Implementation of a wastewater treatment plant operation support tool based on on-line simulation

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Abstract The operators of modern wastewater treatment plants (WWTPs) are faced with increasing demands. Beyond the requirement to consistently meet discharge limits for pollutant loads, the cost efficiency of plant operation is becoming more and more important. This results in new challenges for automatic control and human control action. On-line simulation opens up interesting perspectives to provide comprehensive process information, serving as a base for optimised operation of WWTPs. This paper describes the development and application of a computer analysis and support tool for the large-scale municipal WWTP of the city of Magdeburg, Germany. It will show that by linking a simulation server to the Distributed Control System (DCS) relevant additional features for plant control arise. A good cost–benefit ratio of the system is achieved by using web techniques for implementing the software.

Keywords Activated sludge model; distributed control system; on-line simulation; operation support; process control

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Introduction

During the plant design dynamic simulation makes detailed studies of critical situations of load, different plant layouts, tailor-made automatic control strategies and concepts for plant operation possible. However, one can notice a growing interest by practitioners in a direct application of simulation to support the plant operation itself. In this case, the software system for dynamic simulation has to be linked to the DCS and it is periodically supplied with process data, e.g. the rate and quality of influent, the actual power consumption of the aeration system, the amount of sludge and the amount of internal recycles. Some basic concepts concerning such on-line simulations are reported in Obenaus *et al.* (1999).

Typically, state-of-the-art WWTPs provide many options for process interaction, either for human interaction or for automatic control. To take advantage of these interaction inputs in an optimised manner, two preconditions have to be fulfilled. Firstly, one needs sufficient information on the state of the process and the load situation, both given in time intervals of a few minutes. Secondly, the operator needs a suitable base to estimate the plant's behaviour in the future if some control inputs were changed. By means of dynamic simulation both of these aspects can be dealt with.

The availability and frequency of the use of on-line measuring techniques have shown a significant increase recently. However, even in the best case various process characteristics are not measurable. Dynamic process models, called observer models in this context, which are integrated in the DCS, offer a straightforward way to obtain internal process information. The prediction of effluent values of the WWTP, considering different conditions, can be accomplished by a second model. The initial conditions of this prediction model are based on the present state of the real plant estimated by the observer model.

Several model approaches are available for dynamic simulation of WWTPs. However, the Activated Sludge Models (Henze *et al.*, 1987; Henze *et al.*, 1998) have a suitable degree of detailed description. They are widely accepted within the scientific community, and there are many reports in literature on experience gathered in the application of these models. This is why the model ASM 2d (Henze *et al.*, 1998) was used by the authors for the implementation of the operation support tool at the WWTP Magdeburg.

Operaton support system at the WWTP Magdeburg

Plant description

The WWTP of the city of Magdeburg, capital of Saxony-Anhalt, Germany, is designed for 426,000 PE (total number of inhabitants and population equivalent) and for a dry weather flow of 75,000 m^3/d. Figure 1 shows the simplified flow scheme of the biological treatment stage of the WWTP including relevant measurement instrumentation. The complete sewage is treated by the activated sludge process for biological N and P removal and additional phosphorus precipitation in cascades. The WWTP is split into two lines, each consisting of three cascades. Enhanced biological phosphorus removal is based on the UCT-technology (Wentzel *et al.*, 1991).

All cascades are separated in longitudinal direction into a pre-denitrification tank and a nitrification tank. Each denitrification tank is separated into five compartments by submerged cross-sectional walls. In case of unsuitable conditions for nitrification, especially during periods of low sewage temperature, the volume available for nitrification may be enlarged by additionally aerating some of these compartments. To enable such varied utilisation the compartments are also equipped with stirring and aeration units. Furthermore, the anaerobic tank may be used for denitrification through adequate operation. Thus, if biological P removal is not implemented, the simultaneous precipitation by a dosage of $FeCl_3$ into the last nitrification tank of each cascade has to ensure maintaining the P limits in the effluent.

Integration of simulation into the Distributed Control System

In addition to the task of designing the on-line simulation, a technical environment to implement the system for model-based plant operation is required. Some technical requirements for such a system are:

- on-line access to the process data
- schedule of cyclic and acyclic computational tasks with evaluation algorithms and process simulation

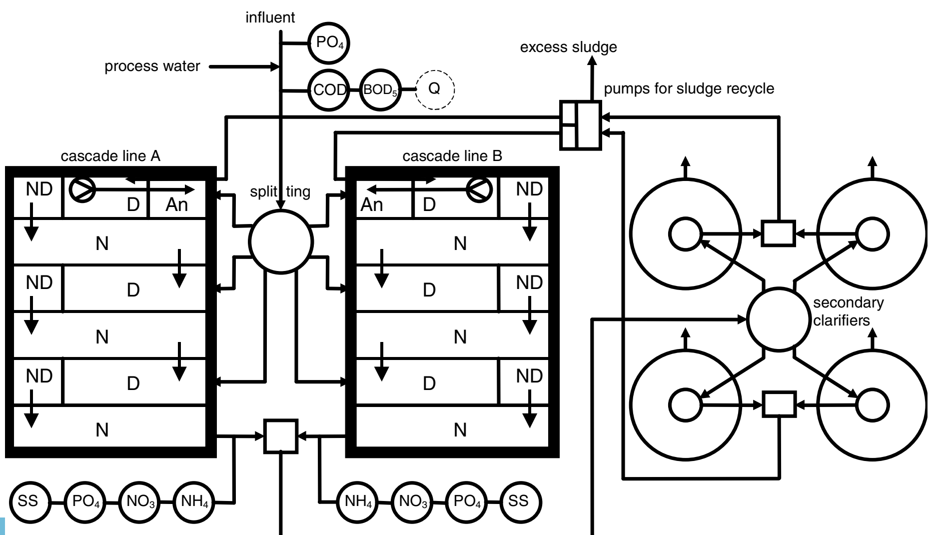

Figure 1 Configuration of the WWTP at Magdeburg

- option to include complex non-linear dynamic models and integration procedures for simulation
- option to include complex non-standard algorithms for signal filtering, correction and supervision of measurement signals, prediction, optimisation etc.
- a tailor-made graphical user interface corresponding to the requirements of operation support.

Standard Distributed Control Systems (DCS) do not provide the necessary properties for this kind of functionality. Another important aspect is the effort which is necessary for the development and implementation of a model based operation support system.

A DCS of the ABB Advant series forms the core of the plant automation at the Magdeburg WWTP. Due to the system's safety reasons and the ABB Advant hardware platform, consisting of HP workstations with a UNIX operation system, the on-line simulation server was implemented using an additional Windows-NT PC (see Figure 2). However, visualisation of simulation results as well as human interaction to control the simulation runs are possible through the ABB Advant stations. The communication system ACPLT/KS (Enste *et al.*, 1999) was applied to link the developed simulation server SIMBA process to the DCS ABB Advant. In principle, the free and open communication system ACPLT/KS makes process data available world-wide, and it is therefore nicknamed "Process Control Engineering Internet" by the developers at the RWTH Aachen, Germany. Applications for process control and process control engineering, as well as office applications, gain access to data (on-line, off-line, parameters, archives), structures, information about information (meta-information) and objects and structure management.

A practical solution for the visualisation and control of simulation was found by employing internet technology and by installing standard HTML browsers on the ABB Advant workstations. HTML provides the platform to present non-dynamic simulation data and to navigate through several information sheets of the graphical user interface. Visualisation of dynamic data and user interaction were programmed by means of Java applets.

Results of using the operation support tool

Gathering additional process information

Additional process information and prediction of the plant's behaviour are the most

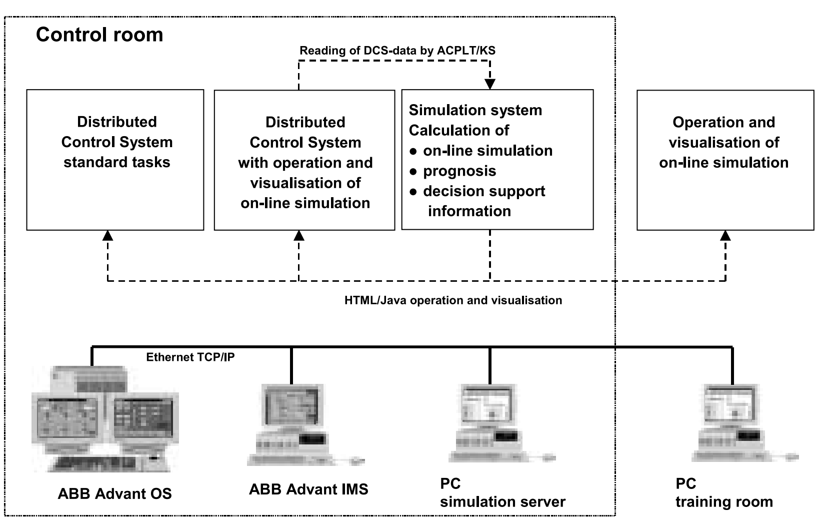

Figure 2 Functional and hardware integration of on-line simulation

relevant application aspects of the operation support tool at the Magdeburg WWTP. In the first case, for instance, concentration profiles of NH_4, NO_3, O_2 and SS are calculated along the three cascades of each line of the plant. Since usually only the on-line measurements at the effluent of the lines are directly available, the model-based virtual measurement information significantly improves the actual process knowledge.

Figure 3 provides an example of such virtual measurement information. For the most relevant variables characterising the sewage, the concentration profiles in the cascade line of the WWTP at Magdeburg are shown.

Although the concentrations of NH_4, NO_3 and PO_4 are measured only at the plant effluent, the complete set of concentration profiles over the cascades are provided by on-line simulation. From this information a qualified assessment of the individual cascades' compartments and the efficiency of biodegradation becomes possible. This assessment is of great importance for an optimised operation. For instance, choosing another proportion of influent entering each of the three cascades will result in different profiles and in different effluent variables as a consequence.

To check that the on-line simulation is properly functioning, the variables calculated by simulation for the effluent are compared with the last measurements actually taken at this point. The comparison is displayed in a table on the screen. Furthermore, recent DCS data of the influent ratio to the three cascades, the data of O_2 concentration measurements and the aeration or stirring state of variable compartments are shown on the screen.

Prognosis simulation

Let us assume that the on-line model matches the actual state of the plant's operation. Let us also assume that a certain scenario of the operation is given. Then, by a predictive simulation the process behaviour in future can be calculated. As a result, the time plots of all concentration outputs of the Activated Sludge Model No. 2 as well as the flow ratio are available. This enables the operator to draw conclusions with respect to:

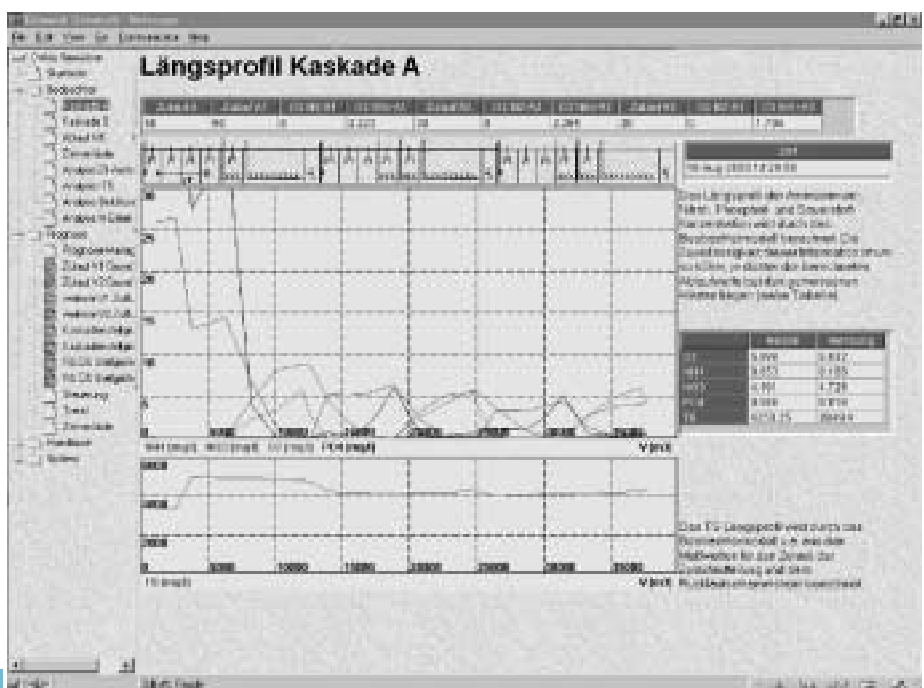

Figure 3 Screen shot of on-line calculated concentration profiles for cascade line A of the WWTP

- predicted treatment capacity of individual cascades of the whole treatment plant
- time response of on-line measurement data of COD, NH_4, NO_3, PO_4 etc. in future
- the time behaviour of non-measurable or not measured variables such as growth rates or concentration profiles

This information can form parts of further functions of the operation support tool, e.g. for analysis or for decision support tasks. Prognosis calculations, which start from the same original state and are conducted with only some transparent modifications with respect to the "normal" operation, ensure that the predicted data is comparable, at least in principle. Therefore, it is possible to easily evaluate different actions of operation with respect to foreseen load situations within a short time.

Taking again the specific example of the Magdeburg cascade WWTP into consideration, prediction of the plant behaviour gives the operator decision support in changing:

- the proportion of influent wastewater entering each of the three cascades
- the aeration capacity by means of switching on or off the optional aeration in some of the reactor tanks (optional usage for nitrification or denitrification)
- the reference value of O_2-concentration control
- between constant return sludge flow or constant recirculation ratio
- the load of the influent wastewater by manipulation of the process water feeder

By variation of these control inputs, the user of the simulation-based operation support tool is able to study the resulting process behaviour for the expected load. In a standard case, prognosis simulation is based on daily hydrographs from the previous day. Alternatively, influent data from another day or data extracted from the database may be used. Different scenarios may result from influent changes with respect to flow rate, COD, N, P or rain events, from operational changes, such as putting a cascade out of operation or a decreased temperature.

A prognosis simulation of two alternatives, which are to be compared, is provided as an example. Both calculations are based on the measured load on August 16, 2000. A rain event in the morning of this day resulted in an increase of the flow rate to 6,200 m^3/h. The control inputs, which are assumed to be constant over the prediction horizon, are chosen as stored in theDCS valid for this time. Both prognosis calculations differ in the proportion of influent entering each cascade. Prognosis I diverts 40% into the 1st cascade, 32% into the 2nd cascade and 28% into the 3rd cascade, which corresponds to the plant design. Prognosis II is calculated with the proportion, set at the start of plant operation: 50%, 30% and 20%. Prognosis simulations begin at 1.30 p.m. on August 18, 2000 and have a horizon of one day. Figure 4 shows, as an example, the predicted NO_3 concentration at the effluent. Furthermore, the time plot of concentration in the past is given.

From the graphs one may conclude that the maximum NO_3 concentration for prognosis II, i.e. for an enlarged supply of the front cascades, is approximately 1 g/m^3 lower than in the prognosis I case. A decreased proportion of sewage supply of the last cascade results in the main part of TKN being already eliminated in the first two cascades. The nitrate, leaving the 2nd cascade, can be biodegraded in the following denitrification (compare the concentration profile in Figure 3). The NO_3 leaving the plant corresponds to a great extent to the nitrogen which is nitrified in the last cascade. This is a motivation for "top-heavy" splitting of the influent to the cascades. However, there are controversial aspects as well, the discussion of which have to be omitted here for reasons of brevity.

Other support functions

A frequent evaluation of the information provided by the simulation-based tool described can efficiently support the operation of the WWTP. The causes of some difficulties in operating the plant and undesired process states can be analysed in detail, and measures to avoid

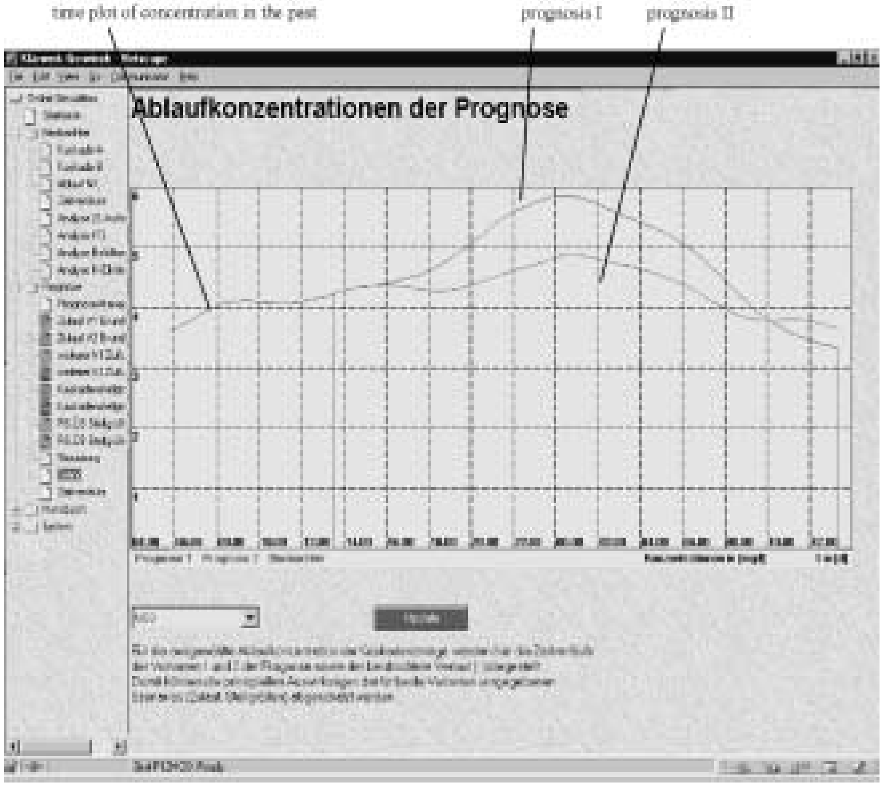

Figure 4 NO_3 concentration at the effluent, calculated by the operation support tool for prognosis I and II

such problems can be found. Some analysis and support functions are provided by the developed tool on dedicated sheets of the graphical user interface.

- The sheet "analysis of the sludge balance" provides information on relevant calculated variables such as SS in the excess sludge or the sludge age. The calculations are based on data from the DCS and provide the average values over one week and over one month.
- By means of the "analysis of nitrification and denitrification zones" it can be checked, whether the biodegradation processes in the subsequent cascades of each line are efficient. The nitrogen concentration, calculated by the model at the end of each zone, forms the criterion to assess the efficiency.
- A special user interface sheet "analysis of the influent splitting to the cascades" reports the measurement data of the water depth and the position of weirs in the splitting construction upstream of the cascades. This data is used by the DCS to calculate the proportion of influent entering each cascade.
- The screen "analysis of aeration" of the graphical user interface displays the ratio of measured and simulated air flow to the cascades. This information supports the recognition of a model mismatch with respect to parameterisation of the aeration system or to the influent modelling of COD and TKN. Furthermore, discrepancies in the actual splitting of influent or in the usage of the alternatively aerated cascade compartments may be detected.

Experiences, gathered in the use of the system, will help to complete the functionality and to further improve the tool developed.

Discussion

The implementation and operation of the system became possible as a result of successful co-operation with the developers of methodology and software, and the customers of the system, i.e. the operators of the WWTP. Introducing a system to support plant operation by an on-line simulation tool results in a reasonable engineering effort, even in the case of following a module-based approach of hardware and software components. This is due to the specifics of each wastewater treatment plant and the special requirements of operation. One of the lessons learned is that such a project has some cycles in its realisation. Some requirements and desired features of the system arise only during the project work. A step-by-step growing knowledge of the project partners involved is one of the reasons for some iterations in designing an advanced simulation-based operation support tool. Since on-line simulation as well as other sophisticated process control solutions do not yet belong to standard automation, a careful definition of requirements and a thorough technical co-ordination are necessary.

To reach a high degree of acceptance and a frequent use of the system, training courses for different levels of users are important as well as agreements on a continuous maintenance and further development of the solution. Considering the application at the WWTP at Magdeburg, the operation of the on-line simulation tool and the provision of maintenance have shown to be very efficient by remote data access to the simulation server.

Conclusions

This paper describes the development of a dedicated on-line simulation operation support tool for a full-scale municipal WWTP. It was shown that on-line models offer suitable possibilities to support the operation of plants. Besides an excellent training environment for operators, on-line simulation models can act as process observers to calculate a detailed image of the process state. Furthermore they can predict the future behaviour of the plant to support manual operation or automatic control.

An efficient use of on-line simulation models causes special requirements on the software system. Besides the coupling with the Distributed Control System, the model algorithms and specific functions for visualisation, remote operation and remote maintenance have to be implemented. The solution, introduced in this paper, using intranet technology, takes into account the given heterogeneous hardware and software platforms and enables a good cost–benefit ratio.

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