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Economic Model Predictive Control of Aeration Systems in a Full Scale Biological Wastewater Treatment Plant

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Abstract

This work presents an economic model predictive control (EMPC) strategy for the control of the dissolved oxygen concentrations in the aerated reactors of a wastewater treatment plant located in Girona, Spain. The control strategy is investigated and evaluated based on the ASM1 simulation benchmark for performance assessment. In addition, the effect of the EMPC controller parameters such as the predictive horizon, the control horizon, the weights of input and the sample time are also investigated and studied. The obtained results applying the EMPC strategy for the control of the aeration system in the wastewater treatment plant show its effectiveness.

Keywords: Model Predictive Control, Wastewater Treatment Process.

1. Introduction

Biological wastewater treatment plants (WWTPs) are complex nonlinear systems with large variations in their flow rates and feed concentrations. These plants have to be operated continuously taking care of strict environmental regulations. Thus, the use of advanced control strategies becomes necessary to make them more efficient.

The implementation of optimal operation strategies is therefore interesting because WWTPs face the challenge of treat water properly and, at the same time, minimize the operational costs. This has been the driving force for the active research in the development of advanced control techniques and hierarchical control schemes to improve the operation of the WWTPs (Holenda et al., 2008; O'Brien et al., 2011; Vilanova et al., 2011; Piotrowskia, 2008; Vega, 2014; Santín, 2015). MPC has been the most successful advanced control approaches applied to control WWTPs. This is due to the fact that a MPC controller is able to directly handle constraints, including constraints on the control input, system outputs and/or internal state. It can predict the appropriate control actions to achieve optimal performance according to defined criteria in the cost function. However, in all of aforementioned references, the control systems are designed to drive the outputs of the wastewater treatment plants to track constant or changing set-points. Effluent quality and operating cost of wastewater treatment plants are addressed indirectly via set-points tracking.

Alternatively, this work presents an economic model predictive control (EMPC) strategy to optimize effluent quality and operating cost directly for the control of the dissolved oxygen (DO) concentrations in the aerated reactors of a wastewater treatment plant located in Girona, Spain. EMPC is a recently type of MPC control that includes the cost of operation in the objective function (Rawlings, 2012).

2. WWTP Description and Modelling

2.1. WWTP description

The Girona WWTP is a biological treatment plant designed to treat the wastewater generated by 275.000 inhabitant-equivalents with a medium daily inflow of 35.000 m^3/d. The process of the plant can be divided into two main treatment lines: water and sludge. The water line is separated into three phases: pre-treatment, primary treatment and secondary treatment. The secondary treatment is designed to convert biodegradable, organic wastewater constituents and certain inorganic fractions into new cell mass and by-products. The plant uses an activated sludge system and has three lines composed of three main reactors that are divided into various compartments and three clarifiers. Each line is made of two anoxic reactors located at the beginning, three aerated tanks and an anoxic tank followed by an aerated one. With this configuration, the plant can nitrify and denitrify with great efficiency. The anoxic and aerobic tanks have volumes of 1335, 4554, 1929, 1929, 1929, 1276, and 1409 m^3, respectively. Oxygen is supplied to aerated tanks by the aeration system which delivers air to each of the aeration tanks. The wastewater and activated sludge are separated into three parallel secondary settlers. The volume of each secondary settler is approximately 5024 m^3. The activated sludge is internally recirculated from the last aerobic zone to the anoxic tank (210% of influent waste). Additionally, the wastewater is recirculated from the secondary settlers to the anoxic tank (45 to 100% of influent waste).

2.2. WWTP modelling

The Benchmark Simulation Model (BSM1) (Jeppsson & Pons 2004) has been adapted to represent the Girona WWTP (see Figure 1). The Activated Sludge Model n.1 (ASM1) describes the biological phenomena taking place in the biological reactors and it is supposed that no biological reactions take place in the settlers. A dynamics of dissolved oxygen for the *j*-th aeration tank is described by the following nonlinear differential equation (Olsson & Newell 1999):

$$\frac{dS_{O,j}}{dt} = \frac{1}{V_j}(Q_{j-1}S_{O,j-1} + r_{S_{O,j}}V_j - Q_jS_{O,j}) + K_La(S_{sat} - S_{O,j}) \tag{1}$$

where, V_j is the reactor volume; Q_j is the reactor flow rate; Q_{j-1} is the reactor inflow rate; $S_{O,j-1}$ is the DO concentration entering the reactor; $S_{O,j}$ is the DO concentration in the reactor; K_La is the oxygen transfer coefficient; $S_{O,sat}$ is the saturation concentration for oxygen, and the observed conversion rate for the dissolved oxygen $r_{S_{O,j}}$ is given by:

$$r_{S_{O,j}} = -\frac{1-Y_H}{Y_H}\mu_H\left(\frac{S_S}{K_S+S_S}\right)\left(\frac{S_O}{K_{O,H}+S_O}\right)X_{B,H} - \frac{4.57-Y_A}{Y_A}\mu_A\left(\frac{S_{NH}}{K_{NH}+S_{NH}}\right)\left(\frac{S_O}{K_{O,A}+S_O}\right)X_{B,A}$$

Y_H and Y_A are the stoichiometric parameters, and μ_H, K_S, K_O ,H, μ_A, K_{NH} and $K_{O,A}$ are the kinetic parameters. S_S is the readily biodegradable substrate, $X_{B,H}$ is the active heterotrophic biomass, S_{NH} is the $NH_4^+ + NH_3$ nitrogen and $X_{B,A}$ is the active autotrophic biomass.

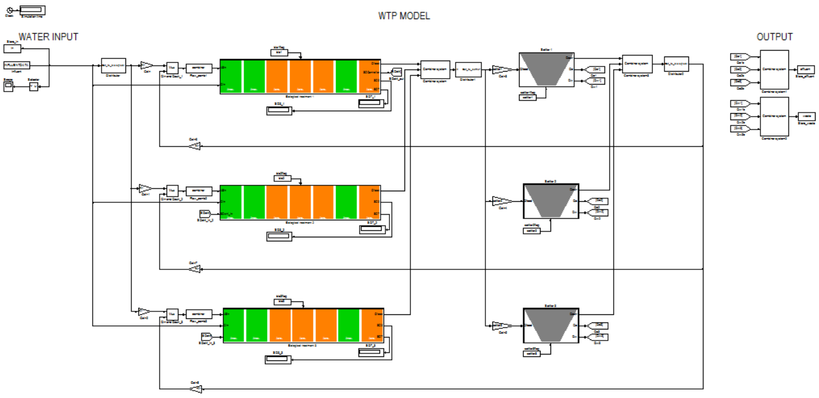

Figure 1: Layout of Girona WWTP

3. Model Predictive Control (MPC) of the Dissolved Oxygen

3.1 Operational goals

The immediate control goal of a WWTP is to meet the water quality level established by the regulations. Predictive control techniques may be used to compute strategies which achieve this, while also optimizing the system performance in terms of different operational criteria, such as:

- *Economic costs*. The main economic costs associated to WWTP are due to: treatment and electricity costs. Water through the WWTP involves important electricity costs in pumping stations in charge of internal and external water recirculations. Evaluating the cost of water treatment (aeration) and electricity separately allows the study of their effects on the optimal solution. For this study, this control objective can be described by the expression

  $$J_1(k) = W_e(\alpha u(k) + \gamma(k)u(k)) \tag{2}$$

  where α corresponds to a known vector related to the economic costs of the water treatment and $\gamma(k)$ is a vector of suitable dimensions associated to the economic cost of the flow through certain actuators (pumps only) and their control cost (pumping). Note the k-dependence of γ since the pumping effort has different values according to the time of the day (electricity costs). The weight matrix W_e expresses the relative priority of this objective with respect to the others in the optimization process.

- *Set-point tracking term*. Several variables can be controlled (e.g. Dissolved oxygen concentration in the aeration tank, effluent ammonia in the secondary settler) by adding a tracking term

  $$J_{track}(k) = (y(k) - y^{sp})^T W_y (y(k) - y^{sp}) \tag{3}$$

  where y^{sp} is the set-point and matrix W_y defines the priority of this objective in the cost function.

- *Output water quality term.* The quality of the output effluent is typically considered as a direct and important indicator of the performance of the control systems as well as the entire WWTP. The concentrations of different compounds (e.g. DQO< 125 mg/l, Nt< 15 mg/l) should be maintained below the pre-specified safety thresholds

$$J_{qual}(k) = \begin{cases} 0 & if \quad x(k) \le \beta \\ (x(k)-\beta)^T W_x (x(k)-\beta) & if \quad x(k) \ge \beta \end{cases} \tag{4}$$

where β is a term which determines the safety thresholds to be maintained for the control law computation and matrix W_x defines the priority of this objective in the cost function.

- *Smooth set-points for equipment conservation*: The operation of WWTP and main valves and pumps usually requires smooth flow set-point variations. To obtain such smoothing effect, the proposed MPC controller includes a fourth term in the objective function to penalize control signal variation between consecutive time intervals, i.e., this term is expressed as

$$J_{smo}(k) = \Delta u(k)^T W_u \Delta u(k) \tag{5}$$

Therefore, the performance function *J(k),* considering the aforementioned control objectives has the form

$$J = \sum_{k=0}^{H_p-1} J_{eco}(k) + \sum_{k=1}^{H_p} J_{track}(k) + \sum_{k=1}^{H_p} J_{qual}(k) + \sum_{k=0}^{H_p-1} J_{smo}(k) \tag{6}$$

4.2 Control strategy computation

The control strategy computation is based on the implementation on a receding horizon as in MPC and solves an optimal control problem at each time *k*.

$$\min_{\tilde{u}_k} J(\tilde{x}_k, \tilde{u}_k, \tilde{d}_k) \tag{7}$$

subject to:

$$\begin{cases} x(k|j+1) = f(x(k|j), u(k|j), d(k|j), \theta(k)) \\ u(k|j) \in \mathbb{U} \quad j = 0, \cdots, H_p - 1 \\ x(k|j) \in \mathbb{X} \quad j = 1, \cdots, H_p \end{cases}$$

where:

$$\mathbb{U} = \left\{ u \in \mathbb{R}^{n_u} \middle| u^{min} \le u \le u^{max} \right\} \qquad \mathbb{X} = \left\{ x \in \mathbb{R}^{n_x} \middle| x^{min} \le x \le x^{max} \right\}$$

and

$$\tilde{u}_k = \left(u(k|j)\right)_{j=0}^{H_{p-1}} = \left(u(k|0), u(k|1), \cdots, u(k|H_{p-1})\right)$$
$$\tilde{x}_k = \left(x(k|j)\right)_{j=1}^{H_p} = \left(x(k|1), x(k|2), \cdots, x(k|H_p)\right)$$
$$\tilde{d}_k = \left(d(k|j)\right)_{j=0}^{H_{p-1}} = \left(d(k|0), d(k|1), \cdots, d(k|H_{p-1})\right)$$

At each time step, a control input sequence $\tilde{u}_k$ of present and future values is computed to optimize the performance function $J(\tilde{x}_k, \tilde{u}_k, \tilde{d}_k)$, according to a prediction of the system dynamics over the horizon H_p.

4. Simulation results

The composition of the influent wastewater to Girona WWTP is varied during the day: Qin (between 35-40.000 m3/d), COD (between 400-650 mg/l), DBO (175 - 225 mg/l) and Nitrogen (between 40 - 65 mg/l). The effect of the EMPC controller parameters such as the prediction and control horizons (Hp , HC) and the length of the prediction step T, on control quality and computation time has been studied and examined. As a result of numerical analysis, the parameters of the EMPC controller were selected as follows: HC=Hp=10 steps and T=5 min. Simulation results for DO control at Girona WWTP are shown in Figs. 2-3. The first scenario consists in controlling the DO concentration in a set-point range between 1 to 2,5 mg/l with the minimum energy consumption. It can be seen in Fig. 2 that oxygen is maintained at the low limit of the set-point range, minimizing the necessary aeration flow and consequently the consumed energy (electricity consumption is a 13.6% lower).

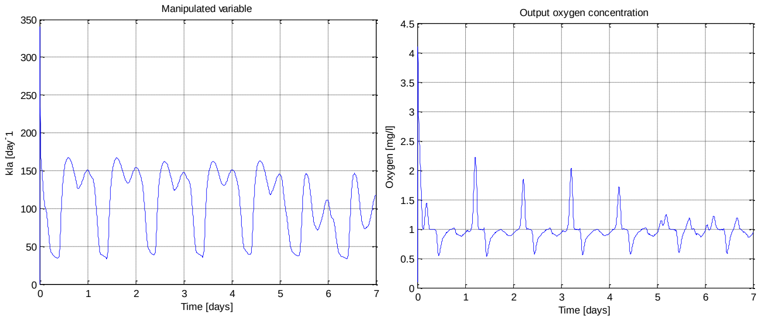

Figure 2: Dissolved oxygen concentration and aeration flow for scenario 1

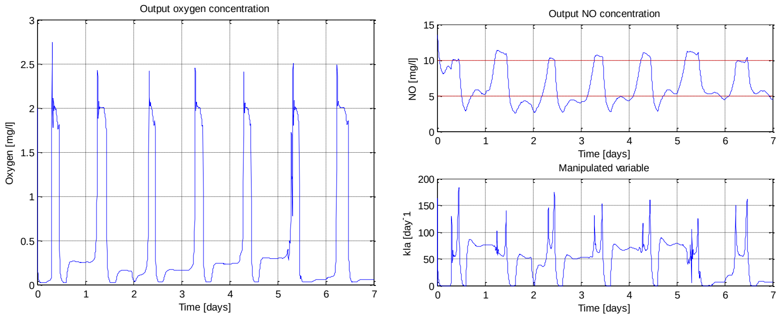

Figure 3: Dissolved oxygen concentration and aeration flow for scenario 2

The second scenario of simulation consists in maintaining the dissolved oxygen at a maximum value of 2 mg/l, so that the concentration of nitrogen removal in the effluent is maintained within the range of 5-10 mg/l. In this case, a PI controller, which is responsible for maintaining the DO at the value calculated by the EMPC is added and implemented in a cascade scheme to the MPC controller. Fig. 3 shows the DO value, the nitrogen concentration and the manipulated variable (aeration flow rate). It can be observed that the oxygen remains within the desired limits, ranging from 0 to 2 mg/l, and in turn, the nitrogen concentration is maintained, with small variations, within the range of 5-10 mg/l. Therefore, the controller reached a compromise for both objectives.

5. Conclusions

This paper has presented the results of the application of an EMPC strategy for the control of the dissolved oxygen concentration in the aerated reactors of a wastewater treatment plant located in Girona, Spain. The biological wastewater treatment model parameters have been estimated by means of a sensitivity analysis and an optimization procedure, using experimental data collected from the wastewater treatment plant. The proposed control strategy has been investigated and evaluated using the ASM1 simulation benchmark for performance assessment. The obtained results applying the EMPC strategy for the control of the aeration system in the wastewater treatment plant has shown its effectiveness.

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