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# NITROGEN REMOVAL UPGRADE OF A WASTEWATER TREATMENT PLANT WITHIN EXISTING REACTOR VOLUMES: A SIMULATION SUPPORTED SCENARIO ANALYSIS

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## ABSTRACT

*A simulation supported scenario analysis for the upgrading of a municipal WWTP Hoogstraten (Belgium) with nitrogen removal is presented. The most cost-effective solution is to create optimal aerobic and anoxic conditions within the existing reactor volumes. The IAWQ-model No.1 was used for the simulation of the biological reactor. A measuring campaign and some specific respirometric tests provided the necessary information for calibration and verification of the biological model.*
*The study consisted of two parts : 1) increase of the denitrification capacity, and 2) optimisation of operation. First, the impact of three measures, i.e. creation of anoxic zones, implementation of step feeding and introduction of internal recirculation, was evaluated by means of simulation. For this purpose a standard time variant influent was defined based on the measuring campaign. This approach made it easy to compare the different scenarios.*
*In the second part of the study some specific problems were handled. To avoid high nitrate concentrations during weekends three possible control actions were simulated. The simulation study also evaluated the usefulness of the primary clarifier in the upgraded design and the effect on the biological process of first flush during intensive rainfall.*

## KEYWORDS

IAWQ-activated sludge model No.1, dynamic modelling, nitrogen removal, simulation, upgrading, wastewater treatment.

## INTRODUCTION

In the past wastewater treatment plants were designed for carbon oxidation (and nitrification) only. Nowadays, due to increasingly restrictive effluent standards for total nitrogen, upgrading of wastewater treatment plants (WWTPs) to complete denitrification becomes imperative in many countries. This can be reached by extension of the total reactor volume. Of course, the construction of additional reactor volume is expensive. In many cases the most cost-effective solution is to create optimal aerobic and anoxic conditions within the existing reactor volumes. This implies that the existing bioreactor should not be overloaded and the sludge age can be kept high enough to maintain autotrophic activity.

Since the publication of the Activated Sludge Model No. 1 by the IAWQ Task Group on Mathematic 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 a WWTP.

## DESCRIPTION OF THE WWTP HOOGSTRATEN

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 on about 100 % of the 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 % originate 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 (denitrification capacity) in the existing plant. Indeed, only a small fraction of the nitrogen was removed because in the front end of the plug flow reactor, anoxic conditions were created when the reactor was highly loaded.

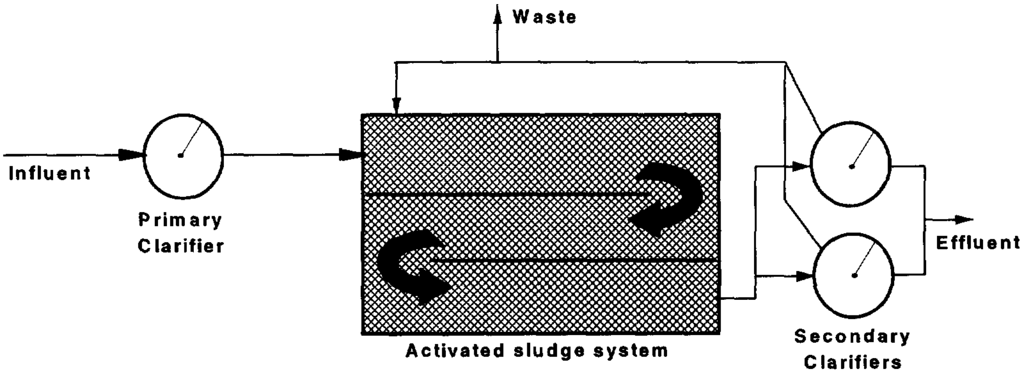

*Figure 1. Schematic representation of the wastewater treatment plant Hoogstraten*

## METHODOLOGY

To simulate a WWTP an overall model of the treatment plant needs to be build. This model should be a good representation of reality. The WWTP consists of different components. The processes in each component are described by an atomic model. The overall model for the WWTP is the combination of the coupled 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.

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, in this case evaluation of upgrade scenarios.

## RESULTS AND DISCUSSION

### Calibration

The aeration tank of the plug flow type was modelled with a N-tanks-in-series model. The number of completely mixed reactors in series was determined to be 9 using a correlation proposed by Chambers and Thomas (1985). The IAWQ-model No.1 (Henze et al., 1987) was used for simulation of the biological

*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.

reactors. A one month measuring campaign provided the necessary information for calibration and validation of the biological model. The measuring campaign also revealed that the sludge had very good settling properties. Consequently the secondary settlers were modelled with a point settler model.

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 over a period of two days. From the full-scale data it was observed that the loading rate and COD/N ratio were lower during weekends. Based on these results a standard influent composition was defined, differentiating for weekend and working day conditions. This approach made it easy to compare the different scenarios. A quantification of the different sludge fractions was made by analysis of the model equations under steady state conditions.

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 & 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 kinetics. For the determination of autotrophic kinetics a pulse of ammonium is added to the RODTOX (Figure 2.b).

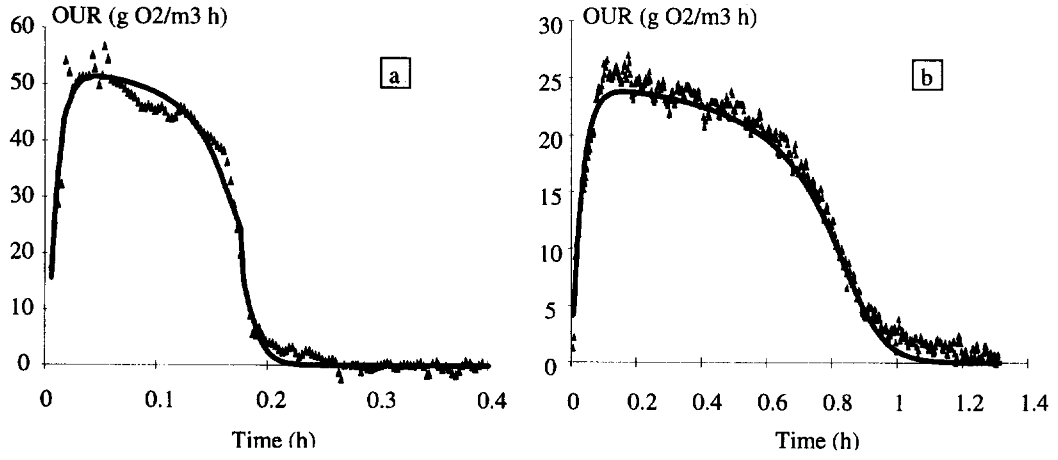

*Figure 2. Respiration rate profiles for determination of the heterotrophic and autotrophic kinetic parameters Dosage of one pulse of influent (left) and a pulse of ammonium (right) at t = 0 h. (Δ = measurements; full line = fit to Monod model)*

## 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. The validation was done for components characterised by slow (e.g. biomass concentration) and fast (e.g. DO concentration) process dynamics.

As can be seen in Figure 3 the sludge concentration decreased substantially during the measuring campaign. This was due to an increased waste sludge flow rate. After two weeks a new steady state was reached. The simulated sludge concentration in the different compartments differed only slightly and fitted with the measurements.

In Figure 4 the measured and predicted oxygen concentration at the beginning of the aeration tank are plotted. The oxygen concentration strongly fluctuates. This is the result of a high variation in loading rate during the day and the absence of DO control. It was assumed that the daily loading rate was distributed over the day following a fixed concentration distribution profile and the frequently measured flow rates. This

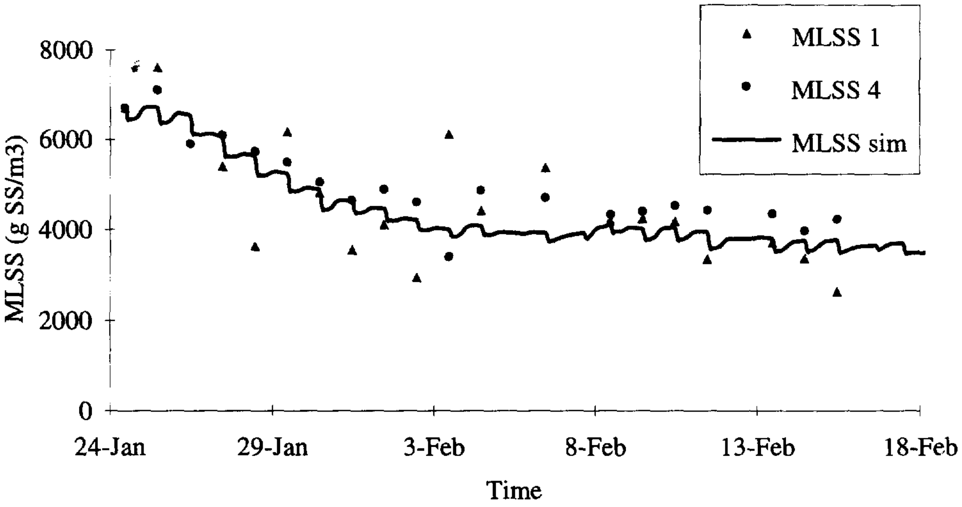

*Figure 3. Validation of the calibrated model : Sludge concentration measured and simulated (the numbers in the legend refer to the place of measurement in the plug flow reactor)*

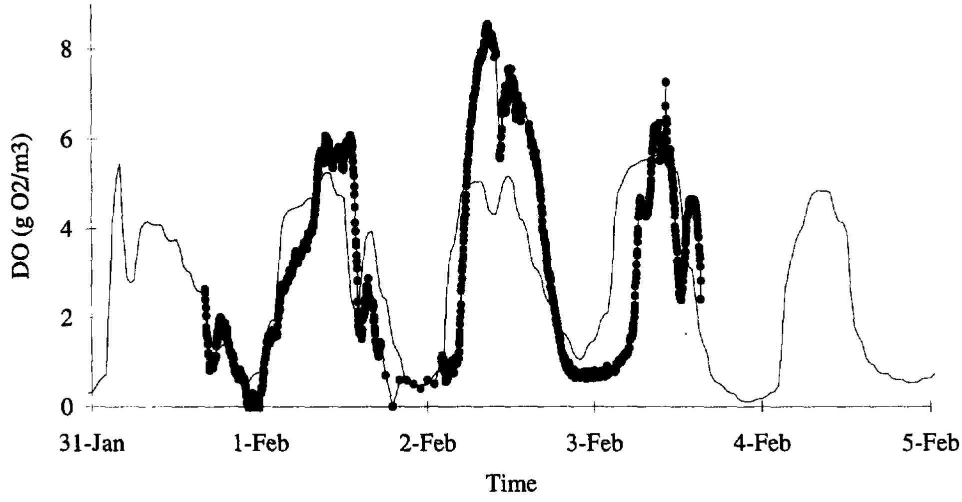

*Figure 4. Validation of the calibrated model : DO measured (•) and simulated (-)*

gives rise to a simulated DO profile, which is differently shaped from day to day. Discrepancy between the real and the assumed loading rate profile was probably the cause of the suboptimal fit between simulation and reality.

## Prediction

### *1. Overall upgrade*

Taking practical limitations into account, the following measures were proposed for the upgrading of the WWTP with biological nitrogen removal (Figure 5) :

- Creation of two anoxic zones in compartments 1 and 4/5 ;
- Implementation of step feeding in 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. With the simulation tool WEST (Wastewater treatment plant Engine for Simulation and Training, Hemmis NV, Kortrijk, Belgium) the measures proposed above were evaluated.

In Figure 6 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 occurred because anoxic conditions were created when the reactor was highly loaded (see also Figure 4). During weekends - at lower loading rate and COD/N ratio - the average oxygen concentration in the aeration tank increased. This implied a decrease in denitrification capacity and thus an increase of the nitrate concentration in the effluent during weekends (Figure 6).

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 broke through in the effluent during periods of high loading rate, i.e. once a day. This increase in ammonium could be avoided by an increase of the aeration capacity. This was simulated by an increased $K_la$.

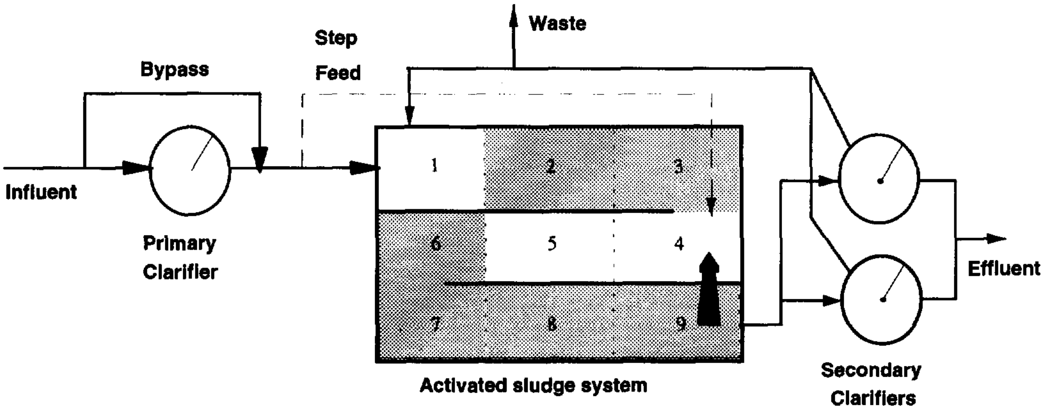

*Figure 5. Schematic representation of the activated sludge system with indication of the proposed measures for nitrogen removal*

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 feed. The second scenario was the configuration without step feed but with one large, 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 fluid entering in compartment 1 is different from the residence time of fluid fed into compartment 4. The mean residence time is independent from the step feed ratio, i.e. the ratio of the influent flow fed into compartment 4 to the total influent flow. Step feeding affects 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. Also the load of organic nitrogen to lane 1 and lanes 2/3 is adapted by step feeding. The step feed 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 by influent in the first lane. This implies that the sludge concentration in the first lane was higher than the sludge concentration in lanes 2 and 3. In this case study step feeding decreased the total nitrogen concentration in the effluent with 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. 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. 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 feed. On weekdays it was found that a high internal recirculation decreased the nitrate concentration in the effluent with 1 g N/m$^3$. During weekends however the influent contained a low amount of COD and the internal recirculation makes that the COD concentration becomes rate limiting for denitrification. This causes during weekends an increase of the nitrate concentration in the effluent with about 3 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. In the following the internal recirculation is not taken into account.

## 2. *Weekend operation*

By means of simulation some operational actions (on top of the modified operation introduced above), aimed to avoid high effluent nitrate concentrations during the weekend were tested :

- Control of the DO in compartment 9 by adjusting the air flow rate ;
- Switching off aeration in compartment 2 during the weekend ;
- Control of the sludge recycle ratio.

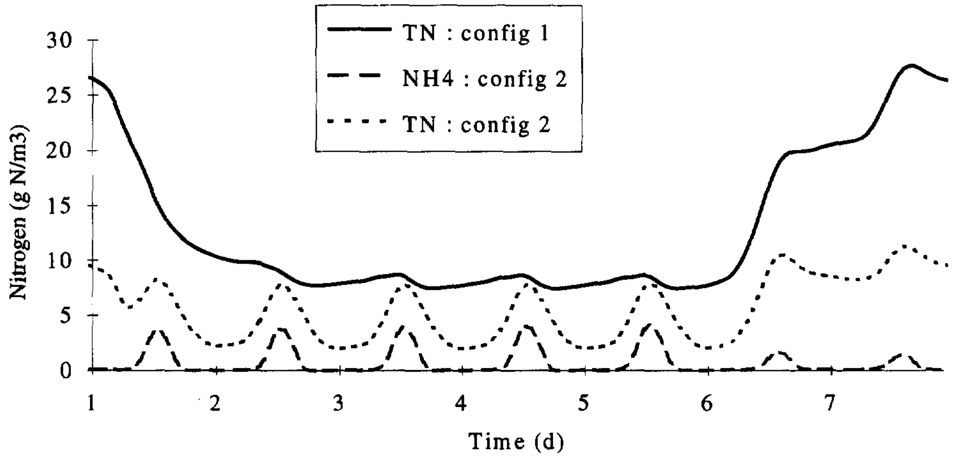

*Figure 6. Simulated total (TN) and ammonium (NH4) nitrogen concentration in the effluent for the configuration without (config 1) and with anoxic zones (config 2) (days 6 and 7 = weekend)*

*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 |

As given in 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 with 1 g N/m$^3$ and 3 g N/m$^3$ respectively. The high nitrate concentration in the effluent could efficiently be reduced by creating an additional anoxic zone at the head of the biological reactor during weekends.

### 3. *Primary clarifier*

The activated sludge system is preceded by a primary clarifier. The usefulness of this primary clarifier within the upgraded WWTP was evaluated. Primary clarification removes particulate material, part of which is slowly biodegradable. In case of a low COD/N ratio in the influent, one can question whether this slowly biodegradable fraction could not be used as carbon source for denitrification. The characterisation of the influent gave interesting information on the COD/N ratio in the influent before and after primary clarification. The results indicate that for optimal denitrification the primary clarifier should be by-passed (Table 3).

*Table 3. COD/N ratio of the influent*

| | Before primary clarifier | After primary clarifier |
|---|---|---|
| Working day | 10.4 | 8.3 |
| Weekend day | 6.6 | 4.7 |

Simulation confirmed that a better effluent quality could be reached when the primary clarifier was by-passed and the raw influent was fed directly to the activated sludge system. The simulation results predicted a decrease of the nitrate concentration with about 4 g N/m$^3$. However, because of the concomitant higher loading rate, the waste sludge flow Qw had to be increased from 94 m$^3$/d to 120 m$^3$/d to keep the sludge concentration constant. This resulted in a lower fraction of autotrophic biomass. The sludge age however could be kept high enough to ensure complete nitrification.

To evaluate the robustness of the upgraded plant for shock loading a one day period of intensive rainfall was simulated. During the first flush (period of two hours) a flow of 3 times the mean dry weather flow (DWF) was passed through the installation. The volume of the primary clarifier is 1000 m$^3$, i.e. 4 hours DWF. Three operational scenarios were evaluated with respect to the impact on the effluent quality. The first two are the options evaluated above.

Scenario 1 Without primary clarifier : the primary clarifier is always by-passed (Qw = 120 m$^3$/d).

Scenario 2 With primary clarifier : the material precipitating in the primary clarifier is wasted and not used for denitrification (Qw = 94 m$^3$/d).

Scenario 3 With storm tank : the primary clarifier is used as a storm tank. Whenever the influent flow rate exceeds 2.5 DWF the storm tank is filled at a rate of 2 DWF. The excess flow is sent to the activated sludge system. In this way the first flush can be buffered. If the flow rate drops below 2.5 DWF the content of the storm tank is pumped to the activated sludge system at a rate of 0.2 DWF (Qw = 120 m$^3$/d).

The simulation results (given in Table 4) revealed that only scenario 3 prevented a high ammonium discharge in the effluent. In scenarios 1 and 2 only a fraction of the first flush ammonium could be converted to nitrate. With the primary clarifier as a storm tank the retention time in the biological reactor was more equally distributed and the first flush could be buffered.

*Table 4. Effect of shock loading on the ammonium discharged in the effluent for the three scenarios*

| | Scenario | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| Peak ammonium (g N/m$^3$) | 15 | 8 | 2 |
| Peak effluent load (kg N/h) | 11 | 6 | 0.5 |
| Total effluent load (kg N) | 22.5 | 10 | 1.2 |

### *4. Discussion*

For a municipal WWTP reference parameters can be used as an initial approximation of the model parameter values. If industry is connected to a municipal WWTP it is recommended to perform additional tests for reliable calibration. In this case study 40 % of the PE originated from industrial activities. However rather small deviations from the reference parameter values were noticed.

Respirometry will be used in the future for on-line loading rate determination. The high measuring frequency of a respirometer allows a more accurate model calibration and improves the predictive value of the model (Vanrolleghem et al., 1994). It is also obvious that the respirometric data better represent the actual loading than COD data. In the measuring campaign of this case study only daily averages of the influent COD were measured. Mainly because of the gap between operational measuring frequencies and process dynamics, there was a suboptimal fit between measured and simulated DO concentrations in the biological reactor.

## CONCLUSIONS

From the simulation of the municipal WWTP with biological nitrogen removal it appeared that the effluent requirements could be reached within the existing reactor volumes and at minimal supplementary investments. The total nitrogen in the effluent could be reduced from an average of 16 g N/m$^3$ to 4 g N/m$^3$. The effect of different operational parameters (anoxic volume, recycle flow, step feeding) was evaluated.
During the weekend the high nitrate concentration in the effluent could be efficiently reduced by creating an additional anoxic zone in the front part of the biological reactor.
The low loading rate and COD/N ratio of the influent made complete denitrification impossible. Therefore, it was shown to be more advantageous to by-pass the primary clarifier.

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