BENCHMARKING WWTP CONTROL STRATEGIES WITH ROBUSTNESS AND ECONOMIC MEASURES AS PERFORMANCE CRITERIA

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ABSTRACT

Carefully conducted model-based simulation studies have become an important part of studies evaluating control strategies for wastewater treatments plants. During the past four years a consortium of researchers and practitioners developed a standard test methodology called the Benchmark, a simulation procedure defined around a simulation model, a plant layout, realistic influent loads and a test protocol that provides an objective measure of performance. It is this measure of performance that is the focus of this paper. First, a total cost index, TCI, is developed that makes a weighted sum of the different performance evaluation criteria (energy consumption, sludge production, effluent quality, …). In addition a robustness index is proposed that aims to evaluate the sensitivity of the performance to the WWTP characteristics. It requires some well-designed additional simulations that evaluate the performance under process conditions that differ slightly from the ones defined in the benchmark protocol.

INTRODUCTION

When new control strategies for wastewater treatment plants are proposed, an increasingly applied step in their development consists of a simulation based evaluation of their performance, prior to the implementation in practice. Such simulation studies allow to analyze the added benefit of the strategy in terms of cost reduction and process stability, allow to optimize the settings of the control algorithm, e.g. set-points and controller gains, and allow to evaluate the sensitivity to abnormal situations (e.g. storm conditions, equipment failures). Simulation can therefore provide convincing elements for a decision to initiate implementation of a novel control strategy, or it can prevent the implementation of a control strategy that would not lead to any benefit or would jeopardize the good operation of the treatment plant.

The IWA Task Group on Respirometry in Control of the Activated Sludge Process and the European COST actions 682 and 624 jointly developed a standard test methodology, called the Benchmark (Spanjers *et al*., 1998; Copp, 2001) for evaluating the performance of WWTP control strategies in a standardized way. This methodology 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. It is the latter aspect that is the focus of this paper.

The standard 'simulation benchmark' plant design is a predenitrifying nitrogen removal system represented by 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 (Spanjers et al., 1998). Simulations are performed with different dynamic influent files (dry, rain and storm weather) and the simulation results are interpreted in terms of process performance.

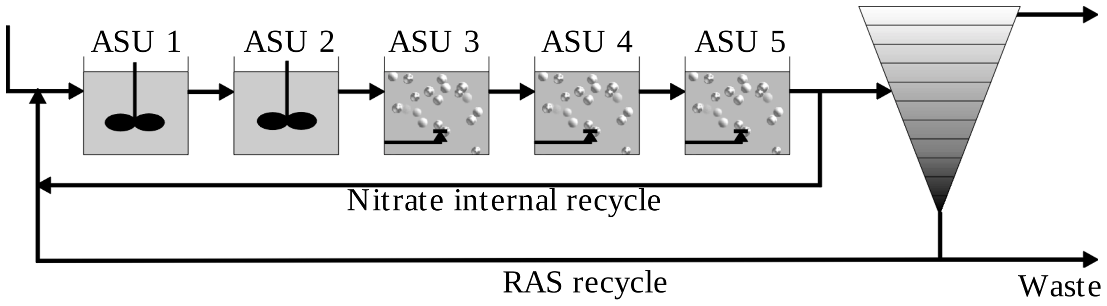

Figure 1. Configuration of the benchmark plant for carbon and nitrogen removal

Currently, to assess performance multi-criteria analysis is done using functions that quantify aeration energy, pumping energy, sludge disposal, controller performance (setpoint tracking errors, control action variability) and effluent quality. The latter 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 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 total no less than 10 criteria evaluate controller performance, another 10 summarize the effluent violations together with a single overall effluent quality index, a further 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 the current benchmark definition.

The bottom line is that it is hard to communicate the results with other benchmarkers and 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. For instance, it is not clear whether a supposedly better controlled system is worth the effort to be implemented. It is our belief that an index in which the different criteria are weighted in an economic sense could provide the means to link the benchmarking results to practice.

Another problem we want to address with the presented work is that in the performance evaluation no attention is given to what extent the performance depends on the specific benchmark plant being used in the evaluation. It is, in our view, 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.

MATERIALS AND METHODS: SIMULATED PLANTS

All simulations were performed in the West® modeling and simulation environment (Hemmis NV, Kortrijk, Belgium, www.hemmis.com) that was “accredited” for benchmark use (Copp, 2001), i.e. it was compared with a range of commercial and dedicated simulation software packages and provided identical results. All simulations were run as specified in the benchmark protocol, i.e. a 100 day steady state calculation is performed first to obtain adequate initial values of the state variables. Then dry weather flow conditions are applied during 3 weeks to the simulated plant followed by either the dry, rain or storm influent conditions for the last week. The simulation results of this last week are used to evaluate the controller performance.

Three control strategies were benchmarked in this study and compared to the open loop Benchmark.

The first strategy (3DO control) was inspired by the finding that the constant aeration intensity (K_La=84 d^{-1}) of the open loop benchmark plant leads to dissolved oxygen in the last tank down to only 0.5 $g.m^{-3}$ during day-time and up to 3.5 $g.m^{-3}$ at night. This clearly shows that the aeration system is not adequate and that significant improvements in treatment performance and energy reduction can be achieved by installing a DO control system. Haemelinck (2000) evaluated different dissolved oxygen control strategies. The best 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}) and set points of 1.0 $g.m^{-3}$ in all tanks.

The second strategy (Surmacz) was inspired by the work of Surmacz *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 (for the simulated plant 1200 $g.m^{-3}.d^{-1}$). 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. Figure 2 provides some of the relevant simulation results of the benchmark plant with this controller active. It can be observed that the respirometry based control strategy is active in low-loaded conditions (and thus especially in the weekends). Under these conditions considerable gains in energy consumption for aeration can be achieved. We also observe that the optimally tuned control strategy corresponds with maintaining a minimum concentration of ammonia of about 4 g NH_4-$N.m^{-3}$.

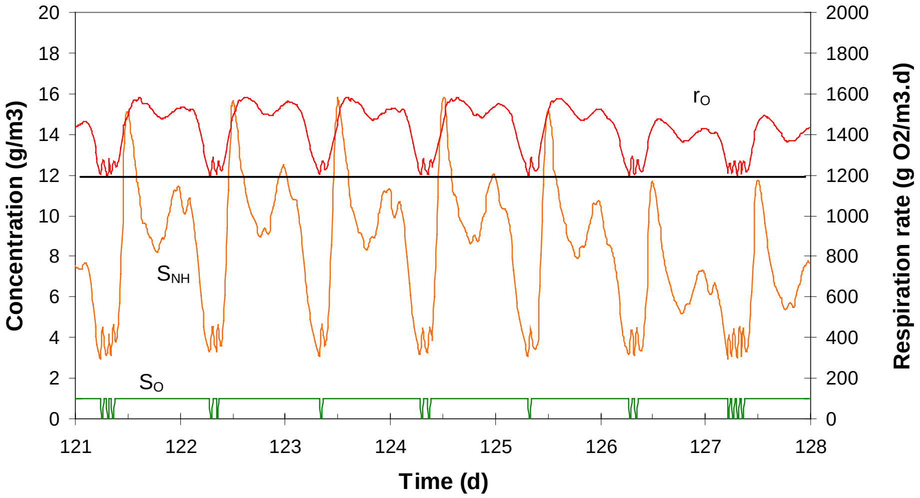

Figure 2. Typical dry weather time profiles of important variable in the reactors controlled by the Surmacz *et al.* (1996) strategy (more details, see text).

The third control strategy (Klapwijk/Surmacz) that was evaluated adds the strategy proposed by Klapwijk *et al.* (1998) on top of the above Surmacz strategy. Its particular 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. The best critical r_O value for this Klapwijk controller was found to be 1675 g O_2.m^{-3}.d^{-1}. Figure 3 illustrates the operation of 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.

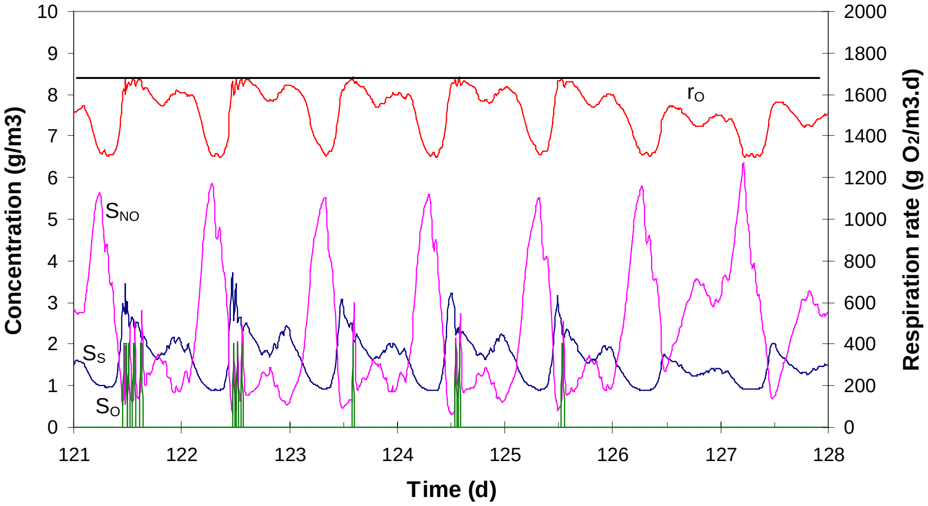

Figure 3. Typical dry weather time profiles of important variable in the reactors controlled by the Klapwijk *et al.* (1998) strategy (more details, see text).

The different strategies introduced above are summarized in Table 1 and illustrated in Figure 4. One can find: (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 set points 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 modeled as small, aerated (DO > 2 g.m^{-3}) continuous flow reactors with short hydraulic retention time (3 minutes).

Table 1. Control strategies evaluated in this study

Characteristic	3 DO control	Surmacz	Surmacz / Klapwijk
Measured variable(s)	S_O [ASU 3 – ASU 4 – ASU 5]	r_O [ASU 3 respirometer] S_O [ASU 3 – ASU 4 – ASU 5]	r_O [ASU 2 – ASU 3 respirometer] S_O [ASU 2 – ASU 3 – ASU 4 – ASU 5]
Controlled variable(s)	S_O [ASU 3 – ASU 4 – ASU 5]	Not relevant S_O [ASU 3 – ASU 4 – ASU 5]	Not relevant – Not relevant S_O [ASU 2 – ASU 3 – ASU 4 – ASU 5]
Setpoint / Critical value	1.0 – 1.0 – 1.0 g O_2.m^{-3}	1200 g O_2.m^{-3}.d^{-1} 1.0 – 1.0 – 1.0 g O_2.m^{-3}	1675 – 1200 g O_2.m^{-3}.d^{-1} 2.0 – 2.0 – 2.0 – 2.0 g O_2.m^{-3}
Manipulated Variable(s)	K_La, [ASU 3 – ASU 4 – ASU 5]	DO Setpoint [ASU 3] K_La [ASU 3 – ASU 4 – ASU 5]	DO Setpoint [ASU 2 – ASU 3] K_La [ASU 2 – ASU 3 – ASU 4 – ASU 5]
Control Algorithm	PI saturation [0,240 d^{-1}]	On/Off cascaded PIOff S_O controller	Off/On [ASU 2] - On/Off [ASU 3] cascaded PIOff S_O controller

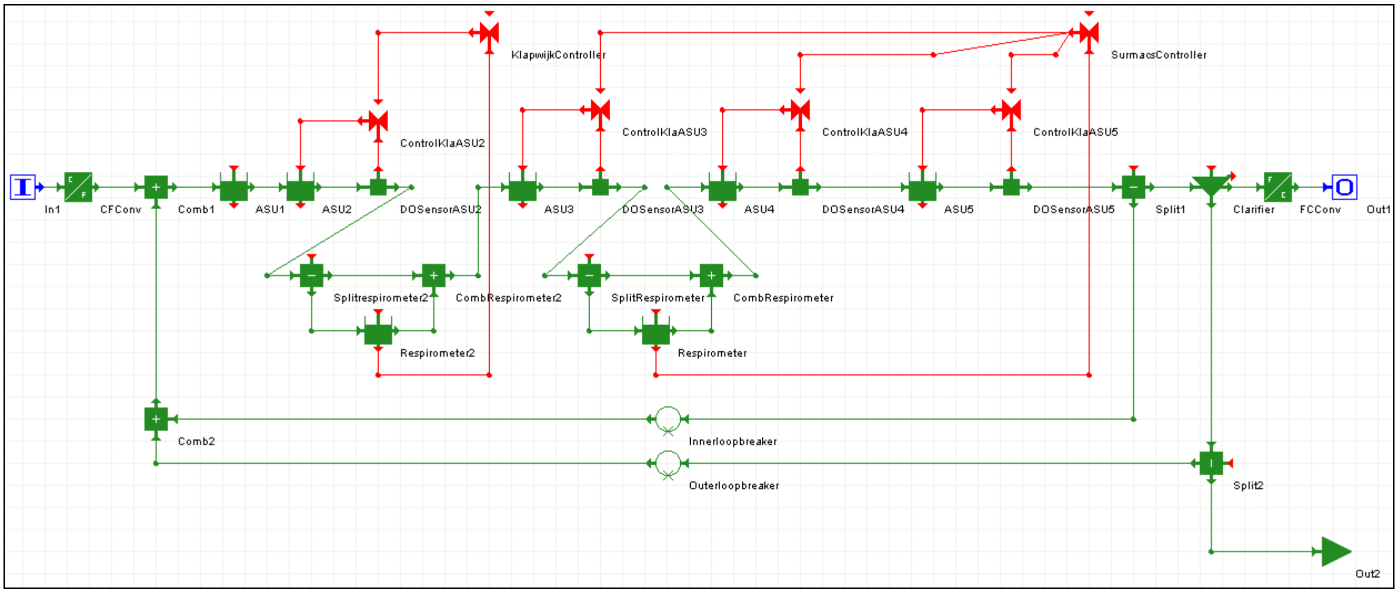

Figure 4 Layout of the combined control strategy showing two on-line respirometers and four slave DO-controllers manipulated by the algorithms of Surmacz-Gorska et al. (1996) and Klapwijk et al. (1998) respectively.

PERFORMANCE INDEX WEIGHTED ACCORDING TO ECONOMIC RELEVANCE: THE TOTAL COST INDEX

Investment and operational costs related to wastewater treatment have been studied in great detail recently (Gillot et al., 1999; Vanrolleghem et al., 1996). Using economic weighting factors, it is currently possible to create a performance index 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. The proposed performance index, called Total Cost Index (TCI), uses the weighting factors given in Table 2 (but any other weighting factors could be used as well to reflect different economic characteristics in other countries) to weigh the criteria calculated in the benchmark protocol (Copp, 2001), i.e. aeration energy (AE, kWh/d), pumping energy (PE, kWh/d), sludge production (P_{sludge}, kg TSS/d) and effluent quality (EQ, kg/d) calculated from simulated COD, BOD, SS, TN, ammonia and nitrate data with a function similar to the one discussed in Vanrolleghem *et al*. (1996). Table 2 is used as follows: 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.

Table 2. Suggested cost multiplication factors to convert benchmark performance criteria into the Total Cost Index (after Haemelinck, 2000).

Cost factor	Multiplier	Units
Effluent fines	**50**	**(€/EQ) EQ expressed in kg/d**
Sludge treatment costs	**75**	**(€/P_{sludge}) P_{sludge} expressed in kgTSS/d**
Energy costs	**25**	**(€/AE) - (€/PE) AE–PE expressed in kWh/d**

The respirometry-based control strategies for nitrogen removal proposed by respectively Surmacz-Gorska et al. (1996) and Klapwijk et al. (1998) and a combination thereof were benchmarked with the TCI as multi-criterion. 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. The 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 these strategies feasible at first sight. At this stage it is already clear that the Klapwijk strategy is not worth the investment of a second respirometer as it does not improve the performance expressed as TCI compared to the Surmacz strategy.

More importantly, however, the very simple scenario of installing three DO-controllers on the aerated tanks was found to be worth only 7.000 $ per year less than the respirometry-based ones. It can therefore be concluded that the additional cost reductions that could be obtained by installing one or two respirometers in addition to 3 DO-control systems are not sufficient to warrant their purchase. 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 that is significantly better than the one of the open loop benchmark that is currently used as reference in the benchmark protocol, we propose to replace the current reference 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

When benchmarking a control strategy, one of the criteria of great interest is the application range of the studied control strategy. In other words, we would like to have a measure of the sensitivity of the benchmarked performance to different properties of the plant. It is proposed here to perform a global sensitivity analysis in which parameters likely to be different for other plants are evaluated.

Such sensitivity study is conducted on a single criterion for performance, i.e. the above mentioned Total Cost Index and the *p* parameters for which the sensitivity is evaluated, may include design criteria (volumetric and biomass loading rate, sludge and hydraulic retention time, anoxic/aerobic ratio, maximum aeration capacity), wastewater characteristics (overall concentration, average flow rate, C/N ratio, rain/storm/dry) and sludge characteristics (max. growth rates, hydrolysis rate, anoxic reduction factors). A vector of relative sensitivities

$$\mathrm{S} = \left[\mathrm{S}_1 \mathrm{S}_2 \cdots \mathrm{S}_p\right] \qquad \text{with} \quad \mathrm{S}_i = \frac{\partial \mathrm{TotalCost}}{\partial \theta_i} \cdot \frac{\Delta\theta_i}{\mathrm{TotalCost}} \quad i = 1, \cdots p$$

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

An overall sensitivity index $\sqrt{\sum_p \mathrm{S}_i^2 / p}$ will be calculated as a balanced indicator of the sensitivity. Its inverse is the desired Robustness Index that should be maximized to achieve the highest range of applicability of the control strategy.

The characteristics chosen in the sensitivity analysis conducted for illustration purposes were focusing especially on the nitrogen removal properties of the plant (Table 3): 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.

The sensitivities reported in Table 3 shed some light on the sensitivity of the different control strategies to 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 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.

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

However, this list of sensitivities brings us in the same difficult situation we were in before introduction of the TCI: 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: Control clearly has no positive effect on the sensitivity of the total costs to changes in plant characteristics. The process becomes less robust against variations. However, these systems are also working at a better performance level which apparently makes that they deteriorate a bit more when confronted with other characteristics. The performance under these deteriorated conditions is still significantly better than the ones obtained with the uncontrolled system.

Importantly, 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 the ones studied here, still holds.

CONCLUSIONS

When benchmarking control strategies with the COST/IWA benchmark protocol one is confronted with the problem of the multitude of criteria to consider. 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 summarizes the sensitivity of the plant performance to different characteristics of the plant. Whether this index can be used to indicate transferability to practice needs to be studied further.

Respirometry-based control strategies were evaluated as an illustrative case study. It 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. On the other hand, a plant in which dissolved oxygen (DO) control is included in all aerated reactors performs significantly better than the open loop, and the costs for implementation can be recovered very quickly from the reduced aeration costs.

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