

ADAPTIVE MODEL BASED CONTROL FOR WASTEWATER TREATMENT PLANTS

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Abstract

In biological wastewater treatment, nitrogen and phosphorous are removed by activated sludge. The process requires oxygen input via aeration of the activated sludge tank. Aeration is responsible for about 60% of the energy consumption of a treatment plant. Hence optimization of aeration can contribute considerably to the increase of energy-efficiency in wastewater treatment. To this end, we introduce an adaptive model based control strategy for aeration called adaptive WOMBAT. The strategy is an improvement of the original WOMBAT, which has been successfully implemented at wastewater treatment plant Westpoort in Amsterdam. In this paper we propose to improve the physics-based model by introducing automatic parameter adaptation. In an experimental model setup the adaptive model based control algorithm proves to result in better effluent quality with less energy consumption. Moreover, it is able to react to the varying circumstances of a real treatment plant and can, therefore, operate without human supervision.

Keywords

Model based control, adaptive control, energy-efficiency, wastewater treatment, aeration, optimization

1. INTRODUCTION

In 2008, the Dutch water boards and the ministry of Economic Affairs signed a contract that obliged the water boards to increase the energy-efficiency of wastewater treatment plants with at least 2% per year, accumulated to 30% in 2020. Since the energy-efficiency is computed as the fraction of the removed waste and the energy consumption, there are two ways to increase the energy-efficiency: (1) improve the effluent quality or (2) reduce the amount of energy used in the treatment process. The contract has been an important impulse for energy-innovation at wastewater treatment plants in the Netherlands.

An important step in the commonly applied biological wastewater treatment process is the activated sludge tank. Activated sludge roughly exists of two types of bacteria. The first type uses oxygen to break down ammonium (NH₄) into nitrate (NO₃). The second type removes nitrate and produces nitrogen gas (N₂), but requires a regime with low oxygen-concentration. Because of the different regimes of both bacteria, the activated sludge tank is usually split into two parts: aerated and non-aerated. Aeration of the activated sludge tank requires a serious amount of energy: about 60% of the energy consumption of a wastewater treatment plant (WWTP). Hence it is natural to start improving the energy-efficiency with a better control of the aeration-process.

To this end Witteveen+Bos and Waternet (water board of the Amsterdam area) have cooperated in optimization of aeration at wastewater treatment plant Westpoort in Amsterdam. The optimization project has resulted in a model based control algorithm using a simple physics-based model for the treatment process (see [1]). The control algorithm called WOMBAT (Witteveen+bos Optimal Model Based AeraTion) has been active at WWTP Westpoort since September 2009. The results are promising: better effluent quality with less energy. Nevertheless, WOMBAT had some shortcomings that caused the model to be suboptimal. Therefore, the goal of this research has been to improve the WOMBAT algorithm. The improvements are presented in this paper. The model has been further simplified (less parameters) and automatic parameter adaptation has been introduced. Parameter reduction was possible by removing the explicit formulation of temperature dependencies from the model. In a simulation model of WWTP Westpoort the adaptive WOMBAT algorithm gives a much better result, both in terms of energy consumption and quality of the effluent.

In this paper, we first shortly introduce the original WOMBAT model, show the performance and sketch the drawbacks of the model. In section 3 we describe the improvements to the model. Thereafter in section 4 the experimental setup and the results are described. Finally we draw conclusions.

2. MODEL BASED CONTROL AT WASTEWATER TREATMENT PLANTS

2.1 Optimal control of aeration

The speed of the biological processes in the activated sludge tank depends on several variables like the amount of dry sludge, the temperature and the oxygen concentration. Under idealized conditions (i.e constant flow, waste and temperature), in [2] the relation between oxygen concentration and the removal of ammonium and nitrate is characterized as sketched in Figure 1. This figure shows the dependency between the O₂ setpoint and total nitrogen (i.e. sum of ammonium and nitrate).

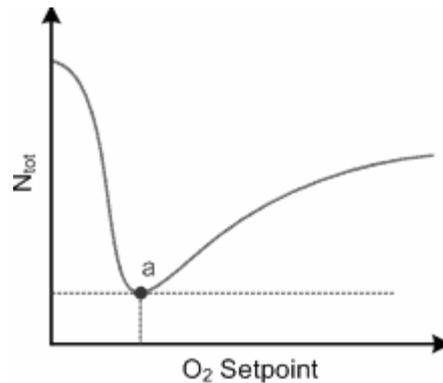


Figure 1. Sketch of dependency of N-total on the O₂-setpoint.

According to figure 1, there is a minimal oxygen level required before the bacteria in the activated sludge start to dissolve the ammonium in the inflow. Above a certain threshold ammonium starts to decrease rapidly, leading to a slight increase of nitrate. With an even higher oxygen level ammonium tends to zero, whereas nitrogen increases approximately linearly. In Figure 1, it can be seen that the total nitrogen level has a minimum for a certain oxygen level. As a result, an optimal control algorithm for the O₂-setpoint should have this oxygen level for output. In practice at a WWTP, however, conditions like inflow, waste and temperature are not constant in time, hence the algorithm has to take that into account.

Since the 1950s many papers have appeared on control theory in a general setting. According to Ang and Chong [3] the proportional-integral-derivative (PID) controller is the most simple and efficient method for system control. In [4] the authors conclude that there are two ways to apply PID controllers: compare measurements to a model or to a rule/heuristic. In industries, like WWTPs, the last type is commonly used. However, the heuristics-based PID controller is hard to apply for minimization of total-nitrogen. The first reason is the nonlinearity of the process and changing circumstances (e.g. temperature). The second reason is the response time of the biological process. A reactive controller like a PID controller starts to increase aeration only after an increase in ammonium has been measured. It takes at least half an hour before the increased aeration has an effect on the concentrations of ammonium and nitrate, so the controller is too late. A slow process like waste water treatment can benefit a lot from predictive control.

Based on Figure 1 we created an alternative for PID: a predictive control of aeration using a physics-based model (see [1]). Given a certain concentration of oxygen, the ammonium and nitrate levels are predicted with a hyperbolic and a linear model respectively. Both models are proportional to the inflow and inversely proportional to temperature. With the predictions of ammonia and nitrate the optimal value for the oxygen level can be determined. The output of the model based control algorithm WOMBAT is therefore twofold: the new O₂-setpoint and the predicted ammonium level. With the O₂-setpoint the aeration mechanism is controlled and the predicted ammonium level provides feedback on the fit of the underlying prediction model compared to reality.

The biological process responds slowly to changes in inflow, temperature and oxygen. For example at dry weather flow the peak in ammonium is usually a few hours after the peak in the influent. For this reason WOMBAT uses filtered and delayed values for flow, oxygen and temperature. The optimal length for filter and delay depends on the layout of the plant.

The original WOMBAT model has two important assumptions: a constant fraction of waste at the inflow and a constant fraction of activated sludge. None of the assumptions hold for a WWTP in practice. Nevertheless both are defensible since in the primary clarifier the influent is mixed and the dry sludge concentrations only vary mildly during a year.

2.2 History of WOMBAT at WWTP Westpoort

WOMBAT has been implemented at one of two identical activated sludge tanks at WWTP Westpoort. WWTP Westpoort is a large wastewater treatment facility in Amsterdam (the Netherlands). The plant receives both communal and industrial wastewater of about 500,000 i.e. (inhabitant equivalents) per year and has an inflow of 55,000 m³/day. Effluent discharge limits require N_{tot} concentrations below 10 mg/l and P_{tot} (total phosphorous) below 1 mg/l. Westpoort uses the biological mUCT (modified University of Cape Town) process for purification. In four parallel aerated activated sludge tanks, nitrogen and phosphorus are removed biologically. Figure 2 contains a schematic of the treatment plant including the activated sludge process.

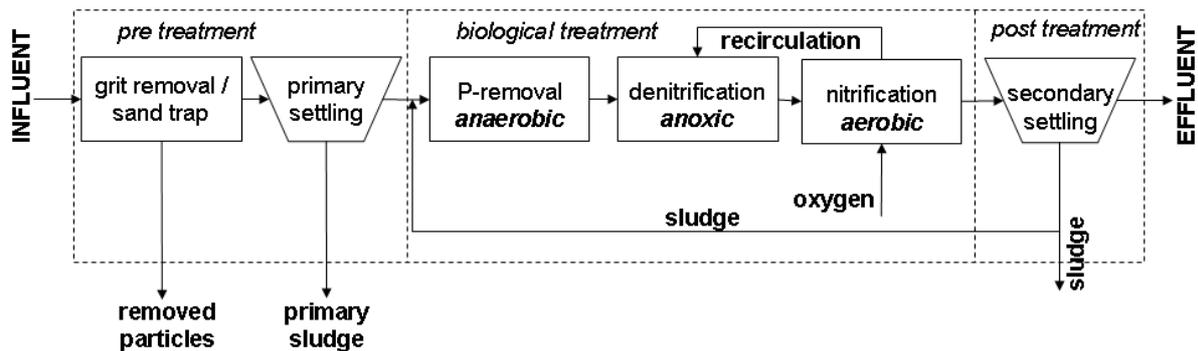


Figure 2. Schematic of the activated sludge process (i.e. biological treatment).

The standard control matrix is used for control of aeration at the other tank. This matrix picks a new O₂-setpoint based on the current measurements of ammonium and nitrate. The model based control algorithm has been active since September 2009 and compared to the control matrix, WOMBAT shows excellent results: (1) about 15% less nitrogen in the effluent, (2) a 20% lower O₂-setpoint, (3) 3-5% reduction in energy requirements, (4) a (not-intended) positive effect on phosphate and (5) more steady steering of aeration. All together the original WOMBAT leads to a significant increase in energy-efficiency and a more robust control of aeration.

2.3 Drawbacks of the model

During the pilot study at Westpoort a few drawbacks of the original WOMBAT were detected. First of all the model has 8 parameters defining the relation between the inflow, temperature, oxygen, ammonium and nitrate. These parameters have meanings like 'waste factor of the influent' and 'temperature effect on the process speed'. Initial values for these parameters can be estimated using a set of measurements. However, after initialization it is quite hard to tune the parameters. Since the conditions at a WWTP are varying (e.g. dry sludge concentration, changes in the sewer system, disturbances in the process at the plant), this implies that the parameters need to be retuned regularly for best performance.

The second drawback is the quality of the underlying model. Comparing the predictions with the measurements of the ammonium and nitrate indicate that the prediction is not good. A better tuning of parameters does not solve this problem. In fact there is no parameter-setting such that there is an overall good fit between model-prediction and measurement. An explanation for that might be the fact that there is a hysteresis effect between temperature and the process speed. From biology and the operators' experience it is known that the biological process behaves differently at the same temperature under increasing and decreasing temperature conditions.

Summarizing, in terms of prediction-error the model result is not sufficient but compared to the control matrix WOMBAT performs well in terms of energy-efficiency. The drawbacks sketched in this section are due to the fact that the model cannot respond to varying circumstances. Therefore we have investigated the possibilities to incorporate automatic parameter adaptation in the model.

3. AN ADAPTIVE WOMBAT

The original WOMBAT model for ammonium contains 8 parameters and 4 of them are related to temperature. We have investigated the possibility to delete all 4 temperature parameters while making the others adaptive. The resulting adaptive model should still be able to deal with the varying temperature and other varying circumstances.

An important component in the original model based control algorithm is the equation for the prediction of the ammonium concentration in the activated sludge tank. For that prediction the improved model uses the following elegant hyperbolic formula:

$$NH_4 = \alpha_2 Q / (O_2 - \alpha_1) + \alpha_3. \quad (1)$$

In this equation the variables Q (inflow) and O₂ (oxygen) are computed from the corresponding measurements at the plant using a filter that includes averaging and time-shifting. The formula contains only three parameters. The influences of the parameters on the prediction are sketched in Figure 3.

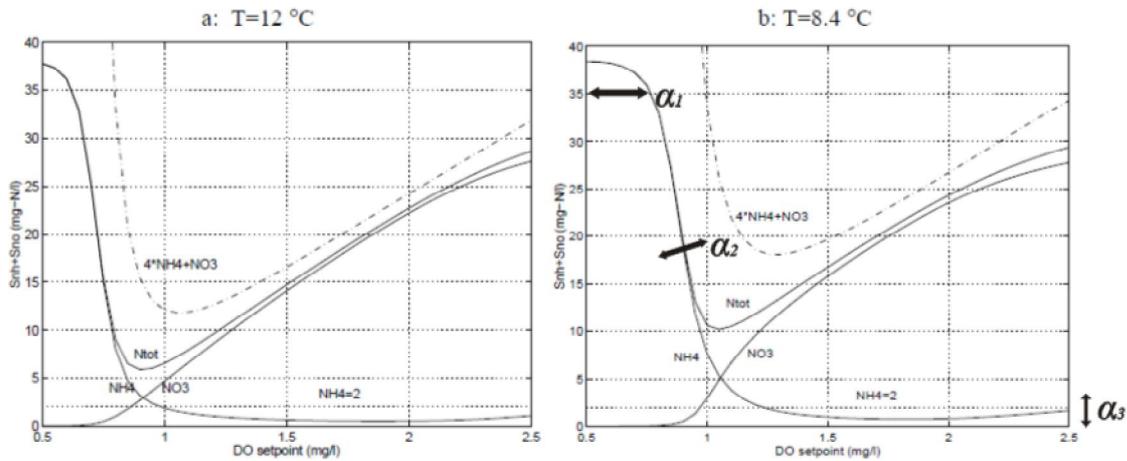


Figure 3. The influences of the remaining parameters, original figure from experiment in [2].

From this figure it can be seen that α_1 represents a lower bound of the oxygen level. Above this threshold the amount of denitrification increases. This lower bound is mainly influenced by temperature, because bacteria are more active at higher temperatures (compare Figure 3 at 12 and 8.4 °C). Therefore, we have chosen to adapt the first parameter to temperature. The updates will be made daily since temperature varies gradually in time. From the set of measurements we found a linear relation between α_1 and temperature.

The second parameter (α_2) in Figure 3 represents the fraction waste factor/process speed. When temperature is constant (which is true if we only look at one day) α_2 is determined by the waste factor and the dry sludge concentration. We therefore adapt this parameter once a day according to the relative difference between the measured and predicted ammonium level. In this way the model corrects itself when the prediction is consistently too high or too low.

The third parameter α_3 is used to deal with sudden changes in the several external impacts, such as the first flush in rainfall water flow. Every time the O₂-setpoint is updated, α_3 is adjusted according to the difference between the prediction of ammonium and the measurements. If the prediction is too high, α_3 is negative and vice versa.

In WOMBAT equation (1) for the prediction of ammonium is combined with a linear prediction of nitrate. Minimization of the sum of ammonium and nitrate gives the equation for the O₂-setpoint:

$$O_{2_SET} = \alpha_1 + \sqrt{(\alpha_2 / \tan(\varphi))Q} \quad (2)$$

Where φ is the angle between nitrate and the O₂-axis. In practice this angle is used by the operators to give priority to ammonium or nitrate. A high value for the angle gives a lower O₂-setpoint, hence more ammonium and less nitrogen and vice versa. To be able to deal with sudden external impacts equation (2) is corrected with a small value proportional to parameter α_3 .

With these parameters we have created an adaptive WOMBAT that deals with both long- and short-term varying circumstances. The parameters are updated at different frequencies and are adapted according to temperature and the ammonium measurements. We tested the improved model with an extensive simulation study, which will be explained in the next section.

4. EXPERIMENTAL SETUP AND RESULTS

Since testing the adaptive WOMBAT at the real plant is expensive, we first validated our model during a simulation study. To this end, we used the SIMBA toolbox of Matlab (see [5]), which is especially designed for simulating wastewater treatment plants. SIMBA uses activated sludge model no 2 as described in [6]. In this section we first briefly describe the simulation model and after this we compare the simulation results of the adaptive WOMBAT with the results of the original model.

In the SIMBA toolbox we virtually rebuilt WWTP Westpoort by adding the correct components of the plant. We added a measurement set of the real plant containing data of influent, temperature and pollution level of the past year. Moreover, we implemented the decision matrix and the original and adaptive WOMBAT control in Matlab in order to compare the controls and validate the results.

The simulation study shows that the prediction model has improved significantly. In Table 1 the results are summarized for model quality, effluent quality and energy savings.

Table 1. Model quality and simulation results relative to decision matrix under idealized conditions

	Model quality		Effluent quality			Energy savings	
	R ²	R ² dwf	NH ₄	NO ₃	N _{tot}	O ₂	Energy
original WOMBAT	0.003	0.24	+34%	-29%	-9%	-23%	-8.9%
adaptive WOMBAT	0.36	0.87	+33%	-27%	-8%	-23%	-9.0%

For the original WOMBAT the correlation coefficient (R²) of the predicted and measured ammonium level was 0.24 for dry weather flow (dwf). The improved model has a correlation coefficient of 0.87. Even at rain weather flow the adaptive WOMBAT model is able to give a reasonable model prediction (R² of 0.36), whereas for the original model the prediction and the measurement have no correlation at all. The improvement in the model quality is illustrated in Figure 4, where model prediction and measurement are plotted for both original and improved WOMBAT. We can conclude that the adaptive parameters result in a much better prediction.

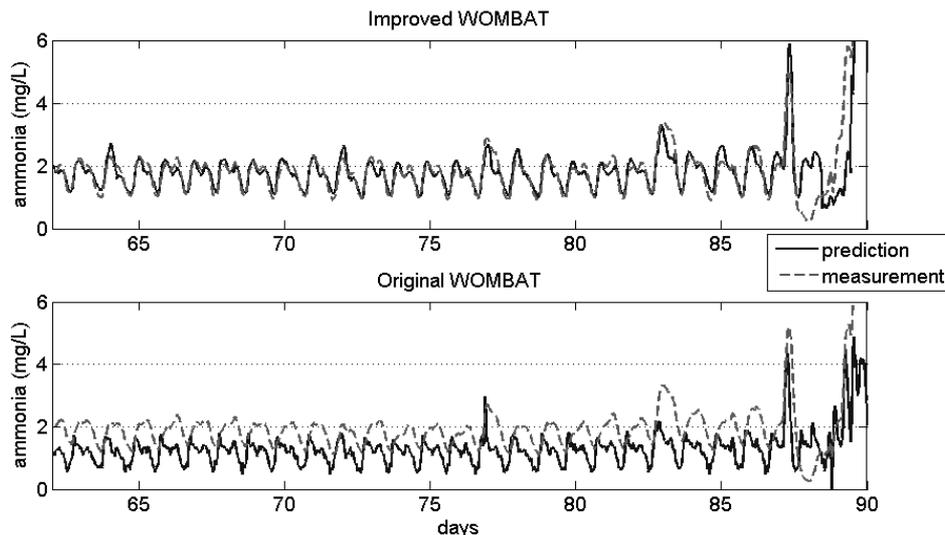


Figure 4. Prediction and measurement of NH₄ improved adaptive WOMBAT (on top) and original WOMBAT.

From Table 1 it is clear that both the original and the adaptive WOMBAT result in a better quality of the effluent while the treatment process consumes less energy. (The energy consumption is calculated via the saturation factor of oxygen in water.) We also conclude that control based on the decision matrix gives O₂-setpoints higher than the optimal setpoint, while WOMBAT gives setpoints closer to the optimum. The cost of saving energy and

increasing the energy-efficiency is an increase in the ammonium level. Since the treatment plants do not have legal upper bounds on this level, this cost is acceptable.

In terms of effluent quality and energy savings the adaptive WOMBAT performs almost equal to the original WOMBAT. This is caused by the fact that the results are generated in the SIMBA model. The SIMBA model has not the full variability of the real plant. Therefore in the model the energy savings are overestimated. In practice the energy consumption reduces only 3-5%. To get more realistic insight in the performance of both models we simulated WWTP Westpoort with random perturbations to the level of waste in the inflow (up to 50% above or below measurements). Moreover we tested the algorithm with a sudden increase of inflow with one third, which corresponds to a parallel activated sludge tank taken out of use. The original WOMBAT is not able to deal with these circumstances and requires retuning of parameters, whereas the adaptive WOMBAT notes the difference between model prediction and measurements and adapts its parameters. From this study it is clear that the adaptive WOMBAT performs significantly better than original WOMBAT and the decision matrix control. This results in better prediction, higher quality of effluent and lower energy consumption.

Concluding, the WOMBAT algorithm gives O₂-setpoints closer to the optimum than the decision matrix, which results in a significant increase in the energy-efficiency. Moreover, the prediction model in the adaptive WOMBAT performs significantly better than the original model and the adaptive model can deal with both short- and long-term variations in the circumstances.

5. CONCLUSIONS

In this paper we have introduced an adaptive model based control strategy for aeration of activated sludge tanks. The algorithm called WOMBAT uses a physics-based model and chooses the oxygen setpoint that gives optimal removal of nitrogen. The original version of the algorithm has been implemented at WWTP Westpoort in Amsterdam. Both the simulations with SIMBA and the data from the real plant prove that the new control strategy leads to closer to the optimal oxygen setpoint, resulting in both better effluent quality and energy savings. In practice, the original model appeared to have two important drawbacks: the quality of the model prediction is not as good as expected and the model is unable to handle the varying circumstances at a real plant.

To increase the flexibility of the model we have proposed an adaptive WOMBAT algorithm in this paper. In this improved algorithm the difference between model prediction and measurements is used to change the parameters in the model. The adaptivity allows simplification of the model by deletion of temperature dependencies. Simulations with the adaptive WOMBAT model in SIMBA showed that the improved control algorithm is able to deal effectively with varying circumstances. In near future, the adaptive WOMBAT will be implemented at WWTP Westpoort and will demonstrate the power of adaptivity in the real plant.

Summarizing, we have developed a model based control strategy for aeration that considerably improves the energy-efficiency and requires less maintenance because it has the capability to adapt to changes in loads and future conditions at the plant.

Future research will focus on the best strategy to adapt the parameters of the model, the development of a more advanced model for nitrate and on the application of the adaptive WOMBAT model to a wider range of wastewater treatment plants.

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