BENCHMARKING TWO BIOMASS LOADING CONTROL STRATEGIES FOR ACTIVATED SLUDGE WWTPs

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ABSTRACT

The "simulation benchmark" proposed by Spanjers et al. (1997) is a standardised procedure for the objective evaluation of control strategies for the activated sludge process. This paper describes the application of the benchmark on two biomass loading control strategies proposed in literature. During implementation, several assumptions about the original proposal had to be made. However, the underlying philosophy of each strategy was retained. Once implemented, tuning of the controllers could not be done by means of the conventional techniques and manual tuning proved necessary. The performance of the strategies was assessed on two levels: effluent constraint violation and operational costs. The benchmark has proven to be very useful when evaluating control strategies by giving objective and comparable information.

KEYWORDS

Activated sludge, control, economy, performance evaluation, respirometry, simulation benchmark.

INTRODUCTION

Carefully conducted model-based simulation studies are important when evaluating control strategies for WWTPs. Spanjers *et al.* (1997) emphasised the need for standardisation of the test procedure by introducing the concept *simulation benchmark*. This methodology for testing activated sludge process control strategies was further developed by both the Task Group on Respirometry of the International Association on Water Quality (IAWQ) and the European COST actions 682 and 624. The benchmark is a platform-independent simulation procedure defined around a simulation model, a plant layout, realistic influent loads and a test protocol that provides an objective measure of performance. An economical analysis is done using a cost function that quantifies aeration energy, pumping energy, sludge disposal and levies on effluent discharges.

In this paper, the benchmark is applied to two respirometry-based control strategies proposed in literature. Both strategies regulate biomass loading (kg COD/kg MLSS.d) by means of sludge storage.

Flanagan (1977) proposed a cascade feedback(FB)/feedforward(FF) control strategy that provides storage in a separate tank in the return activated sludge (RAS) transportation system. The FF controller uses two flow and two respiration rate measurements to calculate the RAS flow rate that results in the desired F/M (Food-to-Micro-organisms) set point. Corrective feedback for this FF control is derived from a third respiration rate measurement: the respiration rate at the outlet end of the oxidation tank is compared with the (estimated) endogenous respiration rate. The FB loop adjusts the F/M set point of the FF controller proportionally to the difference between both respiration rates. Process stability is obtained by manipulating the waste activated sludge (WAS) pumps in order to maintain a pre-set RAS storage tank volume.

Sludge storage in the strategy proposed by Sørensen (1980) is obtained through step feed control. A dissolved oxygen (DO) controller adjusts the rotational speed of the blower so as to maintain a constant DO-concentration. The rpm of the blower, which is a function of the respiration rate, is subsequently used as a signal to adjust the influent flow distribution. The underlying philosophy is to obtain a constant respiration rate in the last aeration tank.
Both strategies were implemented in the WEST simulator (Hemmis nv, Kortrijk, Belgium) and their performance was assessed by means of the benchmark protocol. The main purpose of the study was to detect possible problems when executing the procedure, rather than to evaluate a large number of strategies.

METHODOLOGY

Simulation model and plant layout

The industry-standard Activated Sludge Model (ASM) No.1 (Henze *et al.*, 1987) was chosen to describe the dynamics of the activated sludge processes. The settler's behaviour was simulated with the double-exponential settling velocity function in a 10-layer settler model (Takács *et al.*, 1991). Influent data were deduced from realistic plant loadings. Three scenarios of 14 days each were used: dry, storm and rain weather. The complete set of equations, parameter values and influent files are available on the COST 624 website (http://www.ensic.u-nancy.fr/COSTWWTP).
For both strategies the C-removal configuration of the benchmark plant was selected. That plant consists of five completely mixed aeration tanks in series (600 m^3 each) and a secondary clarifier. For the RAS-storage strategy the underflow from the settler to the storage tank was set to 9223 $m^3.d^{-1}$ (50% of the average influent flow rate) and sludge wastage at 385 $m^3.d^{-1}$. In the step feed plant return sludge pumping was controlled proportionally (100%) to the incoming flow in order to avoid sludge storage in the settler. Wastage had to be increased to 580 $m^3.d^{-1}$ to prevent nitrification activity in the controlled system.

Implementation of the control strategy

The implementation of each control strategy involves five steps: (1) identification of the objectives of the control strategy, (2) identification of the measured, controlled and manipulated variables, (3) identification of the control configuration, (4) identification of the control algorithm and (5) tuning of the controller. For the tuning of the controller criteria such as IAE (integral of the absolute error), ISE (integral of the square error), maximum deviation from the setpoint and error standard deviation were used.

Evaluation of the performance

Both respirometry-based control strategies were implemented in the WEST simulation platform. After initialising the model with steady-state values, dynamic simulations with all three weather files were run. The performance assessment was done using the output data generated at intervals of 0.1 d during simulations with the different weather files. The whole period of 14 d for each weather file was used. Two sets of criteria were considered in the plant performance assessment: effluent constraint violation and operational costs.
Constraints with respect to the effluent quality were defined as follows (Alex, 1999). The flow-weighted average effluent concentrations over the three testing periods had to meet the following standards: COD_e < 100 $g.m^{-3}$, $BOD_{5,e}$ < 10 $g.m^{-3}$, suspended solids SS_e < 30 $g.m^{-3}$, ammonia $S_{NH,e}$ < 4 g $N.m^{-3}$ and total nitrogen $N_{tot,e}$ < 18 g $N.m^{-3}$. The latter two were not considered in the presented control strategy evaluations for no nitrogen removal was pursued. The percentage of time the constraints were violated was reported, as well as the number of violations. The limiting variables were calculated according to the following expressions (using the ASM No.1 nomenclature):

$$\begin{cases} COD_e = S_{S,e} + S_{I,e} + X_{S,e} + X_{B,H,e} + X_{B,A,e} + X_{P,e} + X_{I,e} \\ BOD_{5,e} = 0.25 \cdot \left[S_{S,e} + X_{S,e} + (1 - f_p) \cdot (X_{B,H,e} + X_{B,A,e}) \right] \\ SS_e = 0.75 \cdot (X_{S,e} + X_{B,H,e} + X_{B,A,e} + X_{P,e} + X_{I,e}) \\ S_{NKj,e} = S_{NH,e} + S_{ND,e} + X_{ND,e} + i_{XB} (X_{B,H,e} + X_{B,A,e}) + i_{XP} (X_{P,e} + X_{I,e}) \\ N_{tot,e} = S_{NKj,e} + S_{NO,e} \end{cases}$$

Operational costs were quantified by calculating four indexes:

- The effluent quality (EQ) is expressed as the levies that are to be paid for discharging to a receiving water body. It is calculated as an average over the period of observation T (14 d for each weather file) and is expressed in pollution units (PU):

  $$EQ = N_{organic} + N_{nutrients}$$

  where $N_{organic}$ is the effluent load of oxygen demanding organics and suspended solids:

  $$N_{organic} = \frac{1}{T} \int_{t=t_0}^{t=T} \left[\frac{1000 \cdot Q_e(t)}{180} \left(\frac{0.35 \cdot SS_e(t)}{500} + 0.45 \frac{2 \cdot BOD_{5,e}(t) + COD_e(t)}{1350} \right) (0.4 + 0.6d) \right] \mathrm{d}t$$

  $Q_e(t)$ is the effluent flow rate ($m^3.d^{-1}$) and d the yearly number of days on which discharge is taking place divided by 225 (with $d \le 1$).
  $N_{nutrients}$ represents the effluent load of nutrients:

  $$N_{nutrients} = \frac{365}{T} \int_{t=t_0}^{t=T} \left[Q_e(t) \frac{N_{tot,e}(t) + P_{tot,e}(t)}{10000} \right] \mathrm{d}t$$

  with $P_{tot,e} = 0$ g $P.m^{-3}$ because phosphorus is not considered in the benchmark.

- Pumping energy (PE) is calculated in $kWh.d^{-1}$ (Alex *et al.*, 1999):

  $$PE = \frac{0,04}{T} \int_{t=t_0}^{t=T} (Q_a(t) + Q_{ras}(t) + Q_{was}(t)) \mathrm{d}t$$

  where Q_a the internal sludge recycle, Q_{ras} the return activated sludge flow and Q_{was} the wastage flow rate, all expressed in $m^3.d^{-1}$.

- Aeration energy (AE) is calculated using the following expression for a tank volume of 600 m^3 and an immersion depth of the diffusors of 4 m (Jacquet, 1999):

  $$AE = \frac{24}{T} \int_{t=t_0}^{T} \sum_{i=1}^{5} \left(0.0003 \cdot (K_L a)_i^2 + 0.1479 \cdot (K_L a)_i - 1.4731 \right)$$

  where $K_L a$ is expressed in d^{-1}.

- Sludge production (PS_{disp} and PS_{total}) is expressed in $kg.d^{-1}$ and is calculated from the total solid flow from wastage and the solids accumulated in the system over the period considered:

$$PS_{disp} = \frac{1}{T}\left\{\int_{t=t_0}^{t=T} \frac{0.75}{1000}\left(X_{S,was} + X_{I,was} + X_{P,was} + X_{B,H,was} + X_{B,A,was}\right)\cdot Q_{was}(t)\,\mathrm{d}t + TSS(T) - TSS(t_0)\right\}$$

and

$$TSS(t) = TSS_a(t) + TSS_s(t)$$

where

$$TSS_a(t) = \frac{0.75}{1000}\left(\sum_{i=1}^{5}\left(X_{S,i} + X_{I,i} + X_{P,i} + X_{B,H,i} + X_{B,A,i}\right)\cdot V_i\right)$$

$$TSS_s(t) = \frac{0.75}{1000}\left(\sum_{j=1}^{10}\left(X_{S,j} + X_{I,j} + X_{P,j} + X_{B,H,j} + X_{B,A,j}\right)\cdot z_j \cdot A\right)$$

For the total sludge production the solids leaving the WWTP via the effluent are also taken into account:

$$PS_{total} = PS_{disp} + \frac{0.75}{1000\cdot T}\int_{t=t_0}^{t=T}\left(X_{S,e} + X_{I,e} + X_{P,e} + X_{B,H,e} + X_{B,A,e}\right)\cdot Q_e(t)\,\mathrm{d}t$$

Economical analysis

By expressing those performance indexes in monetary units an approximate economical analysis could be made. Indicative unit prices were found in literature (Jacquet, 1999): levies on effluent discharges 30€/PU, electricity cost 0.072€/kWh and sludge treatment 580€/ton dry matter.

RESULTS AND DISCUSSION

DO-controlled WWTP as a reference

Both biomass loading control strategies were designed for a WWTP in which aeration is controlled in each tank so as to maintain a constant DO-level (2 g O_2.m^{-3}) in the last tank. Because this aeration control itself has an effect on the total performance, it was evaluated separately and further used as a reference for both control strategies. Aeration control was found to cause a reduction in aeration costs of more than 60% in comparison with the non-controlled benchmark plant.

Biomass loading control by means of RAS-storage (Flanagan, 1977)

During the implementation of this strategy in the benchmark, Flanagan's original FF-algorithm that controlled Q_{ras} according to the desired F/M-setpoint turned out to be unstable. An alternative, but similar, FB-algorithm was implemented instead, using the specific respiration rate (R_O) as the controlled variable. Other control loops were not described in detail, so several assumptions had to be made and the final implementation was only an approximation of the original proposal. However, the basic philosophy was retained.

The information obtained from the open-loop behaviour of the controller was of no use. Therefore, tuning of the controllers could not be done by means of the conventional techniques (e.g. Marlin, 1995) and manual tuning (trial-and-error) proved necessary.

On the basis of the performance indexes the respirometry-based control strategy was evaluated (Table 1). The small increase in EQ and in the effluent concentrations was due to the rise in SS in the effluent. The increase in sludge production and the savings in aeration energy are both caused by the higher sludge wastage under Flanagan's control, resulting in a lower sludge age. Pumping energy was doubled because of the need of an extra pump that recycled the RAS sludge from the storage tank back into the system.

The economical analysis (Table 2) showed that the (adapted) RAS-storage strategy of Flanagan caused a rise in the total operational costs.

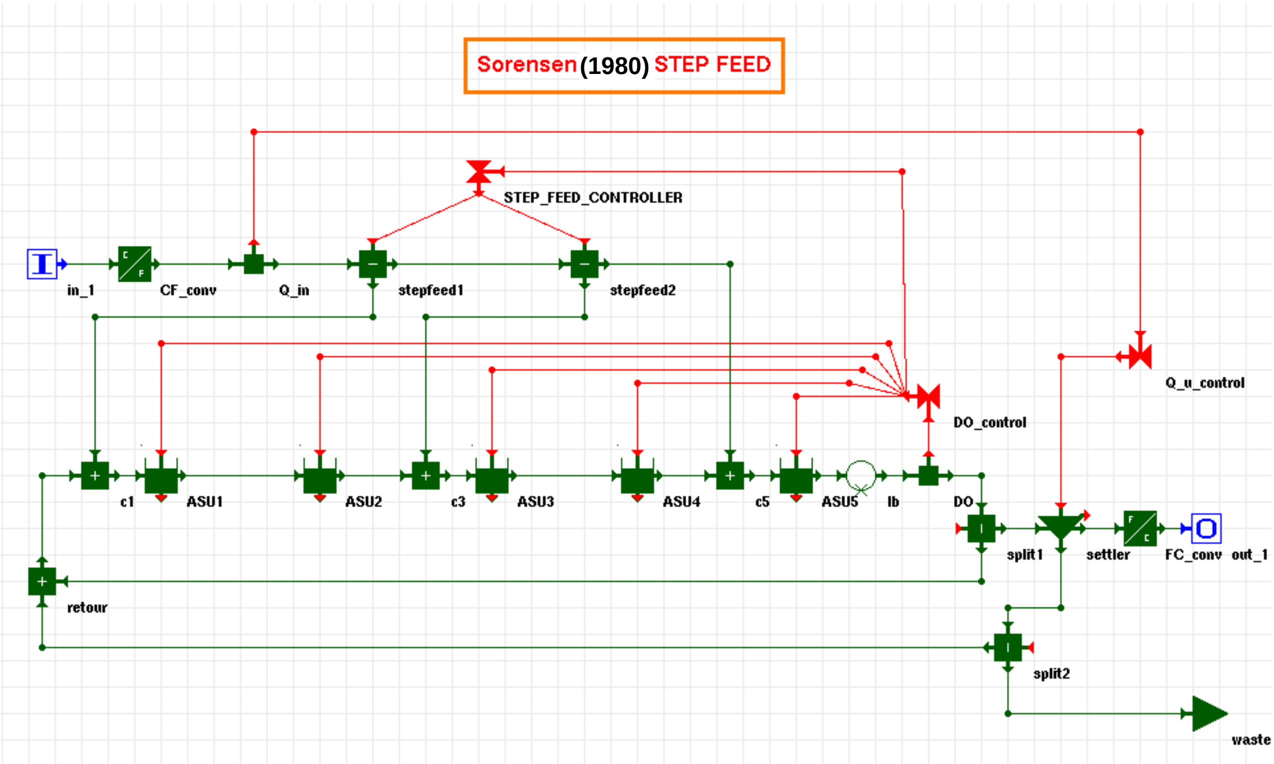

Figure 1 Implementation of the step feed control of Sørensen (1977) in WEST

Biomass loading regulation through step feed control (Sørensen, 1980)

Two variations of a step feed control with inflow points in tank 1, tank 3 and tank 5 were implemented in WEST (Figure 1). The first one was a non-continuous control, i.e. the influent distribution could switch between four fixed patterns. The second was a controller that fed influent to the first tank proportionally to the oxygen demand in the last tank. The controlled variable was the oxygen transfer coefficient (K_La) in the last tank instead of the rpm of the blower as it was proposed in Sørensen's original paper. Tuning of this strategy was not straightforward and also here trial and error appeared to be the only way.

Table 1 Assessment of the performance of two respirometry-based control strategies

	reference WWTP			RAS-storage			step feed non-continuous			step feed proportional		
Indexes												
EQ [PU]	28 234			29 341			29 869			28 823		
PE [kWh.d^{-1}]	384			773			740			740		
AE [kWh.d^{-1}]	5 945			4 927			7 736			7 389		
PS_{disp} [kg.d^{-1}]	2 835			3 014			2 570			2 711		
PS_{total} [kg.d^{-1}]	3 165			3 541			2 940			3 051		
Effluent constraints	A	#	%T	A	#	%T	A	#	%T	A	#	%T
SS_e	17.10	4	3.6	27.70	42	17.2	18.97	4	4.1	17.56	6	2.6
COD_e	52.77	0	0.0	68.74	3	0.7	55.19	0	0.0	53.82	0	0.0
$BOD_{5,e}$	4.33	0	0.0	7.46	7	6.4	4.57	1	0.2	4.45	1	0.2

A = flow-weighted average effluent concentrations (in g.m^{-3}) over the total testing period (T=42d); # = number of violations; %T = percentage of time constraints are violated

Performance evaluation (Table 1) proved that one of the basic objectives of Sørensen’s strategy, namely a more constant effluent quality, could only be confirmed when the negative effect of the strategy on the settler was eliminated by not considering suspended solids concentration in the effluent. A reduction in sludge production was caused by the higher sludge age in this sludge-accumulating system. The economical benefits of this decrease in sludge production (Table 2) is too small to compensate for the extra operational costs. Mainly aeration proved to be very inefficient in the step feed controlled WWTP.

Table 2 Economical analysis of the two tested control strategies (all amounts are in □ per year)

	reference WWTP	RAS-storage		step feed			
				non-continuous		proportional	
		total	difference	total	difference	total	difference
Levies on effl. dis.	847 010	880 232	+ 33 222	896 076	+ 49 066	864 695	+ 17 685
Pumping energy	10 100	20 324	+ 10 224	19 439	+ 9 339	20 853	+10 753
Aeration energy	156 247	129 489	– 26 758	203 320	+ 47 073	194 175	+ 37 928
Sludge treatment	600 165	637 976	+ 37 811	544 004	– 56 161	573 967	– 26 198
Total annual cost	1 613 523	1 668 021	**+ 54 499**	1 662 840	**+ 49 317**	1 653 690	**+ 40 167**

CONCLUSIONS AND FURTHER RESEARCH

The performance of two biomass loading control strategies was evaluated on a qualitative and quantitative base.
Besides an assessment of the performance of two respirometry-based control strategies, attention was drawn to problems that can arise when executing the benchmark procedure. First, control algorithms in the original papers were not always described in detail or were even unstable. A second problem was the lack of proper tuning techniques for WWTP processes. Further research in this area is necessary. Although the benchmark has proven to be very useful when evaluating a control strategy, still some optimisation of the procedure can be done. The cost function should be extended and directly implemented in the simulation platform so as to increase the precision of the calculations and to enable tuning of the strategy on the base of this objective cost function.

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