Control of aeration systems in activated sludge processes – a review

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Abstract
This review attempts to summarise and categorise research performed within the field of control of continuous aeration systems in municipal wastewater treatment plants over the last ten years. The review covers research into various methods to both decide and track the dissolved oxygen set-point but also the control of the total aerated volume. With respect to dissolved oxygen set-point control and determination, the strategies used for control span from modifications and developments of simple control methods that have been explored since the 1970's, to advanced control such as model-based predictive and feedback controllers. Also, fuzzy logic control has gained more interest in the control of continuous processes and is utilised both in the context of deciding and tracking set-points, but also to control the total aerobic volume. The review is supplemented by a discussion on what level of complexity is required for an aeration control system together with a summary of comparisons between control strategies evaluated in full-scale, pilot scale and in simulations.
Keywords: Activated sludge; aeration; control strategies; wastewater treatment

INTRODUCTION

Making dissolved oxygen (DO) transfer from gas to liquid phase is a very energy intensive activity in the treatment plant, as well as crucial for the treatment results. In a nitrifying activated sludge plant, the DO level in an activated sludge process must satisfy the microorganisms' requirements to achieve near complete nitrification of influent ammonia and aeration must also preserve a sufficient level of stirring in the basin to avoid spontaneous settling and filamentous growth. A too high level of aeration is unwanted since it is costly and creates little or no extra treatment effect. To meet the above specifications is an important challenge for the control of aeration systems in treatment plants.

The standard control handle for aeration control is the air flow rate to the aerobic basins which will change the rate of oxygen transfer and hence the dissolved oxygen concentration. This corresponds to the first level of aeration control. Second level control represents the control of dissolved oxygen concentration and higher levels represent the control of treatment results, most often expressed by the effluent ammonia concentration. Apart from control of the dissolved oxygen concentration, other topics of interest for aeration control are the dissolved oxygen profile along a plug-flow basin and control of the aerobic reactor volume.

Overall goals for wastewater treatment on the legislative level involve effluent quality limits of various kinds depending on country, size and effluent recipient. Given the development of advanced treatment methods of late, wastewater can be treated to high levels, given unlimited resources. However, it is not environmentally sound to treat too much, given the resource consumption treatment requires. Therefore, an assumption of cost-effectiveness and efficiency is often incorporated into the goal formulation, and automatic process control is an important tool for achieving this.

The control goal for a plant is often specified in a similar manner to “satisfy effluent requirements consistently and minimise costs while maintaining water quality” (Olsson & Jeppsson, 1994). Another example is “maintain reliable effluent quality despite disturbances against reasonable costs” (Weijers, 2000). A detailed goal is described in Brdys *et al.* (2008): “(i) to meet effluent discharge requirements, (ii) to keep biological sustainability of activated sludge in the treatment plant, (iii) to minimise operational costs (mostly cost of energy and chemicals), (iv) to minimise load of untreated sewage discharged to the receiving waters”.

Different aspects of ICA (instrumentation, control and automation) within the wastewater industry and the water industry can be found in Olsson *et al.* (2005) and Olsson (2006), respectively. Here, the control of unit processes including the aeration and DO control are included and the first reference gives some examples of full-scale results. Weijers (2000) presents a detailed list of control laws for wastewater treatment control up to then, including aeration control. Another overview of different control systems is found in Vanrolleghem (2007), even though the main goal of the report is to describe how model simulation can be a tool in wastewater treatment operation. Jeppsson *et al.* (2002) provide an overview of ICA from a European perspective and conclude that PI control or variations thereof are the most common strategies in full-scale.

This review take a deeper look into aeration control of municipal activated sludge systems with continuous aeration for the purpose of biological nitrogen removal. Alternating or intermittent aeration systems, Sequencing Batch Reactors (SBR) and industrial applications are only mentioned briefly when applicable. Also, applications on conventional activated sludge are stressed, such as predenitrification and similar configurations. Research into other control categories not addressing aeration control explicitly, such as plant-wide control or control of precipitation of chemicals, is not included. The review does not claim to be exhaustive and is focused on published research during the last ten years. After describing the Benchmark Simulation Model, the first part of the review covers oxygen set-point determination and tracking through classical as well as more advanced methods. Special sections are devoted to control of the aerobic volume and results from PhD theses during the period. Finally, the question of what control method is the best is addressed and comparative evaluations between methods in full-scale, pilot-scale and simulations are highlighted.

MODELLING AS AN EVALUATION TOOL

Many of the studies performed on aeration control and on other unit processes in municipal wastewater treatment plants (WWTPs) are investigated through modelling and simulation of the processes. A popular tool for this is the IWA/COST Simulation Benchmark (BSM1) (Copp, 2002), in this review referred to as the Benchmark Simulation Model. The Benchmark Simulation Model is an implementation of the

Activated Sludge Model No. 1 (ASM1) (Henze *et al.*, 1987). In research on control and modelling of WWTPs, ASM1 or simplifications of ASM1 are widely used for evaluation purposes. In fact, full scale testing of control strategies is not very common in literature. In the text that follows, referenced articles are basing results on simulations unless otherwise stated. The positive thing about using benchmark simulations in the evaluation of control strategies is the possibility to have a similar approach in the evaluation of divergent control schemes. A review of how simulations can be used to improve wastewater treatment operation is found in Vanrolleghem (2007). Jeppsson & Vanrolleghem (2011) present publications related to the Benchmark Simulation Model.

DETERMINATION AND TRACKING OF THE DISSOLVED OXYGEN SET-POINT

Classical control and modifications thereof

Classical control procedures, including PID and cascade control, are well known methods for DO set-point tracking. Feedforward of influent ammonia to handle disturbance rejection, often in combination with cascade control, has also been successfully investigated and compared to other control strategies over the last years, see for instance Ingildsen *et al.* (2002), Krause *et al.* (2002), Vrecko *et al.* (2003), Meyer & Pöpel (2003), Yong *et al.* (2005), Vrecko *et al.* (2006), Zhang *et al.* (2008) and Thornton *et al.* (2010). These studies include different types of feedforward controllers and model the feedforward term differently, both in a linear and non-linear manner. Apart from Ingildsen *et al.* (2002) and Thornton *et al.*, 2010, all the previously mentioned publications include simulation work and in some cases pilot plant testing.

A combined feedback controller with feedforward of influent ammonia is used to control both the oxygen set-point and the number of aerated tanks in Krause *et al.* (2002). The combined controller was better at suppressing ammonia peaks than using only feedback control. The same conclusions were made by Vrecko *et al.* (2006) where the air flow was reduced by 45% with a combined feedforward and ammonia cascade control method, compared to PI control with a constant DO set-point. Using only cascade ammonia control reduced the air flow by 23%. The results were verified in a pilot-plant.

An example of a full scale evaluation of a modified cascade controller at Käppala WWTP in Sweden can be found in Thunberg *et al.* (2009). The goal here was to distribute the oxygen demand more evenly along the process. Similar thoughts were presented in (Sahlmann *et al.*, 2002) where four different DO set-point combinations were compared for three aerobic zones in an A^2/O (anaerobi-anoxic-oxic) process. The zone distribution of air flow and standardised oxygen transfer efficiency (αSOTE, measured by off gas method) were analysed for different loads. Energy was saved by balancing the oxygen demand and minimising unnecessary sludge stabilisation.

Ingildsen *et al.* (2002b) present a methodology to balance cost, quality and robustness in the selection of set-points for PI control of DO and internal nitrate recycle. Benedetti *et al.* (2010) use cost functions for evaluation of different control strategies in combination with Monte Carlo simulations and conclude that ammonia cascade PI control offer greater environmental and economic benefits than simple PI control.

Classical PID control has been investigated and developed further. As an example, multivariable PID (MPID) control design has been investigated in Wahab *et al.* (2009) where simulations are used to evaluate different decoupling methods for MPID tuning which only require step or frequency response tests. Tzoneva (2007) evaluates two standard PID tuning methods (Ziegler-Nichols and a relay tuning method) using the Benchmark Simulation Model and also demonstrates how to perform real time tuning. Yoo & Kim (2009) performed full scale testing where different autotuning methods for PID control of DO set-points are evaluated in an industrial WWTP. Together with estimation of the oxygen transfer function (K_La) and respiration rate (R) proposed by Lindberg (1997) and a set-point decision law based on the estimated R, the study demonstrated more stable treatment results for COD (chemical oxygen demand) and an energy saving potential. A similar approach is presented in Yoo *et al.* (2002). The DO set-point is also controlled in a study by Suescun *et al.* (2001) which develop ideas presented in Lindberg & Carlsson (1996). The set-point is adjusted every four hours to compensate for the deviation in actual effluent ammonia compared to the set-point. The DO is controlled with conventional control. There are facultative zones which can be aerobic/anoxic depending on operational aspects. A second SISO (single input single output) controller controls the nitrate by adjusting the internal nitrate recycle flow rate. The controller is verified with good results in a pilot plant. The control loops for nitrate and ammonia were eventually combined with a similar control loop for suspended solids and successfully verified in full scale at the Galindo-Bilbao WWTP (Ayesa *et al.*, 2006).

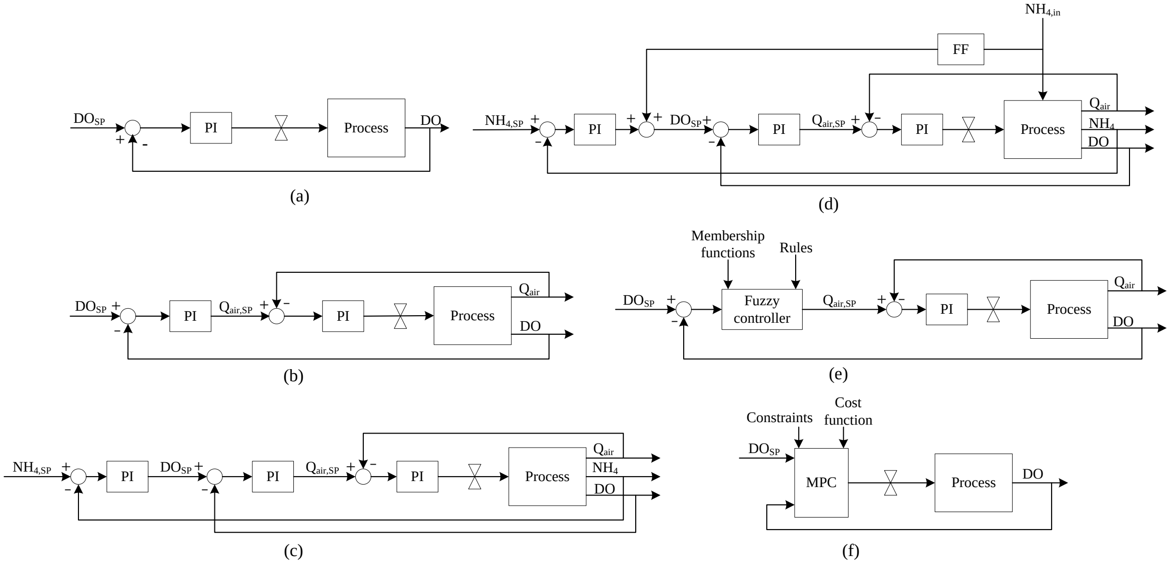

Figure 1. Common control strategies: (a) DO feedback control with fixed set-point, (b) DO cascade control with fixed DO set-point, (c) ammonia cascade control with fixed ammonia set-point, (d) ammonia cascade control with ammonia feedforward, (e) Fuzzy DO control with fixed DO set-point and (f) MPC control of air flow.

Rule-based control

In Krause *et al.* (2002) feedforward-feedback control to determine the DO set-point is combined with rule-based control. Switching points in the operation determine whether the set-points should be increased or decreased in steps. An earlier example of this in a full-scale step-feed plant is found in Husmann *et al.* (1998).

A rule-based feedforward methodology was developed by Shen *et al.* (2010) for an A^2/O process, based on the cumulative frequency distribution of the influent ammonia and the C/N ratio. Optimal set-points for the feedforward rules was created based on steady state simulations and validated in dynamic simulations. No feedback was used.

Rule-based control in the form of fuzzy logic control was traditionally applied for alternating systems and batch reactors; see for instance Traoré *et al.* (2005), Fiter *et al.*, (2005). The trend has recently been to expand the application towards continuous operation in both simulation studies and in pilot and full scale evaluations. Fuzzy logic control is appreciated for its transparency and the possibility to include expert process knowledge into the control system development.

Meyer & Pöpel (2003) performed simulations and pilot plant testing of a predenitrification system controlling the DO set-point and the ratio of aerobic and anoxic zones using a fuzzy controller. The system combined feedforward of influent ammonia with feedback effluent ammonia and nitrate as well as the effluent ammonia time variation. Compared to a fixed set-point of DO with relay control (alternating between 0 and 2 mg/l) and constant zone division, the fuzzy controller air flow was decreased by 24%.

A similar approach to control was made by Yong *et al.* (2006), where apart from the DO set-points, the external carbon dosage was also controlled. Influent and effluent ammonia was used as inputs to the controller and good performance was experienced in simulations and in pilot scale testing. A similar strategy was found in Serralta *et al.* (2002) where DO and nitrate is controlled with supervisory and fuzzy control.

A full scale implementation of a fuzzy logic system in a predenitrification system is found in Baroni *et al.* (2006). Here, both the DO set-point and the air supply was controlled through fuzzy logics. The installations were running for approximately a year and produced long term and short term process stability as well as energy savings. A sophisticated version of fuzzy control was presented by Han *et al.* (2008). The simulation study employ a piecewise linearised relationship between the air flow rate and DO. PI parameter values are tuned for each linear section. A blending of the PI controllers is performed based on Gaussian membership functions.

Evaluation criteria and cost functions

To determine optimality, performance indices have been used extensively for evaluation. In the 1990’s there was a lot of development of evaluation criteria and cost functions for wastewater treatment modelling and control. Vanrolleghem *et al.* (1996) discussed the implementation of an overall decision support index for design and operation of WWTPs to balance cost and treatment results. The construction of such a parameter was further elaborated upon in Vanrolleghem & Gillot (2002) where a total cost index (TCI) was proposed that weighs different operating costs and investments. The same year, Copp *et al.* (2002) presented performance indices for the evaluation of control strategies based on simulations in the Benchmark Simulation Model. The indices include the Effluent

Quality Index (EQI) which integrates the total amount of pollutants for the process with different weights depending on their severity. Another index is the Effluent Violations, which is the percentage of time that the constraints are not met. There are also several Operational Variables, including sludge production, pumping energy, aeration energy and mixing energy. The method outlined in Copp *et al.* (2002) is commonly used when cost functions or performance indices are applied in simulation studies.

Model-based control and hierarchical control

Model-based control includes a large group of control algorithms which all make use of a process model of some kind in the control law. The model can be either black-box or incorporate process equations similar to the ones in ASM1. Often the model can be used to find a controller output that is optimal in some sense. Optimal control, as defined here, assumes a cost function to be mathematically minimised and attempts to find the best solution to the problem given constraints on the optimisation. Both feedback model-based control, such as Linear Quadratic Control (LQC), and predictive control, such as Model Predictive Control (MPC), minimise a cost function. MPC has become a popular control method within many industries for its ability to handle constraints and to include multiple variables. It has been a research topic for WWTPs since the mid 1990’s. There are many developments of the classical MPC method, such as robust MPC, adaptive MPC and non-linear MPC (Weijers, 2000).

Recent full-scale results from an MPC for aeration control is found in O'Brien *et al.* (2011). Here, the previous on/off control strategy for the surface aerators in an activated sludge process for BOD-removal is improved by using a black-box model of the aeration in combination with feedforward of the influent BOD load. A Data Quality Monitor improved the control by removing unreliable measurements.

The set-point of DO was determined with MPC in Sanchez & Katebi (2003). Sub-space identification is used to create models for dissolved oxygen and the authors compare three different MPC controllers with a single PI controller with constant set-point. The evaluation is performed mainly through comparing system overshoot and settling time. The authors conclude that a set-point controller improves the performance and find the controller structure easy to implement.

DO tracking by MPC with a process model incorporating classical DO dynamics is verified by Holenda *et al.* (2008). The effect of sampling time is investigated, but the MPC controller compared to standard PI control only shows marginal improvements on EQI.

Machado *et al.* (2009) decide the most economical set-point for a number of decentralised controllers, controlling for instance the ammonium in the effluent of an A^2/O process. Flores-Alsina (2008) suggests a hierarchical multicriteria optimisation method and applies it both to design of a WWTP and to decide set-points for DO and effluent nitrate. The evaluation resulted in a very low (0.5 mg/L) set-point to promote denitrification.

Steffens & Lant (1999) published results based on different model-based controllers in comparison with classical PI control with fixed DO set-point and set-point through PI ammonia control. The control handles were the DO set-point, internal recycle flow rate, returned activated sludge flow rate and external carbon dosing. The model-based controllers included were LQC, DMC (Dynamic Matrix Control) and non-linear predictive control (NPC). The NPC controller outperformed the other controllers, and improvements were experienced by both DMC and LQC compared to PI control. A later comparison between different model-based control methods is found in Shen *et al.* (2009). Here, DMC, Quadratic DMC (QDMC) and nonlinear MPC were investigated. QDMC is not reported to outperform DMC, and the nonlinear MPC improves performance but at the cost of increased energy consumption. In the same study, feedforward for disturbance rejection is investigated in combination with DMC. Ammonia concentration feedforward brings better results than inflow rate feedforward and a combination of these is even better. Again, performance is improved through feedforward but with increased energy consumption. A similar study (Shen *et al.* 2008) published the year before compared QDMC, QDMC with feed-forward and nonlinear MPC. The authors conclude that non-linear MPC handles disturbances best and with acceptable energy consumption.

Zarrad *et al.* (2004) and Vilanova *et al.* (2009) compare decentralized PI regulators to multivariable model-based controllers in the Benchmark Simulation Model. In the first paper, a nitrate recycle PI loop and an air flow rate PI loop is compared to two model-based controllers. One LQ controller where the disturbance is considered as noise and one disturbance accommodation controller (DAC), which augments the process model with a disturbance model. The PI controllers demonstrated better results than DAC but the state estimator in the DAC was proposed as a tool for estimation of unmeasured disturbances. Vilanova *et al.* (2009) compare the performance of a multiloop PI controller to a multivariable controller in a single aerated reactor. DO and substrate concentration are considered. The results when analysing step responses are comparable for the two controllers.

Examples of where Genetic algorithms have been used for model-based control includes Yamanaka *et al.* (2006) and Beraud *et al.* (2009). Yamanaka *et al.* (2006) evaluate a cost minimisation control scheme using the Benchmark Simulation Model. The control structure is hierarchical where a higher level controller provides the set-points of the process based on optimisation using a simplified process model and Genetic algorithms. The lower level controller follows the set-points. In the case of aeration control, the optimiser determines an appropriate ammonia set-point which the lower level PI controller follows. Sensitivity tests and validations of optimality are performed in the Benchmark Simulation Model. Genetic algorithms were used by Beraud *et al.* (2009) to optimize the set-point in three consecutive aerobic zones and obtain energy reductions of 10-20 % with maintained treatment performance.

A lot of research into model-based control in general and predictive control in particular has been performed within the European research project SMAC (Smart Control of Wastewater Systems). Several studies report on the oxygen concentration tracking. Brdys

& Konarzcak (2001) investigated a non-linear SISO MPC based on the oxygen dynamics. The method was improved through increased computational efficiency by a fuzzy predictive controller in Brdys & Diaz-Maiquez (2002). A nonlinear MPC and an Adaptive Model Reference (DMRAC) controller were compared in Chotkowski *et al.* (2005). In Piotrowski *et al.* (2008), the nonlinear MPC is supplemented by a model of the blower system. The DO controllers above fit into the hierarchical control structure set up by Brdys *et al.* (2008), which is divided into the supervisory control layer, optimising control layer and follow-up control layer. The structure involves integrated control of a treatment plant and sewer system and the optimising control layer involves slow, medium and fast time scales. The manipulated control handle with respect to aeration control is the DO concentration. The optimising control layer involves a MIMO robust MPC and also other advanced methods (Extended Kalman filter, grey box parameter estimation, Weighted Least Squares with Moving Measurement Window) and it is this layer that produces the DO trajectory to the lower level DO controller in the follow-up control layer. Three control strategies are proposed: normal control strategy, disturbed control strategy and emergency control strategy. The objective of the process, and hence the optimisation, varies depending on control strategy. In Brdys *et al.* (2008), the low-level DO controller in the follow-up layer consists of a simple proportional controller, however, the authors argue that a much better solution would be to apply an MPC, as described above, for this purpose. The simulations in the report are based on real data from the Katurzy UCT (University of Cape Town) treatment system in Poland.

Performance criteria and plant design

The ideas of performance criteria and optimality have been used extensively to propose design methods for WWTPs. The design can be performed through mathematical optimisation of a given cost function. Ayesa *et al.* (1998) and Rivas *et al.* (2008) optimise the configuration of a step-feed BNR process, Doby *et al.* (2002) use Genetic algorithms on a static WWTP model to propose design configurations and compare Genetic algorithms to classical non-linear optimisation, Biswasa *et al.* (2007) optimize the treatment train to suggest combinations of unit processes through Genetic algorithms, Flores Alsina (2008) developed a conceptual design method based on optimisation for design/redesign of WWTPs and Hakanen *et al.* (2008) use an interactive multiobjective optimisation approach for design of plants. There are also examples where the cost functions are used for evaluation and a systematic approach to design rather than optimal design is applied, see for instance Benedetti *et al.* (2006) and Benedetti *et al.* (2008).

CONTROL OF AEROBIC VOLUME

Apart from changing the DO levels in the compartments the total aerobic volume can be adjusted by turning aeration on or off in facultative zones. This is performed to compensate for variations in incoming load and has often been performed by control strategies based on estimations of the oxygen uptake rate (OUR), referred to as respirometry. An early example can be found in Brouwer *et al.* (1998) who use a feedforward model-based approach to determine the aerobic volume needed for complete nitrification. Here, a simple process model together with estimation of biokinetic parameters through batch respirometric measurements in one of the plant compartments decides the aerobic volume. Evaluations are performed in a pilot plant. Baeza *et al.*

(2002) varied the total aerobic volume in a pilot plant fed with synthetic wastewater, leading to a 10% increase in nitrogen removal compared to operation with a fixed volume. Estimations of the COD were performed by turning off the aeration for short periods, hence being able to calculate the OUR. The COD estimations served as inputs to a neural network model which determined the total volume to be aerated. Similarly to Brouwer *et al.* (1998), Samuelsson (2005) controls the ammonia concentration in the last compartment through a model-based feedforward strategy which changes the aerobic volume. The approach is based on on-line estimation of the reaction rate of ammonia and combines feedforward with feedback control.

Svardal *et al.*, 2003 use measured air flow to decide on how to adjust the aerobic volume to the ammonia load. The method maximises the anoxic volume given the goal of complete nitrification. The OUR is a good indicator of nitrification performance at low ammonia concentrations, and is also proportional to the air flow rate. The method is based on increasing the aerobic volume when the total air flow passes certain thresholds. The paper presents full-scale results from the Lintz-Asten WWTP which uses an oxidation ditch for nitrification and denitrification. The effluent ammonia concentrations remained below 1 mg/L and the total nitrogen removal rate varied between 70% and 80%.

As mentioned above, Meyer & Pöpel (2003) use fuzzy logic to determine both the DO set-point and the fraction of aerobic volume. Krause *et al.* (2002) also control both the set-point and aerated volume. Through a feedforward model several switching points are determined for compartments 3-5 in a predenitrification plant. Compartment five is always aerated but can take on different DO set-points. Compartment 3 and 4 can be either aerobic or anoxic with a preselected fixed set-point. Suescun *et al.* (2001) also incorporate a facultative zone in the control which can be made aerobic if the DO set-point is at its maximum level.

Ekman *et al.* (2006) developed a method for aeration volume control that only requires measurements of the DO concentration. The method makes use of supervisory control where two out of three zones can be either aerobic or anoxic depending on the DO concentration in all three zones, creating a disturbance rejection effect. The strategy is evaluated in the Benchmark Simulation Model and in the large pilot-plant facility Hammarby Sjöstadsverk, treating municipal wastewater. Simulations compare the strategy to constant DO set-point control and supervisory control based on ammonia measurements.

DOCTORAL THESES

Weijers (2000) develops a thorough methodology for an improved control system design approach. The thesis searches to construct a method for control goal formulation and argues in support of a mathematical approach to set up the design problem. Controller design is systematically covered including control structure design and control law selection and the thesis includes a review of published control laws to date. The case studies of the thesis where the proposed control system design approach is applied are exclusively examples of model-based control. Both a predenitrification system and a carousel system are evaluated by use of simulations with ASM1.

The thesis by Rosen (2001) describes challenges involved in monitoring and control of wastewater treatment operation and outlines the possibilities for multivariate monitoring and control. With respect to control of aeration systems, the thesis covers set-point adjustments based on clustering to make the process return to its preferred process state and a multivariate feedback controller that calculates appropriate set-points for the lower level controllers. The techniques are applied to DO set-point control by simulations of a reduced order ASM1.

Ingildsen (2002) presents valuable results on implementing control strategies in full-scale operation and develops a method to guide the user through the implementation process of new control structures in full-scale environments. In the full-scale experiments, the author concludes that in-situ nutrient measurements in combination with simple control strategies can improve the plant performance significantly. The practical trials have been supported by simulations using the Benchmark Simulation Model. The assessed control structure in relation to aeration control is supervisory feedback control of the effluent ammonia combined with feedforward.

Different aspects of control of nitrogen removal are presented in Samuelsson (2005). Several of those are related to denitrification and the addition of external carbon. The work related to aeration control includes the control of the aerobic volume described above.

Mulas (2006) applies the concept of self-optimising control (when acceptable performance can be achieved with constant set-points of the controlled variables despite disturbances) to aid in the selection of controlled variables. The analysis yields however that the return and waste activated sludge rates are the two variables to control to adjust the nitrate concentration and the sludge age, respectively.

Holenda (2007) investigates methods to optimise the aeration length in an alternating system, but also develops an MPC controller for the purpose of DO set-point tracking. The MPC is based on a linearised version of the ASM1.

ADVANCED OR SIMPLE CONTROL?

The control of aeration systems span from simple and straightforward PI and cascade controllers, via fuzzy rule-based algorithms to model-based control and system optimisation. A fair question to ask is: what control strategy is the best? Different types of controllers can evidently handle different levels of aeration control, but the recommendations from the scientific community in relation to the level of complexity of the control system are not consistent. The scientific community agrees upon that the activated sludge system in itself is a complex multidimensional and non-linear system with several time scales involved and with interactions between process variables. But the conclusions drawn from this fact diverge. Some argue that given the complex nature of the system, simple control cannot guarantee the performance under a full range of conditions (Brdys *et al.*, 2008). Decentralized simple SISO controllers are not robust enough and control of an activated sludge system must be considered a multivariable control problem and should thereby best be handled with model-based control methods, such as MPC (Steffens & Lant, 1999; Weijers, 2000). On the other hand, researchers argue that classical well-tuned control algorithms are enough to achieve acceptable system performance under most conditions as expressed by Stare *et al.* (2007) and Ingildsen (2002). It is possible to find sub-processes that can be controlled with linear controllers that demonstrate little coupling with other processes (Vrecko *et al.*, 2002). That is particularly true for process variables that affect the effluent concentrations, rather than the effluent concentrations themselves, and such an example is the DO concentration.

In the evaluations performed by Stare *et al.* (2007) and Steffens & Lant (1999), the authors use an ideal (i.e. the model incorporated in the control algorithm is the same as that in the simulator for evaluation) MPC controller as a reference case in their comparison between different controller performance for a predenitrification plant, but still end up with different conclusions. Both studies also include the method of cascade PI ammonia control in their evaluations, described above. Stare *et al.* (2007) conclude that the much more complicated control algorithms found in the multivariable and non-linear MPC are not justifiable in practice unless high fines on effluent emissions apply at a highly loaded plant. Steffens & Lant (1999) achieved the best treatment results with non-linear predictive control to the same operating costs as with constant DO set-point. It is important to note that the authors use different evaluation criteria.

To guide through the research within aeration control of activated sludge processes, Table 1 summarises comparative studies between control strategies and covers both full-scale, pilot-scale and simulation results. The table includes research that compares one or several strategies to some reference case and lists the comparative results between those. Papers that have not had a reference case in the analysis are hence not included. The table lists the full control strategy used in the study, since an aeration control strategy often is implemented together with control of other unit processes, such as denitrification. Some papers are listed twice to ease the reading, since they cover several comparisons.

Table 1. Comparisons between control strategies (FB=feedback, FF=feedforward, DO=dissolved oxygen, SISO=Single Input Single Output, MIMO= Multiple Input Multiple Output, EQI= Effluent Quality Index). Types of studies: f=full-scale, p=pilot-scale, s=simulation study.

Author	***Strategy***	***System***	***Study***	***Results***	***Compared to***
O'Brien et al. (2011)	MPC with FF of BOD load	ASP BOD rem.	f	-20 % energy, +25 % process efficiency	On/off control
Shen et al. (2010)	Rule-based FF of DO set-point, internal and external recycle based on influent NH_4 load and C/N ratio	A^2/O	s	11 % increase in P removal, 8.5 % decrease in aeration, 3.4 % decrease in internal recycle	DO PID set-point control, PID control of recycle
Thornton et al. (2010)	FF-FB DO set-points, FB external carbon	Bardenpho	f	-20 % air flow, increase in effluent NH_4, -50 % methanol, maintained NO_3	Fixed DO set-point, fixed methanol dose
Benedetti et al. (2010)	NH_4 FB DO set-point cascade	BSM2	s	Reduced total cost, reduced NH_4 peaks	DO PI fixed set-point
Beraud et al. (2010)	DO set-points and wastage flow-rate optimisation (GA)	BSM1	s	-10 to -20 % energy saving, maintained treatment	DO PI fixed set-point
Shen et al. (2009)	MIMO DMC with Q and NH_4 FF	BSM1	s	-28 % NH_4, -4.5 % EQI, +16 % aeration energy	MIMO DMC
Shen et al. (2009)	MIMO NLMPC (QDMC with penalty function)	BSM1	s	Comparable results, difficulties during large disturbances, NLMPC handles this the best	MIMO DMC/ QDMC
Thunberg et al. (2009)	NH_4 FB DO set-points	UCT	f	-18 % air flow, maintained treatment	Linear air-flow profile along the basin
Machado et al. (2009)	NH_4, NO_3, PO_4 FB, supervisory set-point optimisation	A^2/O	s	-13 % operating cost	DO PI fixed set-point
Holenda et al. (2008)	SISO MPC DO fixed set-point	BSM1	s	-0.6 % EQI, +0.4 % aeration energy, less deviations from set-point	DO PI fixed set-point
Stare et al. (2007)	NH_4 FF-FB, NO_3 FB	BSM1	s	Lower operating cost	Constant air-flow or DO PI, ext. carbon fixed set-point
Stare et al. (2007)	NH_4 FF-FB, NO_3 FB	BSM1	s	Similar operating cost as MPC	MIMO ideal MPC
Zhang et al. (2008)	NH_4 FF-FB DO set-point cascade	reduced BSM1	s	-3.7 to -7.9 % aeration energy, 0 to -2.5 % NH_4, -3.9 to -5.2 % NO_3	DO PI fixed set-point
Ayesa et al. (2006)	NH_4, NO_3 and suspended solids set-point cascade	DRN/DRDN	s, f	S: -15 % air flow, improved effluent quality. F: -15 to -20 % aeration energy, -2 mg/L nitrate	DO PI fixed set-point
Baroni et al. (2006)	Fuzzy DO set-point cascade by NH_4 FB	predenitrification	f	Increased stability of effluent NH_4, eliminated DO oscillations, -4 % energy when implemented in ¼ of the tanks	DO PID fixed set-point
Ekman et al. (2006)	NH_4 FB, facultative zones	predenitrification	s, p	S: Improved disturbance rejection, lower tot-N, lower aeration energy. P: lower tot-N and air flow compared to constant PI control	DO PI fixed set-point/ NH_4 FB
Vrecko et al. (2006)	NH_4 FB DO set-point cascade/ NH_4 FF-FB	MBBR, predenitrification	s, p	P: -23 % air flow per ammonia removed for NH_4 FB, -45 % for NH_4 FF-FB, better	DO PI fixed set-point cascade

				ammonia removal, best with FF	
Chotowski et al. (2005)	MIMO DMRAC	predenitrification with Bio-P	s	More simple implementation, slightly worse performance in step response testing	MIMO NLMPC
Yong et al. (2005)	NH_4 FF-FB DO-set point cascade	predenitrification	s, p	P: -8 to -15 % air flow, -15 to -25 % NH_4	DO PI fixed set-point
Vrecko et al. (2003)	Internal recycle, DO, external carbon FF-FB	BSM1	s	Reduced operating costs and emissions	Fixed PI controllers
Meyer & Pöpel (2003)	Fuzzy DO set-point by NO_3 and NH_4 FF-FB, facultative zone	predenitrification	s	S: -24 % air flow, reduced NH_4 peaks	Fixed DO set-point and zones
Meyer & Pöpel (2003)	Fuzzy DO set-point by NO_3 and NH_4 FF-FB, facultative zone	predenitrification	s, p	S: -14 % air flow, reduced NH_4 peaks P: -23 % air flow, reduced NH_4 peaks	NH_4 FB DO set-point, relay control of zones
Sanchez & Katebi (2003)	3 DO SISO MPC controllers	BSM1	s	Better performance in step response tests	DO PI fixed set-point
Ingildsen et al. (2002)	NH_4 FF-FB DO set-points	predenitrification	f	-5 to -15 % energy saving, maintained treatment	DO PI fixed set-point
Krause et al. (2002)	NH_4 FF-FB DO set-points, facultative zones	predenitrification	s	+6 % air flow , reduction in NH_4 peaks,	NH_4 FB DO set-point, facultative zones
Sahlmann et al. (2002)	Distributed DO profile: 1.2, 1.2, 1.5 mg/L SP in Zone 1, 2 and 3 resp.	A^2/O	f	-15 % total daily air flow rates for low loading period	DO SP: 2, 2, 2 mg/L in zone 1, 2 and 3 resp.
Serralta et al. (2002)	Supervisory NH_4 FB DO set-point, fuzzy DO and internal recycle controllers	Bardenpho	s	-10 % energy, improved denitrification	Fuzzy DO and internal recycle controllers
Suescun et al. (2001)	NH_4 FB, NO_3 FB, facultative zones	predenitrification	s, p	S: -11 % air flow, NH_4 constant, NO_3 decreased	Fixed set-points
Steffens & Lant (1999)	NH_4 and NO_3 FB/LQC/DMC/ ideal MPC	predenitrification	s	Ideal MPC>DMC and LQC>NH_4 and NO_3 FB, with respect to savings and performance	DO PI fixed set-point, ratio control of internal recycle
Husmann et al. (1998)	Rule-based DO set-point stepping, facultative zone, flow-distribution	Step-feed	f	-16 % energy, up to -50 % tot-N	Fixed DO set-point, zone division and flow distribution

CONCLUSIONS

This paper presents a review of research within control of aeration systems in municipal wastewater treatment plants during the last ten years. Despite the developments since the 1970's and the maturity of the research area, it is still an active topic. The last ten years, set-point control through combined feedforward-feedback has been evaluated in simulations and in full-scale operation and several methods to model the feedforward term have been tested. Fuzzy control as an extension to classical control strategies has been used to handle the nonlinearities of the process both in set-point control and in aeration volume control. Model-based control methods such as MPC have continued to evolve together with hierarchical aeration control and plant operation. An increasing number of studies are performed with the help of the Benchmark Simulation Model and it has proven a useful tool for researchers to evaluate algorithms in a unified environment. In spite of the possibility for unified comparisons, whether the process complexity calls for advanced and model-based control methods or if more classical strategies suffice for acceptable performance is still an open research topic. Also, even though examples exist, the availability of full-scale results are still scarce especially with respect to complex control strategies.

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