PI Dissolved Oxygen control in wastewater treatment plants for plantwide nitrogen removal efficiency

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Abstract: In this paper, a PID based hierarchical control structure is proposed to improve the overall WWTP performance. The control problem is focused on the definition of integral efficiency indices for a typical WWTP operation. The efficiency index considered in this work is the ratio between the nitrogen removed in the activated sludge process (Kgr N) and the energy (kWh) required for eliminating that amount of nitrogenated compounds (N/E index). The efficiency index is used as the controlled variable for an upper level PI controller that manipulates the dissolved oxygen (DO) set point to keep the index as close as possible to a desired level. Effect of DO manipulation is analyzed and DO operation is defined in terms of its overall effect instead of local DO dynamics.

Keywords: PID control, hierarchical structures, wastewater treatment plants, performance evaluation, non-linear processes

1. INTRODUCTION

The control and optimization of the operation of wastewater treatment plants (WWTPs) is a challenging task due to the complexity of the biological treatments, the diversity of time constants involved in the biological processes and the variable influent patterns. Nevertheless, the strict quality requirements imposed by European Directives have been the driving force for the active research in the development of control strategies to improve the operation of the WWTPs (Amand et al., 2013; Olsson, 2012; Santín et al., 2016).

In the process industry the optimization strategies are usually focused on economic objectives, but, in processes oriented to public benefits, as WWTPs, some other criteria are worth to be taken into consideration. For example, the removal of the most damaging pollutants, the CO_2 emissions and the appropriated use of the biogas from sludge digestion are, among others, important issues to be considered in the operation of WWTPs (Olsson, 2012; Santín et al., 2016).

Hierarchical strategies are usually employed to optimize the process operation. In the upper level, a real-time optimization (RTO) of the set-points is carried out and they are sent to the basic control level. Generally, the economically optimal set-points are computed using a steady-state plant model which is implemented in the optimization layer of a complex process control architecture (Skogestad, 2000; Vega et al., 2014). In processes that operate under frequent disturbances, the steady-state conditions cannot be attained. In such cases, advanced model predictive control algorithms are used to perform a dynamic optimization of the set-points (Wurth et al, 2011; Vega et al, 2014).

Regarding the application to WWTPs, it is known that the most usual control strategies are based on simple PI controllers and model predictive controllers (MPC) (Vlad et al., 2012; Olsson, 2012; Vilanova et al., 2017). The objective of the control scheme is the regulation of the key variables at a constant set point. However, the advantage of the implementation of hierarchical structures to dynamically adjust the set-points of the basic control loops (aeration, dissolved oxygen control, ammonium control) in the activated sludge process has been demonstrated in several works (Revollar et al, 2017; Vega el al., 2014; Santin et al., 2015). Model predictive controllers (MPC) are widely used in the optimization layer, nevertheless, the use of PID based hierarchical structures to optimize the operation of WWTPs is a sound solution that can be applied in real practice. In Machado et al. (2009), three cascaded linear PI controllers are used to dynamically send set-points to the process controllers considering the minimization of the difference between the cost measurement and the cost set-point.

On the other hand, it is important to highlight that economics is traditionally the main objective in the optimization of process operation. However, other important criteria can be considered to provide decisions with a plantwide perspective as in Meneses et al. (2015) and Barbú et al. (2017) where Life Cycle assessment (LCA) indicators are introduced to evaluate WWTP operation and control strategies. In Mauricio-Iglesias et al. (2016) the trade-off between different objectives in the operation of a WWTP plant is evaluated

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considering performance indicators such as nitrogen removal ratio and the nitrogen removed per Kgr of CO_2 released.

In this paper, process efficiency indices are considered to evaluate process performance of a WWTP from a global viewpoint. The WWTP scenario is defined in terms of the BSM2 in order to capture all the interaction effects between the sludge and water lines. A PID based hierarchical control structure is proposed to improve the overall WWTP performance. The control problem is focused on the definition of integral efficiency indexes for a typical WWTP operation such as nutrient removal (Nitrogen).

The efficiency index is the controlled variable for an upper level PI controller that manipulates the dissolved oxygen (DO) set-point to keep the index as close as possible to a desired level. The indices are the nitrogen removal efficiency respect to the load of nitrogenated compounds in the influent (NTE) and the ratio between NTE and the energy required for eliminating that amount of nitrogenated compounds (N/E index). A PI controller is used to control DO manipulating the oxygen transfer coefficient. The effect of DO manipulation is analysed and DO operation is defined in terms of its overall effect instead of local DO dynamics.

With this approach, a plant-wide operation is proposed where the implied controllers are of PID type. The determination of the DO set-points will be on the basis of the mentioned global efficiency performance index. This index will be kept close to a desired operational value by means of a PID controller. Therefore, the overall plant operation scenario is defined just in terms of PID controllers.

2. PROCESS DESCRIPTION AND PERFORMANCE INDICES

2.1 BSM2 plant

The BSM2 (Benchmark Simulation Model No 2) (Alex et al., 2008) is a simulation benchmark that extends the BSM1 including a primary clarifier and the required units for the sludge treatment: a thickener for the sludge wasted from the secondary settler, a digester for the solids treatment, a dewatering unit for the sludge leaving the digester, and a storage tank before recycling the remaining sludge to the water line. It includes the entire cycle of a WWTP, so the simulation period and the corresponding influent profile for disturbances assessment have been extended to one year, taking into account rainfall effect and temperature seasonal variations. The BSM2 default control strategy is PI control for dissolved oxygen in the aerated tanks of the activated sludge part of the process. The layout of the plant is presented in Figure 1.

2.2 Performance indices

The BSM2 benchmark protocol provides some performance indices explained below in order to measure the effect of the proposed control strategies. The effluent quality index proposed in the BSM2 is:

$$EQI = C_1 \int_{t_0}^{tf\,(days)} \begin{bmatrix} 2 \cdot SS_e + COD_e + 30 \cdot Nt_e \\ +10 \cdot S_{NO,e} + 2 \cdot BOD_e \end{bmatrix} Q_e dt \left[{Kg\ polution}/{d} \right] \quad (1)$$

where:

$$C_1 = \frac{1}{T \cdot 1000} \quad (2)$$

$$BOD_e = 0.25 \cdot \left((1 - 0.08)\left(X_{B,Ae} + X_{B,He} \right) \right) g/m^3 \quad (3)$$

$$COD_e = \left(S_{Se} + X_{B,Ae} + X_{B,He} \right) g/m^3 \quad (4)$$

$$Nt_e = S_{NOe} + S_{NHe} + i_{XB}\left(X_{B,He} + X_{B,Ae} \right) g/m^3 \quad (5)$$

$$SS_e = 0.75 \cdot \left(X_{S,e} + X_{I,e} + X_{B,H,e} + X_{B,A,e} + X_{P,e} \right) g/m^3 \quad (6)$$

and the concentrations and parameters involved are defined precisely in (Alex et al., 2008).

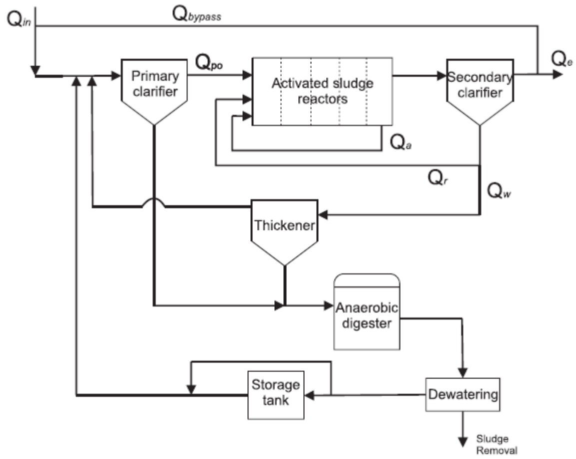

Fig. 1. BSM2 plant layout

In order to either evaluate the plant efficiency or to perform comparisons when other influent data files than the one proposed for BSM2 are used, the Influent Quality Index (IQ) has been defined:

$$IQI = C_1 \int_{t_0}^{tf\,(days)} \begin{bmatrix} 2 \cdot SS_i + COD_i + 30 \cdot Nt_i \\ +10 \cdot S_{NO,i} + 2 \cdot BOD_i \end{bmatrix} Q_i dt \left[{Kg\ polution}/{d} \right] \quad (7)$$

Where SS_i, COD_i, Nt_i, BOD_i are analogous to SS_e, COD_e, Nt_e, BOD_e but considering concentrations in the influent.

If only nitrogen compounds are considered in order to evaluate nitrogen removal efficiency, then the following indices are defined:

$$EQIN = C_1 \int_{t_0}^{tf\,(days)} \left[30 \cdot Nt_e + 10 \cdot S_{NO,e} \right] Q_e dt \left[{Kg\ polution}/{d} \right] \quad (8)$$

$$IQIN = C_1 \int_{t_0}^{tf\,(days)} \left[30 \cdot Nt_i \right] Q_i dt \left[{Kg\ polution}/{d} \right] \quad (9)$$

The global operational cost index (OCI) described in Alex et al. (2008) is:

$$OCI = AE + PE + 3 \cdot SP + 3 \cdot EC + ME - 6 \cdot MP + HE_{net} \quad (10)$$

where AE represents the aeration energy in the activated sludge process, PE is the pumping energy in the full plant (involving all flows), ME is the mixing energy in the full plant, SP is the sludge production for disposal, EC is the external carbon addition and MP is the methane production. and HE_{net} is:

$$HE_{net} = \max\left(0, HE - 7 \cdot MET_{prod}\right) \quad (11)$$

where HE is heating energy necessary to heat the sludge to the digester operating temperature and MET_{prod} is the methane production (kWh/d).

The treatment efficiency (TE) is defined here as the ratio between the pollution removed in the activated sludge process and the pollution load in the influent.

$$TE = \frac{IQI - EQI}{IQI} \left[{Kgr\ Pollution}/{Kgr\ Pollution} \right] \quad (12)$$

Analogously, for the Nitrogen Treatment Efficiency (NTE) the following index has been defined:

$$NTE = \frac{IQIN - EQIN}{IQIN} \left[{KgrN}/{KgrN} \right] \quad (13)$$

Moreover, in this work an efficiency index (N/E) is defined in terms of the energy necessary to remove a unit of Nitrogen. This index is the one that will be used as controlled variable in the proposed control strategy. Then, nitrogen removal efficiency (Nitrogen removal vs Energy required) is defined as a measure of nitrogen removal. The required energy is expressed in terms of PE, AE, HE and ME as:

$$N/E = \frac{NTE}{PE + AE + HE + ME} \left[{KgrN}/{kWh} \right] \quad (14)$$

2.5 Default Control Strategy

The default BSM2 strategy consists on the control of the dissolved oxygen concentration (DO) in the fourth aeration tank manipulating the oxygen transfer coefficient (KLa) of the three reactors that comprise the aeration zone. A PI controller computes the oxygen transfer coefficient for the 4th reactor (KLa_4), whereas KLa_3 and KLa_5 are calculated considering a gain of 1 and 0.5 respectively (KLa_3=KLa_4, KLa_5=0.5 KLa_4). The dissolved oxygen is controlled to a set--point value of 2gr/m3. Additionally, an external carbon source with a concentration of 400000gr/m3 (usually methanol) is added to the first reactor in the anoxic zone with a constant flow of 2m^3/d.

The effluent quality is given by the limits imposed by the environmental regulation over nutrients and organic matter concentration of WWTP discharges. The effluent quality limits defined within the BSM2 are presented in table 1.

Table 1. Effluent quality limits

Total Nitrogen	< 18 grN/m^3
Chemical Oxygen Demand (COD)	<100 grCOD/m^3
Ammonium concentration (S_{NH})	4 grN/m^3
Nitrate concentration (S_{NO})	10 grN/m^3

3. CONTROL PROBLEM FORMULATION

WWTP scenario is defined in terms of the BSM2 in order to capture all the interaction effects between the sludge and water lines. An upper level PI controller for the N/E index is implemented to improve the overall plant performance.

The objective of the proposed control strategy is to minimize the difference between the efficiency index computed with the measured variables and the desired value. This is carried out by an upper-level PI controller in order to increment the efficiency of the plant in terms of treatment efficiency and energy consumption. The controlled variable is the N/E index that measures the ratio between nitrogen removal in the activated sludge process and the energy required to attain this goal. The reference value for this upper level controller is computed considering an improvement respect to the average value of the index achieved using the default control strategy.

The plant operation is defined in terms of manipulation of the DO set points in order to keep the index as close as possible to a desired level. A schematic representation of the proposed control schemes is presented in figure 2.

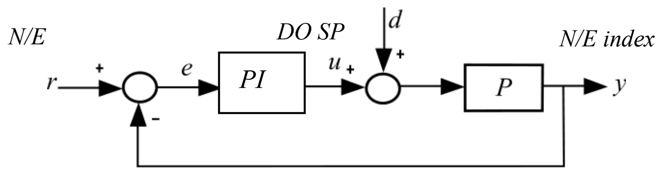

Fig. 2. Proposed control strategy: N/E control strategy

It is important to highlight that, in the N/E strategy, the upper level controller considers the nitrogen removal in the activated sludge process and the energy requirements of the full plant, which provides a link between activated sludge process and digestion process operation.

4. RESULTS

The PID controllers are designed to control the efficiency index. The identification of the model of the system is necessary to tune the PI controllers. Therefore, a series of step changes are applied to the DO set-point considering constant influent flow and influent concentrations as shown in figure 3. The N/E index response to these step changes are presented in figure 4.

Then, the N/E index response is approximated with a first order model:

$$\frac{N/E}{DO} = \frac{K}{Ts+1} = \frac{-0.25}{10s+1} \quad (15)$$

The model and process response are compared in figure 4.

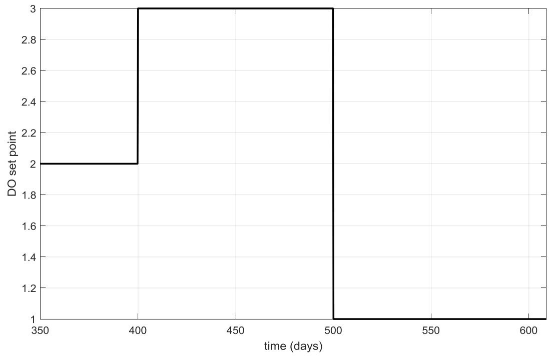

Fig. 3. Step in DO set-point in the fourth reactor to identify the system models

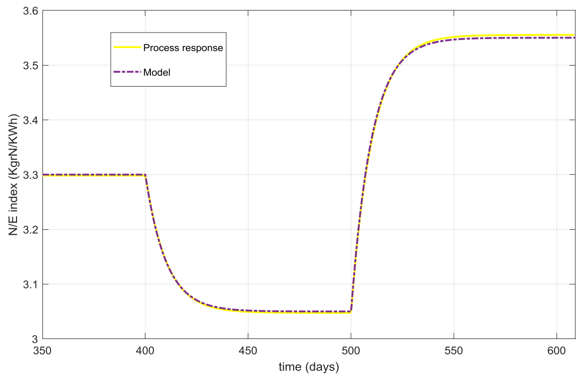

Fig.4. N/E index response

On the basis of this first order model, an IMC approach (Rivera et al., 1986) is followed to design the PI controller. The resulting PI controller parameters obey to the expressions:

$$T_i = T \qquad Kp = \frac{T}{\lambda \cdot K}$$

As it is well known, the selection of the λ parameter has a direct relationship with the closed-loop speed of response. If T_{CL} is the desired closed-loop time constant, then the controller λ can be expressed in a more convenient way as $\lambda = T_{CL} \cdot T$ being T_{CL} the relationship between the open-loop and the closed-loop time constants. A selection of T_{CL} <1 speeds up the closed-loop system whereas with T_{CL} >1 we are selecting a more conservative tuning with a closed-loop system specification slower than the open-loop one. This second option will make sense because of robustness.

4.1 Tests with constant influent pattern

The first test is carried out by introducing a constant influent pattern and the disturbances and set-point changes presented in table 1 are carried out to evaluate the performance of the proposed control strategy in terms of tracking and reaction to the application of the Q_w control strategy. Different PI tunings obtained considering different values of the λ parameter have been evaluated. The evolution of the controlled index and the dissolved oxygen reference changes to achieve the desired values of the indices and the manipulated variables are presented in figures 5, 6 and 7, respectively. The faster response is obtained with the lower λ (λ=2, T_{CL}=0.2), however, a smoother response is obtained with the larger λ that corresponds to T_{CL}=1.2.

Table 2. Test conditions

SP N/E index	3.5	4	3	
N/E SP step time (d)	0	410	500	
SP Q_w (m^3/d)	300	450	300	450
Q_w SP step time (d)	0	180	364	546

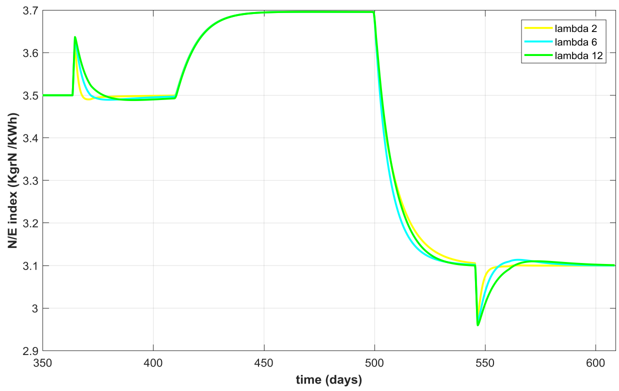

Fig. 5. Controlled N/E index under set-point changes and disturbances in Q_w

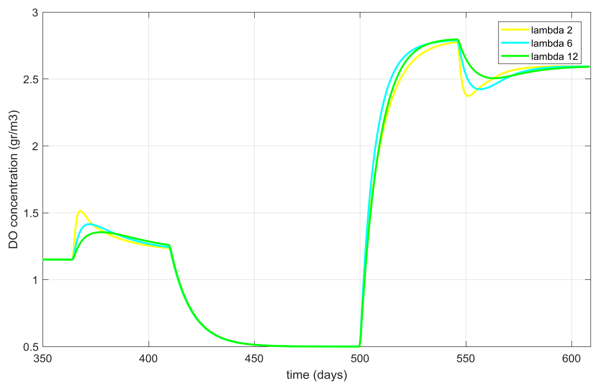

Fig. 6. Dissolved oxygen concentration in the fourth reactor (Manipulated variable for the N/E index controllers).

The N/E control strategy exhibits good set-point tracking and good rejection of disturbances for Q_w adjustment. An off-set is observed in the first set-point change at 410 simulation days. The DO set-point attains its lower value, then it is not possible to achieve the desired value of the N/E index (N/E=4).

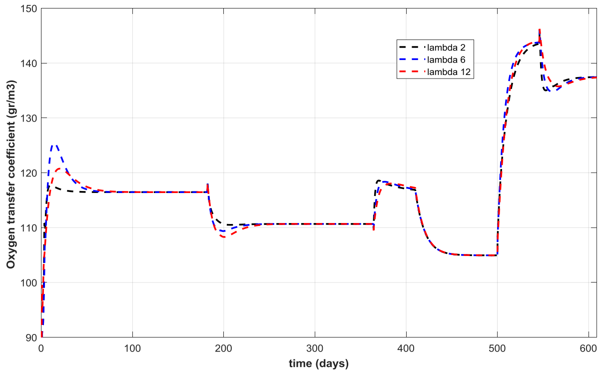

Fig. 7. Oxygen transfer coefficient in the fourth reactor (Manipulated variable for the N/E index controllers)

4.2 Evaluation in a dynamic influent scenario

In order to evaluate the effect of the disturbances introduced by the influent variability the proposed strategy is implemented considering the BSM2 dynamic influent. Since the mean value of the N/E index using the default BSM2 control strategy is N/E=3.5Wh Kgr/kWh, the value to be used as N/E index set-point is chosen to N/E=4. Different values of λ parameter are tested.

The N/E evolution, DO movements are compared with values obtained with the use of the BSM2 default control strategy (Figures 8, 9). The hierarchical PI control strategy improves the N/E index in a large proportion of the operating horizon. The desired values of the N/E index are attained by reducing the aeration energy maintaining a satisfactory operation with lower DO set-points. However, this produces a slight increment in the ammonium concentration in the effluent (Figure 10). The control movements are more aggressive with the lower λ parameter.

These results evidence the ability of the hierarchical PID structure to regulate the efficiency index close to a desired set point in realistic WWTP operating conditions.

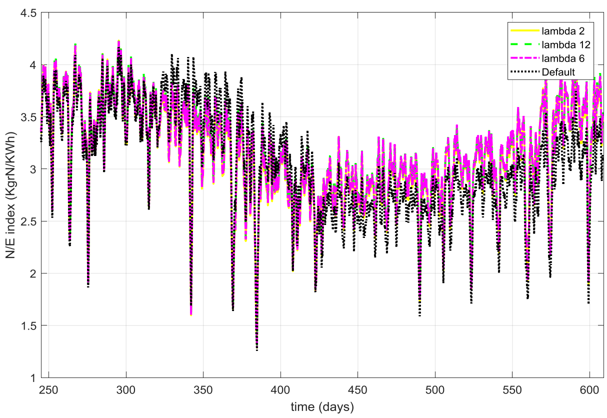

Fig. 8. N/E index evolution in the presence of influent disturbances (BSM2 default strategy and N/E control) and constant SP.

The ammonium concentration in the effluent and the evolution of the treatment efficiency index for the controller with λ =2 are shown in figures 10 and 11. These figures evidence that the implementation of the hierarchical PI control strategy to determine the plant operation on the basis of the N/E index, positively impact the treatment efficiency (TE) in the operating horizon.

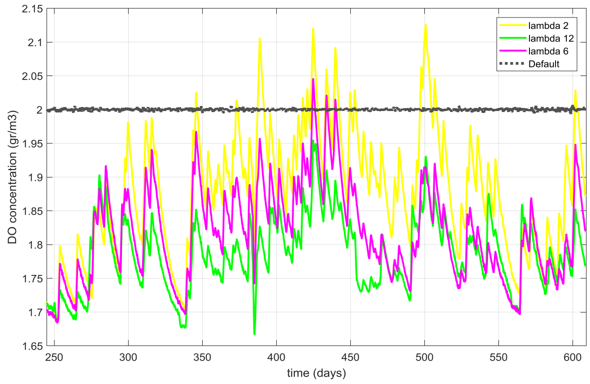

Fig. 9. Dissolved oxygen concentration in the fourth reactor (Manipulated variable for the N/E controller) in the presence of influent disturbances.

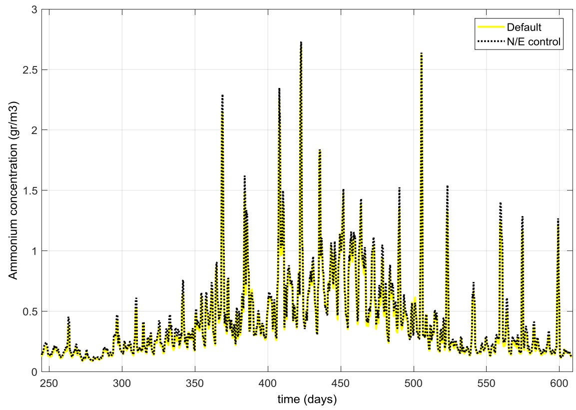

Fig. 10. Ammonium concentration in the effluent using the N/E control strategy in the presence of influent disturbances

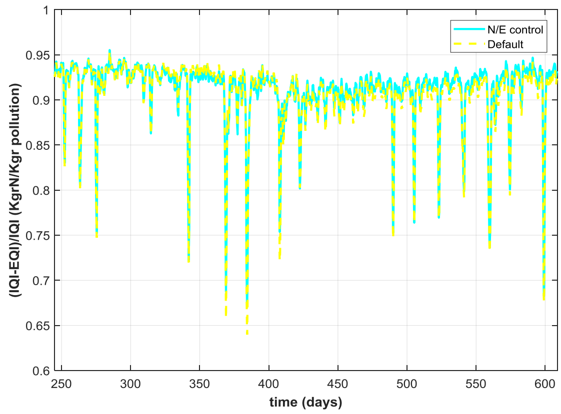

Fig. 11. Treatment efficiency using the N/E control strategy in the presence of influent disturbances

The performance indices computed for one-year operation are presented in table 2. The PI-based hierarchical structure is effective to improve process operation. The index is controlled to values that improve the operation with the default control strategy. The performance indices computed for the whole operating period show a reduction of the overall cost index when using the N/E control strategy, with an improvement in the effluent quality and similar treatment efficiency. Regarding the effect of controller tunings, the lower operating costs (OCI) and effluent quality index (EQI) are obtained with λ=12, nevertheless, this combination if tuning parameters that produces the slower response.

Table 2. Performance indices in one-year operation

	OCI (EUR)	TE	EQI (Kgr pol./d)
Default	9645	0.923	5729
N/E Hierarchical PI (λ=2)	9374	0.926	5532
N/E Hierarchical PI (λ=6)	9338	0.926	5511
N/E Hierarchical PI (λ=12)	**9318**	0.926	**5308**

5. CONCLUSIONS

A PID based hierarchical control structure is proposed to improve the overall WWTP performance. An efficiency index that quantifies the ratio between the nitrogen removed in the activated sludge process (Kgr N) and the energy (kWh) required for eliminating that amount of nitrogenated compounds (N/E index) is used as controlled variable for an upper level PI controller. The consideration of the efficiency indices as controlled define the operation in terms of its overall effect instead of local DO dynamics. Particularly the N/E index provides a link between the energy required for the operation of the whole plant (water line and sludge line) and the efficiency of the activated sludge process to eliminate nitrogen.

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