Optimized Control Structure for a Wastewater Treatment Benchmark

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Abstract: In this paper, we define and implement the design of an optimized control structure for the activated sludge process given as COST/IWA benchmark simulation model No.1. Emphasis is given to the identification of controlled variables that contribute to minimize economic costs while the effluent requirements are met. This is achieved considering the self-optimizing procedure as reference method for the controlled variables selection. The proposed optimal control strategy consists of multivariable PID loops which manipulate the airflow rate in the aerobic basins, the nitrate and sludge recirculation flows and the waste sludge flow proportionally to the influent flow such that the overall cost function is minimized. Dynamic simulations validate the resulting optimized controller structure, showing that minimal costs can be achieved.

Keywords: Activated sludge process, controlled variables selection, optimal setpoints.

1. INTRODUCTION

Continuous challenges are nowadays required from wastewater treatment plants (WWTPs) in order to satisfy new constraints in terms of quantity and quality of the discharged effluent for the compliance with stringent environmental regulations at minimum costs. The European Directive 91/271/CEE, regarding urban wastewater treatment, give rise to both technical and economical challenges since most of the existing plants have to undertake major upgrading, particularly for nutrient removals. In addition to plant improvements attained through the adoption of new equipment technologies, the application of careful considerations on control systems is required to achieve the improved benefits in practice. In particular, designing the control structure such that the overall operation costs are minimized seems to be the right way to proceed, meaning that the control design problem becomes an optimal economic operation problem. Optimization of the biological processes performance has been studied by several authors in different ways. In particular, a number of exercises that focused their attention mainly on the activated sludge process (ASP), the most commonly used technology for organic and nutrient pollutants removal, are suggested in the literature (Gillot et al. (1999), Chachuat et al. (2001), Vanrolleghem and Gillot (2002), Fikar et al. (2004), Devisscher et al. (2006), Samuelsson et al. (2007), Stare et al. (2007), Machado et al. (2009)).

The aim of this paper is to propose a systematic procedure able to define the controlled variables (CVs) and their optimal setpoints for an ASP. The self-optimizing idea (Skogestad (2004)) represents the right way for solving the problem of CVs selection. In fact, the main steps in the procedure: (i) quantify the desired operation by defining a scalar cost function; (ii) use a steady-state model to optimize the operation for various disturbances by minimizing the cost with respect to the available degrees of freedom and (iii) identify the controlled variables with self-optimizing properties, give the proper approach for the problem.

Optimization results show that with simple considerations on control structure design the efficiency of a wastewater treatment plant can be improved, minimizing operational costs while keeping it running optimally and satisfying the effluent requirements.

2. BIOLOGICAL WASTEWATER TREATMENT PLANT

Wastewater treatment plant processes aim at removing pollutants in the wastewater by transformation and separation processes. Depending on the characteristics of the wastewater, the desired effluent quality, and the environmental or social factors, this can be achieved in different ways. In general, wastewater treatment includes as a first step a mechanical treatment to remove floating and settleable solids, then a biological treatment for removal of nutrient and organic pollutants, sludge treatment and water chemical treatment are following. Here the continuous

ASP is considered for the biological wastewater treatment with the main purpose of nitrogen removal.

Based on the COST/IWA Benchmark Simulation Model No.1 (BSM1), the considered layout represents a fully defined protocol that characterizes the process including a plant layout and two conventional control systems. The bioreactor consists of five bioreactors (R_i with $i = 1, \dots, 5$), first two anoxic zones (pre-denitrification) followed by three aerobic ones (nitrification). To maintain the microbiological population, the sludge from the settler is re-circulated into the anoxic basin (returned activated sludge, Q_r), and part of the mixed liquor is recycled to the inlet of the bioreactor (internal recycle, Q_a) to enhance nitrogen removal. The sludge concentration is kept constant by means of sludge withdrawn, Q_w, pumped continuously from the settler. Two feedback control loops are implemented in the default BSM1 configuration: (1) the dissolved oxygen level in the fifth reactor controls aeration in this reactor; (2) nitrate at the exit of the anoxic zones manipulates the internal recycle flow-rate. The benchmark is based on the two de facto accepted process models: the Activated Sludge Model No.1 (ASM1) proposed by Henze et al. (1987) used to model the biological process and a non-reactive Takàcs one dimensional layer model is used to describe the settling process (Takàcs et al. (1991)). Kinetic and stochiometric parameters are provided within the benchmark description.

Influent data are provided in terms of influent flow rates and ASM1 state variables over a period of 14 days with 15 minutes sampling time. A general survey of the benchmark is given by Jeppsson and Pons (2004), and a more technical description is provided by Copp (2002) and Alex et al. (2008).

3. DEFINITION OF THE OPERATIONAL PERFORMANCE

An answer to the optimization problem is given by designing the control structure in such a way that the operational costs are minimized. With this regard, the self-optimizing procedure proposed by Skogestad (2004) provides the perfect approach for defining the controlled variables. In particular, starting from the degrees of freedom (DOF) analysis, the definition of operational objectives, constraints and disturbances, the controlled variables can be defined for the BSM1.

3.1 Degrees of freedom analysis

If we look at the schematic representation of the plant in Figure 1, we notice that the number of manipulated variables is 11, including the influent flow rate. Note further that, the output flow from the aeration tank should not be included since the level in the tank is self-regulating, the same holds for the effluent from the secondary settler; therefore, it follows that there are eight degrees of freedom left. Those should be used to optimize the operation satisfying the constraints.

3.2 Definition of the operational objectives

In this work the operational objective, the total cost function, is expressed in terms of partial costs over a certain range of time T, following the expressions proposed in Alex et al. (2008). The total energy due to the required *pumping energy*, E_P expressed in $[kWh/d]$, depends directly on the recycle flow (Q_r), on the internal recycle (Q_a) and on the waste sludge flow rate (Q_w):

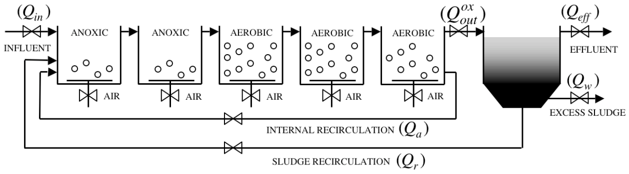

Fig. 1. Schematic representation of the BSM1 activated sludge plant.

$$E_P = \frac{1}{T}\int_{t_0}^{t_0+T}\Big(0.004Q_a(t) + 0.008Q_r(t) \\ +0.05Q_w(t)\Big)dt \tag{1}$$

with the flow rate in m^3/d. The *aeration energy*, E_A in $[kWh/d]$, can be calculated from the following function of the oxygen saturation concentration, S_O^{sat}, the bioreactor volumes, V and the oxygen mass transfer coefficients K_{La} for each bioreactor zone:

$$E_A = \frac{S_O^{sat}}{T \times 1.8 \times 1000}\int_{t_0}^{t_0+T}\sum_{i=1}^{5} V_i K_{La,i}(t)dt \tag{2}$$

with K_{La} expressed in d^{-1} and $i = 1, \dots, 5$ referring to the reactor zone number. The anoxic zones should be mixed to avoid settling and in addition to the aeration system also mechanical mixing might be supplied. The *mixing energy*, E_M expressed in $[kWh/d]$, is a function of the compartment volume:

$$E_M = \frac{24}{T}\int_{t_0}^{t_0+T}\sum_{i=1}^{5}\begin{cases} 0.005\,V_i\,dt & \text{if } K_{La,i}(t) < 20 \\ 0 & \text{otherwise}\end{cases} \tag{3}$$

Assuming a sludge disposal price $k_D = 80$ €$/tonn$, the *disposal cost*, C_D in [€$/d$], is given as:

$$C_D = \frac{1}{T}\int_{t_0}^{t_0+T}(k_D TSS_w(t)Q_w(t))dt \tag{4}$$

where TSS^w represents the total suspended solids wasted with Q_w. Assuming a constant energy price $k_E = 0.09$ €$/kWh$ the total energy cost, i.e., the overall cost function J in €$/d$ is calculated as follows:

$$J = k_E(E_P + E_A + E_M) + C_D \tag{5}$$

3.3 Constraints

The overall cost function in Equation 5 should be minimized subject to regulations for the effluent and some constraints related to process operability.

As for the latter, we identify the dissolved oxygen concentration in the entire aeration tank and the nitrate concentration at the exit of the denitrification zone, to provide adequate aeration. In order to prevent loss of sludge solids in the effluent we define some measures to represent the sludge behavior both in the bioreactor and in the settler. For example, we know that the excess activated sludge produced each day must be discharged to maintain a given *Food to Microorganisms Ratio* (F/M, equivalently, a given *Sludge Retention Time* (SRT, also known as *sludge* *age* or *mean cell residence time*. In such a way, following the suggestions given in Meltcalf and Eddy (1991) and by several authors (Ingildsen (2002), Olsson et al. (2005), Samuelsson et al. (2007)), the cost function optimization can ensure a proper operation for the activated sludge process.

Eventually, the final constraints of the ASP are defined by the legislation requirements for effluents deriving from a wastewater treatment plant. Summarizing, the cost function in Equation 5 is subjected to the constraints reported in Table 1.

Table 1. Nonlinear constraints.

1.5	$\leq$	$S_O^{(3,4,5)}$	$\leq$	4	gO_2/m^3
7	$\leq$	SRT	$\leq$	18	d
0.04	$\leq$	F/M	$\leq$	1.2	$gCOD/gSS/d$
1	$\leq$	$S_{NO}^{p,2}$	$\leq$	4	gN/m^3
0	$\leq$	$S_O^{(1,2)}$	$\leq$	0.5	gO_2/m^3
		COD^{eff}	$\leq$	100	$gCOD/m^3$
		TSS^{eff}	$\leq$	30	gSS/m^3
		TN^{eff}	$\leq$	18	gN/m^3
		S_{NH}^{eff}	$\leq$	4	gN/m^3
		BOD_5^{eff}	$\leq$	10	$gBOD/m^3$

3.4 Disturbances

The definition of influent disturbances has been approached in several different ways in literature, see for instance Isaacs and Thormberg (1998) and Copp (2002). In this paper we consider the influent loads data-files given by the IWA Task Group that provides three different weather/influent conditions (dry weather, storm and rain events) and a "long term file" which focuses on long term process performances and considers temperature variations during one year (Gernaey et al. (2006)).

As steady-state disturbances for the optimization, we consider different conditions from the different data-sets provided in the benchmark. The average composition and flow rate for the rain event is given as d_1. From storm event, we identify the disturbances as d_2 representing the average condition during the whole peak period. Variations in temperature during one year time are given in the "long term" file, we consider the average (d_3), and maximum (d_4) values for the temperature. Starting from the *nominal* conditions, i.e. average values of influent during dry weather, Table 2 summarizes the given disturbances in terms of influent flowrate and influent loads (listed here for sake of conciseness, in terms of chemical oxygen demand (COD), total suspended solids (TSS), total nitrogen (TN) and Temperature ($Temp$)).

Table 2. Steady-steate disturbance sets.

	Q_{in} m^3/d	COD_{in} $gCOD/m^3$	TSS_{in} gSS/m^3	TN_{in} gN/m^3	$Temp$ $°C$
Nominal	18446	381	211	54	15
d_1	21320	333	183	48	15
d_2	19746	353	195	50	15
d_3	20850	347	199	41	14
d_4	20850	347	199	41	21

3.5 Candidate controlled variables

The measured variables considered as candidate CVs are listed in Table 3. In the bioreactor we assume that measurements of dissolved oxygen, ammonia, and nitrate might be available in the entire bioreactor.

The reasons for selecting the measurements in Table 3 are briefly explained in the following. Choosing the dissolved oxygen concentrations (y_1, y_4, y_7, y_{11}, and y_{14}) as a potential CV is a quite common choice in WWTP. Usually, it is associated with aeration control, which has received much attention mainly because aeration is costly in a WWTP. Nitrate sensors are assumed in the whole bioreactor (y_2, y_5, y_8, y_{12}, and y_{15}). Frequently, nitrate measurements at the end of the anoxic zone are considered for the internal recirculation flow rate as in the BSM1 default configuration. In this paper, the placement of the sensor in the basin is left open and measurements in all the five reactor zones are considered possible. The location and number of the ammonium sensors (y_3, y_6, y_9, y_{13}, and y_{14}) are important as well. The measurements of the mixed liquor suspended solids (MLSS, y_{10}) involves a suspended solids sensor at the bioreactor exit. In the literature, MLSS has been selected as CV in several occasions, Vitasovic (1986), Cakici and Bayramoglu (1995), Mulas et al. (2007) as indicator of settling properties and sludge production.

The amount of the main effluent pollutants such as COD and TSS (y_{18} and y_{19}), nitrate and total suspended solids (y_{20} and y_{21}) in the waste sludge stream are considered as further candidate CVs for possible feedback loops. Furthermore, the sludge age (y_{22}) is included in Table 3 as it is one of the most important parameters for avoiding the proliferation of filamentous bacteria. The measurement of this variable involves different suspended solids sensors in the bioreactor and settler, and it is kept at certain value by means of the wastage removed from the settler or from the biological reactor; e.g. Pons and Potier (2008) compare different control structures defining that a constant wastage from the biological reactor could be a good alternative (when no suspended solids sensor is available). Finally, the last eight variables in Table 3 designate the manipulated variables for the plant: keeping them constant might represent a possible suitable option.

4. OPTIMIZED CONTROL STRUCTURE

The eight DOF left are used to minimize the cost function in Equation 5 subjected to the constraints in Table 1 for the BSM1 denitrifying plant. A standard SQP algorithm in Matlab Optimization Toolbox was used to define the optimal solution. The upper and lower bound for the eight unconstrained DOF are given in Table 4.

Table 4. DOF's upper and lower bound.

		Units	Lower	Upper
u_1	Q_r	m^3/d	0	36892
u_2	Q_w	m^3/d	0	1845
u_3	Q_a	m^3/d	0	92230
u_4	K_{La}^1	$1/d$	0	360
u_5	K_{La}^2	$1/d$	0	360
u_6	K_{La}^3	$1/d$	0	360
u_7	K_{La}^4	$1/d$	0	360
u_8	K_{La}^5	$1/d$	0	360

The optimal choice of the controlled variable is an important issue. We are searching in particular for the variable that satisfy certain properties, such as: (i) its optimal

Table 3. Candidate controlled variables.

	Symbol	Units	
y_1	S_O^3	gO_2/m^3	Dissolved Oxygen in the first aerobic reactor
y_2	S_{NO}^3	gO_2/m^3	Nitrate in the first aerobic reactor
y_3	S_{NH}^3	gO_2/m^3	Ammonia in the first aerobic reactor
y_4	S_O^4	gO_2/m^3	Dissolved Oxygen in the second aerobic reactor
y_5	S_{NO}^4	gO_2/m^3	Nitrate in the second aerobic reactor
y_6	S_{NH}^4	gO_2/m^3	Ammonia in the second aerobic reactor
y_7	S_O^5	gO_2/m^3	Dissolved Oxygen in the third aerobic reactor
y_8	S_{NO}^5	gO_2/m^3	Nitrate in the third aerobic reactor
y_9	S_{NH}^5	gN/m^3	Ammonia in the third aerobic reactor
y_{10}	$MLSS$	gSS/m^3	Mixed Liquor Suspended Solids
y_{11}	S_O^1	gO_2/m^3	Dissolved Oxygen in the first anoxic reactor
y_{12}	S_{NO}^1	gN/m^3	Nitrate in the first anoxic reactor
y_{13}	S_{NH}^1	gO_2/m^3	Ammonia in the first anoxic reactor
y_{14}	S_O^2	gO_2/m^3	Dissolved Oxygen in the second anoxic reactor
y_{15}	S_{NO}^2	gN/m^3	Nitrate in the second anoxic reactor
y_{16}	S_{NH}^2	gO_2/m^3	Ammonia in the second anoxic reactor
y_{17}	S_{NH}^{eff}	gN/m^3	Ammonia in the effluent
y_{18}	COD^{eff}	$gCOD/m^3$	Chemical Oxygen Demand in the effluent
y_{19}	TSS^{eff}	gSS/m^3	Total Suspended Solids in the effluent
y_{20}	S_{NO}^w	gN/m^3	Nitrate in the waste activated sludge
y_{21}	TSS^w	gSS/m^3	Total Suspended Solids in the waste activated sludge
y_{22}	SRT	d	Sludge Retention Time
y_{23}	Q_r	m^3/d	Recycle flow rate
y_{24}	Q_w	m^3/d	Wastage flow rate
y_{25}	Q_a	m^3/d	Internal recycle flow rate
y_{26}	K_{La}^1	$1/d$	Oxygen mass transfer coefficient for the first anoxic zone
y_{27}	K_{La}^2	$1/d$	Oxygen mass transfer coefficient for the second anoxic zone
y_{28}	K_{La}^3	$1/d$	Oxygen mass transfer coefficient for the first aerobic zone
y_{29}	K_{La}^4	$1/d$	Oxygen mass transfer coefficient for the second aerobic zone
y_{30}	K_{La}^5	$1/d$	Oxygen mass transfer coefficient for the third aerobic zone

value should be insensitive to disturbances; (ii) it should be easy to measure and control; (iii) its value should be sensitive to changes in the manipulated variables. The right selection is done here by means of the optimization results. The effect of disturbances on the optimal values for the selected variables is given in Table 5, the values from the BSM1 open-loop model are reported as comparison. In the attempt to keep the controlled plant as simple as possible for sake of applicability, a decentralized (multiloop SISO controllers) structure is chosen. On a first analysis, it is noted that active constraint variables can be identify as the most suitable to control and that based on practical experience their pairing with the manipulated variables is straightforward:

- Dissolved oxygen in the aerobic zones (y_1, y_4, y_7) are coupled with the corresponding $K_{La}^{(3,4,5)}$ coefficient.
- Nitrate at the exit of the anoxic zones (y_{15}) controls the internal recycle flow Q_a.
- Airflow at the anoxic basins (given by y_{26} and y_{27}) can be kept constant.
- The ratio $w = Q_w/Q_{in}$ is approximately constant at different disturbance and it reasonable to keep it constant in the proposed configuration.

Q_r remains as the only unconstrained degree of freedom. Being ammonia concentrations, y_9 or y_{17}, active one of them might be chosen as suitable pairing. In an attempt to anticipate correction on the effluent, y_9 might be chosen as possible controlled variable; however according to the Relative Gain Array (RGA, Bristol (1966)) approach, the loop $y_9 - Q_r$ is highly influenced by the others, that is control of ammonia is very difficult. Better results are found controlling y_{10} which provides suitable RGA matrix and Niederlinski Index.

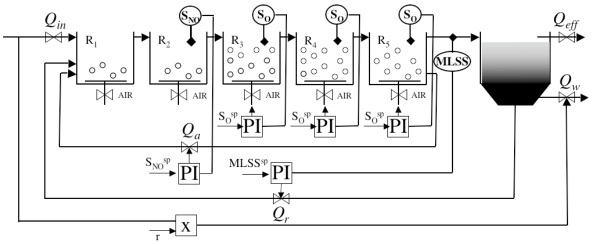

Fig. 2. Schematic representation of the optimized BSM1 controller.

Summarizing, the proposed decentralized control structure and the optimal setpoints for each feedback loop are reported in Figure 2 and Table 4. In particular, the optimal setpoint for y_{10} has been defined by sensitivity analysis, in order to reach the lower ammonia concentration at the effluent.

Table 6. Selected CVs: optimal setpoints

	Setpoint	Units		Constant	Units
y_1, y_4, y_7	1.5	gO_2/m^3	K_{La}^1	0	$1/d$
y_{10}	4300	gSS/m^3	K_{La}^2	37.65	$1/d$
y_{15}	1	gN/m^3	w	0.012	–

It is worth noticing that in this work, online sensors involved in the feedback loops are supposedly to be ideal sensors.

Table 5. Effect of disturbances on optimal values for the candidate CVs.

	Symbol	Units	BSM1	Nominal	d_1	d_2	d_3	d_4
y_1	S_O^3	gO_2/m^3	1.72	1.50	1.50	1.50	1.50	1.50
y_2	S_{NO}^3	gO_2/m^3	6.54	4.92	4.62	4.85	3.63	4.21
y_3	S_{NH}^3	gO_2/m^3	5.55	10.63	10.31	10.57	8.50	9.74
y_4	S_O^4	gO_2/m^3	2.43	1.50	1.50	1.50	1.50	1.50
y_5	S_{NO}^4	gO_2/m^3	9.30	8.69	8.15	8.62	6.22	7.44
y_6	S_{NH}^4	gO_2/m^3	2.97	7.08	6.93	7.05	6.06	6.72
y_7	S_O^5	gO_2/m^3	0.49	1.50	1.50	1.50	1.50	1.50
y_8	S_{NO}^5	gO_2/m^3	10.42	12.17	11.43	12.13	8.68	10.51
y_9	S_{NH}^5	gN/m^3	1.73	4.00	4.00	4.00	4.00	4.00
y_{10}	$MLSS$	gSS/m^3	3277.14	2544.02	2539.20	2441.95	2595.80	1279.41
y_{11}	S_O^1	gO_2/m^3	0.00	0.01	0.03	0.01	0.04	0.19
y_{12}	S_{NO}^1	gN/m^3	5.37	2.35	2.58	1.65	0.96	2.42
y_{13}	S_{NH}^1	gO_2/m^3	7.92	14.58	13.73	15.04	12.51	13.23
y_{14}	S_O^2	gO_2/m^3	0.00	0.07	0.04	0.12	0.26	0.10
y_{15}	S_{NO}^2	gN/m^3	3.66	1.08	1.00	1.00	1.01	1.00
y_{16}	S_{NH}^2	gO_2/m^3	8.34	14.61	14.08	14.58	11.44	13.13
y_{17}	S_{NH}^{eff}	gN/m^3	1.73	4.00	4.00	4.00	4.00	4.00
y_{18}	COD^{eff}	$gCOD/m^3$	47.55	45.52	44.87	45.13	44.79	41.80
y_{19}	TSS^{eff}	gSS/m^3	12.50	11.01	12.19	11.35	12.05	9.66
y_{20}	S_{NO}^w	gN/m^3	10.42	12.17	11.43	12.13	8.68	10.51
y_{21}	TSS^w	gSS/m^3	6393.98	12029.97	8515.68	10706.28	11690.07	12362.37
y_{22}	SRT	d	9.17	11.86	8.11	9.32	11.47	7.00
y_{23}	Q_r	m^3/d	18446.00	4617.34	8525.65	5454.63	5586.47	2105.41
y_{24}	Q_w	m^3/d	385.00	221.11	304.50	244.29	233.93	227.70
y_{25}	Q_a	m^3/d	55338.00	26951.08	23203.51	22081.37	20314.90	14384.18
y_{26}	K_{La}^1	$1/d$	0.00	0.00	20.02	0.00	20.00	76.73
y_{27}	K_{La}^2	$1/d$	0.00	37.65	24.44	56.81	64.30	36.58
y_{28}	K_{La}^3	$1/d$	240.00	180.37	182.16	173.52	111.30	120.86
y_{29}	K_{La}^4	$1/d$	240.00	155.62	156.95	149.32	93.75	101.32
y_{30}	K_{La}^5	$1/d$	84.00	138.26	139.83	132.32	83.11	89.17

5. TEST MOTION

In order to validate the proposed optimized configuration, dynamic simulations have been performed with different input conditions. For sake of conciseness only the results for the temporal evolution with two sets of inputs are reported here: steps based on the disturbances in Table 2 and dynamic inputs based on the benchmark dry weather data-files (in the following Figures only the last week of simulation is reported for the latter conditions).

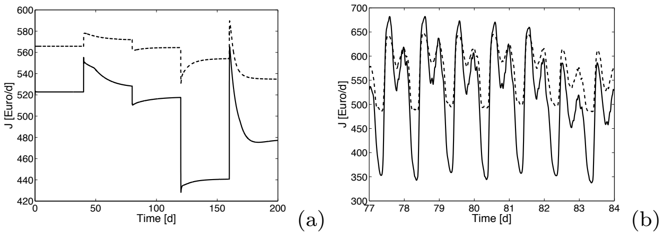

Fig. 3. Total cost function for the optimized (solid-line) and original (dashed-line) BSM1 with step (a) and dry-weather (b) inputs.

The analysis of the total energy consumption, J, for two different input sets (Figure 3) allows to appreciate the potentialities of the proposed control structure. Step inputs (Figure 3a) and dry-weather (Figure 3b) dynamic simulation of the cost behavior demonstrate clearly, how the optimized BSM1(solid-line) is able to reduce the overall costs in the plants with respect to the default BSM1 (dashed-line) configuration.

In Figure 4 and Figure 5, dynamic behavior for the optimized BSM1 (solid-line) is compared with the default BSM1 (dashed-line) for the principal effluent compositions. Results show how effluent violation is avoided; especially ammonia constraint at the effluent is met in a more rigorous manner.

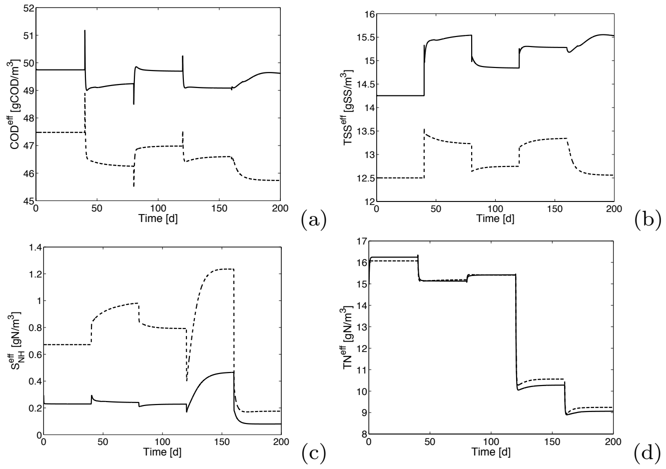

Fig. 4. Concentrations for COD (a), TSS (b), Ammonia (c) and TN (d) at the effluent for the optimized (solid-line) and original (dashed-line) BSM1 with step-inputs.

6. CONCLUSION

In this work we implemented and discussed a systematic procedure for defining an optimized control structure for an activated sludge process in a biological wastewater

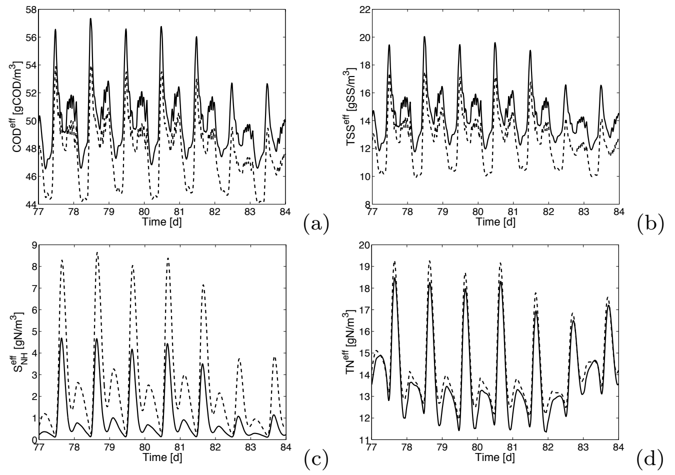

Fig. 5. Concentrations for COD (a), TSS (b), Ammonia (c) and TN (d) at the effluent for the optimized (solid-line) and original (dashed-line) BSM1 with dynamic dry-weather inputs.

plant. In particular, the proposed procedure was applied to the COST/IWA benchmark simulation model No. 1, a fully defined protocol for testing different control strategies on ASPs. Based on the self-optimizing approach starting from the degree of freedom analysis, the optimization of the operational cost function allowed the definition of an optimal set of controlled variables and their optimal setpoints. With this decentralized control approach, the benefits brought by the optimized controller structure to the overall cost improved the effluent quality, while reducing systematically the operating costs. Furthermore, the proposed approach provided a successfully answer to the sensors location for applying simple feedback loops in ASPs.

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