Improving the efficiency of a wastewater treatment plant by fuzzy control and neural networks

M. Bongards
Cologne University of Applied Sciences, Campus Gummersbach, Faculty of Electrical Engineering
Am Sandberg 1, D-51643 Gummersbach, Germany
(E-mail: bongards@gm.fh-koeln.de; Internet: http://www.bongards.de)

Abstract One of the main problems in operating a wastewater treatment plant is the purification of the excess water from dewatering and pressing of sludge. Because of a high load of organic material and of nitrogen it has to be buffered and treated together with the inflowing wastewater.

Different control strategies are discussed. A combination of neural network for predicting outflow values one hour in advance and fuzzy controller for dosing the sludge water are presented. This design allows the construction of a highly non-linear predictive controller adapted to the behaviour of the controlled system with a relatively simple and easy to optimise fuzzy controller. Measurement results of its operation on a municipal wastewater treatment plant of 60,000 inhabitant equivalents are presented and discussed. In several months of operation the system has proved very reliable and robust tool for improving the system’s efficiency.

Keywords Fuzzy control; neural network; wastewater treatment; sludge water; biological treatment

Introduction
In the western part of Germany more than 95% of the population is connected to a wastewater treatment plant and more than 92% of the plants are equipped with a biological treatment so that dissolved organic carbon is removed at a sufficient rate but the removal of nitrogen and phosphorus from the waste water still has to be improved (ATV-Information, 1995).

Modifications of German wastewater quality regulations now under discussion will push forward new developments.

- Until today it is sufficient to keep the quality of effluent wastewater below fixed limit values which are defined by governmental authorities.
- In the future this procedure shall be replaced by new regulations in which the plant has to pay “pollution units” depending on the amount of biological and chemical load in the effluent water (Scholl, 1997).

This new situation will force technical improvements of many wastewater treatment works which can be done by investments (1) in concrete, (2) in machinery, or (3) in intelligent control systems. The results presented in this paper show that option (3) is generating substantial improvements that can be achieved by moderate financial investments.

Wastewater works are not producing anything but they are removing substances with purified water and sludge as “final products”, so that the major design target is the security of operation. Furthermore the variation of process parameters like temperature or pH-value is not possible for economical and ecological reasons. The quality of the inflow is not controllable and its quantity can only be varied in a relatively small range by buffer basins. For an optimal operation wastewater works have to react on very dynamic variations of inflow parameters which shows the relevance of a well adapted closed loop control.

The biological wastewater treatment plant has to degrade the dissolved organic carbon and it has to remove the nitrogen and the phosphorus. Removing the nitrogen is the most
difficult part of the process, if it works well then in most cases the effluent concentration of organic carbon is sufficiently low (Poepel, 1994). Phosphorus is in most cases eliminated by chemical precipitation (ATV M 206, 1994; Poepel, 1991).

Many biological wastewater works have to treat wastewater with a high load of dissolved nitrogen. This can be the process water from sludge pressing or the effluent from waste composting plants or similar sources. Handling these substances becomes more and more critical as the governmental requirements for the outflow limit values increase. This situation motivated the Aegerverband located in Gummersbach (Germany) an operator of nearly 40 wastewater treatment plants to support the development of new control systems.

Different methods for solving the problem of wastewater with high nitrogen load by investment in new machinery and building are discussed by Groemping et al. (1998). In the paper presented here an alternative method is presented to control the removal of nitrogen by combining fuzzy control with the capability of prediction by neural networks. At first the technical background is described followed by the discussion of the controller system and by a presentation of first experimental results.

**Sludge water – a source of nitrogen**

Nitrogen is removed in a two-step-process, nitrification and denitrification. The nitrification process requires aerobic conditions. The concentration of dissolved oxygen has to be in the range of 0.5 to 2 g/m³. The denitrification needs anoxic conditions, so that the concentration of dissolved oxygen has to be as low as possible. Sewage works use different methods for the technical implementation like cascaded, alternating or simultaneous denitrification (Köhne, 1998). In the plant optimised during this project reactions of denitrification and nitrification are proceeded sequentially in consecutive basins.

Unfortunately only about 62% of the inflowing nitrogen dissipates in a gaseous state into the atmosphere. 18% is diffusing into the environment by the outflowing cleaned water. More than 20% is remaining in the sludge which has to be treated separately (Cornel et al., 1998). The sludge must be dewatered for further treatment in landfill or combusting for example by sedimentation, filter-pressing or centrifugation. The sludge water has to be recirculated into the inflow of the plant because it has an extremely high concentration of nitrogen about 500 g/m³ and more. Its carbon load can grow up to 3000 g/m³ BOD₅ and 6000 g/m³ COD which are about 10 times the inflow concentrations of municipal wastewater. The amount is estimated with 2.28 litres per inhabitant equivalent and day (Otto-Witte, 1996). If the plant is working at the limits of its capacity the dosing is a very critical step which has to be controlled by an appropriate strategy.

If the recirculation of the sludge water into the inflow of the plant is done in the daytime during normal hours of operation the ammonium load at the inflow can be increased by 30% or more resulting in an increase of the nitrogen outflow value so that the limit values can be exceeded.
To handle this problem a buffer tank with a capacity of several production days of sludge water is necessary. Furthermore an appropriate strategy of dosing the sludge water into the inflow has to be developed. Figure 1 shows a sketch of the main elements of the controlled system.

The behaviour of the controlled system, the biological part of the wastewater treatment plant, is only very roughly predictable: The activity of the micro-organisms depends on the concentration and biochemical composition of the biologically active sludge and on the amount of biologically degradable biomass which is of central importance for the denitrification. In a more general view the “history” of all these parameters has a decisive influence on the reaction because it determines the composition of the biomass which removes the nitrogen. A typical growth rate of the micro-organisms varies between 1/day to 6/day (Henze et al., 1995). The higher value indicates that a doubling of the population of micro-organisms takes place in less than 4 hours so that during a day the micro-organisms will continuously adapt to changes in their environment.

The simplest control approach is an open loop control using time controlled switches for dosing of the sludge water in times of low biomass load into the inflow. But this solution has two major disadvantages.

- Caused by the time dependent fitness of the complete system the switching program has to be adapted manually from day to day to the capacity of the plant – a time consuming and often neglected work.
- At night in times with low inflowing load the concentration of the natural carbon sources can be too low so that the process of denitrification only works well if additional carbon sources like ethanol are added, causing additional costs of operation.

The behaviour of the controlled system is highly non-linear and there is no clear periodicity from day to day, which means that the open-loop-control must be tuned to a very careful and conservative mode of operation, resulting in problems in the operation of the plant: insufficient amounts of sludge water are pumped out of the buffer tank limiting the sludge pressing.

A more sophisticated approach uses a closed loop control by on-line measurement of the concentration of nitrogen at the outflow of the aeration basin. The control-system normally is a standard PID-controller or a fuzzy controller.

This solution cannot convince in practical applications:

- Due to continuous modifications in the fitness of the biomass the controller has to be adapted continuously to the process, a very complex task in every day operation.
- Optimising a controller by simulation using an analytical model has made a lot of progress in the last few years (Jumar et al., 1998), but it remains a nearly endless job of high complexity caused by the various model parameters to be adapted and by the continuous modifications in system behaviour.
- The retention time of the system is in the range of one to ten hours mainly depending on the amount of inflow into the plant. So especially in the night times a high retention time makes an effective control impossible because then the dosing of sludge water should be reduced one or several hours before an increase of the nitrogen load in the inflow – impossible for the standard control system.

The situation is slightly improved by adding an additional nitrogen measurement at the inflow of the plant. But the problem remains that caused by the long retention time a high dosing rate of sludge water one or two hours before an increase in the nitrogen load at the inflow of the plant can already overload the system. So it will be too late when the inflow measurement detects an increase of the concentration parameters. Furthermore an on-line nitrogen measurement is relatively expensive in investment and operation. To solve this problem a predictive control is necessary and as described above an analytical approach is practically impossible because the modelling is very complex.
Table 1  Governmental Requirements of the maximal outflow concentration starting from the 01.01.2001 for the wastewater works Krummenohl

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Temperature of the wastewater</th>
</tr>
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<tbody>
<tr>
<td>COD</td>
<td>60 g/m³</td>
<td>always</td>
</tr>
<tr>
<td>P-total</td>
<td>2 g/m³</td>
<td>always</td>
</tr>
<tr>
<td>NH₄-N</td>
<td>5 g/m³</td>
<td>always</td>
</tr>
<tr>
<td>N-total</td>
<td>18 g/m³</td>
<td>≥ 12°C</td>
</tr>
</tbody>
</table>

Therefore an attempt was made to use neural networks for the prediction of outflow values. Neural networks have already been used successfully in wastewater treatment to check and validate measurement data (Haeck et al., 1998) or to estimate data which are not present due to breakdown of an analyser (Haeck et al., 1996). In other industrial applications they have predicted process parameters to optimise control (Koo et al., 1993; Peters, 1996).

Experimental analysis – prediction of outflow values

Experimental analyses of the prediction of outflow concentrations for NO₃ and NH₄ using neural networks have been made in 1998 at the wastewater treatment plant Krummenohl in Gummersbach (Germany) (Graner and Weise, 1998). The plant is purifying mainly municipal and some industrial wastewater of 60,000 inhabitant equivalents. The biological part consists of a denitrification tank followed by two aeration chambers.

The aeration is equipped with two natural gas-motors to drive the compressors that are consuming the gas produced in the anaerobic sludge treatment. This results in a very cost effective mode of operation but on the other hand the gas motors are more difficult to control than frequency controlled electrical drives. The main problem is that switching the motors on and off should be avoided as much as possible.

The amount of sludge water produced during normal operation of the plant is about 200 m³/day with a concentration of NH₄–N of about 700 g/m³. But it often happens that the amount of sludge water is doubled for example when the plant is treating the excess sludge of other wastewater works in the neighbourhood.

In the year 2001 the wastewater works has to guarantee new and sharper effluent values (details in Table 1) which was the initial motivation for the research presented in this paper. The process control system of the plant monitors and stores continuously 8 on-line measurements of the water way at a 5 minutes time interval: temperature, conductivity, flow-rate and pH-values at the inflows, the oxygen-concentration in the aerated nitrification area and the ammonium and nitrate concentration at the outflow.

In the first step all these data were used to train a neural network for predicting the ammonium and nitrate concentration at the outflow one hour in advance. A commercially available neural network software was integrated in Microsoft Excel worksheets which made its application easy to use. Multilayer perceptrons (MLPs) were trained with static backpropagation. Jordan/Elman networks were also used but showed no significant improvement of the prediction quality.

A sensitivity analysis of the input data over a complete month of operation showed that most of the input data are of only small relevance to the predicted outflow values. So the network could be simplified by only using the flow-rate and the conductivity at the inflows, the oxygen-concentration in the aerated nitrification area and the ammonium and nitrate concentration at the outflow as input data. Best results were achieved by configuring the neural network with two hidden layers of 15 and respectively 10 neurones. Figure 2 shows the input- and output-channels of the neural network.
Figure 3 shows the prediction of nitrate concentration using a trained neural network in comparison with the measured values. The error of prediction is below 0.3 mg/l which is a well acceptable value because the measurement error of the on-line-monitoring system in everyday operation is a value of the magnitude of 0.5 mg/l. The predicted values of ammonium are in most cases of similar precision so that the neural network could be installed as part of a predictive control system which is described in the following chapter.

**Fuzzy control for dosing the sludge water**

Fuzzy controllers have become a well accepted element in controlling the highly non-linear systems of a wastewater treatment plant (Schmitt *et al.*, 1998). A general problem in the application of this technology is the experimental “trial and error” approach in design and optimisation of the fuzzy rules. The adaptation of a controller to the process is a time-consuming affair which becomes even more complex in systems with many rules. Controlling the removal of nitrogen and phosphorus can require a complex fuzzy controller of 47 rules (Hansen, 1998).
The solution presented in this paper integrates the complex non-linear behaviour of the elements of the wastewater works already in the neural network which predicts the outflow values. Therefore a more simple fuzzy controller can be generated out of 14 rules that are based on the following principal ideas.

- If the buffer tank is nearly full, as much water as possible shall be dosed, otherwise the dosing can be done using a more conservative low-risk-strategy.
- If the predictions for ammonium (NH₄) and total nitrogen, the sum of ammonium and nitrate (NO₃), are low, the dosing should be high, otherwise it should be low.

The controller needs as input only three parameters: the on-line measured level of the buffer tank and the one hour prediction of ammonium and total nitrogen. Output of the controller is a setting value for the amount of sludge water to be pumped into the inflow. Figure 4 shows a graphical presentation of the fuzzy rules.

**Experimental results**

The combination of neural network and fuzzy controller was installed as a prototype on the wastewater treatment plant Krummenohl and was operated for several months.

The outflow values could be predicted with sufficient accuracy even at high signal dynamics. This enabled the controller to dose the optimal amount of sludge water.

In Figure 5 the amount of sludge water is reduced caused by a relatively high predicted value. In everyday operation it often could be seen that the prediction error of the Neural Network tends to overestimate the dynamic of the system which happens here at 22:00. This behaviour is well acceptable because in most cases it will improve security of the control algorithm. After 02:00 the nitrogen concentration is so low that the sludge water is dosed into the inflow with maximal capacity of the pump.

Before introduction of the new controller the oxygen concentration in the nitrification tank increased up to the saturation level during times of low organic load in the night. The new controller improves this situation drastically so that the oxygen concentration is in an optimal range. Figure 6 shows the comparison between two weeks of operation before and after the installation of the new controller.

It is well visible that after installing the new controller the oxygen concentration has decreased resulting in a more cost effective mode of operation because formerly high amounts of excess oxygen were blown into the atmosphere.
Conclusions

The main results can be summarised as follows.

- Before installation of the new controller every two days the time switches for controlling the pump of the buffer tank had to be adjusted. This work has become obsolete.
- The amount of pumped sludge water remained the same because this is only determined by the amount of sludge pressed which did not change. But now the buffer tank is mostly empty or half filled. Before installation of the new controller the buffer tank often was full at the end of the week so sludge could be pressed only in the evening or at the weekend.
- The oxygen concentration in the nitrification tank remains low during the night. Formerly it increased up to its saturation level because the organic load in the night was very low. Now high amounts of sludge water are pumped into the inflow during night hours which equilibrates the load.

Figure 5  Optimal controlling of the amount of sludge water in relation to the predicted outflow value (Measurements from 25.1. – 26.1.1999)

Figure 6  Concentration of oxygen before (Measurement starting 30.10.98) and after (measurement starting 18.01.99) introduction of the new controller
• The outflow concentration of nitrogen is always kept clearly within the governmental requirements.

The system has proved a very reliable tool for controlling the complex behaviour of the wastewater works. The laboratory equipment installed on the plant will now be replaced by an industrial version in close co-operation with a German producer of automation systems for the environmental industry.

The combination of neural network and fuzzy controller has proved a robust and highly adaptive tool to control the complex and extremely non-linear processes at a wastewater treatment plant. Integrating the neural network avoids the necessity of designing complex fuzzy controllers with many input parameters and rules. Furthermore the neural network allows a reliable prediction of process values so that predictive control is possible. This predictive control is especially valuable on wastewater works where strongly varying retention times of several hours occur. In the near future the neural network will be applied to other wastewater works to test and to improve its applicability.

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References


