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Advanced decision control system for effluent violations removal in wastewater treatment plants

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ABSTRACT

This paper presents the application of control strategies for wastewater treatment plants with the goal of effluent limits violations removal as well as achieving a simultaneous improvement of effluent quality and reduction of operational costs. The evaluation is carried out with the Benchmark Simulation Model No. 2. The automatic selection of the suitable control strategy is based on risk detection of effluent violations by Artificial Neural Networks. Fuzzy Controllers are implemented to improve the denitrification or nitrification process based on the proposed objectives. Model Predictive Control is applied for the improvement of dissolved oxygen tracking.

1. Introduction

The control of biological wastewater treatment plants (WWTPs) is very complex due to the following facts. The biological and biochemical processes that take place inside the plants are strongly interrelated and involve a great number of state variables. The flow rate and composition of the influent are very variable. There are legal requirements that penalize the violation of the pollution effluent limits (among others, the European Directive 91/271 “Urban wastewater” established by the European Union). In addition, the improvement of water quality and the reduction of operational costs must be considered.

For the evaluation of control strategies in WWTPs, Benchmark Simulation Model No.1 (BSM1) was developed in Copp (2002). This benchmark was extended in a new version, the Benchmark Simulation Model No.2 (BSM2), in Gernaey, Jeppsson, Vanrolleghem, and Copp (2014). BSM2 includes the entire cycle of a WWTP, adding the sludge treatment. In addition, the simulation period is extended to one-year assessment, rather than a week, as in BSM1. In this work, the simulations and evaluations of the control strategies have been carried out with BSM2. It provides a default control strategy that applies a Proportional-Integral (PI) controller. PI and Proportional-Integrative-Derivative (PID) controllers have attracted the research interest for process control looking for good robustness/performance trade-off (Alcántara, Pedret, & Vilanova, 2010; Alfaro & Vilanova, 2013; Vilanova & Visioli, 2012). However, WWTPs exhibit highly complex dynamics that demand more advanced alternatives.

In the literature there are many works that present different methods for controlling WWTPs. Most of the works use BSM1 as working scenario. In some cases they put the focus on avoiding violations of the effluent limits by applying a direct control of the effluent variables, mainly ammonium and ammonia nitrogen (S_{NH}) and total nitrogen ($S_{N_{tot}}$) (Corriou & Pons, 2004; Shen, Chen, & Corriou, 2008, 2009). Nevertheless, they need to fix the set-points of the controllers at lower levels to guarantee their objective, which implies a great increase of costs. Other works give a trade-off between operational costs and effluent quality, but they do not tackle the effluent violations. They usually deal with the basic control strategy (control of dissolved oxygen (S_O) of the aerated tanks and nitrate nitrogen concentration (S_{NO}) of the second tank ($S_{NO,2}$)) (Belchior, Araujo, & Landeckb, 2011; Cristea, Pop, & Serban,

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Abbreviation: AE, aeration energy (kWh/d); ANN, artificial neural network; ASM1, activated sludge model No. 1; BOD_5, 5-day biological oxygen demand (mg/l); BSM, benchmark simulation model; CL1, first control strategy of the finalization of BSM2 plant layout in Nopens et al. (2010); CL2, second control strategy of the finalization of BSM2 plant layout in Nopens et al. (2010); COD, chemical oxygen demand (mg/l); defCl, default control strategy of the original BSM2 definition in Jeppsson et al. (2007); EC, consumption of external carbon source (kg/d); EQI, effluent quality index (kg/d); FC, fuzzy controller; HE_{net}, net heating energy (kWh/d); ME, mixing energy (kWh/d); MET_{prod}, methane production in the anaerobic digester (kg/d); MPC, model predictive control; MPC+FF, model predictive control with feedforward compensation; OCI, overall cost index; PE, pumping energy (kWh/d); SP, sludge production (kg/d); TSS, total suspended solids (mg/l); WWTP, wastewater treatment plants

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Nomenclature

K_La	oxygen transfer coefficient (d^{-1})
Q	flow rate (m^3/d)
Q_a	internal recycle flow rate (m^3/d)
Q_{bypass}	bypass flow rate (m^3/d)
Q_{po}	overflow rate of the primary clarifier (m^3/d)
q_{EC}	external carbon flow rate (m^3/d)
r_{NH}	conversion rate of ammonium and ammonia nitrogen
r_{NO}	conversion rate of nitrate nitrogen
S_{Ntot}	total nitrogen concentration (mg/l)
$S_{Ntot,e}$	total nitrogen concentration in the effluent (mg/l)
$S_{Ntot,ep}$	prediction of the effluent total nitrogen concentration (mg/l)
S_{NH}	ammonium and ammonia nitrogen concentration (mg/l)
$S_{NH,bypass}$	ammonium and ammonia nitrogen concentration in the bypass (mg/l)
$S_{NH,e}$	ammonium and ammonia nitrogen concentration in the effluent (mg/l)
$S_{NH,ep}$	prediction of the effluent ammonium and ammonia nitrogen concentration (mg/l)
$S_{NH,po}$	ammonium and ammonia nitrogen concentration from the primary clarifier overflow (mg/l)
S_{NO}	nitrate nitrogen concentration (mg/l)
S_O	dissolved oxygen (mg/l)
S_S	readily biodegradable substrate (mg/l)
T_{as}	temperature (°C)
$X_{B,A}$	active autotrophic biomass (mg/l)
$X_{B,H}$	active heterotrophic biomass (mg/l)

2008; Holenda, Domokos, Redey, & Fazakas, 2008), or propose hierarchical control structures that regulate the S_O set-points according to some states of the plant, usually S_{NH} and S_{NO} values in any tank or in the influent (Ostace, Cristea, & Agachi, 2010, 2011; Stare, Vrecko, Hvala, & Strmcnick, 2007; Santín, Pedret, & Vilanova, 2014; Vilanova, Katebi, & Alfaro, 2009, 2011; Vrecko et al., 2006) or S_O in other tanks (Ekman, Bjorlenius, & Andersson, 2006).

Other works in the literature use BSM2 as testing plant. Some of them are focused on the implementation of control strategies in the biological treatment, as the present work. Specifically, they propose a multi-objective control strategy based on S_O control by manipulating the oxygen transfer coefficient (K_La) of the aerated tanks, S_{NH} hierarchical control by manipulating the S_O set-points, $S_{NO,2}$ control by manipulating the internal recycle flow rate (Q_a) or total suspended solids (TSS) control by manipulating the wastage flow rate (Q_w) (Benedetti, Baets, Nopens, & Vanrolleghem, 2009; Flores-Alsina et al., 2009, Flores-Alsina, Gallego, Feijoo, & Rodriguez-Roda, 2010, 2011, 2014; Kim & Yoo, 2014). These referred works have different goals, but all of them obtain an improvement in effluent quality and/or a reduction of costs. In addition to achieving an improvement in the effluent quality it is also possible to reduce the percentage of time of pollution violations. However, none of these articles are focused on reducing peaks of pollutant concentrations until the complete elimination of effluent violations. It is of significant importance because high concentrations of pollutants in the effluent can damage the environment and the health of the population. In addition, there are legal requirements penalized with fines, which result in an increment of costs.

The goal of the presented work is to avoid S_{NH} in the effluent ($S_{NH,e}$) or S_{Ntot} in the effluent ($S_{Ntot,e}$) limits violations and, at the same time, to improve effluent quality and to reduce operational costs. The paper uses BSM2 as working scenario and some of the control strategies are based on Santín, Pedret, and Vilanova (2015b). In addition, it introduces a novel method to deal with the effluent violations. On one hand, the situations of risk of effluent violations are detected by forecasting the future output concentrations of pollutants based on the input variables. On the other hand, specific control strategies are applied in those situations. The proposed advanced control techniques are based on Model Predictive Control (MPC), Fuzzy Controller (FC) and Artificial Neural Networks (ANN). The MPC controllers aim to track the references of S_O in the fourth tank ($S_{O,4}$) and in the fifth tank ($S_{O,5}$) and $S_{NO,2}$. Three FCs are used based on the biological processes. The first one manipulates the S_O references of the MPC controllers based on S_{NH} in the fifth tank ($S_{NH,5}$), to improve effluent quality and to reduce operational costs. The second one manipulates the external carbon flow rate (q_{EC}) to eliminate $S_{Ntot,e}$ violations. Finally, the third one manipulates Q_a to eliminate violations of $S_{NH,e}$. The proposed control strategies to avoid violations of $S_{NH,e}$ and $S_{Ntot,e}$ are applied only when a risk of violation is detected. ANNs are applied with this aim by evaluating the influent at each sample time. In the same way as the referred papers, the sensors used in the proposed work are considered to be ideal.

It is worth to say that an updated version of BSM2 also takes into account greenhouse gases, phosphorus, sulphur and micropollutants. Nevertheless, they have not been considered in the present work to avoid an excessive extension.

The paper is organized as follows: In the following section the BSM2 working scenario is presented. Next, the applied control approaches are described. Then, the proposed control strategies and the tuning of the controllers are explained. Thereafter, results in terms of effluent quality, costs and percentage of time of effluent violations are shown and compared to the default control strategy of BSM2 and with the literature. Finally, the most important conclusions are drawn.

2. Benchmark simulation model No. 2

The simulation and evaluation of the proposed control strategy is carried out with BSM2 (Gernaey et al., 2014).

The finalized BSM2 layout (Fig. 1) includes BSM1 for the biological treatment of the wastewater and the sludge treatment. A primary clarifier, a thickener for the sludge wasted from the secondary clarifier, a digester for treatment of the solids wasted from the primary clarifier and the thickened secondary sludge, as well as a dewatering unit have also been added. The liquids collected in the thickening and dewatering steps are recycled ahead of the primary settler.

The influent dynamics are defined for 609 days by means of a single file, which takes into account rainfall effect and temperature variations along the year. Following the simulation protocol, a 200-day period of stabilization in closed-loop using constant inputs with no noise on the measurements has to be completed before using the influent file (609 days). Only data from day 245 to day 609 is evaluated.

2.1. Activated sludge reactors

The activated sludge reactors consist in five biological reactor tanks connected in series, with an internal recycle from the last tank. The plant is designed for an average influent dry weather flow rate of 20,648.36 m^3/d and an average biodegradable chemical oxygen demand (COD) in the influent of 592.53 mg/l. The total volume of the bioreactor's section is 12,000 m^3, 1500 m^3 each