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Improving the performance of a WWTP control system by model-based setpoint optimisation

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A B S T R A C T

The aim of this work was the improvement of a WWTP control system using a model-based setpoint optimisation. For this purpose, an anaerobic/anoxic/aerobic (A^2/O) pilot WWTP was simulated using the IWA ASM2d model under different influent conditions. Several control strategies for an efficient biological C/N/P removal were evaluated in this WWTP: i) open loop; ii) dissolved oxygen control in the aerated reactors; iii) maximum performance of nutrient removal; iv) optimised fixed setpoints for the controlled variables; v) daily optimised setpoints; vi) two different sets of optimised setpoints for weekdays and weekends and vii) hourly optimised setpoints. A single cost function based on the operating costs by converting the effluent quality into monetary units was chosen for evaluating the plant performance (i.e. the control loops setpoints were optimised to obtain low effluent N and P discharges with the minimum costs). Setpoint optimisation was shown as a good tool to improve the performance of the system. In this case study, control strategy (vi) was selected as the best choice considering the trade-off cost-benefit. The optimised control system resulted in around a 45% decrease of operational costs with respect to the open loop scenario, a significant improvement of the effluent quality and a drastic decrease of the time above discharge limits.

1. Introduction

Stringent legislation for wastewater treatment plants (WWTP) is currently a top driving force for the development of new treatment technologies and for the optimisation of the existing ones. Meeting stringent concentration requirements for C, N and P discharge with minimal costs has raised the need of a more efficient operation. These plants can be redesigned to include new treatments or can be upgraded with new control structures. Although several solutions have been reported so far, a number of plants still operate without being updated.

Model-based optimisation of WWTP configuration has been used for design purposes (Rivas et al., 2008; Ferrer et al., 2008), while the utilisation of automatic control systems has improved the performance of numerous WWTP (Benedetti et al., 2010; Cecil and Kozlowska, 2010). However, little attention has been paid to the tuning of controllers (Ruano et al., 2010) or to the setpoint optimisation for WWTP performance purposes (Stare et al., 2007). Additionally, the development of reliable models has provided tools to allow the model-based optimisation of these control systems. For example, IWA ASM2d (Henze et al., 1999) is a complex kinetic model able to describe biological C/N/P removal processes from wastewater. Although this model has a large number of parameters which are difficult to indentify due to correlation problems (Machado et al., 2009a), it is able to provide an accurate description of the process with its default parameter values.

With respect to control, single feedback controllers on essential parameters have lead to better quality effluents in the last decades; however the efficiency of this strategy is limited by: i) the dynamics of the influent or ii) the inherent complexity of the system since control actions applied in one unit can somehow affect posterior sub processes (Alex et al., 2008). As proposed by Olsson et al. (2007), these problems could be overcome by integrating plant-wide control systems with a continuous retuning of the control loops (e.g. via gain scheduling or using adaptive control) for the optimisation of the overall plant operation.

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On the other hand, most of the control strategies reported so far about improving WWTP operation were based on C and N removal, while P removal wasn't the focus yet (Baeza et al., 2002; Copp et al., 2002; Rivas et al., 2008; Benedetti et al., 2010). However, the current knowledge gained on the enhanced biological phosphorus removal (EBPR) process has raised the opportunity of developing new control structures considering simultaneous C/N/P removal (Ingildsen et al., 2005). Designing new control strategies in such a complex biological system is not a straightforward issue because of the high number of variables involved and the multivariable nature of the problem. In the case of model-based design, the current biological models present a complex structure containing a large number of state variables that evolve transport and transformation processes (Sorour and Bahgat, 2006). In addition, the design of control structures for nutrient removal in WWTP should consider the best pairing of controlled and manipulated variables (Machado et al., 2009b) because it will provide better system controllability with fewer operating costs and the most effective wastewater treatment.

Once designed, the efficiency of these new control strategies needs to be assessed including not only effluent quality but also plant economics. Balancing both issues is not a straightforward topic: the different parameters have to be properly weighted and effluent fines and other costs as investment or man-power are typically location dependent. Moreover, the problem can become even more complex if other criteria as environmental impact or risk of microbiology-related solids separation problems are evaluated (Flores et al., 2008). Therefore, to allow the comparison of control strategies, different authors proposed the evaluation of the plant performance with a single cost function calculated with the main costs involved in the plant operation and adding the effluent quality converted into monetary units (Vanrolleghem et al., 1996; Gillot et al., 1999).

In view of this background, the aim of this work was improving the performance of an A^2/O WWTP with biological C/N/P removal considering criteria of effluent quality and operational costs (OC) by means of the improvement of its control system with a model-based setpoint optimisation. For this purpose, the WWTP was simulated using IWA ASM2d and several control strategies were evaluated using different influents.

2. Materials and methods

2.1. Plant description

The simulated plant (Fig. 1) is a continuous A^2/O system for simultaneous C/N/P removal consisting of four continuous stirred tank reactors (CSTRs) and one settler (modelled using the 10-layer model of Takács et al., 1991). The hydraulic model mimicked the configuration of a real pilot plant (146L), where the best control strategies found in this work were to be further evaluated. The biological kinetic model used to describe C/N/P removal was ASM2d (Henze et al., 1999). R1 is an anaerobic reactor favouring the uptake of organic matter by Polyphosphate Accumulating Organisms (PAO) and thus, further P removal. R2 is an anoxic reactor where the nitrate brought by the internal recycle (Q_{RINT}) is reduced by either the denitrifying fraction of PAO (DPAO) or ordinary heterotrophic organisms (OHO). R3 and R4 are two aerobic reactors where complete organic matter and P removal takes place together with nitrification. The settler produces an effluent stream and a biomass enriched stream. Most of the latter is returned to R1 through the external recycle (Q_{REXT}) and the rest is purged (Q_W). The flow rate and the composition of the influent (Q_{IN}) varied in time according to the influents proposed by the IWA Task Group on Benchmarking (Gernaey and Jorgensen, 2004), being 0.25 $m^3\ d^{-1}$ the average flow-rate value. Three different dynamic plant influents were simulated: Dry-2, Rain-2 and Storm-2. Each influent contained 14 days of data at 15-min intervals.

The simulated plant included four local control loops:

1. Dissolved Oxygen (DO) feedback PI-control in R3 and R4 using the oxygen transfer coefficient (k_La) as the manipulated variable.
2. Effluent ammonium was controlled by the DO setpoint in R3 and R4 (both reactors had the same DO setpoint) using a cascade control structure. DO setpoint limits were 0 and 4 mg $DO \cdot L^{-1}$.
3. Nitrate feedback PI-control in R2 by manipulating Q_{RINT}.
4. Total suspended solids (TSS) feedback PI-control in R4 by acting in the Q_W. To avoid the effect of a possible change in TSS concentration on the treatment capacity or the sludge age and in order to compare the removal efficiency related only with the tested control strategies, TSS were considered as inventory variable (i.e. variables that must be controlled for a proper plant management) and were controlled at a fixed setpoint of 4500 mgTSS L^{-1} (Steffens and Lant, 1999; Machado et al., 2009b).

2.2. Cost function development

Effluent quality and OC are the key parameters when evaluating the effectiveness of different wastewater treatment processes. The cost function proposed by Vanrolleghem and Gillot (2002), which allows rewriting effluent quality in terms of monetary units, was adopted in the present work as the criterion for selecting the best control proposal structure. The OC per m^3 of influent of a WWTP can be estimated with equations (1)–(6). These equations are a modification of the methodology described in Vanrolleghem and Gillot (2002). We propose to include the influent (Q_{IN}) in the cost calculations (equations 2–4, 6) in order to obtain the costs per m^3 of wastewater treated. Thus, specific plant characteristics are avoided and the comparison between different plants becomes easier.

$$OC\left[€\cdot m^{-3}\right] = \gamma_E(AE + PE) + \gamma_{SP}SP + EF \quad (1)$$

AE corresponds to energy invested in aeration, *PE* is the necessary pumping energy, *SP* the sludge production and *EF* the effluent fines, γ_E (0.1 $€\cdot kWh^{-1}$) represents the cost of 1 kWh and γ_{SP} ($5\cdot10^{-4}$ $€\cdot g^{-1}$) stands for the cost of the treatment of 1 g of produced sludge (Stare et al., 2007). The aeration energy *(AE)* was calculated as proposed in Jeppsson (2005) by using equation (2), where k_La_i is the global oxygen transfer coefficient [d^{-1}] of each aerobic reactor.

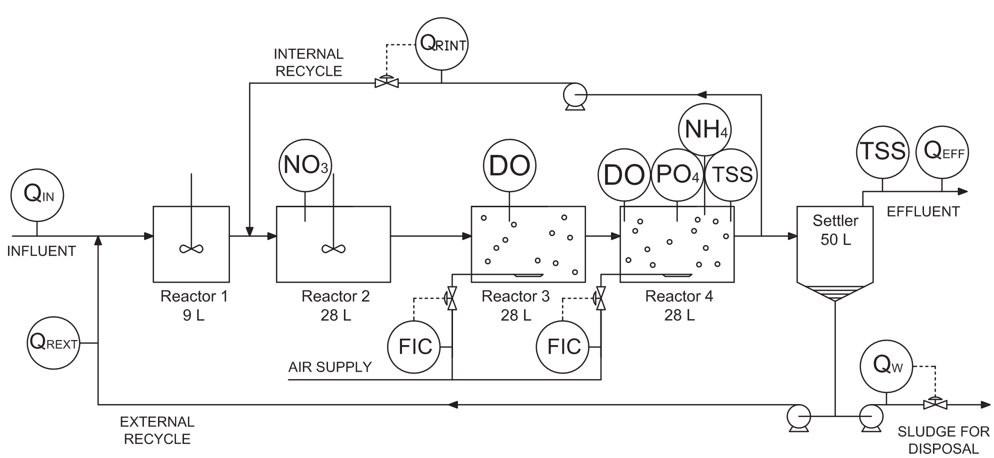

Fig. 1. Scheme of the A^2/O simulated plant for simultaneous C/N/P removal.