Robustness and economic measures as control benchmark performance criteria

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Abstract The objective of this paper was to investigate the usefulness of new multi-criteria measures to evaluate a control strategy through the Benchmark protocol. Using a case study in which respirometry-based control strategies are evaluated, the proposed measures were calculated. An economic index including weighted investment and operating costs (termed Total Cost Index – TCI) appears more powerful than a grey-scale presentation approach. Using the latter approach, it is hard to reflect the relative importance of the criteria investigated, which makes practical decisions rather difficult. In addition, a Robustness Index (RI) is proposed that allows us to evaluate the transferability of control strategies to situations different from the ones defined in the benchmark protocol. Finally, the case study shows that it may be advisable to replace the currently used open loop benchmark reference by a plant in which dissolved oxygen is controlled in all aerated reactors. This quite simple strategy also turned out to be the best one among all evaluated strategies.
Keywords Activated sludge benchmarking; control; economy; multi-criteria analysis; sensitivity analysis

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Introduction

Carefully conducted model-based simulation studies are important when evaluating control strategies for wastewater treatments plants. 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 performance.

The standard *"simulation benchmark"* plant design is comprised of five reactors in series with a 10-layer secondary settling tank (see Figure 1). IWA's Activated Sludge Model No 1 (ASM1) was chosen as the biological process model (Henze *et al*., 1987) and the double-exponential settling velocity function of Takács *et al*. (1991) was chosen as a fair representation of the settling process.

This paper focuses on the performance evaluation required to assess a given control strategy using the Benchmark protocol. On the one hand, the current multi-criteria performance evaluation is scrutinised. An economic index is proposed in the form of a single figure in which the different criteria are weighted. On the other hand, a new performance indicator is elaborated, the Robustness Index (RI), in order to tackle an important criticism made on simulation-based benchmarking, i.e. how "transferable" are the results to systems that differ in design and operation,. These new performance indicators are investigated for 3 control strategies and compared to the ones obtained for the open loop reference.

Materials and methods

All simulations were performed in the West® modelling and simulation environment (Hemmis NV, Kortrijk, Belgium) that was "accredited" for benchmark use (Copp, 2001). All simulations were run as specified in the Benchmark protocol, i.e. perform a 100 day

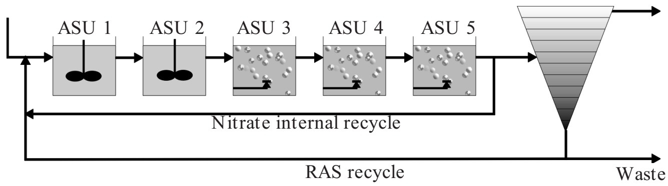

Figure 1 Configuration of the benchmark plant for carbon and nitrogen removal

Table 1 Control strategies evaluated in this study

Characteristic	3 DO control	Surmacz	Surmacz/Klapwijk
Measured variable(s)	SO [ASU 3 – ASU 4 – ASU 5]	rO [ASU 3 respirometer] SO [ASU 3 – ASU 4 – ASU 5]	rO [ASU 2 – ASU 3 respirometer] SO [ASU 2 – ASU 3 – ASU– ASU 5]
Controlled variable(s)	SO [ASU 3 – ASU 4 – ASU 5]	Not relevant SO [ASU 3 – ASU 4 – ASU 5]	Not relevant – not relevant SO [ASU 2 – ASU 3 – ASU 4 – ASU 5]
Setpoint/critical value	1.0 – 1.0 – 1.0 g O2.m–3	1200 g O2.m–3.d–1 1.0 – 1.0 – 1.0 g O2.m–3	675 – 1200 g 1O2.m–3.d–1 2.0 – 2.0 – 2.0 – 2.0 g O2.m–3
Manipulated variable(s)	KLa, [ASU 3 – ASU 4 – ASU 5]	DO Setpoint [ASU 3] KLa [ASU 3 – ASU 4 – ASU 5]	DO Setpoint [ASU 2 – ASU 3] KLa [ASU 2 – ASU 3 – ASU 4 – ASU 5]
Control algorithm	PI saturation [0,240 d–1]	On/off cascaded PIOff SO controller	Off/on [ASU 2] – On/off [ASU 3] cascaded PI Off SO controller

steady state calculation to obtain adequate initial states, run the dry weather flow conditions during 3 weeks and apply the dry, rain or storm influent conditions for the last week.

The control strategies evaluated in this study are summarised in Table 1 and commented upon below. Results are compared to those obtained in the Benchmark (Open loop), as defined in Copp (2001).

Strategy 1 (3 DO control). The evolution of the dissolved oxygen in the last tank of the open loop Benchmark (see Figure 1) clearly shows that the aeration intensity (K_La = 84 d^{-1}) is not adequate during daytime and excessive at night. Inspired by these simulation results, Haemelinck (2000) evaluated different dissolved oxygen control strategies. The best

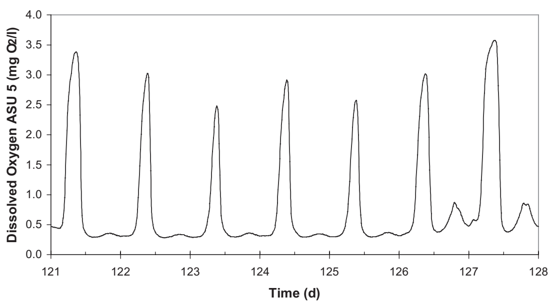

Figure 2 Dissolved oxygen concentration in the last aerated tank (ASU 5) in the open loop Benchmark (dry weather)

option turned out to be the one in which DO was controlled in all aerated tanks using PI controllers with bounded manipulation of the aeration intensity (K_La between 0 and 240 d^{-1}). Although not studied in great detail, (sub-)optimal set points were found to be 1.0 $g.m^{-3}$ in all tanks. Tuning of the controllers led to an optimal gain $K_c = 5000$ $d^{-1}(g\ O_2.m^3)^{-1}$, an integration constant $T_I = 0.01$ d and a control action in the absence of error $U_0 = 200$ d^{-1}.

Strategy 2 (Surmacz). This strategy was inspired by the work of Surmacz-Gorska *et al.* (1996) that suggested to stop aeration in an aerobic phase of an SBR as soon as the respiration rate r_O dropped below a certain threshold. This idea was transferred to the benchmark plant by introducing a single, on-line respirometer that samples from the first aerated tank (i.e. the one with the highest loading) and comparing the measured r_O with a critical value. If r_O is sufficiently low, aeration is switched off in all three normally aerated tanks (ASU 3, 4 and 5) and denitrification can take place, leading to improved nitrogen removal. Measuring r_O in the first aerated tank guarantees that priority is always given to nitrification. The implementation of this control strategy is done through cascade control of the abovementioned DO controllers that now receive their time-varying setpoint (0 or 1 g $O_2.m^{-3}$) from the Surmacz master controller. The critical r_O at which the switch in setpoint occurs was tuned at a value of 1200 g $O_2.m^{-3}.d^{-1}$. Limitations imposed in practice to minimise mechanical stress on the aeration equipment, made us set the minimum time between consecutive switches to 0.5 h.

Strategy 3 (Surmacz/Klapwijk). The control strategy proposed by Klapwijk *et al.* (1998) was added to the above Surmacz strategy. Its aim is to switch on aeration in an anoxic reactor when denitrification is completed. The indicator of this completion is the sudden increase in respiration rate of mixed liquor taken from the anoxic tank/phase. The key idea of the control algorithm is the following. Sludge is continuously sampled from the anoxic reactor and is aerated just prior to its entrance in the respirometer. As long as denitrification goes on, the continuously supplied readily biodegradable substrate (S_S in ASM1 nomenclature) is very low since the denitrification is supposed to be S_S limited in this continuous flow system. Whenever nitrate is completely removed (e.g. due to low nitrogen loading), S_S-removal no longer occurs and it starts to accumulate in the anoxic reactor and, henceforth, the respiration rate in the respirometer increases, indicating the completion of the denitrification. Implementation of this controller was again done in a cascaded way: a fourth DO controller was installed on the normally anoxic tank (ASU 2) and the Klapwijk master controller set the setpoint for this controller, switching aeration on when allowed. Tuning indicated the best critical r_O value for this Klapwijk controller was 1675 g $O_2.m^{-3}.d^{-1}$.

In Figure 2 the different strategies introduced above can be discerned: (1) the 3 DO-controllers (ControlKlaASU3/4/5) in the 3 last tanks using three DO sensors (DOSensorASU3/4/5); (2) the Surmacz-controller that sets the DO setpoints in the cascaded DO-controllers using an on-line respirometer that monitors the respiration rate in the first aerated tank (ASU3) using a bypass of mixed liquor and (3) the Klapwijk controller that sets the DO setpoint in a fourth cascaded DO controller (ControlKlaASU2) on the basis of respiration rates measured in a second respirometer sampling and aerating mixed liquor from the normally anoxic tank ASU2. Respirometers were modelled as small, aerated (DO > 2 $g.m^{-3}$) continuous flow reactors with short hydraulic retention time (3 minutes).

Figure 3 illustrates the operation of the Klapwijk (left) and Surmacz (right) control strategies. In the Klapwijk strategy, one observes that aeration in the anoxic tank is only switched on during high loaded conditions during week days when sufficient readily biodegradable substrate is supplied and, consequently, nitrate is low. It means the strategy operates in the benchmark plant as it was intended to by the authors.

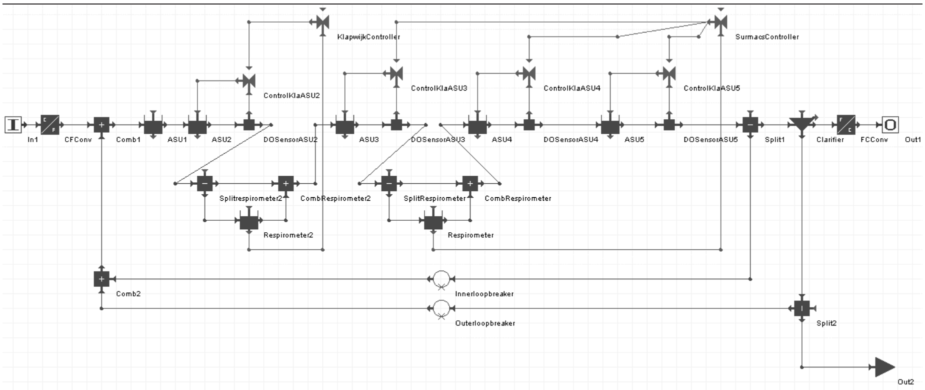

Figure 3 Layout of the combined control strategy showing two on-line respirometers and four slave DO-controllers manipulated by the algorithms of Surmacz-Gorska *et al*. (1996) and Klapwijk *et al*. (1998) respectively

When looking at the Surmacz-relevant trajectories, it can be observed that the respirometry based control strategy is active in low-loaded conditions (and thus especially in the weekends) where considerable gains in energy consumption for aeration can be achieved. We observe that the optimally tuned control strategy corresponds with maintaining a minimum concentration of ammonia of about 4 g NH_4-N.m^{-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 aeration energy (AE), pumping energy (PE), sludge disposal (P_{sludge}), controller performance (setpoint tracking errors, control action variability) and effluent quality (EQ). The latter is evaluated in two ways: (i) a weighted sum of the discharged loads of different pollutants (COD, BOD_5, TSS, NO_3-N and Total Kjeldahl N) is calculated and (ii) constraints with respect to five effluent components (COD, BOD_5, TSS, NH_4-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 total no less than 10 criteria evaluate controller performance, another 10 summarise the effluent violations together with a single overall effluent quality index, 2 criteria relate to energy usage for pumping and aeration, and a last criterion concerns sludge production. Hence, in total no less than 24 criteria must be evaluated.

In addition, it is difficult to evaluate the benchmark 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

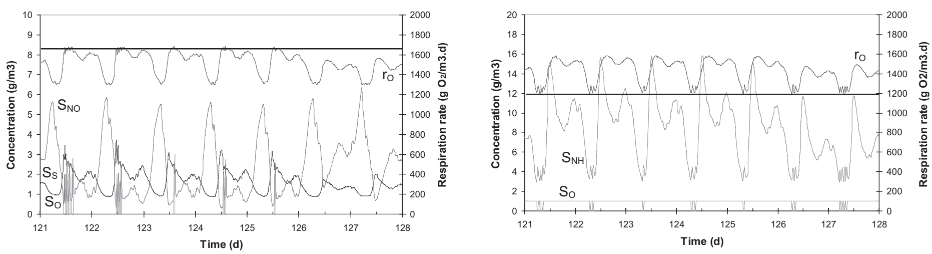

Figure 4 Typical dry weather time profiles of important variable in the controlled reactors (more details, see text). Left: Klapwijk strategy and right: Surmacz strategy

Table 2 Grey-scale representation of the output data obtained for the benchmark plant and the 3 control strategies of Table 1

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

representation of the output data (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.

Table 2 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, were only insignificantly different for the 4 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 would be selected. However, this conclusion very much depends on the look-up table used for associating grey levels to criterion values. In its current, simple version, the grey-scale approach just takes the best and worst criterion values and associates 90 and 10% black to them and then makes a linear interpolation between these values to find the grey levels of the other strategies. Note that including another strategy that is, for instance, significantly better in one of the criteria, could change the "picture" completely.

With the current performance assessment approach, even with the grey-level presentation approach, it still remains hard to communicate the results with other benchmarkers (especially if the same basis for comparison is not used to associate grey levels to criterion values). 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 (i.e. which weights should be adopted?). For instance, it is not clear whether the supposedly better Surmacz and Surmacz/Klapwijk controlled systems are worth the effort to be implemented since, for instance, the increased complexity of the system, the necessary investments in equipment to be made and the increase in maintenance needed to keep the control loop operational have not been investigated. An index in which the different criteria are weighted in an economic sense could therefore provide a means to link the benchmarking results to practice. This is the subject of the next section.

Finally, in the current performance evaluation, 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. In other words, one of the criteria that is to be considered is a measure of robustness of the control performance to benchmark input, model structure or parameter changes. This aspect will be the subject of the final section of the paper.

Performance index weighted according to economic relevance: the total cost index (TCI)

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 Total Cost Index (TCI), that combines effluent quality (fines), energy costs (aeration, pumping), additional investment costs for the implementation of the control strategy (sensors, actuators) and sludge treatment costs.

Naturally these economic weights are location (typically country) dependent. Recent work (Haemelinck, 2000) therefore focused on assessing differences with respect to the operational costs associated with sludge treatment, effluent fines and energy, occurring in different countries in Europe, South-East Asia, Australia and North America. As expected it turned out that the differences can be huge. The approach that is probably most recommendable therefore is that the benchmarker runs the economic performance evaluation protocol with his/her local economic weights. Of course, the raw simulation data (AE, PE, P_{sludge}, effluent quality criteria) must not be recalculated when benchmarking for a different country.

Rather than staying immobilised at this point, a set of acceptable "average" weights that allow reasonable comparison of different control strategies for certain case studies is proposed and applied. In Table 3 factors are suggested to weigh the different operating costs of the benchmark plant. For instance, to transform the energy consumption for aeration and pumping (expressed as kWh/d in the benchmark criteria) to the associated yearly costs, the criterion value should be multiplied with 25 € per kWh/d. On the basis of a comparison that was made between the Flemish standards for effluent quality assessment (Vanrolleghem *et al*., 1996) and the current benchmark EQ-index, Haemelinck (2000) could conclude that the weightings of the different quality indicators (COD, BOD, N, P) are very similar in both criteria. Hence, it could be stated correctly that one Flemish pollution unit corresponds with 0.56 EQs (Haemelinck, 2000). Since, currently, Flemish fines are 30 € per pollution unit, the yearly fine per EQ (expressed in kg/d) was taken as 50 €, for ease of calculation.

To illustrate the approach, the control strategies for nitrogen removal introduced in Table 1 were benchmarked with the proposed TCI and the weights of Table 3. Rather than including the cost for additional sensors and actuators and make an overall economic assessment, it was evaluated how much these strategies would reduce the operating costs and therefore warrant an investment in the necessary additional equipment. In Table 4 the TCIs and the contributing elements are presented. The initial conclusion of the study was that an investment equivalent to a cost of about 40,000 per year could be supported by the reduced operating costs, making the respirometry-based strategies feasible at first sight.

Table 3 Suggested cost multiplication factors to convert benchmark performance criteria into the Total Cost Index

Cost factor	Multiplier	Units
Effluent fines	50	(€/EQ) EQ expressed in kg/d
Sludge treatment costs	75	(€/Psludge) Psludge expressed in kgTSS/d
Energy costs	25	(€/AE) – (€/PE) AE–PE expressed in kWh/d

Table 4 Economic comparison between the standard benchmark and the strategies presented in Table 1 (data for dry weather conditions only)

Cost factor	Benchmark	3 DO control	Surmacz	Surmacz/Klapwijk
Effluent fines (€/year)	347,266 (+1.3%)	342,734	336,864 (–1.7%)	335,480 (–2.1%)
Sludge treatment (€/year)	179,548 (+0.0%)	179,602	179,580 (+0.1%)	179,636 (+0.0%)
Pumping costs (€/year)	10,596 (+0.0%)	10,596	10,596 (+0.0%)	10,596 (+0.0%)
Aeration cost (€/year)	158,976 (+27.2%)	124,978	123,987 (–1.0%)	124,851 (+1.1%)
Total Cost Index (€/year)	*696,386 (+5.9%)*	*657,910*	*651,027 (–1.0%)*	*650,563 (–1.1%)*

Evidently, the added value of the Klapwijk *et al.* (1998) strategy is not worth the investment, although the results in the grey-scale evaluation of Table 2 would have led to a different conclusion. It can therefore be concluded that the focus or weighting of criteria is quite different in both approaches. Consequently, depending on the benchmarker's focus one or the other multi-criteria approach is to be preferred.

Table 4 also points to a very simple scenario (3 DO control) that was not very well ranked in the grey-scale evaluation but warrants some more attention here: this control strategy is worth only 7,000 € 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. On the other hand, the purchase of the three dissolved oxygen probes and the adjustment of the aeration system appears justifiable. Given the above TCI and grey-scale scores that are significantly better than the ones of the open loop benchmark that is currently used as reference in the benchmark protocol, the current reference could be replaced by the plant with 3 DO controllers. Moreover, DO control is well accepted in practice which makes it a quite acceptable choice of reference.

Robustness index of control performance

The best control strategy one could think of is, of course, one that would give good results on any plant under any condition of wastewater composition, sludge properties, temperature, etc. Unfortunately, finding such a control strategy is rather utopian. However, when benchmarking a control strategy, it would be of great interest to have a criterion that could indicate the range of application of the studied control strategy. In other words, we would like to have a measure of the sensitivity of the benchmarked performance to properties of the plant. It is proposed here to perform a global sensitivity analysis in which parameters likely to be different for other plants (or whose values are not precisely defined) are evaluated.

In the first instance, this sensitivity-based criterion is developed for a single criterion of performance, i.e. the above mentioned Total Cost Index, as it already summarises many aspects of the control performance. A vector of relative sensitivities

$$S = \left[S_1 S_2 \cdots S_p \right] \qquad \text{with} \quad S_i = \frac{\partial \text{TotalCost}}{\partial \theta_i} \cdot \frac{\Delta \theta_i}{\text{TotalCost}} \quad i = 1, \cdots p$$

is calculated in which $\Delta\theta$ represents the range over which one can expect a plant parameter to vary for different plants (e.g. Rousseau *et al.*, 2001).

Since the number of sensitivities that can be calculated may become quite significant, leading to the same criteria overload problem as the one discussed above, a means must be sought to reduce the results of this global sensitivity analysis to 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 Robustness Index (RI):

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

Evidently, RI should be maximised to achieve the highest range of applicability of the control strategy.

The p parameters for which the TCI-sensitivity was evaluated, were 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 it 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 were focusing on this aspect of the plant (Table 5): 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 degrees). In addition, the sensitivity of plant performance to rain and storm conditions was used to indicate robustness. Dry weather conditions were used as reference conditions in the sensitivity analysis.

Specifically for the evaluation of the sensitivity to a lower temperature, several changes had to be made to the simulated plant. First, the following kinetic coefficients were changed from their 15 to their 10 degree values: μ_{maxH} (4.0 to 3.0 d^{-1}), b_H (0.3 to 0.2 d^{-1}), μ_{maxA} (0.5 to 0.3 d^{-1}), b_A (0.05 to 0.03 d^{-1}), k_h (3 to 1 d^{-1}) and k_a (0.05 to 0.04 d^{-1}). To maintain sufficient nitrification capacity under these low temperature conditions, the sludge age had to be increased from 10 to 14 days by reducing the waste flow rate from 385 to 300 $m^3.d^{-1}$. It is to be remarked that the total sludge mass in the system increased from 24,000 kg to 35,000 kg TSS (+45%!) which was only feasible given the good sludge settling properties and large settler area adopted in the benchmark. As this increase in sludge age was not even sufficient to achieve reasonable nitrification, the set points of the dissolved oxygen controllers were raised from 1.0 to 2.0 $O_2.m^{-3}$. Evidently, to consider the fact that the oxygen transfer efficiency improves at lower temperatures due to increased oxygen solubility, the saturation oxygen concentration under process conditions was increased.

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, overall, the TCI is more sensitive to changes in influent flow characteristics (rain, storm 10% increase in influent flow rate) when the control algorithms are implemented. On the other hand, these systems seem less vulnerable to reduction in influent COD content. All in all, when looking at this list of sensitivities, the same problem as dealt with above appears: there are too many criteria to consider.

The Robustness Index (lowest line of Table 5) solves this as it summarises the sensitivity analysis results and gives an overall picture: control clearly has a positive effect on the sensitivity of the total costs to changes in plant characteristics. However, no clear difference can be observed between the overall TCI-robustness of the different control strategies. Hence, the above conclusion that the 3 DO controller is probably the best strategy among

Table 5 Sensitivity S_i (expressed in %) of the Total Cost Index to process parameters and the deduced Robustness Index

Sensitivity of TCI to	Benchmark	3 DO control	Surmacz	Surmacz/Klapwijk
Rain conditions	1.42	1.38	1.75	1.61
Storm conditions	0.72	0.74	0.88	0.82
Influent flow rate (+10%)	1.52	1.99	2.30	2.26
Waste flow rate (+10%)	0.03	0.02	0.10	0.06
Influent TN-concentration (+10%)	0.72	1.36	1.54	3.27
Influent COD-concentration (–10%)	0.12	0.06	0.01	0.01
Recycle flow rate = 5 influent flow rate	0.01	0.01	0.00	0.00
Temperature (10°C)	1.16	3.97	1.77	2.44
Robustness Index (*RI*)	14.98	9.16	9.79	8.74

the ones studied here still holds and the proposal to take this system as the new reference for benchmarking is further supported.

Of course, other criteria can be subjected to robustness analysis too. In this study, no less than 19 criteria were evaluated (results not shown). The different control systems have different levels of robustness to changes in plant characteristics, depending on the criterion considered. An overall assessment of robustness should therefore 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.

Conclusions

This paper has addressed the problem of multi-criteria performance evaluation when benchmarking control strategies with the COST/IWA benchmark protocol. The problem of the multitude of criteria to consider was tackled in two ways. First, a grey-scale presentation of the results was proposed and illustrated and, second, a new performance index was proposed, the Total Cost Index (TCI), that weighs the different investment and operating costs associated to each strategy. Since transferability of benchmarking results to plants that have different characteristics than the benchmark plant is important, a measure for transferability was proposed, the Robustness Index. It summarises the sensitivity of the plant performance to variations in its characteristics. Whether this index can be used to indicate transferability to practice needs to be studied further.

The case study has shown that the different new approaches for performance evaluation have a different focus, but that all in all, it can be concluded that the respirometry-based control strategies do not improve performance sufficiently to warrant their implementation. 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 (DO) control is included in all aerated reactors. This system performs significantly better than the open loop and, moreover, such control strategy is already widely applied in practice.

References

Copp, J.B. (1999). The IWA simulation benchmark: Background and use. IWA Scientific and Technical Report Task Group: Respirometry in Control of the Activated Sludge Process – Interim Report #6.

Copp, J.B. (2001). *The COST Simulation Benchmark: Description and Simulator Manual*. Office for Official Publications of the European Community, Luxembourg.

Debusscher, D. (2000). Evaluation of a Respirometry-Based Activated Sludge Control Strategy Proposed by Sørensen (1980) IWA Scientific and Technical Report Task Group: Respirometry in Control of the Activated Sludge Process – Interim Report #4.

Gillot, S., De Clercq, B., Defour, D., Simoens, F., Gernaey, K. and Vanrolleghem, P.A. (1999). Optimisation of wastewater treatment plant design and operation using simulation and cost analysis. In: Proceedings 72nd WEF Conference. New Orleans, USA, October 9–13 1999.

Haemelinck, S. (2000). Evaluatie van sturingsalgoritmen voor de verwijdering van stikstof uit afvalwater (Evaluation of control algorithms for nitrogen removal from wastewaters). Engineers Thesis. BIOMATH, Ghent University. pp. 144. (in Dutch).

Henze, M., Gujer, W., Mino, T. and van Loosdrecht, M. (2000). *Activated Sludge Models ASM1, ASM2, ASM2d and ASM3. IWA Scientific and Technical reports No. 9*. London, UK.

Klapwijk, A., Brouwer, H., Vrolijk, E. and Kujawa, K. (1998). Control of intermittently aerated nitrogen removal plants by detection endpoints of nitrification and denitrification using respirometry only. *Wat. Res.*, **32**, 1700–1703.

Rousseau, D., Verdonck, F., Moerman, O., Carrette, R., Thoeye, C., Meirlaen, J. and Vanrolleghem, P.A. (2001). Development of a risk assessment based technique for design/retrofitting of WWTPs. *Wat. Sci. Tech.*, **43**(7), 287–294.

Surmacz-Gorska, J., Gernaey, K., Demuynck, C., Vanrolleghem, P.A. and Verstraete, W. (1996). Nitrification monitoring in activated sludge by oxygen uptake rate (OUR) measurements. *Wat. Res.*, **30**, 1228–1236.

Spanjers, H., Vanrolleghem, P., Nguyen, K., Vanhooren, H. and Patry, G.G. (1998). Towards a simulation-benchmark for evaluating respirometry-based control strategies. *Wat. Sci. Tech.*, **37**(12), 219–226.

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

Vanrolleghem, P.A., Jeppsson, U., Carstensen, J., Carlsson, B. and Olsson, G. (1996). Integration of WWT plant design and operation – A systematic approach using cost functions. *Wat. Sci. Tech.*, **34**(3–4), 159–171.