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CONTROLLED VARIABLES SELECTION FOR A BIOLOGICAL WASTEWATER TREATMENT PROCESS

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Abstract: This paper considers control structure selection for a biological wastewater treatment process, with emphasis on identifying controlled variables that contribute to minimize economic costs. This is achieved according to the self-optimizing procedure proposed by Skogestad (2000). The aim is to demonstrate how, with simple considerations on the control structure design, the efficiency of a wastewater treatment plant can be improved, minimizing operational costs in the plant, while keeping it running optimally and satisfying the effluent requirements.

Keywords: Self-optimizing control, Cost function, Activated sludge

1. INTRODUCTION

In the last decades, environmental water protection has gained an increasing public awareness, which is also reflected in more strict effluent concentration requirements and regulations. This has, in turn, considerably increased the necessity of efficient and reliable Waste Water Treatment Plants (WWTPs) that have to face an important challenge arising from both regulation fulfillment and cost aspect of plant operation. These regulations hence give rise to both technical and economical problems 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, since inside a biological WWTP, the Activated Sludge Process (ASP) is the most common used technology to remove organic pollutant from wastewater, we focus our attention on this process.
In the literature, ASP optimization has been studied by several authors in different ways. For instance, Chachuat *et al.* (2001) investigate the optimal sequence of aeration and non-aeration time for a small ASP and Samuelsson *et al.* (2005) studied the impact of different nitrate cost functions on the location of the cost optima. Gillot *et al.* (1999) defined an objective cost function in order to standardize the cost calculation procedure integrating both investment, fixed and variable operating costs. Vanrolleghem and Gillot (2002) proposed an economic index including weighted investment and operating costs used to evaluate the transferability of control strategies to different situations. A methodology to estimate costs and benefits of online control for WWTP is developed by Devisscher *et al.* (2006).

In this work, it is shown how optimal operation can be achieved in practice by designing the control structure appropriately. In other words

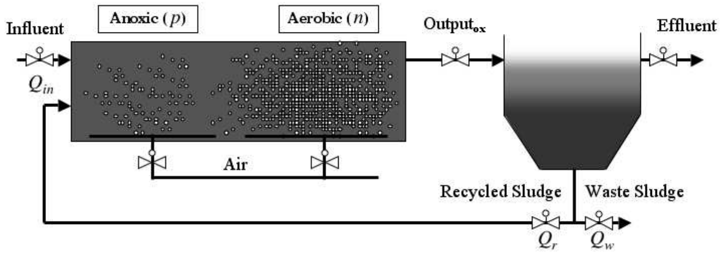

Fig. 1. Schematic representation of an activated sludge plant, with spotlight on manipulable variables.

Influent Flow rate	Q_{in}	=	6152	$[m^3/d]$
Influent Chemical Oxygen Demand	COD^{in}	=	221	$[gCOD/m^3]$
Influent Total Suspended Solids	TSS^{in}	=	46	$[gSS/m^3]$
Influent Nitrate	S_{NO}^{in}	=	0.22	$[gN/m^3]$
Influent Total Kjeldhal Nitrogen	TKN^{in}	=	22	$[gN/m^3]$
Influent Ammonia/TKN ratio	f_{NH}^{in}	=	0.36	−

Table 1. Influent nominal conditions for the considered plant.

the constrained optimization problem is translated into the proper operation in the ASP process. Controlled variables are the important link between layers in the hierarchic control structure and there are many issue involved. First, we should control the active constraints (which are optimal from an economic point of view in terms of minimizing the cost). Second, we need to find controlled variables associated with the unconstrained degrees of freedom. This is the issue of self-optimizing control. We are looking for the controlled variables for the ASP which when kept constant, indirectly achieve optimal operation in spite of disturbances. In order to trade them off against each other in a systematic manner we follow the control structure design proposed in (Skogestad, 2000).

2. ACTIVATED SLUDGE PROCESS

We consider the ASP in the TecnoCasic WWTP located in Cagliari (Italy), reported in (Mulas, 2006), and schematically represented in Figure 1. Here, the bioreactor consists of an anoxic (predenitrification, p in the following) followed by an aerobic (nitrification, n in the following) zone. To maintain the microbiological population, the sludge from the settler is recirculated into the anoxic basin, while the sludge concentration is kept constant by means of sludge withdrawn from the settler.

The ASP layout has the following characteristic features:

- Biological treatment reactor (2000 m^3), with an anoxic zone followed by an aerobic zone. The aeration is obtained with fine pore air diffusers located at the bioreactor bottom. A Dissolved Oxygen (DO) controller maintains the oxygen concentration at 0.09 gO_2/m^3, in the anoxic zone and at 4 gO_2/m^3, in the aerobic one.
- Non-reactive secondary settler with a surface of 707 m^2 and 4 m depth.
- Recycled flow, Q_r, from the secondary settler to the front end of the plant at a constant flow rate of 7000 m^3/d.
- Waste flow, Q_w, intermittently pumped from the secondary settler underflow .

Furthermore, the average influent conditions for the considered plant are reported in Table 1.

The bioreactor is represented by means of the Activated Sludge Model No. 1 (Henze *et al.*, 1987), while the secondary settler representation is obtained with the Takàcs model (Takacs *et al.*, 1991); these models are coupled together in a Matlab/Simulink (R14) environment. Furthermore, in order to take into account the not ideal fluodynamic in the ASP, the biological reactor is formed with six different zones: three anoxic which represent 1/3 of the total volume and three aerated zones, corresponding to the remaining volume.

3. OPERATIONAL OBJECTIVES

In order to run a WWTP economically, costs such as pumping energy and aeration energy should be minimized; nevertheless, the discharge concentrations to recipients should be kept at acceptable level. Hence, the operational objectives includes not only the cost function to be minimized but also the constraints at which it is subjected and the disturbances that may occur in the plant.

3.1 Cost Function

Economically speaking, the overall cost in a wastewater treatment plant is highly dependent on the wastewater system itself and it can be divided into manpower, energy, maintenance, chemical sludge treatment and disposal evaluated on a time basis. Therefore, an inventory has to be made of the different costs so that individual importance of each term is determined. In this work, the following partial costs are considered:

- Pumping costs due to the required pumping energy (E_P expressed in kWh/d);
- Pumping costs due to the required aeration energy (E_A expressed in kWh/d);
- Sludge disposal costs (C_D expressed in €$/d$).

In order, to express the partial costs we adopt the expression proposed in the COST Benchmark (Copp, 2000). Assuming a constant energy price $k_E = 0.09$ €$/kWh$ and a sludge disposal price $k_D = 80$ €$/tonn$, the total cost, J in €$/day$, during a representing time interval T can be calculated as:

$$\begin{aligned} J &= k_E(E_P + E_A) + C_D \\ &= \frac{1}{T}(\int_{t_0}^{t_0+T} (k_E(0.04(Q_r(t) + Q_w(t)) \\ &+ 24\sum_{i=1}^{n}(0.4032k_{la,i}^2(t) + 7.8408k_{la,i}(t))) \\ &+ k_D TSS_w(t)Q_w(t))dt) \end{aligned} \quad (1)$$

where, the first term within the integral represents E_P, the second E_A (with k_{la} expressed in h^{-1} for each reactor zone i) and the third is C_D.

3.2 Constraints

The cost in Equation 1 should be minized subject to some constraints related to process operability and regulation restriction for the effluent, see Table 2.

Operational Constraints					
0.05	$\leq$	DO^p	$\leq$	0.5	$[gO_2/m^3]$
1.5	$\leq$	DO^n	$\leq$	4	$[gO_2/m^3]$
0.05	$\leq$	F/M	$\leq$	1	$[gCOD/gSS/d]$
0.75	$\leq$	$S_{NO}^{p,3}$	$\leq$	1	$[gN/m^3]$
Effluent Constraints					
		COD^{eff}	$\leq$	125	$[gCOD/m^3]$
		TSS^{eff}	$\leq$	35	$[gSS/m^3]$
		TN^{eff}	$\leq$	18	$[gSS/m^3]$
		S_{NH}^{eff}	$\leq$	0.6	$[gN/m^3]$
		S_{NO}^{eff}	$\leq$	10	$[gN/m^3]$

Table 2. Constraints.

In terms of *operational constraints* we can identify the DO concentration in both aerobic and anoxic zones. In the aerobic zone, DO concentration should be sufficient for the microorganisms involved in nitrification reactions. It is a good practice to maintain the DO level between 1.5 and 4 gO_2/m^3, as a further increase does not improve operation, but increases aeration costs considerably. On the other hand, in the anoxic zone a lower aeration is needed in order to satisfy only the mixing requirements.

Furthermore, we know that the nitrate consumption in the last predenitrification zone ($S_{NO}^{p,3}$) should be between 1 and 3 gN/m^3 when internal recirculation is present (Olsson *et al.*, 2005), which is not the case in the considered plant. We verified that $S_{NO}^{p,3}$ between 0.75 and 1 gN/m^3 can assure a good behavior in the anoxic zone. This awards to not excessive air consumption in the aeration zones.

In addition, the constraints related to the optimal operation of the secondary settler have to be considered. It is also important to prevent the loss of sludge solids in the effluent in order to guarantee the required degree of treatment. Hence, we consider an index that is able to represent the sludge behavior such as the Food to Microorganisms ratio (F/M). According to the literature (Meltcalf and Eddy, 1991), it must not exceed certain level as summarized in Table 2.

3.3 Disturbances

One of the major reasons for control is the presence of disturbances, and compared to most other process industries a wastewater treatment plant is subject to very large disturbances. In order to give a representation of the system behavior when disturbances occur, the nominal average circumstances are augmented by 20% (Table 3).

Constant Q_{in}		Variable Q_{in}	
d_1:	COD^{in} + 20%	d_4:	$\left.\begin{matrix} Q_{in} \\ COD^{in} \end{matrix}\right\}$ +20%
d_2:	TKN^{in} + 20%	d_5:	$\left.\begin{matrix} Q_{in} \\ TKN^{in} \end{matrix}\right\}$ +20%
d_3:	$\left.\begin{matrix} TKN^{in} \\ COD^{in} \end{matrix}\right\}$ +20%	d_6:	$\left.\begin{matrix} Q_{in} \\ COD^{in} \\ TKN^{in} \end{matrix}\right\}$ +20%

Table 3. Disturbances.

Two different situations are considered. The case with constant influent flow rate Q_{in} (d_1, d_2, d_3), from a practical point of view, it may happen if there is a large equalization basin before the ASP. For disturbances d_4, d_5 and d_6 also a 20% change in Q_{in} is included.

4. MANIPULATED VARIABLES AND DEGREES OF FREEDOM

In order to define the number of Degrees Of Freedom (DOF) for optimization, N_{opt}, we must identify the number of degrees of freedom for control,

N_m. If we look at the schematic representation of that plant in Figure 1, we note that there are only few variables that we can manipulate; this is quite common in a biological wastewater treatment plant, (Olsson and Newell, 2002). However, there is potential to make a better use of the existing manipulated variables.

From Figure 1, we observe that there are 7 valves, but we identify only 4 degrees of freedom for control because the levels in the aeration tank and in the secondary settler need to be controlled at constant values (they are actually self-regulating) and because the influent flow rate is a disturbance and not a manipulated variable. It should be noted that inventory of sludge in the secondary settler should be controlled, but since the inventory has a steady-state effect, this does not affect the number of degrees of freedom. We assume that the DO concentration in both anoxic and aerobic zones are constant at the setpoint values by the airflow controllers meaning that we have two remaining degrees of freedom. In the following two different cases are examined:

- CASE1: we assume that: 1) there is not disturbance in the influent flow rate Q_{in} and 2) Q_r is constant. There is then one controlled variable left to select.
- CASE2: we here want to select two controlled variables. An objective is to check if fixing Q_r/Q_{in} is
  a good policy, which is the is common practice in most wastewater treatment plant, in the case where also disturbances in Q_{in} are considered. In this case, there are two remaining DOF.

5. OPTIMIZATION PROCEDURE AND CANDIDATE CONTROLLED VARIABLES

As the beginning of the optimization procedure, we examine the existing operating conditions for the considered plant and we notice that aeration is responsible for 99% of the total cost. Therefore, the first attention focuses on the pumping cost for the aeration and on the DO controller present in the WWTP. A preliminary optimization was carried out to find the setpoint values for the DO concentration in both controlled anoxic and aerobic zones. The results are reported as "improved" in Table 4 and we can observe a remarkable cost reduction with respect to the existing initial condition.

Now, we can go a step further in the self-optimizing procedure and propose the candidate controlled variables. According to Skogestad (2000), these should be easy to measure and control, but sensitive to changes in the manipulated variables and their optimal value should be insensitive to disturbances. The following candidates are suggested:

- Sludge Retention Time, SRT [d];
- Food to Microorganisms ratio, F/M [$gCOD/gSS/d$];
- Effluent ammonia, $S_{NH}^{eff}[gN/m^3]$;
- Mixed Liquor Suspended Solids, MLSS [gSS/m^3];
- Nitrate in the last anoxic zone, $S_{NO}^{p,3}[gN/m^3]$.

The used setpoint values for these variables (Table 5) are the average of various operation points.

		Initial	Improved (Nominal)
$DO^{p,sp}$	$[gO_2/m^3]$	0.09	0.22
$DO^{n,sp}$	$[gO_2/m^3]$	4	2.5
Q_r/Q_{in}	$[-]$	1.14	1.49
Q_w	$[m^3/d]$	60	77
Cost	[€/d]	2200	1466

Table 4. Steady-state operation before and after the preliminary optimization.

SRT^{sp}	F/M^{sp}	$S_{NH}^{eff,sp}$	MLSS^{sp}	$S_{NO}^{p3,sp}$
9.77	0.74	0.17	1482	0.78

Table 5. Setpoint values used for the candidate controlled variables.

With regard to CASE1, we optimize the system with respect only to one possible manipulated variable, Q_w, with constant values Q_r/Q_{in} fixed at its optimum value found with the optimization procedure. Using oxygen concentration values at constant setpoints, as reported in Table 4, it allows us to investigate the steady state process behavior at nominal conditions and different Q_w.

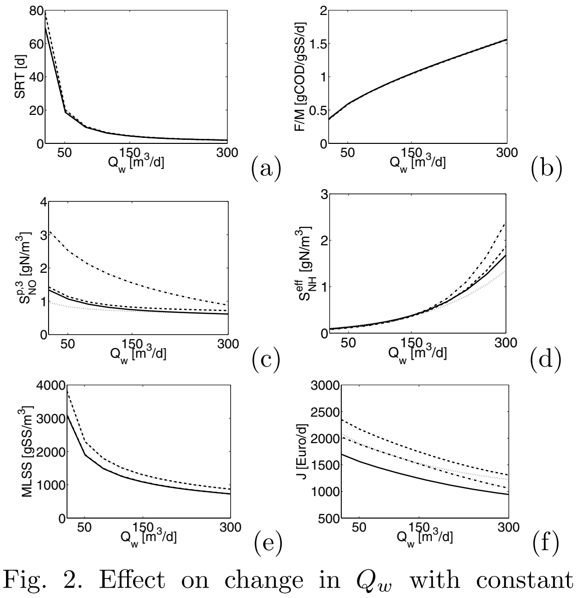

Fig. 2. Effect on change in Q_w with constant Q_r/Q_{in}, $DO^{p,sp}$ and $DO^{n,sp}$ [Nominal condition (solid); d_1 (dot); d_2 (dot-dashed); d_3 (dashed)].

In Figure 2, the operating variables behavior at different Q_w is shown with fixed Q_r/Q_{in}, $DO^{p,sp}$ and $DO^{n,sp}$ (with values from Table 4). In this way, we can define an operating region for this particular situation. In fact, we note that the operative constraints are respected for Q_w ranging between 60 and 100 m^3/d and that in this region we expect costs of 1400-2000 €$/d$ (Figure 2f).

In CASE2, we optimize with respect to two manipulated variables: Q_w and the ratio Q_r/Q_{in} with fixed $DO^{p,sp}$ and $DO^{n,sp}$ as reported in Table 4. We investigate the process behavior using the operating space diagrams, which are contour plots of an output variable against the manipulated variables as reported in Figure 3. We note that the constraints are satisfied only for $40 < Q_w < 100$ m^3/d and for a Q_r/Q_{in} ratio ranging from 0.5 and 1.5. The total cost is not actually dependent on variations in the recycle ratio Q_r/Q_{in} whereas it decreases as the wastage flow rate increases (Figure 3f).

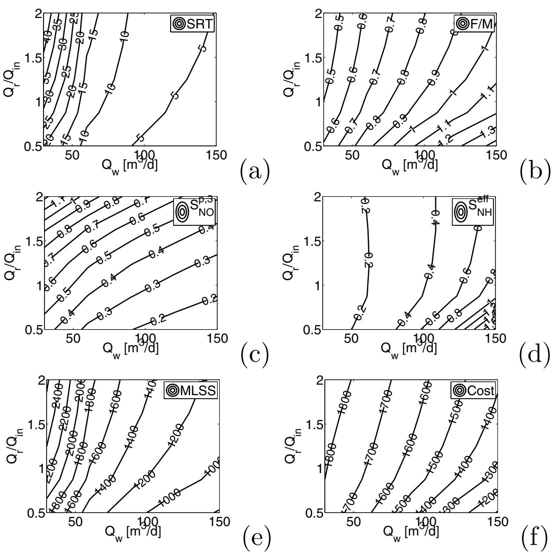

Fig. 3. Effect on change on Q_w and Q_r/Q_{in} with constant $DO^{p,sp}$ and $DO^{n,sp}$.

	Configuration	$\underline{\sigma}$
c_1	$(Q_r/Q_{in})^{const}$-SRT	**6.50**
c_2	$(Q_r/Q_{in})^{const}$-F/M	1.004
c_3	$(Q_r/Q_{in})^{const}$-S_{NH}^{eff}	1.338
c_4	$(Q_r/Q_{in})^{const}$-MLSS	**32.20**
c_5	SRT-F/M	0.13
c_6	SRT-S_{NH}^{eff}	1.00
c_7	SRT-MLSS	0.83
c_8	SRT-$S_{NO}^{p,3}$	**1.49**
c_9	F/M-S_{NH}^{eff}	0.76
c_{10}	F/M-MLSS	0.00
c_{11}	F/M-$S_{NO}^{p,3}$	0.86
c_{12}	S_{NH}^{eff}-MLSS	1.14
c_{13}	S_{NH}^{eff}-$S_{NO}^{p,3}$	1.02
c_{14}	MLSS-$S_{NO}^{p,3}$	**1.41**

Table 6. Minimum singular value for the proposed configurations.

In Table 6, all considered control configurations are reported with the associated minimum singular value. The controlled variable sets corresponding to the larger minimum singular value ($\underline{\sigma}$) are preferred. From these, we remark that the configurations from c_5 to c_{14} take into account Q_r/Q_{in} and Q_w as inputs which means that two controller loops are involved. Configurations from c_1 to c_4 consider the recycle ratio fixed at the optimum, assuming this is a good self-optimizing variable, and the SRT, F/M, S_{NH}^{eff} and MLSS controlled by Q_w. We note that the best configurations with a large minimum singular value are c_1 and c_4 which are made fixing Q_r/Q_{in}. We then expect that those configurations are the best also in an economic point of view, but for sake of completeness, we investigate also c_8 and c_{14}. In this case, the acceptable loop pairing leads to the following control configurations:

- control SRT (or MLSS) by manipulating Q_w;
- control the nitrate concentration in the last anoxic zone, $S_{NO}^{p,3}$, by manipulating the ratio Q_r/Q_{in}.

We note that the candidate controlled variables involve SRT and MLSS. We know that keeping the SRT a constant setpoint value implies to hold the nitrification capacity of the sludge (measure of the maximum nitrification rate) at a constant level, and especially when the flow rate and load are not constant this should be allowed to develop in the system as a result of an increase influent (Olsson *et al.*, 2005). Also for this reason, we expect that the configurations regarding mixed liquor suspended solid measurements will be preferable.

Having defined the canditate controlled configurations, we investigate the different situations in order to select the one that contribute to minimize the cost in the plant.

6. CONTROLLED VARIABLES SELECTION

We here consider in detail the actual cost for the considered configurations. From Table 7, it is clear that for disturbances d_1, d_2, and d_3 the cost is considerably reduced and it is possible to obtain further saving if a MLSS controller is implemented in the ASP.

Also when the influent flow rate is not constant (d_4, d_5, and d_6), the best way to operate is to fix the ratio Q_r/Q_{in} and control the MLSS concentrations by means of the waste flow rate Q_w. It follows that the recycled sludge pump will change Q_r on the basis of influent flow rate measurements, assuring an appropriate amount of biomass in the system.

In both situations, with and without flow rate disturbances the adjustment of waste activated

Configuration			Cost [€/d]			
			Nominal	d_1	d_2	d_3
CASE1	c_1	Q_r/Q_{in} -SRT	1440	1739	1752	1993
	c_2	Q_r/Q_{in} -F/M	1460	1775	1773	2032
	c_3	Q_r/Q_{in} -S_{NH}^{eff}	1479	1832	1759	2038
	c_4	Q_r/Q_{in} -MLSS	**1446**	**1632**	**1752**	**1869**
	(Q_r/Q_{in} Q_w): Open Loop		1466	1777	1783	2046
				d_4	d_5	d_6
CASE2	c_1	Q_r/Q_{in} - SRT	1440	2390	2442	2779
	c_4	Q_r/Q_{in} - MLSS	**1446**	**2056**	**2269**	**2344**
	c_8	SRT - $S_{NO}^{p,3}$	1481	2470	2440	2805
	c_{14}	MLSS - $S_{NO}^{p,3}$	1490	2045	2257	2552
	(Q_r/Q_{in} Q_w): Open loop		1466	2436	2458	2823

Table 7. Cost investigation for the considered configurations.

sludge flow is based on MLSS measurements and on the ratio between the recycled sludge and the influent flow rate, proving that even if the Q_w is usually a small fraction of the influent flow, a careful control may have a significant effect on the performance of an activated sludge system.

Eventually, the open loop behavior is also reported; this is a poor policy to adopt, but it is frequently used and is a good reference to understand how the system can be improved by applying controller.

7. CONCLUSION

In this paper, the control design of an ASP in a biological wastewater treatment plant is studied from a process economic point of view. The self-optimizing procedure gives a clear chance to obtain a cost-efficiently controlled process, respecting the effluent requirements as well as the operative conditions. Two different plant situations have been studied. In one case the influent flow rate is considered constant whereas the same flow rate is varing in the second case. In both situation, the best configuration (Q_r/Q_{in} - MLSS) involves the mixed liquor suspended solids controlled by the waste flow and keeping the recycle ratio fixed.

REFERENCES

Chachuat, B., N. Roche and M. A. Latifi (2001). Dynamic optimization of small size wastewater treatment plants including nitrification and denitrification processes. *Comput. Chem. Eng.* **25**(4/5), 585–593.

Copp, J. B. (2000). COST action 624 - the COST simulation benchmark: Description and simulator manual. Technical report. European Community.

Devisscher, M., G. Ciacci, L. Fé, L. Benedetti, D. Bixio, G. De Gueldre, S. Marsili-Libelli and P. A. Vanrolleghem (2006). Estimating costs and benefits of advanced control for wastewater treatment plant - the MAgIC methodology. *Water Sci. Technol.* **53**(4-5), 215–223.

Gillot, S., D. De Clercq, D. Defour, F. Simoens, K. Gernaey and P. Vanrolleghem (1999). Optimization of a wastewater treatment plant design and operation using simulation and cost analysis. In: *Proceeding of 72nd annual WEF Conference and Exposition.* New Orleans, USA.

Henze, M., C. P. Leslie Grady, W. Gujer, G. V. R. Maris and T. Matsuo (1987). Activated Sludge Process Model No. 1. Scientific and Technical Report 1. IAWQ. London, UK.

Meltcalf and Eddy (1991). *Wastewater Engineering: treatment, disposal and reuse.* McGraw Hill.

Mulas, M. (2006). Modelling and control of activated sludge processes. PhD thesis. Università di Cagliari, Italy.

Olsson, G. and B. Newell (2002). *Wastewater treatment systems - Modelling, diagnosis and control.* IWA Publishing.

Olsson, G., M. K. Nielsen, Z. Yuan, A. Lyngaard-Jensen and J. P. Steyer (2005). Instrumentation, control and automation in wastewater systems. Technical Report 15. IWA Publishing.

Samuelsson, P., B. Halvarsson and B. Carlsson (2005). Cost-efficiency operation of a denitrifying activated sludge - an initial study. Technical report. Div. of System and Control, Dep. of Information Technology. Uppsala University, Sweden.

Skogestad, S. (2000). Plantwide control: the search for the self-optimizing control structure. *J. Process Contr.* **10**, 487–507.

Takacs, I., G. G. Patry and D. Nolasco (1991). A dynamic model of the clarification-thickening process. *Water Res.* **25**(10), 1263–1271.

Vanrolleghem, P. and S. Gillot (2002). Robustness and economic measure as control benchmark performance criteria. *Water Sci. Technol.* **45**(4-5), 117–126.