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NEW CONTROL STRATEGY DESIGN TO IMPROVE EFFLUENT QUALITY IN WASTEWATER TREATMENT PLANTS

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Abstract: The Benchmark of the European group COST 624 aims to compare control strategies of activated sludge processes in Wastewater Treatment Plants. In this paper, the design of the control strategy has been oriented so as to improve the effluent quality. An accurate reduced model of the ASM1 model has been established using singular perturbations techniques. This model has been used in a sensitivity analysis for the selection of I/O variables for the controller. The results lead to a new control strategy, which is tested with an L/A control law. The simulation results show that the effluent quality is really improved. *Copyright © 2002 IFAC*

Keywords: Water pollution, model reduction, sensitivity analysis, bio control, process control

1. INTRODUCTION

Wastewater treatment plants are non-linear systems subject to large perturbation in flow and load, together with uncertainties on the composition of the incoming wastewater. Nevertheless these plants have to be operated continuously, meeting stricter and stricter regulations.

A Benchmark (Alex *et al*., 1999) has been proposed by the European program COST 624 for the evaluation of control strategies in wastewater treatment plants. The Benchmark is based on the most common wastewater treatment plant: a continuous flow activated sludge plant, performing nitrification and pre-nitrification. This study is strictly conformed to the Benchmark methodology especially for the control performances.

Because of the really important complexity of the process, we have focused our study to understand better the process behaviour, and to point out how improving the effluent quality. This represents according to us the necessary first step of the whole design of an accurate control strategy.

In a first step, a reduced model of the ASM1 model is established. This model has to be on one hand the most accurate as possible so as to be used as a simulation model to establish the control strategy, and on the other hand sufficiently simple to be also used further in a model based control. Generally the reduced order models that can be founded in the literature (Weijers, 2000) are very simplified, more often to be easily included in a control law, or because of the lack of sensors to test the new model on pilot plants.

As the dynamic of the ASM1 model is very complex, the singular perturbation theory, scaling the states in slow and fast variables, seems a good methodological approach for a precise reduced model. If some attempts have been tried (Weijers, 2000), the difficulty remains to determine the way of scaling the variables. A methodological approach is proposed here. This reduced model has been further simplified with some physical simplifying assumptions and compartment aggregation.

Based on this reduced model and in the purpose of improving the Effluent Quality Criterion, a study of the sensitivity of different candidate control variables on the concentration of the different state variables

has been carried out. The sensitivity analysis is studied via sensitivity functions, which have the same validity domain as the model. That point is important because of the great non-linearity of the process. The results lead us to modify both the measured and manipulated variables.

At last the new control strategy determined previously is tested on the Benchmark simulation platform, using a simple control law, which seems to us well adapted to bioprocess, which is the L/A control law. The results are those expected: improving of nitrogen removal. Some discussion is given in the conclusion.

2. ASM1 MODEL REDUCTION

2.1 Plant description and ASM1 model

The plant (figure 1) consists of a 5-compartiment bioreactor and a secondary settler. The first two compartments of the bioreactor are not aerated whereas the last three are aerated. All the compartments are considered fully mixed. The secondary settler is modelled as a series of 10 layers (one-dimensional model based on Takacs model) (Takacs *et al.*, 1991).

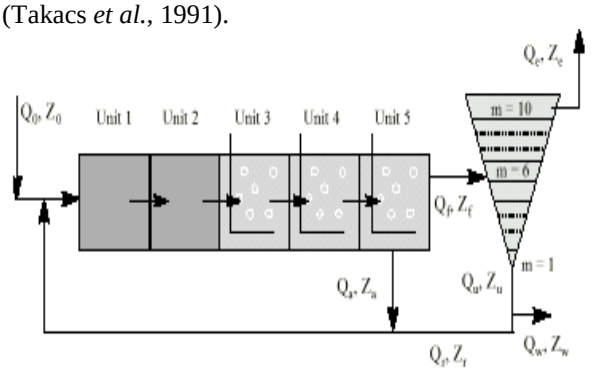

Fig. 1. Plant layout

The IAWQ Activated Sludge Model (ASM) N°1 (Henze *et al.*, 1986) was chosen to simulate the biological processes. The functional diagram of the ASM1 model is represented on figure 2 (ρ1 to ρ8 correspond to the processes rates). Some state variables that are independent of the nitrogen removal phenomenon, i.e. the soluble and particulate inert organic matter and the alkalinity, have not been represented.

The state variables are:

S_S : Readily biodegradable substrate
X_S : Slowly biodegradable substrate
$X_{B,H}$: Active heterotrophic biomass
$X_{B,A}$: Active autotrophic biomass
X_P : Particulate products arising from biomass decay
S_O : Dissolved oxygen
S_{NO} : Nitrate and nitrite nitrogen
S_{NH} : $NH_4^+ + NH_3$ nitrogen
S_{ND} : Soluble biodegradable organic nitrogen
X_{ND} : Particulate biodegradable organic nitrogen

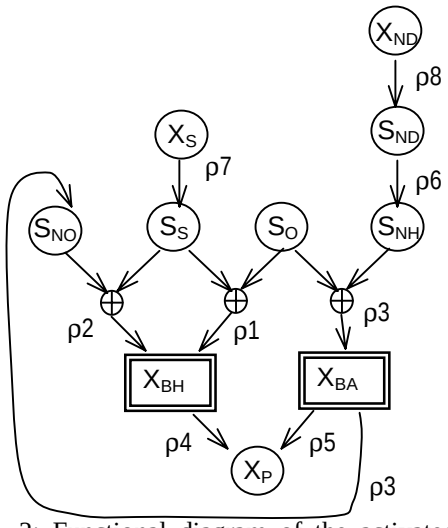

Fig. 2: Functional diagram of the activated sludge process

Model equations:

- For k = 1 (unit 1)

$$\frac{dZ_1}{dt} = \frac{1}{V_1}\left(Q_a Z_a + Q_r Z_r + Q_0 Z_0 + r_1 V_1 - Q_1 Z_1\right) \quad (1)$$

$$Q_1 = Q_a + Q_r + Q_0 \quad (2)$$

- For k = 2 to 5

$$\frac{dZ_k}{dt} = \frac{1}{V_k}\left(Q_{k-1} Z_{k-1} + r_k V_k - Q_k Z_k\right) \quad (3)$$

$$Q_k = Q_{k-1} \quad (4)$$

- Special case of oxygen ($S_{O,k}$)

$$\frac{dS_{O,k}}{dt} = \frac{1}{V_k}\begin{pmatrix} Q_{k-1} S_{O,k-1} + r_k V_k \\ + (k_1 a)_k V_k \left(S_O^* - S_{O,k}\right) \\ + Q_k S_{O,k} \end{pmatrix} \quad (5)$$

V is the volume of each unit, Q the flow, Z the vector of the state variables and S_O^* the concentration at saturation of dissolved oxygen.

Observed conversion rates: $r_k = \sum_{j=1}^{8} \nu_{kj} \rho_j$ (6)

2.2 Singular perturbations approach

Activated sludge systems exhibit stiff dynamic with time scales ranging from seconds to weeks, which behaviour fits well to singular perturbation approach.

Singular perturbation generality. A singularly perturbed system is a system for which the state equations can be written in the standard form:

$$\frac{dX_1}{dt} = f_1(X_1, X_2, u, \varepsilon) \quad (7)$$

$$\varepsilon \frac{dX_2}{dt} = f_2(X_1, X_2, u, \varepsilon) \quad (8)$$

where $X_1 \in R^{n1}$, $X_2 \in R^{n2}$, f_1 and f_2 are regularly vectorial functions of (X_1, X_2, u, ε), and ε is a parameter, positive and small.

In the limit of $\varepsilon \to 0$, the system of slow dynamics is:

$$\frac{dX_1}{dt} = f_1(X_1, \psi(X_1, u), u, 0) \quad (9)$$

$$X_2 = \psi(X_1, u) \quad (10)$$

In the limit of $\varepsilon \to 0$, the system of fast dynamics is:

$$\frac{dX_1}{d\tau} = 0 \quad (11)$$

$$\frac{dX_2}{d\tau} = f_2(\overline{X}_1(t), \overline{X}_2(t) + X_2(\tau), u, 0) \quad (12)$$

Where: $\tau = t/\varepsilon$; $\overline{X}_1(t)$, $\overline{X}_2(t)$ are considered constant

Scaling the ASM1 model. So as to determine the ε parameter, each term of the ASM1 model equations is scaled. These terms are constituted of 2 parts: one is the rate part (noted ρ) and the other the hydrodynamic part. A really important dilution rate may potentially be the main origin of the dynamical behaviour of a recycled process (Kumar and Daoutidis, 2000). In our configuration, the flow-recycled rate of the internal recycled flow (Qa) with respect to the input flow rate (Q_0) is only 50%, which is not enough to be a good candidate to the ε parameter.

The rates are constituted of a product of three terms: parameters, Monod laws, and biomass concentrations. The Monod law is a saturation term depending from a substrate concentration and is comprised between 0 and 1. The worst case is taken into account, so the Monod laws are considered to be at their maximum. The rates are therefore calculated as the product of parameters and steady state value of the biomass concentration (to avoid local effect if a peak of the biomass concentration arise).

Table 1: Estimation of the rates

	Rate	Evaluation
Large	ρ1max	10 000
	ρ2 max	8 000
	ρ7 max	7 700
Medium	ρ4 max	770
Low	ρ8 max	250
	ρ6 max	130
	ρ3 max	70
	ρ5 max	7

Then the classification showed on Table 1 is established. This scaling is about the same for the 5 compartments. The originality is that ε is not a single parameter, but a general one:

$\varepsilon \cong 1/\rho 1\max \cong 1/\rho 2\ \max \cong 1/\rho 7\ \max$

Finally, after writing the ASM1 model in the standard form, the fast state variables are: Z'=[S_S, X_S, $X_{B,H}$, S_O, S_{NO}, S_{NH}] and the slow state variables Z"=[$X_{B,A}$, X_P, S_{ND}, X_{ND}]. To keep information on nitrogen removal, the system of fast dynamics is used. Then this leads to an algebro-differential system of only 6 state variables for each compartment.

2.3 Further simplifications

Separation of anoxic and aerobic models. In the purpose of simplifying the model equations, the model has been separated in two phases: anoxic and aerobic. The main simplifications are achieved for the anoxic case, in which the oxygen concentration is considered to be null. Moreover the nitrification rates (ρ1 and ρ3) are neglected. For both cases, the behaviour of the biomass $X_{B,H}$ has been considered to be influenced only by hydrodynamics. At last the Monod functions of each rates have been simplified (saturation or linear approximation) every time that could be possible.

Aggregation of compartments. Providing a large reduction of the number of states, the model can be easily aggregated with a very good precision. In the purpose of using this model for the design of the control strategy, the model has to describe some variables at specific locations: the output of the anoxic phase, the input and the output of the aerobic phase. Therefore the final model is composed of only 3 units: the first two compartments, the 3rd and the 4th together, and the last one. The aggregation is realized by identifying new parameters for the rate part of the equations with least square method.

Finally, the reduced model is :

$$\begin{cases} \dfrac{dZ_1'}{dt} = \dfrac{1}{V_1 + V_2}\left(Q_a Z_a' + Q_r Z_r' + Q_0 Z_0' - Q_2 Z_2'\right) + r'_2 \\ \quad \text{with } r'_2 = \sum_i a_i \rho_i' \quad i = 2,6,7 \quad a_i \text{ constants} \\ Z_2'' = g_2(Z_2', Z_2'') \end{cases} \quad (13)$$

$$\begin{cases} \dfrac{dZ_4'}{dt} = \dfrac{1}{V_3 + V_4}\left(Q_2 Z_2' - Q_4 Z_4'\right) + r'_4 \\ \quad \text{with } r'_4 = \sum_i b_i \rho_i'' \quad i = 1,2,3,6,7 \; b_i \text{ constant} \\ Z_4'' = g_4(Z_4', Z_4'') \end{cases} \quad (14)$$

$$\begin{cases} \dfrac{dZ_5'}{dt} = \dfrac{1}{V_5}\left(Q_4 Z_4' - Q_5 Z_5'\right) + r_5' \\ \quad \text{with} \quad r'_5 = \sum_i \nu_{5i} \rho_i'' \qquad i = 1,2,3,6,7 \\ Z_5'' = g_5(Z_5', Z_5'') \end{cases} \quad (15)$$

Reduced model validation. The model has now only 18 state variables (65 states in the initial model), and is much more simple. Its precision is still very accurate, as it is shown on figure 3. The advantage of this approach is that there is in fact a set of reduced models that can be used independently or in combination.

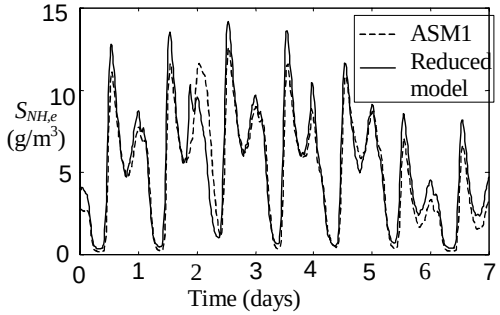

Fig. 3: Validation on Ammonium concentration

3. CONTROL AND MEASURED VARIABLES DETERMINATION

3.1 Variables to be measured for quality

According to the benchmark, the Effluent Quality Index (EQ) is defined by:

$$EQ = \frac{1}{T.1000}\int_{t=7days}^{t=14days} PU(t)Q_e(t)dt \qquad (16)$$

with

$$\begin{cases} PU(t) = B_{TSS}TSS_e(t) + B_{COD}COD_e(t) + B_{BOD}BOD_e(t) \\ \quad + B_{TKN}TKN_e(t) + B_{NO}NO_e(t) \\ TSS_e(t) = 0.75\left(X_{S,e} + X_{BH,e} + X_{BA,e} + X_{P,e} + X_{I,e}\right) \\ COD_e(t) = S_{S,e} + S_{I,e} + X_{BH,e} + X_{BA,e} + X_{P,e} + X_{I,e} \\ BOD_e(t) = 0.25\left(S_{S,e} + X_{S,e} + (1-f_p)\left(X_{BH,e} + X_{BA,e}\right)\right) \\ TKN_e(t) = S_{NH,e} + S_{ND,e} + X_{ND,e} + i_{XB}\left(X_{BH,e} + X_{BA,e}\right) \\ \quad + i_{XP}\left(X_{P,e} + X_{I,e}\right) \\ NO_e = S_{NO,e} \end{cases}$$

Factor	B_{TSS}	B_{COD}	B_{TKN}	B_{NO}	B_{BOD}
Value(g pollution unit/g)	2	1	20	20	2

The greater weighting factors Bi are clearly those linked with nitrogen in both forms: B_{TKN} and B_{NO}. Considering B_{TKN} factor, in TKNe expression, the most significant variable is S_{NH}. For the other variables, either the value is very small, either the variable influence (for S_{ND} and X_{ND} e.g.) can be neglect after time integration. Therefore the most significant variables for the effluent quality are S_{NO} and $S_{NH.}$

3.2 Preliminary analysis

The purpose is to find out both the best sensors' location as well as the right control variable to improve nitrogen removal. To understand better the behaviour of the process, a succession of steps of different magnitudes has been first applied on the recycling flow Qa, with constant inputs. The results are showed on figure 4 (S_{NH}) and 5 (S_{NO}).

The Figures 4 and 5 show that the state variables in the 2nd compartment are really influenced by the flow, which confirms that it is a possible action to control the process. But it is also clear that it has practically no influence on the aerated compartments. However the effluent quality depends precisely on the concentration at the output of the process, and is clearly not decreased. It is therefore important to choose a measured variable and a sensor location such that their influence on both control action and real criterion of depollution is maximised. Moreover it is a guaranty that nothing can happen (disturbance or failure) that cannot be detected in the 3 last compartments.

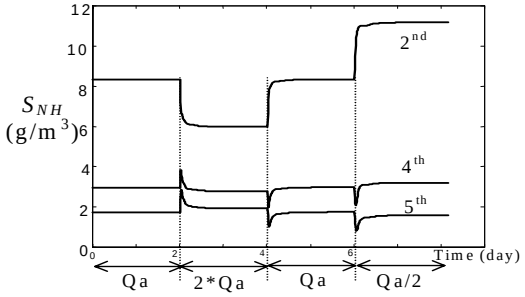

Fig. 4: Response of S_{NH} concentration

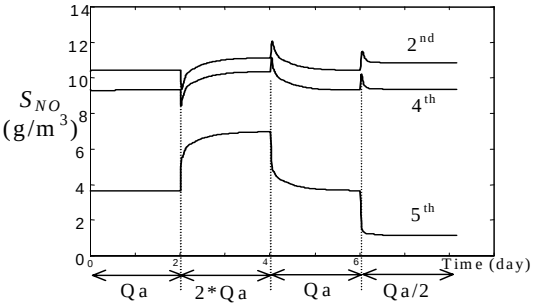

Fig. 5: Response of S_{NO} concentration

An explanation is that if the recycle is large, a lot of nitrate (S_{NO}) will be brought with the recycled sludge. A large concentration of nitrate will increase the rates of the de-nitrification process, which decreases the concentration of S_{NO} at the output of the anoxic part. However the ammonium ($S_{NH.}$) is created by hydrolysis reaction and nitrate by nitrification from ammonium. These reactions are not affected by the flow regulation, and consequently the last compartment contains the same concentrations of nitrogen.

Comparing now the 2 figures, something interesting appears: the recycling flow Qa is not acting in the same way for S_{NO} and $S_{NH.}$ This is due to the dilution effect: proportionally for a large recycling flow, the S_{NO} fraction will increase and the S_{NH} fraction will decrease. So acting on both variables in the same way with only the action of Qa is not possible.

In conclusion, the controlled variables have to be measured at the end of the process. In addition a good candidate for control variable would act in the same way all the nitrogen fractions.

3.3 Sensitivity analysis

The system sensitivity, as a general concept, refers to the change in an output variable, which can be attributed to a change of one of the system parameters (coefficients or, in some cases, system inputs). The sensitivity functions behaviour is available on the whole validity domain of the model.

Choice of the control variable. As the input or output flows will increase the treatment time and will cause problems of tank size, 3 possibilities are left: Qa, kla and S_{Sin}. Usually carbon addition (S_{Sin}) is not considered as a manipulated variable, though some solutions exit to make it varying: by using a pre-treatment with S_{Sin} control at the output, or a S_{Sin} complement with respect to the non-controlled input. This last case is sometimes done when there is a lack of carbon source. The sequel will show that this technique is really improving the process performances, though it has not been yet, according to us, fully quantified.

The sensitivity function can be defined as follows:

$$\gamma(\theta) = \frac{\partial T^k}{\partial \theta} \qquad (17)$$

where θ is one of (Qa, kla5, S_{Sin}) and T is one of ($S_{NH,i}$, $S_{NO,i}$), i=2, 4 or 5.

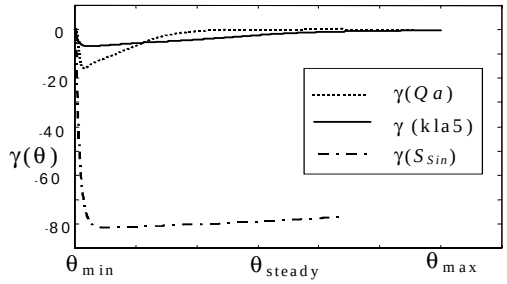

Fig.6: Sensitivity functions on S_{NO} for the last compartment

On figure 6 appears clearly that the only possible control variable that really influences the nitrate in the last compartment is the incoming readily biodegradable substrate, which acts directly on the reaction, and acts on the same way to both S_{NO} and S_{NH}, and especially at the end of the process. Finally S_{Sin} is chosen as the manipulated variable.

4. CONTROL SIMULATION AND RESULTS

The proposed control strategy can now be tested on simulation.

L/A control principle. This control comes from the observation that there are generally physical constraints on real processes, as positivity of variables or the actuators saturation, which is the case for bioprocesses. The control L/A principle is to apply non linear static transformations to variables so as to implicitly always verify the positivity constraint on variables. Lakrori introduced this approach for bioprocesses control (Lakrori, 1989). It presents good performances in comparison with classical algorithms, and besides their structure is very simple and the controllers are easy to design and to tune.

The L/A control principle is shown on figure 7: U is the action variable, Y and Y* are respectively the measured variable and the reference variable.

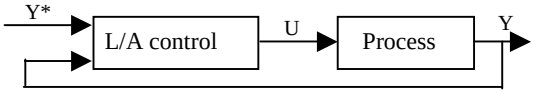

Fig. 7: L/A control structure

The positivity constraints are relaxed by applying exponential and logarithmic transformations on the real process. For a classical numerical PI, the L/A control law is directly deduced from the PI controller by replacing the summation by products, the subtractions by divisions and products by exponent.

The control law is then (K1, K2: tuning parameters):

$$U_k = U_{k-1}\left(\frac{Y_{k-1}}{Y_k}\right)^{K1}\left(\frac{Y_k^*}{Y_k}\right)^{K2} \qquad (18)$$

Parameters tuning. Usually the parameters are tuned by taking into account the saturation of the actuator (Béteau *et al.*,1991). When the measurement is Δ above (or under, depending if the control law is direct or not) the set point Y*, then action reach its saturation value, U_{max}. The smaller Δ is, the faster the system response. If U_e is the value of the control variable for the output Y*, then:

$$K2 = \frac{1}{\alpha+1}\ln\left(\frac{U_{max}}{U_e}\right)\Big/\ln\left(\frac{Y^*}{Y^*-\Delta}\right) \qquad (19)$$

$$K1 = \alpha K2$$

Simulation results. The control law is simulated with a set point of 10 g/m3 for the total nitrogen (S_{NH} + S_{NO}), with S_{Sin} as the manipulated variable.

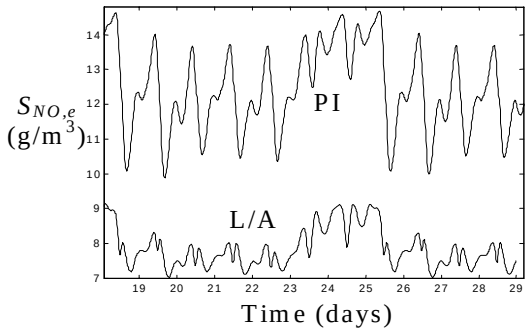

Fig.8: Comparison of PI control (Benchmark) and L/A control on the effluent nitrate concentration

The Figure 8 shows that the nitrate concentration of the effluent is clearly decreased (both the mean value and the magnitude). However the ammonium concentration (S_{NH}) is not really influenced by this

control law. It was clear that the influence would not be strong, but no influence is astonishing. This point would need to be further studied. The figure 9 shows the control variable, which is following the concentration variations.

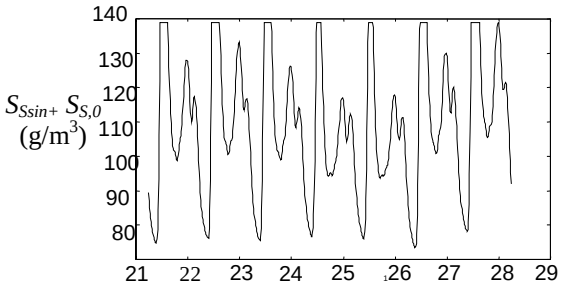

Fig. 9: Total carbon (control variable S_{Sin} + input $S_{S,0}$) for L/A control

Table 2: Comparison of the performance criteria between the PI (Benchmark) and L/A control

	PI control (average)	L/A control
E.Q. (g.d-1)	7 605.79	5983.32
Psludge(kgSS/d)	2 442.87	2688.08
AE	7245.8	7422.69
PE	1458.47	2966.76
Nb Viol. Ntot,e	7	0
Nb Viol. SNH,e	5.2	5
% Viol. Ntot,e	19.66	0
% Viol. SNH,e	17.37	16.96

The table 2 point out the comparison of the performance criteria between the PI control of the Benchmark and the proposed L/A control. The Effluent Quality criterion is far much better, as well as the violations of total nitrogen that has disappeared. The ammonium is remained unchanged. The quantity of sludge is increasing, as the pumping energy, because the recycling flow Qa is remained unchanged. So the cost is more elevated, and more sludge is produced in a day. The Aerating Energy is nearly the same.

All these criteria show that the proposed control strategy is really interesting so as to improve nitrogen removal. The needed energy is increased, but the treatment is regular and more important than with the PI control. A point to go further is how controlling the ammonium concentration (S_{NH}). The control algorithm can be easily improved, including the reduced order model in an advanced control structure.

5. CONCLUSION

In that study, an accurate reduced order model of the very complex ASM1 model has been established. The singular perturbation theory has been successfully used, associated with aggregation of the compartments and classical simplifying assumptions. The resulting model is sufficiently simple to be in a further step included in a control law.

This model has been used to study the choice of input and output of the control law. The analysis of candidates of measured and manipulated variables have been done through sensitivity functions. The conclusion leads to a rather different control strategy than the benchmark classical strategy, using *Ssin* as control variable, and (S_{NH} +S_{NO}) of the 5th compartment as measured variables. Choosing *Ssin* is not usual because it is not so easy to manipulate, but some solutions exists and the good results justify this choice.

The proposed strategy is tested successfully in simulation on the benchmark plant. The effluent quality is really improved, and violations of nitrate have disappeared. The process is consuming more energy, as it is also treating more influent. A point is still to clarify: how to control ammonium concentration (S_{NH}). However the results could be even improved by the design of a more advanced control law, using the reduced order model, which will be realised in a further work.

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