

ABSTRACT

Dynamic simulation can be used to improve the design and performance of the activated sludge process. This is illustrated by means of two case studies:

1. The simulation of a full scale industrial plant treating nitrogen-rich wastewater by an intensive nitrification-denitrification process. By means of simulation the most important operational cost (dosage of an external carbon source) was optimised and a control strategy was proposed.

2. The simulation of a municipal wastewater treatment plant with the extension of nitrogen removal. Based on simulation the feasibility of the redesign was evaluated.

In both cases the wastewater composition was characterised and the biological model (the activated sludge IAWQ-model No. 1) calibrated. By means of respirometry and standard laboratory analyses it was possible to estimate the COD fractions of the wastewater and the parameters for heterotrophic and autotrophic growth of biomass. © 1997 IAWQ. Published by Elsevier Science Ltd

KEYWORDS

IAWQ-activated sludge model No.1; dynamic modelling; nitrogen removal; wastewater treatment.

INTRODUCTION

Since the Activated Sludge Model No. 1 was published by the IAWQ Task Group on Mathematical Modelling for Design and Operation of Biological Wastewater Treatment (Henze *et al.*, 1987) the use of simulation in wastewater technology has become more and more widespread. Simulation has proven to be useful in solving problems of optimisation, design and upgrading of WWTPs.

In the past most wastewater treatment plants were designed for carbon oxidation (and nitrification) only. Nowadays, due to increasingly restrictive effluent nitrogen standards, attention is paid to create and/or improve denitrification capacity. This can be reached by creation of anoxic conditions, improvements to process operation (e.g. feeding strategy, internal recirculation) and control via DO, ammonia and nitrate measurements. If denitrification is limited by a lack of biodegradable substrate, an external carbon source will be needed. As pointed out in many papers (Londong, 1992; Nyberg *et al.*, 1992; Isaacs *et al.*, 1994) a control strategy based on carbon source addition provides an on demand increase in the rate of denitrification and thus allows compensation for peak nitrogen loads.

DESCRIPTION OF THE CASE STUDIES

The objective of the work was to assess how simulation can be used to optimise the performance of two full scale wastewater treatment plants, one industrial and one municipal respectively.

The industrial WWTP

The first case study was the simulation of a full scale industrial plant treating nitrogen rich wastewater in a predenitrification system (Figure 1). From the aerated compartment a high internal recirculation brings nitrate to the anoxic compartment. Due to the low COD/N ratio in the influent, an external carbon source (methanol) is added continuously in the denitrification compartment. Dosage of methanol allowed the mean effluent nitrate concentration to decrease from 130 g N/m^3 to 40 g N/m^3. The aim of the study was the reduction of operating costs related to energy consumption, external carbon source consumption and levies. The sludge treatment costs are only of secondary importance because the waste sludge is used in agriculture. The addition of methanol, however, represents an important operating cost. The methanol solution (80%) costs approximately 100 ECU per m^3 and is consumed at a rate of 0.18 m^3/h.

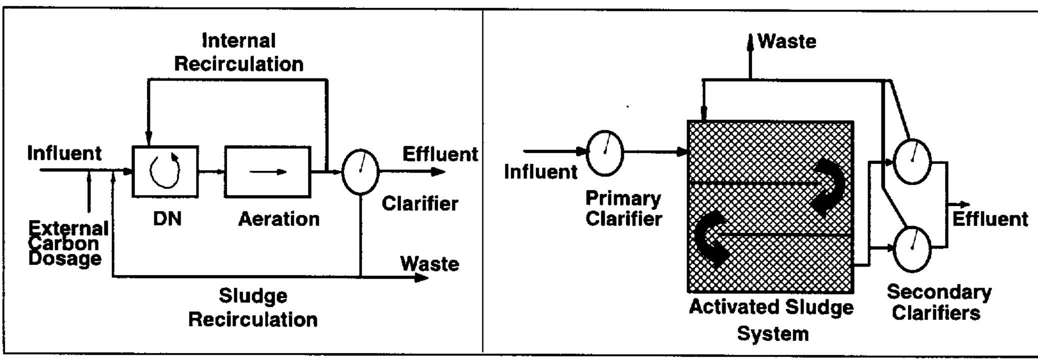

Figure 1. Schematic representation of the industrial WWTP (left) and the municipal WWTP (right).

The municipal WWTP

The WWTP Hoogstraten (Belgium) consists of a primary clarifier, an aeration tank of the plug flow type and two secondary clarifiers (Figure 1). The recycle ratio is fixed at about 100% of the mean influent flow rate. The aeration tank is equipped with air diffusers. The WWTP has been designed for 45000 PE. Only 21000 PE are actually treated, of which 40% originates from industrial activities. In recent years measuring campaigns revealed that the effluent criterion for total nitrogen (15 g N/m^3) was frequently violated over considerable periods of time (up to several days). The main reason for this seemed to be the lack of anoxic conditions in the existing plant. Simulation is used to upgrade the WWTP for complete denitrification. A scenario analysis is performed to evaluate the use of different operational strategies.

METHODOLOGY

To simulate a WWTP an overall model of the treatment plant needs to be built. This model should be a good representation of reality. A WWTP consists of different components (e.g. biological reactor, settler, etc.) and the processes in each component are described by an atomic model. The overall model for the WWTP is the combination of the atomic models. Based upon the results of a measuring campaign, experience and common sense the decision has to be made which processes are important to model. The calibration of the model for the WWTP is carried out following the procedure in Table 1. The first step in the calibration is the determination of the hydraulics for each component and the choice of a model for description of the processes. Secondly, the influent characteristics, initial conditions and parameters of the atomic models need to be determined.

Table 1. Procedure for calibration of the WWTP model

- Hydraulics :
  Determination of the hydraulics of the settler, the aeration tank, ...
- Choice of the atomic models :
  Determination of the model for the description of biotransformation, sedimentation, sludge thickening.
- Characterisation of the influent :
  Estimation of the COD fractions of the wastewater by means of respirometry and standard laboratory analyses.
- Characterisation of the sludge :
  Determination of the different fractions of the sludge based on analysis of the model equations under steady state conditions.
- Calibration of the atomic models :
  Determination of the parameters for heterotrophic and autotrophic growth.
  Determination of the sedimentation parameters.

Figure 2 gives two examples of the procedure applied for calibration of the biological model. By means of respirometric experiments with the biosensor RODTOX (Rapid Oxygen Demand and TOXicity tester) the Monod parameters for autotrophic and heterotrophic growth were estimated (Vanrolleghem and Verstraete, 1993). In Figure 2(a) the respiration rate for an experiment with addition of influent sample is shown. Autotrophic activity is inhibited by addition of ATU. Fitting of the Monod model to the experimental data gives the parameters for heterotrophic growth. For the determination of autotrophic kinetics a pulse of ammonium is added to the RODTOX (Figure 2 (b)). After calibration of the WWTP model it is necessary to check whether the model is a good reflection of reality. This validation is performed with experimental data not used for calibration. If the validation is successful, the model can be used for prediction (e.g. optimisation of operation or evaluation of upgrade scenarios). The simulations described below were performed with the simulation platform WEST (Hemmis NV, Kortrijk, Belgium).

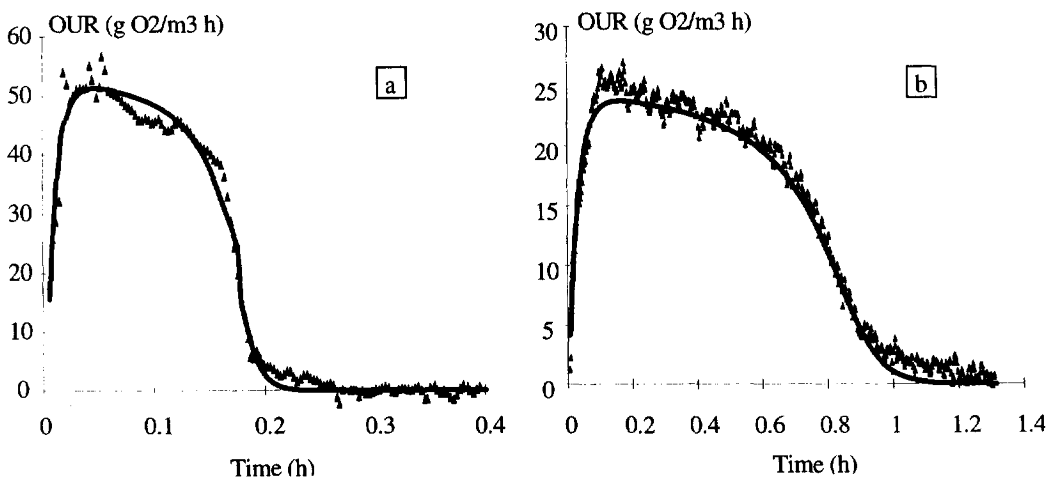

Figure 2. Respiration rate profiles for determination of the heterotrophic and autotrophic kinetic parameters Dosage of one pulse of influent (left) and a pulse of ammonium (right) at t = 0 h. (▲ = measurements; full line = fit by Monod model).

RESULTS

The industrial WWTP

Calibration

The anoxic reactor was assumed completely mixed. The residence time distribution of the aerated reactor was modelled with a N-tanks-in-series model. Chambers and Thomas (1985) proposed a correlation to estimate the number of completely mixed tanks in series. This correlation revealed that the hydraulics of the aerated reactor could be modelled with 4 tanks in series.

For simulation of the industrial WWTP the IAWQ-model No.1 was used (Henze *et al.*, 1987). This model assumes that only one substrate can be assimilated by the heterotrophic biomass. In this case study however two substrates, i.e. the readily biodegradable influent fraction and the external carbon source, were taken into account. Biokinetic and stoichiometric parameters for the oxidation of both substrates were different. This made an adaptation of the IAWQ-model necessary. The parameters associated with heterotrophic and autotrophic growth were estimated by means of respirometry (Vanrolleghem and Verstraete, 1993) and found to be different from those mentioned in literature (Henze *et al.*, 1987). Most of the literature parameter values are related to municipal wastewater.

The settler was modelled with a ten layer model. The settling velocity was described by means of a double exponential function (Takacs *et al.*, 1991). Stationary settling tests were performed during the measuring campaign to estimate essential settling velocity parameters.

Validation

The validation was carried out by comparing operational data (daily averages) gathered over a period of one month with the simulated effluent quality. More details can be found in Coen *et al.* (1995).

Prediction

Figure 3 shows the measured Kj-N loading rate and effluent nitrate concentration. The measuring campaign revealed that complete denitrification is achieved in the anoxic reactor and all Kj-N is converted to nitrate in the aerobic reactor. This implies that the nitrate concentration in the effluent and in the internal recycle are related to the Kj-N concentration in the denitrification compartment. The time lag between the Kj-N loading rate in the influent and the response of nitrate in the effluent or methanol in the anoxic reactor is about two days. This is equal to the residence time of nitrate in the system.

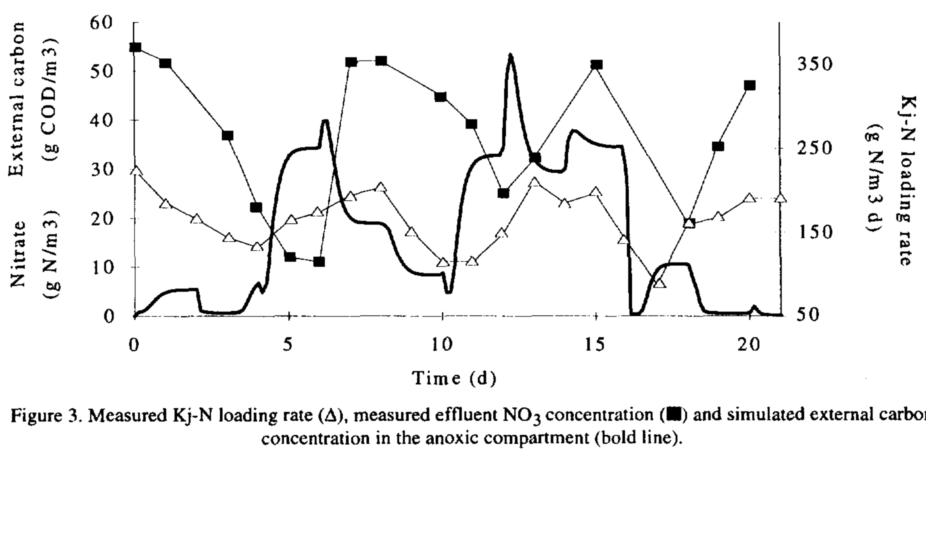

Figure 3. Measured Kj-N loading rate (Δ), measured effluent NO_3 concentration (■) and simulated external carbon concentration in the anoxic compartment (bold line).

To check the efficiency of the constant dosage of external carbon source the concentration of methanol in the anoxic compartment was calculated (Figure 3). During the measuring campaign it appears that an excess of methanol was added. The excess methanol amount (i.e. the area under the methanol concentration curve times the volume of the denitrification reactor) needs to be oxidised in the nitrification compartment to ensure the effluent quality. This results in a higher energy consumption for aeration and increased sludge production. Hence, to reduce the total cost of carbon source addition an optimisation is justified.

A proportional feedback control of the methanol dosing flow rate was proposed using hourly measurements of the nitrate concentration in the denitrification compartment. A nitrate setpoint of 5 g N/m^3 was proposed. Simulation revealed that the addition of methanol could be reduced by 30%. This represents a saving of about 50,000 ECU per year. Moreover, the control guarantees that denitrification is not limited by a lack of carbon source and that the effluent criterion for nitrate can be met (as long as the maximum denitrification capacity is not exceeded).

In this case study the addition of external carbon source plays a central role in the denitrification process. Hence, an alternative carbon source, in case glycol, was compared to methanol for its denitrification characteristics. It was assumed that the growth of heterotrophic biomass under anoxic conditions is proportional to the growth of heterotrophic biomass under oxic conditions (Henze *et al.*, 1987). Hence, respirometry can be used to determine the heterotrophic growth on both carbon sources. Figure 4 shows the DO-profiles after addition of methanol and glycol to the RODTOX biosensor. The activated sludge used for the experiment was first adapted to both carbon sources. Kinetic parameters were estimated for both substrates by fitting a Monod model to the data. Figure 5 shows the evolution of the specific heterotrophic growth rate as a function of substrate concentration. At low substrate concentration addition of methanol or glycol results in about the same growth rate. At substrate concentrations higher than 5 g/m^3 the growth on glycol is considerably faster than on methanol. These results are of major importance for the tuning of the nitrate controller. For a proper choice of the carbon source not only denitrification rate but also the direct cost of the carbon source, the amount of sludge produced and the safety of the product have to be taken into account.

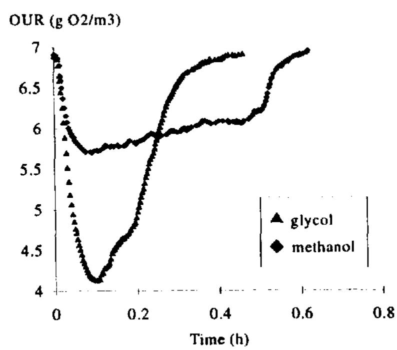

Figure 4. DO profiles for glycol and methanol.

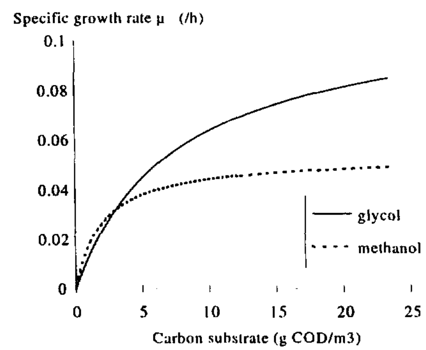

Figure 5. Specific growth rate for glycol and methanol.

The municipal WWTP

Calibration

The aeration tank of the plug flow type was modelled with a N-tanks-in-series model. The correlation used above resulted in the number of completely mixed reactors in series to be equal to 9. A one month measuring campaign provided the necessary information for calibration and validation of the used IAWQ model No. 1 (Henze *et al.*, 1987). The measuring campaign also revealed that the sludge had very good settling properties, so that a point settler model was found adequate.

The influent before and after primary clarification was characterised according to the method proposed by Lesouef *et al.* (1992). A daily loading rate distribution profile was estimated based on measurements of the influent composition every two hours for a period of two days. The characterisation of the influent gave interesting information on the difference in the influent COD/N ratio between weekends and weekdays. From the full-scale data it was observed that the loading rate and COD/N ratio were lower during weekends.

It was noticed that the total nitrogen removal decreased considerably during weekends. Based on these results a standard influent composition was defined, differentiating between weekend and weekday conditions. The definition of a standard influent made it easy to compare the simulation results of different scenarios. A quantification of the different sludge fractions was made by analysis of the model equations under steady state conditions.

Validation

Validation of the model was performed using full-scale oxygen, ammonium, nitrate, COD and biomass measurements at 4 equidistant places in the plug flow reactor. A more elaborate description of the validation is given in Coen *et al.* (1996).

Prediction

1. Overall upgrade

Taking practical limitations into account, the following measures were proposed for upgrading the WWTP with biological nitrogen removal (Figure 6) :

- Creation of two anoxic zones in compartments 1 and 4/5;
- Implementation of step feeding to compartments 1 and 4;
- Internal recirculation from compartment 9 to compartment 4.

The goal of the study was to redesign and operate the sewage treatment plant in such a way that the conditions for nitrification and denitrification are optimised for maximal nitrogen removal.

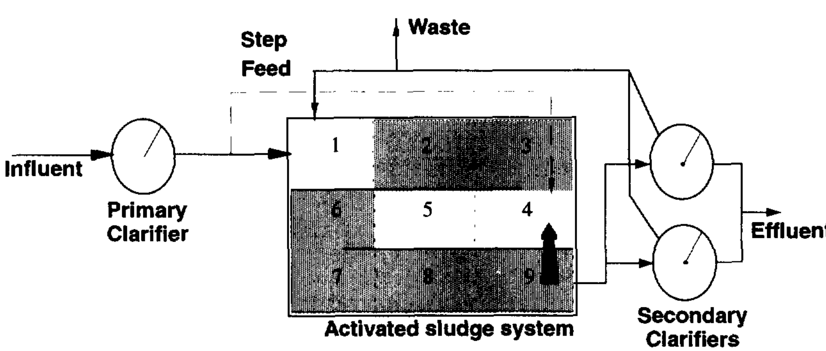

Figure 6. Schematic representation of the activated sludge system with indication of the proposed measures for nitrogen removal.

In Figure 7 the total nitrogen concentration (TN) in the effluent is shown when the standard influent is fed to the configuration without anoxic zones (config 1) and the configuration with the proposed anoxic zones (config 2). Without anoxic zones all ammonium is nitrified and the nitrogen in the effluent is present as nitrate. Without specific measures some denitrification already occurs because anoxic conditions are created when the reactor is highly loaded. During weekends - at lower loading rate and COD/N ratio - the average oxygen concentration in the aeration tank increases. This implies a decrease in denitrification capacity and thus an increase of the nitrate concentration in the effluent during weekends (Figure 7).

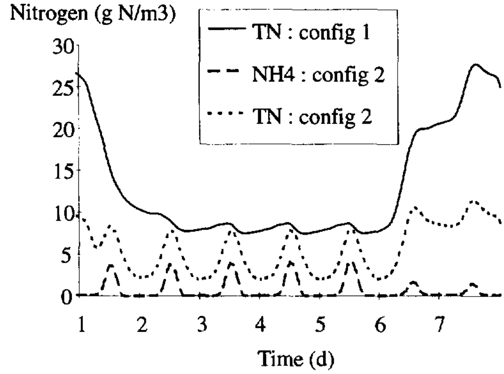

Figure 7. Effect of anoxic zones on the effluent quality (days 6 and 7 = weekend).

It is obvious that creation of anoxic zones reduces the nitrification capacity. Hence, within the existing reactor volume a compromise has to be sought between nitrification and denitrification capacities. The optimal denitrification volume was calculated to be about one third of the total reactor volume. With such denitrification capacity total nitrogen concentration decreased with about 5 g N/m^3. The concomitant reduction of the nitrification volume only slightly increased the ammonium concentration in the effluent. Ammonium was found in the effluent during periods of high loading rate. This increase in ammonium can be avoided by an increase of the aeration capacity, simulated by an increased K_La.

To evaluate the usefulness of step feeding two scenarios were simulated. The first one was a configuration with two anoxic zones (compartments 1 and 4/5) combined with step feeding. The second scenario was the configuration without step feeding but with only one, larger, anoxic zone (equally sized as in the first scenario, i.e. compartments 1, 2 and 3). By introduction of step feeding the hydraulic residence time of wastewater entering in compartment 1 is different from the residence time of wastewater fed into compartment 4. The step feeding ratio, i.e. the ratio of the influent flow fed into compartment 4 to the total influent flow, does not affect the mean residence time. Step feeding influences the biological growth rate in two ways. On the one hand, it changes the concentrations of ammonium and COD in the fed compartments. Optimal conditions for denitrification are created by an improved distribution of the COD load. In addition, the load of organic nitrogen to lane 1 and lanes 2/3 is balanced by step feeding. The step feeding ratio should not be too high to avoid exceeding the nitrification capacity of lane 2 and 3. On the other hand, step feeding reduces the dilution of recycled sludge by influent in the first lane. This implies that the sludge concentration in the first lane is higher than the sludge concentration in lanes 2 and 3. In this case study step feeding decreased the total nitrogen concentration in the effluent by about 1 g N/m^3. The optimal step feeding ratio was found to be 0.5.

Implementation of an internal recirculation from compartment 9 to compartment 4 had an ambiguous effect. Figure 8 shows the positive effect of internal recirculation during weekdays and the opposite during weekends. The nitrate concentration in the effluent is determined by two factors: on the one hand by the retention time in the anoxic zones, on the other hand by the denitrification kinetics. The internal recirculation has no impact on the overall retention time. With respect to the kinetics one should note that the internal recirculation flow contains a high amount of nitrate but practically no biodegradable COD. Hence, the internal recirculation increases the amount of nitrate fed into compartment 4 but dilutes the available COD from the step feeding. On weekdays it was found that a high internal recirculation decreased the nitrate concentration in the effluent by 1 g N/m^3 (Figure 8). During weekends however the influent contained a low amount of COD and the internal recirculation means that the COD concentration becomes rate limiting for denitrification. This causes during weekends an increase of the nitrate concentration in the effluent by about 2 g N/m^3 compared to the situation without internal recirculation. Hence, for optimal operation, it must be possible to adjust the flow during weekends.

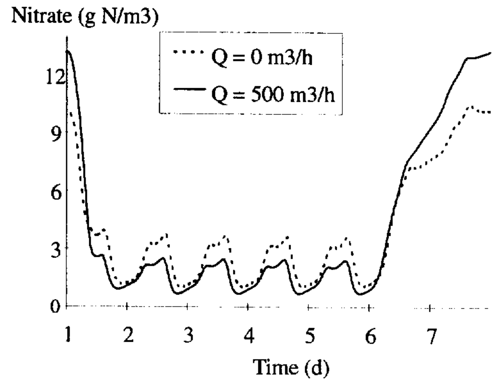

Figure 8. Effect of internal recirculation (days 6 and 7 = weekend).

2. Weekend operation

By means of simulation some operational actions (on top of the modified operation introduced above) were tested with the aim to avoid high effluent nitrate concentrations during the weekend (Table 2).

Adaptation of the sludge recycle flow to the decreased influent flow during weekends and control of the DO in compartment 9 could only diminish the nitrate concentration by 1 g N/m^3 and 3 g N/m^3 respectively. The high nitrate concentration in the effluent could efficiently be reduced by switching off aeration in compartment 2 during weekends, consequently increasing the anoxic volume during that period of low organic loading.

Table 2. Simulation results of the specific control actions during the weekend

Weekend control action	Average effluent nitrate concentration during the weekend (g N/m^3)
None	10
Control of DO in compartment 9	7
Switching off aeration in compartment 2	5
Sludge recycle ratio control	9

CONCLUDING REMARKS

In this paper it was shown that the available simulation models are capable of reproducing the performance of both an industrial and a municipal WWTP and that they offer a tool for optimisation. To model the industrial WWTP the readily biodegradable substrate had to be split up into two fractions, one related to the influent, the other being the external carbon source. Therefore, an adaptation of the IAWQ model No. 1 was necessary.

The calibration of the biological model for the industrial WWTP delivered a set of parameter values which were not within the ranges mentioned in literature. For each industrial WWTP an extensive calibration of the biological model may be required. For a municipal WWTP reference parameters can be used as an initial approximation of the model parameter values. If industry is discharging to a municipal WWTP it is recommended to perform additional tests for reliable calibration. In the second case study 40% of the PE originated from industrial activities. However, in this particular case rather small deviations from the reference parameter values were noticed.

Simulation of the industrial WWTP revealed that the dosage of an external carbon source for denitrification was too high. Therefore, a control strategy was proposed which prevented the addition of excess external carbon source and had as such an important impact on the operating costs. In addition, a comparison between the heterotrophic growth (and, therefore, the denitrification capacity) on methanol and glycol was made. From the simulation of the municipal WWTP with biological nitrogen removal it appeared that the effluent requirements could be reached with minimal supplementary effort. The effect of different operational parameters (anoxic volume, recycle flow, step feeding) were evaluated. During the weekend the high nitrate concentration in the effluent could be efficiently reduced by creating an additional anoxic zone in the first part of the biological reactor.

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