European Control Conference ECC'99

31. AUGUST - 3. SEPTEMBER 1999
KARLSRUHE, GERMANY

under the auspices of the
European Union Control Association (EUCA)
in cooperation with IFAC
and in collaboration with the
IEEE Control Systems Society

Conference Proceedings

Organized by
VDI/VDE-Gesellschaft Mess-
und Automatisierungstechnik (GMA)

BENCHMARK FOR EVALUATING CONTROL STRATEGIES IN WASTEWATER TREATMENT PLANTS

J. Alex[1], J.F. Beteau[2], J.B. Copp[3], C. Hellinga[4], U. Jeppsson[5], S. Marsili-Libelli[6], M.N. Pons[7*], H. Spanjers[3], H. Vanhooren[8]

[1] IFAK, Steinfelderstr. (IGZ) D-39179 Barleben - Germany
[2] LAG-CNRS-ENSIEG, BP 46, F-38402, Saint-Martin-d'Hères cedex, France
[3] AEST, Wageningen Agricultural University, NL-6700 EV Wageningen, The Netherlands
[4] Dept of Biochemical Eng, Delft Univ. of Technology, Julianalaan 67, NL - 2628 BC Delft, The Netherlands
[5] IEA, Lund Institute of Technology, PO Box 118, S-22100 Lund, Sweden
[6] Dept Systems & Comp., Univ. of Florence, Via S. Marta, 3, I-50139 Florence, Italy
[7*] LSGC-CNRS-ENSIC-INPL, 1, rue Grandville, BP 451, F-54001 Nancy cedex, France,
Fax: +33 3 83 17 53 26 E-mail: pons@ensic.u-nancy.fr
[8] BIOMATH, Univ. of Ghent, Coupure Links 653, B-9000 Gent, Belgium

Keywords : Wastewater treatment plant, performance criteria, benchmarking, control strategy, performance assessment

Abstract

The paper describes the development of a benchmark for the evaluation of control strategies in wastewater treatment plants. The benchmark is a platform-independent simulation environment defining a plant layout, a simulation model, influent loads, test procedures and evaluation criteria. Several different research teams have contributed to the development of the benchmark and have obtained results using several simulation platforms (GPS-X™, Simulink™, Simba™, West™, FORTRAN code).

1 Introduction

Wastewater treatment plants are non-linear systems subject to large perturbations in flow and load, together with uncertainties concerning the composition of the incoming wastewater. Nevertheless these plants have to be operated continuously, meeting stricter and stricter regulations. Many control strategies have been proposed in the literature but their evaluation and comparison, either practical or based on simulation is difficult. This is partly due to the variability of the influent, to the complexity of the biological and biochemical phenomena and to the large range of time constants (from a few minutes to several days) inherent in the activated sludge process. Also complicating the evaluation is the lack of standard evaluation criteria. That is, effluent requirements and treatment costs (i.e. labour costs) are often location specific. This makes it difficult to judge the particular influence of an applied control strategy from a reported performance increase, as the reference situation is often less than optimal. Due to the complexity of the systems it takes a substantial effort to develop alternative controller approaches; hence, a fair comparison of different options rarely is made. And, even if this is done, it remains difficult to conclude to what extent the solution is process or location specific. To enhance the acceptance of innovative control strategies the evaluation should be based on a rigorous methodology including the definition of a comprehensive simulation model of the plant, plant layout, influent load, controllers, performance criteria and test procedures.

This paper describes the development of such a methodology, termed a "benchmark", and focusses special attention on the assessment of control performance. The benchmark is a simulation environment defining a plant layout, a simulation model, influent loads, test procedures and evaluation criteria. For each of these items, compromises were pursued to combine plainness with realism and accepted standards. However, most importantly, the benchmark is not linked to a particular simulation platform: direct coding (C/C++, FORTRAN) as well as commercial WWTP simulation software packages can be used. Once the user has validated the simulation code being used, any control strategy can be applied and the performance can be evaluated according to the defined criteria.

The work was initiated by Working Group No 2 within the framework of the European COST Action 682 "Integrated Wastewater Management" and is now continued under COST 624. The full set of equations and all the parameter values are available on the COST 624 website (http://www.ensic.u-nancy.fr/COSTWWTP).

2 Plant description

A common and relatively simple layout (Figure 1) was selected that combines nitrification with predeni-trification. The plant was designed to treat an average flow of 20 000 $m^3.d^{-1}$ with an average biodegradable COD concentration of 300 $g.m^{-3}$. The plant consists of a 5-compartment bioreactor (5 999 m^3) and a secondary settler (6 000 m^3). For a sludge concentration of 3 kg.m^{-3} this corresponds to a sludge load of approximately 0.20 kg BOD_5.kg^{-1} sludge.day^{-1} which is sufficient at 15°C, to insure that the effluent composition will be sensitive to the applied control strategy.

The first two compartments of the bioreactor are not aerated whereas the last three are aerated. All the compartments are considered to be fully mixed. The secondary settler is modelled as a series of 10 layers (one-dimensional model).

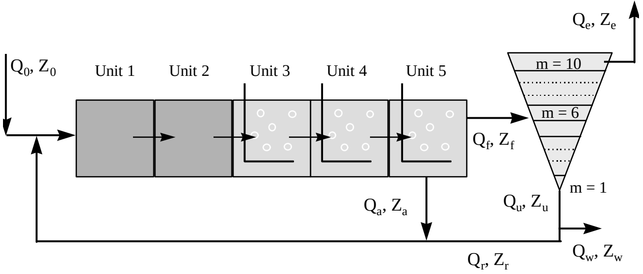

Figure 1 : Plant layout

The IAWQ Activated Sludge Model (ASM) N° 1 [1] was chosen to simulate the biological processes. The double-exponential settling velocity model proposed by Takács *et al.* [2] was selected to describe the behaviour of the settler. As in many plants, oxygen supply (by means of the oxygen transfer coefficients, k_La, in each aerated compartment), the internal and external recycle flow rates (Q_a and Q_r respectively) and the waste flow rate (Q_w) can be used as manipulated variables.

3 Influent load

Simulated influent data are available in three two-week files derived from real operating data [3, 4]. The files were generated to simulate three different weather situations. The first file is meant to be representative of a dry weather period. The file exhibits characteristic diurnal variations in flow and component concentrations. Also incorporated in the file is a substantial (20%) decrease in flow and load during the 'weekend'. The second and third files are based on the dry weather data with an added rain event during the second week. The first of these rain files has, during the second week, a sustained rain event which results in a constant increase in influent flow and lasts for two days. In particular, this file depicts a constant hydraulic load increase without any increase in COD or nitrogen load as compared to the dry weather file. The second of these rain files has two storm events during the second week. These storm events are shorter in length than the rain event, but are more intense. Also, in addition to increasing the hydraulic load, these storm events have an associated increase in particulate load as compared to the dry weather data (representing a first-flush event in the sewer system). Any control strategy should be tested using each of these weather files. Figure 2 shows a few variables from the storm weather file (flow rate, inert particulate material and ammonia concentration).

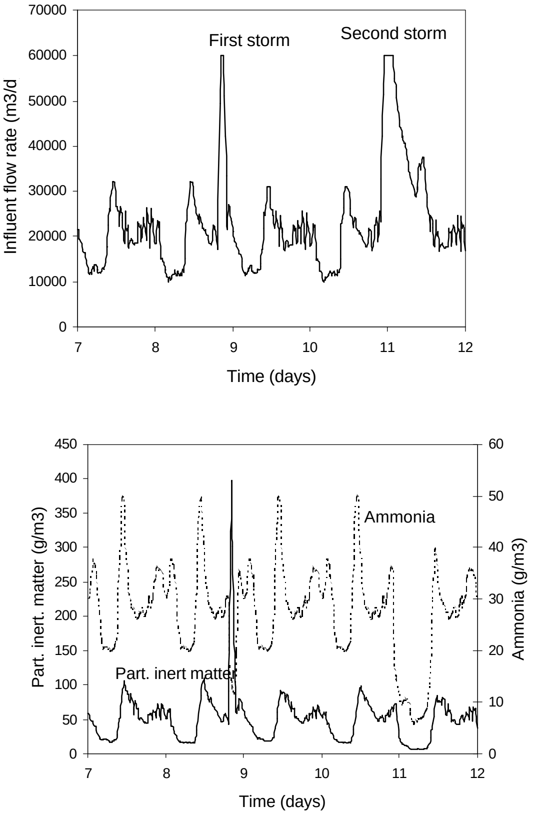

Figure 2 : Storm-weather influent file

4 Simulation software assessment

In order to check the simulation software being used, the following procedure has been devised. All controllers are disabled (open-loop) and all variables are set to constant values including all flows and influent constituents (flow-weighted average values from the dry weather influent file). Then 100 days (approximately 10 sludge ages) are simulated under these constant conditions. The steady state values after 100 days are then compared to reference values provided on the COST website. If agreement between the different data sets exists then the model implementation is assumed to be correct [5]. After initializing the model with the steady state values, the dry weather file should be used to test the dynamic response. This also is done in open-loop and with constant aeration, recycle and waste flow rates. Again, values obtained can be compared with values available on the website.

5 Control strategy

A basic control strategy is proposed to validate the user's simulation code. That is, prior to defining and testing a new control strategy users must validate their software by implementing a predefined control strategy. The generated output can then be compared to a standardised output as defined in the benchmark. The basic control strategy consists of:

- control of the dissolved oxygen concentration in the last compartment of the bioreactor to a set point of 2 g.m^{-3}, with a PI controller, by manipulation of the aeration rate *via* the oxygen transfer coefficient, k_La (unit 5). The dissolved oxygen probe is assumed to be ideal (zero delay, lag and noise).
- control of the nitrate level in the second non-aerated compartment at a set point of 1 gN.m^{-3} by manipulation of the internal recycle flow rate from compartment 5 to compartment 1 (Q_a). The nitrate sensor operates at a sampling rate of once every 10 min, with a delay of 10 min. The signal is affected by white, gaussian (standard deviation = 0.1 gN.m^{-3}) , zero-mean noise.

When performing a closed-loop experiment a 100-day period of stabilisation (with no noise on the nitrate measurement) followed by the dry weather file (14 days) should be completed prior to testing any of the three weather files. If the controllers are tuned properly, the limits on the effluent composition as mentioned in Section 6 should be met most of the time. At this stage the model equations should not be used for controller design and tuning. These requirements should ensure confidence in the software being used.

6 Control strategy: effluent constraints and performance assessment

The performance assessment is done using the output data generated during simulations using the weather files. That is, the performance assessment is based on the data generated during the second week of each weather file. Constraints with respect to the effluent quality are defined as follows. The flow-weighted average effluent concentrations over the three testing periods (dry, rain and storm weather) should obey the following limits: total nitrogen $N_{tot,e} < 18$ gN.m^{-3}, $COD_e < 100$ g.m^{-3}, ammonia $S_{NH,e} < 4$ gN.m^{-3}, suspended solids $SS_e < 30$ g.m^{-3}, $BOD_{5,e} < 10$ g.m^{-3}. The percentage of time the constraints are not met must be reported, as well as the number of violations. The limiting variables are calculated according to the following expressions (using the standard ASM1 nomenclature [1]:

$$\begin{cases} Ntot_e = S_{NKj,e} + S_{NO,e} \\ S_{NKj,e} = S_{NH,e} + S_{ND,e} + X_{ND,e} + i_{XB} \cdot \left(X_{BH,e} + X_{BA,e}\right) + \\ \qquad i_{XP} \cdot \left(X_{P,e} + X_{I,e}\right) \\ COD_e = S_{S,e} + S_{I,e} + X_{S,e} + X_{BH,e} + X_{BA,e} + X_{P,e} + X_{I,e} \\ SS_e = 0.75 \cdot \left(X_{S,e} + X_{BH,e} + X_{BA,e} + X_{P,e} + X_{I,e}\right) \\ BOD_{5,e} = 0.25 \cdot \left(S_{S,e} + X_{S,e} + \left(1 - f_P\right) \cdot \left(X_{BH,e} + X_{BA,e}\right)\right) \end{cases}$$

The performance assessment is made at two levels. The first level concerns the local control loops, assessed by IAE (Integral of the Absolute Error) and ISE (Integral of the Squared Error) criteria, by maximum deviation from set points, and by error standard deviation. Basically, this serves as an indication that the proposed control strategy has been applied properly. The second level quantifies the effect of the control strategy on plant performance and it can be divided into two sub-levels:

✓ effluent quality: levies or fines are to be paid due to the discharge of pollution to a receiving water body:

An effluent quality index *E.Q.* is proposed. Through a weighting system, this index combines the effluent loads of compounds that have a major influence on the quality of the receiving water. Also included in the index are compounds that are usually included in regional legislation. The indexed value is an average over the period of observation T(d) (i.e. 7 days for each weather file). It is defined as:

$$E.Q. =$$

$$\frac{1}{T \cdot 1000} \int_{t=7days}^{t=14days} \cdot \begin{pmatrix} B_{SS} \cdot SS_e(t) + B_{COD} \cdot COD_e + \\ B_{NKj} \cdot S_{NKj,e}(t) + B_{NO} \cdot S_{NO,e}(t) + \\ B_{BOD5} \cdot BOD_{5,e}(t) \end{pmatrix} Q_e(t) \; dt$$

where the B_i values are weighting factors for the different types of pollution to convert each term to pollution units.

✓ cost factors for operation

- ✗ sludge production (kg.d^{-1}): calculated from the total solid flow from wastage and the solids accumulated in the system over the period considered, i.e. 7 days for each weather file,
- ✗ controllers output variations: the maximum values and the standard deviations of the manipulated variables variations should be given. This will provide an indication on peak loads and the wear of the pumps and aeration devices,
- ✗ aeration and pumping energy (kWh/d) (recycle and waste pumps).

The aeration energy, *AE*, should take into account the plant peculiarities (type of diffuser, bubble size, depth of submersion, etc.) and is calculated from the k_La in the three aerated compartments according to the following relation (valid for Degrémont DP230 porous disks at an immersion depth of 4m):

$$AE = \frac{24}{T} \int_{t=7\ days}^{t=14\ days} \sum_{i=3}^{i=5} \left(0.4032 \cdot \left(k_L a\right)_i^2 + 7.8408 \cdot \left(k_L a\right)_i\right) \cdot dt$$

where k_La is expressed in h^{-1}.

The pumping energy, *PE*, is calculated as:

$$PE = \frac{0.04}{T} \int_{t=7\ days}^{t=14\ days} \left(Q_a(t) + Q_r(t) + Q_w(t)\right) dt$$

where all flows are expressed in m^3.d^{-1}.

7 Results

The implementation of the PI controllers for the dissolved oxygen in the last aerated tank and for the nitrate concentration in the second anoxic tank is described using FORTRAN and Matlab/Simulink. The implementation of the simulation model in open-loop using both platforms has been described elsewhere [5].

7.1 Implementation using FORTRAN

Both PI controllers are of the discrete type and have anti-windup capabilities. Let *Dt* be the time interval between two actions of a controller, *y(k)* the measurement at time *kDt*, and y^{set} the setpoint . The action to be applied, *u(k),* is calculated as follows :

$$u(k) = Du + u(k-1)$$

with $Du = K \left\{ [e(k) - e(k-1)] + \frac{\Delta t}{T_i} e(k) \right\}$

under the following constrains :

$|Du| \le Du_{\max}$ (limit on u variation between two successive actions)

$u_{\min} \le u(k) \le u_{\max}$ (permissible values of u)

e(k) and *e(k-1)* are respectively the errors at time *kDt* and *(k-1) Dt* :

$$e(k) = y^{set} - y(k)$$

K and T_i represent the proportional and integral constants of the PI controller, respectively. After manual tuning, the settings given in Table 1 were obtained .

Table 1: PI controller settings using FORTRAN

	Oxygen controller	Nitrate controller
K	0.7 $h^{-1}.(g.m^{-3})^{-1}$	210 $(m^3.h^{-1})(g.m^{-3})^{-1}$
T_i (h)	0.06	3
Dt (h)	0.02	0.17
y^{set} ($g.m^{-3}$)	2	1
u_{min}	0 h^{-1}	0 $m^3.h^{-1}$
u_{max}	10 h^{-1}	3843 $m^3.h^{-1}$
Du_{max}	0.5 h^{-1}	500 $m^3.h^{-1}$

7.2 Implementation using Simulink

The controller structure used in the Simulink implementation of the benchmark is for both the nitrate and oxygen control a continuous PI-controller with anti-windup capability. The reason for implementing anti-windup is because of the output limitations of the controllers (both the manipulated variables k_La and Q_a are limited). Otherwise, the overshoot due to the integral part of the controller may seriously reduce the performance of the controllers.

The controllers are implemented as:

$$u(t) = K \cdot \left[e(t) + \frac{1}{T_i} \int_0^t e(t)\,dt \right] + \frac{1}{T_t} \int_0^t [u_{\lim}(t) - u(t)]\,dt$$

where $u_{\lim}$ is the limited value of the control output u and $e(t) = y^{set} - y(t)$. The desired control signal u is first computed and then it is verified whether or not the actual controller output exceeds the defined limits:

$$\begin{cases} u_{\lim} = u_{\min} & \text{if } u < u_{\min} \\ u_{\lim} = u & \text{if } u_{\min} \le u \le u_{\max} \\ u_{\lim} = u_{\max} & \text{if } u > u_{\max} \end{cases}$$

If the control signal is saturated, then the difference $u_{\lim}–u$ will cause a change of the integral part until the saturation effect disappears. Consequently, windup is avoided.

The parameters of the controllers were tuned manually to provide ‘reasonable’ behaviour of the process. The chosen values are given in the Table 2.

Table 2: PI controller settings using Simulink

	Oxygen controller	Nitrate controller
K	20.8 $h^{-1}.(g.m^{-3})^{-1}$	625 $(m^3.h^{-1})(g.m^{-3})^{-1}$
T_i (h)	0.024	1.2
T_t (h)	0.0048	0.72
y^{set}($g.m^{-3}$)	2	1
$u_{\min}$	0 h^{-1}	0 $m^3.h^{-1}$
$u_{\max}$	10 h^{-1}	3843 $m^3.h^{-1}$

7.3 Implementation results

Figure 3 depicts the performance of the PI controllers using FORTRAN one day before and three days after the switch between the stabilisation period and the dry weather file.

The dissolved oxygen controller works as intended but large fluctuations can been observed for the nitrate concentration in the second anoxic reactor. Similar results were obtained with the controllers implemented on the Simulink platform although the latter maintains the controlled variables closer to the set points, at the expense of larger variations on the manipulated variables (Table 3).

It is clear from the results shown that the oxygen controller is capable of maintaining the oxygen level in the 5th reactor close to the set point of 2 $g.m^{-3}$. However the performance of the nitrate controller is not as good. There may be several reasons for the poorer performance. For example, noise and delay time have been added to the measurement signal. However, the primary problem is related to the time delay of the process itself. A change of the internal recycle flow rate does not have an immediate effect on the nitrate concentration in the second reactor because the flow first must pass through the first reactor, which imposes a delay in the response time between controller action and process response. Moreover, the first reactor is also denitrifying. This means that a part of the expected concentration change is affected by the behaviour of the first reactor, of which the controller has no influence. A model-based controller or a feed-forward controller is necessary to significantly improve the performance of the nitrate controller.

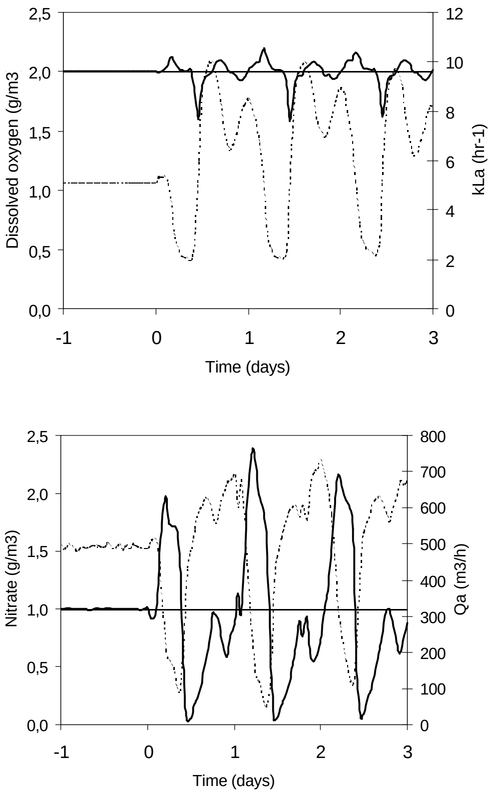

Figure 3: PI controllers behaviour using FORTRAN (a) dissolved oxygen (—), k_La (- - -); (b) nitrate (—), Q_a (- -)

Table 3: Comparison of some performance criteria of the PI controllers; *s{e}*= standard deviation of error; *s{Du}*= standard deviation of variation of *u*.

	FORTRAN	Simulink
Dissolved oxygen		
$Max\lvert e\rvert$ (g.m^{-3})	0.42	0.007
$s\{e(O_2)\}$ (g.m^{-3})	0.073	0.002
$s\{Dk_La\}$ (h^{-1})	0.017	0.24
Nitrate		
$Max\lvert e\rvert$ (g.m^{-3})	1.44	0.89
$s\{e(S_{NO})\}$ (g.m^{-3})	0.34	0.29
$s\{DQ_a\}$ (m^3.h^{-1})	11.6	69

7.4 Performance assessment

Table 4 compares the performance criteria using the FORTRAN and Simulink for the dry weather case. The two platforms do not produce exactly the same steady-state results [5], but the performance assessment lead to comparable results, both in open-loop and closed-loop. The proposed control strategy does not improve significantly the quality of the effluent (as defined by the effluent quality index), the main effect being on the release of ammonia to the receiving body. The aeration cost is slightly increased but there are significant savings in the pumping energy.

Table 4 : Comparison of the performance criteria obtained using FORTRAN and Simulink for the dry weather data file ; P_{disp_sludge}= average daily production of sludge to be sent to disposal ; Nb viol. = number of times the limit has been violated ; %T = percentage of time the limit has been violated.

	Simulink		FORTRAN	
	Open-loop	Closed-loop	Open-loop	Closed-loop
E.Q. (g.d^{-1})	3.06 10^6	2.94 10^6	2.76 10^6	2.78 10^6
P_{disp_sludge} (kg.d^{-1})	2435	2440	2487	2492
AE (kWh.d^{-1})	6476	7240	6528	7184
PE (kWh.d^{-1})	2967	1490	2980	1160
Nb Viol. $N_{tot,e}$	5	7	6	11
Nb Viol. $S_{NH,e}$	7	5	5	5
%T_{viol} $N_{tot,e}$	8.2	18.3	10.9	36.4
%T_{viol} $S_{NH,e}$	62.5	17.3	57.8	14.8

Table 5 presents the results obtained using Simulink (results using FORTRAN show the same trends) for the rain and the storm data files. As for the dry weather case the proposed control strategy contributes to a decrease in effluent ammonia.

7.5 Other control strategies

Once the user have validated his/her results according to the procedures defined in this paper, any control strategy can be applied and the performance evaluated according to the defined criteria. For this reason a variety of different sensors (e.g. for flow rate, ammonia and suspended solids measurements) will be defined with regard to delay time, noise level and so on, and the capabilities and limitations of different actuators described. The user will select the sensors required to implement the control strategy of his/her choice (e.g. model-based control, adaptive control, feed-forward control) and compare the performance with other strategies. There naturally also will be a penalty associated with the number of sensors used. Hopefully in the future, the results can be posted on the website giving other 'benchmarkers' a source of results for comparison. This way the website may serve as a database for control strategy evaluation.

Table 5 : Comparison of the performance criteria obtained using Simulink for the storm and rain weather data files

	Storm weather		Rain weather	
	Open-loop	Closed-loop	Open-loop	Closed-loop
E.Q. ($g.d^{-1}$)	$3.60\ 10^6$	$3.35\ 10^6$	$3.96\ 10^6$	$3.72\ 10^6$
P_{disp_sludge} ($kg.d^{-1}$)	2599	2605	2352	2358
AE ($kWh.d^{-1}$)	6476	7285	6476	7169
PE ($kWh.d^{-1}$)	2967	1730	2967	1930
Nb Viol. $N_{tot,e}$	4	7	3	5
Nb Viol. $S_{NH,e}$	7	7	7	8
Nb Viol. SS_e	1	2	0	0
$\%T_{viol}$ $N_{tot,e}$	8.5	15.8	4.8	11.3
$\%T_{viol}$ $S_{NH,e}$	64.4	26.8	63.2	26.8
$\%T_{viol}$ SS_e	0.1	0.3	0	0

8 Conclusions

A large number of different control strategies for wastewater treatment plants have been described in the literature over the years. In many cases the performances of the proposed strategies have been demonstrated, either by means of simulations or by real experiments in pilot- or full-scale wastewater treatment plants. However, the results are in many cases troublesome to compare as they have been achieved using different mathematical models, different plant configurations, a variety of influent wastewater characteristics, etc. It is consequently often impossible to determine whether the presented results are primarily due to local factors or if the control strategy is generally applicable. By defining a simulation environment including the model of the plant, plant layout, influent wastewater characteristics, evaluation criteria, test procedures, etc., as proposed in this paper, it is now possible to set up a consistent and unbiased methodology for the evaluation of control strategies in the future. Every new proposed strategy can be objectively compared to other strategies and the general applicability of a strategy can be determined. The authors have chosen to start with one of the most common type of wastewater treatment plants – a continuous flow activated sludge plant performing nitrification and predenitrification. In the future, similar benchmark models should be developed for other commonly used processes, e.g. enhanced biological phosphorus removal, biofilm processes and sequencing batch reactors.

References

[1] Henze M., Grady Jr C.P.L., Gujer W., Marais G.v.R., Matsuo T.: Activated sludge model n°1, IAWQ Scientific and Technical Report n°1, IAWQ, London (1986)
[2] Takács I., Patry G.G., Nolasco D.: A dynamic model of the clarification thickening process, Water Research, 25, 10, 1263-1271 (1991)
[3] Vanhooren H., Nguyen K.: Development of a simulation protocol for evaluation of respirometry-based control strategies, Technical Report, University of Gent, Gent, Belgium (1996)
[4] Copp J.B.: Development of standardised influent files for the evaluation of activated sludge control strategies. IAWQ Scientific and Technical Report Task Group: Respirometry in Control of the Activated Sludge Process – internal report (1999)
[5] Pons M.N., Spanjers H., Jeppsson U.: Towards a benchmark for evaluating control strategies in wastewater treatment plants by simulation, Escape9, Budapest (1999)

Acknowledgements

The authors wish to thank the COST Program and all those who participated to the discussions: J. Alex, JF Beteau, C. Bengt, J. Copp, D. Dochain, E. Demokos, B. Gioli, C. Hellinga, S. Isaacs, U. Jeppsson, J.M. Le Lann, A. Karpati, K. Keesman, N. Havla, S. Marseli-Libelli, M. Nielsen, G. Olsson, X. Ostolaza, M. Pelkonen, M.N. Pons, W. Rauch, C. Rosen, H. Spanjers, J.P. Steyer, H. Vanhooren, P. Vanrolleghem, M. Zec.

List of symbols

AE	Aeration Energy ($kWh.d^{-1}$)
B_i	weight factors in Effluent Quality index
BOD_5	Biological Oxygen Demand – 5 days
COD	Carbon Oxygen Demand
E.Q.	Effluent Quality index
k_La	oxygen transfer coefficient
N_{tot}	total nitrogen concentration
PE	Pumping Energy ($kWh.d^{-1}$)
Q_0	influent flow rate
Q_a	internal recycle flow rate
Q_e	effluent flowrate
Q_r	external recycle flow rate
Q_w	wastage flow rate
Q_u	underflow rate
S_{NH}	ammonia concentration
S_{NKj}	Kjeldahl nitrogen concentration
S_{NO}	nitrate concentration
SS	suspended solids concentration
T	time period of performance assessment
Z	state variable