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Model Predictive Control of the Wastewater Treatment Plant Based on the Benchmark Simulation Model No.1-BSM1 with Reactive Secondary Settler

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Abstract

Wastewater treatment processes suffer large variations in their flow rates and feed concentrations, making the control of the process a challenging task. This is the motivation making advanced control strategies be needed in order to obtain good control performance. In this paper two control strategies are suggested and evaluated for the Waste Water Treatment Plant (WWTP) operating with a reactive secondary settler. The first strategy presents a feedback Model Predictive Control (MPC) that is deployed at the regulatory control level and the second control architecture presents the MPC controller implemented at the supervisory control level. For the second control setup MPC provides, from the upper control level, an optimal set point for a classical PI controller of the regulatory control level but also it directly regulates the input to the plant. The simulation results show the advantages of the supervisory MPC control scheme over the regulatory MPC control setup, as WWTP influent disturbances are rejected in a more efficient way. For this study the Simulation Benchmark No.1-BSM1 with a reactive secondary settler model had been used to test the control strategies. The novelty of the study also consists in using a reactive model for the secondary settler, as this makes the WWTP model closer to the real plant behaviour and process control more complex.

Key words: *MPC, WWTP, reactive settler.*

Introduction

Humans, animals and plants need clean water to ensure their existence. Although the surface of the planet is mainly water, clean water resources are limited. In modern world the main sustainable development concept is to save water. The purpose of wastewater treatment plants is to remove pollutant agents from the wastewater by means of (bio)chemical and physical processes. Depending on the nature of the wastewater the removal of pollutants is achieved in various ways.

Modern wastewater treatment plants use biological nitrogen removal, which relies on nitrifying and denitrifying bacteria to remove the nitrogen from the water, this process is known as Activated Sludge Process or ASP for short. As they grow, the microbiological cultures use the organic pollutants from the wastewater as food and energy sources. The nitrogen removal is done in two steps using two types of bacteria. To work effectively, each step of the process requires different ambient conditions making the procedure difficult. Concentrations and flow rates change drastically over time, in the aerobic reactors air must be dissolved; wastewater and sludge have to be recycled. The process has to be thoroughly controlled to ensure the efficiency of the treatment process, reason that makes mathematical models and computer simulations essential to describe, predict and control the complicated interactions of the processes [1]. Mathematical models are important tools that allow investigation of the dynamic behaviour and control strategies of systems, greatly reducing the costs and the time spent for practical experiments.

Model description and control approach

The COST Benchmark Simulation Model No.1-BSM1 [2] was used as a standard model for performance assessment and evaluation of the control strategy. BSM1 consists of five biological reactors and a secondary settler. The reactors are based on the most common biological wastewater treatment processes, the IAWQ Activated Sludge Model No. 1, first presented in 1987 by Henze *et al.* [3]. The ASM1 based WWTP model consists in a set of ordinary differential equations which describes the dynamic changes of several process variables, such as soluble inert organic matter, readily biodegradable substrate particulate inert organic matter, slowly biodegradable substrate, active heterotrophic biomass, active autotrophic mass, NH_4^+ and NH_3 nitrogen, nitrate and nitrite nitrogen, soluble biodegradable organic nitrogen, particulate products arising from biomass decay, particulate biodegradable organic nitrogen, total suspended solids and Chemical Oxygen Demand (COD) throughout the process units. In order to define the components in the model, COD and nitrogen are divided into fractions that are represented by state variables. Kinetic and stoichiometric parameters are also described in the model. Figure 1 presents the schematic view of the WWTP. The suspended material contains bacteria, micro-organisms, organic and inorganic particles. It is desired to maintain suspended material in the waste water by stirring or aeration. Biochemical processes, performed in aerated and non-aerated (anoxic) reactors, transform the organic matter in biological sludge and nitrogen compounds in nitrogen released in the atmosphere. In the aerated reactors the bacteria oxidize ammonium to nitrate by the so-called nitrification process. In the anoxic reactors takes place the denitrification process where bacteria change nitrate into nitrogen, using oxygen present in the nitrate ions.

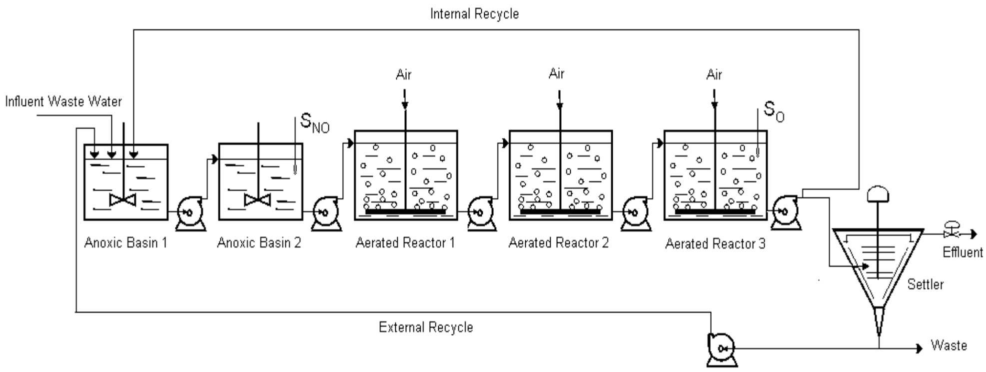

Fig.1. Layout of the BSM1 benchmark simulation platform plant.

The plant is composed of five rectors arranged in series and a secondary settler. The first two reactors are non-aerated and have a volume of 1000 m^3. The last three reactors are aerated and each has a volume of 1333 m^3 and a maximum aeration (oxygen transfer coefficient) K_{La} of 10 hr^{-1}. The total biological volume is 5999 m^3. All of the five reactors are considered to be fully mixed. There are two WWTP recycles: nitrate internal recycle from the fifth rector to the first one and an external recycle from the underflow of the settler to the first reactor of the plant.

The most important physical process in a WWTP is the separation of solids from water by gravity and density difference between solids and liquid [4]. The separation of biomass from water is done in the secondary settler located in the downstream of the biological reactors. To get a more realistic model of the plant the secondary settler was not considered to be ideal, as in the original ASM1 model, but the biochemical reactions that take place in it have been also taken into account. The reactive secondary settler model was obtained by combining the settler model of Takács et al. (1991) [5] with the ASM1 model. Takács settler model is one-dimensional with 10 layers of constant thickness. The model predicts the solids concentration profile in the settler by performing a solids balance around each layer. By combining the settler model with the full set equations of the of the ASM1 reactor, each layer acts as an activated sludge reactor. The dynamics of the solids/liquid separation processes is described by the double-exponential settling velocity function of Takács which is based on the solid flux theory and is applicable to both hindered and flocculent settling conditions.

$$v_{sj} = v_0 \cdot e^{-r_h \cdot X_f^*} - v_0 \cdot e^{-r_p \cdot X_f^*} \text{ and } 0 \le v_{sj} \le v_0' \quad (1)$$

In order to calculate the solids flux, the description of total suspended solids was extended and a flux for each of the suspended component was computed [6]. The physical attributes of the secondary settler were maintained the same as in the *Simulation benchmark BSM1*, with a volume of 6000 m^3 (area of 1500 m^2, depth of 4 m) and a feed point at 2.2 m elevation from the settler bottom.

The control strategy has two control loops. The first one involves the control of the Dissolved Oxygen (DO) in the fifth rector by manipulating the air flow rate (indirectly by the oxygen transfer coefficient K_{La}). The set point for the DO is 2 gm^{-3} and the K_{La} is constrained to a maximum of 10 hr^{-1}. The second control loop has to maintain the nitrogen level in the second rector to a set point of 1 gm^{-3} by manipulating the internal recycle flow which is constrained to a maximum 92230 $m^3 day^{-1}$. Both DO and nitrogen sensors are considered to be ideal, having no delay or noise.

Predictive controllers are often provided for the regulatory control level, but in industrial applications they may be implemented at the supervisory control level in parallel configuration with conventional controllers. Model predictive controllers make prediction of the process future behaviour over an output prediction horizon based on the current time measurements and the nominal model of the process. MPC algorithm computes the manipulated variable sequence over an input horizon in order to minimize an objective performance function. Only the first step of the computed manipulated variable sequence is implemented starting form the present sampling moment up to the next time step when a new set of measured values becomes available. Prediction and optimization are repeated again for a new manipulated variable sequence computation, with input and output time horizons shifted one step ahead into the future.

Results of the control strategy

This paper presents two control strategies for the wastewater treatment process. The first one presents a model predictive controller which is implemented at the regulatory control level and is denoted as the feedback MPC [7,11]. The feedback MPC controller directly controls the input to the plant in order to control the process to a given set point. The schematic of the control architecture is represented in Figure 2 (on the next page).

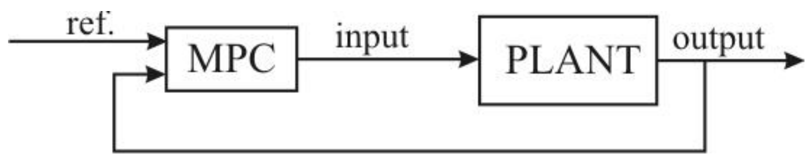

Fig. 2 Regulatory MPC.

The second control structure presents a predictive controller deployed at supervisory and regulatory control level in a two layered architecture. The MPC controller provides an optimal set point for a conventional PI controller [10] but in the same time it controls the input to the plant. In this case the manipulated variable sent to the plant is the sum of control variables from the PI controller and MPC controller [8, 9]. This supervisory control architecture is presented in Figure 3.

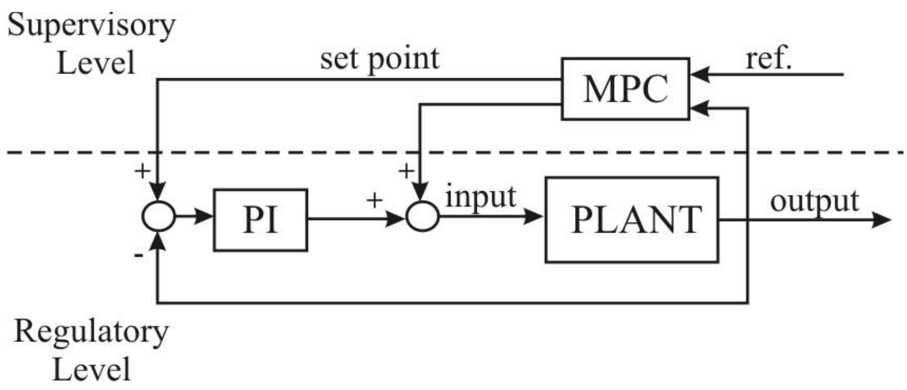

Fig. 3 Supervisory MPC.

For the MPC controllers it was used a sampling time of T=1 [min]. The prediction horizon and the control horizon have been set to the values of p=200 and m=3. The predictive controllers were tuned by performing simulations. For each of the two control loops conventional PI controllers have been used at the supervisory level of the control architecture.

Both the WWTP simulator model and the two investigated control architectures have been implemented in the Matlab/Simulink^{TM} platform. The secondary settler model has been extended with additional balance equations on all components of interest, accounting for the biochemical reactions also taking place in the settler. The WWTP control was simulated for a period of 14 days using the *dry weather* influent disturbance conditions. Control with different influent weather conditions (*rain* and *storm weather*) has been also tested and comparison between the regulatory and the supervisory MPC control structures has been also investigated. The simulation of the WWTP with reactive secondary settler is able to improve the fit between the real process behaviour and the model.

Figure 4 (on the next page) presents the results for the nitrogen control, for both control schemes, over the last seven days of the simulation.

The simulation results show that supervisory model predictive controller has better control performance compared to the feedback MPC controller directly used at the regulatory control level. The supervisory MPC has a maximum deviation from the set point of 0.0062 [gN/m^3] while the maximum deviation of feedback MPC is four times higher with a value of 0.0257 [gN/m^3].

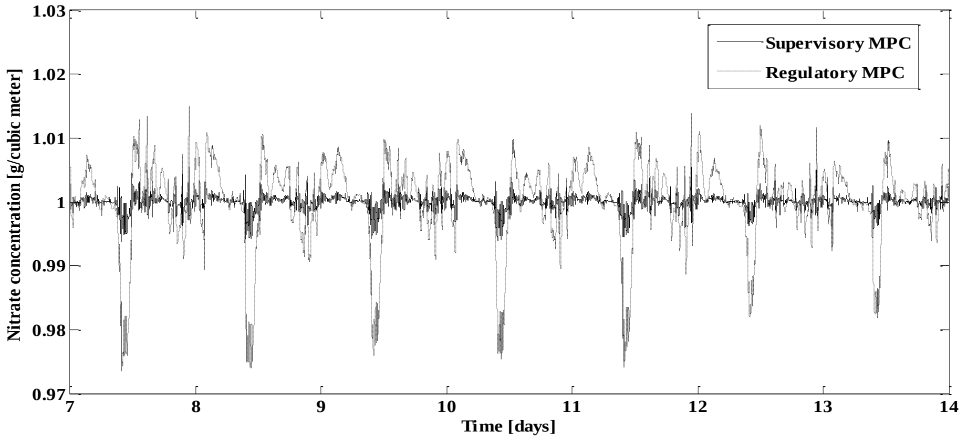

Fig. 4. Comparison between Regulatory MPC and Supervisory MPC of the nitrate concentration control.

The superiority of the supervisory MPC scheme is proven also for dissolved oxygen control. In this case the regulatory MPC has a maximum deviation of 0.021 [gCOD/m^3], i.e. three times greater than the supervisory predictive controller overshoot which is only 0.007 [gCOD/m^3]. Figure 5 presents the results for the DO control for both supervisory and regulatory investigated control schemes.

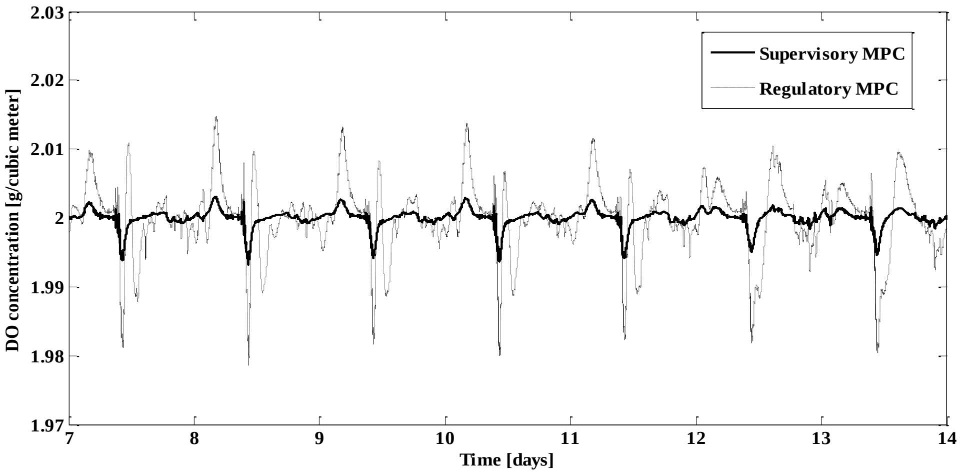

Fig. 5. Comparison between Regulatory MPC and Supervisory MPC of the DO concentration control.

The results presented above show the advantages of the supervisory MPC control scheme over the regulatory MPC control setup, as WWTP influent disturbances are rejected in a more efficient way. It is worthy to mention that by the use of the reactive secondary settler the dynamics of all process variables becomes more complex, making control a more demanding task.

Conclusions

The task of controlling the Wastewater Treatment Plant is complex and requires good control strategies. The process is multivariable, nonlinear and presents large time constant. Additionally, the process is continuously submitted to important disturbances. These arguments make mathematical models essential to develop new and effective model based control architectures. The paper proposed and implemented in the model a reactive secondary settler in order to realistically account for reactions still present in the separation unit. Using the reactive secondary settler model for The Benchmark Simulation Model No.1 the dynamics of the simulated WWTP changed, making control more complex.

In this work two control architectures have been investigated and compared, both of them based on the Model Predictive Control algorithm. The first one is the regulatory MPC and the second one is the supervisory MPC scheme. Each of the investigated control schemes proved to be good candidates for controlling the challenging WWTP. Although the MPC implemented at the regulatory level performed a good control for nitrate and DO concentration the supervisory MPC has shown superior performance, as disturbances have been rejected with reduced overshoot and shorter time. The overall effect is the improvement of the nitrogen removal in the WWTP while keeping the plant close to the nominal operating conditions.

Nomenclature

- f_{ns}: non- settable fraction of X_{in};
- r_h: settling parameter characteristic of the hindered settling zone;
- r_p: settling parameter characteristic of low solids concentration;
- v_{sj}: settling velocity in layer j;
- v_0: maximum settling velocity;
- v_0': limit of v_0;
- X_{in}: mixed- liquor suspended solids entering the settler;
- X_j^*: $X_j - X_{min}$;
- X_j : total suspended solids concentration in layer j;
- X_{min}: minimum attainable suspended solids concentration;
- X_{min}: $f_{ns} \cdot X_{in}$;

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Reglarea predictivă după model a instalaţiei de tratare a apelor uzate bazată pe Benchmark Simulation Model No.1-BSM1 cuprinzând decantor de tip reactiv

Rezumat

Instalaţiile de tratare a apelor uzate sunt supuse la perturbaţii semnificative ale debitelor si concentraţiilor de alimentare, ceea ce reprezintă o mare provocare pentru sistemele de reglare. Acest fapt motivează utilizare tehnicilor de reglare avansată pentru a putea obţine performanţe de reglare bune. În această lucrare sunt propuse două arhitecturi de control, bazate pe reglarea predictivă după model (RPM), pentru instalaţia de epurare a apelor uzate. Prima structură de control prezintă un regulator RPM aflat pe un singur nivel de conducere, iar a doua o structură de reglare de tip RPM supervisory constituită din două nivele de conducere, la nivelul superior fiind implementat un regulator RPM iar la nivelul de bază un regulator PI. Rezultatele simulărilor demonstrează avantajele structurii de reglare RPM supervisory care realizează o mai eficientă eliminare a efectului perturbaţiilor. Acest studiu s-a bazat pe Benchmark Simulation Model No.1-BSM1 cu modificări aduse modelului decantorului luându-se in considerare şi reacţiile biochimice care au loc în acesta.

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