DEPARTMENT OF APPLIED MATHEMATICS,
BIOMETRICS AND PROCESS CONTROL

Control of Activated Sludge Wastewater Treatment by using Respirometry

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1. Introduction

Control theory is not the primary topic of this contribution. However, some background must be given here in order to clarify the discussion below. The elementary control concepts presented here are focused on respirometry-based control. Therefore, in some cases we will divert somewhat from general control concepts if this improves the clarity.

In the operation of wastewater treatment plants the ***basic objective*** is to keep the plant running, while meeting the effluent standards and minimising costs. To achieve the basic objective a number of ***operational objectives*** have to be defined (Fig. 1). Typical operational objectives are:

- grow the right biomass population;
- maintain good mixing where appropriate;
- maintain adequate loading;
- maintain adequate aeration intensity;
- favour good settling properties.

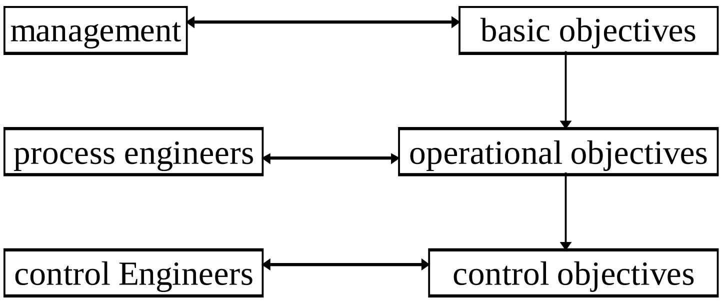

Figure 1. Levels of objectives and relation to professionals involved.

In order to be accomplished, these objectives cannot be implemented in control strategies right away. Therefore, more specific *control objectives* have to be formulated, such as:

- keep the respiration rate at 42 mg $l^{-1}h^{-1}$;
- keep the mixed liquor suspended solids concentration at 3 g l^{-1};
- track the dissolved oxygen concentration according to a given pattern.

The correct choice of these objectives requires thorough knowledge of the process including couplings between different process units. Note that each level of objectives is dealt with by a different group of professionals. The control objectives can be achieved by using manual or automatic controllers. The task of a controller is twofold: set point tracking and disturbance rejection. Set point tracking means that the controller tries to let the ***controlled variable*** follow a changing desired value, the ***set point***. Disturbance rejection means that the controller tries to compensate for the effects induced by external disturbances to keep the controlled variable on the set point value.

1.1. System description

The activated sludge process can be considered in terms of system theory (Fig. 2). Variables that influence the process are called ***inputs***. Some of these can be manipulated, so these are called ***manipulated variables***. Typical manipulated variables are: aeration intensity, waste flow rate, recycle flow rate or influent flow distribution ratio. Other inputs are not manipulated or cannot be manipulated and these are defined as ***disturbances***.

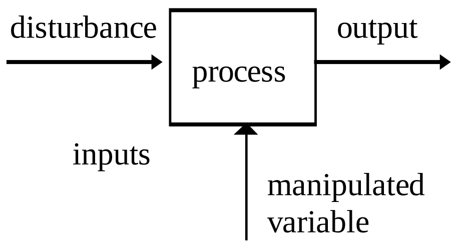

Figure 2. Activated sludge process system.

Some of the disturbances can be measured. Many, but not all the disturbances to a treatment plant are related to the influent, like the influent flow rate and concentrations. Other disturbances are caused by the operation of other processes than the activated sludge process, like filter back washing or digester supernatant recycling. Disturbances are also due to equipment failures. How a variable is defined depends on the context and the corresponding system definition. For example, the waste flow rate sometimes can be manipulated. If not, it is considered a disturbance, e.g. when the waste flow rate changes due to pump failure or blockage.

Variables that one is interested in and that are influenced by the inputs are called ***outputs****.* For example, the output respiration rate is influenced by the input (as a disturbance or as a manipulated variable) waste flow. However, in a different system definition, the same variable respiration rate can be considered as an input (disturbance), while another variable like DO concentration acts as an output. Hence it is important to define the context if a process, i.e. to identify the variables of interest (outputs) and the variables influencing these (inputs).

1.2. Controller structures

In addition to the three process system variable types (disturbance, manipulated variable and output), in a controller structure there is also a set point. In a controlled system (including process and controller) the set point and output always refer to one and the same variable: the ***controlled variable***.

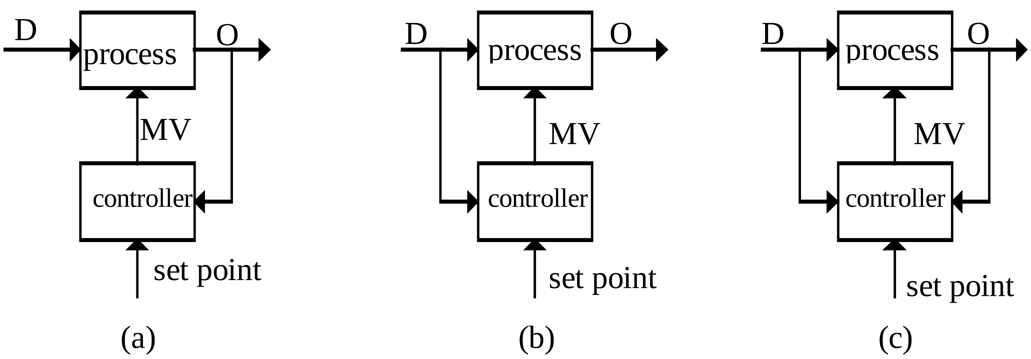

Figure 3. Controller structures: a) Feedback, b) Feedforward and c) Feedforward/Feedback. D=disturbance, MV=manipulated variable, O=output.

The standard ***feedback*** (FB) control scheme is depicted in Fig. 3a. Measured variables are passed on to the controller and compared to *set point* (or reference) values. The objective of the controller is to keep the measured value (of the controlled variable) as close as possible to the set point value, despite the disturbances (disturbance rejection). Usually the set point value is constant, but it may also be varying (set point tracking). As shown below, in ***cascaded control*** the output of one controller (the manipulated variable) becomes the set point of another controller.

When disturbances can be measured, ***feedforward*** (FF) control can be applied. The manipulated variable is adjusted to compensate for the anticipated effect of the disturbance on the controlled variable. The ideal is that the effects of the measured disturbance and the FF control action exactly cancel out, and there is no deviation from the set point. The basic design principle of a FF controller is illustrated in Fig. 3b.

It is obvious that a FF controller needs a method to calculate how much adjustment of the manipulated variable is required to cancel out the effect of the disturbances, i.e. a model is required. Since the result of the disturbance on the plant output has not yet been seen, the controller has to be able to calculate its consequence before it actually happens. A car driver, for example, acts with FF control. Any disturbance ahead, like an uphill road or an obstacle, should be acted upon before it has influenced the car behaviour (measured by speed and position). The driver needs a good (mental) model of the car dynamics to compensate for such disturbances. For instance, he speeds up before he reaches the hill or turns at a sufficient distance from the obstacle. It is not possible to completely cancel the influence of a disturbance with FF control, since models and measurements are not perfect. Therefore, it is always strongly recommended to combine a FF controller with a FB controller, Fig. 3c. The FF controller makes a fast compensation for the disturbance, while the FB controller adjusts in a slower time scale, acting on the measured response on the non-compensated part of the disturbance. This is how response speed can be combined with accuracy.

1.3. Examples

To illustrate the concepts of system descriptions and its relations to controller structures, let us consider two control strategies, DO control and respiration rate control. Before we look into the control configurations we have to understand the various cause-effect relationships (models!). Fig. 4 depicts three variables, substrate concentration S_S (here we only consider one substrate), DO concentration S_O and respiration rate r_O. It is apparent that r_O will be influenced by inputs like pH, temperature, biomass concentration, toxicity, etc. If the inputs are not manipulated or cannot be manipulated, these are considered disturbances. The influent substrate concentration $S_{S,in}$ will affect the substrate concentration in the aeration tank, S_S which in turn will influence r_O. Likewise, the aeration intensity F_{in} will affect S_O, which in turn will affect r_O. However, the coupling between r_O, substrate concentration and DO concentration is bi-directional. A changing respiration rate in turn will influence the substrate concentration and the DO concentration. The actual direction of the cause-effect relationship depends on the control system definition specified by the control engineer with a particular control objective in mind.

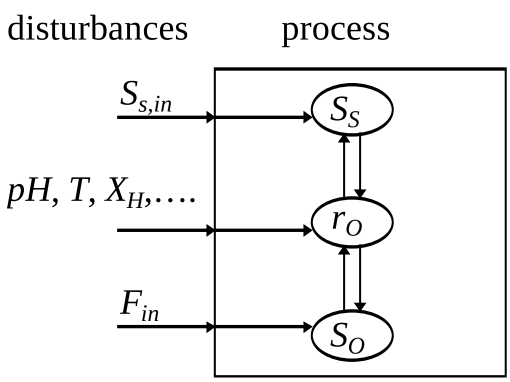

Figure 4. Relationship between substrate concentration S_S *, DO concentration* S_O *and respiration rate* r_O *.*
Ovals indicate variables, and arrows cause-effect relationships.

Example 1: DO control strategy

Consider a traditional DO controller, Fig. 5. The feedback part of the control is obtained by measuring the DO concentration (output variable). This value is compared with the DO set point, and the aeration intensity is subsequently manipulated to keep the DO concentration close to the set point, despite disturbances. The feedback DO controller does not consider the respiration rate. With respect to the process the respiration rate r_O is a disturbance in the same way as any other disturbance. For example, assume that activated sludge is washed out from the clarifier or that a malfunction of the return sludge pump causes the biomass concentration to decline. As a result, r_O will drop. The feedback DO controller will notice that less air is needed to reach the DO set point value and reduce the aeration intensity, but it does not explicitly recognise the disturbance. A decreasing substrate concentration would have caused the same control action. If the respiration rate is measured in the aeration tank, this signal of the process disturbance can be fed forward to the controller, thus improving the control performance. This can be noted in the DO concentration because the transient deviation due to the disturbances in respiration rate will be significantly reduced. In the ideal case it will be cancelled out by the feedforward controller. The fact that there is a coupling back from the DO concentration to r_O, as shown in Fig. 4, is not considered by this control structure.

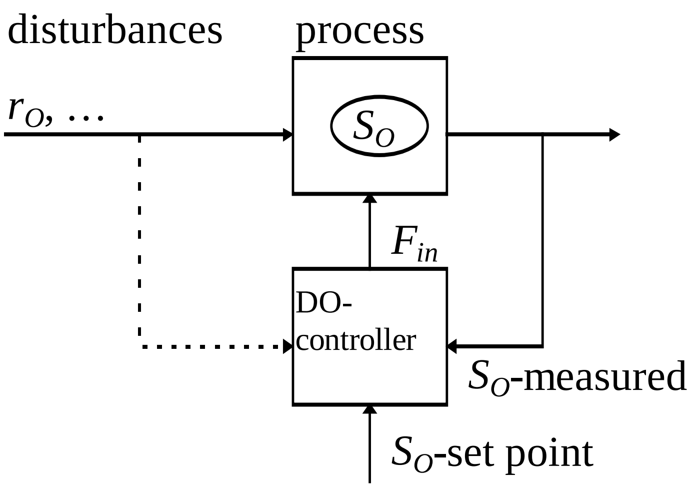

Figure 5. Traditional DO feedback control with potential feedforward from substrate concentration or respiration rate.

Example 2: Cascaded DO control strategy

Usually the DO controller does not directly manipulate the aeration intensity via some valve or by changing the aerator power. Rather, the controller typically manipulates just the set point of the aeration intensity, i.e. the aeration intensity that is desired to keep the DO concentration close to its set point. Then, a separate controller will manipulate a valve or aerator power so that the desired aeration intensity is accomplished (Fig. 6). This is particularly valuable when, for instance, the valve is non-linear, i.e. will have a different gain for different air flows. When one controller affects the set point of another controller it is a *cascaded* control system. The inner loop can be tuned completely independent of the outer loop. The DO controller then is easier to tune and to commission. Note here that the “aeration intensity controller” and “DO controller” are different things.

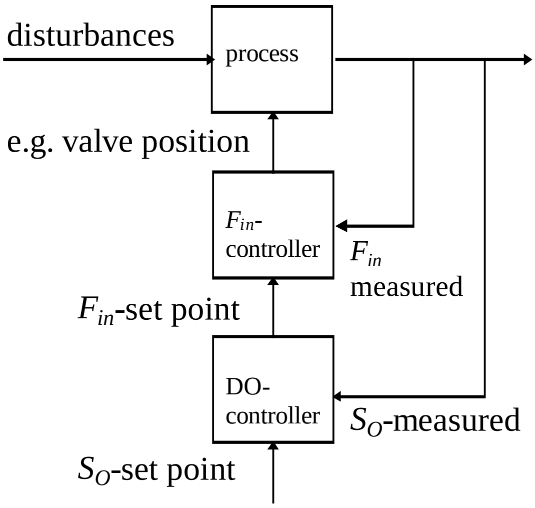

Figure 6. Cascaded control of DO.

Example 3: Respiration rate control strategy

As a comparison to example 1, consider a respiration rate control strategy (Fig. 7). The objective of the controller here is to keep the maximum respiration rate ($r_{O,max}$) close to its set point value. The maximum respiration rate is here used as a surrogate for the biomass concentration and the controller therefore aims at keeping the biomass concentration at a desired level, expressed as a $r_{O,max}$ set point. Consequently, the maximum respiration rate is measured and compared to the set point. The controller manipulates, for example, the return sludge flow Q_{ras} to achieve this goal. For the DO controller, r_O was considered a disturbance. Here r_O is the controlled variable. Note that the biomass concentration (X_H) can be considered an input variable influencing variable the maximum respiration rate that is changed by manipulating the return sludge rate so that $r_{O,max}$ is changed adequately. The controller does not specifically know the biomass concentration. The respiration rate is changed due to disturbances, like the influent flow rate pushing biomass out of the aeration tank into the settler. If the influent flow rate is measured, then this signal can be fed forward to the controller. Ideally, the FF controller should command a change of the return sludge rate before the disturbance has appeared in $r_{O,max}$. Thus, a good model of the dynamics of respiration as a function of the influent flow rate is needed. Note that the choice of the controller structure imposes the directions of the cause-effect relationships between flow rate, respiration rate and activated sludge concentration.

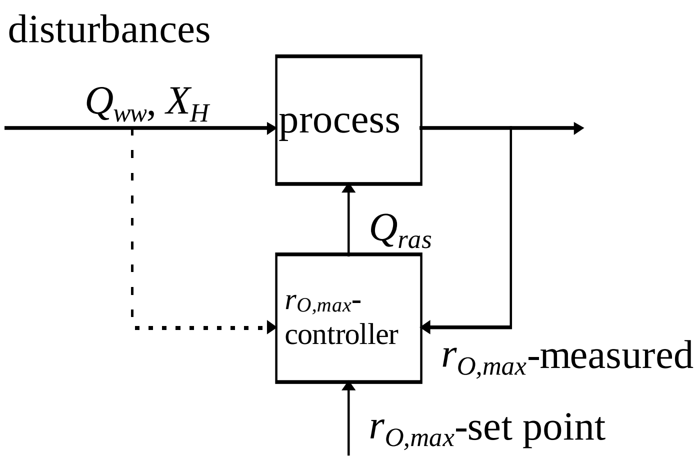

Figure 7. Respiration rate control, by manipulating return sludge flow (Q_{ras}), with possible feedforward from an influent flow measurement.

Example 4: Cascaded respiration rate control

The scheme in Fig. 7 can be further refined, as depicted in Fig. 8. Instead of letting the maximum respiration rate controller influence the return sludge flow rate directly it will only change the return sludge flow rate set point. Then an inner control loop, a Q_{ras} controller, will make Q_{ras} change until the return flow rate has reached the desired set point. The advantage of this cascaded control is that the outer loop, the respiration rate controller, does not have to deal with the dynamics of the recycle sludge pump: it is taken care of by the inner loop. Naturally, the cascaded control can be combined with a FF controller.

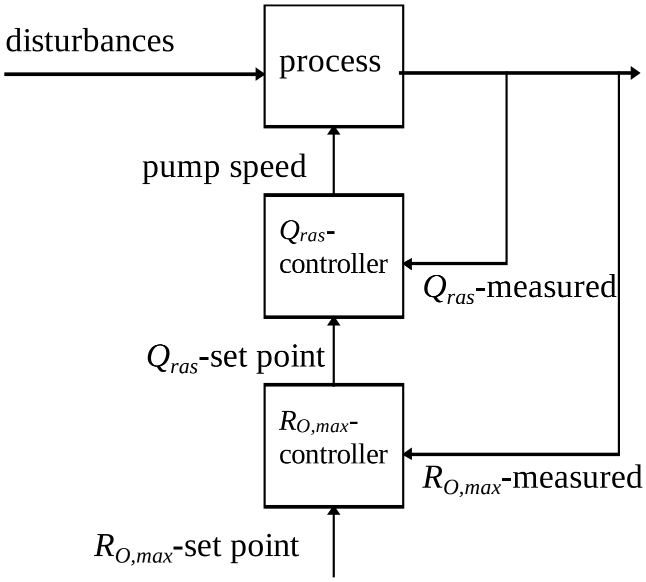

Figure 8. Cascaded respiration rate control.

1.4. Concluding remarks

Above some elementary control concepts were reviewed in order to facilitate the discussion on respirometry-based control in the next section. It was shown that the objectives in wastewater treatment can be classified in three levels: basic objectives, operational objectives and control objectives, and that each of these is dealt with by a different group of professionals. The wastewater treatment process can be described by defining three kinds of process system variables: disturbances and manipulated variables (both considered as inputs) and outputs. On the basis of these variables, three basic controller structures were discussed: FB, FF and a combination of these. A number of examples were given and it was illustrated that respiration rate can be considered as a (measure of a) disturbance as well as a (measure of a) controlled variable in different system descriptions and control structures.

2. Respirometry in activated sludge process control: Delineation

The original aim of the study reported in this contribution was to summarise the potential applications of respirometry, to evaluate the relative merits of the control strategies found using consistent criteria, and from that to develop a how-to-do protocol. For reasons given below, however, the work had to be restricted to the presentation of a structured overview of strategies found.

This section addresses four items. First, the method by which different strategies were collected and the procedure adopted to decide on inclusion or exclusion of a strategy is presented. Subsequently, the reasons for the absence of an evaluation of the strategies by the Task Group are presented. Third, the different possibilities for structuring the control strategies are reviewed, illustrating the great number of aspects of respirometry-based control strategies. Finally, the control strategies retained are described within the structure adopted and are illustrated with some examples.

A literature study and discussions with practitioners were done. Sixty years of literature were covered as the first reference found dated back to 1936 ("Odeeometer: Its place in the control of activated sludge plants", L.H. Kessler, Water Works and Sewerage, 83, 13). Control strategies were retained in which information obtained from a respirometer was used somehow within the control strategy. Basically, all strategies are included in which the respiration rate or a deduced variable is used as input to the controller.

During the collection of these proposals and applications, no a priori judgement was made on the plausibility of the strategy. The measurement and control strategy and its implementation were assumed to be as the author intended these to be. As applications we considered bench, pilot and full-scale implementations of these strategies. A prerequisite for inclusion in the list of control strategies was that at least the controlled variable (i.e. the control objective of the strategy) and the manipulated variable were clearly stated.

2.1. Why no evaluation of control strategies by the IWA Task Group?

One of the goals of the Task Group was to evaluate control strategies in which respirometry plays a role. However, for three main reasons given below, this task could not be completed.

2.1.1. Lack of insight and common terminology

One reason causing difficulties when evaluating the proposals is insufficient insight demonstrated in many papers and lacking overview by the proposers of one of the disciplines involved, i.e. control engineering and (bio)process engineering (Fig. 1). Some problems encountered in control engineering proposals are due to the misunderstanding of measurements. Examples are the application of respiration measurements under wrong conditions or the belief that any respiration rate measurement principle provides a correct measurement of the respiration rate in the reactor. In contrast, process engineers tend to apply control theory intuitively. For instance, they do not provide a stability analysis of their proposal or have not considered tuning the controller's parameters adequately.

A related problem is a lack of common terminology. For instance the word "control" is used in such combinations as "waste flow control", "MLSS control" and "sludge age control" although "control" has different meanings in each case. (In fact these aspects all pertain to one strategy: control of MLSS concentration by using waste flow rate as the manipulated variable with the secondary objective to track a given sludge age.) As a result, the Task Group had to devote significant effort to redefine the proposals to fit within the adopted control terminology. In some cases the original objective could not be retrieved from the publications and there was a hazard that the Task Group would misinterpret the strategy.

2.1.2. Lack of consistent criteria for comparison

Another difficulty with the evaluation of the control strategies was that it is virtually impossible to compare the merits of different proposals when they are developed for completely different plant configurations, influent characteristics, process operations, etc.

Evidently, some restricted evaluations can be done directly on the proposal itself. On the one hand, an evaluation can be made in absolute terms. For instance, the stability of the proposed control strategy can be evaluated, or the appropriateness of an underlying assumption can be checked. On the other hand, a relative evaluation can be done. This is especially feasible for those proposals that have been evaluated within the reported study. Mostly this is done by comparing a performance criterion before and after the control strategy was implemented. For some studies, two or more strategies were tested on the same configuration and these results could have been reported here. However, it was felt that this would not contribute to a good general evaluation of the usefulness and limitations of respirometry-based control. In fact, questions that one would like to answer on the basis of such evaluation (e.g. "Where would my plant performance benefit most if I were to acquire a respirometer: Return activated sludge flow rate manipulation or influent flow distribution?") cannot be answered with the information currently available.

2.1.3. No evaluation by the proposer

A control strategy preferably should be evaluated by full scale trials or, if this is not possible, by bench scale tests. An alternative to practical tests is the evaluation by computer simulations. In most proposals, however, no attempt is made to evaluate the performance of the suggested or implemented control strategy. It was not the mission of the Task Group to conduct detailed evaluations of the proposed control strategies. It is important, however, to realise why such evaluations were not conducted in these previous studies as this may be the cause for the slow introduction of respirometry-based control strategies. Three reasons can be given here.

First, few strategies are proposed with a preliminary simulation study because at the time most of the strategies reported here were proposed, neither the simulation tools nor the generally accepted models in use today were available.

Second, in contrast to other sensors such as dissolved oxygen probes for which even microprobes are routinely built, not all respirometers can be down-scaled at will. Typical volumes of bioreactors contained within respirometers are up to 10 litres. Consequently, considerable (mixed liquor; wastewater) sample volumes are necessary for operating such respirometers. This has seriously hampered the use of these devices in bench-scale or even small pilot-scale tests (where most of the development in control engineering is based upon). Indeed, the necessary sample volumes are too large not to create considerable disturbances to the facility by installing a respirometer.

Third, because no cost-benefit could be associated with respirometry-based control, full-scale experimentation with respirometers and newly developed control strategies has not been encouraged. Worse, as in this way no cost-benefit results could be gathered, a vicious circle emerged. Today, models, simulation tools and computing power are up to the task of realistically evaluating respirometry-based control strategies a priori and these studies could make is possible to break the vicious circle.

2.2. *Classification of respirometry-based control strategies*

Given the great number of respirometry-based control strategies, a listing as such is not informative. Hence, an attempt was made to classify the control strategies according to some criterion that is easy to trace and, therefore, also useful for future classification. The following characteristics on which a classification could be based were considered: the location of the respirometer, the respirometric variable or deduced variable thereof, the control objective or controlled variable and, finally, the manipulated variable in the control strategy. Below, the possible values these attributes were given are reviewed. The Task Group considered it important to list these as this may give the reader some perspective on the ubiquitousness of trials conducted with respirometry in control of activated sludge processes.

2.2.1. Location of respirometer

Respirometry-based control strategies have been proposed in which the respirometer has been located at nearly any spot within the wastewater treatment plant. Note that in this report the location of the measurement is not considered decisive for the interpretation of the measuring result. If, for example, activated sludge from the aeration tank and wastewater from the influent line are combined in order to obtain respirograms (measured rate r_O*[at,ww,resp]*), the instrument may be located either at the aeration tank or at the influent line. In either case sludge or wastewater would be transported to the instrument. In an alternative measurement set up, but with the same objective, the biomass is grown separately (measured rate r_O*[scul,ww,resp]*. Logically, the respirometer would then be located at the influent line, close to the plant or further upstream. Table 1 summarises the possible origins of biomass and substrate.

Table 1. Instances of the origin of biomass and substrate.

	Origin of biomass and substrate
ww	influent line of WWTP
at	activated sludge tank (any location)
ras	return activated sludge line
rl	return liquor
scul	specific culture, e.g. in an isolated reactor
at*1*	inlet of plug flow reactor
at*n*	outlet of plug flow reactor
eff	effluent line of WWTP

2.2.2. Measured or deduced variable

The diversity of data that can be obtained from respirometers has obviously led to a considerable potential of using this information for control of wastewater treatment processes. Apart from using the respiration rate directly, the result of the measurement is frequently converted to a deduced variable (Section 4.3). All these, listed in Table 2, have been used in control strategies.

2.2.3. Controlled variable

A rather complicated issue encountered when analysing many proposals was to find out what is the actual controlled variable in the control strategy (see discussion in 6.2.1). In the end, the list presented in Table 2 was put together.

Notice that in this overview only the control objectives of the strategies are retained and not the operational or basic objectives (Fig. 1). It is obvious that the basic objective of the strategy is to obtain good effluent at the lowest possible cost.

Table 2. Measured or deduced variable, and controlled variable.

		Measured or deduced variable	Controlled variable
B_I	inhibitor loading rate		x
B_V	volumetric loading rate		x
B_X	sludge loading rate		x
BOD_{st}	short-term BOD	x	x
$\%I$	percentage inhibition	x	x
$\%I_A$	%I of autotrophs	x	
$\%I_H$	%I of heterotrophs	x	
K_{NH}	autotrophic saturation coefficient for S_{NH}	x	
R_{COD}	specific carbonaceous respiration rate	x	x
$r_{O,act}$	actual respiration rate	x	x
$r_{O,end}$	endogenous respiration rate	x	x
$r_{NH,max}$	max. nitrification rate	x	x
S_A	concentration of VFA's	x	x
S_{NH}	concentration of NH_4^+	x	x
S_{NO2}	NO_2^- concentration		x
S_{NO}	NO_3^- concentration		x
S_O	DO concentration		x
S_S	concentration of readily biodegradable substrate	x	x
SBH	sludge blanket height		x
t.t.e.	time to endogenous	x	x
X	total solids	x	x
μ_{mA}	maximum specific growth rate autotrophic biomass	x	
θ_X	sludge age		x

2.2.4. Manipulated variable

The variables that have been manipulated to on the basis of respirometry encompass most actuators available in current treatment plants. The variables manipulated in feedforward and feedback manner using respirometric information are listed in Table 3. Other manipulated variables, like chemical dosage rate, nitrate recycle flow rate and sludge treatment return liquor flow rate, also have been reported. However, these publications do not meet the criteria for inclusion in this report.

Table 3. Manipulated variables.

Manipulated variables	
K_La	oxygen mass transfer coefficient
f_{Qww}	influent flow distribution
Q_{ras}	flow rate of return activated sludge
Q_{store}	flow rate of sludge storage
Q_{was}	flow rate of waste sludge
Q_{ww}	flow rate of influent
T_{cycle}	cycle length in periodic process

2.2.5. Choice of manipulated variable as classification criterion

Classification of the strategies could be based on any of the different elements of a respirometry-based control system presented above, especially measured or deduced (input or output) variable, manipulated variable or controlled variable. Discussions of the Task Group with interested parties revealed that some classifications are more prone to confusion and misunderstanding than others and it was decided, and approved at the IAWQ Specialised Conference on Sensors in 1995, that a classification based on the manipulated variable is the most appropriate since this variable is probably the easiest to identify in a control strategy.

3. Description of respirometry-based control strategies

Some 80 control strategies in which respirometric data plays a role were retained in the study. Table 4 summarises and classifies these according to the manipulated variable and the control scheme, i.e. feedforward, feedback or combined.

Note that, if respiration rates and deduced variables are used in feedback manner, this implies that a respirometric control objective is pursued. For instance, a control strategy which manipulates the mass transfer coefficient K_La in a feedback mode may aim to keep the respiration rate on a certain desired value. In case of a FF controller, the respirometric information is used to quantify a disturbance the effect of which is to be anticipated by the controller. Finally, for a combined FF/FB controller the respirometric information can both be used to assess deviations from the set point (feedback) or to measure a disturbance (feedforward).

Table 4. Number of control strategies per class of manipulated variable and control scheme.

	FF	FB	FF/FB	Total
K_La	5	6	10	21
Q_{ras}	5	10	3	18
Q_{was}	5	6	2	13
Q_{ww}	7	6	0	13
f_{Qww}	4	4	0	8
T_{cycle}	1	2	0	3
Q_{store}	1	0	0	1
Total	**28**	**34**	**15**	**77**

The number of strategies per class given in Table 4 is indicative of the efforts spent on their development. In fact, these numbers also reflect the importance inferred by the developers to the different manipulated variables and the type of control strategy (FF, FB, FF/FB). This importance is related to the expected economic benefit and the assumed reliability of these controller characteristics.

It is not the objective to present and explain all proposals for respirometry-based control strategies in this report. Rather, the main ideas will be illustrated and the reader is referred to the literature to find out more about these. For each of the manipulated variables, one or more examples (covering the different control schemes) will be presented in the next sections.

3.1. Mass transfer coefficient K_La

From Table 4 it is obvious that improving process behaviour by manipulation of the mass transfer coefficient has, as in general in activated sludge process control, also received most attention within the context of respirometry-based control.

Example 1 (FF). Many authors have tried to do respirometric analysis with an influent sample (r_O*[*;ww;*])* to predict the forthcoming oxygen demand in the facility and to calculate the setting of the aeration intensity. In a simpler approach, the respiration rate in the aeration tank is measured instead of being predicted from respirometry with an influent sample. As an example, for a given K_La - airflow relationship:

$$K_L a = \alpha F_{in} + \beta \tag{1}$$

the necessary air flow rate F_{in} can be calculated from the oxygen mass balance over the aeration tank (with the inlet oxygen concentration assumed to be negligible):

$$\frac{dS_O}{dt} = K_L a \left(S_O^* - S_O\right) - \frac{Q_{ww} + Q_{ras}}{V} S_O - r_O \tag{2}$$

for a steady state desired oxygen S_O value:

$$F_{in} = \frac{1}{\alpha}\left(\frac{\frac{Q_{ww} + Q_{ras}}{V} S_O^{setp} + r_O}{S_O^* - S_O^{setp}} - \beta\right) \tag{3}$$

As with all FF controls, the performance of such a strategy depends a lot on the quality of the underlying model that predicts the effect of the disturbance. In this case the performance depends on an accurate description of the K_La-F_{in} relationship (α, β), the appropriate values of the saturation concentration (S^*_O) the volume (V) and flow rates (Q_{ww}, Q_{ras}) and, in case the respiration rate (r_O) in the aeration tank is to be calculated from an influent measurement, the model that predicts r_O. Finally, it must be stressed that even then the desired value will only be reached under steady state conditions.

Example 2 (FB). Strategies have been proposed that aim at maintaining the respiration rate at a particular value (FB control) by manipulating the oxygen supply, thus making the degradation process oxygen limited (Fig. 4). It is obvious that in this way substrate degradation will be incomplete, which may be desirable in certain instances, e.g. when the controlled activated sludge system is part of a two-sludge system in which the second system is a denitrifying one. It is clear that the air supply and the concomitant energy costs are reduced by this strategy.

Example 3 (FF/FB). Probably one of the most studied applications of respiration rate measurements is its addition as a feedforward component to the standard feedback dissolved oxygen control. In this way controller performance is increased further as the effect of changing respiration rates (that are disturbances of the dissolved oxygen concentration, Fig. 4) can be anticipated. Respiration rate measurements also have been used as input to a gain scheduling scheme that ensures optimal performance of a standard dissolved oxygen controller under the time-varying conditions the activated sludge process is subject to.

One of the “classics” in advanced wastewater treatment process control is a combined estimation/adaptive control algorithm developed in the early eighties. The basic idea is to loosen the strict control that can be obtained using a standard feedback dissolved oxygen controller and using the induced dynamics in the dissolved oxygen concentration to estimate (i) the respiration rate and (ii) the time varying relationship between the mass transfer coefficient K_La and the applied control input. This high-quality information then allows adjustment of the controller to maintain good performance under changing load conditions or equipment performance.

Example 4 (FB). Measuring the respiration rate of biomass from the outlet of the aeration tank (r_O*[atn;-;inst]*) has been used as input to the outer loop of a cascade controller that sets the dissolved oxygen set points in the previous stages of a plug flow-like aeration tank, making process oxygen limited. In this way substrate can be distributed over the next compartments. This cascade control system ensures that the oxygen demand is evenly distributed over the different stages.

Example 5 (FB). A MIMO (multiple input, multiple output) strategy has been suggested in which the aeration intensity and the return activated sludge flow rate are manipulated on the basis of a dissolved oxygen measurement in the aeration tank and a measurement of respiration rate with a sample from the effluent line, indicating effluent pollutant load (r_O*[*;eff;*]*). The study was valuable as it also involved adaptation of the control law using these two measurements only.

3.2. *Return activated sludge flow rate* Q_{ras}

The return activated sludge flow rate is mostly, if changed at all, manipulated on the basis of either influent flow rate measurements (ratio control) or (turbidimetric) biomass concentration measurements. The main idea behind these control strategies is to maintain a desired sludge loading rate B_X. The control strategies manipulating Q_{ras} on the basis of respirometry have the same idea.

Example 1 (FF). Feedforward control strategies have been proposed in which the measurement of respiration rates with two different biomass sources are combined to predict the loading rate. In one case the respiration rate of the return mixed liquor (r_O*[ras;-;inst]*) is measured as an indication of the biomass concentration in the return line, and this information is combined with a measurement of the respiration rate in the first part of a plug flow-like biological stage r_O*[at1;-;inst]* to calculate the necessary return sludge flow rate for a given sludge loading rate. This strategy was later extended with a feedback component to eliminate the errors induced by the modelling errors always present when only FF control is applied. The control objective of this combined strategy was to keep the respiration rate at the outlet of the aeration tank (r_O*[atn;-;inst]*) at a desired low value, indicative of low remaining substrate concentrations. Summarising, in this strategy respirometric values of three different biomass sources are combined to manipulate a single variable, the return activated sludge flow rate.

Example 2 (FB). Feedback control systems have been developed with the objective to maintain a certain respiration rate, indicative of the biomass concentration in the aeration tank. A number of exercises has been performed in which the specific oxygen uptake rate R_O is controlled, while in another approach an active biomass concentration is deduced from the measured respiration rate and compared to the desired active biomass concentration.

Example 3 (FB). Another FB control strategy uses the ratio between the respiration rate of sludge from the outlet of the aeration tank (r_O[atn;-;inst]) and the maximum respiration rate of the same sludge sample in the presence of an excess amount of wastewater (r_O[atn;ww;inst;exc]). Using manipulation of Q_{ras} the control objective is to keep this ratio at a predefined level. It is assumed that the ratio is indicative of the extent of substrate removal at the outlet of the aeration tank, i.e. the lower the ratio the better.

Example 4 (FB). The MIMO controller of the abovementioned example 5 (section 6.4.1) is, in addition to being used to manipulate the aeration intensity, also used to manipulate Q_{ras} to control effluent substrate concentrations as measured with a respirometer.

Example 5 (FF/FB). In another MIMO controller, respirograms obtained under different experimental conditions are used to characterise the wastewater and the activated sludge (r_O[at;*;resp]). This information is subsequently used in a control strategy as measurement of the disturbance, and to adjust the parameters of the model-based control algorithm. Supplemented with additional (turbidimetric) biomass concentration measurements, the aim of the control strategy is to maintain a constant biomass concentration in the aeration tanks and keep the sludge blanket height constant by manipulating the return and waste sludge flow rates.

3.3. ***Sludge waste flow rate*** Q_{was}

Sludge wastage control is traditionally performed manually using daily measurements of biomass concentrations. Adjustment of the waste flow rate is never drastic. Given the slow dynamics of the sludge concentration, this smooth manipulation is quite acceptable. The main objective of the control actions is to maintain a certain solids retention time (sludge age) or a desired biomass activity in the system. Some strategies will be reviewed below that attempt to automate the sludge wastage control using respirometric biomass activity measurements.

Example 1 (FF/FB). As explained in the previous Q_{ras} example, a MIMO control strategy using respirometric information obtained with influent has been used to manipulate both Q_{ras} and Q_{was} with the aim to maintain the sludge concentration and the sludge blanket height at a desired value. A rather slow controller has to be implemented to guarantee stable control.

Example 2 (FF). Similar to the Q_{ras} control strategy presented in the above example 1, it has been proposed to manipulate Q_{was} in a FF control scheme on the basis of a combination of (i) the respiration rate of the return activated sludge (r_O*[ras;-;inst]*) and (ii) the respiration rate of the sludge from the inlet of a plug flow-like aeration tank (r_O*[at1;-;inst]*). Using this information sludge is wasted to such an extent that the sludge loading rate B_X is kept at a desired value. Here too, a slow (low gain) controller is required to prevent excessive oscillations in biomass loading rates.

Example 3 (FB). A FB control strategy has been proposed that uses the ratio between the respiration rate from the outlet of the aeration tank (r_O*[atn;-;inst]*) and the respiration rate of the same mixed liquor sample to which an excess of wastewater is added (r_O*[atn;ww;inst;exc]*). This ratio is an indication of the extent of substrate removal. The higher this ratio is, the more the sludge is overloaded indicating that the sludge concentration is too low to deal with the waste load. The control strategy, therefore, consists of manipulating Q_{was} to maintain a certain ratio. Because a diurnal variation of this ratio will be observed, appropriate averaging of the measured ratio is necessary before it is submitted to the controller.

Example 4 (FB). A simpler control strategy for Q_{was} uses a measurement of the respiration rate of the mixed liquor leaving the aeration tank early in the morning. At this time of the day, the sludge is assumed to be in an endogenous state so that the measured respiration rate would be a measure of the active biomass concentration. Hence, sludge wasting on the basis of this measurement allows to maintain the sludge activity at a desired level. Evidently, the basic concept of an endogenous respiration rate can also be implemented in a different way, e.g. by incorporating a holding tank in which the sampled mixed liquor is brought to endogenous state before the respiration rate is measured (r_O*[at;-;intv]*).

3.4. Influent flow rate Q_{ww}

Although the wastewater flow cannot really be manipulated at will, some possibilities may exist when rain detention basins are available or when the capacity of the sewer system can be taken advantage of. Especially in industrial plants, calamity basins are constructed for emergency actions. Basically the purpose of manipulating influent flow rate is to protect activated sludge processes against toxic spills or to balance the load.

Example 1 (FF). One of the most widespread examples of FF control is its application in protection of a treatment process against toxic spills. Respirometry can quickly detect the presence of toxic substances in an influent, and this information can be fed forward to a control system that can manipulate the intake of such wastewater to a level where no detrimental effects on plant performance are predicted. Provided the capacity to temporarily store this toxic wastewater is available, this strategy is the most appropriate one to deal with toxic wastewaters as all the wastewater will eventually be treated.

Example 2 (FF). Load balancing has been advocated by many authors. Respirometric measurements involving additions of wastewater samples (r_O*[*;ww;*]*) can provide insight to the pollutant load and, provided an appropriate model is used, allow calculation of the flow rate that gives a desired waste loading to the plant.

Since it is a feedforward scheme, no information on the result of such control strategy is fed back to the controller so that any (modelling or measurement) errors will deteriorate the performance of the control strategy.

Example 3 (FB). Several attempts have been made to measure respiration rate of the mixed liquor as an indication of the pollution load. This information is subsequently used in feedback mode to adjust the intake of wastewater to keep the respiration rate constant at a desired value. In this way it is attempted to obtain a desired loading of the sludge. In most cases the respirometer samples at the head of the aeration tank to allow sufficiently fast reaction to increased loadings. Sampling at the end of the aeration tank may lead to a delay between a load change and measurement of the effect thereof. This would hamper the effectiveness of a control strategy that would use such delayed information.

3.5. Influent flow distribution f_{Qww}

In a number of plants the possibility exists to distribute the influent flow over different inlets along a plug flow-like aeration tank. This mode of operation is termed step feeding, and manipulation is mostly based on influent flow rate measurements as it is mostly used to deal with hydraulic overloads. Bypassing wastewater to the receiving body can also be considered a form of influent flow distribution and is sometimes used in case the hydraulic capacity of the plant is exceeded.

Example 1 (FF). Control actions have been proposed in which toxic wastewaters are allowed, as a last resort, to bypass the treatment plant in the hope that the dilution effect of the receiving body is sufficient to attenuate the damage of the toxic substance. This strategy protects the treatment facility from considerable damage that might take it out of action for some time with possibly more damage to the environment than bypassing the toxic pulse.

Example 2 (FF and *FB).* In two-stage systems the idea has been formulated and implemented to balance the load over the two sludges using a respirometric measurement in between both stages. Basically, a FB control on the first stage and a FF control on the second stage are used in this set-up. The objective of the control strategy is, for instance, to optimise nitrogen removal in the second stage by releasing more or less carbonaceous material to it.

Example 3 (FB). The specific oxygen uptake rate R_O has been a deduced variable often applied as input to a step feed control system. The driving force for the development of such control strategies was the intent to balance the load over different aeration tanks positioned in series. Keeping R_O at a specified value above the typical endogenous respiration rate ensures that some of the pollutants still have to be degraded at the location where the respirometer is sampling mixed liquor. In some strategies a respirometer samples from the outlet of the aeration tank. In another proposal R_O is measured along the aeration tank and an objective of the controller is specified that consists of maintaining the mean value of all measured R_O's on a specified value and to keep the variation of R_O's to a minimum. All this is performed by manipulating the distribution of wastewater f_{Qww} along the aeration tank.

Example 4 (FF). Finally, a feedforward strategy was suggested in which the overall respiration rate in the aeration tanks is used to deduce the load to the plant. With this information influent flow distribution is manipulated in such a way that the aeration capacity is used in an (energy) optimal way. At low loading all wastewater is directed to the last tank, and sludge can be stored in the first tanks for use during more highly loaded periods when the feed is introduced increasingly towards the head of the facility.

3.6. *Cycle time T_{cycle}*

Cycle time is an important variable in periodic processes for biological nutrient removal because an optimal scheduling of redox conditions (aerobic, anoxic, anaerobic) must be achieved. Classic systems for nutrient removal that are based on this time scheduling are alternating systems and sequencing batch reactors (SBR).

Example 1 (FB). The activity of the two nitrification steps (oxidation of ammonia to nitrite in the first step and oxidation of nitrite to nitrate in the second) can be obtained at regular intervals from a specific respirometric experiment (r_O*[at;-;resp;inhibitor]*). This information has been suggested as input to a controller that switches off aeration as soon as the rate of the first reaction step (ammonia oxidation) drops significantly. This drop indicates exhaustion of the ammonia from the mixed liquor. Such a control strategy was shown to reduce aeration costs, and it provides a means to increase the cycle time for the subsequent denitrification period.

Example 2 (FF). For a plug flow-like reactor it has been suggested to use a respirogram obtained from batch experiments with a well-defined mixture of wastewater and sludge to manipulate in feedforward manner the required aerobic volume for complete nitrification ($r_O[at;ww;resp;S_{t0}/X_{to}]$). This control strategy may also be classified among the controllers manipulating K_La, but clear similarity between plug-flow and SBR's allows its inclusion in this section. Indeed, the aerobic volume fraction in a plug flow-like reactor corresponds to the cycle time in the time schedule of a SBR.

Example 3 (FF). Recently respirometry has been suggested as a basis for control of biological phosphorus removal systems. The respirometric information is used to adjust the cycle time of the anaerobic phase. The principle is that the respiration rate in a reaerated mixed liquor sample taken from the anaerobic reactor (r_O*[at;-;resp]*) will generate high respiration rates when readily biodegradable substrate is still present, while the anaerobic phase can be interrupted when the carbon source is no longer present as indicated by a reduced respiration rate.

A similar control strategy has been proposed for interrupting the denitrification phase. Here the measurement set-up is similar, i.e. a mixed liquor sample is taken from the anoxic reactor and, after reaeration, respiration rates are indicative of the presence of readily biodegradable substrate. When nitrate is no longer present in the mixed liquor sample, readily biodegradable substrate concentration will be higher, as indicated by an increased respiration rate. Hence, the respiration rate measured in the reaerated sample will be a good indication of the termination of denitrification and can be used as input to a control strategy with T_{cycle}-manipulation.

3.7. *Sludge storage flow rate* Q_{store}

In some wastewater treatment plants provision is made to temporarily store sludge. This storage capacity can be used to deal with hydraulic disturbances that could lead to settler washout, but stored sludge can also be activated when increased biological activity is required to accommodate higher loads. Respiration rates can trigger the release of sludge from the sludge storage tank.

4. Concluding remarks

In Table 5 an overview is provided of the occurrences of the different control structures dealt with in this review. A differentiation has been made between control strategies that were only proposed in the paper and the ones that were also applied on a lab, pilot or full scale.

First, from the table it is obvious that a large fraction of the proposals were never applied. Second, one would expect that the feedforward proposals would have difficulty to work without a feedback component to correct for it, and this should be reflected in a lower fraction of the proposals actually being applied in practice. However, one finds similar ratios between proposals and applications for the three classes of control strategies (FF, FB and FF/FB). Third, if one focuses on the total number of control actions proposed and applied, it is obvious that the manipulations of the aeration system on the basis of respiration rate data have been successfully applied, as are the strategies manipulating the wastewater inflow or its distribution. The latter two mainly have to do with the toxicity prevention that can be achieved by this manipulation while the former is due to an economic incentive, i.e. aeration cost. Return and waste activated sludge flow rates have attracted a lot of attention and several proposals have been generated, but the application of these control strategies is clearly lagging behind. For the waste flow rate (a slow controller), it is probably due to the fact that control based on laboratory analysis is more than sufficient within the current state of treatment plant operation. For the lack of application of return activated sludge control strategies it is hypothesised that this manipulation may have too little control authority.

Finally, this overview has made clear that the creativity of using respirometry in control of activated sludge processes has been significant, but that the stage is reached where unbiased evaluations are required that will support the user community in deciding for better respirometer set-up/control strategies. Future work will have to bring the necessary information together.

Table 5. Occurrences of proposals (p) and applications (a) of respirometry-based control strategies

	FF		FB		FF/FB		Total	
	p	a	p	a	p	a	p	a
K_La	2	3	3	3	6	4	11	10
Q_{ras}	5	0	9	1	3	0	17	1
Q_{was}	5	0	5	1	2	0	12	1
Q_{in}	4	3	4	2	0	0	8	5
Q_{dis}	1	3	2	2	0	0	3	5
T_{cycle}	1	0	1	1	0	0	2	1
Q_{store}	1	0	0	0	0	0	1	0
Total	**19**	**9**	**24**	**10**	**11**	**4**	54	23