Model-based control structure design of a full-scale WWTP under the retrofitting process

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ABSTRACT

The anoxic–oxic (A/O) municipal wastewater treatment plant (WWTP) of Manresa (Catalonia, Spain) was studied for a possible conversion to an anaerobic/anoxic/oxic (A2/O) configuration to promote enhanced biological phosphorus removal. The control structure had to be redesigned to satisfy the new necessity to control phosphorus concentration, besides ammonium and nitrate concentrations (main pollutant concentrations). Thereby, decentralized control structures with proportional-integral-derivative (PID) controllers and centralized control structures with model-predictive controllers (MPC) were designed and tested. All the designed control structures had their performance systematically tested regarding effluent quality and operating costs. The centralized control structure, A2/O-3-MPC, achieved the lowest operating costs with the best effluent quality using the A2/O plant configuration for the Manresa WWTP. The controlled variables used in this control structure were ammonium in the effluent, nitrate at the end of the anoxic zone and phosphate at the end of the anaerobic zone, while the manipulated variables were the internal and external recycle flow rates and the dissolved oxygen setpoint in the aerobic reactors.

Key words | control structure design, enhanced biological phosphorus removal, WWTP

INTRODUCTION

Enhanced biological phosphorus removal (EBPR) from wastewater requires an anaerobic step that is not often present in wastewater treatment plants (WWTPs; Tchobanoglous et al. 2003). To convert old WWTP facilities with chemical oxygen demand (COD) and nitrogen (N) removal into new ones with additional EBPR, a retrofitting process should be carried out, including a new control structure design, since two variables will appear inside the control system: the phosphorus concentration (usually at the effluent stream, as a controlled variable) and the biomass recycle stream (as a manipulated variable).

The control structure design enables: the choice and order of the most important controlled and manipulated variables, selection of the type of arrangement among variables (feedback control, feedforward control, on-off control), and establishment of the kind of controller to be implemented (decentralized or centralized) (Skogestad 2004). The best pairing of controlled and manipulated variables for decentralized control loops can be selected by relative gain array (RGA) (Bristol 1966) and minimized condition number analysis (Boyd 1994).

RGA analysis could help to evaluate the weight of the optimization problem in cases using a model predictive control (MPC) (Maciejowski 2002; Stare et al. 2006). As there is a noticeable difference in the effort spent to implement decentralized (easier) and centralized control structures, this work presents systematic comparisons between control structures designed for a full-scale WWTP at Manresa (Catalonia, Spain), which is an A/O plant that should be converted into an A2/O plant. Physically, this conversion is possible since two of the six anoxic basins of the current plant could be modified to operate without the influence of the nitrate recycle.

Therefore, the main objective of this work was to study the effect of the retrofitting process of a WWTP in its controllability. The RGA of the main controlled and manipulated variables (control matrix) was evaluated with the new A2/O configuration to identify the best control structure. The different control alternatives were optimized to achieve the maximum effluent quality with minimum operating costs.
MATERIALS AND METHODS

The WWTP of Manresa consists of a pre-treatment (coarse and fine screening), primary treatment with two clarifiers and a secondary stage (biological removal) based on a modified Ludzack–Ettinger configuration. There are two main treatment lines in the secondary stage, each with three anoxic reactors (1,460 m³), one aerobic reactor made up by two parts of 3,390 m³ and a settler (1,385 m³). The average treated flow rate is 27,000 m³/d.

The new A²/O plant configuration for the Manresa WWTP was modeled based on the IWA ASM2d model (Henze et al. 2000). The Takács et al. (1991) model was used for describing settling. The dynamics of the measured variables at the effluent due to the settler hydraulics were also considered. The complete model description of the full-scale WWTP is presented in Machado et al. (2014). The influent was characterized for the application of the ASM2d, and plant data for 3 years were used to calibrate the non-linear model according to the ‘seeds’ methodology (Machado et al. 2009a). This procedure is based on the Fisher Information Matrix (FIM) and allows calibration of models with the lowest number of parameters and assessment of its confidence interval, avoiding correlation between the parameters optimized. The A²/O configuration proved the best one for this WWTP after performing a systematic set of comparisons with other plant configurations, such as the UCT (University of Cape Town) and BARDENPHO (BARnard-DENitriification-PHosphorus). The criteria used to decide the best plant configuration were the minimal investment and operation costs (CAPEX and OPEX) and the best effluent quality (Machado 2012).

For process control analysis, a set of first-order plus time-delay (FOPTD) linear transfer functions were obtained from the non-linear model previously calibrated by linearization at the conventional operating point. A sequence of known perturbations on the input variables (like dissolved oxygen (DO) setpoint, internal and external recycle flow-rates) was applied to the non-linear model to generate an output vector \( y(t) \), which is the variable of interest (like ammonium, nitrate and phosphate concentrations) and a black-box algorithm was used to identify the input–output relationships, producing the Output-Error (OE) model (Ljung 1999; Machado et al. 2009b) in a simulation environment (Simulink®, Matlab). The OE model structure is represented in Equation (1):

\[
y(t) = \frac{B(q)}{F(q)} u(t - n_K) + e(t)
\]

where \( y(t) \) is the output (controlled variable), \( u(t-n_K) \) is the input (manipulated variable) at \( n_K \) sample intervals before the current time. The variable \( e(t) \) is the prediction error; \( B(q) \) and \( F(q) \) are polynomials that represent the process model \( G(q) \) (relationship between the input and the output) and their parameters should be identified. Polynomials \( B(q) \) and \( F(q) \) are expressed by Equations (2) and (3):

\[
B(q) = b_1 + b_2 q^{-1} + ... + b_{nb} q^{-nb+1}
\]

\[
F(q) = 1 + f_1 q^{-1} + ... + f_{nf} q^{-nf}
\]

where \( nb \) and \( nf \) are the orders of \( B(q) \) and \( F(q) \), respectively. Variable ‘\( q \)’ is the shift operator. So, \( q^{-1} \) applied to \( y(t) \) produces \( y(t-1) \), which is the previous value of \( y(t) \). The coefficients of \( B(q) \) and \( F(q) \) are determined, therefore, solving an optimization problem in which the squared prediction error is minimized over the whole set of input–output data of \( N \) entries. The optimization variables of this problem are the coefficients of \( B(q) \) and \( F(q) \). The objective function is presented in Equation (4):

\[
V_N = \sum_{i=1}^{N} \left( y(t) - \frac{B(q)}{F(q)} u(t - n_K) \right)^2
\]

The discrete model identified with the OE algorithm was converted to the continuous domain for tuning the process controllers. All the model relationships among plant inputs (DO setpoint in the aerobic zone, internal \( Q_{RINT} \) and external \( Q_{RAS} \) recycling flow-rates) and outputs (ammonium in the effluent \( [NH_4]^+_{EFF} \), nitrate in the effluent \( [NO_3]_{EFF} \) and at the end of the anoxic zone \( [NO_3]_{ANOX} \), and phosphate in the effluent \( [PO_4]_{EFF}^3- \) and at the end of the anaerobic zone, \( [PO_4]_{ANAER}^3- \)) were determined. Figure 1 shows an example of data used for model identification between the input DO setpoint in the aerobic basin and the ammonium concentration in the effluent, presented as deviation variables.

Regarding the model’s uncertainty due to its identification in a single operating point, as the linear models were used for controller design, and they work inside a feedback loop, the uncertainties do not matter significantly since the feedback behavior is present. The main idea behind the controller design used in this work is to have controllers that are easy to implement in a real environment. If the linearization point is correctly selected, the WWTP will operate most
of the time near this operating point, where the controller performance will be higher but, in any case, the feedback structure will allow for the correcting of any deviations if the system is operating far from the linearization point.

The RGA gives information to help decide suitable and non-suitable input/output pairings. RGA interaction measurements are defined for linear models, which are usually obtained in just a single operating point. Then, the analysis obtained is only strictly valid with in a small neighborhood of the linearization point (Halvarsson 2010). In addition, dynamic RGA calculation can also be limited by changes in best pairing results obtained at different frequencies and also by the assumptions considered in the nonlinear model used for obtaining the linear models. Hence, controllers designed with RGA recommendations should be finally tested in wide operating conditions.

The RGA was calculated for the different subsets created with the previously developed FOPTD transfer function matrix of the plant, following the procedures detailed in Machado et al. (2009b). Decentralized control structures (three loops per structure) were made using the PID controllers and the centralized ones with an MPC. The MPC used was a standard fourth generation like the DMC-Plus (Honeywell, Houston, TX, USA) with a constraint optimization problem being solved at each time step with a receding horizon. In addition, some of the decentralized control structures were tested within an optimization setpoint program of the three control loops in order to minimize the total operating cost, which takes account of the costs of aeration, sludge treatment, pumping and effluent quality (Copp et al. 2002; Stare et al. 2007; Machado et al. 2009b). The operating costs were calculated the same way for all the tested control structures.

The experimental data used for evaluating controller performance and operating costs were based on real WWTP data for a period of 1 year, which included daily variations measured in the influent. The experimentally determined influent stream characteristics (Montpart 2010) were $S_I = 0.080$ COD, $X_I = 0.035$ COD, $X_S = 0.450$ COD and $S_F = 0.410$ COD, and these ratios were assumed to be constant. The values of the influent variables $X_{TSS}, S_{NH_4}, S_{NO_3}, S_{PO_4}$ and COD were assumed to be equal to the experimental observations (analysis of daily composite samples). The variables $S_A, X_{PHA}, X_{PAO}, X_{PP}, S_{N_2}, S_{O_2}, X_A$ and $X_{MEP}$ were assumed to be zero. The WWTP was first simulated during 1,200 days under average influent data to obtain steady state conditions. Then, dynamic simulations for 1 year were performed using the real influent daily data.

Four possible sets of control and manipulated variables (Figure 2) were compared for controlling the proposed $A^2/O$ plant configuration (decentralized control structures). Note that the pairing selected was similar: the DO was manipulated to control the ammonium concentration at the aerobic zone, while the internal recycle and the external recycle were manipulated to control nitrate ($[NO_3]_{ANOX}$ or $[NO_3]_{EFF}$) and phosphate ($[PO_4^{3-}]_{ANAER}$ or $[PO_4^{3-}]_{EFF}$), respectively. The three manipulated variables were the same for all the structures, while the three controlled
variables were modified. The objective of the A²/O-1 structure is controlling nitrate, ammonium and phosphate in the effluent, manipulating the internal recycle flowrate, the DO setpoint in the aerobic reactors and the external recycle flowrate. This structure could be of interest because the quality of the effluent can be monitored with the same online nutrient sensors used for control. However, from a controllability point of view, the measurements are all in the last point of the WWTP; hence, a delayed update of information is expected for the controller, introducing low performance under dynamic conditions. The A²/O-2 structure moves the measuring point of nitrate to the end of the anoxic zone, improving the response time for the nitrate control loop and providing lower interactions among the control loops. The A²/O-3 structure moves the measurement point of phosphate to the end of the anaerobic reactor. This change decreases the response time of the phosphate loop, theoretically improving its controllability. The three sampling points in this structure for nitrate, ammonium and phosphate are located in different parts of the plant (anoxic reactor, effluent and anaerobic reactor, respectively) providing probably the lower interaction among the three control loops. In the last control structure, A²/O-4, phosphate is controlled at the end of the anaerobic reactor as in A²/O-3, while the nitrate and ammonium are controlled at the effluent, as in A²/O-1. It is worth noting that these four control structures were chosen to be tested based on the criteria to pair ammonium with DO setpoint, nitrate concentration to the internal recycle flowrate and phosphate concentration to the external recycle flowrate. The abovementioned control and manipulated variables produce 24 possible combinations of control structure. The four selected control structures are the most usual and would be well accepted by plant owners, process engineers and WWTP workers since they are readily understandable.

It is important to note that adding external biodegradable COD (bCOD) to the influent to improve nitrate control was not evaluated since the number of possible control structures to analyze would increase substantially. Moreover, the operating costs would increase to a proportion that the plant owner could not afford. Conversely, the internal recycle flow rate is the typical manipulated variable when denitrification must be controlled. Both nitrate concentration in the anoxic reactor and the nitrate concentration in the effluent can be used as controlled variables from a control point of view.
view, as a modification of the internal recycle flowrate has an effect on both variables, even under limited bCOD availability, as in the Manresa WWTP.

RESULTS AND DISCUSSION

FOPTD linear models (Table 1) were identified for the main inputs (DO setpoint in the aerobic reactors, internal and external recycle flowrates) and outputs (ammonium in the effluent, nitrate in the anoxic reactor and in the effluent, and phosphate in the anaerobic reactor and in the effluent) using the complete ASM2d model for both the A/O and the retrofitted A²/O configurations.

The comparison of the unit step response of the FOPTD transfer function models for both configurations (Figure 3) shows some interesting features. The effect of Q_RINT and Q_RAS on ammonium in the effluent in both configurations is very different, because an increase of these flowrates in the A²/O configuration produces a higher decrease of ammonium in the effluent. The A²/O configuration also improves denitrification control since the time constant of model [NO₃]_EFF vs Q_RINT (or also [NO₃]_ANOX vs Q_RINT) was reduced after the retrofitting process. In addition, there was a simultaneous increase of the gain for the model [NO₃]_EFF vs Q_RINT and a decrease for the model [NO₃]_ANOX vs Q_RINT, indicating that the A²/O configuration improves the denitrification process in the WWTP. In this sense, the same increase of internal recycle produces a lower increase of [NO₃]_ANOX in the A²/O configuration (higher capacity to remove nitrate in the anoxic reactor) and there is a higher decrease in [NO₃]_EFF (higher reduction of nitrate in the effluent). Finally, the FOPTD models for phosphate show that the manipulated variables have negligible effects for the A/O configuration, decreasing its identifiability and providing very low gains or high time constants. These results appear because of the lack of anaerobic reactor in the A/O configuration not allowing the growth of polyphosphate accumulating microorganisms (PAO). For the A²/O configuration, higher and faster effects are observed for the change of the manipulated variables and the transfer functions can be identified. In addition, the

<table>
<thead>
<tr>
<th>Controlled variables [g m⁻²]</th>
<th>DOset [g O₂ m⁻³]</th>
<th>Q_RINT [m³ d⁻¹]</th>
<th>Q_RAS [m³ d⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/O Model (current WWTP configuration)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>[NH₄]_EFF</td>
<td>−0.615 e⁻¹s</td>
<td>5.176 s + 1</td>
<td>−3.827 · 10⁻⁷ e⁻¹s</td>
</tr>
<tr>
<td>[NO₃]_ANOX</td>
<td>0.317 e⁻¹s</td>
<td>6.101 s + 1</td>
<td>2.868 · 10⁻⁵ e⁻¹s</td>
</tr>
<tr>
<td>[NO₃]_EFF</td>
<td>0.443 e⁻¹s</td>
<td>5.818 s + 1</td>
<td>−1.470 · 10⁻⁵ e⁻¹s</td>
</tr>
<tr>
<td>[PO₄]_ANAER</td>
<td>Non-existent</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[PO₄]_EFF</td>
<td>−1.470 · 10⁻⁵ e⁻¹s</td>
<td>2.984 s + 1</td>
<td>2.777 s + 1</td>
</tr>
<tr>
<td>A²/O Model (retrofitted WWTP configuration)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[NH₄]_EFF</td>
<td>−0.697 e⁻¹s</td>
<td>5.243 s + 1</td>
<td>−1.958 · 10⁻⁶ e⁻¹s</td>
</tr>
<tr>
<td>[NO₃]_ANOX</td>
<td>0.164 e⁻¹s</td>
<td>4.686 s + 1</td>
<td>1.424 · 10⁻⁵ e⁻¹s</td>
</tr>
<tr>
<td>[NO₃]_EFF</td>
<td>0.480 e⁻¹s</td>
<td>4.323 s + 1</td>
<td>−4.19 · 10⁻⁵ e⁻¹s</td>
</tr>
<tr>
<td>[PO₄]_ANAER</td>
<td>0.016 e⁻¹s</td>
<td>5.379 s + 1</td>
<td>1.608 · 10⁻⁶ e⁻¹s</td>
</tr>
<tr>
<td>[PO₄]_EFF</td>
<td>0.025 e⁻¹s</td>
<td>3.996 s + 1</td>
<td>1.214 · 10⁻⁶ e⁻¹s</td>
</tr>
</tbody>
</table>

The model time constants and the time delays are reported in days.
**Figure 3** | Unit step response of A/O and A²O linear models. Inputs are the DO setpoint at the aerobic zone (DO), the internal recycle (Q_{RINT}) and external recycle (Q_{RAS}) flow rates setpoint. Outputs are the ammonium concentration at the effluent, the nitrate concentration at the end of the anoxic zone, the nitrate concentration at the effluent, the phosphate concentration at the end of the anaerobic zone and, finally, the phosphate concentration at the effluent.
phosphate transfer functions in the new anaerobic reactor can be obtained.

The pairing among manipulated and measured variables with the best control characteristics can be provided by RGA analysis. Table 2 shows the RGA results obtained with these four control structures.

Considering the steady state ($\omega = 0$ rad/d) and the dynamic RGA ($\omega = 1$ rad/d), controlling all three pollutant concentrations at the effluent stream ($A^2/O$-1) is not the best choice since a strong coupling between $Q_{RINT}$ and $Q_{RAS}$ is observed. For example, RGA values (for $\omega = 1$ rad/d) when modifying $Q_{RINT}$ are 2.3655 and −1.6082 for nitrate and phosphate in the effluent, indicating an important effect of a change in the internal recycle in both controlled variables. Conversely, the value for ammonium is 0.2427, showing a very low effect of the internal recycle on the ammonium concentration in the effluent.

The control structure $A^2/O$-2 is also not recommended for the plant since there is a strong coupling between nitrate and phosphate, denoted by the close values of the RGA channels of inputs $Q_{RINT}$ and $Q_{RAS}$ in both frequencies. Moreover, the RGA matrix considerably changes from the steady-state frequency to the dynamic frequency, indicating the change of interactions among variables at different frequencies of operation of the controller. Moreover, phosphate in the effluent is highly affected by all three input variables, probably due to the effect of a significant amount of nitrate and oxygen being carried out to the anaerobic zone.

The most decentralized control structure is $A^2/O$-3, and the pairing would not be the most conventional pairing: $Q_{RINT}$ would be used to control the phosphate concentration in the anaerobic reactor and $Q_{RAS}$ would be used to control the nitrate concentration at the end of the anoxic zone. Such a result indicates that the current value of $Q_{RAS}$ and $Q_{RINT}$ (operating point of the process control model) are probably not the best value for improving denitrification and that the nitrate load brought by $Q_{RINT}$ is not being completely denitrified since changes in $Q_{RINT}$ poorly affect nitrate concentration at the end of the anoxic zone. That would also affect phosphate removal, as a higher recycling of nitrate reduces the COD availability for PAO. The utilization of internal recycle for controlling phosphate concentration allows a decrease in the entrance of nitrate to the anoxic reactor, which would result in more organic matter diverted to biological phosphorus removal, as recently reported by Guerrero et al. (2014). In addition, anaerobic fermentation processes are not favored when nitrate is present, reducing volatile fatty acids production, which is a key requisite to enhance P-removal activity for PAO (Guerrero et al. 2017).

Finally, the RGA of the structure $A^2/O$-4 indicates that the best pairing is also different to the common practice: the internal recycle should be used to control phosphate instead of nitrate. Such an inversion also denotes the excess of nitrate and oxygen being recycled to the anaerobic zone by $Q_{RAS}$ and to the anoxic zone by $Q_{RINT}$.

Although the most recommended control structure for the $A^2/O$ configuration, considering RGA results, is the $A^2/O$-3, the robustness of the most straightforward relationship among the manipulated variables and controlled variables (structure $A^2/O$-1) was also tested. Such a control structure is a conventional choice for implementing a control structure in full-scale WWTP plants since the controlled variables are the same as those commonly monitored with respect to European discharge limits. Figure 4 shows the results of the control loop for ammonium in the effluent.
when using the control structure A\textsuperscript{2}/O-1. When the ammonium concentration rises, the controller immediately increases the DO setpoint at the aerobic basin, trying to promote nitrification. The automated change of DO setpoint saves electrical energy because it adapts blower operation to the current ammonium load. Figure 4 also shows that strong load disturbances affect the WWTP performance and sometimes the system is not able to meet legal restrictions even when working at the maximum DO setpoint (3 mg·L\textsuperscript{-1}).

Both control structures were also tested under optimized conditions. The optimization problem was formulated by minimizing the total operating cost (calculated with the WWTP simulation using the non-linear model) as the objective function and the setpoints of the controlled variables as the optimized parameters, keeping the same PI and PID tuning during each iteration of the problem (Machado et al. 2009b). Such an optimization problem mitigates the influence of limitations of the tuning rules for PI and PID controllers and of the considerable degree of uncertainty of the black-box models when the available plant data are far from the linearized operating point.

The MPC was implemented and tested using the variables of the decentralized A\textsuperscript{2}/O-1 and A\textsuperscript{2}/O-3 control structures, generating the centralized control structures A\textsuperscript{2}/O-1-MPC and A\textsuperscript{2}/O-3-MPC. Figures 5 and 6 show some results from the control structure A\textsuperscript{2}/O-3-MPC. The MPC controller places the manipulated variable Q\text{RINT} at its maximum allowed value most of the time because nitrate concentration in the anoxic reactor is generally lower than the setpoint. The Q\text{RAS} value is also set to its maximum value by the MPC to achieve the required P setpoint in the anaerobic reactor.

A summary of average daily operating costs for all the tested control structures for 1 year of operation is presented in Table 3. These results demonstrate that the new A\textsuperscript{2}/O configuration with only DO control improved the total operating costs by around 2.0\%, obtaining a better effluent quality (lower effluent quality costs) at a similar cost for aeration, pumping, and sludge treatment. Control structure A\textsuperscript{2}/O-1 improved the operating costs of only DO (−2.6\% with respect to A/O), mainly because the aeration and pumping costs were reduced by 9.3\%, but the overall gain was not very high because the effluent quality was lower. As expected by the RGA analysis, control structure A\textsuperscript{2}/O-3 provided lower total operating costs (−3.2\% with respect to A/O). The costs of aeration, pumping, and sludge treatment were 18.9\% lower than the A/O plant, but the lower effluent quality determined the limited improvement when considering the total costs.

The results obtained by control structures A\textsuperscript{2}/O-1 and A\textsuperscript{2}/O-3 were not the best possible results that could be obtained with these structures because setpoints used for the controlled variables were based on averaged values of these variables under open loop operation. When the setpoints of the controlled variables were optimized as in Machado et al. (2009b), the improvement in total operating costs was higher (−2.8\% and −3.8\% with respect to A/O, for A\textsuperscript{2}/O-1 and A\textsuperscript{2}/O-3, respectively).
Finally, the centralized control structures brought better results than the decentralized ones since they use a full matrix of transfer function models that compensates for the effects of more than one manipulated variable on a specific controlled variable. They provided considerably lower effluent quality costs but also higher total operating costs without effluent quality, making the final overall costs slightly lower than the decentralized control structures (−3.5% and −3.9% with respect to A/O, for A²/O-1-MPC and A²/O-3-MPC, respectively). The total cost improvement provided by the control structures was not very high for this plant, probably because saturation of some manipulated variables was observed (Figures 5 and 6) due to limitations in the wastewater composition and in the WWTP.

Figure 5 | Nitrate concentration at the end of the anoxic zone (control variable) and its setpoint (upper graph) during the test of the A²/O-3-MPC running. The lower graph shows the manipulated variable $Q_{\text{int}}$.

Figure 6 | Phosphate concentration at the end of the anaerobic zone (control variable) and its setpoint (upper graph) during the test of the A²/O-3-MPC running. The lower graph shows the manipulated variable $Q_{\text{ras}}$. 
operational limitations. Conversely, higher improvements are expected, including hourly variability of influent composition or flow-rate and real operation with unexpected disturbances, and it can be further enhanced with optimized setpoints. Additional benefits of the control structure, such as obtaining an effluent with more stable quality, are also foreseeable.

CONCLUSIONS

The choice of introducing an anaerobic zone to the existent A/O plant in the retrofitting process was proved to be a good way of improving the WWTP capacity and controllability, as the comparison between the linear models of the A/O and A²/O plant configuration have shown. The tested control structures improved the total operation costs in the simulated scenario, with daily modification of influent concentrations and hence limited dynamics.

The centralized control structure A²/O-3-MPC achieved the lowest operating costs with the best effluent quality for the A²/O plant configuration for the Manresa WWTP. Such a control structure could reduce the operating costs by 3.9% regarding the current plant configuration with the current control structure, or by about 2.0% with respect to the system that worked using only the DO control.

The centralized control structures provided better results than the decentralized ones since they use a full matrix of transfer function models that compensates for the effects of more than one manipulated variable on a specific controlled variable. Conversely, the implementation efforts of a centralized control structure could result in the plant owner deciding to implement the correspondent decentralized control structure A²/O-3 with the optimization setpoint program with acceptable results.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge Ricard Tomas and Ana Lupón (Aigües de Manresa S.A.) for all the support provided in conducting this work. Vinicius Cunha Machado received a pre-doctoral scholarship from the AGAUR (Agència de Gestió d’Ajuts Universitaris i Recerca – Catalonia, Spain), within European Community Social Fund programs. This work was supported by the Spanish Ministerio de Economía y Competitividad (CTM2010–20384).

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First received 25 August 2014; accepted in revised form 13 March 2015. Available online 27 March 2015