UPTEC W11 034
Examensarbete 30 hp
December 2011

Energy savings with a new aeration and control system in a mid-size Swedish wastewater treatment plant

Viktor Larsson

ABSTRACT

Energy savings with a new aeration and control system in a mid-size Swedish wastewater treatment plant
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Within this study it was investigated how much energy and money that could be saved by implementing new aeration equipment and aeration control in Sternö wastewater treatment plant (WWTP).

Sternö WWTP is a full-scale plant built in 1997 and dimensioned for 26 000 population equivalents. The plant has two parallel biological treatment lines with pre-denitrification. During the study, one of the treatment lines was used as a test line, where new aeration equipment and control was implemented. The other line was used as a reference line, where the aeration equipment and control was maintained as before.

The new aeration equipment that was implemented to support the test line was an AtlasCopco screw blower, fine bubble Sanitaire low pressure diffusers and measurement equipment. Two control strategies were tested: oxygen control and ammonium control.

The results show that 35 percentage points of the test line energy consumption was reduced with the new screw blower. The diffusers saved another 21 percentage points and by fine tuning the controllers, the oxygen concentrations and the air pressure a further 9 percentage points could be saved. The ammonium control gave no energy savings, since the lowest allowed DO set-point (0.7 mg L^{-1}) kept effluent ammonium below the ammonium set-point of 1 mg L^{-1}. The final energy savings of the test line was 65 ± 2 %.

Each aeration equipment upgrade increased the energy savings with:

- Blower 35 %.
- Diffusers 32 %.
- Oxygen control with decreased DO concentrations and air pressure 21 %.

The final savings correspond to 13 % of the total energy consumption of Sternö WWTP. These savings are equivalent to annual savings of 178 MWh, which decreases the energy costs by 200 000 SEK per year. The payback period of the implemented aeration equipment and control was 3.7 years.

Keywords: Aeration, wastewater treatment, nitrogen removal, aeration control, BSM1

Uppsala University
Department of Information Technology
Box 337
SE-751 05 Uppsala

REFERAT

Energibesparingar genom ett nytt luftnings- och reglersystem i ett medelstort svenskt avloppsreningsverk
Viktor Larsson

I denna studie har det undersökts hur mycket energi och pengar som kan sparas genom att installera ny luftningsutrusning och luftningsreglering i Sternö avloppsreningsverk. Reningsverket är beläget i Karlshamn och dimensionerat för 26 000 personekvivalenter. Den biologiska reningen är uppdelad på två parallella reningslinjer, där den ena användes till försök och den andra som referenslinje i denna studie. Den biologiska reningen utgörs av en konventionell aktivslamprocess med fördenitrifikation.

Studien innefattade en simulering där två olika reglerstrategier för luftningen jämfördes. Simuleringen gjordes i programmet *Benchmark Simulation Model no 1* och modellen anpassades för att efterlikna Sternö reningsverk på bästa sätt. De två reglerstrategierna för luftningen utgjordes av luftstyrning baserad på syrekoncentration i bioreaktorerna och luftstyrning baserad på utgående ammoniumkoncentration från bioreaktorerna. Simuleringen visade att energibesparingen från ammoniumreglering jämfört med en syrereglering är liten. Fördelen med ammoniumreglering är istället att den önskade reningsgraden lättare kan uppfyllas över året, trots varierande temperatur.

Vid fullskaleförsök vid försökslinjen installerades ny luftningsutrustning (AtlasCopco blåsmaskin med skruvteknologi, Sanitaire småbubbliga diffusorer, samt mätningsutrustning) och ny luftstyrning. Två luftstyrningsstrategier testades: syrereglering och ammoniumreglering. Resultaten visade att blåsmaskinen gav en energibesparing på 35 procentenheter, att diffusorerna gav en energibesparing på 21 procentenheter och att fininställd syrereglering tillsammans med sänkta syre- och lufttrycksnivåer gav en sänkning på 9 procentenheter. Ammoniumregleringen gav ingen energibesparing eftersom den lägst tillåtna syrekoncentrationen (0,7 mg L^{-1}) höll ammoniumkoncentrationen under sitt börvärde på 1 mg L^{-1}. Den slutliga energibesparingen för testlinjen var 65 ± 2 %.

Varje luftningsutrustning bidrog med följande energibesparing:

- Blåsmaskin 35 %.
- Diffusorer 32 %.
- Ny syrereglering med sänkta syre- och lufttrycksnivåer 21 %.

Den slutliga energibesparingen i testlinjen motsvarar 13 % av Sternö reningsverks totala energiförbrukning, vilket gör att 178 MWh kan sparas per år. Den minskade energiförbrukningen sänker energikostnaden för reningsverket med 200 000 SEK per år. Återbetalningstiden på den till försökslinjen installerade utrustningen var 3,7 år.

Nyckelord: Luftning, avloppsvattenrening, kväveavlägsning, luftflödesstyrning, BSM1

Uppsala universitet
Institutionen för informationsteknologi
Box 337
SE-751 05 Uppsala

PREFACE

This is the report for my Master Thesis, finishing my Master of Science degree in Environmental and Water Engineering at Uppsala University.

The master thesis was performed at Xylem, Sundbyberg, with Aleksandra Lazic (Xylem) as my supervisor. I am thankful for all our good discussions and your support.

I also want to thank my subject reviewer Bengt Carlsson (Department of Information Technology, Uppsala University) for your well directed guidance and your help.

The examiner of this master thesis was Allan Rodhe (Department of Earth Sciences, Uppsala University). Thank you for all the good comments on the report.

I would also like to thank Leif Sedin and Thore Månsson at Xylem for good companionship during the work. The staff at Sternö WWTP has been very helpful and welcoming, special thanks to Ida Schyberg, Per Karlsson and Stefan Lennartsson.
I am also thankful for the help with literature from Linda Åmand (IVL Swedish Environmental Research Institute Ltd.) and I want to thank Ulf Jeppsson (Department of Industrial Electrical Engineering and Automation, Lund University) for letting me use his implementation of BSM1 in Matlab/Simulink.

Last but not least, thank you Johanna for your steady support.

Uppsala, 2011

Viktor Larsson

UPTEC W 11 034, ISSN 1401-5765
Printed at the Department of Earth Sciences, Geotryckeriet, Uppsala University, Uppsala 2012.

POPULÄRVETENSKAPLIG SAMMANFATTNING

I svenska reningsverk renas organiska ämnen och kväve genom ett biologisk reningssteg. Denna rening utförs av mikroorganismer, främst bakterier, som konsumerar dessa ämnen för att växa och få energi.

Den biologiska reningen utförs i olika steg, där man i ett steg tillför luft för att bakterierna ska få tillgång till syre. Detta utförs i bassänger som ofta är 4-6 meter djupa. En vanlig metod för att få en tillräcklig mängd bakterier som utför reningen är att först låta bakterierna utföra reningen i den luftade bassängen, för att sedan låta dem åka vidare till en sedimenteringsbassäng. Vid sedimenteringsbassängen sedimenteras bakterierna till botten och pumpas sedan tillbaka till den luftade bassängen. På så sätt får man en konstant hög koncentration av bakterier i den luftade bassängen.

Luftningen sker ofta från botten av den luftade bassängen med hjälp av så kallade diffusorer, som släpper ut luften i små bubblor i tanken genom ett gummimembran. Luften kommer då från en blåsmaskin, som är en slags kompressor, som leds via rör ned till diffusorerna.

Luftningen är visserligen kostsam, men också mycket viktig eftersom den är en del i processen som renar avloppsvattnet från miljöbelastande näringsämnen, som annars skulle kunna påverka sjöar och hav. Luftningen är dyr eftersom blåsmaskiner generellt sett är energikrävande och vid vissa avloppsreningsverk kan blåsmaskinerna förbruka så mycket som 56 % av den totala energin. Därför är det viktigt att luftningsutrustningen är effektiv och att luftningen styrs på ett bra och energisnålt sätt. Luftningsstyrning görs generellt genom att reglera en ventil som kontroller hur mycket luft som släpps fram till diffusorerna. Ventilen kan regleras baserat på olika faktorer, där en variant är att man mäter syrehalten i bassängen och styr ventilen så att man hela tiden upprätthåller samma syrehalt.

Syftet med denna studie var att undersöka hur mycket energi och pengar som kan sparas genom att installera ny luftningsutrusning och ny luftningsstyrning i Sternö avloppsreningsverk.

Sternö avloppsreningsverk är beläget i Karlshamn och är ett medelstort svenskt reningsverk, dimensionerat för att kunna rena avloppsvattnet från 26 000 personer. Reningsverkets biologiska rening är uppdelad på två parallella reningslinjer, där den ena linjen användes till försök och den andra linjen användes som referenslinje vid denna studie.

Studien innefattade både simuleringsförsök och fullskaleförsök på Sternö reningsverk. Simuleringsförsöken utfördes i simuleringsmodellen *Benchmark Simulation Model no 1*, vilken modellerar det biologiska reningssteget i ett avloppsreningsverk. Modellen använder sig av en mängd ekvationer för att efterlikna de biologiska reaktionerna som sker i det biologiska reningssteget. I modellen testades två olika luftningsstyrningar. Den ena luftningsstyrningen syftade till att hålla syrehalten konstant (syrereglering) den andra luftningsstyrningen syftade till att hålla ammoniumhalten konstant (ammoniumreglering). Båda metoderna använde luftflödet som styrparameter.

Resultaten från simuleringsstudien visade att energibesparingen från ammoniumregleringen var liten, jämfört med den från syreregleringen. Fördelen med ammoniumreglering är istället att den önskade reningsgraden av ammonium lättare kan uppfyllas över året, trots varierande temperatur.

Vid fullskaleförsök vid försökslinjen på Sternö avloppsreningsverk installerades ny luftningsutrustning (blåsmaskin, diffusorer samt mätningsutrustning) och ny luftstyrning (syrereglering och ammoniumreglering). Denna utrustning installerades i flera steg med syfte att kunna urskilja hur mycket energibesparing respektive utrustning bidrar med.

Resultatet av testerna visade att blåsmaskinen gav en energibesparing på 35 procentenheter, att diffusorerna gav en energibesparing på 21 procentenheter och att fininställd syrereglering tillsammans med sänkta syre- och lufttrycksnivåer gav en ytterligare sänkning på 9 procentenheter. Ammoniumregleringen gav ingen energibesparing eftersom den lägst tillåtna syrekoncentrationen (0,7 mg L^{-1}) höll ammoniumkoncentrationen under sitt börvärde på 1 mg L^{-1}. Den slutliga energibesparingen för testlinjen var 65 ± 2 %.

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DEFINITIONS

AOR	actual oxygen requirement
BOD	biochemical oxygen demand
CO_2	carbon dioxide
DO	dissolved oxygen
F/M	food-to-microorganism ratio
M&C	monitor & control
MOV	most open valve
N	nitrogen
NO_3^-	nitrate
NH_4^+	ammonium
NH_3	ammonia
$Nm^3\,h^{-1}$	airflow corrected to 0^oC and 101.3 kPa
OTE	oxygen transfer efficiency
OTR_f	oxygen transfer rate in field conditions
P	phosphorous
Recipient	water body receiving wastewater from WWTP
SAE	standard aeration efficiency
SCADA	supervisory control and data acquisition
SOTE	standard oxygen transfer efficiency
SOTR	standard oxygen transfer rate
SRT	solids retention time
WWTP	wastewater treatment plant

TABLE OF CONTENTS

1 INTRODUCTION

In a typical wastewater treatment plant (WWTP) with an activated sludge process, the largest energy usage comes from the activated sludge aeration (56 %), followed by primary clarifier and sludge pump (10 %), heating (7 %) and solids dewatering (7 %) (Tchobanoglous et al. 2003). Consequently, aeration is generally by far the largest single energy consumer in WWTPs and if this energy usage could be decreased, substantial improvements to the total electricity consumption could be made.

According to EPA (2010), energy costs in the wastewater industry are rising. A number of reasons are mentioned, among them increased electricity rates and implementation of more stringent effluent requirements. Stringent effluent requirements could lead to an increased need for aeration, which makes aeration more energy intense. Based on the rising energy costs for wastewater aeration, large economical savings could be made if the energy consumption could be decreased.

A common form of aeration is subsurface aeration (EPA 1999), where a blower through piping supports the bottom-placed diffusers with air. To achieve a subsurface aeration system with high energy efficiency, it is important that the involved equipment (blower, piping, diffusers) is well sized, configured and uses energy efficient technology. A reasonable payback period for new aeration equipment is suggested to be less than 10 years (EPA, 2010).

An aid to meet effluent requirements and to decrease energy consumption is automatic control, which could be used to control the aeration. Implementation of aeration control in certain WWTPs has attained energy savings of 10-20 % (Carlsson & Hallin, 2010). One common control strategy is dissolved oxygen (DO) control, which aims at keeping a constant DO level in the aerated tank. Another control strategy is ammonium control, which is used around the DO control. Energy savings have been performed with ammonium control in full-scale WWTPs (Ingildsen 2002, Thunberg et al. 2007).

The overall objective of this master thesis was to save as much energy as possible by implementing new aeration equipment and control in Sternö WWTP, a full-scale WWTP in Karlshamn, Sweden. The specific aims of the study were:

- To preserve treatment results of BOD and ammonium.
- To achieve more stable DO concentrations in the basin.
- To automatically control effluent ammonium concentration.
- To evaluate the total energy and economical savings of the WWTP.
- To calculate the return period of the implemented equipment.

1.1 DELIMITATIONS

In this master thesis the following delimitations were made:

- No oxygen credit from denitrification was accounted for.
- The focus of the literature study was on full-scale trials.
- Only treatment related to aeration was taken into account. This means that treatment of organic constituents and ammonium was considered, but neither treatment of total nitrogen nor phosphorous.

1.2 OVERVIEW OF THE STUDY

This study included several components:

- A literature study of aeration control (chapter 3.3.4).
- A simulation study of different control strategies implemented in Sternö WWTP (chapter 4). It was investigated if energy savings could be performed and how the effluent concentration of ammonium would be affected if ammonium control was implemented in the first of the two aerated zones in a test line. Also, the ammonium PI controller parameters were obtained through tuning, which could be used for full-scale trials.
- Full-scale trials in Sternö WWTP (chapter 5). New aeration equipment and control (blower, diffusers and DO cascade control) were installed in the test line before the master thesis started. Within the master thesis, the DO cascade controllers were tuned, the DO profile was changed, the air pressure was lowered through MOV-logic and ammonium control was implemented. The aeration energy savings from each equipment and control upgrade was evaluated based on standard aeration efficiency (kg O_2 kWh^{-1}). The WWTP's total energy savings and economical savings were calculated based on the aeration energy savings, and the return period for the implemented equipment was calculated.

2 BIOLOGICAL WASTEWATER TREATMENT

2.1 WASTEWATER TREATMENT IN GENERAL

A WWTP consists of several different treatment steps and normally they are divided into preliminary, primary, secondary and tertiary treatment.

The purpose of the preliminary treatment is to remove large objects (like rags, paper, plastics etc.) from the wastewater, before they enter the WWTP. This treatment is often performed by screening and grit chambers. Screening is purely mechanical and is often performed by bar screening, whereas grit chambers use the higher sedimentation speed of sand, grit, etc. to remove these particles from the wastewater.

In the primary treatment, heavy suspended solids are removed from the wastewater through sedimentation. Since the heavy suspended particles are smaller than those removed in the preliminary treatment, the speed of the wastewater needs to be lower than in the preliminary treatment. The primary treatment reduces the BOD concentration in the wastewater and thereby decreases the load on the secondary treatment.

The secondary treatment is a biological treatment, performed by microorganisms. This treatment process is executed within an aerated biological reactor, so that the microorganisms are supplied with air and particles are kept in suspension. Further reading about biological treatment can be found in Chapter 2.2.

Some WWTPs also have tertiary treatment, in which phosphorous is removed through precipitation. There are several process solutions available where different precipitation chemicals can be used and added at different locations in the WWTP.

After the main treatment, the wastewater is most often filtrated through a granular filter before the wastewater is discharged to the recipient. This further reduces the amount of suspended solids.

This project concerned aeration and aeration control in the biological treatment, but actually aeration could be used in various parts of a WWTP. It could be used not only to perform treatment of BOD and nitrogen but also to prevent odours and for mixing of wastewater. Generally, the by far largest aeration need is in the biological treatment.

2.2 BIOLOGICAL WASTEWATER TREATMENT IN PARTICULAR

Biological wastewater treatment is performed by microorganisms, mainly bacteria (Tchobanoglous et al. 2003; Carlsson & Hallin, 2010). Bacteria are prokaryotic cells with a typical composition of 50 % carbon, 22 % oxygen, 12 % nitrogen, 9 % hydrogen and 2 % phosphorous (Tchobanoglous et al. 2003).

For cell growth and proper function, bacteria need energy, carbon and several inorganic elements. There are different types of bacteria and in this study it is the aerobic heterotrophic, aerobic autotrophic and facultative heterotrophic bacteria that are of greatest interest.

Aerobic heterotrophic bacteria live in aerobic environments and perform aerobic oxidation. They get their carbon and energy from organic compounds and use oxygen as an electron acceptor to produce CO_2 and H_2O.

Aerobic autotrophic bacteria live in aerobic environments and perform nitrification. They get their carbon from CO_2 and their energy from NH_4^+ or NO_2^-. They use oxygen as an electron acceptor and the product of nitrification is NO_2^- or NO_3^-.

Facultative heterotrophic bacteria can live in anoxic environments but prefer aerobic environments. If they live in an anoxic environment they can perform denitrification and they use organic compounds as their carbon and energy source. They use NO_2^- and NO_3^- as their electron acceptor and the end product of denitrification is N_2.

2.2.1 Treatment of organic constituents

Effluent organic constituents pollute the environment partly since the degradation of organic constituents is oxygen consuming. Therefore, problems with anaerobic or anoxic conditions could occur if these constituents are poorly treated in the WWTPs.

Treatment of organic constituents is to the greatest extent performed by aerobic heterotrophic bacteria. They oxidize the organic pollutants, which in WWTPs often is measured as BOD. BOD is the bacteria's oxygen demand during degradation of organic matter. The measurement process of BOD is hereby explained in a simplified way: A sample of wastewater is diluted with oxygen saturated and nutrient prepared water in a bottle, whereupon the DO concentration is measured. The bottle is then stoppered and incubated in 20 °C for a number of days, often 5 (BOD_5) or 7 (BOD_7). After this time the DO concentration is measured again and the BOD is calculated according to:

$$BOD = \frac{DO_1 - DO_2}{P} \qquad (1)$$

where,

BOD = Biochemical oxygen demand, [mg L^{-1}]
DO_1 = DO concentration of diluted sample immediately after preparation [mg L^{-1}]
DO_2 = DO concentration of diluted sample after incubation [mg L^{-1}]
P = Fraction of wastewater sample volume to total combined volume [-]

The oxygen decrease measured in BOD is a result of three processes: *oxidation*, *synthesis* and *endogenous respiration*. To provide short explanations of the processes:

- Oxidation of organic matter is done by the microorganisms to usurp energy.
- Synthesis is the process within the organisms when new cell tissue is created.
- Endogenous respiration is the process when the organisms oxidize internal storage reserves in order to maintain essential life processes.

The chemical reactions of these processes can be seen in equation 2, 3 and 4 (Tchobanoglous et al. 2003).

Oxidation:

$$COHNS + O_2 + bacteria \rightarrow CO_2 + H_2O + NH_3 + other\ end\ products + energy \quad (2)$$

Synthesis:

$$COHNS + O_2 + bacteria + energy \rightarrow C_5H_7NO_2 \quad (3)$$

Endogenous respiration:

$$C_5H_7NO_2 + 5O_2 \rightarrow 5CO_2 + NH_3 + H_2O \quad (4)$$

where,

COHNS = Organic matter by the elements carbon, oxygen, hydrogen, nitrogen and sulphur

$C_5H_7NO_2$ = Cell tissue

It is important to notice that BOD (measured in a bottle in a lab) does not necessarily correlate with the oxygen demand in the WWTP process, since the three reactions mentioned above might differ in lab environment and process environment. Also, if BOD is measured for 10 days or more, nitrification (discussed in Chapter 2.2.2) might also occur (Lind et al. 2007a).

To make an example, high and low incoming concentrations of organic matter (COHNS) could be compared. If the incoming concentration is high, the bacteria will perform oxidation and synthesis to a great extent. This means that the oxygen requirement per *incoming* concentration of organic matter is relatively low. On the other hand, if the incoming concentration of organic matter is low, the bacteria will oxidize the incoming organic matter but since there is too little substrate (food for the microorganisms), they also perform endogenous respiration to a great extent. This means that the oxygen requirement per *incoming* concentration of organic matter is relatively high. The oxygen requirement per incoming BOD concentration therefore depends on the process conditions in the WWTP.

There are different approaches to approximate the carbonaceous oxygen demand; one of them is suggested in EPA (1989) and uses the operating conditions temperature and total SRT to approximate the oxygen consumption ratio, according to Figure 1.

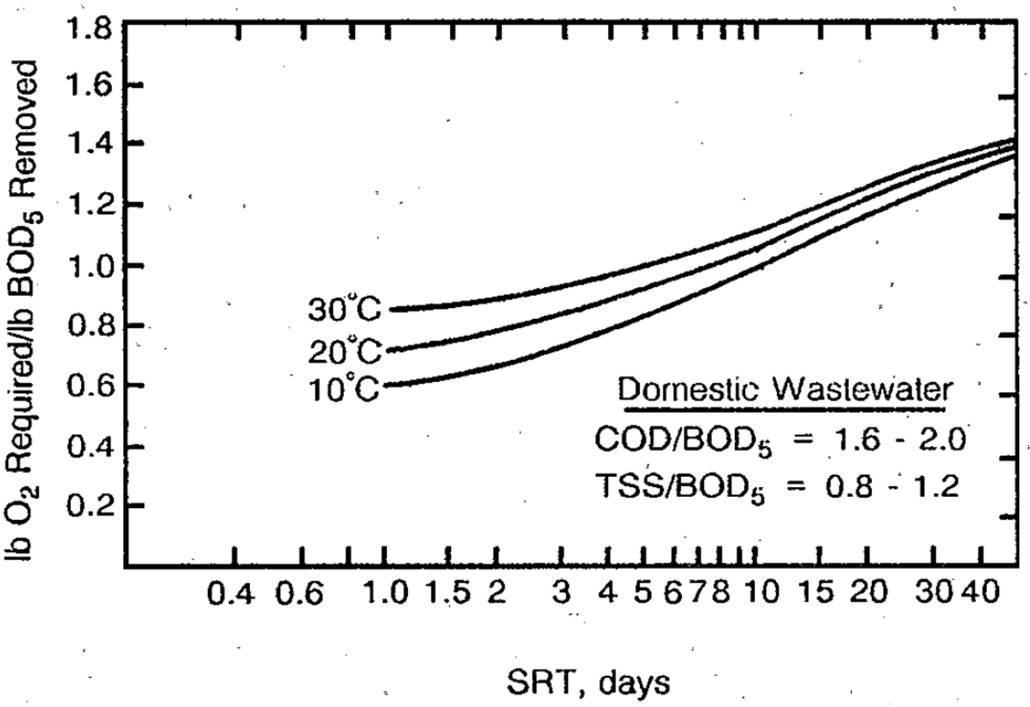

Figure 1 Oxygen consumption ratios for carbonaceous oxygen demand. From U.S. EPA, 1989.

Figure 1 shows that at higher temperatures the oxygen demand per removed BOD_5 is increased. The figure also shows that for a higher sludge retention time (SRT, as defined in Chapter 2.3.3), the oxygen demand per removed BOD_5 is higher. This is a result of the endogenous respiration, which the method implicitly considers. If the SRT is higher F/M is lower, which increases the endogenous respiration and therefore increases the oxygen demand per amount of BOD_5 removed.

2.2.2 Treatment of nitrogen

Nitrogen is one of the most important nutrients and can produce eutrophication in seas and lakes if discharged in large amounts. It is therefore important that nitrogen is treated to a large extent before the wastewater is discharged to the recipient.

Organic bound nitrogen is transformed into ammonium through the chemical process ammonification according to U.S. EPA (2008):

$$Organic\ nitrogen \rightarrow NH_4^+ \qquad (5)$$

Ammonification often occurs in wastewater piping systems, why incoming nitrogen to WWTPs often is in the form of ammonium. But ammonification can also occur as an effect of endogenous respiration and decay in the WWTP bioreactors, why effluent ammonium concentration theoretically could be higher than influent ammonium concentration.

Nitrogen is partly removed through bacteria synthesis; generally 10-30 % of the incoming nitrogen load is removed in this way (Carlsson & Hallin, 2010) and therefore accumulated in the microorganisms. For complete nitrogen removal, two processes are required: nitrification and denitrification.

Nitrification is the process where ammonium is oxidized to nitrate in two steps; see equation 6 and 7. The two steps are performed by two different groups of nitrifying bacteria. These bacteria are aerobic autotrophic and a common genera for the first step is *Nitrosomonas* and a common genera for the second step is *Nitrobacter* (U.S. EPA, 2008). The total reaction (8) gives the theoretical oxygen need of 4.57 kg O_2 (kg N)$^{-1}$, according to equation 9.

$$NH_4^+ + 3/2\,O_2 + 2HCO_3^- \rightarrow NO_2^- + 2H_2CO_3 + H_2O \tag{6}$$

$$NO_2^- + 1/2\,O_2 \rightarrow NO_3^- \tag{7}$$

$$NH_4^+ + 2\,O_2 + 2HCO_3^- \rightarrow NO_3^- + 2H_2CO_3 + H_2O \tag{8}$$

Theoretical oxygen demand for oxidation of ammonium:

$$\frac{kg\ O_2}{kg\ NH_4 - N} = \frac{M(2O_2)}{M(N)} = \frac{4 \times M(O)}{M(N)} = \frac{4 \times 16.00}{14.01} = 4.57 \tag{9}$$

Aerobic autotrophic bacteria assimilate carbon from CO_2 and this process is highly energy consuming – therefore these bacteria can use only 2-10 % of the free energy for synthesis (Carlsson & Hallin, 2010). This makes the aerobic autotrophic bacteria grow very slowly, slower than the aerobic heterotrophic bacteria. Since the growth rate of nitrifying bacteria is low, these bacteria are often restricting the biological wastewater treatment performance needed to achieve effluent quality defined by authorities. The growth kinetics of nitrifying bacteria is (Tchobanoglous, 2003):

$$\mu_n = \mu_{nm}\left(\frac{N}{K_n + N}\right)\left(\frac{DO}{K_O + DO}\right) - k_{dn} \tag{10}$$

where,

μ_n = specific growth rate of nitrifying bacteria, [d^{-1}]
μ_{nm} = maximum specific growth rate of nitrifying bacteria, [d^{-1}]
N = nitrogen concentration [kg m^{-3}]
K_n = half-velocity constant, substrate concentration at one-half the maximum specific substrate utilization rate [kg m^{-3}]
DO = dissolved oxygen concentration [kg m^{-3}]
K_O = half-saturation coefficient for DO [kg m^{-3}]
k_{dn} = endogenous decay coefficient for nitrifying organisms [d^{-1}]

In equation (10), nitrogen is used instead of ammonia. Also, the maximum specific growth rate (μ_{nm}) is a function of temperature - higher growth rates can be accomplished by higher temperatures. Nitrification can occur in wastewater temperatures of 4 to 35 °C and the nitrification rate doubles for every 8 to 10 °C rise.

From equation (10) it is important to notice that the specific growth rate μ_n increases with higher nitrogen (ammonium) and DO concentrations.

Denitrification is a process where nitrate is being reduced to nitrogen gas (N_2), see equation 11. Denitrification is performed by microorganisms in order to use nitrate as an oxidizing agent, to oxidize organic matter. The following process constitutes denitrification (U.S. EPA, 2008) and is carried out in one single bacteria cell (Carlsson & Hallin, 2010):

$$NO_3^- + organiccarbon \rightarrow N_2(g) + CO_2(g) + H_2O + OH^- \qquad (11)$$

The reduction of nitrogen is done in 4 steps, according to Carlsson & Hallin (2010):

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2 \qquad (12)$$

Denitrifying bacteria are facultative heterotrophic and can "breathe" with both oxygen and nitrate – but it is only with the latter that they perform denitrification. If the denitrification process is started and the bacteria get access to oxygen, the bacteria can stop the denitrification process (since the energy profit is higher when breathing with oxygen according to Carlsson & Hallin (2010)). This leaves a half-finished denitrification process where N_2O could be the end product, which is bad from an environmental perspective since N_2O is a strong greenhouse gas, stronger than N_2.

2.3 ACTIVATED SLUDGE PROCESS

2.3.1 Simple process solution

Activated sludge is a process solution for biological wastewater treatment in which microorganisms are suspended in the bioreactor. The microorganisms are then settled and some of them are returned to the bioreactor as return sludge. The return sludge is necessary because the incoming concentration of microorganisms is too low for the treatment process operation.

One of the simplest versions of an activated sludge process consists of an aerated basin and a clarifier, as can be seen in Figure 2. The aerated basin is provided with incoming water from the primary sedimentation as well as return sludge. In order not to overload the bioreactor with microorganisms, the excess sludge is removed and thereafter thickened and dewatered before disposal.

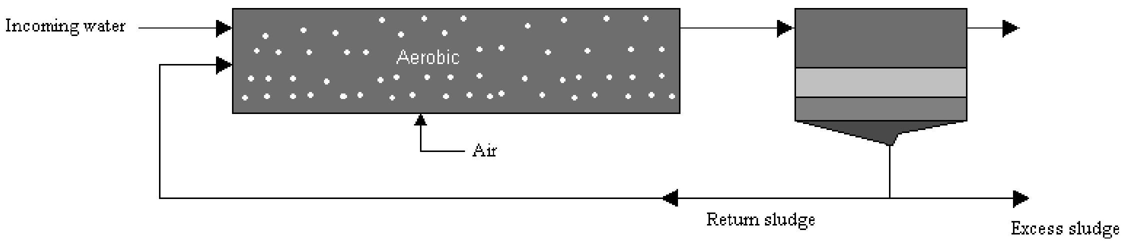

Figure 2 A simple version of an activated sludge process.
Modified from Carlsson & Hallin, 2010.

The simple activated sludge process reduces organic constituents and ammonium.

2.3.2 Process solution with nitrogen removal

With the foundation of the simple version of an activated sludge process mentioned above, it is possible to achieve a nitrogen removing process by adding an anoxic compartment. To remove nitrogen from wastewater, both nitrification and denitrification are required and the nitrification is performed in aerated (aerobic) basins and the denitrification in un-aerated (anoxic) basins. There are different process solutions available; one possible process solution is to have pre-denitrification where denitrification is performed before nitrification, as seen in Figure 3.

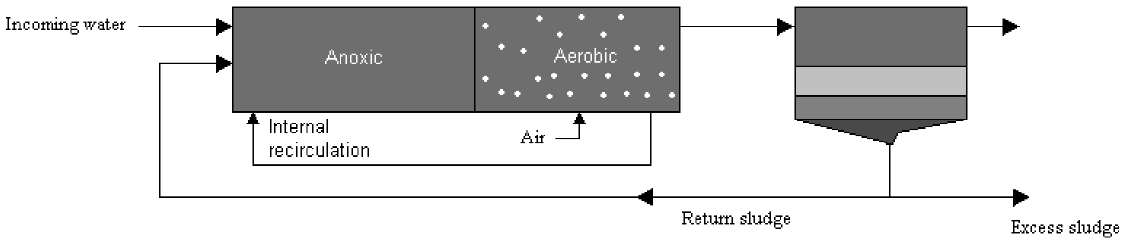

Figure 3 Activated sludge process with pre-denitrification.
Modified from Carlsson & Hallin, 2010.

With pre-denitrification, the denitrifying microorganisms can use the organic compounds in the influent water as their carbon source. To supply the denitrifying microorganisms with nitrate, internal recirculation is needed. Since the water in the last aerated zone will be transported to the anoxic basin, it is important that the oxygen level of the last aerated zone is relatively low since it otherwise disturbs the denitrification process.

2.3.3 Solids retention time (SRT)

The solids retention time, or *sludge age* as it is sometimes called, is a parameter of how long a sludge particle on average remains in the activated sludge process before it is removed as excess sludge. SRT can be measured both as *aerated* and *total*. SRT is defined according to Tchobanoglous et al. (2003):

$$SRT = \frac{VX}{(Q - Q_W)X_e + Q_W X_R} \tag{13}$$

where,

V = aerated or total volume [m^3]
X = biomass concentration [$kg\ m^{-3}$]
X_e = concentration of biomass in the effluent [$kg\ m^{-3}$]
X_R = concentration of biomass in the return line from clarifier [$kg\ m^{-3}$]
Q = flow rate [$m^3\ d^{-1}$]
Q_w = waste sludge flow rate [$m^3\ d^{-1}$]

For practical reasons, the biomass concentration is often approximated by *suspended solids*, as stated in Lind et al. (2007b).

3 AERATION

3.1 OXYGEN TRANSFER

3.1.1 Oxygen transfer coefficient K_La

One purpose of aeration is to transfer oxygen to the wastewater. Oxygen transfer can be described by the volumetric mass transfer coefficient K_La. The coefficient can be determined in a laboratory if the respiration (r_m) and DO concentration is measured (ASCE, 2006):

$$K_L a = \frac{r_m}{DO_s - DO} \tag{14}$$

where,

K_La = volumetric mass transfer coefficient
r_m = rate of mass transfer per unit volume (respiration rate)
DOs = dissolved oxygen saturation concentration
DO = dissolved oxygen concentration

Lindberg (1997) suggested a nonlinear model of K_La with respect to airflow rate; a typical shape is shown in Figure 4.

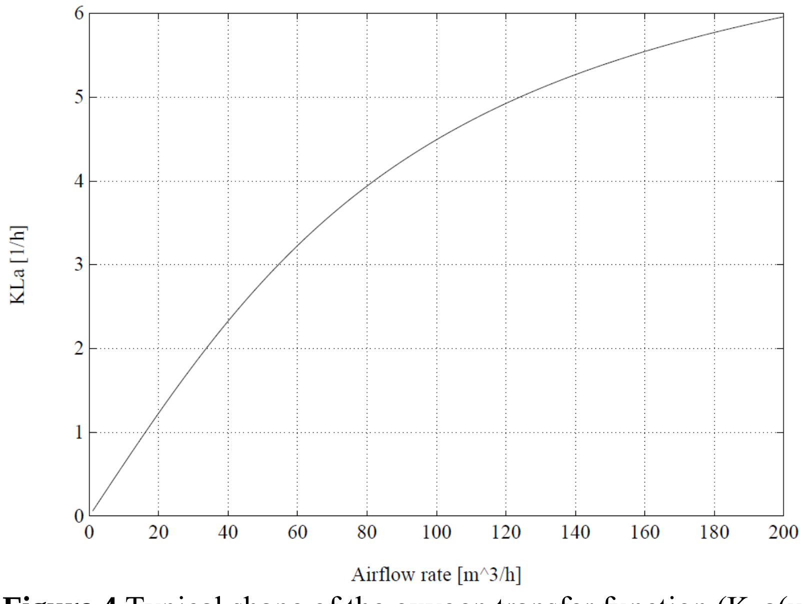

Figure 4 Typical shape of the oxygen transfer function ($K_La(u)$) as a function of the airflow rate. From Lindberg, 1997.

According to Lindberg (1997, p 83), K_La in a WWTP depends on several factors, such as "type of diffusers, wastewater composition, temperature, design of the aeration tank, tank depth, placement of diffusers, etc, but the main *timevarying* dependence is the airflow rate".

3.1.2 Dissolved oxygen mass balance

In a completely mixed reactor the dissolved oxygen mass balance can be described by (Lindberg, 1997):

$$\frac{dy(t)}{dt} = \frac{Q(t)}{V}(DO_{in}(t) - DO(t)) + K_L a(u(t))(DO_{sat} - DO(t)) - r_m(t) \tag{15}$$

where,

Q(t)	=	wastewater flow rate
V	=	volume of the wastewater
$DO_{in}(t)$	=	DO of the input flow
DO(t)	=	DO in the zone
K_La	=	oxygen transfer function
u(t)	=	airflow rate into the zone from the air production system
DO_{sat}	=	saturated value of the DO
$r_m(t)$	=	respiration rate

In equation 15 the oxygen transfer function K_La is directly affecting the dissolved oxygen concentration. The higher K_La, the easier it is to aerate the wastewater. One can also see from the equation that it is easier to increase DO when the DO is low, since this gives a larger difference DO_{sat} – DO(t).

Aeration is more efficient in clean water than in wastewater; clean water requires less air flux than wastewater to reach a certain DO-value. This can be explained as differences in K_La between clean water and wastewater. The reason for the difference in K_La can be related to difference in total dissolved solids concentration (Tchobanoglous, 2003) and surfactants (Thunberg, 2007).

The ratio between K_La for wastewater and clean water is called α, see equation 16. The value of α is generally below 1, since it is more difficult to transfer oxygen to wastewater than to clean water.

$$\alpha = \frac{K_L a_{wastewater}}{K_L a_{clean\,water}} \tag{16}$$

The value α does not only depend on the properties of the water and the wastewater, but also on the equipment that is used. Since α varies both with wastewater composition and with equipment it has to be determined – or well estimated – for every single application.

3.1.3 Actual oxygen requirement (AOR)

Actual oxygen requirement is the oxygen requirement during process operating conditions, i.e. the conditions in the biological reactors. Actual oxygen requirement is defined according to U.S. EPA (1989):

AOR = Carbonaceous Process Oxygen Requirement + Inorganic Chemical Process Oxygen Requirement + Nitrification Process Oxygen Requirement – Denitrification Process Oxygen Credit (17)

In (17) Carbonaceous process oxygen requirement is the oxygen requirement stated in Chapter 2.2.1.

Inorganic chemical process oxygen requirement corresponds to reduced material such as sulphide, sulphite, ferrous iron and reduced manganese (U.S. EPA 1989) that are oxidized in the aerated zones of the WWTP.

Nitrification process oxygen requirement is the oxygen requirement stated in Chapter 2.2.2.

Denitrification process oxygen credit is the amount of oxygen provided to the microorganisms from the denitrification process (theoretically 2.86 kg O_2 (kg NO_3^-)$^{-1}$ denitrified).

3.1.4 Oxygen transfer rate (OTR_f)

To be able to compare oxygen requirement of one WWTP with other WWTPs, AOR needs to be adjusted to standardized conditions. This is done by converting AOR to oxygen transfer rate during field conditions (OTR_f) and then OTR_f to standard oxygen transfer rate (SOTR), as described below.

According to U.S. EPA (1989):

$$OTR_f = AOR \tag{18}$$

where,
OTR_f = oxygen transfer rate [kg d^{-1}]
AOR = actual oxygen requirement [kg d^{-1}]

For designing aspects, OTR_f and AOR are the same and the difference is just an issue of definition; AOR is the requirement and OTR_f is the actual transferred oxygen. However, (18) does not account for oxygen transferred to the wastewater that is not consumed by the microorganisms (the measured DO concentration), because (18) and (19) were not intentionally made for evaluation, but for design aspects where excessive oxygen was not accounted for.

3.1.5 Standard oxygen transfer rate (SOTR)

The standardized oxygen transfer rate (SOTR) is a “hypothetical value based on zero DO in the aeration zone; this condition is not usually attainable in real aeration systems operating in process water” (ASCE, 1988). SOTR is defined in U.S. EPA (1989):

$$SOTR = \frac{OTR_f \times C^*_{\infty 20}}{\alpha F \theta^{(T-20)} (\Omega \tau \beta C^*_{\infty 20} - C)} \tag{19}$$

where,
SOTR = standard oxygen transfer rate [kg d^{-1}]
OTR_f = oxygen transfer rate [kg d^{-1}]
α = process water K_La of new diffuser/ clean water K_La of new diffuser [-]

F = process water K_La of diffuser after given time / process water K_La of new diffuser [-]
θ = correction factor for temperature on K_La [-]
T = temperature [°C]
Ω = correction factor for pressure on C^*_∞ [-]
τ = correction factor for temperature on C^*_∞ [-]
β = process water C^*_∞ / clean water C^*_∞ [-]
$C^*_{\infty 20}$ = steady-state DO saturation concentration attained at infinite time for a given diffuser at 20 °C and 1 atm [kg m^{-3}]
C = process water DO concentration [kg m^{-3}]

SOTR is the oxygen transfer rate converted to zero DO, standardized temperature (20 °C) and pressure (101.3 kPa) and clean water K_La.

3.1.6 Standard aeration efficiency (SAE)

SAE [kg O_2 kWh^{-1}] is a measure of oxygen transfer per unit power input (ASCE, 2007):

$$SAE = \frac{SOTR}{Power\ input} \tag{20}$$

SAE is an energy efficiency parameter which is comparable between different treatment lines and WWTPs.

3.1.7 Standard oxygen transfer efficiency (SOTE)

Standard oxygen transfer efficiency (SOTE) can be described as the fraction of oxygen in the injected air dissolved to the wastewater under standard conditions (ASCE, 2007):

$$SOTE = \frac{SOTR}{W_{O_2}} \tag{21}$$

where,
SOTR = standard oxygen transfer rate [kg day^{-1}]
W_{O2} = mass flow of oxygen in air stream [kg day^{-1}]

The mass flow of oxygen in air streams is calculated according to:

$$W_{O_2} = \rho_{air} \times [O_2] \times Q_{air} \tag{22}$$

where,
ρ_{air} = density of air [kg m^{-3}]
$[O_2]$ = concentration of oxygen in the air [%]
Q_{air} = airflow [m^3 day^{-1}]

3.2 AERATION EQUIPMENT

Aeration is needed in the activated sludge process for two reasons. Firstly, the aeration transfers oxygen to the wastewater so that the microorganisms can perform oxidation, synthesis and respiration. Secondly, the aeration provides mixing so that the microorganisms get in contact with the suspended and dissolved substrate, which also prevents settling in the aeration tanks.

There are different kinds of aeration and the most common configuration for an activated sludge process is using a blower, piping and diffusers (this is called diffused aeration). Aeration can also be performed with jet aerators, aspirators and U tubes, which are not investigated further in this thesis.

Diffused aeration can be performed either with a common manifold set-up (where several blowers are connected to one pipe) or with one blower per tank. The details of diffused aeration are further developed below. In Figure 5 a basin in Sternö WWTP is shown where diffused aeration is installed.

Figure 5 An empty tank in Sternö WWTP with fine bubble diffused aeration.

3.2.1 Blower

A blower is used to pull in outside air, compress and transfer it to the distribution pipes that support the WWTP aeration basins with air. The blowers consist of air moving devices (lobes, screws or impellers) mounted on a rotating shaft powered by a motor.

The compression is needed since the air pressure at the diffusers needs to be higher than the water pressure. Since the diffusers often are placed at a depth of 4-6 m, the water pressure is a substantial part of the pressure that the blower has to perform. Also, there are pressure losses in the piping system and a minimum required pressure for the diffusers, why the blower pressure needs to be even higher.

There are many blower technologies available on the market and they are categorized into two big technology groups: *positive displacement* and *centrifugal*. In general, centrifugal blowers can provide a wide range of airflow, but only at a narrow pressure. They are commonly used in WWTPs where there is a high airflow requirement (greater than 425 m^3 min^{-1}, Tchobanoglous et al. 2003) Positive displacement blowers are used in WWTPs where there is a low airflow requirement. The positive displacement blowers can provide a wide range of pressures but only at a narrow range of airflow.

There are two main types of positive displacement blowers: *rotary lobe* and *rotary screw*. The lobe technology is an old and widely used technology. The technology uses a pair of lobe shaped rotors and the compression type is called external compression. This means that the air is compressed outside the case when air is transferred back to the case from the pressure side. The screw technology is relatively new in wastewater applications. This technology uses two screws which compress the air internally – the intervening space between the screws decrease from the inlet side to the outlet side why the air is compressed inside the case when the air is moved forward. Internal compression could make the screw technology more energy efficient than the lobe technology.

To improve the energy efficiency of positive displacement blowers, variable frequency drive (VFD) can be used. VFD varies the frequency of the power delivered to the motor and therefore makes it possible to control the speed of the blower. This makes it possible to run the blower efficiently for different loads. But if the load is static, VFD should give no energy savings.

3.2.2 Air piping

The blower is typically connected to the rest of the aeration system through a manifold, where multiple blowers can be connected. The piping system generally consists of stainless steel for the part from the blower to the aerated basin until one meter above the basin floor, where the stainless steel pipe is connected to another pipe that is coherent with the diffuser grid, often made of PVC.

3.2.3 Valves

Before the pipe system turns down into the bioreactor, there are valves controlling the airflow to each zone. The opening of the valves is done by actuators and the actual valve opening can often be surveilled through the SCADA system. Normally, the set-point of the valve opening is calculated by the control system.

A common type of valve is the butterfly valve, partly because it is relatively cheap. A negative aspect of the butterfly valve is that it has non-linear characteristics, which makes it slightly difficult to control the airflow through the valve. As can be seen in Figure 6, an opening of for example 10 % increases the airflow unequally depending on how much the valve was open from the beginning.

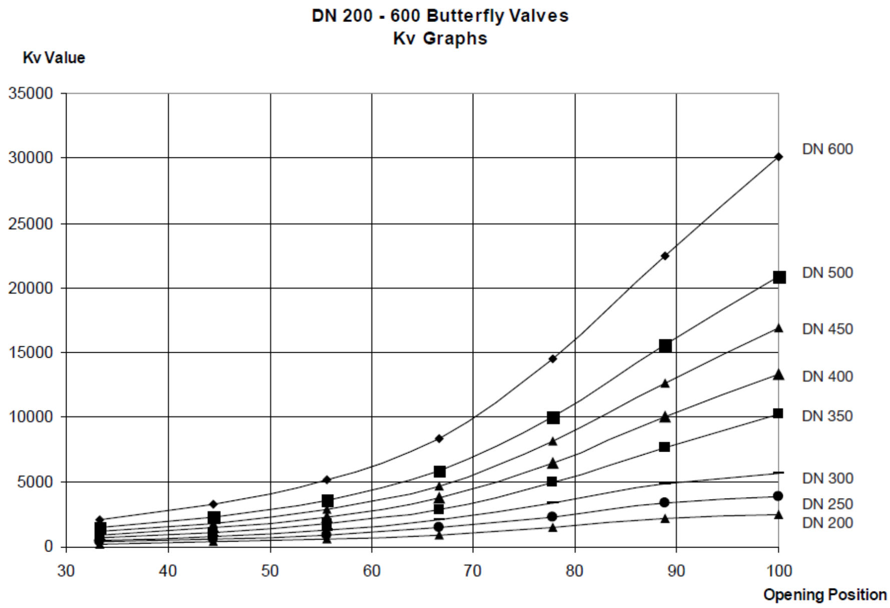

Figure 6 Valve characteristics of butterfly valves. From AVK, 2011.

Another type of valve is the plug valve. It has linear characteristics, which is better out of an airflow control perspective since it increases the airflow equally independent of how much the valve was open from the beginning. On the other hand, plug valves are generally more expensive than butterfly valves.

3.2.4 Diffusers

A diffuser is an aeration device that is connected to the piping system and releases the air to the wastewater. There are many different kinds of diffusers, and they can be categorized into two main diffuser types after the size of the bubbles they create: coarse bubble and fine bubble diffusers.

Coarse bubble diffusers are typically nonporous diffusers and have a low OTE. These kinds of diffusers are therefore not energy efficient but can be suitable in some applications, for example in sludge aeration where fine bubble aeration cannot provide the same mixing ability.

Fine bubble diffusers are generally porous diffusers with higher OTE than coarse bubble diffusers. The high OTE generally makes fine bubble diffusers more energy efficient with respect to SAE. The diffusers consist of a holder and a membrane with slits in it, through which the air is passing to the wastewater. Depending on the slits and on the quality of the membrane, the diffuser pressure loss can be varying. Negative aspects of fine bubble diffusers are that they are susceptible to fouling (further described below) and might also give the effect that because of their high efficiency, mixing criteria might be dictating for minimum airflow instead of the microbial oxygen demand.

Fouling describes the phenomena when microorganisms attach to the aeration equipment and decrease the performance and lower the aeration efficiency. This occurs since microorganisms attach to all available surfaces in the bioreactors, including the aeration equipment. To prevent fouling, cleaning of the diffusers is necessary. This can be performed either by air bumping (which is a big increase in airflow that stretches the membrane and cracks the bio film) or by chemical cleaning (which can be performed by acid or alkaline washing or gas injection).

The increase in OTE for fine bubble diffusers is related to K_La of the diffuser, which can be related to the specific surface area. In Table 1, the specific surface area for a typical coarse and fine bubble is shown. Also, the bubble size affect K_La since it affects the rise time – smaller bubbles have a longer rise time than larger bubbles, which gives a longer time to interact with the wastewater. The diffuser density (diffuser area per tank bottom area) is also important – the higher diffuser density the more effective is the aeration. But this also makes the aeration system more expensive since more diffusers are required.

Table 1 Area to volume ratio for a typical coarse and fine bubble.

Bubble type	Typical diameter [m]	Surface area [m^2]	Volume [m^3]	Specific surface area [m^2 m^{-3}]
Coarse	0.01	1.26E-03	4.19E-06	300
Fine	0.001	1.26E-05	4.19E-09	3 000

Fine bubble diffusers are available in different shapes, among them discs and tubes. These kinds of diffusers are shown in Figure 7 and 8.

Figure 7 Fine bubble tube diffusers of unknown brand in (empty) basin in Sternö WWTP. The large pipe at the bottom is the air piping and the small pipe is the diffuser.

Figure 8 Newly installed Sanitaire fine bubble disc diffusers in (empty) basin in Sternö WWTP.

3.3 AERATION CONTROL

There is a large variety for aeration control strategies, some WWTPs use simple time based control while other plants use more high-technology control strategies. On an over-all basis, aeration control is needed in order to aerate according to the actual load. Using a good aeration control system can give energy savings and decrease effluent environmental pollutants such as organic constituents and nitrogen.
PI controllers are commonly used for process industries and WWTPs, since these controllers are relatively easy to implement and tune. The PI controller consists of two parts, a *proportional* part and an *integrating* part. The proportional part makes the control signal proportional to the control error and therefore increases the control signal when the control error increases, whereas the integrating part secures that the control error over time converges towards zero

The PI controller is a linear controller, which gives some limitations when controlling non-linear processes, such as the non-linear butterfly valve. The equation of a PI controller is:

$$u(t) = K(e(t) + \frac{1}{T_i}\int e(\tau)\, d\tau) \qquad (23)$$

where,
u = control signal
K = gain
e = control error
T_i = integral time

The control error is the difference between the set-point and the output signal from the process:

$$e = r - y \qquad (24)$$

where,
r = set-point
y = the output signal from the process

3.3.1 DO control

The basic DO control strategy is to use one PI controller that controls the airflow valve. In this case, the DO measurement corresponds to the output signal from the process y, the DO set-point corresponds to r (set by the WWTP staff) and the control error is the difference between DO set-point and the actual DO value. The control signal is the command signal to the valve, which is sent to the actuator that opens/closes the valve, see Figure 9.

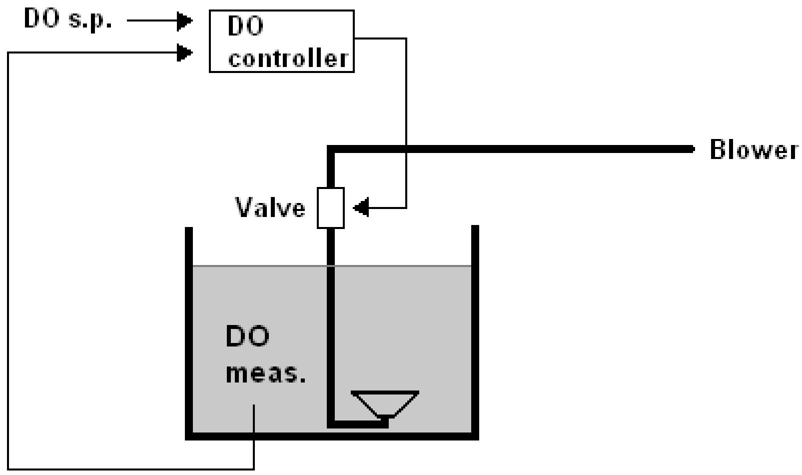

Figure 9 Basic DO control. In the figure, s.p. is set-point.

3.3.2 DO cascade control

DO cascade control is a serial connection of controllers, where the inner control loop controls the airflow and the outer control loop controls the DO concentration. To do this, DO and airflow measurements are required on-line.

The outer control loop, the DO control loop, gets its set-point from the WWTP staff. Based on the set-point, the actual DO and the parameters K and T_i, the controller calculates the control signal which is the airflow set-point.

The airflow set-point is used by the inner control loop, the airflow loop, which compares the airflow set-point with current airflow and thereafter calculates the valve set-point, sent to the actuator. The overall principle is visualized in Figure 10.

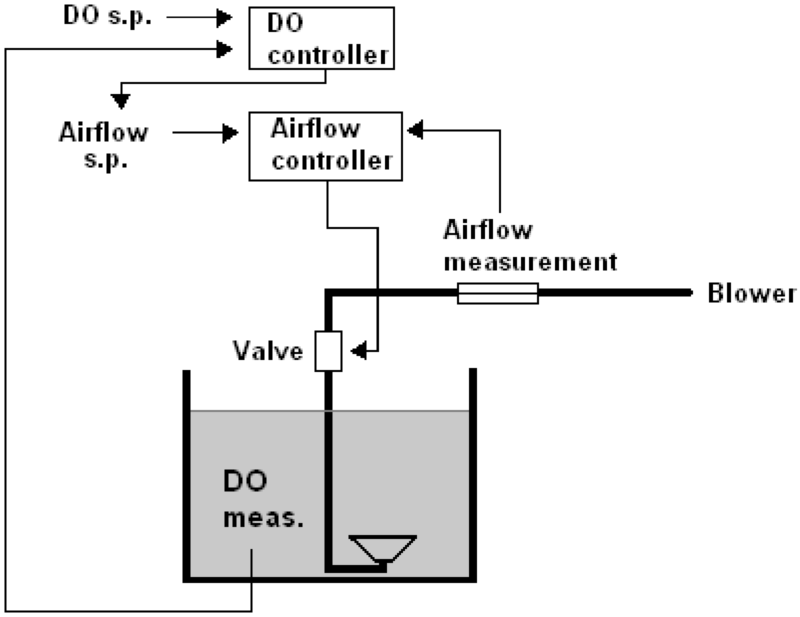

Figure 10 DO cascade control. In the figure, s.p. is set-point.

The main advantage with DO cascade control is when using non-linear valves, for example butterfly valves. When using non-linear valves and DO cascade control, the non-linear characteristic of the valve is counteracted. This is possible since the control is made in two steps where the airflow controller keeps track of the airflow – if a too big jump in valve opening is made the controller will correct for this. The disadvantage of DO cascade control is that it requires airflow meters, which might be expensive.

3.3.3 Ammonium control

Ammonium control is one further step of control, where one more control loop is added around the existing control. The ammonium control could be implemented around, for instance, DO cascade control and requires one more PI controller and also on-line ammonium measurements. With ammonium control, the WWTP staff set the ammonium set-point, which will be used by the ammonium controller to calculate the DO set-point, which will function as described above.

Ammonium control can be advantageous to use because when only using DO cascade control, a big difficulty is to determine a good DO set-point. The set-point should be high enough to result in good treatment, but still low in order to aerate as little as possible and thus save airflow and energy. In order to determine a good DO set-point it is therefore necessary to measure ammonium, which requires an ammonium sensor. Ammonium control can also be useful since the nitrification capacity changes during the year (as a result of change in load, temperature, etc.), and in order to perform the wanted treatment results throughout the year, the DO set-point needs to be changed continuously. One possible configuration of ammonium control, around DO cascade control, can be seen in Figure 11.

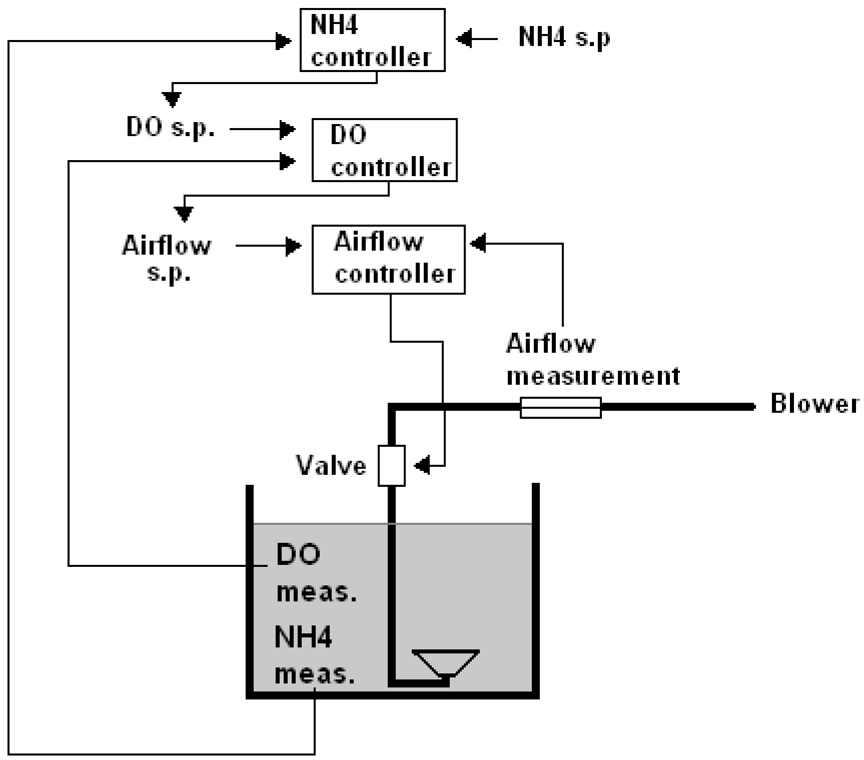

Figure 11 Ammonium control. In the figure, s.p. is set-point.

A negative aspect with ammonium control is that an ammonium sensor is required, which can be relatively expensive.

3.3.4 Most open valve logic

Most open valve (MOV) is a system that aims to decrease air resistance over the valves. The system aims at having the valves as much open as possible, which minimizes the air resistance over the valves and therefore makes it possible to run the blower at a lower air pressure. This could save energy since the blower in that case can work less to fulfil the pressure set-point. The MOV-logic is visualised in Figure 12.

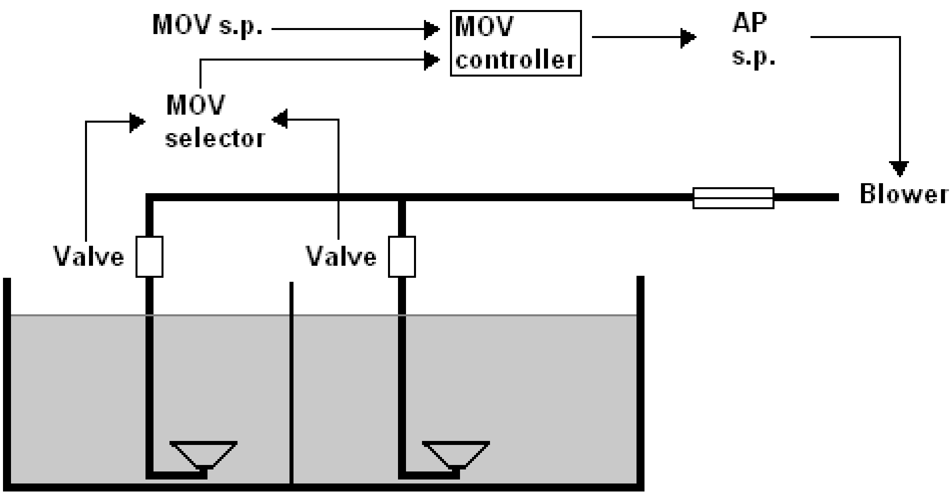

Figure 12 Visualisation of MOV logic.
s.p. is set-point and AP is air pressure.

When using MOV, the input to the controller is valve opening. Typically, the valve opening set-point is in the range 70-90 %; it is not 100 % because if the valve is 100 % open there is no control ability for the DO control in case more air is needed.

3.3.5 Tuning

The PI controller described above can be used in different positions in the aeration, as has been shown above. If the PI controller shall work well, it has to be properly tuned before performing. The tuning of a PI controller is described below according to the Lambda method, with all equations from Carlsson & Hallin (2010). This method allows the controllers to be tuned relatively easy without requiring that the system is fully described by equations.

The Lambda method starts with setting the controller in manual mode, thereafter a step, which is a change of the control signal, is performed. This results in a change of the output signal from the process. Increase of the output signal from the process (in percentage of measurement range) is denoted Δy and increase of control signal (in percentage of measurement range) is denoted Δu. The process gain, K_s, can then be calculated according to:

$$K_s = \frac{\Delta y}{\Delta u} \tag{25}$$

The dead time, L, and the 63 % rise time, T, can be determined graphically as shown in Figure 13. The 63 % rise time is simply the time it takes to reach 63 % of the change of the output signal from the process.

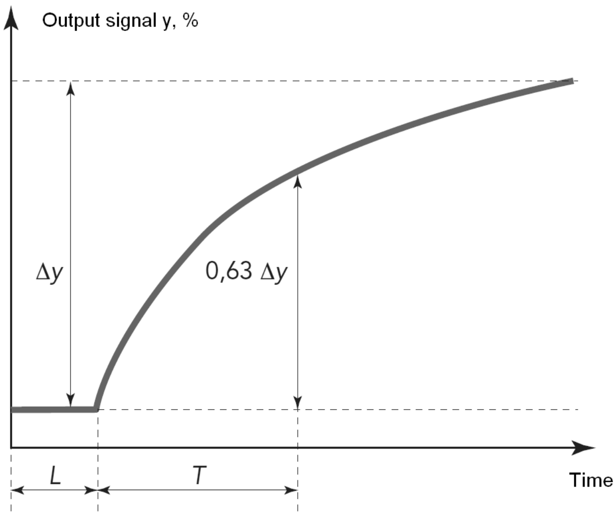

Figure 13 An example of a step response test. Modified from Carlsson & Hallin, 2010.

The parameter Lambda (λ) is calculated according to equation 26, where p is a user choice that increases or decreases the speed of the controller. This also affects the robustness of the controller and a high p (>3) gives slow but stable control, and a low p (<1) gives fast but more sensitive control.

$$\lambda = p \times T \tag{26}$$

The parameters gain, K, and integral time, T_i, can then be calculated according to equation 27 and 28.

$$K = \frac{T}{K_s \times (\lambda + L)} \tag{27}$$

$$T_i = T \tag{28}$$

This tuning method is a method that is relatively straight forward and not too difficult to perform. But in order to get reliable tuning results, several tests might be needed and perhaps also some manual fine-tuning.

3.4 PREVIOUS AERATION CONTROL STUDIES

3.4.1 Positioning of the ammonium sensor

In order to control, measurements of the process parameters are required. For the case of the ammonium measurements, the best position of the measurements is not clear. In Olsson et al. (2005) it is discussed where the best position of the ammonium sensor is – there are positive and negative aspects irrespective of where one chooses to position it: If the sensor is placed in the last aerobic zone, effluent ammonium concentration can be surveyed, but there is a lag time if disturbances occur with incoming wastewater, due to the hydraulic retention time. If the sensor is instead placed in the middle of the aerobic zones, the lag time from disturbances decreases but then the control of the effluent ammonium concentration is lost. Also, it is difficult to determine a good ammonium set-point in the middle of the aerobic zones. To put the sensor in the effluent after the settler is generally seen as a fairly bad solution since it increases the hydraulic retention time.

3.4.2 Full-scale DO control studies

Åfeldt (2011) tested zone-individual DO cascade control and compared it with the old aeration control (DO cascade control where the airflow was evenly spread out to all aerated zones). The study was performed in Himmerfjärdsverket WWTP, Sweden, and the main goals of the study were lowered energy consumption and maintained or improved treatment. Earlier, problems with alternately high ammonium and DO concentrations, sometimes as high as 10 mg L^{-1} and 8 mg L^{-1} respectively, had occurred at the WWTP. Since the WWTP is a post-denitrification plant with settlers between the nitrification and the denitrification process, the denitrification process was not damaged by high DO concentrations. But from an energy perspective, it is not good to reach as high DO concentrations as 8 mg L^{-1}.

The results from the study showed that energy consumption could be decreased with 10 % with the zone-individual DO cascade control compared to the old aeration control. Also, DO concentration peaks were lowered but not the ammonium concentration peaks, which could still reach 10 mg L^{-1} also with the new zone-individual DO cascade control. The author suggests that the aeration capacity was too low to keep the ammonium peaks down.

Nordenborg (2011) tested two control strategies: (1) DO cascade control (where a DO set-point is set daily according to effluent ammonium concentration) and (2) constant airflow (where the airflow set-point was determined based on sliding effluent ammonium concentration and sliding DO concentration in the last aerated zone). The idea was that by reducing airflow and DO fluctuations, energy could be saved due to the non-linear K_La function. The study was performed in Käppala WWTP, Sweden, and the goal was to reduce energy consumption. The pre-existing control strategy was ammonium feedback control.

The results showed that airflow could be reduced with 11 % when airflow was held constant and with 15 % when DO concentration was held constant, compared to airflow requirements for ammonium feedback control.

3.4.3 Full-scale ammonium control studies

In a full-scale study on control strategies in Källby WWTP, Sweden, Ingildsen (2002) compared a feedforward controller, a feedback controller (settler effluent measurements), a feedforward-feedback (settler effluent measurements) controller and an in situ feedback controller (last aerobic zone measurements). In the feedforward control, ammonium is modelled as a tracer with no reactions taking place. The reason for this is that the intention is to know when the influent ammonia reaches the aerobic zones, instead of knowing the exact concentrations. The study showed that the in situ feedback controller was the best with airflow savings of 10-15 %, compared to a constant DO profile. At the same time, the ammonium effluent concentrations were better with the in situ feedback controller.

Ingildsen (2002, p 271) states that *"It shows that the process is not faster, nor more complex, than it is controllable by simple feedback control provided the feedback sensor is located at the end of the aerobic reactor(s)"*. The feedforward and the feedforward-feedback controllers also performed airflow savings, but not to the same extent as the in situ feedback controller.

Thunberg et al. (2007) investigated the performance of three different control strategies in Käppala WWTP, Sweden. The tested control strategies were (1) zone-individual DO cascade control, (2) ammonium feedback control and (3) ammonium feedback control with zone-individual DO cascade control. The control strategies were compared with the previous control system, where DO set-points were gradually decreasing from the first to the last zone. The total airflow was determined from a DO sensor in the first zone and the slope for the DO set-points was determined from a DO sensor in the last zone.

This study focused on lowering DO peaks in the last aerated zone, which sometimes could reach several hundred percent of DO set-point, and to decrease energy consumption. The results showed that control strategies 1 and 3, which both had zone-individual DO cascade control, lowered airflow peaks in a satisfying way. The ammonium load was displaced further down the aerobic zones, which lowered the DO peaks in the last aerobic zone. Strategy 2 did not lower the DO peaks in a satisfying way.

Strategy 3 was the best strategy regarding energy savings (airflow decrease of 18 %), closely followed by strategy 1 (airflow decrease of 16 %). With strategy 2, airflow savings were 9 %. The overall best strategy was considered to be number 3, which not only lowered DO peaks in the last aerobic zone and decreased airflow the most, but also kept control of effluent ammonium concentration.

4 SIMULATION STUDY

4.1 INTRODUCTION TO BSM1

Benchmark Simulation Model no. 1 (BSM1) is a model of a standardized pre-denitrification WWTP with two anoxic zones followed by three aerobic zones and a secondary clarifier – it is designed for both nitrification and denitrification. The simulation model can be implemented in different platforms; it is not linked to any one in particular.

One purpose of the model is to have a controlled environment where it is possible to test control strategies. The standard aeration control in BSM1 is control of the oxygen transfer coefficient (K_La) in unit 3 and 4, and DO control in unit 5, see Figure 14.

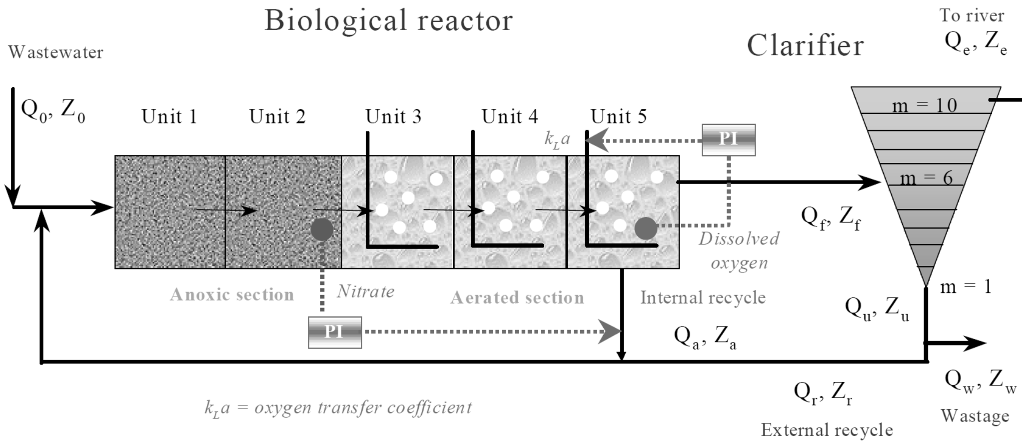

Figure 14 Overview of BSM1 (Alex et al. 2008).

The BSM1 WWTP is designed for an inflow rate of 18 446 m^3 day^{-1} and an incoming average concentration of COD of 300 g m^{-3}. The hydraulic retention time of the biological reactor is 7.2 hours, and the same for the clarifier. The total sludge age is about 9 days.

BSM1 was developed by the working groups of COST Action 624 and 682 and was later on continued within IWA Task Group on Benchmarking of Control Strategies for WWTPs (Alex et al. 2008). The biological processes in the reactors are described by Activated Sludge Model no. 1 (ASM1), which consists of a number of equations that calculate the reactions taking place.

BSM1 requires an inflow for the calculations, described by the influent parameters in Table 2. The inflow is described as a matrix and can be static (inflow consist of two rows with all parameters constant except for the time variable) or dynamic. BSM1 has one static and three dynamic inflows as standard, corresponding to constant influent, dry weather, storm weather and rain weather.

Table 2 Influent parameters in ASM1 and BSM1.

Definition	**Notation**
Soluble inert organic matter	S_I
Readily biodegradable substrate	S_S
Particulate inert organic matter	X_I
Slowly biodegradable substrate	X_s
Active heterotrophic biomass	$X_{B,H}$
Active autotrophic biomass	$X_{B,A}$
Particulate products arising from biomass decay	X_P
Oxygen	S_O
Nitrate and nitrite nitrogen	S_{NO}
NH_4^+ + NH_3 nitrogen	S_{NH}
Soluble biodegradable organic nitrogen	S_{ND}
Particulate biodegradable organic nitrogen	X_{ND}
Alkalinity	S_{ALK}

4.2 SIMULATION STUDY METHOD

The purpose of the simulation study was to test if ammonium feedback control in zone 1 and DO control in zone 2 was more energy efficient than using DO control in both zone 1 and zone 2. The goal was to find an ammonium controller which resulted in lowered energy consumption with preserved or improved ammonium treatment.

The BSM1 used in this master thesis was implemented in Matlab/Simulink. Matlab version *R2011a* was used.

The number of reactors and their volumes were changed to better resemble Sternö WWTP. Two anoxic tanks and two aerobic tanks were used, with volumes according to Table 3.

Table 3 Total tank volume.

	Anaerobic [m^3]	**Anoxic [m^3]**	**Aerobic [m^3]**
Original BSM1	0	2 000	4 000
Sternö WWTP	600	1 650	1 232
New BSM1	0	2 250	1 232

BSM1 use a number of kinetic parameters in the biological processes. In standard, those are set to resemble a temperature of 15 °C. In this simulation study the performance of the controller was evaluated both at 15 °C and 10 °C. The kinetic parameters used are seen in Table 4.

Table 4 Kinetic parameters used.

Kinetic parameters	**Symbol**	**15 °C (standard BSM1)**	**10 °C**
Heterotrophic max. specific growth rate	μ_H	4	3
Heterotrophic decay rate	b_H	0.3	0.2
Half-saturation coefficient (hsc) for heterotrophs	K_S	10	20
Oxygen hsc for heterotrophs	$K_{O,H}$	0.2	0.2
Nitrate hsc for denitrifying heterotrophs	K_{NO}	0.5	0.5
Autotrophic max. specific growth rate	μ_A	0.5	0.3
Autotrophic decay rate	b_A	0.05	0.05
Oxygen hsc for autotrophs	$K_{O,A}$	0.4	0.4
Ammonia hsc for autotrophs	K_{NH}	1	1
Correction factor for anoxic growth of heterotrophs	η_g	0.8	0.8
Ammonification rate	k_a	0.05	0.04
Max. specific hydrolysis rate	k_h	3	1
Hsc for hydrolysis of slowly biodeg. Substrate	K_X	0.1	0.01
Correction factor for anoxic hydrolysis	η_h	0.8	0.4

In this simulation study, constant and dry weather influents were used. The influent characteristics were changed according to Table 5 to better resemble the influent of Sternö WWTP.

Table 5 Influent characteristics that were changed.
The concentrations are flow proportional average values.

	S_{NH} [mg L^{-1}]	**S_{ND}** [mg L^{-1}]	**X_{ND}** [mg L^{-1}]	**Tot-N** [mg L^{-1}]	**S_S** [mg L^{-1}]	**X_S** [mg L^{-1}]	**$X_{B,H}$** [mg L^{-1}]	**$X_{B,A}$** [mg L^{-1}]	**BOD_7** [mg L^{-1}]	**Flow** [m3d^{-1}]
Sternö WWTP influent	13.4			30.2					109.6	4291
New BSM1 static influent	13.4	6.9	10.5	30.9	87.9	259.7	35.7	0	109.4	4291
New BSM1 dynamic influent	13.4	6.9	10.5	30.9	87.9	259.7	35.7	0	109.4	4291

The changes of the dry weather influent were done so that the variations of the dry weather influent from BSM1 were kept, but that the average values of the influent resembled the influent of Sternö WWTP.

The parameter S_{NH} was set to the yearly mean influent of ammonium to Sternö WWTP, and S_{ND} and X_{ND} were calculated so that total nitrogen influent in the simulation corresponded to the yearly mean influent of total nitrogen to Sternö WWTP. S_S, X_S and $X_{B,H}$ was calculated so that BOD_7 corresponded to the yearly mean influent of BOD_7 to Sternö WWTP. In BSM1, BOD_7 is calculated according to (29), where f_P is a dimensionless stoichiometric parameter with value 0.08.

$$BOD_7 = 0.25 \times (S_s + X_s + (1 - f\_P) \times (X_{BH} + X_{BA})) \qquad (29)$$

Except for the changes in the influent file and the size of the reactors, the following changes from the original BSM1 was made in order to better resemble Sternö WWTP and to try the ammonium controller:

- Maximum K_La was set high (100 000) so that the airflow capacity was not limiting.
- Sensor noise was turned off for the aeration part.
- Internal recirculation was set to the mean inflow.
- The sludge age of the model was changed to 19 days (by changing Q_w).
- The DO control that is standard in bioreactor 5 in BSM1 was used in both aerated bioreactors. The parameters (K, T_i) of the DO controller were not changed.
- An ammonium controller was used around the DO controller in aerobic tank 1.
- The ammonium controller was tuned with step-response tests according to the Lambda tuning method before the actual tests.
- The ammonium controller was given different constraints regarding maximum allowed DO concentration to see how that affected energy efficiency and treatment results.

The model was validated by using the same DO profile as was used in the reference line in Sternö WWTP (1.8 / 0.7 mg L^{-1}) for 15 °C. The resulting effluent ammonium concentration was then 0.8 mg L^{-1} which was very far from effluent concentration in the reference line in Sternö WWTP. At that time (14/9 – 21/9), mean temperature was 17.2 °C and the uncalibrated ammonium sensor showed that effluent NH_4^+ was 0.74 mg L^{-1}. Later on (after weekly laboratory measurements) it was discovered that effluent concentration from secondary sedimentation (where effluent concentration should be lower than in the aerobic zone) was 0.1 mg L^{-1}. Therefore, the verification regarding ammonium concentration was reasonable, but not tremendous.

Each simulation was first run with a steady state model and static influent to stabilize the processes in the model. Thereafter, the full model was run with dynamic influent.

The three evaluated DO profiles were profiles that are actually used in Sternö WWTP. During summer and warm spring and fall, a DO profile of 1.8/0.7 is often used. In the winter, when the wastewater is colder, a DO profile of 2.2/1.0 is not unusual. In the test line, a DO profile of 0.8/1.0 was tested during the beginning of the autumn 2011.

The ammonium feedback controller that was used did only set a DO-set point in zone 1. In zone 2, a constant DO set point was used since it is important to keep the DO level low there. If wastewater with a high DO level is recirculated to the anoxic basin, the denitrification might be disturbed.

For the ammonium feedback two different set points were used depending on temperature. For 10 °C the NH_4 set-point was 5 mg L^{-1} and for 15 °C the NH_4 set-point was 1 mg L^{-1}. These concentrations were seen as sufficient treatment results of ammonium.

For this simulation study, a simple evaluation method was used according to:

$$Aeration\ efficiency = \frac{Aeration\ energy}{removed\ NH_4} \tag{30}$$

where,

Aeration efficiency	=	amount of energy used per amount of removed ammonium [kWh kg^{-1}].
Aeration energy	=	Energy used for aeration [kWh d^{-1}], taken from BSM1 evaluation file *perf_plant.*
Removed NH_4	=	Removed amount of ammonium [kg d^{-1}], taken from BSM1 evaluation file *perf_plant.*

In BSM1 there is a standard evaluation program than can be run to evaluate the process, called *perf_plant*. The parameters *Aeration energy* and *removed* NH_4 was used from that evaluation program.

The aeration efficiency was compared between different controllers as the parameter *savings*. For this, the standard DO set-point used in Sternö WWTP (zone 1/zone 2) was used as reference, (2.2/1.0) mg L^{-1}1 during cold weather simulations (10 °C) and (1.8/0.7) mg L^{-1} during warm weather simulations (15 °C).

The controllers were also evaluated based on effluent quality of ammonium, which was also obtained from *perf_plant* as *Effluent* NH_4^+ (mg L^{-1}). This parameter was calculated in BSM1 as a flow proportional concentration by dividing the total effluent load with the total flow rate.

4.3 SIMULATION STUDY RESULTS

Controller parameters for the ammonium controller were found through the Lambda method to be K = -1.18 and T_i = 0.056 days.

A summary of the results obtained in the simulation study can be seen in Table 6.

Table 6 Results from simulation study. In the table, s.p. stand for set point and NH_4-fb stand for ammonium feedback. Savings are compared to r*eference*.

Temp [°C]	DO s.p. zone 1 [mg L^{-1}]	Max DO [mg L^{-1}]	DO s.p. zone 2 [mg L^{-1}]	Effluent NH_4^+ [mg L^{-1}]	Removed NH_4^+ [kg d^{-1}]	Aeration energy [kWh d^{-1}]	Aeration efficiency [kWh kg^{-1}]
10	2.2		1	5.1	35.5	977	27.5
	1.8		0.7	12.3	4.8	878	182.7
	0.8		1	23.2	-41.7	755	-
	NH_4-fb	3	1	5.1	35.6	993	27.9
	NH_4-fb	2.5	1	5.2	35.2	976	27.8
	NH_4-fb	2.2	1	5.3	34.9	958	27.5
	NH_4-fb	2	1	5.4	34.5	945	27.4
15	2.2		1	0.7	54.5	1062	19.5
	1.8		0.7	0.8	53.8	997	18.5
	0.8		1	1.0	53.4	920	17.2
	NH_4-fb	3	0.8	1.0	53.3	927	17.4
	NH_4-fb	3	1	0.9	53.5	923	17.3
	NH_4-fb	1.5	1	0.9	53.5	923	17.3
	NH_4-fb	1	1	0.9	53.5	922	17.2

The results show that for 10°C, the effluent quality is only approved for one of the constant DO profiles (2.2/1.0), with an effluent ammonium concentration of around 5 mg L^{-1}. The other DO profiles have high effluent ammonium concentration. The effluent quality is good for all ammonium feedback controllers, around 5 mg L^{-1}.

For 10°C, the aeration efficiency of the most energy efficient DO profile is almost as high as the most energy efficient ammonium feedback control.

For 15 °C, the treatment result is good for all tested controllers (below 1 mg L^{-1}). The aeration efficiency of the most energy efficient DO profile and the most energy efficient ammonium feedback control is equal (17.2 kWh kg^{-1}).

4.4 SIMULATION STUDY DISCUSSION

First of all, in Table 6 the removed NH_4^+ for 10 °C and constant DO profile (0.8/1.0) is -41.7 kg d^{-1}. This is not an error but an effect of ammonification in ASM1 (where S_{ND} is turned into S_{NH}) and poor nitrification.

The simulation study shows that the high aeration efficiency can be reached *both* with a well set constant DO profile and an ammonium controlled DO profile. But, to constantly achieve a good DO profile, the DO profile needs to be tuned frequently according to the change of the influent characteristics such as temperature, BOD_7 and NH_4^+. If the DO profile is tuned e.g. on a weekly basis, a constant DO profile is probably the most energy efficient solution. To do this, a NH_4^+ sensor is required (in order to keep track of effluent quality). Also, someone has to execute the tuning.

The benefit with ammonium control is that the DO profile is set continuously according to treatment results. Therefore, the ammonium feedback control adapts the aeration to the current conditions. This makes the treatment results more stable with ammonium control than with a constant DO profile. An example of this reliability is the treatment result for the profile 1.8/0.7 for 15 °C and for 10 °C - the treatment is good and fairly energy efficient for 15 °C but bad and not at all energy efficient for 10 °C. It would not be recommended to use this DO profile for both summer and winter conditions in the real plant. Another aspect of the ammonium control is that it is less arduous since it does not require frequent tuning of the DO profile, the DO profile adjusts itself.

The energy evaluation in this simulation study was made based on kWh per removed kg of NH_4^+. This type of evaluation is relevant for the simulation study since the aeration demand is constant (due to constant load), but it does not include treatment performance.

The results show that the ammonium control efficiency increase if the maximum allowed DO value is lowered. This is as expected and a result of the non-linear K_La-function – it requires more air to raise DO from e.g. 2 to 2.5 than from 1.5 to 2 and therefore a controller that uses a lower DO for a longer time is more energy efficient than a controller that uses a higher DO for a shorter time.

Another aspect is that the lower the maximum allowed DO value is, the more difficult it is to control effluent ammonium to the set-point. Therefore, some configuration of the ammonium controller is required on a frequent basis since a suitable maximum allowed DO value is perhaps 1 mg L^{-1}during the summer and 2 mg L^{-1}during the winter.

To use DO control in zone 2 and ammonium control in zone 1 was shown to be feasible with respect feedback to effluent quality and energy efficiency if constraints on maximum allowed DO concentration are used. The simulation shows that reasonable ammonium feedback controller parameters are K = -1.18 and T_i = 0.056 days.

5 FULL-SCALE TRIALS IN STERNÖ WWTP

5.1 INFORMATION ON STERNÖ WWTP

5.1.1 General information

Sternö WWTP is located in Karlshamn in the south of Sweden. The WWTP was completed in 1997 and it is dimensioned for 26 000 population equivalent (pe), calculated on BOD_7 load 70 g (pe day)$^{-1}$. The treatment plant has pre-, primary and secondary treatment and an overview of the plant can be seen in Appendix 1. The pre-treatment consists of screening (which removes bigger objects, e.g. rags) and grit removal (which decreases the levels of sand and grit in the water). The next step is the primary treatment which consists of the primary sedimentation, where heavy suspended solids are removed to decrease organic and nitrogen load on the secondary treatment. The secondary treatment is a pre-denitrifying type with nitrogen and phosphorus removal, divided into two treatment lines, see Figure 15.

The aerobic compartments are divided into different zones and all aerobic zones have diffusers installed, but zone 11a and 21a also have mixers installed. This means that zone 11a and 21a can be used as anoxic compartments instead of aerobic if the circumstances decrease the need for aeration, for instance if the load is low or the temperature high. In that case aeration is turned off and the mixers are activated (to prevent sedimentation and make sure that the microorganisms get in contact with the suspended and dissolved substrate).

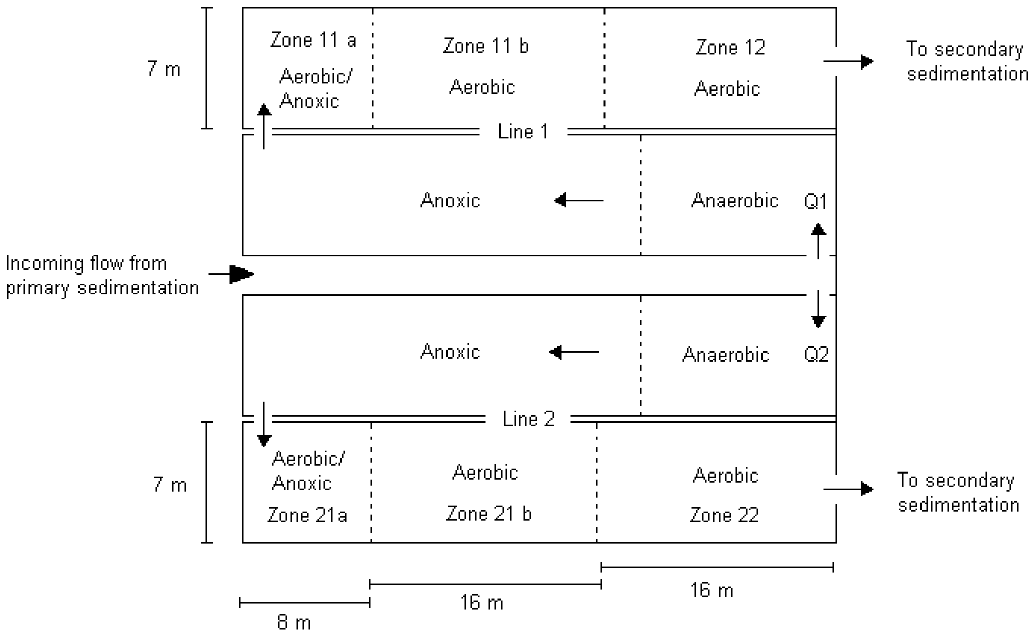

Figure 15 Flowchart of the biological treatment in Sternö WWTP.

The aeration is divided into 4 grids, which means that there are 4 independent diffuser areas. One valve controls the airflow to each grid, which means there is one valve to zone 11a/11b, one to12, one to 21a/21b, and one to 22.

Aeration to 11a/11b is identical (unless 11a is switched off) and aeration to 21a/21b is identical (unless 21a is switched off).

Tests were performed in the aerobic compartments of line 1 (test line) and line 2 was used as a reference line. The treatment lines were identical except for the aeration equipment in them (discussed below). The treatment lines were divided into zones according to Table 7. During this master thesis, zone 11a and 21a were un-aerated and therefore anoxic, except for a short period in July.

Table 7 Zone volumes of each treatment line (when zone 11a and 21a were anoxic).

Zone	Volume [m^3]
Anaerobic	600
Anoxic	1650
Aerated	1232

As all WWTPs, Sternö WWTP had effluent restrictions. The effluent restrictions of Sternö WWTP regarded total Nitrogen, Phosphorus and BOD_7 and can be seen in Table 8.

Table 8 Influent and effluent quality in comparison with discharge restrictions for Sternö WWTP. Data from Karlshamns kommun, 2011.

	Flow [$m^3\ h^{-1}$]	Total N [$mg\ L^{-1}$]	Total P [$mg\ L^{-1}$]	BOD_7 [$mg\ L^{-1}$]
Average influent 2010	8581	30.2	4.3	145.3
Annual mean effluent restriction		12	0.3	-
Monthly mean effluent restriction		-	0.5	10
Average discharge 2010		8.9	0.07	2.8

When Sternö WWTP was constructed it was dimensioned for 26 000 pe and year 2010 the actual load was 17 814 pe (based on $\frac{70\ g\ BOD_7}{pe \times d}$). Thus, the WWTP is dimensioned for a pe load of 46 % more than the load 2010. Year 2010, the electricity consumption was 1345.5 MWh (Karlshamns kommun, 2011). An overview of the blowers in Sternö WWTP can be seen in Table 9.

Table 9 Overview of the blowers in Sternö WWTP.

Blower no	Manufacturer	Power [kW]	Blower technology	Speed drive	Treatment line
1	HV-turbo	30	Lobe	Variable (VFD)	2
2	HV-turbo	25/31	Lobe	2 stage	2
3	AtlasCopco	45	Screw	Variable (VFD)	1
4	Mapner	22	Lobe	1 stage	2

5.1.2 Specific information on the reference line (line 2)

The reference line had old aeration equipment and aeration control from the construction of the WWTP.

The aerated sludge age was calculated to 11.5 days and the total sludge age (which is more uncertain due to less precise measurements) was calculated to 39 days.

Aeration equipment

The blowers supporting the reference line were all lobe blowers (no 1, 2 and 4). These were made by HV-turbo (from the construction of the WWTP) and Mapner (installed 2008). These blowers were connected through a common manifold. Blower no 1 had VFD.

The airflow valves were butterfly valves of an unknown brand (it was not possible to identify it) and they were from the construction of the WWTP.

The diffusers in the reference line were tube diffusers and from the construction of the WWTP. The diffuser brand was not possible to identify but the diffuser is shown in Figure 7. The distribution can be seen in Table 10.

Table 10 Diffuser distribution in treatment line 21a.

Zone	Diffusers	Total diffuser area (Ad) [m^2]	Tank zone area (At) [m^2]	Ad/At [%]
21a	30	3.55	56	6.34

Aeration control

The aeration control system in the reference line was made by the automation firm *LMT Elteknik AB*. The control logic was DO control (without cascade control), meaning that a DO controller determined valve opening based on control error in DO concentration.

Blower 1 (with VFD) and 2 were run on constant air pressure, which could be manually changed by the WWTP staff. The staff could manually activate blower 4 if necessary.

The constant air pressure meant that the air pressure set-point would have to be sufficient for the top loads and therefore higher than necessary during smaller loads. Normally, the (gauge) pressure 70 kPa was used.

5.1.3 Specific information on treatment the test line (line 1)

The test line originally had the old equipment from the construction of the WWTP, but was upgraded in several steps, as will be described below.

The aerated sludge age was calculated to 10.5 days and the total sludge age (which is more uncertain due to less precise measurements) was calculated to 36 days.

Aeration equipment

The blower supporting treatment line no 1, the test line, was an AtlasCopco ZS 45$^+$ VSD. The blower use screw technology and Variable Speed Drive (VSD) technology, which is like VFD. This blower was installed in April 2011 and has a motor power of 45 kW and can deliver between 259 and 1145 $Nm^3\ h^{-1}$.

The airflow valves were butterfly valves of an unknown brand (it was not possible to identify it). The valves were installed at Sternö WWTP when the plant was constructed.

In April 2011, the test line used diffusers of the same type as the reference line (tube diffusers installed when the WWTP was built).

During May and June 2011, new 9'' Sanitaire Silver Series II LP 2300, shown in Figure 8, were installed in the test line. These diffusers are a low-pressure (LP) version of the Silver Series II. The diffusers have a rubber membrane and were placed at a depth of 5.4 m, 0.1 m above the bottom. In total, there were 440 diffusers in the test line, with a distribution between the zones as seen in Table 11.

Table 11 Diffuser distribution in the test line.

Zone	No. of diffusers	Total diffuser area (Ad) [m^2]	Tank zone area (At) [m^2]	Ad/At [%]
11a	90	3.42	56	6.1
11b	175	6.65	112	5.9
12	175	6.65	112	5.9

In Sanitaire Silver Series II LP, the airflow distribution to the diffusers is secured with a small orifice. The orifice gives all the diffusers practically the same head loss and therefore an even airflow distribution. To secure that sufficient mixing is fulfilled, the minimum airflow should be at least 1 Nm^3 $hour^{-1}$ m^{-2} (which means 112 Nm^3 $hour^{-1}$ for zone 11b and 12), provided that the primary treatment is working good.

Aeration control

In April 2011, DO cascade control was implemented in the test line. This DO cascade control was not tuned in April but rather adjusted with the same controller parameters as the reference line, just to be stable and working. The control was implemented together with MOV-logic, which was activated in September 2011, when the DO cascade control was fine tuned. The MOV logic was adjusted to operate the air pressure so that the valves were open between 75 and 95 % of their controllable range.

The aeration control was made in the software Maestro, which was implemented through the ITT Flygt control box *APX 761*. The control box consists of a cabinet, an input/output unit, a panel and a data processor.
APX761 has got analogue and digital inputs and digital outputs. The total number of inputs and outputs can be expanded to 600, which makes the controller highly adaptable. The controller is equipped with serial communication ports and an ethernet port. This makes it possible to communicate with a SCADA system through local and network connections, which makes it possible to download data from distance.

The aeration control was also equipped with a fouling preventive control, called *air bumping* or simply *cleaning*.

The method uses the stretch ability of the diffuser membrane to crack the bio film. By maximizing the airflow for a short time, approximately 5 minutes, the diffuser membrane is sufficiently stretched for the bio film to be broken. Logic for air bumping was programmed in Maestro and does once a week increase the airflow to close to maximum airflow.

In October 2011, ammonium feedback control was implemented in the test line. This feedback control controls the aeration in zone 1, whereas the DO cascade control was left untouched in zone 2.

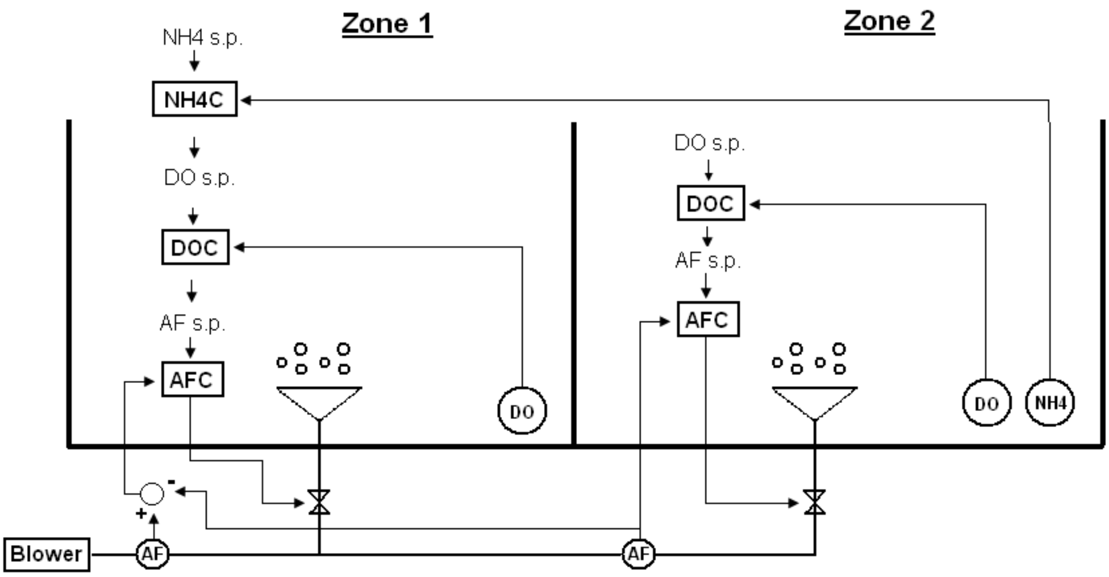

Figure 16 Visualisation of the overall control in Sternö WWTP. NH4C is ammonium feedback control, DOC is DO control and AFC is airflow control. The circles with NH4, DO and AF represent measurement of ammonium, DO and airflow.

The control philosophy of the ammonium control, showed in Figure 16, is that effluent ammonium (measured in the end of zone 2) controls the airflow in zone 1. The purpose of the feedback control was to maintain desired effluent ammonium concentration. The ammonium controller did only control the airflow in zone 1 because the DO set-point in zone 2 was sought to be kept constant – if DO concentration in zone 2 during certain periods would have been allowed to get too high it could have disturbed the denitrification in the anoxic zone.

5.2 FULL-SCALE TRIALS METHOD

5.2.1 Measurements

For this master thesis a number of measurements were required to provide the necessary data for aeration control and evaluation. An overview of the measurements can be seen in Table 12 and Figure 17.

Table 12 An overview of thesis measurements in Sternö WWTP.

Measurements	Unit	Time basis	Position
Total flow	$m^3\ h^{-1}$	On-line	WWTP inlet
Flow fraction to line 1 and 2	%	Once	Before inlet to anaerobic zone
NH_4-N	$mg\ L^{-1}$	Weekly	Inlet to line 1 and 2
BOD_7	$mg\ L^{-1}$	Weekly	Inlet to line 1 and 2
NH_4-N	$mg\ L^{-1}$	Weekly	Outlet from secondary sed. 1 and 2
BOD_7	$mg\ L^{-1}$	Weekly	Outlet from secondary sed. 1 and 2
DO	$mg\ L^{-1}$	On-line	Zone 11b, 12, 21b, 22
Temperature	^oC	On-line	Zone 11b, 12, 21b, 22
NH_4-N	$mg\ L^{-1}$	On-line	End of zone 12 and 22
NO_3-N	$mg\ L^{-1}$	On-line	End of zone 12 and 22
Power consumption	kWh	On-line	Blower 1, 2, 3, 4
Airflow	$Nm^3\ h^{-1}$	On-line	Zone 11, 12 and (21+22)
Valve position	%	On-line	Zone 11, 12, 21, 22

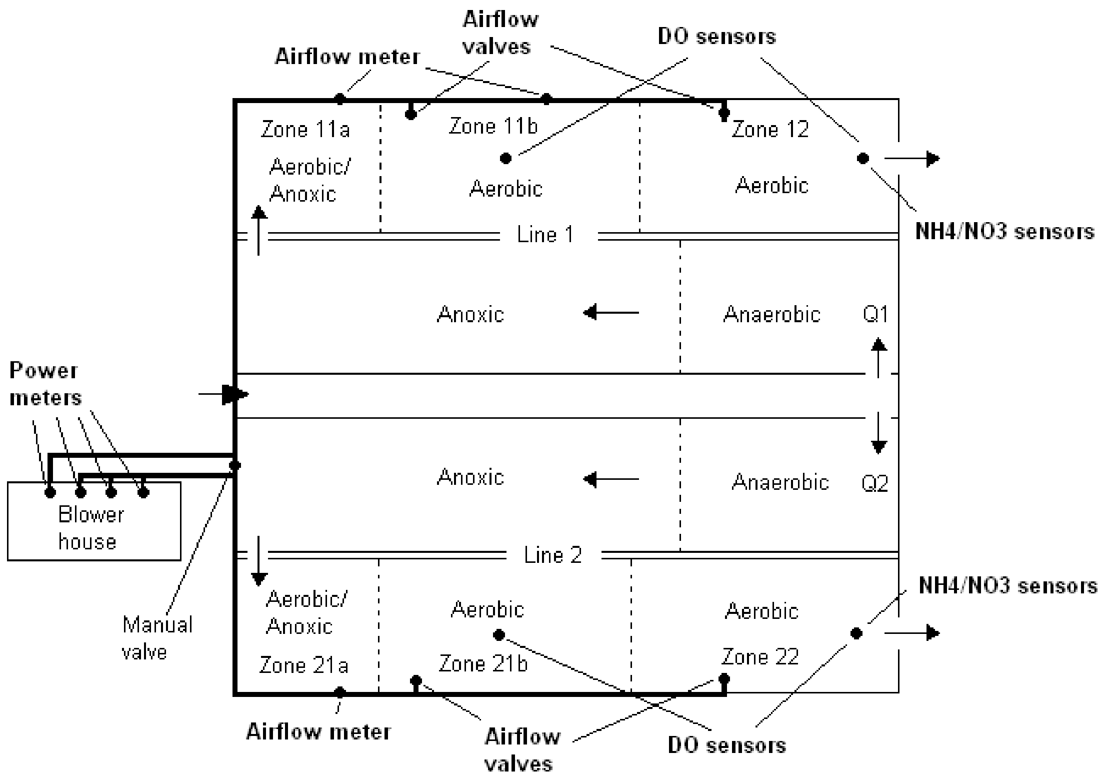

Figure 17 Position of on-line measurements in the biological treatment of Sternö WWTP.

The measurements performed for aeration control were:

- DO concentration.
- Ammonium concentration.
- Airflow.
- Valve position.

These measurements were done on-line and the sensors to measure DO concentration, ammonium concentration and airflow were newly installed (April-May 2011), since these are all sensitive measurements that need to be correct, fast and reliable.

Ammonium (NH_4^+) and nitrate (NO_3^-) was measured with the WTW in-situ combination sensor VARiON® Plus 700 IQ. The sensor has separate electrodes for ammonium and nitrate. It also has a reference electrode and an ammonium compensation electrode with potassium (K^+). The nitrate compensation is included in the nitrate electrode. The sensor use ion selective measuring - the tension between the reference electrode and the measuring electrode is determined for ammonium and nitrate, respectively. The tension is then transformed to a measuring value of ammonium or nitrate. The measurement accuracy in laboratory standard solutions is ± 5 % of measured value ± 0.2 mg L^{-1}. For the ammonium electrode the response time t_{90} < 3 min, measured at a concentration change from 10 to 100 mg L^{-1} NH_4-N, at 20 °C. For the nitrate electrode the response time t_{90} < 3 min, measured at a concentration change from 5 to 50 mg L^{-1} NO_3-N, at 20 °C.

Dissolved oxygen (DO) was measured with the WTW sensor FDO® 700 IQ. The sensor uses optical technology and by stimulating a fluorescent dye in the membrane with short wave length light, the dye emits long wave light when the electrons fall back to the passive state. The long wave light is recorded as a measurement signal and is transformed to a concentration of DO. If oxygen reaches the dye by diffusing through the membrane, the back scattering of the long wave light is affected according to the oxygen concentration in the water. To counteract the effects of the ageing of the optical components, there are two separate light sources with equal paths where one works as a reference path and one as a measuring path. No flow rate is required for measuring. The measurement accuracy is ± 0.05 mg L^{-1} in the range < 1 mg L^{-1} and ± 0.1 mg L^{-1} in the range > 1 mg L^{-1}. The response time t_{90} < 150 s, according to ISO 15839.

Airflow was measured with the ABB Sensyflow FMT 400-VTS, which is a thermal mass flow meter. This meter uses two temperature-sensitive platinum resistors that are part of an electrical bridge circuit, which are placed inside the gas flow. One of the resistors is unheated and adapts the gas temperature while the other resistor is heated by a current. This is done so that the temperature difference between the two resistors is constant. The electrical power of the heated resistor compensates its heat loss to the gas flow. Therefore, the current providing the power to the heated resistor represents the airflow. The measurement error is ≤ ±1.8 % of measured value ± 0.10% of possible end value. The response time T_{63} = 0.5 s.

The measurements used for evaluation were:

- Total flow to biological treatment.
- Flow fraction to line 1 and 2.
- Weekly (laboratory measurements) of influent and effluent NH_4.
- Weekly (laboratory measurements) of influent and effluent BOD_7.
- DO concentration.
- Temperature.
- Power consumption.
- Airflow.

The total flow to the biological treatment is the incoming flow to the WWTP plus the internal load, which for example could be flush water from filter cleaning. The total flow is divided between treatment line 1 and 2 by a dividing plate. This plate is not straight but bent and therefore it does not distribute the total flow evenly between the lines. During June 29 2011, field measurements were performed to determine the flow in each treatment line. The measurements were done by using two acoustic doppler velocity meter “Vectrino” from Nortek, which measured the velocity of the water. One velocity meter was used to measure the velocity 3 m upstream the plate to approximate the total flow. The other velocity meter was used to measure the velocity in 12 points (3 horizontal planes and 4 vertical planes) for each side of the plate to approximate the flow on each side of the plate. By measuring the total flow at the same time as the flow on each side of the plate was measured, a flow fraction could be calculated to 53 % to the reference line and 47 % to the test line (Wessman, 2011).

The weekly measurements on influent and effluent (with respect to the bioreactor) BOD_7 and NH_4 were made by Sternölaboratoriet, which is an accredited laboratory at Sternö WWTP. These samples were taken on a flow proportional basis by a sampling machine. The samples were stored in a bucket inside the sampling machine case and collected daily. The daily collected samples were frozen and the samples from the measurement week were put together, thawed and the filtered before analysed.

DO concentrations used for evaluation were based on the WTW DO on-line measurements, described above. Temperature was measured with the WTW DO sensor described above. Power consumption was measured on-line on each blower as wire power, which is the total electricity consumption each blower has. Airflow was measured on-line with the ABB airflow meter described above.

5.2.2 Evaluation periods

The implementation of new equipment and new control system in the test line was made in several steps and based on these installations there are four evaluation periods, as can be seen in Table 13. There was a long break between evaluation period 1 and 2 because the change of diffusers (Sanitaire SS II LP) took a long time, since it involved emptying the basin, installing the diffusers and also repairing baffles between the aeration zones.

Table 13 Evaluation periods with new aeration equipment in the test line.

Evaluation period	Time period	New aeration equipment
1	April 6 - 20	AtlasCopco ZS 45+ VSD
		DO cascade control
2	July 6 - Sept. 7	Sanitaire SS II LP
3	Sept 7 - Okt. 26	Cascade control fine-tuned
		DO profile fine-tuned and correct
		MOV-logic
4	Okt. 26 - Nov. 16	Control system with NH_4-feeback

Evaluation period 1 involved a new AtlasCopco blower and also new DO control. However, the DO control was not fine-tuned; instead it was implemented with the parameters K and T_i that the DO controllers in the reference line used before. This period was therefore more an evaluation of the energy efficiency of the blower and also a way to see that the DO cascade control did work well.

The second evaluation period involved new Sanitaire diffusers which were installed between period 1 and 2. During the end of August the DO profile (DO set-point in zone 1/zone 2) was also changed from (1.7/0.7) to (0.7/1.0) mg L^{-1}, but because of a measurement error DO was not correctly measured and therefore the upgraded DO profile was not activated. The purpose of the new DO profile was to decrease the oxidation of organic constituents and ammonium in zone 1 and therefore save some load to zone 2, in order to use the aeration capacity in a more energy efficient way.

To the third evaluation period, the DO measurement error was solved. This period involved fine-tuning of the DO cascade control and since the measurement was correct, the new DO profile was activated during this period. Also, MOV-logic was activated which allowed the blower to work at a lower air pressure.

The fourth evaluation period included implementation of ammonium feedback control.

5.2.3 Oxygen transfer calculations

In this master thesis the efficiency of the two treatment lines was based on the parameter SAE (as kg O_2 kWh^{-1}). SAE is calculated from AOR, as visualized in Figure 18. This is based on what has been earlier described in the Chapter 3.1.

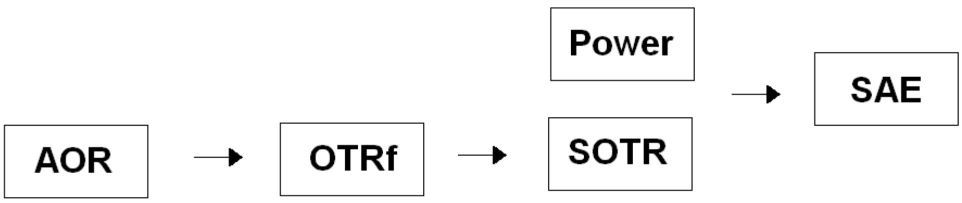

Figure 18 Overview of calculations to find SAE.

These calculations were made on a weekly basis from Wednesday to Wednesday. The reason for this is that the laboratory doing the analyses has routines to perform these types of analyses on Wednesdays. To calculate the parameters in Figure 18, a number of assumptions and constants must be used, which are described below.

For AOR, the carbonaceous process oxygen requirement was calculated as a factor (X) times the BOD_5 reduction. The factor X was chosen according to Figure 1 (with a total sludge age of about 30 days and a temperature of about 15 °C) to 1.2.

Nitrification process oxygen requirement was calculated (according to what was stated in Chapter 2.2.2) a factor (Y) times the NH_4^+-reduction. The factor Y was chosen to 4.57 according to (9).

Inorganic chemical process oxygen requirement was not considered in this study since these are seen to have an insignificant oxygen requirement.

Denitrification process oxygen credit was not considered in this study because the necessary measurements to determine the amount of nitrate denitrified from each treatment line were not made.

For the measurements performed in Sternö WWTP, AOR was, according to the assumptions and choices made above, calculated according to:

$$AOR = Q \times \left(X \times (BOD_{5,in} - BOD_{5,eff}) + Y \times (NH_{4,in} - NH_{4,eff}) \right) \quad (31)$$

where,

AOR = oxygen transfer rate [kg O_2 d^{-1}]
Q = flow [m^3 d^{-1}]
X = oxidation coefficient [kg O_2 (kg BOD_5)$^{-1}$]
$BOD_{5,in}$ = influent BOD_5 [kg m^{-3}]
$BOD_{5,eff}$ = effluent BOD_5 [kg m^{-3}]
Y = oxidation coefficient [kg O_2 (kg NH_4^+)$^{-1}$]
$NH_{4,in}$ = influent NH_4 [kg m^{-3}]
$NH_{4,eff}$ = effluent NH_4 [kg m^{-3}]

In Sternö WWTP BOD_7 is measured, and not BOD_5 as in the AOR-equation above. Therefore, a conversion factor between BOD_7 and BOD_5 was used. The conversion factor was selected to 1.15 (Norrström, 1976), according to equation 32.

$$BOD_5 = \frac{BOD_7}{1.15} \quad (32)$$

The constants used for the AOR calculations are showed in Table 14.

Table 14 Summary of constants used in the AOR calculations.

Parameter	**Value**	**Unit**
X	1.2	-
Y	4.6	-
BOD_5/BOD_7	1.15	-

In this study, OTR_f was calculated according to equation 33. Equation 33 is not the same as equation 18 because the latter was made for aeration design and not evaluation.

$$OTR_f = AOR + (Q \times DO) \tag{33}$$

where,

OTR_f = oxygen transfer rate [kg d^{-1}]
AOR = actual oxygen requirement [kg d^{-1}]
Q = flow through the treatment line [m^3 d^{-1}]
DO = average dissolved oxygen concentration in the treatment line [kg m^{-3}]

SOTR is calculated according to equation 19. The following are parameters in these calculations. Correction factor for pressure on C^*_∞, Ω, was calculated according to U.S. EPA (1989):

$$\Omega = \frac{P_{field}}{P_{msl}} \tag{34}$$

where,

P_{field} = field atmospheric pressure [Pa]
P_{msl} = mean sea level atmospheric pressure [Pa]

Steady state DO saturation concentration for a given diffuser at 20 °C and 101.3 kPa, $C^*_{\infty 20}$, is calculated as a tabular value corrected to the diffuser depth according to:

$$C^*_{\infty 20} = C^*_{s20} \times \left(1 + \frac{P_{water}}{P_{water} + P_{msl}}\right) \tag{35}$$

where,

$C^*_{\infty 20}$ = steady-state DO saturation concentration attained at infinite time for a given diffuser at 20 °C and 1 atm [kg m^{-3}]
C^*_{s20} = tabular value of DO surface saturation concentration at 20 °C, a standard total pressure of 1.00 atm (101.3 kPa) and 100 % relative humidity [kg m^{-3}]
P_{msl} = mean sea level atmospheric pressure [Pa]
P_{water} = water pressure [Pa], calculated as (36).

$$P_{water} = \rho \times g \times h \tag{36}$$

where,

ρ = density of water [kg m^{-3}]
g = acceleration of gravity [m s^{-2}]
h = diffuser depth [m]

Time effect of diffusers, F, was not considered in this master thesis and therefore chosen to be 1. The parameter describing wastewater K_La compared to clean water K_La, α, was measured to 0.65 for the new diffusers in a previous test. Even though this value is not precise in this study due to different wastewater composition etc., this value was treated as reasonable and therefore chosen.

In order to compare the diffusers in the two treatment lines on a fair basis, the same α was used for both treatment lines. This is reasonable because the two treatment lines have the same wastewater composition and are both supported by fine-bubble diffusers, even though the diffusers are different and therefore probably have slightly different α.

Temperature coefficient, τ, was considered by using tabular DO surface saturation values already corrected to the current temperature ($C^*_{\infty\ T}$) according to ASCE (2007). The constants used for the SOTR calculations are shown in Table 15.

Table 15 Summary of constants used in the SOTR calculations.

Parameter	Value	Unit
C^*_{s20}	9.09	kg O_2 m^{-3}
α	0.65	-
F	1	-
θ	1.024	-
Ω	0.99	-
β	0.98	-

SAE was calculated according to equation 20 and the power input to the four blowers was measured on-line as wire power, i.e. the power drawn by each motor. SAE was calculated for each treatment line and therefore the power input to the blowers supporting each treatment line was added up.

5.2.4 Controllers

The airflow and DO controllers in the test line were tuned in Sternö WWTP 6-7 September on site, according to the Lambda method described in Chapter 3.3.4. All controllers were PI controllers which require adjustments of two parameters, the gain and the integral time. The following text describes how this tuning was performed.

First, the controller was set in manual mode and the output signal was allowed to stabilize. Thereafter, the control signal was changed with a step and the output signal was manually written down on a computer every 5^{th} second (Airflow controller) or every 20^{th} second (DO controller) after watching the real-time data screen on the APX761. The data collection stopped when the output signal had stabilized again, which meant that a graph with output signal versus time could be made. This made it possible to calculate the dead time and the 63 % rise time.

After this, the calculations began to search the process gain (K_s), choose p to calculate λ and then finally calculate the gain (K) and the integral time (T_i) of the controller. The airflow controllers were tuned with p=1 (since they need to be fast), the DO controller in zone 1 was tuned with p=2.5 and DO controller in zone 2 was tuned with p=2. The DO controller in zone 2 was given a higher p than the one in zone 1 because the DO response in zone 2 was experienced as slow. The NH_4 controller was tuned in BSM1.

The tuning was performed 2 times for each airflow controller (they are easy to tune since the relationship between valve opening and airflow is not easily disturbed when air pressure is kept constant) and 3 times for each DO controller (they are more difficult to tune since the DO concentration is easily disturbed due to changes in load and flow). The chosen controller parameters P and T_i for each controller were then calculated as a mean of all the tests. Also, some DO controller tuning tests were excluded and remade due to too big disturbances of the DO concentration due to load variations.

The ammonium controller was attempted to be tuned, but failed because of too low NH_4 concentration, which was about 0.2 g m^{-3} at that time. The low ammonium concentration was difficult to affect with an increase in DO concentration, there was simply too little ammonium to be controllable. The ammonium controller set-point was 1.0 mg L^{-1}.

The controller performance was evaluated as the DO standard deviation. If the ammonium controller would have been activated, the ammonium standard deviation could have been calculated as well, but that was not of current interest. The DO standard deviation was calculated according to:

$$std = \frac{\sum_{j=1}^{n} \left(x_j - \bar{x}\right)^2}{n-1} \qquad (37)$$

where,

std	=	DO standard deviation [mg L^{-1}]
x_j	=	DO sample value [mg L^{-1}]
$\bar{x}$	=	DO sample average value [mg L^{-1}]
n	=	number of samples

Standard deviation was calculated from Wednesday to Wednesday according to the evaluation periods, since the laboratory made the analyses on Wednesdays.

5.2.5 Treatment performance

To secure that energy improvements did not occur due to decreased treatment performance, the BOD_5 and NH_4 reduction was calculated as percentage of incoming load. The reduction was based on incoming load to biological treatment and effluent load from each secondary sedimentation, from laboratory analyses.

5.2.6 Energy savings

Energy savings were calculated both as energy savings per week and energy savings with respect to the reference line.

Energy savings per week were calculated based on SOTR in the test line and the SAE values in the test and the reference line:

$$E_{weekly\ savings} = 7 \times \left(\frac{SOTR_{test}}{SAE_{ref}} - \frac{SOTR_{test}}{SAE_{test}} \right) \qquad (38)$$

where,

$E_{weekly\ savings}$	=	energy savings per week [kWh $week^{-1}$]
7	=	number of days per week [days $week^{-1}$]
$SOTR_{test}$	=	standard oxygen transfer rate of test line [kg O_2 day^{-1}]
$SOTR_{ref}$	=	standard oxygen transfer rate of reference line [kg O_2 day^{-1}]
SAE_{test}	=	SAE of test treatment line [kg O_2 kWh^{-1}]
SAE_{ref}	=	SAE of test reference line [kg O_2 kWh^{-1}]

Energy savings in relation with respect to the reference line were calculated on an SAE-basis, according to:

$$E_{savings\,\%} = 100 \times \left(1 - \frac{SAE_{ref}}{SAE_{test}}\right) \quad (39)$$

where,

$E_{savings\,\%}$ = energy savings of the test line compared to the reference line [%]
SAE_{test} = SAE of test treatment line [kg O_2 kWh^{-1}]
SAE_{ref} = SAE of test reference line [kg O_2 kWh^{-1}]

Airflow savings in relation with respect to the reference line were made on a SOTE-basis, according to:

$$AF_{savings\,\%} = 100 \times \left(1 - \frac{SOTE_{ref}}{SOTE_{test}}\right) \quad (40)$$

where,

$AF_{savings\,\%}$ = airflow savings of the test line compared to the reference line [%]
$SOTE_{test}$ = standard oxygen transfer efficiency of test line [%]
$SOTR_{ref}$ = standard oxygen transfer efficiency of reference line [%]

The decrease [%] on the total energy consumption of Sternö WWTP was also calculated. This was done by comparing the aeration energy consumption (measured by the kWh meters on the four blowers) with the total energy consumption of the whole plant (attained from the energy invoices). With the $E_{savings\,\%}$ of the test line, the decrease of the total energy consumption could be calculated. Also, the decrease of the total energy consumption [%] was calculated for a hypothetical scenario if *both* the test line and the reference line would have been upgraded. For this scenario it was assumed that the same $E_{savings\,\%}$ could be achieved in the reference line as in the test line.

5.2.7 Economic analysis

The economic analysis is an addition on the energy savings, where the energy price is also considered.

The weekly economical savings were calculated based on the weekly energy savings in (38):

$$SEK_{weekly\ savings} = energy\ price \times E_{weekly\ savings} \quad (41)$$

where,

$SEK_{weekly\ savings}$ = economical savings per week [SEK $week^{-1}$]
Energy price = energy price for Sternö WWTP [SEK kWh^{-1}]
$E_{weekly\ savings}$ = energy savings per week [kWh $week^{-1}$]

The economical evaluation also considers the return period, according to equation 43. In order to calculate the return period the annual savings first need to be calculated:

$$Annual\ savings = Energy\ consumption \times \frac{Energy\ savings}{100} \times Energy\ price \qquad (42)$$

where,

Energy consumption	=	total energy consumption for Sternö WWTP [kWh year^{-1}]
Energy savings	=	total energy savings for Sternö WWTP due to improved aeration [%]
Energy price	=	energy price for Sternö WWTP [SEK kWh^{-1}]

The energy price for Sternö WWTP used in this master thesis was the total average energy price for the period January 2011 to October 2011 (1.120 SEK kWh^{-1}). This was calculated as the invoice sum (SEK) divided by the amount of energy used (kWh). This time period was used since it is a recent time period plus that in includes both winter and summer (where energy prices differs).

$$Return\ period = \frac{Total\ price}{Annual\ savings} \qquad (43)$$

where,

Return period	=	time it takes before the investment is retuned [year]
Total price	=	total price of the investment [SEK]
Annual savings	=	savings per year [SEK year^{-1}]

The total price of the aeration equipment supporting the test line (blower, diffusers, measurement equipment and control system, including installation costs) was 725 000 SEK. The price of each component is not official.
The total price of the aeration equipment if both the test line and the reference line would be upgraded (blower, diffusers, measurement equipment and control system, including installation costs) would be 1 227 000 SEK. The total price of upgrading both treatment lines is not the double price for upgrading only one treatment line since some equipment, for example control system, can be used for both treatment lines.

5.3 FULL-SCALE TRIALS RESULTS

5.3.1 Controllers

The airflow, DO and NH_4 controllers in the test line were given the final parameters according to Table 16.

Table 16 Gain and integral time for the aeration controllers in the test line.

	Zone 1			Zone 2	
Parameter	Airflow controller	DO controller	NH_4 controller	Airflow controller	DO controller
K	0.45	0.57	-0.40	0.50	0.62
T_i [s]	17	335	3600	13	270

The DO concentration for evaluation period 1, 2, 3 and 4 in both lines can be seen in Figure 19. The gap between April and July is when the diffusers were installed and the gap in August is due to missing data. Figure 19 shows that DO concentrations were high in the test line between July and the beginning of September. After September, the DO concentration in the test line was lower than in the reference line.

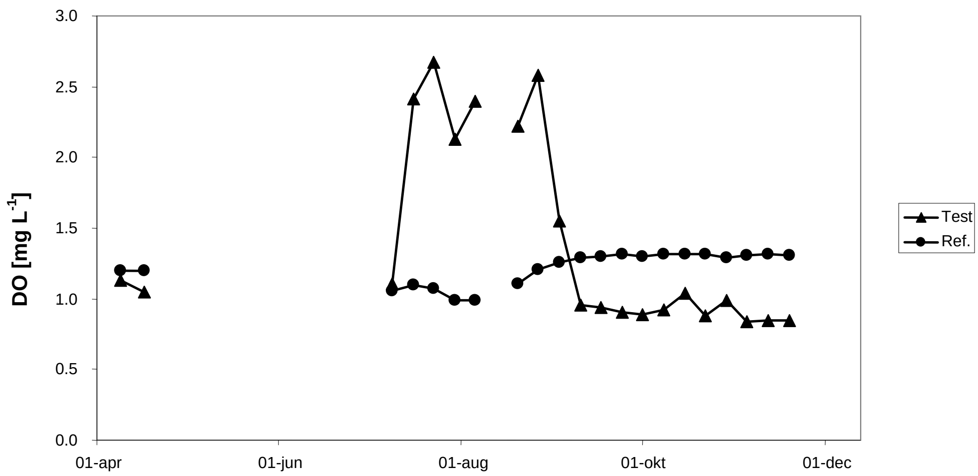

Figure 19 Average DO concentration in the two treatment lines.

A short extract from evaluation period 4 shows how the DO values were controlled in the test line and the reference line, which can be seen in Figure 20 and 21, respectively. In the test line, DO in zone 1 was kept at 0.7 mg L^{-1} at a steady concentration, while zone 2 was kept at 1.0 mg L^{-1}, but in a more unsteady way.

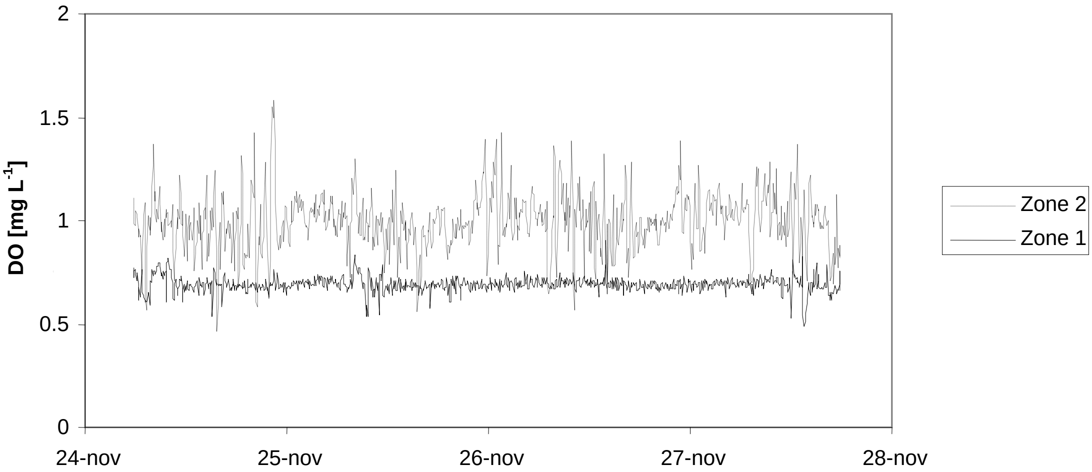

Figure 20 DO concentrations in the test line for zone 1 and zone 2.

In the reference line, DO in zone 1 was kept at 1.8 mg L^{-1} and this was made in a more unsteady way than in the test line. Zone 2 was kept at 0.7 mg L^{-1} and about as unsteady as in zone 2 in the test line.

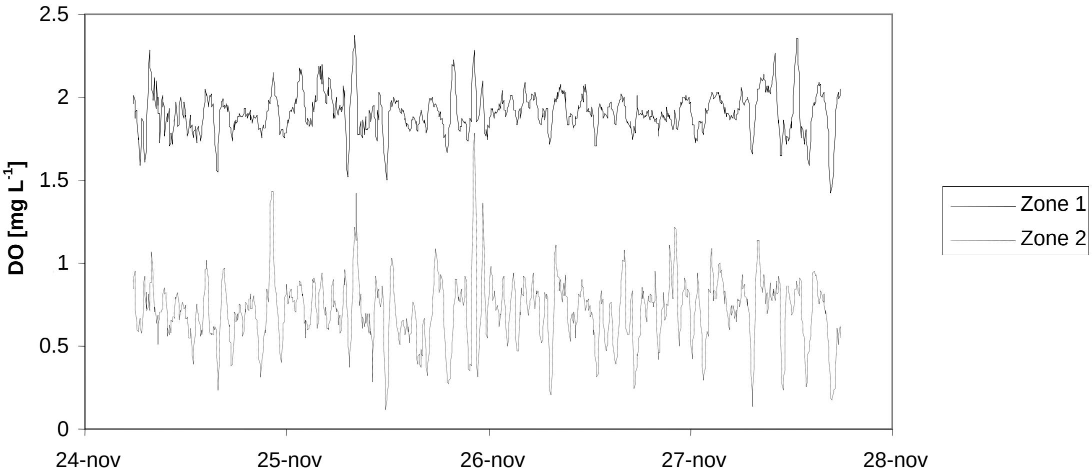

Figure 21 DO concentrations in the reference line for zone 1 and zone 2

Figure 22 shows the DO standard deviation for zone 1 for each treatment line during evaluation period 3 and 4. For the test line, there are also corrected values where variations due to tuning were excluded. The figure shows that the standard deviation for the test line was well below the standard deviation of the reference line except for the measurement period around October 31st, when the standard deviation was 0.6 mg L^{-1} for the test line.

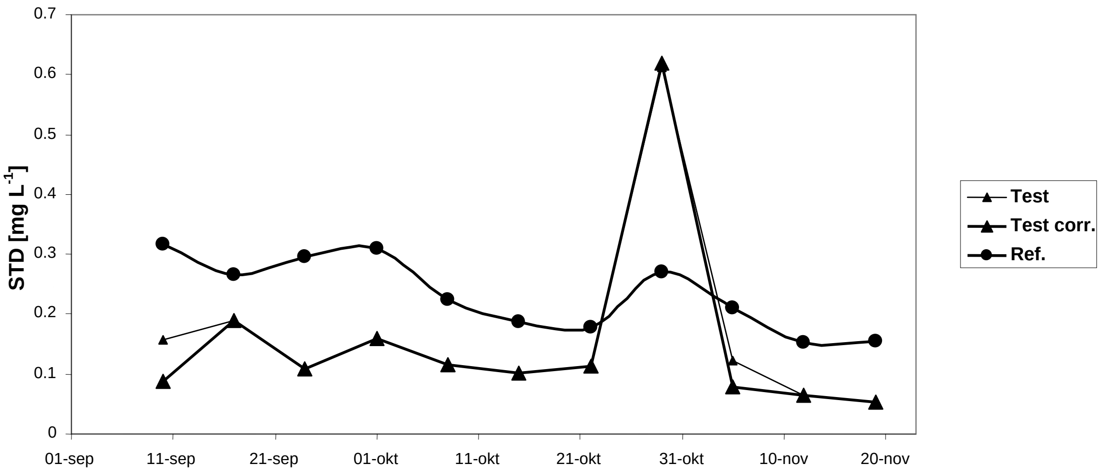

Figure 22 DO standard deviation for zone 1 for the test line, the reference line and corrected values for the test line.

Figure 23 shows the DO standard deviation for zone 2 for each treatment line during evaluation period 3 and 4. For the test line, there are also corrected values where variations due to tuning and air bumping were excluded. The graph shows that the standard deviation for the reference line was relatively constant just above 0.2 mg L^{-1}. The standard deviation of the test line was unstable and had peaks above 0.3 mg L^{-1} at the measurement periods around October 1st, October 15th and October 29th.

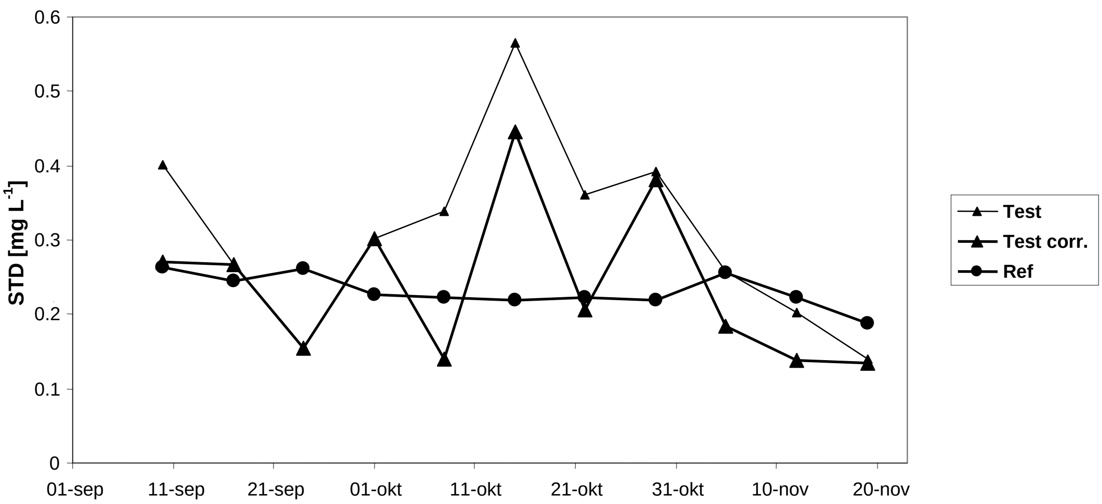

Figure 23 DO standard deviation for zone 2 for the test line, the reference line and corrected values for the test line.

5.3.2 Treatment performance

The reduction of BOD_5 and NH_4 for the four evaluation periods is shown in Table 17 and the BOD_5 treatment is almost the same (96 to 97 %) for both treatment lines for all periods. The NH_4 reduction was not as good in the test line as in the reference line during the first evaluation period (71 % against 88 %). For the three other evaluation periods the NH_4 reduction was good in both treatment lines (99 %).

Table 17 Average reduction of BOD_5 and NH_4.

	BOD_5-reduction [%]		**NH_4-reduction [%]**	
Evaluation period	Test line	Ref. line	Test line	Ref. line
1	96	97	71	88
2	97	97	99	99
3	96	97	99	99
4	96	97	99	99

In Figure 24 a short extract of the effluent ammonium concentration from each treatment line is shown, based on on-line measurements. The ammonium sensors were calibrated just before the shown period started. During this period (evaluation period 4 included), effluent ammonium in the test line was lower than effluent ammonium in the reference line. The ammonium concentration in the test line was constantly below set-point of 1.0 mg L^{-1}.

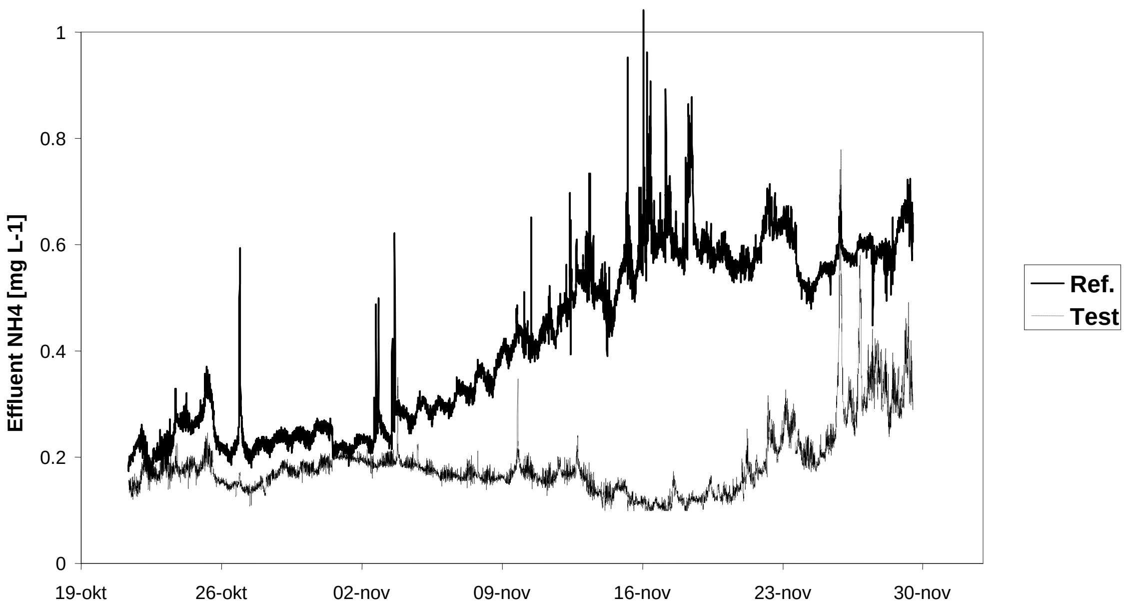

Figure 24 Effluent ammonium concentration in each treatment line.

5.3.3 Energy savings

The average SAE, airflow and energy savings can be seen in Table 18, which shows that SAE was constantly higher for the test line than for the reference line. Airflow savings are not shown for evaluation period 1 due to old airflow meters, but for evaluation period 2 to evaluation period 4, the airflow savings were constantly increasing. The energy savings [%] were constantly increasing from evaluation period 1 to evaluation period 4, in Table 18 shown with standard deviation. The highest energy savings as kWh $week^{-1}$ were during evaluation period 2. Data for every measurement period is shown in appendix III.

Table 18 Average SAE, airflow and energy savings for the evaluation periods.

Evaluation period	SAE [kg O_2 kWh^{-1}] Test line	Ref. line	Airflow savings [%]	Energy savings [%]	Energy savings [kWh $week^{-1}$]
P1	3.4	2.2		35 ± 1	1579
P2	2.9	1.3	20	56 ± 7	4493
P3	3.4	1.2	29	66 ± 2	4011
P4	3.7	1.2	31	66 ± 4	4199
P3 + P4	3.5	1.2	30	65 ± 2	4067

The standard deviation for the energy savings is particular high for evaluation period 2. During this period, there were problems with the primary sedimentation, giving a fluctuating load to the biological treatment lines.

If the energy savings during evaluation period 3 and 4 would be evaluated together as one data series (which will be further discussed in Chapter 5.4) the average energy savings would be 65 ± 2 %.

The air (gauge) pressure in the test line aeration system during period 2, 3 and 4 was ranging between 57 and 60 kPa.

The contribution of each aeration upgrade to the total energy savings can be seen in Table 19. The table shows the difference between the improved efficiency in % and percentage points. The diffuser savings are calculated based on difference between period 2 and period 1. The savings from control, DO profile and MOV-logic are calculated based on the differences between period 3 + 4 (evaluated together) and period 2.

Table 19 The contribution of each aeration upgrade to the energy savings.

Aeration equipment	Increase of energy savings [%]	Increase of energy savings [percentage points]
Blower	35	35
Diffusers	32	21
Control, DO profile, MOV	21	9

Figure 25 is a box plot for the energy savings where period 3 and 4 are evaluated together. The figure shows that the box plot for the first evaluation period is not possible to evaluate, since it is so small because of only 2 values. The box plot for evaluation period 2 is relatively high, showing that the energy savings are widely distributed. The box plot for evaluation period 3 + 4 is relatively low, indicating that the data is distributed over a narrow range. Also, the median of this box plot (65.5 %) is close to the top of the box, suggesting that the distribution has a negative skew. Also, the top whisker is quite long which implies that the maximum value is a bit diverging.

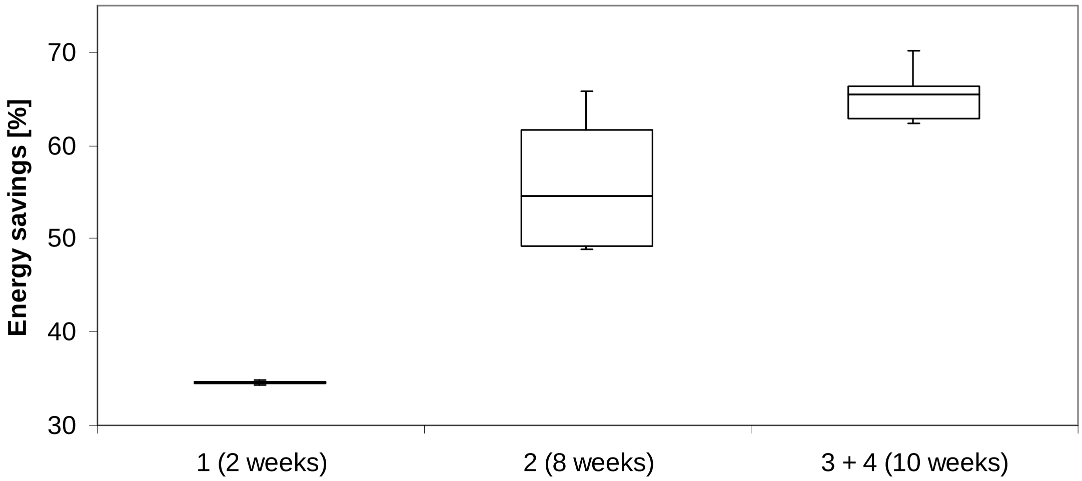

Figure 25 Box plot for the evaluation periods with 1 value per measurement week. The whiskers are from minimum to maximum value.

Figure 26 shows how the total energy consumption would have been distributed if test line had not been upgraded. The graph shows that the aeration would have been 44 % of the total energy consumption of Sternö WWTP.

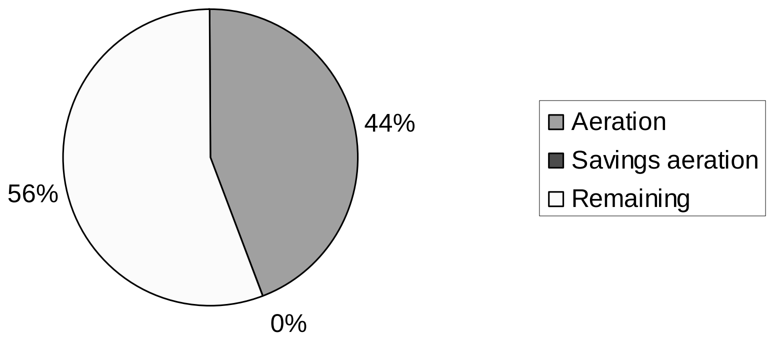

Figure 26 Total energy consumption of Sternö WWTP in October 2011 without upgraded aeration system in the test line.

Figure 27 shows how the total energy consumption was distributed with the test line upgraded. The graph shows that the aeration represents 31 % of the total energy consumption of Sternö WWTP, with aeration savings of 13 % of the total energy consumption.

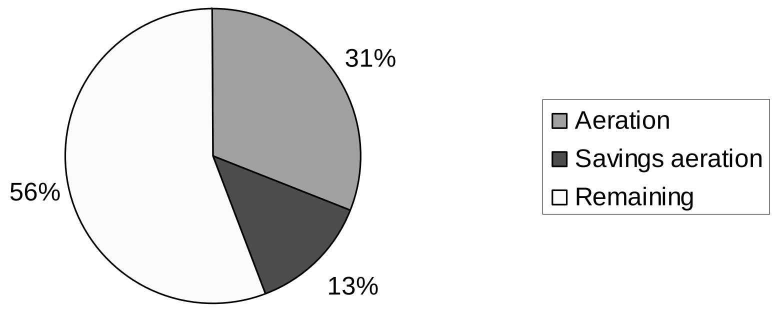

Figure 27 Total energy consumption of Sternö WWTP in October 2011 with upgraded aeration system in the test line.

Figure 28 shows how the total energy consumption would have been distributed if both the test line and the reference line had been upgraded. The graph shows that the aeration would constitute 15 % of the total energy consumption of Sternö WWTP, with aeration savings of 29 % of the total energy consumption (due to aeration savings).

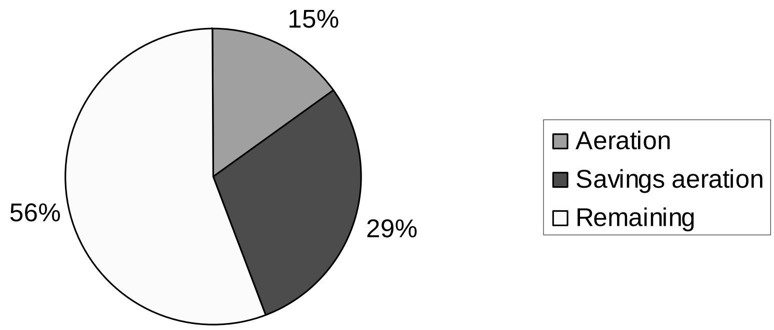

Figure 28 Total energy consumption of Sternö WWTP in October 2011 if both the test line and the reference line would have had upgraded aeration system.

5.3.4 Economic analysis

The weekly savings can be seen in Table 20; both for the actual savings with the test line upgraded and the potential savings if both the test line and the reference line would be upgraded. The savings are lowest for evaluation period 1 and highest for evaluation period 2.

Table 20 Average weekly savings for the three evaluation periods.

Evaluation period	Actual save Test line [SEK $week^{-1}$]	Potential save Both lines [SEK $week^{-1}$]
1	1 800	4 300
2	5 000	10 100
3	4 500	10 000
4	4 700	10 000

The annual savings with the upgraded aeration equipment in the test line would be 200 000 SEK $year^{-1}$, calculated on a total decrease of Sternö WWTP's energy consumption with 13 %. This would lead to a payback period of 3.7 years with the investment cost of 725 000 SEK.

If the aeration equipment would have been upgraded in both the test line and the reference line, the annual savings had been 435 000 SEK $year^{-1}$, calculated on a total decrease of Sternö WWTP's energy consumption of 29 %.
This would lead to a payback period of 2.9 years with the investment cost of 1 227 000 SEK.

5.4 FULL-SCALE TRIALS DISCUSSION

5.4.1 Controllers

The mean DO concentration fluctuated a lot in the test line (as shown in Figure 19) due to a scaling error which made DO high during evaluation period 2. The error was not possible to detect via the SCADA system which made the error difficult to find. During evaluation period 3 and 4, the DO concentrations in the test line were possible to control as desired.

As shown in Figure 20 and Figure 22, the DO control had a low deviation in zone 1 in the test line, except for the high standard deviation during the week around October 29^{th}.
That week the standard deviation was high due to a software malfunction – the controller locked itself to have the valve open at 89 %, which also gave the effect that the MOV-logic increased the air pressure to maximum air pressure. This occurred twice before the problem was solved and during these two periods, DO was almost 5 mg L^{-1} at its highest, compared to set-point 0.7 mg L^{-1}. The reason for the software malfunction was that the ammonium feedback control was recently implemented and this brought an error regarding the deadband of the controller. The error was solved by decreasing the deadband from 1 % to 0 %. Generally, the DO control in zone 1 in the test line had a low deviation and this is probably because of the DO cascade control and the fine tuning that was made. Therefore, the goal of more stable DO control was seen to come true.

It is important to have a low DO deviation since it gives a smoother control, which is better for the valves (since they need to make fewer big changes) and out of an energy perspective since it provides a more stable airflow. A more stable airflow is desirable since the maximum airflow is decreased, which according to the K_La function is better out of an oxygen transfer perspective and therefore also out of an energy perspective.

As shown in Figure 23, the standard deviation of the DO control in zone 2 in the test line was rather high and fluctuating during evaluation period 3. This zone was therefore seen as the problematic zone and one reason for the high standard deviation in zone 2 is probably that there was less load to zone 2 than to zone 1, since some of the load had already been taken care of in zone 1. This created an environment in zone 2 where DO was easily raised since there was not a lot of substrate left. Therefore, air bumping raised DO really fast in zone 2, which was a part of the high standard deviation seen in Figure 23. During the end of evaluation period 3 the time for cleaning was changed from 8:00 to 17:00 in order to decrease the impact on the process since the load was higher in the afternoon than in the morning.

The problem with high DO standard deviation (and during certain periods also with high DO concentration as can be seen in Figure 19) could be solved with a better aeration design. As it is now, the test line is divided into one small basin (11a) and two larger basins (11b and 12) (as can be seen in Figure 14) where the small basin has a mixer installed so that the aeration can be turned off without fulfilling sedimentation. A better alternative could be to use an even smaller aeration area than 11b and 12 – for example by aerating 11a and 11b and installing a mixer in 12. This would lead to a more flexible system where 11a and 11b could be used for aeration during low load and 11b and 12 (or even 11a, 11b and 12) could be used for aeration during high load. The benefit of such a system would be that it would be easier to fulfil the mixing criteria, which means that aeration would never be dictated by mixing criteria, but only by oxygen transfer. This would be more energy efficient and also decrease DO peaks in zone 2.

5.4.2 Treatment performance

The treatment performance between the test line and the reference line (Table 17) was considered to be equal with respect to BOD_5 – both had reduction of 96% to 97% during the whole evaluation period. The effluent concentration of BOD_5 was below 5 mg L^{-1} during all measurement periods, which is well below the restriction of 10 mg L^{-1}.

The treatment performance regarding ammonium was not as good for the test line as for the reference line during evaluation period 1. No explanation has been found for this. The treatment of ammonium was good (99 %) for both treatment lines during evaluation period 2, 3 and 4, when effluent (from secondary clarifier) concentration based on laboratory measurements were constantly below 0.1 mg L^{-1}.

The results from this study are not really comparable with previous aeration control studies mentioned in this thesis. One reason for this is that the load to Sternö WWTP is quite the opposite from other plants, for example as described by Åfeldt (2011) where effluent ammonium sometimes could reach 10 mg L^{-1} in Himmerfjärdsverket WWTP. During evaluation period 2, 3 and 4, ammonium never reached above1 mg L^{-1} in the end of the bio reactor in Sternö WWTP.

Effluent ammonium might increase in Sternö WWTP when temperature decreases during winter time, since the nitrification is highly dependent on temperature. In that case, a scenario similar like that in Himmerfjärdsverket WWTP (with alternately high ammonium concentrations) might occur. If that happens in Sternö WWTP, it will not be the aeration capacity that is limiting for the nitrification capacity, but the temperature.

The ammonium controller could not control effluent ammonium concentration, since the lowest allowed DO set-point (0.7 mg L^{-1}) kept effluent ammonium below the ammonium set-point of 1 mg L^{-1}. Hopefully, the ammonium controller will contribute to decreased effluent concentrations of ammonium in the future, when ammonium concentrations could be higher due to winter conditions and decreased treatment performance.

5.4.3 Energy savings

The energy savings performed in the test line were high and finished at 66 ± 4 % (evaluation period 4). However, the increase in energy savings from period 3 to period 4 is not a result of a better aeration and control system, but rather a coincidence. The savings do not come from the ammonium controller, since the ammonium concentration during evaluation period 4 was well below the set-point of 1.0 mg L^{-1} in the test line. Therefore the ammonium controller chose minimum allowed DO concentration as DO set-point, which practically made it a DO cascade controller during evaluation period 4.

Since evaluation period 4 is only three weeks long, it is thought to be more representative to evaluate period 3 and 4 together as one data series, since they still have the exact same configuration (the same aeration equipment and DO cascade control). The energy savings when evaluation period 3 and 4 were evaluated together as one series were 65 ± 2 %, which are considered to be the final savings made from the new aeration and control system.

I consider the box plot for evaluation period 3 + 4 in Figure 25 to have a negative skew, which is supported by the fact that the median of the distribution (65.5 %) is higher than the average (65.1 %). This adds credibility to the savings performed in evaluation period 3 and 4. Also, the average saving is based on data from more than 10 weeks of measurements.

For evaluation period 1 a new blower and DO cascade control were installed. The DO cascade control was given the same controller parameters as the reference line and therefore it should not have contributed to the energy savings. The energy savings of evaluation period 1 (35 ± 1 %) are therefore believed to come solely from the new blower. The low standard deviation of this period could be related to the few (2) measurement weeks of this period.

The diffuser savings are considered to be the total savings of evaluation period 2 (56 ± 7 %) minus the blower savings. Since this period has a high standard deviation, the diffuser savings are a bit uncertain. The diffusers contributed with 21 percentage points to the total savings, which is an increase of 32 %. This makes the savings from the diffusers almost equal to the savings from the blower (35 %).

The savings from the diffusers do not only come from lowered airflow consumption from a more efficient oxygen transfer, but is also an effect of the lowered air pressure (10 kPa) since the head loss over the diffusers is lower than in the reference line.

The savings from a more efficient DO profile, MOV-logic and controller tuning are considered to be the final savings of evaluation period 3 and 4 (65 ± 2 %) minus the total savings of evaluation period 2. Therefore, these savings account for savings of 9 percentage points, which is an increase of 21 %.

The savings from DO profile, MOV-logic and controller tuning are difficult to categorize, since they were performed simultaneously. Most probably, the MOV-logic and the improved DO profile contribute the most to the savings. The MOV-logic contribution to these energy savings is the lowered air pressure from 60 to 57 kPa. The improved controllers probably mostly bring an increased stability. But the improved controllers could also provide improved aeration efficiency due to a more constant airflow (which could be more energy efficient due to the non-linear oxygen transfer coefficient K_La).

5.4.4 Economic analysis

The energy savings performed in the test line during October decreased the total energy consumption of the WWTP with 13 %. The annual savings of 200 000 SEK gives a payback period of 3.7 years, which is considered to be relatively short with respect to the investment. To determine the lifetime of aeration equipment is difficult, but it is not unreasonable to presume that it is at least 10 years. This would provide large savings after the payback period and also perform a decreased environmental footprint of the WWTP. But one should also keep in mind that service and maintenance generally increases when the equipment gets older.

If the equipment would be upgraded in both the test line and the reference line, the payback period would decrease from 3.7 years to 2.9 years. The reason for this is that there is some equipment that could be used for both treatment lines, for example blower control and aeration control.

The payback period is also affected by load; the reference line generally has a higher load than the test line (due to a higher flow and sometimes also higher concentrations). This higher load gives a larger aeration demand and with the same percentage of energy savings in the reference line as in the test line, the actual kWh savings are greater from the reference line than from the test line. Therefore, the reference line will probably pay off faster than the test line.

6 CONCLUSIONS

The simulation study showed that the DO profile needs to be adjusted over the year to preserve treatment results. This could be made either with DO control that is manually adjusted, or with ammonium control. The energy efficiency of the two control strategies were about the same when the DO profile was well adjusted.

With ammonium control, the energy consumption decreases with lowered maximum allowed DO set-point, but this also made it more difficult to fulfil effluent requirements. The simulation was especially useful in order to make a first tuning of the full-scale implemented ammonium controller, which was difficult to tune in field due to disturbances and a long response time.

The full-scale trials showed that 65 ± 2 % of the aeration energy for the test line was saved thanks to a new blower (35 percentage points), new diffusers (21 percentage points) and a new aeration control with decreased air pressure (9 percentage points).

Each aeration equipment upgrade increased the energy savings with:

- Blower 35 %.
- Diffusers 32 %.
- New aeration control with decreased air pressure 21 %.

Ammonium control did not contribute to keep effluent concentration of ammonium or decrease energy consumption during this master thesis. The reason for this was that the WWTP was low loaded with respect to its treatment performance and the lowest allowed DO set-point (0.7 mg L^{-1}) kept effluent ammonium below the ammonium set-point of 1 mg L^{-1}.

DO cascade control was more stable than regular DO control, which was determined through calculating the DO standard deviation of each zone. To achieve a low deviation, good tuning and a good aeration design is also needed.

Aeration could be made more efficient in Sternö WWTP if a mixer would be installed in the last aerated basin since this would secure that aeration is always dictated by oxygen transfer and not mixing. As it is today, the air flow to the last zone in the test line is sometimes at lowest allowed level, which is determined by the mixing criteria. During these occasions, too much aeration is performed with respect to oxygen transfer.

The payback period for the implemented aeration system was calculated to 3.7 years. The energy savings of the new aeration equipment decreased the total energy consumption of the plant with 13 %, which correspond to annual savings of 200 000 SEK.

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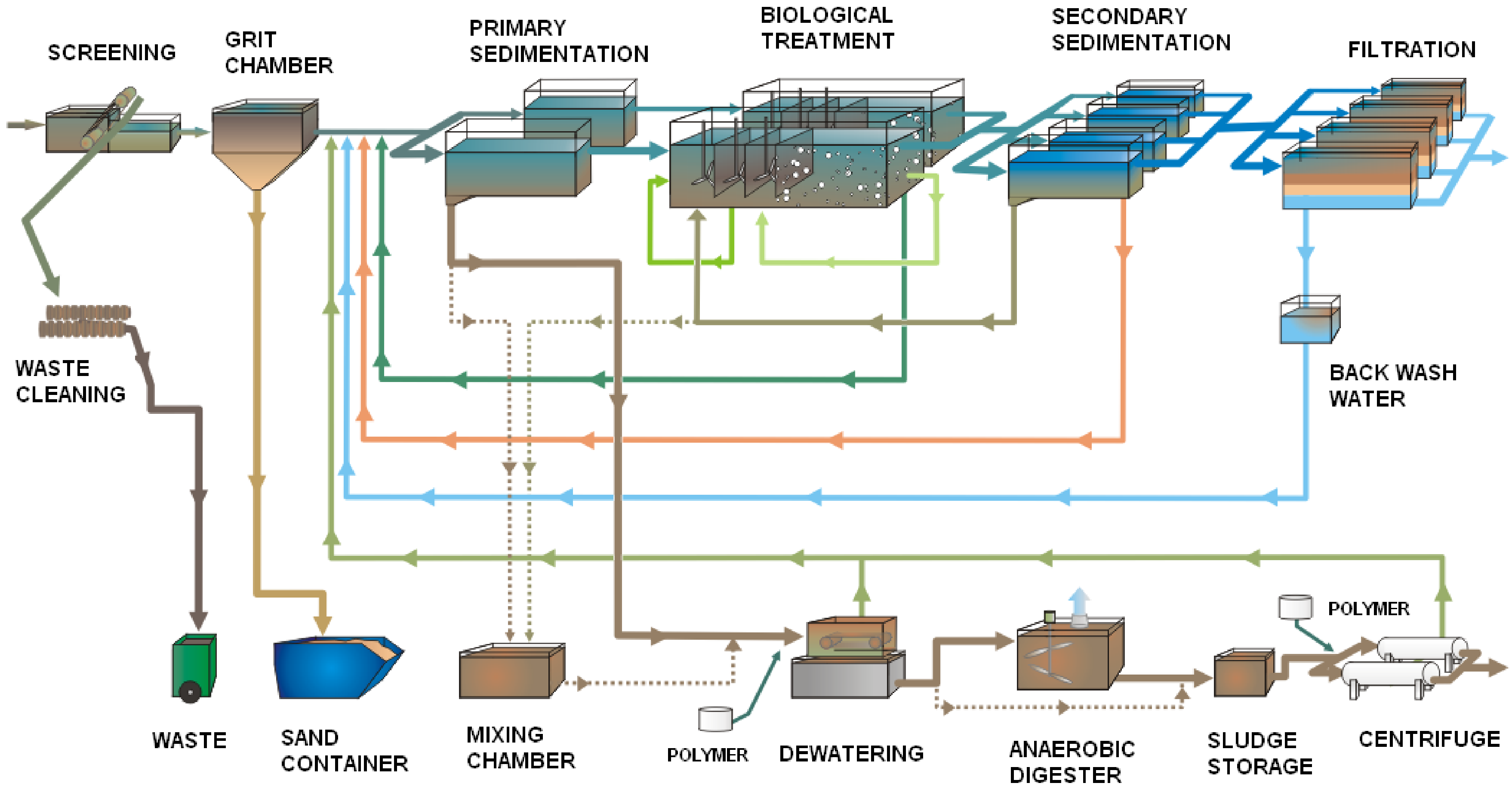
APPENDIX 1

Sternö WWTP layout (translated to English). Source: Miljörapport 2011, Karlshamns kommun.



APPENDIX 2

Input data for the test line and the reference line. Shaded area means that appreciated values were used.

Test line

Evaluation period	Date	Incoming BOD_7 [mg L^{-1}]	Incoming BOD_7 [kg d^{-1}]	Outgoing BOD_7 [mg L^{-1}]	Incoming NH_4-N [mg L^{-1}]	Incoming NH_4-N [kg d^{-1}]	Outgoing NH_4-N [mg L^{-1}]	Q-L2 [m^3 d^{-1}]	T (ave) [°C]	DO,field [mg L^{-1}]	W [kWh day^{-1}]	Airflow [Nm^3 day^{-1}]
P1	6-13 / 4	130	607	4.1	22	103	7.6	4671	9.2	1.13	421	13946
	15-20 / 4	100	422	4.8	18	76	4.1	4222	10.1	1.04	432	14064
P2	6-13 / 7	120	414	4.0	16	55	0.1	3449	17.9	1.11	578	20172
	13-20 / 7	150	619	4.0	13	54	0.1	4124	18.3	2.41	661	24735
	20-27 / 7	140	538	4.0	15	58	0.1	3842	18.8	2.67	614	21630
	27/7 - 3/8	84	367	4.0	11	48	0.1	4365	18.6	2.13	441	16532
	3/8 - 10/8	85	379	3.0	11	49	0.1	4459	18.8	2.40	465	15592
	10/8 - 17/8	110	472	3.0	9.9	43	0.1	4295			425	14400
	17/8 - 24/8	130	492	3.0	12	45	0.1	3784	18.7	2.22	461	15845
	24/8 - 31/8	120	452	3.0	12	45	0.1	3766	18.8	2.58	435	16060
	31/8 - 7/9	140	554	3.0	13	51	0.1	3960	18.4	1.55	357	13239
P3	7/9 - 14/9	84	389	3.0	11	51	0.1	4635	17.7	0.95	313	11125
	14/9 - 21/9	65	348	3.0	11	59	0.1	5352	17.4	0.94	307	11014
	21/9 - 28/9	73	344	3.0	11	52	0.1	4718	16.9	0.91	314	11410
	28/9 - 5/10	110	454	3.0	13	54	0.1	4124	17.1	0.89	320	11835
	5/10 - 12/10	92	388	3.0	12	51	0.1	4212	16.2	0.93	334	12340
	12/10 - 19/10	72	302	3.6	11	46	0.1	4189	14.9	1.04	300	11196
	19/10-26/10	85	326	3.1	12	46	0.1	3836	14.6	0.88	293	11195
P4	26/10-2/11	110	439	3.3	12	48	0.1	3989	14.5	0.99	288	11141
	2/11-9/11	100	379	4.5	13	49	0.1	3789	14.3	0.84	312	12255
	9/11-16/11	110	395	4.4	13	47	0.1	3590	13.8	0.85	314	12532
	16/11-23/11				11	39	0.1	3531	13.4	0.84	322	12843

Reference line

Evaluation period	Date	Incoming BOD$_7$ [mg L^{-1}]	Incoming BOD$_7$ [kg d^{-1}]	Outgoing BOD$_7$ [mg L^{-1}]	Incoming NH$_4$-N [mg L^{-1}]	Incoming NH$_4$-N [kg d^{-1}]	Outgoing NH$_4$-N [mg L^{-1}]	Q-L2 [m^3 d^{-1}]	T (ave) [^{o}C]	DO,field [mg L^{-1}]	W [kWh day^{-1}]	Airflow [Nm^3 day^{-1}]
P1	6-13 / 4	170	895	4.6	19	100	4	5267	9.1	1.20	895	
	15-20 / 4	140	667	4.7	14	67	0.5	4761	10.0	1.20	935	20245
P2	6-13 / 7	130	506	4.0	15	58	0.1	3889	17.7	1.06	1305	25954
	13-20 / 7	100	465	4.0	14	65	0.1	4651	18.4	1.10	1328	26423
	20-27 / 7	160	693	4.0	17	74	0.1	4333	18.9	1.07	1318	26053
	27/7 - 3/8	98	482	4.0	11	54	0.1	4923	18.7	0.99	1088	22254
	3/8 - 10/8	110	553	3.0	10	50	0.1	5029	18.8	0.99	1026	20319
	10/8 - 17/8	98	475	3.0	10	48	0.1	4843			949	18641
	17/8 - 24/8	130	555	3.0	12	51	0.1	4267	18.7	1.11	1007	20015
	24/8 - 31/8	120	510	3.0	12	51	0.1	4247	18.9	1.21	1103	21410
	31/8 - 7/9	130	580	3.0	13	58	0.1	4465	18.5	1.26	1086	20625
P3	7/9 - 14/9	86	450	3.0	12	63	0.1	5227	17.8	1.29	1129	21077
	14/9 - 21/9	77	465	3.0	12	72	0.1	6035	17.2	1.30	1092	20053
	21/9 - 28/9	86	458	3.0	11	59	0.1	5320	17.1	1.31	1099	20385
	28/9 - 5/10	100	465	3.0	13	60	0.1	4651	17.2	1.30	1059	20237
	5/10 - 12/10	87	413	3.0	12	57	0.1	4750	16.3	1.31	1123	20254
	12/10 - 19/10	86	406	3.0	11	52	0.1	4724	15.1	1.31	1044	18412
	19/10-26/10	89	385	3.0	12	52	0.1	4326	14.8	1.31	1030	19251
P4	26/10-2/11	90	405	3.3	12	54	0.1	4498	14.7	1.29	975	18793
	2/11-9/11	98	419	3.3	13	56	0.1	4273	14.4	1.31	1056	20484
	9/11-16/11	110	445	3.6	14	57	0.1	4048	14.0	1.31	1031	19592
	16/11-23/11				12	48	0.1	3982	13.5	1.31	1032	19085

APPENDIX 3

Output data for the test line and the reference line.

Test line

Evaluation period	Date	BOD_5-red [kg day^{-1}]	BOD_5-red [%]	NH_4-red [kg day^{-1}]	NH_4-red [%]	AOR [kg O_2 day^{-1}]	OTR,f [kg O_2 day^{-1}]	SOTR [kg O_2 day^{-1}]	SOTE [%]	SAE [kg O_2 kWh^{-1}]
P1	6-13 / 4	511.4	96.8	67.3	65.5	921.0	926.3	1660.5		3.9
	15-20 / 4	349.5	95.2	58.7	77.2	687.6	692.0	1235.2		2.9
P2	6-13 / 7	347.9	96.7	54.8	99.4	668.1	671.9	1210.4	20.2	2.1
	13-20 / 7	523.6	97.3	53.2	99.2	871.5	881.4	1804.4	24.6	2.7
	20-27 / 7	454.4	97.1	57.2	99.3	806.9	817.2	1721.5	26.8	2.8
	27/7 - 3/8	303.7	95.2	47.6	99.1	581.9	591.2	1175.4	24.0	2.7
	3/8 - 10/8	318.0	96.5	48.6	99.1	603.7	614.4	1257.1	27.2	2.7
	10/8 - 17/8	399.6	97.3	42.1	99.0	671.9	671.9			
	17/8 - 24/8	417.8	97.7	45.0	99.2	707.2	715.6	1436.5	30.6	3.1
	24/8 - 31/8	383.2	97.5	44.8	99.2	664.6	674.3	1406.5	29.5	3.2
	31/8 - 7/9	471.7	97.9	51.1	99.2	799.5	805.6	1512.5	38.5	4.2
P3	7/9 - 14/9	326.5	96.4	50.5	99.1	622.7	627.1	1114.3	33.8	3.6
	14/9 - 21/9	288.5	95.4	58.3	99.1	612.9	617.9	1096.6	33.6	3.6
	21/9 - 28/9	287.2	95.9	51.4	99.1	579.6	583.9	1033.8	30.5	3.3
	28/9 - 5/10	383.7	97.3	53.2	99.2	703.6	707.3	1250.0	35.6	3.9
	5/10 - 12/10	326.0	96.7	50.1	99.2	620.3	624.2	1107.7	30.3	3.3
	12/10 - 19/10	249.1	95.0	45.7	99.1	507.6	512.0	917.5	27.6	3.1
	19/10-26/10	273.2	96.4	45.7	99.2	536.5	539.9	954.6	28.7	3.3
P4	26/10-2/11	370.1	97.0	47.5	99.2	661.1	665.0	1186.9	35.9	4.1
	2/11-9/11	314.7	95.5	48.9	99.2	601.0	604.2	1064.8	29.3	3.4
	9/11-16/11	329.6	96.0	46.3	99.2	607.2	610.2	1076.4	28.9	3.4

Reference line

Evaluation period	Date	BOD_5-red [kg day^{-1}]	BOD_5-red [%]	NH_4-red [kg day^{-1}]	NH_4-red [%]	AOR [kg O_2 day^{-1}]	OTR,f [kg O_2 day^{-1}]	SOTR [kg O_2 day^{-1}]	SOTE [%]	SAE [kg O_2 kWh^{-1}]
P1	6-13 / 4	757.6	97.3	79.0	78.9	1270.1	1276.4	2299.4		2.6
	15-20 / 4	560.1	96.6	64.3	96.4	965.9	971.6	1753.9		1.9
P2	6-13 / 7	426.1	96.9	57.9	99.3	776.2	780.3	1399.5	18.2	1.1
	13-20 / 7	388.2	96.0	64.6	99.3	761.3	766.4	1379.4	17.6	1.0
	20-27 / 7	587.7	97.5	73.2	99.4	1039.9	1044.6	1874.1	24.2	1.4
	27/7 - 3/8	402.4	95.9	53.7	99.1	728.1	732.9	1305.3	19.8	1.2
	3/8 - 10/8	467.9	97.3	49.8	99.0	789.0	793.9	1413.6	23.4	1.4
	10/8 - 17/8	400.1	96.9	47.9	99.0	699.2	699.2			
	17/8 - 24/8	471.2	97.7	50.8	99.2	797.4	802.2	1444.3	24.3	1.4
	24/8 - 31/8	432.1	97.5	50.5	99.2	749.4	754.6	1371.3	21.6	1.2
	31/8 - 7/9	493.1	97.7	57.6	99.2	855.0	860.6	1571.7	25.7	1.4
P3	7/9 - 14/9	377.3	96.5	62.2	99.2	737.0	743.7	1362.1	21.8	1.2
	14/9 - 21/9	388.4	96.1	71.8	99.2	794.3	802.1	1470.6	24.7	1.3
	21/9 - 28/9	384	96.5	58.0	99.1	725.7	732.7	1345.5	22.2	1.2
	28/9 - 5/10	392	97.0	60.0	99.2	744.9	750.9	1376.7	22.9	1.3
	5/10 - 12/10	347	96.6	56.5	99.2	674.7	680.9	1250.2	20.8	1.1
	12/10 - 19/10	341	96.5	51.5	99.1	644.4	650.6	1194.0	21.9	1.1
	19/10-26/10	324	96.6	51.5	99.2	623.5	629.2	1154.5	20.2	1.1
P4	26/10-2/11	339	96.3	53.5	99.2	651.6	657.4	1203.3	21.6	1.2
	2/11-9/11	352	96.6	55.1	99.2	674.2	679.8	1246.3	20.5	1.2
	9/11-16/11	375	96.7	56.3	99.3	706.6	711.9	1305.3	22.5	1.3

APPENDIX 4

Savings for each measurement week. *Actual savings* is the savings performed in the test line and *potential savings* are the savings if both test and reference line would have been upgraded.

Evaluation period	Date	Energy savings [%]	Energy savings [kWh week^{-1}]	Actual savings [SEK week^{-1}]	Potential savings [SEK week^{-1}]	Airflow savings [%]
P1	6-13 / 4	34.9	1577	1770	4221	
	15-20 / 4	34.3	1581	1774	4293	
P2	6-13 / 7	48.8	3855	4325	9325	10.1
	13-20 / 7	62.0	7532	8450	14911	28.4
	20-27 / 7	49.3	4174	4683	9781	9.6
	27/7 - 3/8	55.0	3774	4234	8935	17.5
	3/8 - 10/8	49.0	3132	3514	7465	13.7
	10/8 - 17/8					
	17/8 - 24/8	54.0	3784	4245	8514	20.4
	24/8 - 31/8	61.6	4875	5469	10801	26.9
	31/8 - 7/9	65.9	4820	5407	11026	33.3
P3	7/9 - 14/9	66.1	4275	4797	10660	35.5
	14/9 - 21/9	62.3	3551	3984	9327	26.3
	21/9 - 28/9	62.8	3708	4161	9575	27.2
	28/9 - 5/10	66.7	4491	5039	10588	35.6
	5/10 - 12/10	66.4	4623	5187	11042	31.2
	12/10 - 19/10	62.6	3514	3942	9072	20.9
	19/10-26/10	65.7	3915	4392	9705	29.7
P4	26/10-2/11	70.1	4716	5291	10655	39.9
	2/11-9/11	65.4	4130	4633	10057	30.0
	9/11-16/11	63.0	3751	4208	9311	22.4