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MULTI-CRITERIA EVALUATION OF CONTROL STRATEGIES FOR WASTEWATER TREATMENT PROCESSES

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Abstract: This paper deals with the simulation Benchmark multi-criteria evaluation of the performance of control strategies for biological wastewater treatment plants. In particular, the usefulness of more compact multi-criteria measures is discussed. For an illustrative selection of control strategies, an economic index weighing operating costs appears more powerful than a grey-scale presentation approach. The use of a robustness index, indicating the transferability of control strategies to situations different than the ones defined in the Benchmark protocol, is also evaluated. *Copyright © 2002 IFAC*

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1. INTRODUCTION

Carefully conducted model-based simulation studies are important when evaluating control strategies for wastewater treatments plants. For this reason, the Task Group on Respirometry of the International Water Association (IWA) and the European COST actions 682 and 624 developed a standard test methodology, called the Benchmark (Spanjers *et al.*, 1998; Copp, 2001). 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 control performance.

The standard simulation Benchmark plant design is comprised of five bioreactors in series with a 10-layer secondary settling tank (see Figure 1). Denitrification takes place in the anoxic reactors (ASU 1 and 2), while the aerated reactors (ASU 3, 4 and 5) serve for carbon removal and nitrification. IWA's Activated Sludge Model No 1 (ASM1) was chosen as the biological process model (Henze *et al.*, 2000) and the double-exponential settling velocity function of Takács *et al.* (1991) was chosen as a fair representation of the settling process.

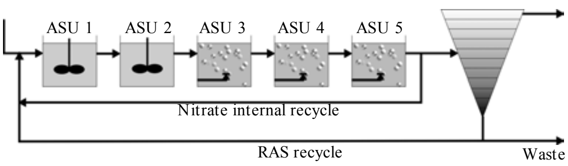

Fig. 1. Configuration of the benchmark plant for carbon and nitrogen removal.

This paper focuses on the performance evaluation required to assess a given control strategy using the Benchmark protocol. The current complicated, multi-criteria performance evaluation is scrutinized. An economic index in the form of a single expression, the Operating Cost Index (OCI), is discussed. In an attempt to tackle an important criticism on simulation-based benchmarking, further attention is dedicated to a new performance indicator, the Robustness Index (RI), indicating how 'transferable' benchmark results are to systems that differ in design and operation. The above mentioned performance indices have been investigated by means of a simulation study for the open loop Benchmark reference and for three different control strategies.

2. CONTROL STRATEGIES UNDER STUDY

Simulations have been performed in the West® modelling and simulation environment (Hemmis NV, Kortrijk, Belgium, www.hemmis.com) that is 'accredited' for Benchmark use (Copp, 2001). All simulations have been run as specified in the benchmark protocol, i.e. perform a 100 day steady state calculation to obtain consistent initial states, run the dry weather flow conditions during 3 weeks and apply the dry, rain or storm influent conditions for the last week. Simulations for the assessment of the multi-criteria Benchmark evaluation procedure have been performed for dry weather dynamic conditions only. For the evaluation of the sensitivity of the results to changes in influent flow characteristics, dynamic simulations for rain or storm have been executed as well.

The dynamic results obtained in this way are compared to the uncontrolled (open loop) Benchmark case as defined in Copp (2001). The constant aeration intensity of the open loop plant leads to dissolved oxygen concentration (S_O) levels in the last reactor compartment, too low during day-time and too high at night, compared to the optimum level for microbial growth.

Inspired by these observations, clearly showing that significant improvements in treatment performance and energy reduction can be achieved by installing a dissolved oxygen (DO) control system, Haemelinck (2000) proposed a strategy in which DO is controlled in all aerated tanks (ASU 3, 4 and 5) using PI controllers with bounded manipulation of the aeration intensity and constant S_O set points in all tanks.

A second control strategy allows the aeration to be turned off in all three normally aerated tanks, so that denitrification can take place and nitrogen removal is improved. The setpoint for the three DO controllers now either is zero, or has the constant value applied in the first strategy. By analogy with the work of Surmacz et al. (1996), aeration is stopped as soon as the respiration rate (rate at which bacteria consume oxygen) in the first aerated tank (ASU 3) becomes sufficiently low, indicating completion of nitrification. The 'setpoint switch' of the DO controller is implemented through cascade control with an on/off master controller, that compares the measured respiration rate to a critical value. Simulations have confirmed the Surmacz strategy to be active in low-loading conditions (especially during weekends), when considerable gains in aeration energy consumption can be achieved.

Klapwijk et al (1998) proposed to switch on aeration in an anoxic reactor when denitrification is completed, as indicated by a sudden increase in respiration rate in a coupled respirometer. In this study, the Klapwijk strategy has been added to the Surmacz strategy to form a third control strategy. Implementation of the Klapwijk controller has also been done in a cascaded way: a fourth DO controller has been installed in the normally anoxic reactor ASU 2 with the Klapwijk master controller setting the setpoint of the DO controller, switching aeration on and off according to the measured respiration rate. Simulations have shown that aeration in this reactor is only switched on during high loaded conditions, as intended.

More details on the three control strategies as well as simulation results have been given by Vanrolleghem and Gillot (2001).

3. MULTI-CRITERIA BENCHMARK PERFORMANCE ASSESSMENT

In the current Benchmark protocol, the assessment of control performance is done using multi-criteria analysis on the basis of functions that quantify effluent quality, operational costs and controller performance. Effluent quality (EQ) is evaluated in two ways: (i) a weighted sum of the discharged loads of different pollutants (COD, BOD5, TSS, NO3-N and Total Kjeldahl N) is calculated in a single overall effluent quality index and (ii) constraints with respect to five effluent components (COD, BOD5, TSS, NH4-N and Total N) are defined and the percentage of time that the constraints are not met and the number of violations are reported in the form of 10 criteria. For operational cost calculation, consideration is given to pumping energy (PE) and aeration energy (AE) requirements and the amount of sludge produced (P_{sludge}), using one criterion for each. The controller performance is evaluated in terms of setpoint tracking errors and control action variability by means of 10 additional criteria. Hence, in total no less than 24 criteria must be evaluated.

3.1 Grey-scale representation of evaluation results.

There are not only a lot of Benchmark evaluation criteria, it is also difficult to evaluate the results as such (i.e. as absolute values): the values only have meaning when comparing different strategies. Henceforth, because of the variable nature of the output data generated by the benchmark simulations and the multifaceted response, the IWA Task Group on Respirometry-based Control of the Activated Sludge Process suggested that a grey-scale approach be adopted as a visual representation of the output data, with the convention being that the lighter the colour, the better the output variable (Copp, 1999). The merit of the grey-scale model is that the benchmarker is supported in interpreting the enormous amount of output data because there is no longer need to examine the magnitude of specific indicative variables.

The precise procedure for developing the grey-scale chart is still under discussion and development. At this stage, for every criterion, colours from 10% to 90% black are associated with the best and worst criterion values respectively, while grey levels of the other strategies are determined by linear interpolation between these values. Table 1 gives an example of this grey-scale approach for the case study used in this paper. Only a subset of the 24 criteria is presented. Sludge production and pumping energy, for instance, showed only insignificant differences for the four systems evaluated and were not retained. The conclusion of this multi-criterion evaluation is straightforward in this case: the Surmacz/Klapwijk strategy comes out as the 'whitest' and is selected as the 'best' on the basis of the criteria considered.

However, this conclusion depends to a great extent on the look-up table used for associating grey levels to criterion values. This look-up table is based on the limited number of output values generated in these particular simulations. Note that including another strategy that is, for instance, significantly better in one of the criteria, could change the picture completely. Omitting a strategy could also have significant effect: the less strategies are considered, the less information is obtained, as the 10% and 90% boundary conditions will become more important. This is illustrated in Table 2, where the grey-scale analysis is done for the 3 control strategies only, omitting the open loop Benchmark case. From the resulting picture, one would judge the 3 DO control as displaying very bad performance, although it doesn't look that bad in Table 1.

Table 1 Grey-scale performance representation for the open loop Benchmark plant and the 3 control strategies under study.

Output Variable	Benchmark	3 DO Control	Surmacz	Surmacz / Klapwijk
EQ (kg/d)	6945	6854	6737	6710
Aeration Energy (kWh/d)	6359	4999	4959	4994
Total N violation (% time)	8.36	6.58	5.84	5.39
Max. NO_3-N ($g.m^{-3}$)	12.26	10.80	10.03	10.08
Max. NH_4-N ($g.m^{-3}$)	9.84	9.79	10.32	9.62

Table 2 Grey-scale performance representation for the 3 control strategies under study.

Output Variable	3 DO Control	Surmacz	Surmacz / Klapwijk
EQ (kg/d)	6854	6737	6710
Aeration Energy (kWh/d)	4999	4959	4994
Total N violation (% time)	6.58	5.84	5.39
Max. NO_3-N ($g.m^{-3}$)	10.80	10.03	10.08
Max. NH_4-N ($g.m^{-3}$)	9.79	10.32	9.62

While judging control strategies on the grey-scale basis, one always has to keep in mind that this approach only provides relative comparison among the strategies for which simulation results are available. As the grey-scale approach is defined now, no conclusions can be drawn if only one control strategy is tested, and conclusions become more objective as more control strategies are taken into account. Copp (1999) has stated that ideally, a series of global grey-scale interpolation models (i.e. one for each output variable) would be used, although at this time it is not possible to anticipate a complete range of output values that may be generated in future.

3.2 Performance index weighted according to economic relevance: the Operating Cost Index (OCI).

With the current performance assessment approach, even with the grey-level presentation approach, it still remains hard to communicate the results with other benchmarkers. It is even more difficult to relate them to practice since, as yet, no direct relation is made with the different importance that is given by practitioners to each of the different criteria. It is our belief that an index in which the different criteria are weighed in an economic sense could provide a way to link the benchmarking results to practice.

In recent years considerable efforts were done to get an overview on the investment and operational costs related to wastewater treatment (Vanrolleghem *et al.*, 1996; Gillot *et al.*, 1999). Using economic weighting factors, it is currently possible to define a performance index, here called the Operating Cost Index (OCI), that combines effluent quality (fines), energy costs (aeration, pumping), and sludge treatment costs:

$$OCI = \gamma_1 \cdot EQ + \gamma_2 \cdot (AE + PE) + \gamma_3 \cdot P_{sludge} \qquad (1)$$

The economic weights γ_i are typically location (country) dependent. It seems most recommendable that each benchmarker uses local economic weights, although the Benchmark simulations themselves, leading to values for EQ, AE, PE and P_{sludge}, do not have to be performed again when benchmarking for another country.

Table 3 Suggested cost multiplication factors to convert Benchmark performance criteria into the Operating Cost Index

Cost factor	Economic weight	Value	Units
Effluent fines	γ_1	50	(€/EQ) EQ in kg/d
Energy costs	γ_2	25	(€/P_{sludge}) P_{sludge} in kgTSS/d
Sludge treatment costs	γ_3	75	(€/AE) or (€/PE) AE or PE in kWh/d

On the basis of a comparison between Flemish standards (Vanrolleghem *et al.*, 1996) and the current benchmark EQ-index, as recently performed by Haemelinck (2000), a set of acceptable 'average' weights is proposed in Table 3.

It is important to note that the proposed OCI doesn't reflect the results of an overall economic assessment as it only includes operating costs. In this way, information on investment costs for necessary additional equipment has to be gathered only for control strategies promising substantial operational cost savings. The operating cost savings, referenced to the Benchmark case, are equivalent to the yearly investment cost that can be supported.

To illustrate the approach, the control strategies under study have been benchmarked with the proposed OCI and the weights of Table 3. Results are summarized in Table 4. Giving rise to an operating cost saving of almost 40000 € per year, the purchase of the three DO probes and the adjustment of the

Table 4: Economic comparison between the open loop Benchmark and the three control strategies

Cost factor	Benchmark	3 DO control	Surmacz	Surmacz / Klapwijk
Effluent fines (€/year)	347 266	342 734	336 864	335 480
Sludge treatment (€/year)	179 548	179 602	179 580	179 636
Pumping costs (€/year)	10 596	10 596	10 596	10 596
Aeration cost (€/year)	158 976	124 978	123 987	124 851
Operating Cost Index (€/year)	***696 386***	***657 910***	***651 027***	***650 563***
Operational Cost Savings (€/year)	***0***	***38 476***	***45 359***	***45 823***

aeration system, necessary to implement the 3 DO control strategy surely seems justifiable. Although the 3 DO strategy was not that well ranked in the grey-scale evaluation of Table 1 and completely disapproved on the basis of Table 2, it is worth only 7000 € per year less than the much more complex Surmacz strategy. Given the fact that the latter requires the non-negligible investment in an on-line respirometer and the added maintenance coming with it, it is clear from an economic point of view that one would never opt to implement the Surmacz strategy. The OCI results are even more explicit for the Surmacz/Klapwijk strategy, that only offers an extra yearly saving of about 500 € compared to the Surmacz strategy, for the investment in an extra respirometer and additional complications of the control configuration.

At first sight, the results of the grey-scale evaluation of Table 1 would have led to a different conclusion, even though here also only operating cost aspects are considered. The merit of the OCI approach is that, even though investment costs are not directly considered, the operational cost savings calculated indicate which strategies can immediately be rejected on economic grounds and for which strategies further analysis should be performed. In theory, the investment costs could also be included in the grey-scale evaluation – even though they do not make part of the current Benchmark evaluation criteria - , but even then it would not be possible to reject a control strategy on an economic basis in the same straightforward way, as the weighting criteria applied in the grey-scale approach are from a very different nature. A possible future global grey-scale model is not likely to solve this problem either, since the operating and investment costs still would not be compared to each other, but independently for the different control strategies.

However, although it is rather difficult to attribute economic weights to setpoint tracking errors and control action variability in order to define a cost index that accounts for controller performance, the latter can be easily evaluated in a grey-scale study. A possible Benchmark evaluation strategy in terms of compact measures could therefore be to first calculate OCI in order to reject control strategies which are obviously not economically feasible. In a second step, the grey-scale approach could be used to evaluate intrinsic controller performance for the remaining control strategies only. Also, a more thorough economic analysis should consider investment costs and other associated costs such as maintenance in more detail.

Note that the grey-scale and OCI scores for the 3 DO control are significantly better than those of the open loop Benchmark that is currently used as reference in the Benchmark protocol. For this reason, it is proposed to replace the current Benchmark reference by the plant with 3 DO controllers. DO control is well accepted in practice which makes it a quite acceptable choice of reference. Another reason not to take into account the Benchmark case is that, in the grey-scale approach, its bad performance masks slight differences between other strategies. Moreover, when it comes to compare more advanced control strategies, it seems more logic to take a basic control strategy as a reference instead of an open loop system.

3.3 Robustness index (RI) of control performance.

In the current Benchmark performance evaluation, as well as in the evaluation based on the OCI discussed above, no attention is given to the extent to which the performance depends on the specific Benchmark plant being used in the evaluation. It is, however, important to address the issue whether the performance will deviate significantly when it is applied to a (slightly) different system. This can be done by means of a global sensitivity analysis in which parameters likely to be different for other plants are evaluated.

A sensitivity-based criterion is developed here for a single criterion of performance, namely the above mentioned Operating Cost Index, as it already summarizes many aspects of the control performance. A vector of relative sensitivities

$$S = \lfloor S_1 \quad S_2 \quad \cdots \quad S_p \rfloor \tag{2}$$

with

$$S_i = \frac{\partial OCI}{\partial \theta_i} \cdot \frac{\Delta\theta_i}{OCI} \tag{3}$$

for i = 1, …p, is calculated in which $\Delta\theta$ represents the range over which one can actually expect a plant parameter to vary for plant modifications of interest. (e.g. Rousseau *et al*., 2001).

Since the number of sensitivities that can be calculated may become quite significant, leading to

Table 5: Sensitivity S_i of the Operating Cost Index to individual process parameters and the deduced Robustness Index.

Sensitivity of OCI to	Open loop	3 DO Control	Surmacz	Surmacz / Klapwijk
Rain conditions	0.119	0.118	0.132	0.127
Storm conditions	0.0847	0.0863	0.0936	0.0904
Influent Flow rate (+10%)	0.123	0.141	0.152	0.150
Waste Flow rate (+10%)	0.0177	0.0138	0.0323	0.0249
Influent TN-concentration (+10%)	0.0848	0.1166	0.124	0.181
Influent COD-concentration (-10%)	0.0347	0.0244	0.0104	0.0110
Recycle Flow rate = 5 Influent Flow rate	0.0115	0.0116	-0.00170	-0.000279
Temperature (10^{o}C)	0.108	0.199	0.133	0.156
Robustness Index (RI)	***11.9***	***9.16***	***9.79***	***8.74***

the same criteria overload problem as the one discussed above, a means must be sought to reduce the results of this global sensitivity analysis into a single value. To this end a normalised sum of squared sensitivities was adopted as a measure of global sensitivity and its inverse is taken as the desired Robustness Index (RI):

$$RI = 1 \Big/ \sqrt{\frac{1}{p}\sum_{i=1}^{p} S_i^2} \qquad (4)$$

Evidently, RI should be maximized to achieve the largest range of applicability of the control strategy.

The p parameters for which the OCI-sensitivity has been evaluated, have been chosen to reflect process characteristics that are most likely to affect performance. For the benchmark plant it is known that settler performance is never problematic since the settler was designed sufficiently large and the adopted Takács settling properties reflect good settling. Hence, one would not be able to transfer the benchmark results to plants with limitations at the level of clarification. On the other hand, the nitrogen removal is problematic in the plant (the benchmark plant was a little designed with this in mind). Therefore, the characteristics chosen in the sensitivity analysis focus on this aspect of the plant: overall loading (through increased influent flow rate), N- and COD-loading (increased N and decreased COD concentrations), sludge age (via increased waste flow rate), nitrate recycle flow rate (5 instead of 3 times the influent flow rate) and temperature (10 instead of 15°C). In addition, the sensitivity of plant performance to rain and storm conditions, referenced to dry weather conditions, has been used to indicate robustness with respect to other dynamic simulation conditions, since only dry weather dynamic simulations have been performed in this study. Note that only one disturbance of every process characteristic has been used to calculate the sensitivity. This implies that the variation of the OCI is assumed to be linearly proportional to the variation of every process parameter, as is commonly done in a sensitivity analysis.

The results reported in Table 5 shed some light on the sensitivity of the different control strategies on changing process characteristics. Again, we notice that different process characteristics lead to different effects on the performance index. For instance, we observe that, overall, the OCI is more sensitive to changes in influent flow characteristics (rain, storm 10% increase in influent flow rate) when the control algorithms are implemented than in the open loop Benchmark case. On the other hand, the controlled systems seem less vulnerable to reduction in influent COD content.

All in all, when looking at this list of sensitivities, we end up in the same problem as dealt with above: there are too many criteria to consider. The Robustness Index (lowest line of Table 5) solves this as it summarizes the sensitivity analysis results and gives an overall picture. The RI has the heighest value in the open loop case, from which it is concluded that the OCI will then vary the least, in other words it will remain high. The performance of the controlled systems will vary more when applied to different systems, but their original OCIs (as calculated in Table 4) are better (lower) than the high OCI of the open loop system, so controlled systems will probably still perform better than the open loop system.

The main use of the current RI is to reject control strategies with obviously lower RI for use in systems with plant parameters differing from the Benchmark case, as in most practical cases. In this study, the value of the RI appears to be about the same for all control strategies. Hence, the above conclusion that the 3 DO controller is probably the best strategy among the ones studied here, is not denied. A problem here is that the absolute value of the RI doesn't have a physical meaning. For this reason, it is not clear whether the 0.63 difference in RI between the 3DO control and the Surmacz control strategy has significant practical implications. Experience from practice is needed to link the extent of transferability to practice to the numeric value of the RI.

Of course, other criteria than the OCI can be subjected to robustness analysis too. An overall assessment of robustness should be performed by calculating the Robustness Index for all performance criteria evaluated, including for instance maximum concentrations of certain pollutants, their average values and standard deviations, etc.

4. CONCLUSIONS

In this paper, the problem of multi-criteria performance evaluation when benchmarking control strategies with the COST/IWA benchmark protocol has been addressed. The usefulness of more compact multi-criteria measures has been investigated for three particular control strategies.

A grey-scale presentation was made for this case study. It appears to give a clear overview of the performance of competing strategies, but is very dependent on the specific strategies considered and thus recommended for internal comparison of these strategies rather than for communication with other benchmarkers and relating them to practice.

In an attempt to deal with this generalization problem, an economic index weighing the different operating costs associated to each strategy, termed the Operating Cost Index (OCI), is introduced. The OCI seems to be particularly useful for early stage rejection of control strategies that are not economically feasible. For subsequent evaluation of setpoint tracking errors and control action variability, the grey-scale approach is recommended.

As a compact measure for transferability of Benchmark performance to plants that have different characteristics, the Robustness Index (RI) has been proposed. It summarizes the sensitivity of the plant performance in terms of the OCI to plants with different operating conditions. Experience from practice is still needed here to relate numeric values of the RI to the extent of transferability to practice.

As a side-result of the study it is advocated to replace the current reference system used in the benchmark protocol, i.e. the open loop plant, with a plant in which dissolved oxygen control is included in all aerated reactors.

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