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Aeration Control with Gain Scheduling in a Full-scale Wastewater Treatment Plant

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Abstract: Process control is important at wastewater treatment plants to meet effluent criteria and minimise resource use. In a nitrogen removal plant, the aeration costs in the biological treatment part constitute the largest single electricity user at the plant. This study has investigated gain scheduling PI control at the Käppala wastewater treatment plant in full-scale operation and by simulation using a calibrated model of the plant. The aim was to vary the controller settings based on the nitrogen removal performance to achieve an energy saving. The best results were reached when scheduling the controller output limit, achieving a higher energy saving compared to a controller without gain scheduling.

Keywords: Process control, gain scheduling, ammonium control, aeration control, wastewater treatment

1. INTRODUCTION

Wastewater treatment is a process industry subject to many disturbances. Like other process industries, a wastewater treatment plant (WWTP) produces products (e.g. treated wastewater, sludge and biogas) out of a raw material (wastewater). Unlike most other process industries the treatment plants cannot control the raw material to the plant. Due to the need for disturbance rejection, an increased focus on resource efficiency as well as more stringent discharge limits, process control at WWTPs is becoming increasingly important. Despite e.g. high daily influent variations and rain events the plants consistently treat wastewater at all times.

Most WWTPs have discharge criteria on nutrients and organic material, since the receiving water bodies otherwise risk eutrophication and oxygen depletion. The nutrients in the incoming wastewater are mainly present as ammonium (NH_4^+) and phosphate (PO_4^{2-}) ions. Removal of nitrogen and organic material is performed through biological treatment, a process which requires aeration. The aeration process is the largest single user of electricity at WWTPs constituting 45-75 % of the total requirement (Rosso *et al.*, 2008).

There are two ways to control the aeration process for the purpose of energy and process performance optimisation. Either the total aerobic volume or the aeration intensity is changed. A common method to change the aeration intensity is to adjust the dissolved oxygen set-points in the process based on the ammonium concentration in the effluent. Since ammonium is a target variable, ammonium feedback control can change the aeration intensity to match the process requirements without wasting energy. Ammonium feedback control has been shown to decrease the air flow requirement by approximately 5 to 25 % (cf. Åmand *et al.*, 2013).

This paper presents experiments with ammonium feedback control where the ammonium controller uses gain scheduling to change the controller settings depending on the process state. Gain scheduling refers to a set of linear controllers where a process parameter is chosen as scheduling variable and the controller is determined depending on the level of the this variable (Rugh and Shamma, 2000). This creates a non-linear controller. Within process control one common example is scheduling of PID-controller parameters to handle a non-linear process. An example of a version of gain scheduling in wastewater treatment is Gerkšič *et al.* (2006).

Käppala WWTP was the case study in this work where gain scheduling is investigated by simulations and in full-scale experiments. The purpose with using gain scheduling was to achieve an energy reduction, to react on variations in treatment performance and to handle the time delay in the ammonium signal caused by the present position of the ammonium sensor. Preliminary results were presented by Åmand and Carlsson (2013).

2. KÄPPALA WWTP

The first step in a WWTP is primary treatment which involves several mechanical treatment steps (Fig. 1). The core of the nitrogen removal process is the biological treatment where ammonium is oxidised via nitrate to nitrogen gas with the help of microorganisms.

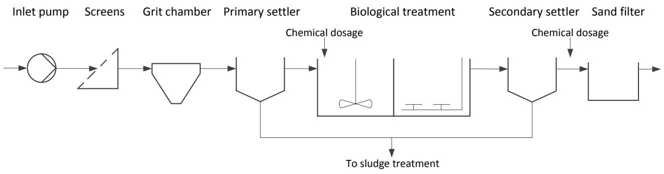

Fig. 1 Process scheme at Käppala WWTP. A close-up of the biological treatment and secondary settler is found in Fig. 2.

The most common process configuration for biological removal of organic matter and nitrogen is the activated sludge process. The sludge in the activated sludge process is microorganisms that feed on organic material and nitrogen in the wastewater. The key characteristic of the process is the separation of the sludge retention time from the hydraulic retention time by returning sludge from a settler. In the biological treatment (Fig. 1), one part of the process is aerated and another part has stirring to accommodate the two biological processes responsible for nitrogen removal: nitrification (aerated) converting ammonium to nitrate and denitrification (non-aerated) converting nitrate to nitrogen gas. A detail of the activated sludge process at Käppala WWTP including instrumentation is found in Fig. 2.

Käppala WWTP treats wastewater from around 450 000 inhabitants in northern Stockholm. The volumes in the activated sludge process are 143 850 m^3 divided into 11 parallel treatment lines. The total nitrogen concentration in the influent is 46 mg/l, and the annual discharge limit is 10 mg/l. The plant attempts to achieve complete nitrification, i.e. zero ammonium in the effluent, during dry weather flow. The inflow profile for 2012 is depicted in Fig. 3.

In aeration control it is important to be aware of that the ammonium removal process is non-linear and slow: (1) Too high dissolved oxygen (DO) concentrations add little effect on the ammonium concentration, (2) high air flow rates are less energy efficient and (3) the response time of ammonium as a response to a step change in the DO set-point is in the range of several hours.

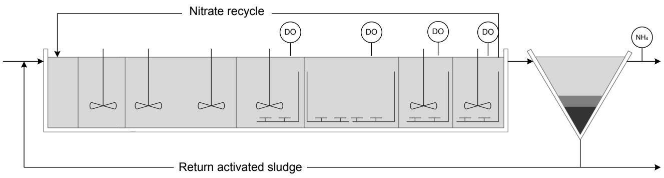

Fig. 2. The activated sludge process with nitrogen removal at Käppala WWTP. Each treatment line is divided into zones. DO = dissolved oxygen, NH_4 = ammonium.

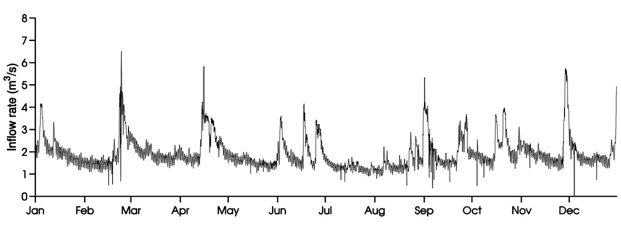

Fig. 3. Hourly inflow variations to Käppala WWTP 2012.

3. METHODS

3.1 *Control structure*

In this project, ammonium cascade control was used (Fig. 4). The ammonium concentration was the controlled variable and the manipulated variable was the position of the air flow valves determined by the air flow controllers. The air flow set-point was determined by each DO controller which achieves their set-point from the ammonium controller. The ammonium sensor was placed after the secondary settler (Fig. 2), leading to a delay of 5 to 6 hours in the controlled variable signal. It is more common to place the sensor in the last zone of the activated sludge process but at Käppala WWTP the ammonium sensor did not operate well in the hostile environment in the aeration tank, hence its present position.

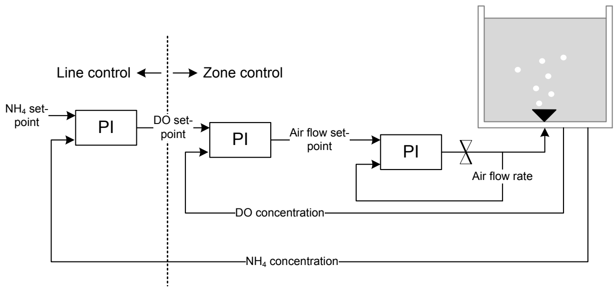

Fig. 4. Cascade NH_4 control. The NH_4 controller determines the DO set-point to the first three aerated zones in one treatment line (Fig. 2). The last aerated zone has a fixed DO set-point.

3.2 *PI control*

All controllers in the cascade were proportional-integral (PI) controllers on the following form:

$$u(t) = K\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d\frac{de(t)}{dt} \right) \qquad u_{\min} < u(t) < u_{\max} \qquad (1)$$

where *u(t)* is the controller output, *K* is the controller gain, T_i is the integral time, *e(t)* is the control error, and u_{min} and u_{max} are the upper and lower limits of the controller output, respectively. All controllers have anti-windup and use tracking, making e.g. bumpless transfer possible.

3.3 *Gain scheduling control*

The overall aim with gain scheduling was to: (1) Avoid high DO concentrations when these are not necessary and (2) avoid fast ammonium control at all times. Resource efficiency combined with non-linear process dynamics motivates the first aim and the placement of the ammonium sensor motivates the second aim.

The motivation behind the full-scale experiments with gain scheduling at Käppala WWTP was to study what was achievable in the plant control system and to select the best settings for the gain scheduling controller. The motivation behind the simulations with the plant model was to further improve the results from the full-scale experiments and to quantify the effect of gain scheduling on the energy consumption and on the treatment results.

Gain scheduling often involves linearisation of a non-linear process model around several operating points and the design of linear controllers for each linear model (Rugh and Shamma, 2000). In this study the approach did not involve linearisation of a process model; instead gain scheduling was used to change the settings in the ammonium controller at high ammonium concentrations. The basic controller implementation was as follows, using two controller zones:

$$u(t)=\begin{cases} K_1\left(e(t)+\frac{1}{T_{i,1}}\int_0^t e(\tau)d\tau\right), & u_{\min}<u(t)<u_{\max,1} \quad if \;\; SV(t)<ZL \\ K_2\left(e(t)+\frac{1}{T_{i,2}}\int_0^t e(\tau)d\tau\right), & u_{\min}<u(t)<u_{\max,2} \quad if \;\; SV(t)>ZL \end{cases} \qquad (2)$$

where *u(t)* is the output from the ammonium controller, i.e. the DO set-point, K_1, $T_{i,1}$, K_2 and $T_{i,2}$ are PI controller parameters in the two respective zones, *SV* is the scheduling variable and *ZL* is the zone limit deciding when the controller should switch to another zone.

This study evaluated three versions of gain scheduling in full-scale operation (Fig. 5). The first controller (F1) used the ammonium concentration directly as the scheduling variable while the second controller (F2) used the DO concentration in the first aerated zone. Since the DO set-point was controlled in closed-loop by the ammonium controller, the DO concentration will eventually rise when the ammonium concentration increases. These two controllers scheduled the controller gain and integral time. The third controller (F3) used the ammonium concentration as scheduling variable and scheduled the controller gain, integral time and also the upper DO set-point limit.

Three types of gain scheduling ammonium controllers were investigated by simulation of Käppala WWTP. The first controller was a combination of F1 and F2 investigated in full-scale (S1, Fig. 6). The second controller (S2) was equal to F3. The third controller was a combination of S1 and S2, i.e. the scheduling was based on the ammonium concentration and the DO concentration. In S2 and S3 the upper limit on the control signal, controller gain and integral time were scheduled.

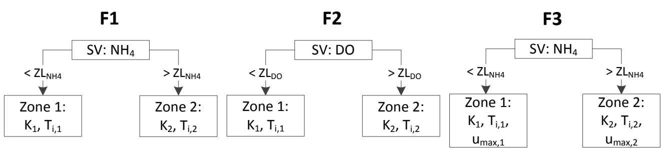

Fig. 5. The three gain scheduling controllers investigated at Käppala WWTP. The zone 1 controller was slower than the zone 2 controller.

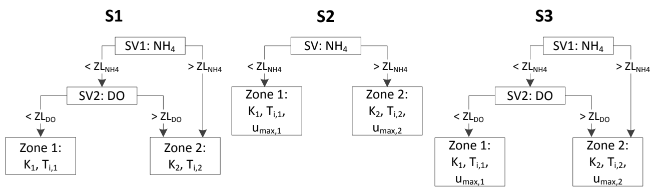

Fig. 6. The three gain scheduling controllers investigated in the Käppala simulator.

3.4 Controller evaluation

Gain scheduling was implemented in two out of eleven treatment lines at Käppala WWTP by configuring and switching on the gain scheduling extension C6 in the PIDCONA PC element (ABB Industrial Systems, 1998) in the Käppala WWTP control system (ABB 800xA). Extension C5 was switched on to allow for an externally supplied limit on the control signal which was needed to schedule u_{max} in F3.

Gain scheduling was also investigated in a simulation model, using the Activated Sludge Model No. 1, ASM1 (Henze *et al.*, 1987). ASM1 is a model with thirteen state variables, nineteen model parameters and eight process equations (ordinary differential). The processes include growth of biomass, decay and hydrolysis. The simulation platform was the Benchmark Simulation Model No. 1 Long-term, BSM1_LT (Gernaey *et al.*, 2014), developed as a tool for control strategy comparison. The simulated control strategies were evaluated for a full year, representing 2012, in a MATLAB implementation of BSM1_LT. An air flow model was included in BSM1_LT (Dold and Fairlamb, 2001). Results from the model calibration are given in Fig. 7. The default volumes, influent and ASM1 model parameters were changed to fit Käppala WWTP. Calibration was based on historic on-line daily or hourly measurements (flows, DO concentrations, sludge concentrations, air flow rates, temperature) and weekly composite lab samples (ammonium, nitrate, organic material) (Åmand, 2014). Model validation was successful for the period August to December 2011.

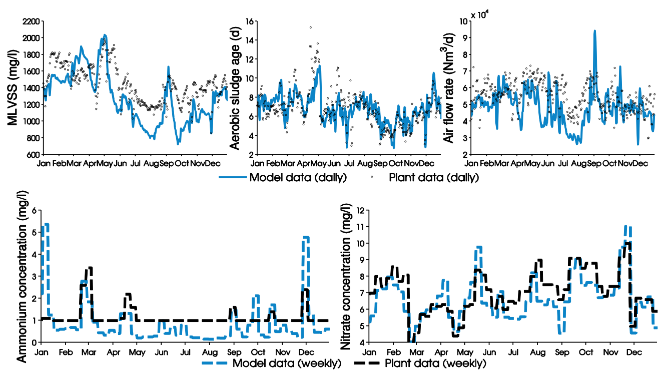

Fig. 7. Calibration results for the Käppala model 2012. Mixed liquor volatile suspended solids (MLVSS), sludge age, air flow rate (top) and effluent ammonium and nitrate concentrations (bottom). The detection limit for the lab ammonium measurement was 1 mg/l.

3.5 Controller settings

At Käppala WWTP, small improvements of the air flow and DO controllers were made during the experiment using lambda tuning (Åström and Hägglund, 2006). When the ammonium sensor is placed after the settler the sensor will read a delayed signal compared to the actual concentration in the aeration basin. Therefore, the gain scheduling ammonium controller was manually tuned to be fast at high ammonium concentrations and slower at lower concentrations, trying to avoid daily variations in DO concentrations at low ammonium concentrations. The controller settings in the ammonium controller at Käppala WWTP are presented in Table 1. The DO set-point limits were determined in communication with the plant operators.

The BSM1 controllers work with engineering units instead of percent. The scaling of the DO and NH_4 sensor signals was set-up in such a way that scaling of the controller gain in the simulator was not necessary. The controller settings in the simulations are presented in Table 2.

Table 1. Controller settings at Käppala WWTP. The NH_4 set-point was 0.8 mg/l.

	Zone	ZL_{NH4}/ ZL_{DO} (mg/l)	K	T_i (s)	u_{min} (mg/l)	u_{max} (mg/l)
F1	1	3/-	-0.05	4500	1.2	2.2
	2	3/-	-0.2	1000	1.2	2.2
F2	1	-/1.5	-0.05	4500	1.2	2.2
	2	-/1.5	-0.2	1000	1.2	2.2
F3	1	3/-	-0.05	4500	1.3	1.8
	2	3/-	-0.2	1000	1.3	2.3

Table 2. Controller settings in the Käppala WWTP simulator. The NH_4 set-point was 0.8 mg/l.

	Zone	ZL_{NH4}/ ZL_{DO} (mg/l)	K	T_i (d)	u_{min} (mg/l)	u_{max} (mg/l)
S1	1	3/1.5	-0.05	0.05	1.2	2.2
	2	3/1.5	-0.2	0.015	1.2	2.2
S2	1	3/-	-0.05	0.05	1.2	1.7
	2	3/-	-0.2	0.015	1.2	2.2
S3	1	3/1.5	-0.05	0.05	1.2	1.7
	2	3/1.5	-0.2	0.015	1.2	2.2

4. RESULTS AND DISCUSSION

4.1 Full-scale gain scheduling control

Gain scheduling with different settings has been operated for a year at Käppala WWTP. An example from gain scheduling based on the effluent ammonium concentration is found in Fig. 8. The slow controller was switched to a faster controller on October 18 when the ammonium concentration passed ZL_{NH4}. The negative aspect of this controller was a slow decrease of the DO concentration after an ammonium peak. The ammonium concentration passed ZL_{NH4} and the controller was again slow, but the DO concentration was high despite no ammonium in the effluent.

To avoid the slow decrease in DO after an ammonium peak, the controller was re-programmed making the DO concentration in the first aerobic zone the scheduling variable. This controller was fast as long as the DO concentration was high (Fig. 9). The key experience from the DO scheduling controller was that the DO zone limit should be updated relatively often (a couple of times per month). The operator would have to develop a feeling for how to change the zone limit based on the process state unless an automatic procedure could be developed for this purpose. However, the zone limit cannot be changed in the face plate (operator window) of the controller, but only in the PC element, which requires the involvement of a programmer.

One negative aspect of the DO scheduling controller was that at times the controller was made fast without need. Since the ammonium controller was integrating, DO increased slowly over time which could trigger a zone shift even at low ammonium concentrations. An example is given in Fig. 10 where the DO concentration was increased to its upper limit even though the effluent ammonium concentration just barely reached above its set-point of 0.8 mg/l.

The final controller evaluated in full-scale was the controller which scheduled the PI controller parameters and the upper limit of the DO set-point. An example of the behaviour of F3 compared to F2 is found in Fig. 11. The high ammonium concentrations were due to snow melting in early January 2014. The ammonium concentration was expected to be exaggerated in the treatment line where F3 operated. Despite this exaggeration, the average DO concentration was in average lower in the treatment line with F3.

When the ammonium concentration passed the zone limit the ammonium controller became fast, and the upper DO limit was increased. During January 12 and January 15 the ammonium concentration for F3 was for a period above its set-point of 0.8 mg/l but below the zone limit of 3 mg/l and the upper DO limit was decreased.

After the first ammonium peak the ammonium sensors experienced a shift of the signal which was corrected when the sensors were calibrated on January 15. The shift was higher in the sensor used in the controller with F3. This is common behaviour of the ammonium sensors after high ammonium peaks. The sensor often settles at a value above the ammonium set-point but below 3 mg/l which is the ZL_{NH4}. By scheduling the upper DO set-point, unnecessary aeration can be avoided during periods of sensor shifts.

To evaluate the effect of gain scheduling on treatment results and energy consumption is difficult in full-scale operation due to measurement errors and differences between parallel treatment lines. This motivates quantitative comparisons using a process model.

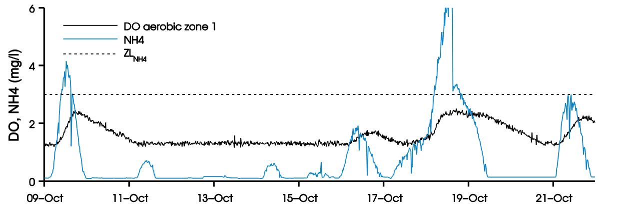

Fig. 8. Gain scheduling with F1 at Käppala WWTP (15 min data). NH_4 concentration as scheduling variable.

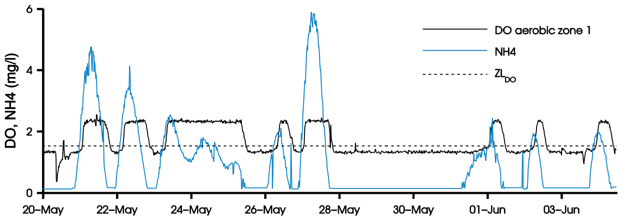

Fig. 9. Gain scheduling with F2 at Käppala WWTP (15 min data). DO concentration as scheduling variable.

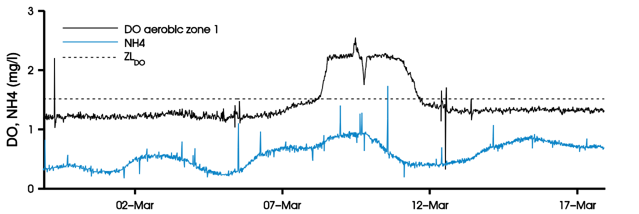

Fig. 10. Example of when the DO-scheduling GS controller increases the DO concentration without need.

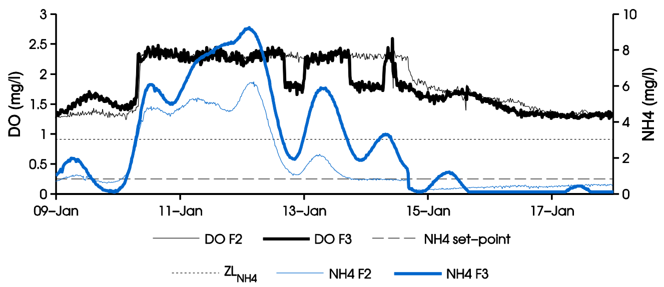

Fig. 11. Gain scheduling with F2 and F3 at Käppala WWTP (15 min data). NH_4 concentration as scheduling variable.

4.2 Simulation of gain scheduling control

The gain scheduling controllers were compared with two reference controllers: a simulation with constant DO concentrations and a zone 1 ammonium controller without gain scheduling and with an upper DO limit of 2.2 mg/l. The DO concentrations from these controllers are found in Fig. 12. The ammonium profile with constant DO control is presented in Fig. 13.

A close-up from October, November and December of the DO concentrations in the three modelled gain scheduling ammonium controllers are found in Fig. 14 to Fig. 16. Simulations were not performed at the exact same period as the full-scale experiments, but the plant performance was assumed to be comparable between the two periods.

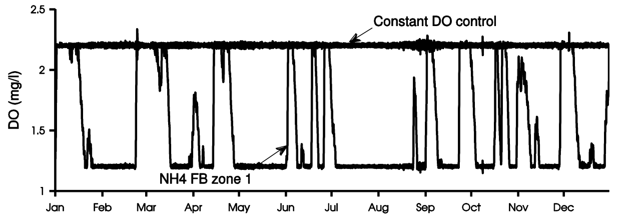

Fig. 12. DO concentrations in the two reference controllers. The NH_4 FB zone 1 refers to the controller in zone 1 (K = -0.05 ant T_i = 0.05 d).

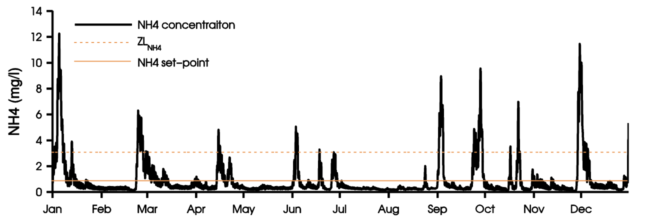

Fig. 13. Effluent NH_4 profile during 2012 with NH_4 set-point and ZL_{NH4} marked. Data from a simulation with DO set-point of 2 mg/l.

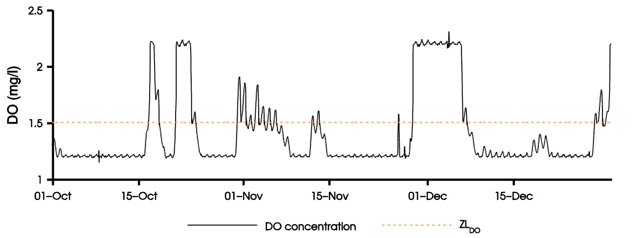

Fig. 14. DO concentration with S1 (scheduling on NH_4 and DO concentration).

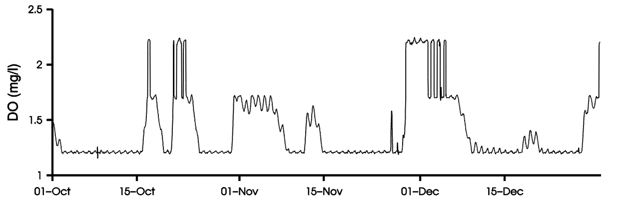

Fig. 15. DO concentration with S2 (scheduling on NH_4, different upper DO limits in zone 1 and 2).

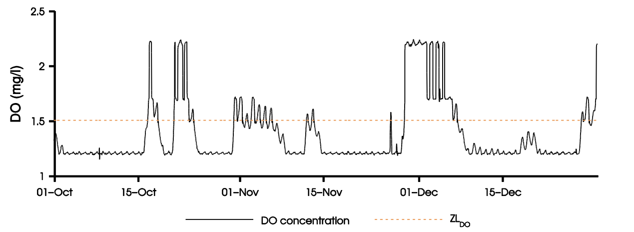

Fig. 16. DO concentration with S3 (scheduling on NH_4 and DO, different upper DO limits in zone 1 and 2).

The three gain scheduling controllers achieved the goal of increased aeration intensity during high ammonium concentrations. Through scheduling on the DO concentration (S1 and S3), the slow decrease in DO after the peak as seen in Figure 9.2 was avoided – thereby minimising energy loss. Through scheduling the upper limit of the control signal and not only the gain and integral time (S2 and S3); the DO concentration was only high when motivated by higher ammonium concentrations.

The three gain scheduling controllers are in some respects similar to having a look-up table to decide the DO set-point based on fixed levels of the ammonium concentration. The gain scheduling controllers are however smoother than control based on a look-up table and also offers less wear and tear on the control valves and blowers.

A summary of ammonium concentrations, DO concentrations and energy consumption (measured as air flow rate) is given in Table 3. The constant DO controller had lower average and maximum ammonium concentrations since the DO concentration was high at all times but at the cost of high air flow rates.

At the ten peak ammonium events during 2012 when the Zone 1 controller reached its upper limit in Fig. 13, the best performance was found with the S3 controller, with a 6.7 % energy saving compared to the constant DO controller and a 4.2 % saving compared to the Zone 1 ammonium controller (Table 3). The average reduction over the whole year was 11.4 % compared to constant DO control and 1.3 % compared to the Zone 1 ammonium controller for the GS3 controller. The effluent ammonium concentration was slightly higher when using ammonium feedback control.

Table 3. Summary of simulation results. Constant DO control and slow NH_4 FB are reference controllers.

Controller	Average NH_4 (mg/l)	Max NH_4 (mg/l)	Average DO (mg/l)	Peak NH_4 energy red. (%)
Constant DO	1.23	12.35	2.20	
Zone 1 NH_4 FB	1.34	12.45	1.49	-2.5
S1	1.23	12.45	1.41	-4.6
S2	1.26	12.50	1.38	-6.2
S3	1.27	12.50	1.36	-6.7

5. CONCLUSIONS

Gain scheduling was investigated at Käppala WWTP in full-scale operation and in a simulation study. Full-scale experiments and simulations showed that gain scheduling offers the best possibilities if not only the PI controller gain and integral time are scheduled, but also the limitation of the upper limit of the control signal from the ammonium controller (i.e. the DO set-point). It is an obstacle that a programmer is required to change the settings when gain scheduling is switched on in the control system at Käppala WWTP.

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