

Validation and implementation of model based control strategies at an industrial wastewater treatment plant

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Abstract In this paper, the practical implementation and validation of advanced control strategies, designed using model based techniques, at an industrial wastewater treatment plant is demonstrated. The plant under study is treating the wastewater of a large pharmaceutical production facility. The process characteristics of the wastewater treatment were quantified by means of tracer tests, intensive measurement campaigns and the use of on-line sensors. In parallel, a dynamical model of the complete wastewater plant was developed according to the specific kinetic characteristics of the sludge and the highly varying composition of the industrial wastewater. Based on real-time data and dynamic models, control strategies for the equalisation system, the polymer dosing and phosphorus addition were established. The control strategies are being integrated in the existing SCADA system combining traditional PLC technology with robust PC based control calculations. The use of intelligent control in wastewater treatment offers a wide spectrum of possibilities to upgrade existing plants, to increase the capacity of the plant and to eliminate peaks. This can result in a more stable and secure overall performance and, finally, in cost savings. The use of on-line sensors has a potential not only for monitoring concentrations, but also for manipulating flows and concentrations. This way the performance of the plant can be secured.

Keywords Activated sludge; dynamic simulation; industrial wastewater treatment; model based control; on-line sensors

Introduction

The treatment of wastewater has come a long way. A first phase in wastewater treatment focused on the removal of organic components. Later on more attention was paid to the removal of nutrients by means of nitrification, denitrification and biological or chemical phosphorus removal. While nutrient removal is actually a hot topic and is being implemented in several treatment units, another phase is yet to come. In Flanders more and more industrial plants are confronted with the fact that stringent legislation makes the discharge into a municipal wastewater treatment plant more difficult. The disconnection from the municipal sewer system forces industry to produce an effluent that meets the standards for surface water discharge. There is no doubt that in many cases efforts close to or even exceeding the BATNEEC (Best Available Technique Not Entailing Excessive Costs) principle are needed.

Basically this evolution requires a wastewater treatment plant that is working at its best performance and beyond. This situation is even further complicated by the fact that the number of processes that take place simultaneously is increasing which makes it more difficult to manage the overall functioning of the plant.

The use of control strategies might provide an answer to this complex situation. Control strategies for activated sludge systems, particularly the ones for aeration control, have been investigated intensively. However, in practice still very little use is being made of the potential of these emerging control techniques (Kalker *et al.*, 1999). The use of control techniques, apart from pH control and straightforward aeration control based on dissolved

oxygen, hardly has been introduced in wastewater treatment. In order to support the thesis that control can help to overcome the problems faced in wastewater treatment nowadays, this paper presents the development, the implementation and validation of model based control strategies at an industrial wastewater treatment plant.

Methods

Description of the plant

The test case was a wastewater treatment unit of a pharmaceutical plant in Belgium. A schematic presentation of the plant is given in Figure 1. The load to the system is about 15 tons of COD or 7 tons of BOD per day.

The average influent and effluent composition for the most important parameters is given in Table 1. The mean influent COD concentration was about 6150 mg/l and ranged from 3100 to 10,100 mg/l in 90% of the measurements. The overall mean BOD concentration was 2785 mg/l. The nitrogen in the influent can be split up into different parts. The average Kjeldahl nitrogen concentration was 256 mg/l of which only 10% was ammonia nitrogen. The remaining 231 mg/l was organic nitrogen. The influent total phosphorus concentration ranged between 0 and 2 mg/l in 90% of the measurements.

The influent was characterised by a large variation of the day-to-day composition. This is illustrated by a frequency histogram of the difference in COD concentration for 2 consecutive days in Figure 2.

The volumetric loading rate of the trickling filters was 4.4 kg COD/m³.d. Temperature

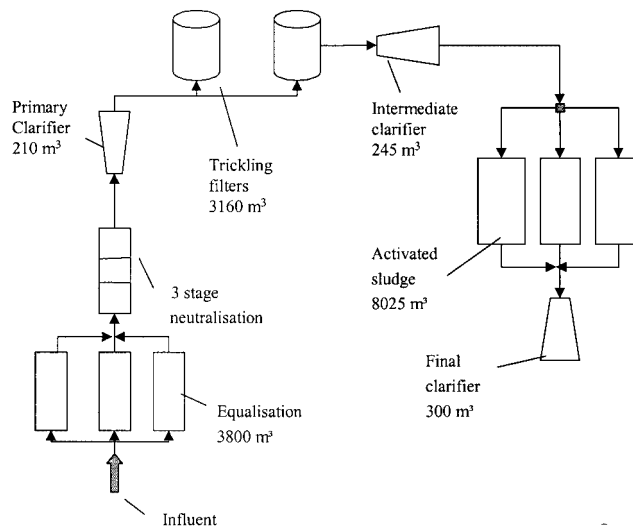


Figure 1 Schematic presentation of the wastewater treatment plant

Table 1 Average influent and effluent composition

	Influent	Effluent trickling filters	Effluent activated sludge
Flow (m ³ /d)	2500		
COD (mg/l)	6150	2760	681
BOD (mg/l)	2785	1407	179
TKN (mg/l)	256	144	112
Organic N (mg/l)	231	135	76
NH ₄ ⁺ -N (mg/l)	25	9	36
Total P (mg/l)	1		2

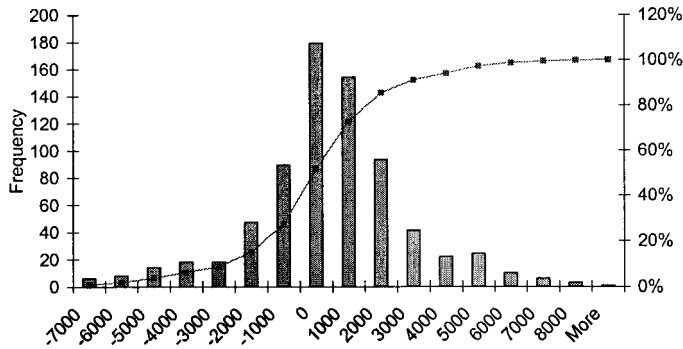


Figure 2 Frequency histogram of day to day COD variation in the pre-treatment, measured as COD at day x minus COD at day $x-1$

and loading influenced the efficiency of the trickling filter. The reduction of COD and BOD was on the average 50%.

The volumetric loading of the activated sludge system was on the average $0.83 \text{ kg COD/m}^3\cdot\text{d}$ and 90% of the values were within the interval of 0.60 to $1.47 \text{ kg/m}^3\cdot\text{d}$. The sludge loading rate was $0.2 \text{ kg COD/kg SS}\cdot\text{d}$ and was higher than 0.32 for 5% of the measurements. As a consequence, it can be concluded that the activated sludge system was on the average not overloaded. However, important fluctuations had to be dealt with.

The effluent mean COD and BOD concentration was about 681 mg/l and 179 mg/l respectively. In general, the effluent quality varied strongly. The removal efficiency of the activated sludge system was 72%. When the complete treatment plant is considered, 87% of the influent COD was removed. The effluent quality of the plant was strongly related to the loading rate and mainly to the variation of the load. About 56% of the Kjeldahl nitrogen was removed in the system. The bulk of the nitrogen removal was achieved in the trickling filter. Nitrification was not obtained.

Integration of on-line sensors

In the framework of the project additional on-line sensors were installed at the full-scale plant. An overview of the existing and additional sensors is given in Table 2. The data of all sensors were collected on a central PC. The data could be accessed remotely by means of a modem. This made a close follow up of the performance of the plant and the sensors possible.

The level sensors were already present at the plant. A TOC sensor (ISCO UV 3500, Applitek, Belgium), using UV detection and peroxide as an oxidant, was used to monitor the organic load after equalisation. A respirometer (ROD TOX, Kelma, Belgium) was

Table 2 Overview of sensors

Location	Type of sensor
Equalisation system	Level
Effluent of the equalisation system	TOC Respirometer
Effluent trickling filter	Respirometer
Effluent activated sludge	Ammonia Phosphate Turbidity Flow
Final clarifier	Settrometer Sludge blanket height meter

installed before the trickling filter to monitor toxicity and short term BOD concentration. This apparatus could be operated in a multiplexed way so that it alternately characterised the influent and the effluent of the trickling filter. Ammonia, phosphate, turbidity and flow were measured on-line in the effluent of the activated sludge plant. The settling characteristics of the sludge were monitored with both a sludge blanket height meter (Staiger Mohilo, Applitek, Belgium) and the Settlimeter (Applitek, Belgium). This last sensor is measuring the main settling parameters, SV, SVI and settling velocity on-line.

Development of the model

For a model-based optimisation of a wastewater treatment plant, it is not sufficient to consider merely the biological aspects. Knowledge of the hydrodynamic behaviour is also needed (De Clercq *et al.*, 1999). This was done using a tracer test with LiCl. A tanks-in-series model for the trickling filter and the activated sludge was developed resulting in an overall hydraulic model for the plant. As an example the lay-out of the hydraulic model of the activated sludge plant as it was implemented in the wastewater treatment plant simulator WEST (Hemmis, Kortrijk, Belgium) is depicted in Figure 3.

To simulate the behaviour of the trickling filter system, the simplified mixed-culture biofilm model developed by Rauch *et al.* (1999) was used (Vanhooren *et al.*, 2000). The Activated Sludge Model No. 1 (Henze *et al.*, 1987) was used for the activated sludge system. However, the model structure of both models had to be modified in order to describe the specific wastewater composition at the plant. The models originally describe carbon and nitrogen removal but especially the activated sludge model was modified to account for the phosphorus deficiency (Coen *et al.*, 1998). For most of the parameters the default values were used (Henze *et al.*, 1987). Only the yield of biomass growing on organic substrate (Y_H), the maximum specific growth rate of the biomass (μ_{max}) and the decay rate of the biomass (b_H) were tuned. The adapted structure and the estimation of kinetics and influent characteristics were based on profiles of substrate degradation related Oxygen Uptake Rate (OUR) (Coen *et al.*, 1998). Intensive measuring campaigns were used to support the model calibration and validation.

The behaviour of the settling characteristics as a function of the polymer dosing was successfully implemented in a 1-D dynamic settler model (Vanderhasselt & Vanrollegheem, 1999). However, as secondary clarifiers exhibit rather complex processes, it is difficult to model the complete settling behaviour. Aspects like shock waves, rising sludge or erosion were therefore not considered.

Development of the control strategies

The control strategies were developed and tuned using the models of the different units of the wastewater treatment plant. Based on the analysis of the wastewater treatment performance it was decided to develop control strategies for the equalisation, the polymer dosage and the phosphorus dosage.

A schematic presentation of the control algorithm for the equalisation is given in Figure 4. As mentioned before, the influent varied strongly and, moreover, increasing production capacity resulted in a continuous increase of the loading to the wastewater treatment plant. Increasing the buffer volume could be a solution to these problems but based on the standard design criteria it could be calculated that an additional working volume for the equalisation of approximately 3,600 m³ would have been needed. As an alternative, it was intended to level out fluctuations by means of a more stringent control of the equalisation system.

The control algorithm used the water level in the three equalisation tanks and the TOC concentration of the outlet as inputs. The development of the control strategy resulted in a

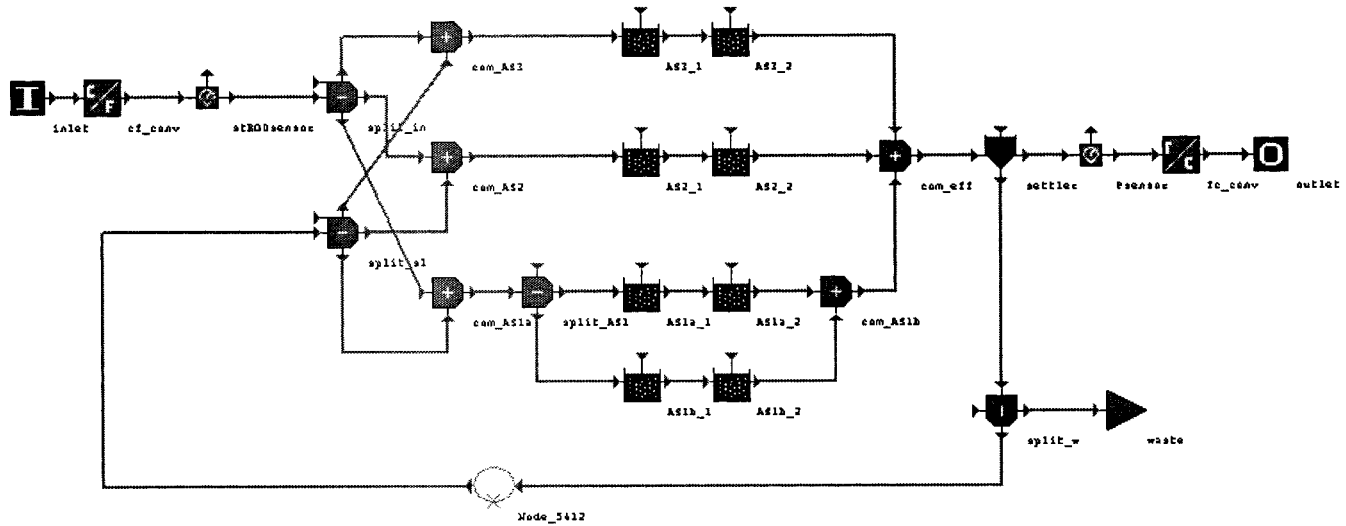


Figure 3 Hydraulic lay-out of the activated sludge process model

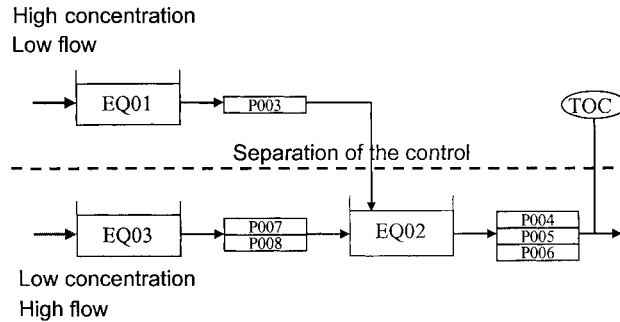


Figure 4 Control algorithm for the equalisation

change of operation of 2 of the 3 basins of the equalisation from parallel operation to an operation in series. The control could be divided into two subtasks, namely the control of the flow and the control of the TOC concentration. The control of the flow was achieved by operating the equalisation with varying volumes. The TOC concentration was equalised by controlling the flow from the equalisation basin containing highly concentrated wastewater (EQ01).

Indeed, in the configuration outlined in Figure 3, the volumes of EQ02 and EQ03 were used to stabilise the flow, while the highly concentrated wastewater in EQ01 was used to buffer the output substrate concentration. The second controller (the one computing the flow from EQ01) was a simple Proportional Integral Derivative (PID) controller. The flow rates from EQ03 and EQ02 could then relatively simply – and optimally – be computed using a complete state feedback Linear Quadratic (LQ) controller. In this case where PID and LQ control were integrated into one control system, no concentrations needed to be estimated, since the only measurement that was needed by the control law was precisely the output waste concentration that was measured on-line.

The proposed control scheme gave good results when part of the state of the system (e.g., the volumes) were far enough from their constraints (e.g., low and high volume limits). In other words, the control scheme gave good performance but only when the three tanks were not full or empty. In these two extreme situations (volumes full or empty), the control system missed the necessary degree of freedom to buffer both the output flow rate and the output TOC concentration. The control thus inevitably led to poor performance (Harmand *et al.*, 1999).

To overcome the problems underlined in the previous section it was thus mandatory to force the state to remain in a given pre-defined space around the operating point. Therefore, a supervisory control approach was used that allows adaptation of the operating point by computing the set points to be used. In fact, this system corrected the flow rates in order to keep the volumes within their hard constraints. With this configuration, the set points were no longer constant. Instead, they were the outputs of a fuzzy control system into which the tank volumes (measured on-line) entered (Harmand *et al.*, 1999). The following example can illustrate the idea. The supervisory system decides, for example, to decrease the set point of the output flow rate if it is established that both EQ02 and/or EQ03 are almost empty. To design such a supervisory system, it was decided to use fuzzy logic because of its interest in handling non-linear but “intuitively understandable” situations. Indeed, even though advanced control schemes are scarcely used in the wastewater treatment field, there is often an important human expertise about the best way to operate a plant. Thus, since fuzzy control rules naturally capture the acquired experience of human operators, it is a very powerful tool to control these processes. It can also incorporate semi-quantitative

information into simplified models and it is able to put subjective information into a form usable by computers.

A second control strategy for the dosing of polymer at the final clarifier was designed. Different control algorithms, using respectively the sludge blanket height (feed-back, FB), the hydraulic loading (feed-forward, FF), the sludge loading (FF) and the sludge volume loading (FF), were tested for their ability to keep the sludge blanket height below a critical level. The control strategy, based on the hydraulic loading was the least efficient one with respect to minimising polymer dosing. The others appeared equally effective provided they were properly tuned. Using the level of the sludge blanket as a criterion for the evaluation of the control effectiveness, strategies based on more than one measurement were shown to be less sensitive to suboptimal tuning (Vanderhasselt *et al.*, 1999).

Finally, a controller for the dosing of phosphorus was developed. The dosing of orthophosphoric acid can be optimised with a feed back PI-controller or a combination of feed forward and feed back control.

Integration and implementation of the control strategies

The final step was the integration and validation of the control strategies at full scale. Figure 5 presents the architecture of the equalisation controller. The system was designed according to all the engineering and safety requirements of the plant.

The signals from the sensors (4–20 mA from level control and TOC) were collected by data logging modules and transferred to the PLC, which transfers the data to the control PC. The control algorithm was executed in MATLAB. A SCADA system established the link between the sensors, actuators and users. The output of the control action was a set point of the flow. The determined flow was finally achieved by timed on/off control of the screw pumps. The PLC supervised the controller actions in all cases and assured that no safety limits were exceeded.

Results

Simulation results of the equalisation controller action for the flow are plotted in Figure 6. The variation of the flow for a period of about 2 months illustrates the effectiveness of the controller. Only when the water volume in the basins of the equalisation tended towards its upper limit, peak flow rates were observed. The standard deviation of the flow could be reduced by a factor 3. The results of the control of the TOC concentration are given in

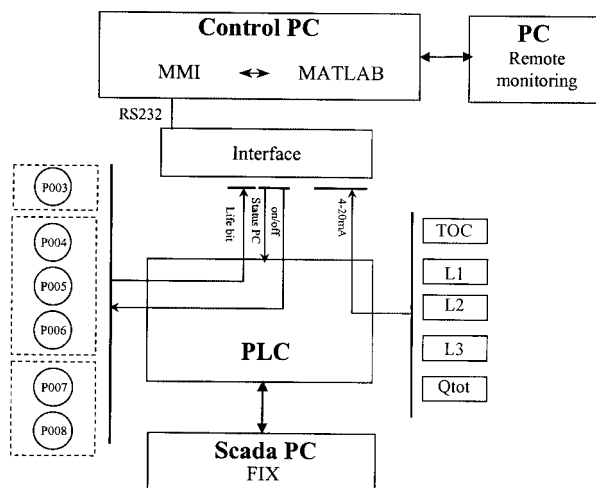


Figure 5 Practical integration of the control for the equalisation

Figure 7. The figure presents the influent concentration of the main wastewater stream, the set point and the outlet concentration. It is shown that in some cases the outlet concentration is lower than the set point. This was due to the correcting action of the fuzzy control supervisor, because the level in the tank containing the highly concentrated wastewater reached its minimal limit.

With respect to the settler control, simulation results indicated a reduction of polymer dosing by a factor of about 250 by using the developed control strategies. A major part of this difference could be linked to the design of the clarifier. Using the full-scale operational procedures, e.g. to keep the sludge blanket below 0.5 m and to avoid sludge wash out in the simulation, the difference between the actual full-scale polymer consumption and the simulated one was reduced to a factor 10. Part of this difference could be explained by a significant reduction of the effectiveness of the polymer caused by a considerable period of high turbulent mixing after injection of the polymer (Vanderhasselt *et al.*, 1999).

It is believed that the addition of phosphorus will optimise the effluent quality. However, some problems were encountered during the integration of phosphorus dosing at the full-scale plant because of precipitation of phosphorus salts. This aspect was not included in the model. Hence, tuning of the controller based on simulations could only provide approximations of the parameters of the controller. To date, full-scale tests are being performed.

Conclusions

The different phases of the project illustrate that the complex behaviour of an industrial wastewater treatment plant can be described by means of mathematical models. The volume of the tanks, the flow and the concentration completely determine the model of the equalisation. On the other hand, modelling the behaviour of the biological systems, e.g. trickling filter and activated sludge, demands intensive measuring campaigns, supported by on-line sensors and laboratory experiments. The sludge sedimentation can be enclosed in a 1 D dynamic settler model.

Although not all variations observed in the plant could be described with the models, the level of accuracy of the model made detailed concept engineering of control strategies possible. The model based control system was designed according to the engineering and safety requirements of the plant. An integrated system of control-PC and the PLC of the wastewater treatment plant, with reliable communication between the two systems, met all of these requirements.

The results of the implementation of the control strategies at an industrial wastewater treatment plant indicate that on-line sensors and advanced control strategies are valuable tools for optimising the performance of a plant, without immediate needs for expansion. Also the use of on-line control has a big potential in cutting the operational costs by for example optimising the addition of chemicals.

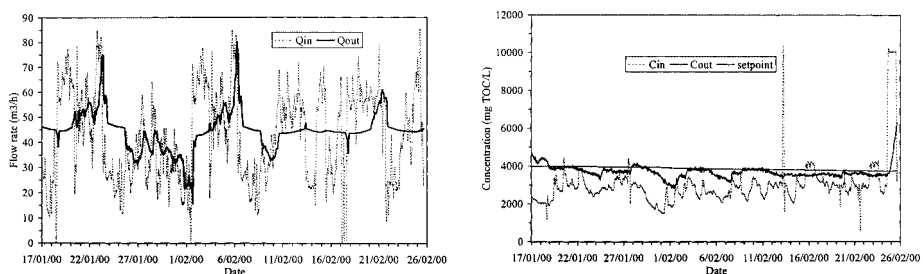


Figure 6 Flow prior to and after EQ

Acknowledgement

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