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A PROCEDURE FOR BENCHMARKING SPECIFIC FULL-SCALE ACTIVATED SLUDGE PLANTS USED FOR CARBON AND NITROGEN REMOVAL

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Abstract: To enhance development and acceptance of new control strategies, a standard simulation benchmarking methodology to evaluate the performance of wastewater treatment plants has recently been proposed. The proposed methodology is, however, for a typical plant and typical loading and environmental conditions. Thus, benchmarking a full-scale plant working under different situations is still a problem that needs to be solved. This paper proposes a realistic approach to benchmark specific full-scale activated sludge plants used for carbon and nitrogen removal, based on real design, operational and performance data. An illustrative example is also presented in this paper. Copyright © 2002 IFAC.

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1. INTRODUCTION

Wastewater treatment plants (WWTP's) are complex non-linear systems, which are subject to large variations in environmental conditions, and in influent load and composition. Nonetheless, WWTP's have to meet strict effluent standards. To achieve these strict standards at reduced costs, several control strategies have been proposed (see Lukasse, 1999; Weijers, 2000). However, evaluation of these and similar strategies, either practically or by simulation, is a real problem due to lack of standard evaluation criteria, process complexity and due to large variations in plant configuration. To enhance development and acceptance of new control strategies, the IWA Task Group on Respirometery together with the European Co-operation in the field of Scientific and Technical Research (COST) 624 (COST 2000a; Copp, 2000) have recently proposed a standard simulation benchmarking methodology for evaluating the performance of activated sludge plants. The *COST* Group defines the benchmark as "*A protocol to obtain a measure of performance of control strategies for activated sludge plants based on numerical, realistic simulations of the controlled plant*". According to this definition, the benchmark will be consisting of a description of the plant layout, a simulation model and definitions of (controller) performance criteria.

The benchmarking methodology followed by COST and IWA Working Groups is, however, developed for benchmarking a typical plant that works under typical loading and environmental conditions. The question remains how results obtained from evaluating a control strategy under such typical design and operating conditions can be transferred to a full-scale plant working under different situations. Very recently Vanrolleghem and Gillot (2001) have tried to solve this problem by proposing the robustness index that allows transferability of control strategy evaluation results to situations different than typical conditions. Our paper proposes a direct benchmarking approach, which uses real design, operational and performance data to benchmark specific full-scale activated sludge plants (see Abusam, 2001 for details). The paper also evaluates performance of some control strategies in a full-scale oxidation ditch plant, as an illustrative example.

2. THE PROCEDURE

As shown in Fig. 1, the proposed procedure consists of 11 steps. In this section these steps will be described in more details.

2.1 Collection of plant design data

Collect the following design and operational information: (i) volume and dimensions (length, width and depth) of the reactor and the secondary settler, (ii) number of aerators, their design capacity (kgO_2/h), locations and daily operational patterns, (iii) design organic loads (kg*COD*/d and kg*N*/d) and hydraulic loads (m^3/d), (iv) actual flow measurements (m^3/d) for the influent stream, effluent stream, wasted activated sludge (*WAS*) and recirculated activated sludge (*RAS*), and (v) average horizontal velocity, (m/s).

2.2 Collection of plant performance data and COD fractionation

Conduct a daily measuring campaign, for about two weeks, in order to collect the following averaged daily performance data:

- **Concentration measurements (**mg/l): (i) *DO*, total *COD*, *TN*, *TKN*, NH_4, NO_3, and *TSS* concentrations in the influent and the effluent streams (composite samples), (ii) *TSS* concentrations in *WAS* and *RAS* streams (iii) *DO* concentrations, at a number of points along the reactor and especially at the in/outlet ports, and (iv) influent and effluent alkalinity, in moles/m^3.
- **Energy consumption (**kWh/d**)** in terms of aeration energy (*AE*), per aerator, and pumping energy (*PE*), per pump.

Carry out an **intensive measuring campaign** (sample time is 2-4 hours), for 2 or 3 days, in order to determine the dynamics of the influent and effluent flow, *COD*, NH_4 and NO_3.

Break down of the various concentrations measured in this step into the corresponding components of *ASM No. 1*, using previous knowledge about wastewater characteristics at the plant. Here, carrying out some additional laboratory experiments (see for example Sollfrank and Gujer, 1991; Henze, 1991; STOWA, 1996 and 2000) may be needed.

2.3 Development of a basic simulation model

Neglecting all other treatment units, model the plant as consisting of only a reactor and secondary settler. Note that the simulation model can be developed on any simulation platform, e.g. GPS-X, Matlab\Simulink, or its shell SIMBA.

Use a *CSTR's* model to model the hydraulics of the reactor, and use ASM No. 1 (Henze *et al.* 1987) to model biochemical processes that take place along the reactor. Use, for instance, the double exponential settling velocity model (Takács *et al.* 1991) to model the secondary settler.

2.4 Model calibration

Before starting the calibration process, think about the data needed to validate the model. If it is not planned to collect a new set of performance data at a different season of the year, leave half of the data collected in step 2 for model validation step (the next step).

Use default or literature values for all parameters of *ASM No. 1*, except the following most sensitive ones such as: Y_H, b_H, K_S, k_h, K_{NH}, K_X, μ_A , η_g, η_h and k, where $k = K_L a \cdot V_A$ is the aeration constant (see Abusam *et al.*, 2001a). Try to accurately determine, through experiments, the actual values of the parameters that are claimed to be measureable, such as: Y_H, b_H, and K_S (see for example Ekama *et al.*, 1986; Kappeler and Gujer, 1992).

Estimate the values of 3 to 5 of the most sensitive parameters mentioned above, using a conventional calibration procedure or the (novel) procedure, which is based on response surface analysis (*RSM)*, proposed by Abusam *et al*., (2001b). According to STOWA (2000), where it is assumed that K_La is known in advance, one may calibrate first sludge production, then effluent ammonia concentration, and finally nitrate concentration. With the new calibration procedure, the three above-mentioned functions can simultaneously be calibrated together with K_La or the aeration constant k

(*see* Abusam *et al*., 2001c*)*. Note that steps 2 and 3 may need to be repeated until a well-calibrated model is obtained (see Fig. 1). For example, in step 2 one may look for data with more excitations, whereas in step 3 one may change the number of *CSTR's*.

2.5 Model validation

Validate the model, using data collected in a different season. If it is not available, use the data left for this purpose in step 4. For obtaining appropriate results, the last step or even last three steps may need to be repeated (see Fig. 1).

2.6 Development of performance criteria

Use the performance criteria proposed by *COST* and *IWA* Working Groups (see *Copp*, 2000) to evaluate conventional activated sludge systems. Note that for other activated sludge systems, these criteria need to be modified in order to take into account any special features of the system. In addition to the process data used in the previous step to validate the model one may also use performance criteria data, as will be demonstrated in what follows.

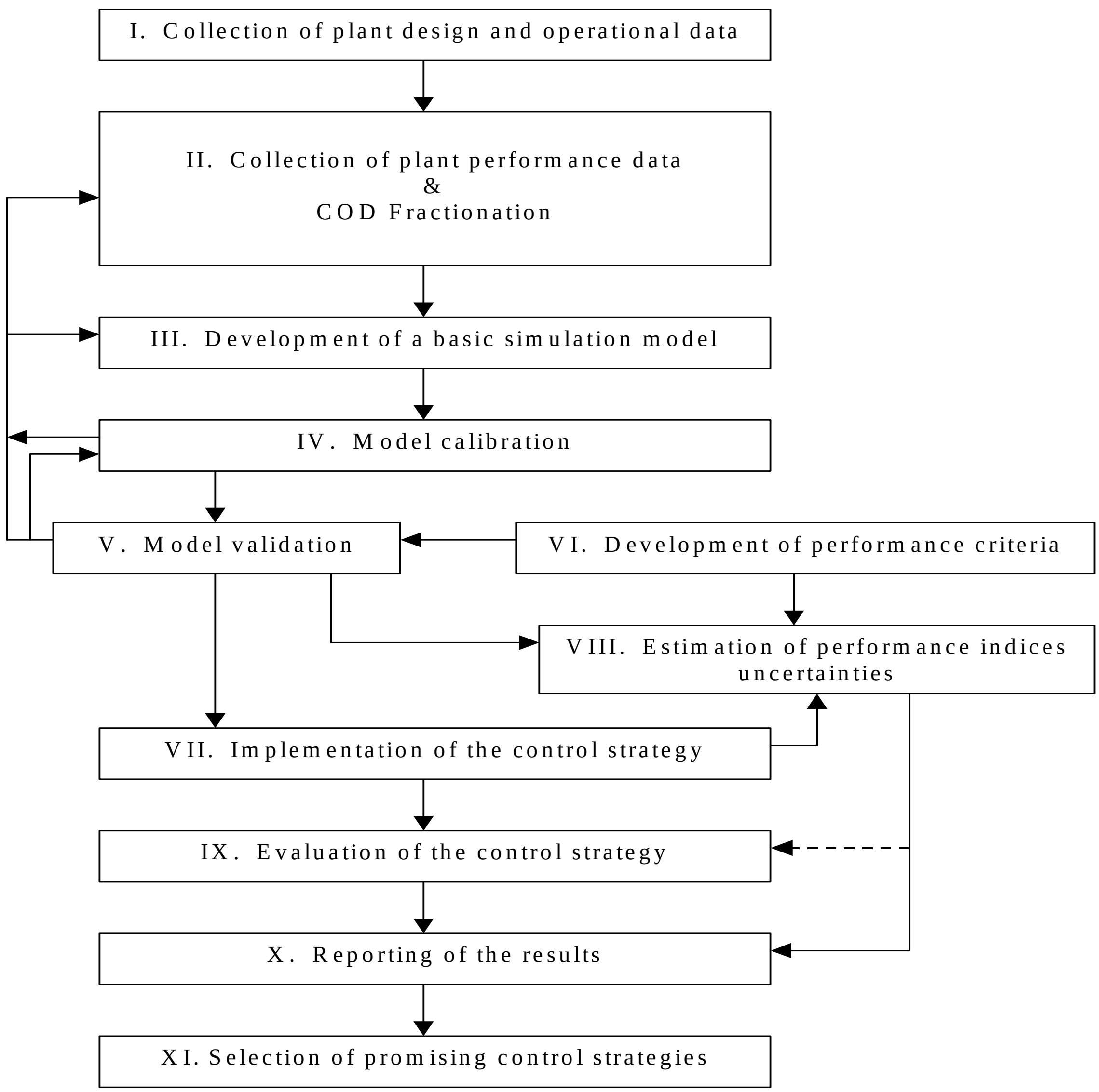

Fig. 1. A scheme of the procedure for benchmarking a specific full-scale activated sludge plant.

2.7 Implementation of the control strategy

Study thoroughly the control strategies that will be evaluated, in order to identify the following: (i) control objective, (ii) measured, controlled and manipulated variables, and (iii) control configuration and algorithms.

Implement models of *DO* and N sensors where measurements will be taken. Measurement locations are usually specified in the description of the control strategy. Similarly, actuator models can be implemented.

Tune the controllers, for example, using the Ziegler and Nichols method for PID controller tuning, or any other common tuning method.

2.8 Estimation of performance index uncertainties

Quantify the influence of the various sources of uncertainty on the performance indices developed in the previous step. Examples of the uncertainties that need to be studied are uncertainties in parameters value, in initial conditions and in model structure. Here the procedure demonstrated in Abusam *et al.*, (2001d) can be used. Note that uncertainties should be estimated under the existing control strategy and any control strategy to be evaluated (see Fig. 1). Results obtained in this step have to be summarized in terms of standard deviations or ranges, for each performance index.

2.9 Evaluation of the control strategy

Download the various weather influent files (dry, stormy and rainy conditions) provided by COST 624 on their web site (COST, 2000a) and scale them to the flow of the plant under study.

At open-loop conditions (sensors are OFF), carry a simulation until steady state is reached (usually in the order of 100 days), using the average concentrations of the dry weather influent file. Here, *RAS* and *WAS* should be kept constant at some typical values.

Using the steady state values as initial conditions, conduct dynamic simulations of the closed loop (sensors ON) in order to evaluate the implemented control strategy under various weather conditions (real, dry, storm and rain weather files) and under typical off-normal situations, as in case of sensor/actuator failures.

Evaluate the plant performance under the new-implemented control strategy, for each weather file separately, in terms of performance indices together with uncertainties and violation times of the effluent constraints.

2.10 Reporting of the results

Report in a table format, for each evaluated control strategy, the values of performance indices and time of violations obtained in the previous step. Report also the performance indices uncertainties obtained in **step 8**.

2.11 Selection of promising control strategies

Select the most promising strategies. In fact, this is not a trivial task. The rational approach to be followed in this case is to formulate multi-objective criteria. Obviously, operational costs as well as investment costs (sensors and instrumentation) and effluent quality will be part of the criteria. Reliability of the operation and robustness against model uncertainty should also be elements of the criteria. Reliability addresses issues such as how to maintain the plant running and how to avoid process upsets. Examples of process upset are sludge washout, loss of biological activity, too high *MLSS* concentrations and sludge bulking. Of course, there may be some other plant specific objectives that need to be included in such criteria. The plant manager has to decide that. Also the plant manager has to decide how the trade-offs between the various objectives can be carried out.

3. ILLUSTRATIVE EXAMPLE

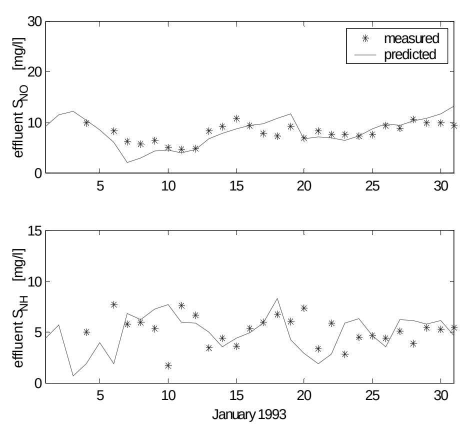

Fig. 2. Results of model recalibration

As an illustrative example, the procedure described above was used to benchmark the performance of a 300000 p.e. carrousel WWTP located in Rotterdam (The Netherlands). This plant consists of two main parallel treatment lines. Each line has two primary settlers, one selector, one carrousel (406.25m x 8m x 4m deep), and three circular secondary settlers (each has a diameter = 52.9 m and side wall depth = 2 m). Each carrousel has four surface aerators.

Steps 1-4 of the proposed procedure were followed in order to come up with a calibrated model for one treatment line (see Fig. 2). The Arrhenius relationship was used to model the temperature effect. For more information about temperature effects see Abusam *et al.* (2001a). The calibrated model was then validated (**step 5**) with a different set of data (see Fig. 3).

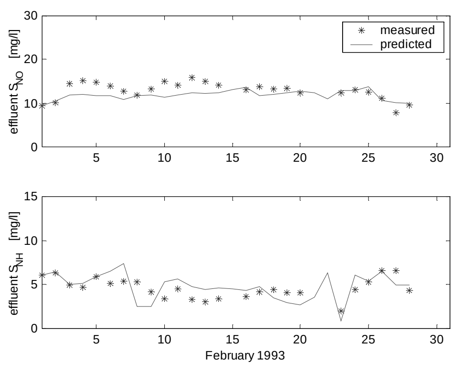

Fig. 3. Results of model validation

Oxidation ditch performance criteria (**step 6**) were developed by modifying the criteria proposed by *COST624* and *IWA* Working groups. One of the main features of oxidation ditches is the use of surface aerators, which perform dual function: aeration and recirculation of the flow around the ditch. Thus, main changes were made in the aeration energy (*AE)* and pumping energy (*PE)* equations (see Abusam *et al.*, 2001a).

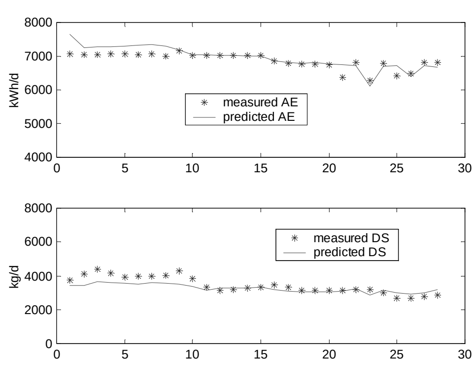

Fig. 4. Results of the benchmark validation.

The benchmark (calibrated model and performance criteria) was then validated by comparing real measurements of *AE* and *DS* (disposed sludge index, kg/d) with the benchmark predictions (Fig. 4). Note that values reported in this figure are for the whole treatment plant (i.e. the two treatment lines). As can be seen, the benchmark prediction of both *AE* and *DS*, is generally acceptable. Deviation of benchmark predictions from the real measurements is, on average, less than 10 per cent. The relatively poor fit obtained during the first 10 days can be attributed to low initial biomass concentrations. Except in these 10 days, changes in the performance indices seem to be predicted fairly well by the benchmark. It should be noted, however, that the natural variations in the observed data is too limited to allow for a more thorough validation.

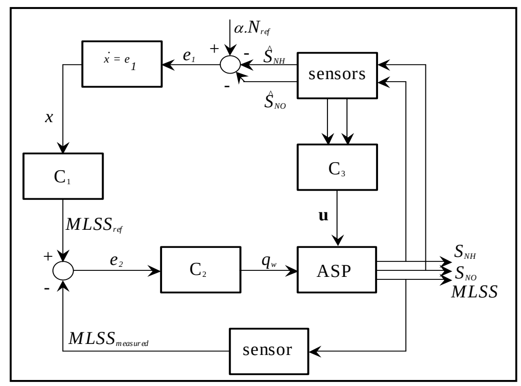

Fig. 5. Feedback control loop for yearly-averaged TN control (Lukasse, 1999)

Performance index uncertainties, under the existing control strategy, were quantified (**step 8**) and reported in Table 1, as deviations from the default values. Lukasse's (1999) proposed control scheme (see Fig. 5) was then implemented (**step 7**). This control strategy aims to reduce both *DS* and *AE* costs by optimizing the amount of biomass (*MLSS*) needed during the different seasons of the year in order to meet a specified *yearly average TN* effluent quality. In fact, a modified version of Lukasse's control scheme was implemented by omitting the *DO* controller, C_3, and using the fixed ON-OFF aerators operational pattern (existing control strategy) for the whole year.

Performance evaluations of Lukasse's modified scheme (**step 9**) are reported in Table 1 and compared with the plant performance under the existing control strategy (**step 10**). From Table 1, it is clear that Lukasse's control strategy significantly reduces the costs of *DS* and *EQ*. Because the *DO* controller (C_3) was not implemented, however, there is a slight increase in *AE* costs and more violations of NH_4-N limits. In short, the new control strategy has a number of interesting features. The plant manager, however, has to consider many other factors such as costs and reliability of operation, before he selects this strategy (**step 11**) as one of the most promising control strategies for his plant.

Table 1 Results of implementing a simplified version of Lukasse (1999) control scheme in comparison to the existing control scheme

Control strategy		Existing strategy	Lukasse's strategy (simplified)
EQ [kg/d]		26254 (± 500%)	20832
AE [kWh/d]		13672 (± 64%)	14332
DS [kg/d]		7530 (± 65%)	4680
*EQ*costs [Euro/d]		787620	624960
AE costs [Euro/d]		984	1032
DS costs [Euro/d]		4367	2714
Violation time (%)	NH_4-N	50.9	89.2
	TN	8.6	0.5

4. CONCLUSIONS

A realistic procedure for benchmarking specific full-scale activated sludge plants has been proposed. As an illustrative example, performance of a full-scale oxidation ditch plant is evaluated, under a proposed control strategy, using the plant real data.

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