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A multilevel coordinated control strategy for energy conservation in wastewater treatment plants

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Abstract: Wastewater treatment is an energy-intensive process pursuing two objectives: pollution abatement and energy conservation. To achieve these goals automatic control must be applied. This paper describes the performance improvement obtained by the coordinated automation of some basic process operations. Starting with the basic dissolved oxygen control, coordinated control actions are then introduced and their performance assessed. After discussing the design alternatives, the performance of the best combination is selected on the basis of energy conservation, provided that the effluent quality meets the environmental standards. It is shown that a combination of properly tuned PID and fuzzy regulators considerably improves the energy efficiency of the process.

Keywords: Process control; PID control; Fuzzy control; Water pollution; Waste treatment.

1. INTRODUCTION

A wastewater treatment plant (WWTP) is a complex process for pollution removal through microbiological reactions. In the last decade much work has been done to formalize WWTP process models and provide a reference environment to assess the efficiency of control actions. In pursuit of this goal two concerted EU actions (COST 682 and COST 624) have defined the Benchmark platform (Alex et al., 1999; Copp, 2002; Rosen et al., 2004; Devisscher et al., 2006; Nopens et al., 2010) as a standardized combination of process structure, input files, performance indicators, and basic control structures.

1.1. Process model

This paper describes a new set of coordinated control actions developed along the Benchmark guidelines, using an improvement of the ASM3 model (Henze et al., 2000) incorporating a two-step nitrification-denitrification process (Iacopozzi et al., 2007). The WWTP process considered in this study is a simplified version of the Benchmark configuration and includes a pre-denitrification anoxic tank followed by an oxidation tank. Simple PID controllers (Aström and Hägglund, 1995; Visioli, 2010) were used for their performance and ease of tuning, in addition to fuzzy regulators (Babuska, 1998).

1.2. Controller structure

The process model and control structures are shown in Fig. 1. Three control actions are considered:

1. Set-point control of dissolved oxygen (DO) acting upon air flow rate (U_a) (controller 1)
2. Hierarchical DO control, where the set-point DO_{sp} is adjusted according to the ammonium-N concentration (NH_4-N) in the oxidation tank (controllers 1 + 2)
3. Coordinated control of DO and residual nitrate – nitrite (NO_x) in the anoxic tank (controllers 1+2+3).

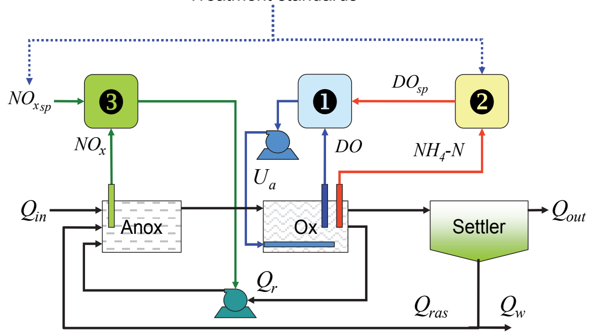

Fig. 1. Overall scheme of the WWTP process and the controllers. The low-level controller 1 can operate either in a stand-alone mode or in a master/slave combination with controller 2. The set-points of controllers 2 and 3 are determined by the treatment standards.

1.3. Input files

The Benchmark protocol (Copp, 2002) has defined three differing two-week long input time-series, representative of dry, rain, or storm weather conditions. All of them account for the daily and weekly variations of the three most relevant input variables: flow, COD and NH_4-N, as shown in Fig. 2.

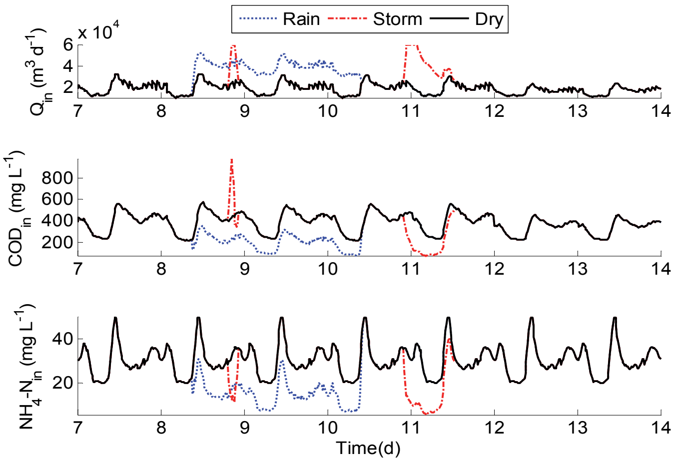

Fig. 2. Benchmark time series for dry, rain, and storm weather.

1.4. Performance assessment

Following the Benchmark approach, performance evaluation is based on both the effluent quality (EQ) and energy consumption. Since the simulations are based on a ASM-like model, there quantities are defined in terms of model variables over the control horizon T, normally defined as the second week of the input time-series. For the symbols used in (1 – 4) please refer to the Benchmark variables definitions (Copp, 2002; Iacopozzi et al., 2007).

- Effluent quality (kg BOD d^{-1})

$$EQ = \frac{1}{T \cdot 1000}\int_{t}^{T}[2 \cdot TSS_e(t) + COD_e(t) + 2 \cdot BOD_e(t) + 20 \cdot TKN_e(t) + 20 \cdot S_{NOX_e}(t)] \cdot Q_e(t) \cdot dt \quad (1)$$

where the subscript 'e' refers to the *effluent* and the quantities are defined according to the ASM3_2N model variables as

$$\begin{aligned} TSS_e &= 0.75(X_I + X_S) + 0.9(X_H + X_{ns} + X_{nb}) + 0.6X_{STO} \\ COD_e &= S_S + S_I + X_S + X_I + X_H + X_{ns} + X_{nb} + X_{STO} \\ BOD_{5,e} &= 0.25(S_S + X_S + (1 - f_p)\cdot(X_H + X_{ns} + X_{nb} + X_{STO})) \\ TKN_e &= S_{NH4} + (S_S \cdot i_{NSS}) + (S_I \cdot i_{NSI}) + (X_S \cdot i_{NXS}) \\ &\quad + i_{NBM}\cdot(X_H + X_{ns} + X_{nb}) + (X_I \cdot i_{NXI}) \\ S_{NOX,e} &= S_{NO2,e} + S_{NO3,e} \end{aligned} \quad (2)$$

- Aeration costs (kWh d^{-1})

$$AE = \frac{24}{T}\int_{t_o}^{t_o+T}\left(\sum_{k=1}^{N} 0.4032\ K_La^2 + 7.8408\,K_La\right)dt \quad (3)$$

where K_La is the oxygen mass transfer coefficient (d^{-1}).

- Pumping costs (kWh d^{-1})

$$PE = \frac{0.02}{T}\int_{t_o}^{t_o+T}(Q_{int} + Q_r + Q_w)\,dt \quad (4)$$

- Effluent limits

The output water quality must comply with the effluent limits set by the Water Framework Directive (WFD, EU 2000/60) and implemented by the Italian legislation through the Legislative Act 152/2006, prescribing the limits of Table 1.

Table 1. Effluent standards set by the Italian legislation.

Pollutant and units	***Limit value***
Ammonium-N (mg-N L^{-1})	≤15
Nitrite-N (mg-N L^{-1})	≤0.6
Nitrate-N (mg-N L^{-1})	≤20
BOD_5 (mg O_2 L^{-1})	≤25
COD (mg O_2 L^{-1})	≤125

1.5. Plant characteristics

The process characteristics and open-loop settings are listed in Table 2. They follow the Benchmark sizing, though in this implementation only one anoxic and one oxidation tank are used, instead of two and three respectively.

Table 2. Plant design parameters.

Process parameter	**Value**
Anoxic tank volume (m^3)	2,000
Oxidation tank volume (m^3)	4,000
Secondary settler volume (m^3)	6,000
Input flow Q_{in} (m^3 d^{-1})	18,443
Return flow Q_{ras} (m^3 d^{-1})	18,443
Internal recycle flow Q_e (m^3 d^{-1})	55,338
Waste flow Q_w (m^3 d^{-1})	385

2. LOW-LEVEL CONTROLLER

Controller 1 in Fig. 1 implements the Dissolved Oxygen set-point regulation. This is the basic control action that must be designed before any higher-level control can be attempted. An incremental discrete-time PID regulator is selected for this controller, producing the incremental airflow signal $\delta u_a(t)$ which, upon discrete integration, produces the full airflow command $U_a(t)$

$$\begin{aligned} \delta u_a(t) &= DO_{sp} - \{\Gamma_i DO_t - \Gamma_2 DO_{t-1} + DO_{t-2}\}, \\ U_a(t) &= U_a(t-1) + \delta u_a(t) \end{aligned} \quad (5)$$

where the coefficients in (5) are computed as

$$\begin{aligned} \Gamma_{sp} &= K_p K_i T_s \\ \Gamma_1 &= K_p\left(1 + K_i T_s + \frac{K_d}{T_s}\right) \\ \Gamma_2 &= K_p\left(1 + 2\frac{K_d}{T_s}\right) \\ \Gamma_3 &= K_p\frac{K_d}{T_s} \end{aligned} \quad (6)$$

where T_s is the sampling time, and $\boldsymbol{P} = [K_p, K_i, K_d]^T$ is the vector of PID parameters. Two differing tuning methods are now discussed to minimize the combined performance functional

$$ITAEU = \frac{1}{T}\int_0^T (|e(t)| + \lambda|\delta u_a(t)|)dt\,, \quad (7)$$

where $e(t) = DO_{sp} - DO(t)$ and $\lambda = 10^{-3}$ is the weighting factor for the incremental air flow $\delta u_a(t)$.

2.1. Flexible polyhedron optimization

Starting with a manually tuned PID with initial parameter values $\boldsymbol{P}_o = [70\ 50\ 0.05]^T$, its parameters were optimized through a flexible polyhedron direct search. This algorithm is an improved version of the classical Simplex flexible polyhedron search (Himmeblau, 1972), which is based on four basic operations: reflection, expansion, contraction, and reduction. The most important of them is the expansion, often achieving the largest error reduction. In this improved version, the set of fixed parameters governing the expansion is replaced with a unidirectional optimization procedure that searches for a local minimum along the current search direction using the golden section method. With this improvement there is no upper limit to the extent of the expansion and the polyhedron can adapt to the shape of the error function, making the search more expedite, especially in "narrow valley" cases. This algorithm is fully described in (Marsili-Libelli, 1992) and its properties are further analyzed in Marsili-Libelli et al, (2003). The PID parameter optimization loop is shown in Fig. 3, where the performance index is defined by (7).

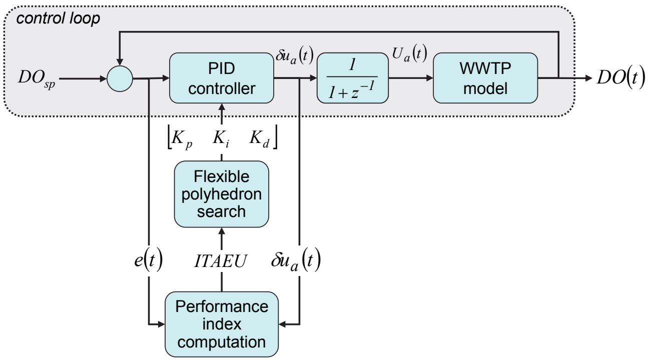

Fig. 3. PID parameters optimization loop.

Upon convergence the following PID parameter values were obtained for the week-long control horizon

$$\boldsymbol{P}^* = [304.5694\ 64.0083\ 0.0001]^T . \tag{8}$$

The control performance of the optimized PID is compared with the open loop case in Table 3 and graphically shown in Fig. 4.

The energy saving is clearly demonstrated in Fig. 4 showing the lower airflow U_a required to achieve an efficient tracking around DO_{sp} = 2 mg L^{-1}.

Table 3. Performance of low-level PID.

Performance evaluation metrics	Open loop	Optimized PID (1)
ITAEU (7)	-	1344.80
EQ (kg BOD d^{-1})	6775.82	6753.18
AE (kWh d^{-1})	7532.13	5552.26
Energy saving (%)	-	26.28

The EQ improvement can be explained by the fact that the main purpose of this control action is to provide the right amount of oxygen at any one time, typically 2 mg L^{-1}, coping with the disturbance represented by the time-varying organic loading, and that the removal efficiency is not directly affected unless the DO concentration falls much below this level. On the other hand aeration costs are directly related to DO set-point tracking with dramatic energy saving, as shown by the drop in AE, in the third row in Table 3, with a net saving of over 26%.

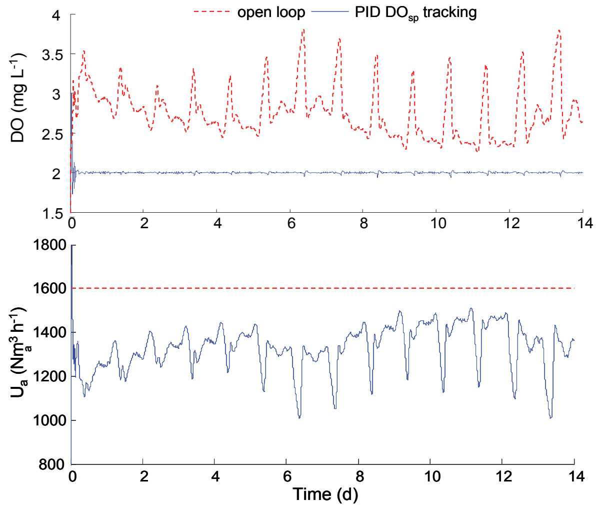

Fig. 4. Control results of the low-level PID in tracking a constant DO_{sp} of 2 mg L^{-1}.

3. A TWO-LEVEL MASTER/SLAVE DO CONTROL

The next logical step is to make the DO_{sp} of controller 1 dependent on the DO level required to obtain a desired ammonium-N residual in the oxidation tank. The rationale is that the higher the residual NH_4-N, the more oxygenation should be provided, and this can be accomplished by increasing the DO_{sp} value. On the contrary, a lower NH_4-N concentration would require less oxygenation, with obvious energy saving. So controllers 1 and 2 are now operated in a master/slave configuration, in which controller 1 (slave) has a variable set-point, provided by controller 2 (master), depending on the NH_4-N concentration in the oxidation tank.

With PID 1 serving as the slave regulator, the master controller 2 is designed to implement the relationship between residual NH_4-N and DO_{sp}, that is difficult to express in simple mathematical terms. This controller is thus based on the following rules:

- An increasing NH_4-N concentration denotes insufficient oxidation, hence the DO_{sp} set-point should be increased;
- If the NH_4-N level is in the middle of the operating range keep the DO_{sp} unchanged;
- If the NH_4-N level decreases, implying an excessive aeration, the DO_{sp} should be lowered.

These simple rules are implemented by the general fuzzy implication

$$if \;\; NH_4 - N \;\; then \;\; DO_{sp} \, , \tag{9}$$

where the five rules of Table 4 are used to implement (9).

Table 4. Fuzzy rules for the DO_{sp} master controller 2.

Rule n.	Antecedent (NH_4-N)	Consequent (DO_{sp})
1	Low (L)	Very Low (VL)
2	Low Medium (LM)	Low (L)
3	Medium (M)	Medium (M)
4	Medium High (MH)	High (H)
5	High (H)	Very High (VH)

The membership function for the antecedent (NH_4-N) and the consequent (DO_{sp}) are shown in Fig. 5, after having been adjusted by trial and error to obtain the best controller 2 performance.

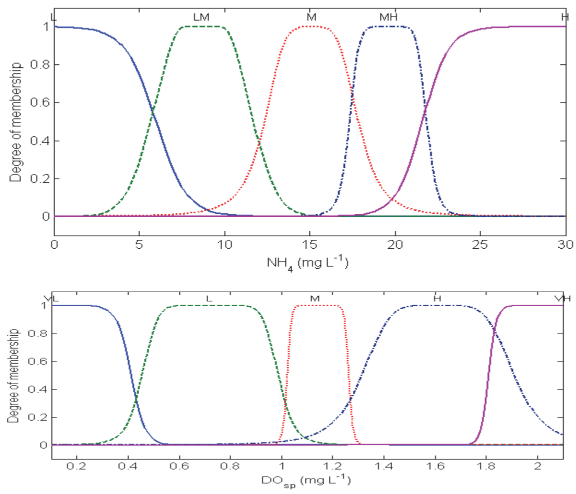

Fig. 5. Membership functions of the fuzzy logic of Table 4.

The transfer function of the fuzzy logic controller (9) is shown in Fig. 6 w here a maximum NH_4-N concentration of 20 mg L^{-1} was considered and the maximum allowable DO_{sp} was set at 2 mg L^{-1}, so that if the NH_4-N concentration is low, less oxidation capacity is required and the airflow can be decreased accordingly for energy conservation. The membership functions of Fig. 5 were heuristically tuned to obtain a good energy saving without impairing the nitrification capacity of the process.

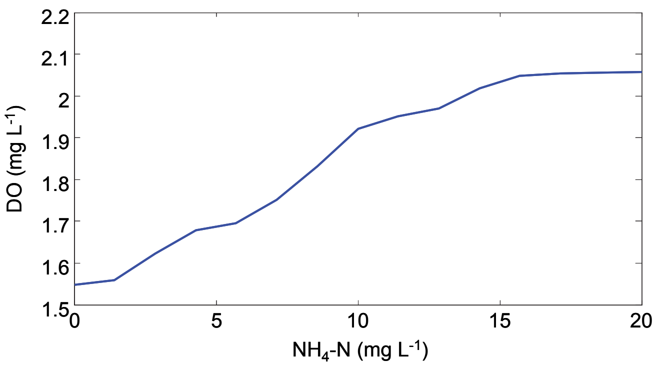

Fig. 6. Input-output transfer function of controller 2.

Fig. 7 shows that effective set-point tracking can be obtained by operating the low-level PID 1 in slave mode, with the master controller 2 providing a time-varying set-point DO_{sp}. In addition to demonstrating successful tracking, Fig. 7 also shows that a sizable energy conservation can be achieved by lowering the DO concentration below the conventional value of 2 mg L^{-1}. This results in a slightly higher NH_4-N concentration than in the open–loop configuration, but still below the effluent limit. On the other hand a considerable energy saving is achieved, as the last row of Table 5 shows.

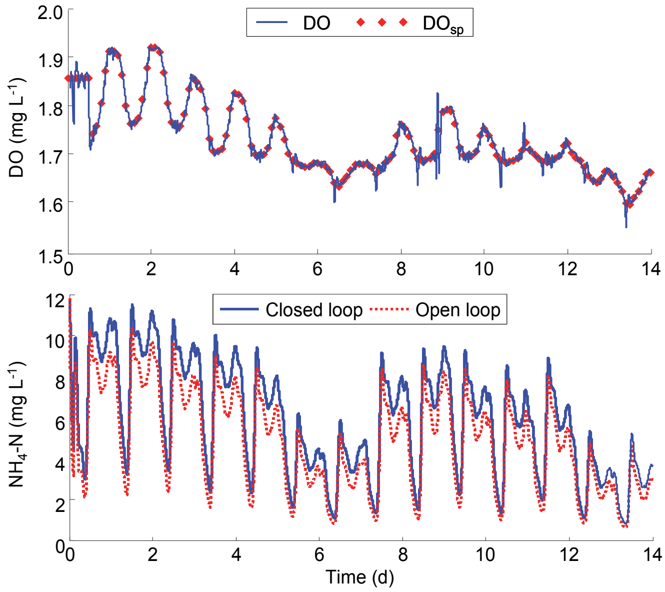

Fig. 7. Variable DO_{sp} operation obtained with the master/slave combination (1 + 2). Successful tracking (above) and resulting NH_4-N concentration (below).

Table 5. Performance of the master/slave controller 1 + 2 compared with the stand-alone PID (1) (Table 3).

Performance evaluation metrics	Open loop	Stand-alone PID (1)	PID (1) + Fuzzy (2)
ITAEU	-	1344.80	1426.3
EQ (kg BOD d^{-1})	6775.82	6753.18	7601.88
AE (kWh d^{-1})	7532.13	5552.26	4797.73
Energy saving (%)		26.28	36.30

4. INTERNAL RECYCLE CONTROL

The last control action to be implemented is the internal recycle of NO_x from the oxidation tank to the anoxic tank for denitrification, acting on the recycle flow Q_r. This action is required to transfer the oxidized nitrogen (NO_x) back into the anoxic tank where it can be reduced to molecular nitrogen (N_2), thus completing the nitrogen removal process. The control problem consists of recycling the right amount of NO_x, compatible with the availability of organic carbon (COD) for the $NO_x \rightarrow N_2$ reduction. As shown in Fig. 1, this loop relies on the NO_x measurement in the anoxic tank to control the internal recycle flow Q_r. This control action implies an efficient DO set-point control, as already implemented by the 1 + 2 combination, controlling the NO_x production.

Both a simplex-optimized PID (3a) and a heuristically-tuned fuzzy controller (3b) were tested, with the latter yielding the best performance, especially in terms of energy conservation (see Table 7). The reason for the good performance of the fuzzy controller, or rather for the poor performance of the PID, can be explained with the presence of a delay in the control loop. In fact, there are several dead-times involved in this loop: the intrinsic delay of the measuring equipment and of the electric motor drive, and the sluggish nature of the nitrogen removal kinetics taking a long time to respond to flow changes. This explains the oscillatory behaviour of the PID, which is almost impossible to remove. There are also conceptual differences in the two controllers: while the PID operates in a rigid set-point tracking mode, the fuzzy logic implemented in this loop is intended to keep the anoxic NO_x below a given threshold, here set at 2 mg L^{-1}, by acting on the recycle flow Q_r. This is accomplished by a set of rules based on the error $\Delta NO_x = NO_{xsp} - NO_x$, similar to (10), which in this case take the general form

$$\textit{if}\ \ \Delta NO_x\ \ \textit{then}\ \ Q_r\,. \tag{10}$$

The pertinent rules are summarized in Table 6.

Table 6. Fuzzy rules for the NO_x controller 3b.

Rule n.	Antecedent (ΔNO_x)	Consequent (Q_r)
1	Low (L)	Low (L)
2	Medium (M)	Medium (M)
3	High (H)	High (H)

The rationale behind the rules of Table 6 is that if the error ΔNO_x is small (high NO_x concentration) then denitrification is approaching its maximum capacity and therefore less NO_x should be recycled from the oxidation stage. The reverse is true is ΔNO_x is high, whereas Q_r should be kept unchanged if ΔNO_x is in the middle of the allowed range. The membership functions of Fig. 8 were adjusted by heuristic tuning using the performance metrics (1 – 4) as a guideline.

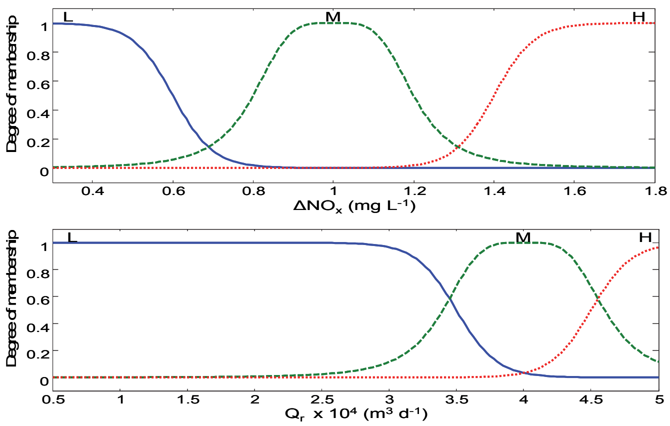

Fig. 8. Membership functions used for the fuzzy logic of Table 6.

The performance of the two NO_x recycle controllers are compared in Fig. 9. In the PID case the parameters were determined by simplex optimization and anti-windup was applied.

Basically the two controllers (PID and Fuzzy) yield a comparable response, with each regulators presenting its own assets and liabilities. In fact the fuzzy controller produces a better effluent quality with less oscillations, whereas the PID has the following advantages:

- Smaller ITAEU;
- Larger energy saving;
- Smaller sludge production.

However, its oscillatory behaviour may outweigh these achievements when it comes to its practical implementation.

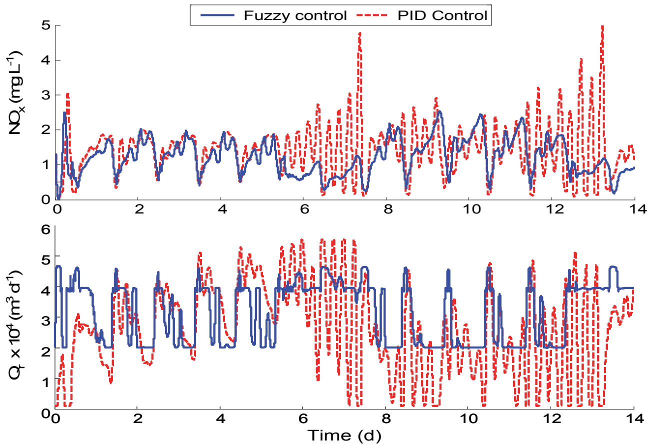

Fig. 9. Performance of the two NO_x controllers 3a and 3b.

5. PERFORMANCE EVALUATION

An assessment of the three control actions can now be made.

- The stand-alone low-level DO control is best carried out by an optimized PID, achieving a considerable energy saving connected to aeration (see Table 3);
- The master/slave combination (1+2) provides a good time-varying DO_{sp} tracking in response to the changing NH_4-N concentration. This arrangement results in a considerable energy conservation related to the aeration;.
- The third controller, acting on the internal recycle, has the task of supplying the denitrification stage (anoxic tank) with the right amount of NO_x that can be reduced to molecular nitrogen N_2, given the available carbon source (input COD). This control action can contribute to energy conservation by limiting the pumping (Q_r) of NO_x.

The performance of these control actions are summarised in Table 3 for the controller 1, in Table 5 for the combined controllers 1+2 and in Table 7 for controller 3. From these results some general conclusions can be drawn:

- The stand-alone low-level PID regulator for set-point tracking of DO has a negligible influence on EQ (1), but produces a considerable energy saving in terms of aeration costs (3) abatement;
- The effluent quality (EQ) of the Master/Slave combination 1+2 is slightly worse than both the open loop and the PID 1 stand-alone controller, but produces a considerable saving in aeration costs by adjusting the DO level to the minimum nitrification requirements;

- Of the two choices for controller 3, the PID (3a) yields a better ITAEU, a larger energy conservation (39.53% vs. 37.74%), and a lower sludge production, whereas the fuzzy controller produces a better effluent quality. However its oscillatory behaviour may prove critical in its implementation whereas the fuzzy controller (3b) surely has an edge in robustness.

Table 7. Summary of controller 3 performance.

Performance assessment metrics	Open loop	PID (3a)	Fuzzy (3b)
ITAEU	-	1513.4	1579.4
Effluent Quality	6775.82	7944.53	7210.51
AE (kWh d^{-1})	7532.13	4442.72	4595.11
PE (kWh d^{-1})	1764.93	1179.03	1472.22
Energy saving (%)		39.53	37.74
Sludge production (ton y^{-1})	2524.606	2341.15	2474.49

6. CONCLUSIONS

This paper has examined three possible control solutions for a conventional biological wastewater treatment process with a pre-denitrification stage for nitrogen removal. This exercise is based on the Benchmark framework from which it borrows criteria and performance metrics, but uses a more advanced process model.

The low-level DO control 1 is the necessary prerequisite to any further control action. A PID regulator with constant set-point DO_{sp} was optimized with respect to a combined precision vs. effort cost functional (7). Table 3 shows that such simplex-optimized PID yields a considerable albeit local (i.e. limited to aeration costs) energy saving.

The second step was to incorporate the previous stand-alone PID in a master/slave structure where the set-point DO_{sp} is determined by the higher-level controller 2 on the basis of the oxidation requirements measured by the residual NH_4-N. As Fig. 7 shows, this combination was set to produce a lower DO level with obvious energy saving, though this is achieved at the expenses of a modest EQ increase (see Table 5).

The third controller acts on the internal recycle and performs a balancing action with respect to controller 2. In fact, whereas the latter controls the amount of residual NH_4-N after nitrification, the controller 3 is designed to keep the residual NO_x in the denitrification stage below a prescribed level. This implies that only the amount of NO_x that can be effectively reduced to N_2 is recycled, whereas a larger amount of NO_x might exceed the organic carbon availability, resulting in a higher NO_x with higher (and useless) pumping costs. A further improvement in fuzzy controller 3 could be membership optimization instead of heuristic tuning.

Though a considerable energy saving is achieved by these simple control actions, a further development of this study will be pursued in the future, with a stronger coordination between controllers 2 and 3. This would generate a multi objective functional involving the combined optimization of NH_4-N and NO_x removal with related energy savings. This problem could be tackled by searching the Pareto front of the two-criteria and is expected to produce a further improvement in energy conservation. Another possible improvement, before moving to the experimental field, could be the use of a more comprehensive process model, particularly the BSM2 (Rosen et al., 2004; Nopens et al., 2010).

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