Information Retrieval from Mathematical Models for Process Optimisation in Waste-Water Treatment

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Abstract

For the operation of a sewage plant it is of great importance always to know the current state of the biological processes inside the plant as precisely as possible. For supporting the operator in this task we present in this paper a new approach of information retrieval from mathematical simulation models combined with knowledge-based techniques. In this approach a well-known and widely used mathematical model of the biological processes inside a sewage plant, the „Activated Sludge Model“ has been implemented together with a model of the plant’s sludge settling processes in an existing real-time simulator. This allows a clear structuring of the model and thus it is more understandable to the operators. For a computer-aided identification of the process-state within the biological part of the sewage plant, the simulation is run on-line in parallel to the real cleaning process. The measured and simulated process-data are fed into an on-line real-time diagnosis system that evaluates the state of the cleaning process and gives suggestions to the operator for an optimal process control. In the simulation system these suggestions again can be evaluated by simulating the future behaviour of the cleaning process with the changed control parameters.

1. Introduction

Process supervision is an important topic in wastewater treatment. Down-times of a plant are expensive and in this domain they even may cause environmental problems. Anyway, most of the current supervision systems restrict to displaying only large numbers of sensor-values which require an experienced operator to determine the current status of the cleaning process. In case of an error normally there are dozens of messages about limit-violations in some process-parameters that only to a limited extent give a hint to the actual failure. What is even more important, many of the process-parameters are not on-line available.

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Here it is an important task to supply the appropriate information about the process-state to the operator and visualise it in a way that covers the vital information and is easy to understand.

In this paper we propose an approach so support the plant-operator with a decision-support system based on dynamic simulation of the biological processes in the plant to acquire deeper information about the process-state from the simulation model than we can get only from on-line measurements. With the support of such a knowledge-based system that can access on-line measurements as well as simulated values of the cleaning-process, the operator is able to detect deviations from an optimal cleaning-process earlier than before. The decision-support-system will provide suggestions for re-establishing this optimal process-state. These suggestions can then be verified by simulating the future development of the cleaning-process with several control-strategies, starting from the current status.

In the next chapter we will introduce the way how simulation-models for waste-water cleaning processes are described currently. In chapter three we will then show how such information can be transformed into a simulation model whose graphical representation visualises the problem more adequately to the operator. Afterwards in chapter four we will describe the decision-support system, consisting of data-acquisition-, simulation- and diagnosis-modules. This system finally has to detect sub-optimal process-states, visualise them to the operator and suggest recovery-actions to re-establish the desired optimal cleaning-process. We conclude our paper with the experiences made with an installation of a prototype of the described system at a sewage-plant of the Bremer Entsorgungsbetriebe (BEB)[3] in Bremen-Seehausen. A short outlook on future trends will close our discussions.

2. Biological Processes in a Sewage Plant

Modern wastewater treatment plants are designed to eliminate several pollutants from the incoming water. Besides removing organic substances an important task in wastewater treatment is the removal of nitrogen (and nitrogen-compounds) and phosphorous. In modern sewage plants this is done in a nitrification / denitrification process for the organic components and nitrogen-compounds and by chemical and biological phosphorous-elimination.

The current standard for describing these processes in sewage treatment is set by the International Association on Water Quality (IAWQ). Currently most simulation is based on the „Activated Sludge Model No. 1„ (ASM1) (Henze et al. 1987) that describes the biological processes as a set of eight differential equations (equal to eight processes covered by the model) with thirteen parameters (for thirteen

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Component j	1	2	3	4	Process rate
i Process	$\boldsymbol{S_S}$	$\boldsymbol{X_S}$	$\boldsymbol{X_B}$	$\boldsymbol{S_O}$	ρi
Measurement variable	COD			-COD	
Eng. unit	[g m^{-3}]			[g m^{-3}]	[d^{-1}]
1 Aerobe growth Biomass	$-\frac{1}{Y}$		1	$-\frac{1-Y}{Y}$	$\mu \frac{S_S}{K_S + S_S} \frac{S_O}{K_O + S_O} X_B$
2 Necrotising		1	-1		$b \cdot X_B$
$r_j = \sum_i \nu_{i,j} \cdot \rho_i$					

Table 1
Original description of part of the process-model of a sewage plant

substances in the wastewater that are affected). The processes modelled in ASM1 include growth and necrotising of biomass, as well as ammonification and hydrolysis of organic compounds. This model covers the nitrification / denitrification process but it is not sufficient for modelling other important processes like phosphorous-elimination or fermentation. In order to eliminate this weak point of the model, AMS1 was extended to the „Activated Sludge Model No. 2“ (AMS2) which in addition to ASM1 also covers these processes (Henze et. al. 1995). However, the model of the phosphorous-elimination is still quite immature so AMS1 is still used as a standard for describing wastewater-cleaning processes. In the example of table 1 a description of two biological sub-processes of this model is shown that affects four variables.

Additionally the sludge-thickening process is also described in a similar way. The sludge in the wastewater that has passed the biological stage settles down in „settling tanks“. Most of that sludge is re-fed into the biological stage and only a small percentage is removed from that circulation and taken to the surplus-sludge treatment. In order to get a realistic model of the sludge-circulation in the whole cleaning process a model for the settling of the sludge is needed. In contrast to the biological processes described above, in the settling tanks only the physical processes of the sinking sludge are of interest. In the literature there are several models for these processes. They start with models of ideal settlers that completely separate solid and soluble fractions (SIMBA 1995) but can also be quite complicated models that subdivide the settling tanks in several layers with different sludge concentrations and that describe transport-processes of the several fractions between these layers (Härtel 1990, Otterpohl 1995, Takacs et. al. 1991).

3. Visualising the Process Structure in a Simulation Model

Since the presentation of the simulation model in its original form is not very useful for the plant-operators, the information contained has to be presented in a manner that is intuitively understood. Within the ESPRIT project "WaterCIME" (Project No. 8399) we implemented in close co-operation with the Bremer Entsorgungsbetriebe an ASM1 representation in the simulation tool CSS (Core Simulation System) (CGS-Project 1995**)**, that has been developed at Daimler-Benz Aerospace AG Space Infrastructure Division.

This tool with its graphic editor allows modelling the processes in a very clear manner. It supports a structural decomposition of the system by its ability to model it hierarchically. Basic functionalities are modelled in so-called „basic building blocks„ that are composed to „composite blocks„. Flow of data and matter is modelled by interconnections between the blocks.

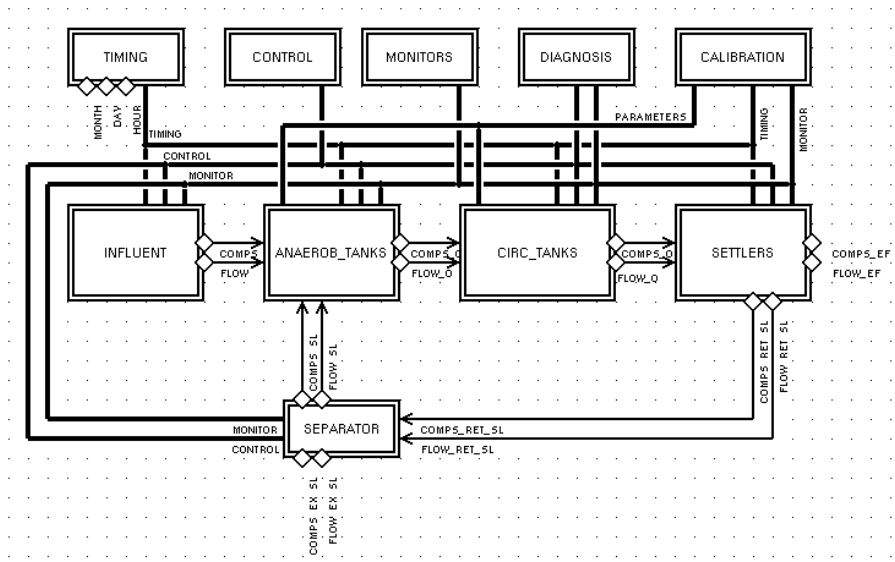

Figure 1
Model structure of the whole purification plant (top level of the model)

In the scope of the WaterCIME-project we established a simulation model of the biological part of the sewage plant and the settling tanks. The pre-clarification, where coarse-grained particles settle down before the waste-water enters the biological stage was not within our interest since this physical process is very stable and there are no options for the operators to intervene. Also the sludge-treatment process was outside our scope.

The part of the sewage plant that is covered by our simulation model is decomposed according to the different stations the water passes during the purification-process (Figure 1). In the block describing the influent the decomposition of the wastewater coming from the pre-clarification into the biological part is modelled. The thirteen fractions of solid and soluble substances in the water, that are of interest, are computed here according to the available on-line measurements. Furthermore the wastewater-flow into the plant is measured here. From all this information a state-vector is computed that describes the current state of the wastewater. During all the following cleaning-stages this state-vector will be updated according to the processes that take place there, so that at every point in the simulation-model a characterisation of the wastewater is available that can later be used within the diagnosis module.

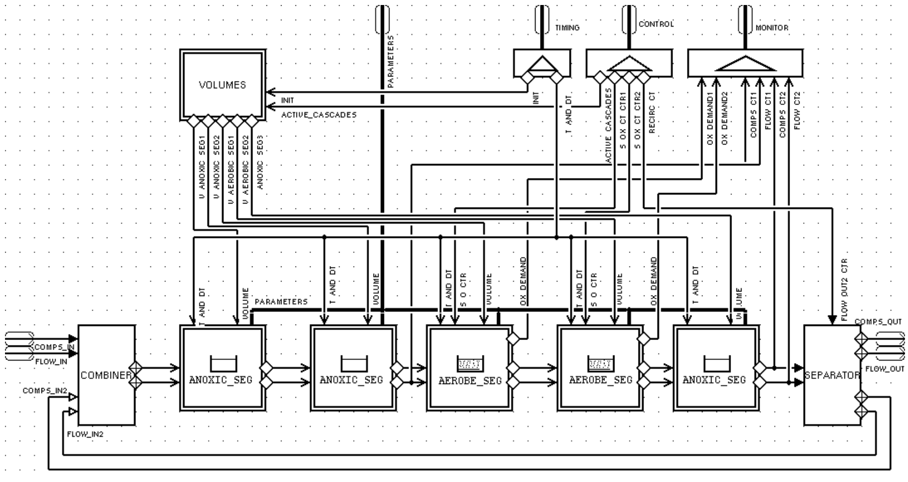

Figure 2
Model structure of the circulation tanks

In the following anaerobe and circulation tanks the cleaning processes are modelled. Two main processes can be distinguished here: In the anaerobe tanks the denitrification-processes take place, in the following circulation-tanks the nitrification is the main process to be modelled. The tanks themselves are again decomposed into different segments where different biological processes take place (Figure 2). Within the segments there are finally the basic function blocks that realise as well the internal flow control within the segment as the biological processes themselves. However, instead of having to model the whole set of differential equations of ASM1 to describe the processes, here only that subset of equations is needed that covers the processes that run in the respective segment of the tank (e.g. anaerobe growth of bacteria in one segment vs. aerobe growth in another one).

In the same way the settling tanks are modelled. In one composite block there is again a function block for the description of the settling process itself and another one for controlling the flow of the sludge taken from the tank and the cleaned water that is released to the environment.

With such a structured approach the model becomes clearer than in its original form and is easier to understand to the operators. Another advantage of that approach is that the single process-models allow building up a component-library. With such a library complex models can be built up quite easily and the model components can be re-used for generating models of other plants that are configured differently.

4. The Decision-Support System

The application of this simulation-model described in chapter three is to support the operator at the sewage plant in controlling the biological processes and in always achieving an optimal process state. Therefore the information that is derived from the on-line simulation of the model is not only directly visualised in the simulator's „Model Observation and Control System„ (MOCS), this information is also used, together with on-line-data from the process, to detect such sub-optimal process states. Therefore the simulation is integrated into a decision-support system.

4.1 Architecture of the Decision-Support System

The decision support system is built up from several independent modules that exchange their data via a local network (Figure 3).

The acquisition of the on-line measurements from the cleaning process is performed by a SCADA[4]-system. This software[5] is directly coupled to the sewage plant's data bus and thus has direct access to the on-line sensor values available in the plant's central control system. Additionally all control information (e.g. status of pumps, valves etc.) of the plant's devices is available there.

Within the SCADA-system a pre-processing takes place. The diagnosis module needs as input from several sensors average values over a certain time rather than on-line measurements. Furthermore some computed values are necessary for the evaluation of the state of the cleaning process, e.g. differences between measurements of the same substance inside the waste water at different locations in the plant. These computations are also performed inside the SCADA-system.

All on-line measurements and control information necessary for the simulation system are passed to it from the SCADA-system via an interfacing- and control-component.

[4] Supervision, Control and Data-Acquisition
[5] CIMVIEW, a commercial tool developed by CIMTECH, Nivelles, Belgium

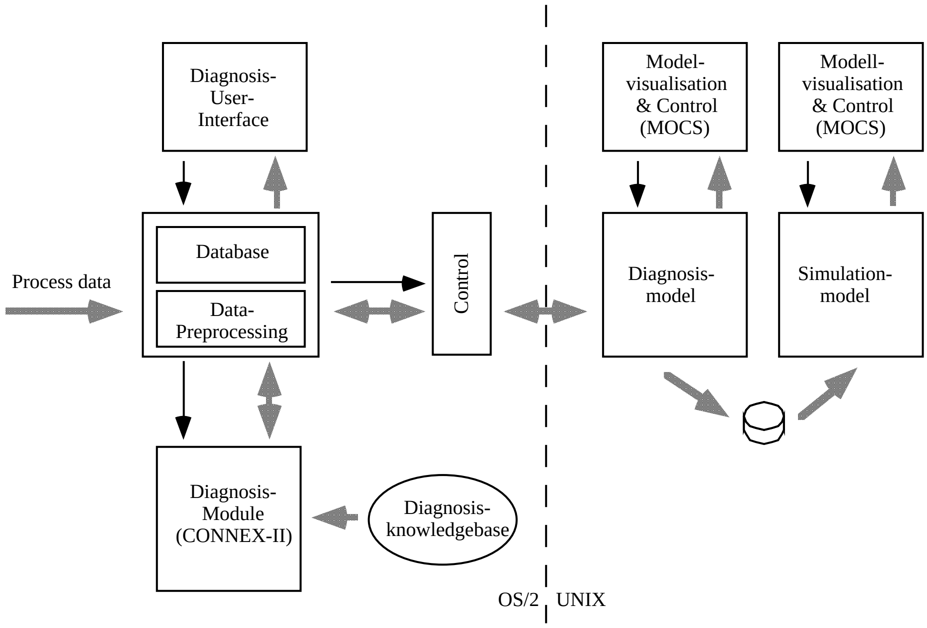

Figure 3
Architecture of the decision-support system

The simulation-system consists of two models of the sewage-plant that are run independent from each other. The first one (the so-called „diagnosis-model“) is run in parallel to the cleaning process and is permanently fed with on-line sensor values to ensure that the simulation covers the cleaning-process as good as possible. From this model additional process-data are retrieved, that can not be measured on-line but that are of interest to the diagnosis module. These data are fed into the SCADA-system and processed like other on-line values.

The other simulation-model is used for simulations into the future. Based on a given state of the on-line simulation (usually the current state of the process when the diagnosis system has detected a non-optimal state), the user can simulate the effects of different control-strategies on the future behaviour of the cleaning-process. Therefore this simulation-model is controlled by the simulator’s „Model Observation and Control System“ (MOCS) which allows the user to control the simulation and observe any value inside the simulation he is interested in. Although the diagnosis-model is completely controlled from the decision-support system’s interfacing- and control-component, it is also accessible via MOCS to allow the user to visualise simulated process-parameters he is interested in.

All on-line and simulated sensor values are fed from the SCADA-system into the diagnosis-module „CONNEX-II“ (CONNection-matrix EXpert system) that has also been developed by Daimler-Benz Aerospace AG Space Infrastructure Division. With an inference engine that is able to process data in real-time this module detects deviations from the optimal process-state, informs the user and suggests actions to improve the quality of the cleaning-process. This diagnosis-software will be described in detail in chapter 4.2.

The main user-interface of the decision-support system is the diagnosis user-interface. This interface has been implemented within the SCADA-system and provides comfortable access to the diagnosis module. Here the diagnosis-process can be controlled, according to several possible configurations of the sewage plant several knowledgebases can be loaded, sensor-values can be read and finally the diagnosis-results are displayed.

4.2 The Diagnosis System CONNEX-II

CONNEX-II is a Failure Detection, Isolation and Recovery (FDIR) System that was primarily developed within European space projects for on-board failure detection and isolation. It is based on explicit symptom-failure relationships to identify failures from observed exceptions.

Diagnosis in CONNEX-II is performed in a two-step approach that is shown in figure 4. At first for a predefined set of symptoms it has to be checked which of these have evolved. This is done in a pre-processing step: The on-line sensor values of the system under supervision will be treated by a configurable noise-filter to remove the inevitable noise of the sensors and to smooth the signal. Afterwards for each symptom that is related to a sensor (the number of symptoms attached to a sensor is not limited) it is checked to which degree that symptom has evolved. This is done by comparing the actual (smoothed) sensor value to a predefined set of fuzzy functions that describe for each symptom its degree of evaluation depending on the sensor value.

These symptom weights are now fed into the connection matrix that forms the kernel of the inference mechanism. Here the given symptom pattern is compared to the expected symptom patterns of a set of predefined possible failures. A proximity measurement among these patterns then selects the most probable diagnoses.

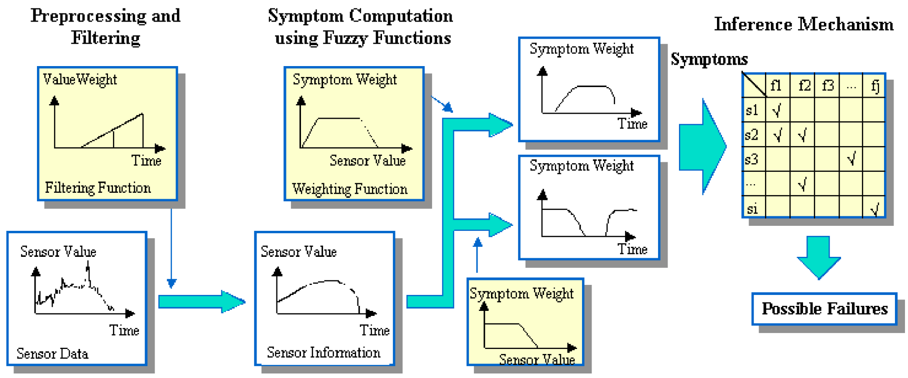

Figure 4
Inference process of the diagnosis system

5. Conclusions

On-line simulation of biological processes is a topic directly at the frontier of research in wastewater treatment. In this paper we presented an approach, how this information gathered from such complex simulation models can be condensed and visualised to the plant-operators in an understandable way. Furthermore, we showed how this information can be used for process-supervision in the plant to extend the information gathered by on-line measurements. We presented a new kind of process-supervision and decision-support software that combines both kinds of information available and uses it as a basis for the identification of the current process-state of the biological cleaning process.

A software prototype of the presented system has been implemented by mid June 1997 in the sewage plant Bremen-Seehausen of the Bremer Entsorgungsbetriebe. In tests it was run in parallel to the plant's actual SCADA-system. First experiences showed that this technique helps the operators to detect deviations from an optimal process state much earlier than they would with conventional systems. The diagnoses of the decision-support system also allow a quicker identification of the primary cause of the non-optimal state of the cleaning-process and the simulation module is valuable for validating the measures proposed by the diagnosis system. Therefore the implemented prototype allows a more effective operation of the sewage plant which finally results in a better cleaning of the wastewater.

For the future the scope of work to be done has slightly shifted: Besides further improvement of the knowledgebase of the diagnosis system the calibration of the simulation model is an important topic. Since there is always a drift in the process-parameters, the simulation model should be re-calibrated quite frequently. An important area of work here is an on-line re-calibration-module for the simulation-model that performs this task.

Another future field of application for the described techniques is the on-line data reconciliation of sensor measurements. With an adapted knowledgebase the diagnosis system described in this paper can not only be used for supervising the cleaning process as a whole but it is also valuable for checking the consistency of the sensor measurements themselves. Thus we can provide more reliable data to the operator as a basis for an improved management of the sewage plant.

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