Ammonia-based aeration control with optimal SRT control: improved performance and lower energy consumption

Oliver Schraa, Leiv Rieger, Jens Alex and Ivan Miletić

ABSTRACT

Ammonia-based aeration control (ABAC) is a cascade control concept for controlling total ammonia nitrogen (NH_x-N) in the activated sludge process. Its main goals are to tailor the aeration intensity to the NH_x-N loading and to maintain consistent nitrification, to meet effluent limits but minimize energy consumption. One limitation to ABAC is that the solids retention time (SRT) control strategy used at a water resource recovery facility (WRRF) may not be consistent with the goals of ABAC. ABAC-SRT control is a strategy for aligning the goals of ammonia-based aeration control and SRT control. A supervisory controller is used to ensure that the SRT is always optimal for ABAC. The methodology has the potential to reduce aeration energy consumption by over 30% as compared to traditional dissolved oxygen (DO) control. Practical implementation aspects are highlighted for implementation at full scale, such as proper selection of the set point for the supervisory controller, proper calculation of the rate of change in sludge inventory, using a mixed liquor suspended solids (MLSS) controller, and tuning of the controllers. In conclusion, ABAC-SRT is a promising approach for coordinated control of SRT, total ammonia nitrogen, and dissolved oxygen in the activated sludge process that balances both treatment performance and energy savings.

Key words | ammonia-based aeration control, energy, modeling, nutrient removal, simulation, SRT control

Oliver Schraa (corresponding author)
Leiv Rieger
Ivan Miletić
inCTRL Solutions Inc.,
107-7 Innovation Drive, Dundas, ON, L9H 7H9,
Canada
E-mail: *schraa@inctrl.ca*

Jens Alex
ifak e.V. Magdeburg,
Werner-Heisenberg-Str. 1, 39106 Magdeburg,
Germany

INTRODUCTION

Ammonia-based aeration control (ABAC; Rieger *et al.* 2014) is a cascade control concept for controlling total ammonia nitrogen (NH_x-N) in the activated sludge process. Its main goals are to tailor the aeration intensity to the NH_x-N loading and to maintain consistent nitrification, to meet effluent limits but minimize energy consumption and improve nutrient removal (Rieger *et al.* 2012).

One limitation to ABAC encountered by the authors is that the solids retention time (SRT) control strategy used at a water resource recovery facility (WRRF) may not be consistent with the goals of ABAC. For example, ABAC may not be able to handle peak loads if the SRT is too low and may reach minimum airflow constraints if the SRT is too high. In order to overcome this limitation, Schraa *et al.* (2016) introduced the concept of ABAC-SRT control, where an ABAC system is combined with a dynamic SRT controller. A higher-level supervisory controller is used to coordinate the two controllers. The supervisory controller determines an optimal SRT set point that ensures the ammonia controller can meet its goals without encountering constraints. The objectives of the current study are to review the methods available for calculating SRT, to determine the most appropriate SRT calculation method in the context of feedback control, to introduce the ABAC-SRT control concept, to demonstrate the economic benefits of ABAC-SRT control, and to explore practical implementation aspects.

CONTROL CONCEPTS

SRT control

The SRT is an important design and control parameter for the activated sludge process. It represents the average length of time that bacteria stay in the process before

doi: 10.2166/wst.2019.032

being wasted or lost in the effluent. The selected SRT directly affects the bacterial composition in an activated sludge system. Maintaining an appropriate SRT is necessary to ensure that slow-growing bacteria, such ammonia-oxidizing organisms, are not washed out of the system.

In the wastewater treatment literature, SRT is usually considered from a steady-state perspective. At steady-state, the static SRT is defined as the mass of microorganisms in the system divided by the mass of microorganisms wasted per day:

$$SRT = \frac{X_{MLSS} V_a}{X_{RAS} Q_w + X_e Q_e} \tag{1}$$

where:

V_a = total volume of aeration tanks, m^3
X_{MLSS} = total or volatile suspended solids (VSS) concentration in the mixed liquor, mg/L
X_{RAS} = total or VSS concentration in the return activated sludge (RAS), mg/L
X_e = total or VSS concentration in the secondary effluent, mg/L
Q_w = waste activated sludge (WAS) flow rate, m^3/d
Q_e = effluent flow rate, m^3/d

As shown in Equation (1), the VSS or total suspended solids (TSS) concentrations are typically used as surrogate measurements for the microorganism concentrations. The static SRT is only equal to the actual SRT at steady-state because if the WAS flow rate is changed the formula suggests that the SRT has instantly changed, which is not true in reality because the system takes considerable time to respond. This limitation can be overcome by filtering the static SRT with a low-pass filter or calculating the dynamic SRT as demonstrated later in this paper. Equation (1) also ignores the active microorganisms in the clarifier sludge blanket, which could be significant but are difficult to measure accurately.

For a completely mixed activated sludge system, a mass balance on microorganisms can be re-arranged to calculate the specific substrate utilization rate, which is the mass of substrate utilized per day per mass of active microorganisms:

$$U = \frac{1 + b_h SRT}{Y(SRT)} \tag{2}$$

where:

U = specific substrate utilization rate, mass chemical oxygen demand (COD)/mass VSS/d
Y = activated sludge yield coefficient, mass VSS/mass COD
b_h = endogenous decay rate, d^{-1}

As shown in Equation (2), the specific substrate utilization rate is directly related to the yield, decay rate, and SRT. Both the activated sludge yield and decay rate are considered to be constant for practical purposes, leaving the SRT as the main parameter used to control the substrate utilization rate.

The SRT in a WRRF is typically controlled by adjusting the WAS flow rate. One especially important factor to consider in SRT control is the speed of response. A plant's SRT takes at least two to three times the steady-state SRT to stabilize after a change in waste flow. As a result, SRT control cannot remove the variations in SRT caused by the diurnal loading variations. These occur at too high a frequency to be attenuated by changing the waste flow rate. The main goals of an SRT controller are to maintain a consistent SRT, and to respond to seasonal variations and storm events.

Equation (1) can be simplified by assuming that the biomass lost in the effluent is negligible. Using this assumption, a common SRT control strategy is hydraulic wasting (Garrett 1958) where sludge is wasted directly from the aeration tanks and the desired waste flow rate becomes the volume of the aeration tanks divided by the desired SRT:

$$Q_w = \frac{V_a}{SRT} \tag{3}$$

When sludge is wasted from the recycle line, with recycle ratio *r*, the hydraulic wasting formula becomes (WEF 1997):

$$Q_w = \left(\frac{r}{r+1}\right)\frac{V_a}{SRT} \tag{4}$$

Stephenson *et al.* (1981) and Brewer *et al.* (1995) show practical applications of implementing hydraulic wasting strategies. Hydraulic wasting is simple to understand and execute, but one potential disadvantage is that for a constant SRT the waste flow does not vary and this may not be optimal during storm events and seasonal variations.

SRT can also be controlled with an automatic feedback control algorithm that uses on-line measurements of mixed liquor suspended solids (MLSS), recycled activated sludge total suspended solids (RAS TSS), and waste flow rate as suggested by Vaccari *et al.* (1988) and Ekster (2001). A potential algorithm could use the on-line measurements to calculate the SRT using Equation (1), filter the static SRT using a low-pass filter, and have the feedback controller adjust the waste flow rate to keep the filtered SRT at the set point. The concept is illustrated in Figure S1 in the Supplementary Material (available with the online version of this paper). The filtering of the SRT calculation (or the flowrate and TSS measurements) is used as the steady-state SRT responds too rapidly to dynamic process variations and set-point changes. Using a moving-average SRT is not ideal as its response is not smooth enough for proper feedback control.

Vaccari *et al.* (1985) developed a dynamic sludge age (DSA) function based on an age-balance equation in order to overcome the limitations of the static SRT. Analytical expressions for the DSA were developed by Vaccari *et al.* (1985) for four common cases. Takács & Patry (2002) and Takács (2008) developed the dynamic SRT (DSRT) which is the solution of the following ordinary differential equation:

$$\frac{dSRT}{dt} = 1 - \frac{SRT(F_p)}{M} \tag{5}$$

where:

$\frac{dSRT}{dt} =$ age change of solids (change in age of solids [in days] per days of real time)

$M =$ mass of solids in the system

$F_p =$ mass flow of solids produced in the system (true sludge production)

The DSA of Vaccari *et al.* (1985) and the DSRT of Takács & Patry (2002) can be shown to be equivalent using simulation provided that the same definitions are used for model variables such as true sludge production. Takács (2008) estimated the true sludge production using a model presented by Dold (2007). Alternatively, true sludge production can be estimated using the following equation from Vaccari *et al.* (1988):

$$F_p = \frac{M - M_0}{\Delta t} + Q_w X_w + Q_e X_e \tag{6}$$

where:

$M =$ mass of solids in the system at the current time (g)

$M_0 =$ mass of solids in the system at the previous time interval (g)

$\Delta t =$ time interval between calculations of the sludge production (d)

$Q_w =$ waste flow rate (m^3/d)

$X_w =$ TSS concentration of waste stream (g/m^3)

Vaccari *et al.* (1988) proposed feedback proportional-integral-derivative (PID) control of the DSA, but their investigations did not consider how the SRT set point itself should be optimized. This is one of the main objectives of the current study and will be addressed in the section below on ammonia-based aeration control with optimal SRT control (ABAC-SRT).

Comparison of SRT calculation methods

A comparison of selected SRT calculation methods was performed using SIMBA# water, a dynamic simulator for WRRFs. The SRT calculations were compared using an example nitrifying WRRF presented by Ekama & Wentzel (2008). The model of the WRRF (Figure 1) includes diurnal influent flow and COD, ammonia and ammonium nitrogen (NH_x), and soluble phosphorus (SP) concentration patterns (Diurnal Influent block), primary clarifiers, three bioreactors in series, and a layered clarifier model (Secondary clarifiers block). A separate dissolved oxygen (DO) controller is used for each bioreactor and each DO controller sends an airflow set point to a lower level flowrate controller that manipulates a control valve (contained within the Ammonia and SRT Controllers block). A detailed aeration system sub-model is included as part of the simulation model (Schraa *et al.* 2017) to provide a realistic test environment (contained within the Ammonia and SRT Controllers block). The aeration system model includes three 4,800 Nm^3/h (3,075 standard cubic feet per minute – scfm) turbo blowers, aeration piping including fittings (based on a typical aeration piping layout), and membrane disc diffusers. A total airflow controller adjusts the blower output and number of blowers in service to match the sum of the three airflow controller set points.

The diurnal patterns are created using the influent generation tool developed by the HSG group (Langergraber *et al.* 2008, 2009). The pattern is adjusted on the weekends so that the loadings are reduced by 10% and the patterns are delayed by 1 hour.

Proportional recycle is used and wasting is done from the third bioreactor to provide an SRT of 11 days at design conditions. The SRT of 11 days was calculated as the minimum SRT for nitrification at 10 °C, a desired steady-state effluent NH_x concentration of 1 mgN/L, and a safety factor of 1.5 days using the design equation presented by van Haandel & van der Lubbe (2012).

The model of the example WRRF developed in SIMBA# uses the inCTRL-ASM biokinetic model along with the Otterpohl & Freund (1992) model for the primary clarifier and the Takács *et al.* (1991) clarification model with 10 layers for the secondary clarifiers. The Takács *et al.* (1991)

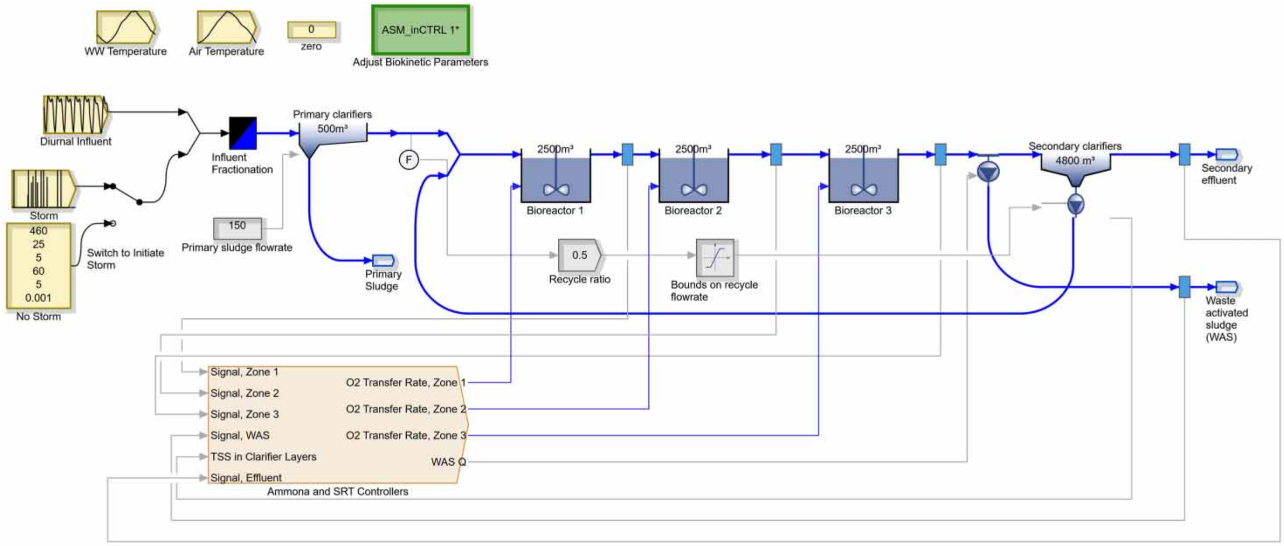

Figure 1 | Example WRRF as represented in SIMBA#.

model is used as it can be calibrated to predict an increase in the solids lost in the effluent as the flowrate increases. This is important in the current study as the SRT calculation is affected by the loss of solids in the clarifier effluent and by movement of solids from the aeration basins to the clarifier due to high flows. Although deficiencies in the Takács *et al.* (1991) model have been identified (Plósz *et al.* 2011; Bürger *et al.* 2013), the model is thought to be adequate for the current study as we are interested in the relative changes in the effluent TSS in response to changes in plant flows and loads and whether our proposed control concept can adapt to these changes. When implemented in practice, the SRT calculations will use actual TSS measurements.

The SRT calculation methods explored are as follows:

- Dynamic SRT calculation (Equations (5) and (6))
- Static SRT calculation (Equation (1))
- Filtered Static SRT and a filter time constant of 7 days (Equation (1))
- Hydraulic SRT (Equation (3) re-arranged to solve for SRT).

Dynamic simulations were conducted to compare the response of the SRT calculations to a step change in WAS flow rate and to a storm event at a wastewater temperature of 10 °C. The simulations were initialized by first running a 100-day simulation with the diurnal loading pattern at 10 °C to achieve a stable operating point, and then 60-day diurnal simulations were conducted to study the impact of a WAS flow change and a storm event.

A plot of the response of the different SRT calculation methods to a diurnal influent loading pattern with a step change in WAS flow rate at 5 days is shown in Figure 2. The hydraulic SRT starts at 11 days, while the other SRT values average 10.5 days as they consider the solids lost in the effluent. As shown in Figure 2, the hydraulic SRT and the static SRT are very sensitive to changes in the WAS flow and instantly move to the new SRT. An instantaneous increase in SRT is unrealistic as the SRT cannot increase by more than 1 day per day with no wasting. The dynamic SRT responds much more smoothly and slowly to the change in WAS flowrate and is better suited to automatic SRT control. The filtered static SRT is a reasonable approximation to the dynamic SRT for changes in WAS flow, but the filter time constant used becomes a tuning parameter and would need to be varied depending on the desired SRT set point.

In the Supplementary Material (available online), Figure S2 shows a plot of the response of the different SRT calculation methods to a diurnal influent loading pattern with a storm event that occurs after 10 days with a constant wasting rate. It is found that the hydraulic and traditional SRT calculation methods differ considerably from the dynamic SRT during a storm. The hydraulic SRT stays constant throughout the entire simulation because the wasting rate does not change. The static SRT calculation shows a large drop in the SRT during the storm, due to the loss of solids in the effluent, but then quickly returns back to its original value, which is not possible because the SRT cannot increase by more than 1 day per day. Clearly, the hydraulic and static SRT calculations are unrealistic under storm conditions.

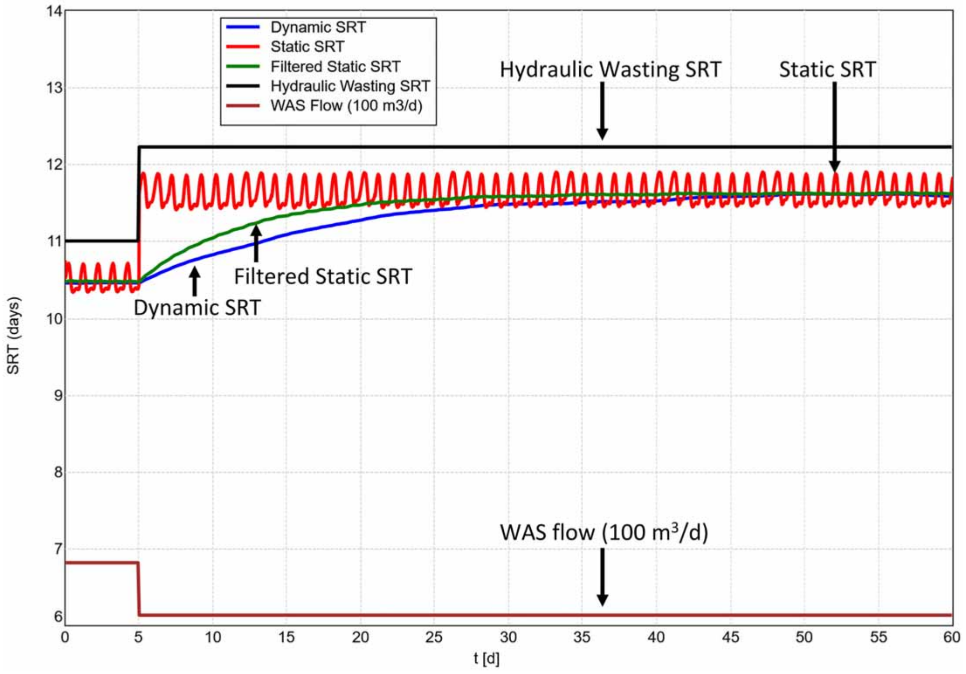

Figure 2 | Comparison of different SRT calculations after a step change in WAS flow rate.

The dynamic SRT and the filtered static SRT both drop in response to a storm but do so more slowly and then take much longer to return to the original SRT. Clearly, the dynamic SRT and the filtered static SRT are more realistic and appropriate for feedback control than the traditional or hydraulic wasting SRT calculations as they have a smoother dynamic response with the correct rate of change.

Ammonia-based aeration control (ABAC)

As discussed earlier, ABAC is a cascade control concept for controlling total ammonia nitrogen (NH_x-N) in the activated sludge process. A diagram illustrating the concept of ABAC is shown in Figure 3.

Ammonia-based aeration control with optimal SRT control (ABAC-SRT)

The ABAC-SRT control concept developed by Schraa *et al.* (2016) is shown in Figure 4. A feedback controller measures NH_x-N and manipulates the set point of a DO controller that manipulates an air flowrate set point for an airflow controller. A supervisory controller manipulates the set point of the SRT controller to ensure that the ammonia controller can achieve its goals without encountering constraints on minimum airflows or the nitrifier population. The supervisory controller is a feedback controller that controls the average DO concentration calculated by the ammonia controller. Averaging of the DO set point calculated by the ammonia controller is performed using a low-pass filter.

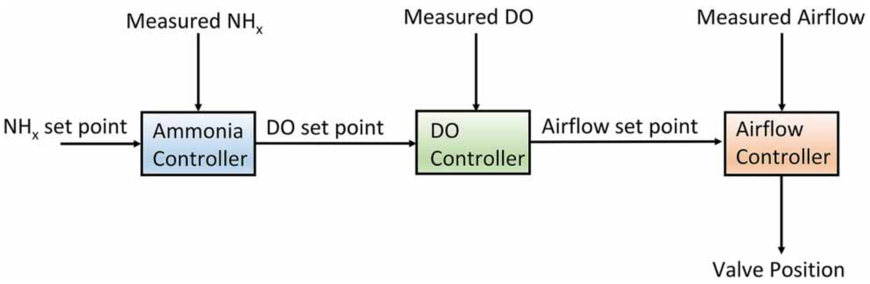

Figure 3 | Control concept for ammonia-based aeration control (ABAC).

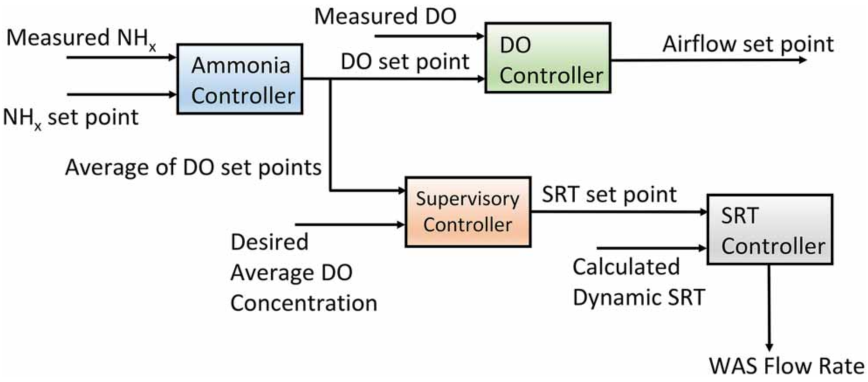

Figure 4 | Control concept for ammonia-based aeration control combined with optimal SRT control (ABAC-SRT).

The SRT controller controls the estimated dynamic SRT (Takács & Patry 2002) by manipulating the WAS flow rate.

Another important consideration is the selection of the SRT controller output bounds. At low WAS flows, the resulting MLSS could be too high and cause clarifier failure. To ensure that the MLSS stays in an acceptable range, the SRT controller cascades to an MLSS controller that has bounds on the MLSS set point, as shown in Figure S3 in the Supplementary Material (available online). Bounds are also placed on the SRT set point calculated by the supervisory controller so that the SRT does not become too low or too high (see Table 1).

RESULTS AND DISCUSSION

Comparison of control strategies

A case study of the ABAC-SRT concept was conducted by Schraa *et al.* (2016) but did not reveal the full benefits of the methodology as the practical aspects of selection of the average DO set point for the supervisory controller and proper selection of controller bounds had not been fully developed. The objective here is to demonstrate the potential benefits while providing guidance on practical implementation issues.

Table 1 | Summary of simulated scenarios for comparing performance of DO control, ABAC, and ABAC-SRT

Scenario	Airflow control	DO control	NH$_x$-N control	MLSS control	SRT control	Supervisory control
Case 1	- Airflow set point provided by DO controller for each zone	- DO set point of 2 mg/L in all zones	- Not used	- MLSS set point = 2,000 mg/L - WAS flow rate bounded between 100 and 3,500 m^3/d	- Not used	- Not used
Case 2	- Airflow set point provided by DO controller for each zone	- DO set point provided by NH$_x$-N controller - Airflow set point bounded between minimum airflow for mixing and maximum airflow per diffuser	- NH$_x$-N set point = 1 mg/L - DO set point bounded between 0.5 and 2 mg/L	- MLSS set point = 2,000 mg/L - WAS flow rate bounded between 100 and 3,500 m^3/d	- Not used	- Not used
Case 3	- Airflow set point provided by DO controller for each zone	- DO set point provided by NH$_x$-N controller - Airflow set point bounded between minimum airflow for mixing and maximum airflow per diffuser	- NH$_x$-N set point = 1 mg/L - DO set point bounded between 0.5 and 2 mg/L	- MLSS set point provided by SRT controller - WAS flow rate bounded between 100 and 3,500 m^3/d	- SRT set point provided by supervisory controller - MLSS set point bounded between 1,000 and 3,500 mg/L	- Average DO set point of 1 mg/L - SRT set point bounded between 3 and 20 days

The ABAC-SRT control concept was implemented in SIMBA# and applied to the example WRRF introduced earlier. A year-long simulation is conducted in SIMBA# with 12 storm events and seasonal temperature variation (air and wastewater). The wastewater temperature varies between 12.4 and 24 °C, and the air temperature varies between −7.1 °C and 23.6 °C based on data taken from a wastewater treatment plant in Ontario, Canada.

To demonstrate the benefits of ABAC-SRT control, three cases are compared: Case 1 – DO control with MLSS control, Case 2 – ABAC with MLSS control, and Case 3 – ABAC-SRT. For the DO control and ABAC options, the MLSS is controlled using a proportional-integral (PI) controller with a set point of 2,000 mg/L. MLSS control is used in Cases 1 and 2 as it is thought to represent a common control strategy at many WRRFs due to concerns about clarifier failure at high MLSS concentrations. The supervisory controller has minimum and maximum output bounds of 3 days and 20 days respectively, to impose bounds on the SRT set point. The SRT controller has MLSS bounds of between 1,000 and 3,500 mg/L. The simulated scenarios are summarised in Table 1.

In Case 1, the NH_x-N is uncontrolled and over-aeration is possible. In Cases 2 and 3, the NH_x-N set point in the third bioreactor is set to 1 mgN/L in order to achieve potential energy savings. The airflow controllers are bounded between 0.22 Nm^3/h per m^2 of floor area (0.12 $scfm/ft^2$ based on USEPA (1989)) and 14 Nm^3/h per diffuser (7.6 scfm/diffuser) to ensure adequate airflow for mixing and to remain within the upper airflow limit for the diffusers. The DO set point calculated by the ammonia controller is bounded between 0.5 mg/L (to prevent extended operation at low DO concentrations in cases without SRT control) and 2 mg/L (to prevent excessive aeration). The ammonia controller is a PID controller and all the remaining controllers are PI controllers.

The year-long influent flowrate and air and wastewater temperature patterns are shown in Figure 5. Figure 6 shows the resulting simulated dynamic SRT (controlled variable) and the WAS flow rate (manipulated variable) for Case 1 – DO control with MLSS control, Case 2 – ABAC with MLSS control, and Case 3 – ABAC-SRT. As shown, in Case 3 the WAS flow rate is adjusted so that the SRT varies throughout the year. The SRT variation follows the wastewater temperature variation. The lower SRT and MLSS bounds of 3 days and 1,000 mg/L respectively become active during the warmer months.

Figure 7 shows the load-based average NH_x-N in the third bioreactor (controlled variable) and the load-based average DO in the first bioreactor (manipulated variable). In all three cases, the ammonia controller cannot keep the daily average Zone 3 NH_x-N at the set point of 1 mgN/L at all times. In Case 1, this is because a DO of 2 mg/L is maintained in all three zones, which is sufficient for full

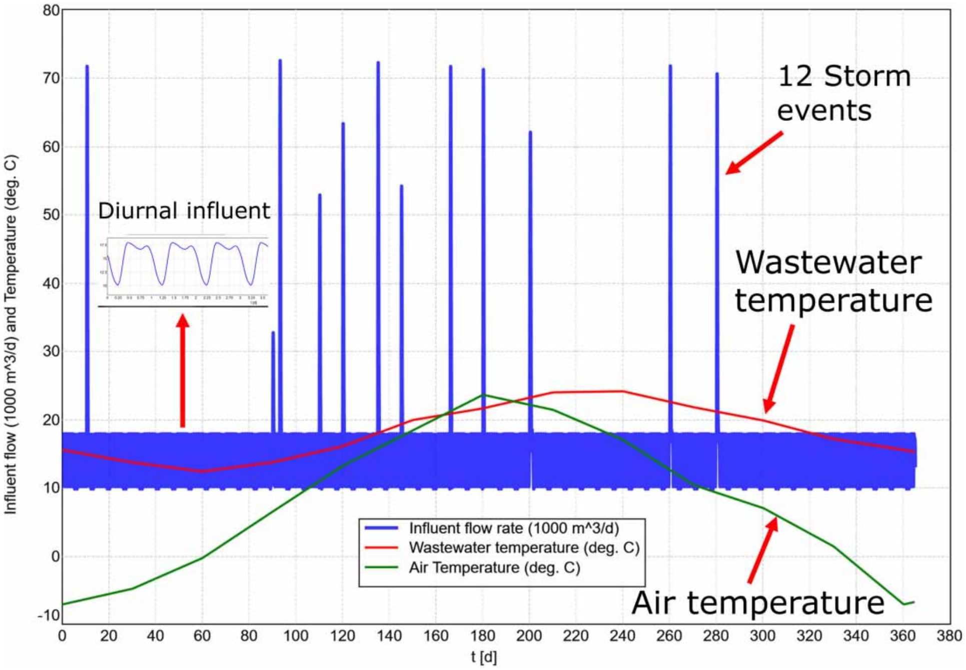

Figure 5 | Diurnal flow pattern including 12 storm events, a seasonal liquid temperature pattern, and a seasonal air temperature pattern for the 365-day simulation.

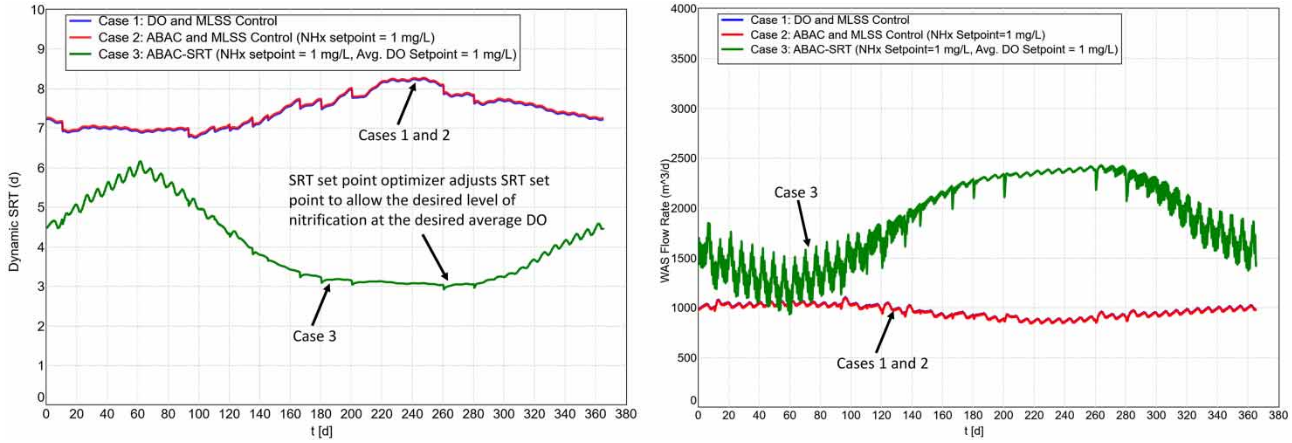

Figure 6 | Simulated dynamic SRT (left plot) and WAS flow rate (right plot) for DO and MLSS control, ABAC and MLSS control, and ABAC-SRT control.

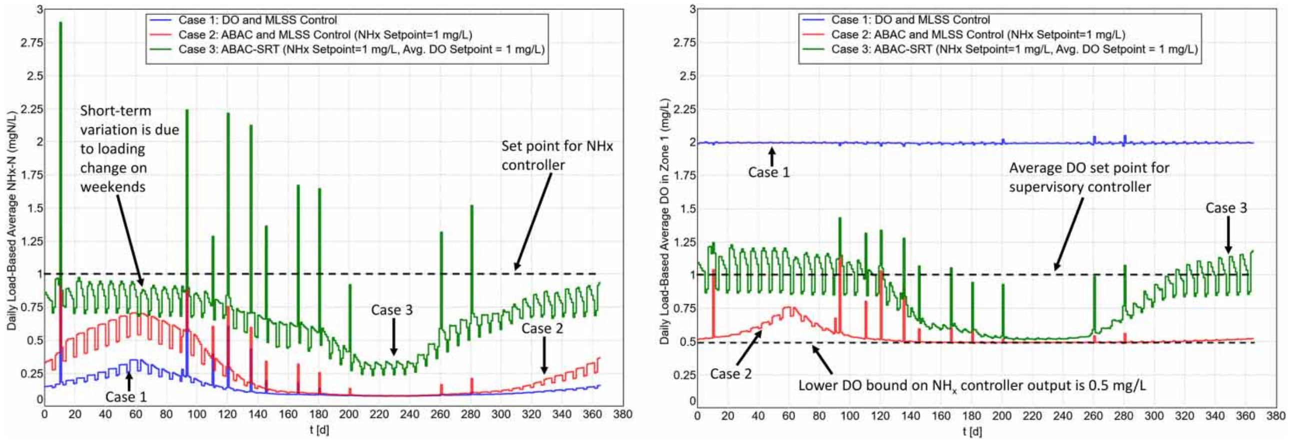

Figure 7 | Simulated load-based average NH_x-N in third bioreactor (left plot) and Zone 1 DO (right plot) for DO and MLSS control, ABAC and MLSS control, and ABAC-SRT control.

nitrification at the operating SRT (7 days and above). In Case 2, the ammonia controller reaches its lower DO bound of 0.5 mg/L, but the DO in the last zone is consistently above 2 mg/L because of the minimum airflow bound for mixing. At the SRTs encountered, this is enough to keep the daily average Zone 3 NH_x-N significantly below the 1 mgN/L set point. The ABAC-SRT controller performs best in terms of achieving the NH_x-N set point because of the supervisory controller.

In Case 3 with ABAC-SRT, the goal of the supervisory controller was to keep the average DO at 1 mg/L. This is achieved during the colder months but the average DO drops lower than 1 mg/L in the warmer months because of the minimum SRT bound of 3 days. The minimum SRT bound also causes the ammonia controller to be limited by its lower DO set point bound of 0.5 mg/L, which in turn allows the daily average Zone 3 NH_x-N to drop much lower than its set point during warmer months.

The ABAC-SRT control concept ensures that the SRT is long enough to attenuate peak loads while at the same time ensuring that aeration system constraints do not always limit control authority. Despite this, ABAC-SRT can still be limited to some extent by the bounds on SRT, MLSS, and DO set points, which provide a measure of safety. These set point bounds can be fine-tuned to allow unconstrained operation of the control system if desired.

Aeration energy consumption was calculated by the model for the three cases and was 3,260 kWh/d for DO and MLSS control, 2,550 kWh/d for ABAC with MLSS control, and 2,220 kWh/d for ABAC-SRT control. See Figure S4 in the Supplementary Material (available with the online version of this paper) for the cumulative energy consumption for the entire simulation for the three cases. The ABAC with MLSS control strategy results in a 22% reduction in energy consumption as compared to DO and

MLSS control. This energy reduction is consistent with that reported by Amand *et al.* (2013) and Rieger *et al.* (2012) for full-scale WRRFs that implemented ABAC.

The ABAC-SRT control strategy results in a 32% reduction in energy consumption as compared to DO and MLSS control, an additional 10% in savings due to SRT set-point optimisation. Another potential benefit of the ABAC-SRT strategy is a lower MLSS concentration, which helps minimize solids loss during storms for plants operated at high MLSS concentrations. As shown, the level of savings with ABAC and ABAC-SRT depends on the NH_x-N set point. They are also impacted by the lower bound on the DO set point and, in the case of ABAC-SRT, by the lower bound on the SRT and MLSS set points.

Controller implementation issues

An important consideration when implementing ABAC-SRT is the selection of the average DO set point of the supervisory controller. In the case study discussed earlier, the average DO set point of the supervisory controller was 1 mg/L. The average DO set point determines whether the SRT is in the correct range so that the ammonia controller can function properly to prevent NH_x-N break-through and to ensure that energy savings are maximized. See Figure S5 in the Supplementary Material (available online) for the impact on the controlled NH_x-N when the average DO set point is changed to 0.6 mg/L.

Another implementation issue is the selection of the time interval used in Equation (6). Longer time intervals serve to filter the impact of diurnal variations on the calculation of the sludge production and the impact of solids being pushed into the clarifiers during storms. If Δt is too small, the dynamic SRT will vary considerably in response to diurnal variations and will be incorrectly impacted by solids being pushed into the clarifiers during a storm (as the solids are temporarily lost as far as the calculation is concerned unless the solids mass in the clarifier is tracked). A time interval of 1 day in Equation (6) was found to provide a reasonable compromise between accuracy and eliminating the negative impact of high frequency flow variations.

Proper controller tuning is also very important for the ABAC-SRT control strategy. The system contains a number of cascaded controllers that could exhibit poor performance if not tuned properly. The lowest loops in the cascade (i.e. airflow controllers and the MLSS controller) should be tuned for a faster response than the loops higher in the cascade. As a starting point for controller tuning, correlations such as Ciancone & Marlin (1992) can be used. Use of tuning correlations requires knowledge of the process gain, time constant, and transportation lag for each control loop, which can be determined using a simulation model or plant step-response tests.

In the SIMBA# model, the controllers were fine-tuned by introducing step changes in the controller set points and adjusting the tuning constants to achieve the desired dynamic response. The MLSS and SRT controllers were tuned for a slow dynamic response to ensure that the WAS flow variations were not overly aggressive. The controller integral times are on the order of days for the SRT-related controllers and on the order of minutes for the ammonia, DO, and air flowrate controllers. The SRT-related controller gains depend on the SRT range that the system is operating within, suggesting that gain scheduling could be beneficial.

CONCLUSIONS

ABAC-SRT control is a strategy for aligning the goals of ammonia-based aeration control and SRT control. A supervisory controller is used to ensure that the SRT is always optimal for ammonia-based aeration control. The methodology has the potential to reduce aeration energy consumption by over 30% as compared to traditional DO control. Practical implementation aspects were highlighted for implementation at full scale, such as proper selection of the average DO set point for the supervisory controller, selection of the time interval used in calculating the rate of change in sludge inventory, using an MLSS controller to ensure that the SRT controller does not lead to excessively low or high MLSS concentrations, and proper tuning of the controllers. In conclusion, the ABAC-SRT concept is a promising approach for coordinated control of SRT, total ammonia nitrogen, and DO in the activated sludge process, which balances both treatment performance and energy savings.

DECLARATION

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REFERENCES

Amand, L., Olsson, G. & Carlsson, B. 2013 Aeration control – a review. *Wat. Sci. & Tech.* **67** (11), 2374–2398.

Brewer, H. M., Stephenson, J. P. & Green, D. 1995 Plant Optimization Using Online Phosphorus Analyzers and Automated SRT Control to Achieve Harbour Delisting. In: *Proceedings of WEFTEC 1995*, Miami, FL.

Bürger, R., Diehl, S., Farås, S., Nopens, I. & Torfs, E. 2013 A consistent modelling methodology for secondary settling tanks: a reliable numerical method. *Wat. Sci. & Tech.* **68** (1), 192–208.

Ciancone, R. & Marlin, T. 1992 Tune controllers to meet your performance goals. *Control* **5**, 50–57.

Dold, P. L. 2007 Quantifying Sludge Production in Municipal Treatment Plants. In: *Proceedings of WEFTEC 2007*, October 13–17, San Diego, CA.

Ekama, G. A. & Wentzel, M. C. 2008 *Biological Wastewater Treatment: Principles, Modelling and Design*. IWA Publishing, London, UK, Ch. 4 and 5.

Ekster, A. 2001 Automatic Waste Control. In: *Proceedings of the 1st IWA International Conference on Instrumentation, Control and Automation (ICA)*, June 3–7, Malmö, Sweden.

Garrett, M. T. 1958 Hydraulic control of activated sludge growth rate. *Sew. Ind. Wastes* **39** (3), 253–261.

Langergraber, G., Alex, J., Weissenbacher, N., Woerner, D., Ahnert, M., Frehmann, T., Halft, N., Hobus, I., Plattes, M., Spering, V. & Winkler, S. 2008 Generation of diurnal variation for dynamic simulation. *Wat. Sci. & Tech.* **59** (9), 1483–1486.

Langergraber, G., Spering, V., Alex, J., Ahnert, M., Cernochoca, L., Dürrenmatt, D. J., Frehmann, T., Hobus, I., Weissenbacher, N., Winkler, S. & Yücesoy, E. 2009 Using numerical simulation to optimize control strategies during activated sludge plant design. In: *Proceedings of the 10th IWA Conference on Instrumentation, Control and Automation (ICA)*, June 14–17, Cairns, Australia.

Otterpohl, R. & Freund, M. 1992 Dynamic models for clarifiers of activated sludge plants with dry and wet weather flows. *Wat. Sci. & Tech.* **26** (5–6), 1391–1400.

Plósz, B. G., Nopens, I., De Clercq, J., Benedetti, L. & Vanrolleghem, P. A. 2011 Shall we upgrade one-dimensional secondary settler models used in WWTP simulators? – an assessment of model structure uncertainty and its propagation. *Wat. Sci. & Tech.* **63** (8), 1726–1738.

Rieger, L., Takács, I. & Siegrist, H. 2012 Improving nutrient removal while reducing energy use at three Swiss WWTPs using advanced control. *Water Environ. Res.* **84** (2), 171–189.

Rieger, L., Jones, R. M., Dold, P. L. & Bott, C. B. 2014 Ammonia-based feedforward and feedback aeration control in activated sludge processes. *Water Environ. Res.* **86** (1), 63–73.

Schraa, O., Rieger, L. & Alex, J. 2016 Coupling SRT control with aeration control strategies. In: *Proceedings of WEFTEC.16*, New Orleans, LA, USA.

Schraa, O., Rieger, L. & Alex, J. 2017 Development of a model for activated sludge aeration systems: linking air supply, distribution, and demand. *Wat. Sci. & Tech.* **75** (3), 552–560.

Stephenson, J. P., Monaghan, B. A. & Laughton, P. J. 1981 Automatic control of solids retention time and dissolved oxygen in the activated sludge process. *Wat. Sci. & Tech.* **13**, 751–758.

Takács, I. 2008 *Experiments in Activated Sludge Modelling*. PhD Thesis, Ghent University, Belgium, pp. 267.

Takács, I. & Patry, G. G. 2002 The dynamic solids residence time. In: *Proceedings of IWA World Water Congress 2002*, Melbourne, Australia.

Takács, I., Patry, G. G. & Nolasco, D. 1991 A dynamic model of the thickening/clarification process. *Wat. Res.* **25** (10), 1263–1271.

U.S. Environmental Protection Agency (USEPA), Office of Research and Development 1989 *Design Manual: Fine Pore Aeration Systems*. EPA/625/1-89/023, U.S. E.P.A., Cincinnati, OH.

Vaccari, D. A., Fagedes, T. & Longtin, J. 1985 Calculation of mean cell residence time for unsteady-state activated sludge systems. *Biotech. Bioeng.* **27**, 695–703.

Vaccari, D. A., Cooper, A. & Christodoulatos, C. 1988 Feedback control of activated sludge waste rate. *Journal WPCF* **60**, 1979–1985.

van Haandel, A. C. & van der Lubbe, J. G. M. 2012 *Handbook of Biological Wastewater Treatment: Design and Optimisation of Activated Sludge Systems*. IWA Publishing, London.

WEF 1997 *Automated Process Control Strategies*. Water Environment Federation, Alexandria, VA, USA.

First received 19 October 2018; accepted in revised form 9 January 2019. Available online 23 January 2019