CHALMERS

Aeration Control of Activated Sludge Basins

Master's Thesis in Automatic Control

ANDREAS SANDBERG

Department of Signals & Systems
Systems, Control & Mechatronics
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Abstract

The aeration of activated sludge basins is expensive. In this thesis, a model of the activated sludge basins at Gryaab's wastewater treatment plant, Ryaverket in Gothenburg, Sweden, is created for the purpose of simulating different control strategies. The main effluent pollutant investigated are nitrate and nitrite, NO, and biological oxygen demand, BOD. Optimizations are preformed to find better control strategies for the aeration than the currently used strategy. Results show that there is a large potential in reducing both costs and effluent concentrations through simple change of operations. The recommended new control strategy suggested is to aerate 60 % with set points below half the currently used set points.

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1

Introduction

Wastewater treatment plants (WWTP) has more and harder regulations on their effluent today than ever before. Two of these regulations concern the concentration of nitrogen and biochemical oxygen demand (BOD). The consequence of the regulation on nitrogen can, in this work, be translated to reduction demands on nitrate and nitrite (NO). By adding an external carbon source to the wastewater more NO can be removed, this is expensive and less carbon added is therefore preferred. To remove as much biodegradable hydrocarbons (BOD) as possible, the wastewater is aerated. This, however, is also expensive and therefore a strategy for controlling this aeration is studied in this thesis. BOD can be used as carbon source for the removal of NO if there is no oxygen in the wastewater. The capacity to remove NO is higher when a smaller volume of the basin is aerated. On the other hand BOD is better removed by aerating a larger part of the basins. A control strategy that aerates the basins in a more cost effective way is investigated. The plant studied in this work is Gryaab's plant Ryaverket in Göteborg, Sweden.

2

The Plant

2.1 Description

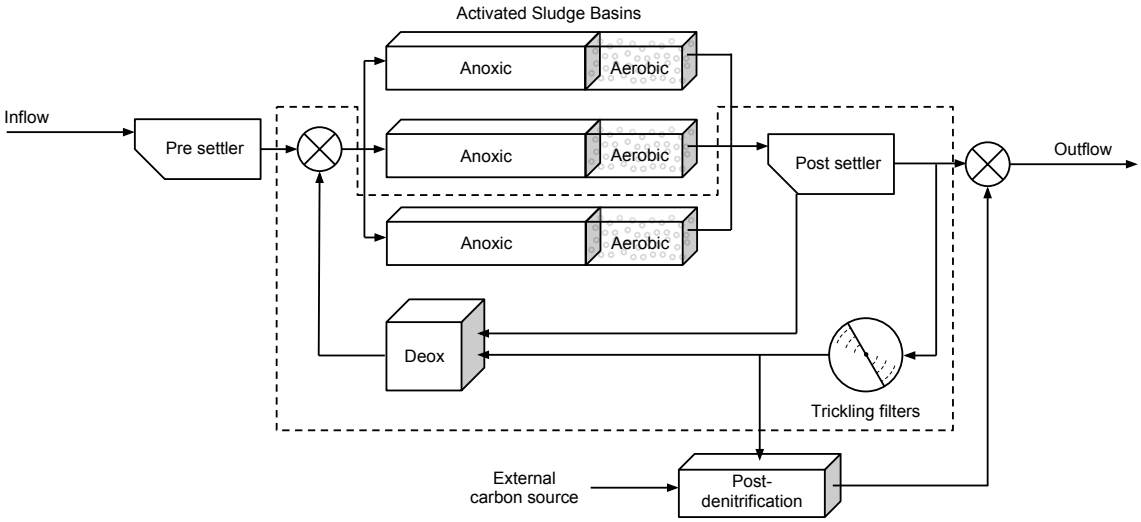

Figure 2.1: The plant investigated.

The wastewater treatment at Ryaverket, which is illustrated in Figure 2.1, is roughly divided into three parts; mechanical, biological and chemical. The mechanical part applies filtering in the beginning of the process which removes trash and paper, and finer filters are also used at the end of the process where small particles are removed. In the chemical part of the process, iron sulfate is added to the wastewater to obtain a precipitation of phosphorus that can be removed through sedimentation.

In the biological part, bacteria decomposes organic materials and releases the nutrient

nitrogen from the wastewater. Ryaverket has three parallel lines of activated sludge basins. In the basins, bacteria decomposes organic matter in two different parts. In the first part of the basins, the anoxic part, no air is added, and when oxygen is lacking nitrate and nitrite is used in the degradation, which has the effect that they are converted into nitrogen gas. In the second part, the aerobic part, the basin is aerated and the bacteria uses oxygen instead to decompose the organic matter.

After the activated sludge basins, the wastewater is sedimented to remove the sludge. About half of the settled wastewater is sent to the last filtering process before it leaves the plant, and the other half goes through trickling filters where ammonium is nitrified. One part of the nitrified wastewater goes to basins for post denitrification, where a carbon source is added to remove the remaining nitrate. The rest of the flow, along with some of the sludge from the sedimentation, is deoxidized and mixed with the influent to the activated sludge basins [1].

2.1.1 Activated sludge basins

The three parallel lines of activated sludge basins have the same layout. The first 40 % of the basins is not aerated, the last 40 % is always aerated and the 20 % in the middle of the basins can be either aerated or not aerated.

In the basins, heterotrophic bacteria grows by using oxygen and organic carbon to make biomass and energy.

The bacteria behave differently if there is oxygen present (aerobic), nitrate present (anoxic) or neither oxygen nor nitrate present (anaerobic). When the wastewater is aerobic the bacteria prefer to use oxygen rather than nitrate, but if the conditions are anoxic the bacteria grow utilizing the oxygen in the nitrite and nitrate. When neither oxygen nor nitrate or nitrite is present the growth of the bacteria is stalled [2].

2.1.2 Nitrification and denitrification

The conversion of ammonia into nitrate is a two step procedure. Both steps are done by autotrophic bacteria but of different species. The first step, to oxidize ammonia into nitrite, is

$$NH_4^+ + 1.5O_2 \rightarrow NO_2^- + H_2O + 2H^+ \tag{2.1}$$

and the second step that convert nitrite into nitrate is

$$NO_2^- + 0.5O_2 \rightarrow NO_3^-. \tag{2.2}$$

These two steps are mainly taking place in the trickling filters after the activated sludge basins. Then some of the nitrified wastewater is mixed with the influent to the activated sludge basins, and some goes through the post-denitrification basins. In the post-denitrification basins, a source of carbon has to be added because the easily biodegradable compounds needed there have been removed earlier in the process.

Denitrification is when nitrate is transformed into nitrogen gas. This occurs when the conditions are anoxic and the heterotrophic bacteria use nitrate instead of oxygen to decompose the biodegradable compounds giving an approximate stochiometry for nitrogen

$$4NO_3^- + 2H_2O \rightarrow 2N_2 + 5O_2 + 4OH^-. \tag{2.3}$$

This is done in the anoxic part of the activated sludge basins [3]. Note that all stoichiometric expressions presented are simplified and only contains the components relevant here.

2.2 Plant model

To be able to simulate different control strategies for the aeration and get a deeper understanding of the process, a model of the activated sludge basins was developed in Simulink/Matlab.

The model is limited to the activated sludge basins, the deox basins, the post-settler and the trickling filters, as illustrated inside the dashed line in Figure 2.1.

A lithium trace study has shown that each of the three lines can be modelled as eight perfectly mixed tanks connected in series, as shown in Figure 2.2 [4].

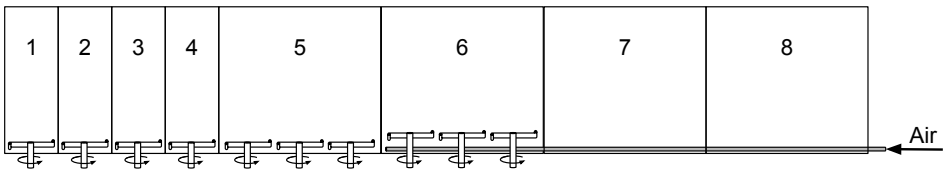

Figure 2.2: Tanks 1-5 are stirred but not aerated (anoxic), tank 6 is stirred and can be aerated and tanks 7-8 are not stirred and always aerated (aerobic).

The activated sludge basins is one of many parts of the wastewater treatment plant. As can be seen in Figure 2.1, there are more processes included in the same loop as the wastewater that passes through the basins. To achieve a complete feedback loop the trickling filters and secondary sedimentation are implemented as ideal components, that is, all ammonia is converted to nitrate in the trickling filters, as in equations (2.1) and (2.2), and all particles are removed in the post-settler.

2.2.1 Mantis

To describe the chemical processes in the activated sludge process a mathematical model is used.

In a project called Morya 2010, the complete plant at Ryaverket was modelled in an application called GPS-X from Hydromantis, Inc. The mathematical model used in GPS-X is called Mantis and is a further development of the Activated Sludge Model No.

Table 2.1: Arrhenius coefficients for the kinetic parameters.

θ_{μ_H}	1.050
θ_{μ_A}	1.123
θ_{k_H}	1.072
θ_{k_A}	1.029
θ_{b_H}	1.029
θ_{b_A}	1.072

1 (ASM1)[4] [2].

Mantis and ASM1 are identical except for three improvements in the Mantis model:

1. Additional growth processes are introduced for the autotrophic and the heterotrophic organisms. The organisms can use nitrate as a nutrient source under conditions of low ammonia and high nitrate.
2. The kinetic parameters are temperature dependent. An Arrhenius equation is used to describe the temperature dependence of some of the kinetic parameters. For the maximum specific growth rate of heterotrophs, μ_H, the equation is

$$\mu_H = \mu_{H,20\,^\circ\mathrm{C}} \cdot \theta_{\mu_H}^{(T-20\,^\circ\mathrm{C})}, \tag{2.4}$$

   where $\mu_{H,20\,^\circ\mathrm{C}}$ is μ_H at 20 °C, θ_{μ_H} is the temperature coefficient for μ_H, and T is the temperature. The Arrhenius coefficients used in the model are listed in Table 2.1.

3. Denitrification in aerobic processes.

Mantis is described by the Petersen matrix in Table 2.2. The matrix contains fourteen components and ten processes.

Table 2.2: Petersen matrix for Mantis

Component	i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Process rate, ρ_j
		S_I	S_S	X_I	X_S	X_{BH}	X_{BA}	X_U	X_{ND}	S_O	S_{NO}	S_{NN}	S_{NH}	S_{ND}	S_{ALK}	
j	Process															
1	Aerobic growth of heterotrophs on ss with sub		$\frac{-1}{Y_H}$			1				$\frac{-(1-Y_H)}{Y_H}$			$-ibhn$		$\frac{-ibhn}{14}$	$\mu_H\left(\frac{S_S}{K_{SH}+S_S}\right)\left(\frac{S_O}{K_{OH}+S_O}\right)\left(\frac{S_{NH}}{K_{NH}+S_{NH}}\right)\left(\frac{S_{ALK}}{K_{ALK}+S_{ALK}}\right)X_{BH}$
2	Anoxic growth of heterotrophs on ss with sub		$\frac{-1}{Y_H}$			1					$\frac{-(1-Y_H)}{2.86Y_H}$	$\frac{(1-Y_H)}{2.86Y_H}$	$-ibhn$		$\frac{-ibhn}{14}+\frac{(1-Y_H)}{14\cdot 2.86Y_H}$	$\eta_g\cdot\mu_H\left(\frac{S_S}{K_{SH}+S_S}\right)\left(\frac{K_{AD}}{K_{AD}+S_O}\right)\left(\frac{S_{NH}}{K_{NH}+S_{NH}}\right)\left(\frac{S_{NO}}{K_{NO}+S_{NO}}\right)\left(\frac{S_{ALK}}{K_{ALK}+S_{ALK}}\right)X_{BH}$
3	Aerobic growth of heterotrophs on ss with sub		$\frac{-1}{Y_H}$			1				$\frac{-(1-Y_H)}{Y_H}$	$-ibhn$				$\frac{-ibhn}{14}$	$\mu_H\left(\frac{S_S}{K_{SH}+S_S}\right)\left(\frac{S_O}{K_{OH}+S_O}\right)\left(\frac{K_{NH}}{K_{NH}+S_{NH}}\right)\left(\frac{S_{NO}}{K_{NO}+S_{NO}}\right)\left(\frac{S_{ALK}}{K_{ALK}+S_{ALK}}\right)X_{BH}$
4	Anoxic growth of heterotrophs on ss with sub		$\frac{-1}{Y_H}$			1					$-ibhn-\frac{(1-Y_H)}{2.86Y_H}$	$\frac{(1-Y_H)}{2.86Y_H}$			$\frac{-ibhn}{14}+\frac{(1-Y_H)}{14\cdot 2.86Y_H}$	$\eta_g\cdot\mu_H\left(\frac{S_S}{K_{SH}+S_S}\right)\left(\frac{K_{AD}}{K_{AD}+S_O}\right)\left(\frac{K_{NH}}{K_{NH}+S_{NH}}\right)\left(\frac{S_{NO}}{K_{NO}+S_{NO}}\right)\left(\frac{S_{ALK}}{K_{ALK}+S_{ALK}}\right)X_{BH}$
5	Decay of heterotrophs			$1-fuh$	-1			fuh	$ibhn$ $-fuh\cdot iuhn$							$b_H\cdot X_{BH}$
6	Hydrolysis of entrapped organics		1		-1											$k_H\left(\frac{X_S/X_{BH}}{K_X+X_S/X_{BH}}\right)\left(\left(\frac{S_O}{K_{OH}+S_O}\right)+\eta_h\left(\frac{K_{OH}}{K_{OH}+S_O}\right)\left(\frac{S_{NO}}{K_{NO}+S_{NO}}\right)\right)X_{BH}$
7	Hydrolysis of entrapped organic nitrogen								-1					1		$r_6\cdot\left(\frac{X_{ND}}{X_S}\right)$
8	Ammonification of soluble organic nitrogen												1	-1	1/14	$k_A\cdot S_{ND}\cdot X_{BH}$
9	Growth of autotrophs						1			$\frac{-(4.57-Y_A)}{Y_A}$	$\frac{1}{Y_A}$		$-iban-\frac{1}{Y_A}$		$\frac{-iban}{14}-\frac{1}{Y_A\cdot 7}$	$\mu_A\left(\frac{S_{NH}}{K_{NH}+S_{NH}}\right)\left(\frac{S_O}{K_{OA}+S_O}\right)\left(\frac{S_{ALK}}{K_{ALKA}+S_{ALK}}\right)X_{BA}$
10	Decay of autotrophs				$1-fua$		-1	fua	$iban$ $-fua\cdot iuan$							$b_a\cdot X_{BA}$
		Soluble inert organics ($gCODm^{-3}$)	Readily biodegradable soluble substrate ($gCODm^{-3}$)	Particulate inert organics ($gCODm^{-3}$)	Slowly biodegradable particulate substrate ($gCODm^{-3}$)	Active heterotrophic biomass ($gCODm^{-3}$)	Active autotrophic biomass ($gCODm^{-3}$)	Unbiodegradable particulates from cell decay ($gCODm^{-3}$)	Particulate biodegradable organic nitrogen (gNm^{-3})	Oxygen ($g(-COD)m^{-3}$)	Nitrate and nitrite nitrogen (gNm^{-3})	Dinitrogen (gNm^{-3})	Ammonia nitrogen (gNm^{-3})	Soluble biodegradable organic nitrogen (gNm^{-3})	Alkalinity ($molem^{-3}$)	

The mass balance for a specific component within a system is

$$Accumulation = Inflow - Outflow + Reaction, \tag{2.5}$$

where the reaction rate, r, for a component, i, is obtained by summing the products of the coefficients ν_{ij} and the process rates ρ_j over j, i.e.

$$r_i = \sum_j \nu_{ij}\rho_j. \tag{2.6}$$

For example, the reaction rate for active autotrophic biomass, X_{BA}, is

$$r_{X_{BA}} = \mu_A \left(\frac{S_{NH}}{K_{NH}+S_{NH}}\right)\left(\frac{S_{NH}}{K_{NA}+S_{NH}}\right)\left(\frac{S_O}{K_{OA}+S_O}\right)\left(\frac{S_{ALK}}{K_{ALKA}+S_{ALK}}\right)X_{BA} - b_a \cdot X_{BA}. \tag{2.7}$$

In a perfectly mixed tank the dynamic behaviour of the active autotrophic biomass becomes

$$V \cdot \frac{dX_{BA}}{dt} = Q \cdot (X_{BA,In} - X_{BA}) + V \cdot r_{X_{BA}}, \tag{2.8}$$

where V is the tank volume, Q is the flow through the tank and $X_{BA,In}$ is the incoming concentration of the biomass. By applying (2.8) to each component in the Petersen matrix and every tank, a model of the complete activated sludge process is achieved.

Since some of the tanks are aerated an additional term is added to the dynamic behaviour of dissolved oxygen, S_O. The oxygen that is transferred from the air bubbles into the water is determined by

$$V \cdot K_L \cdot a \cdot (S_{O,Sat} - S_O), \tag{2.9}$$

where K_L is the transfer coefficient for oxygen into the water, a is the ratio of bubble area to water volume, $S_{O,Sat}$ is the saturation concentration for the dissolved oxygen and S_O is the dissolved oxygen concentration. Here, $S_{O,Sat}$ is temperature dependent as given by Wik [5] as

$$S_{O,Sat} = 14.53 - 0.411T + 9.6 \cdot 10^{-3}T^2 - 1.2 \cdot 10^{-4}T^3 \ \ \mathrm{gO_2/m^3}. \tag{2.10}$$

The transfer coefficient for oxygen into the water, K_La, is described by

$$K_La = k_1(1 - e^{-k_2 \cdot q_{O_2}}), \tag{2.11}$$

where q_{O_2} is the airflow and k_1 and k_2 have been estimated for Ryaverket to the values in Table 2.3 by Hedegärd and Wik [6].

Table 2.3: Estimated parameters for $K_L a$.

	Tank 6	Tank 7	Tank 8
k_1	391	326	163
k_2	$1.58 \cdot 10^{-4}$	$1.90 \cdot 10^{-4}$	$3.80 \cdot 10^{-4}$

2.2.2 Simulink

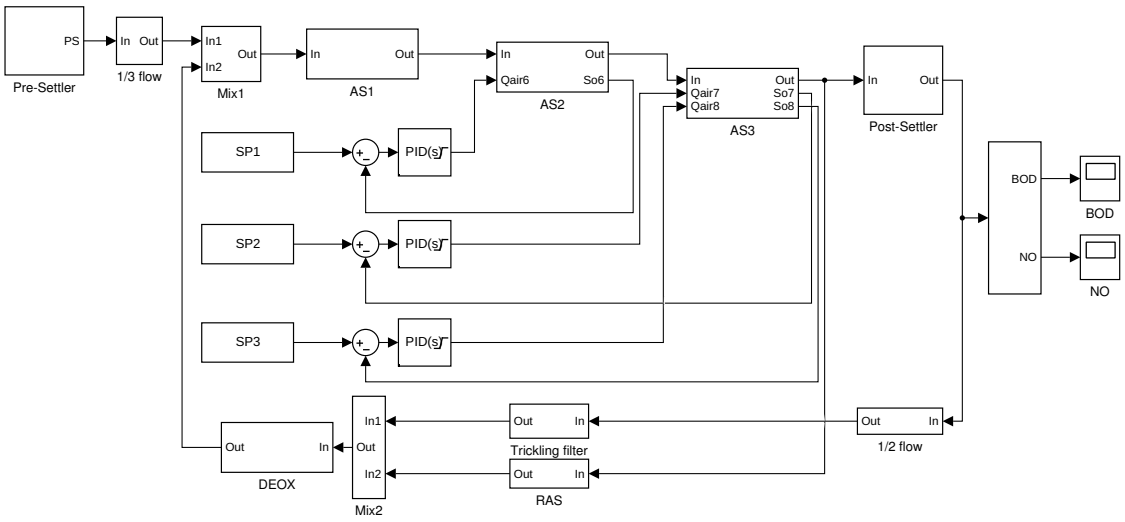

Figure 2.3: Simulink model

The model of Ryaverket was implemented in Simulink (see Figure 2.3). The influent to the model is the wastewater that comes from the pre-settler. To represent the wastewater, the components in the Petersen matrix as well as the temperature and flow rate are used as variables passed between the blocks. The influent is mixed with the recirculated wastewater from the deox tanks. Then the wastewater goes through the activated sludge basins and further to the post-settler. Half of the settled wastewater is transported to the effluent and the other half passes the trickling filters. After the trickling filters one part of the wastewater goes to the post-denitrification and the other part gets mixed

with the recycled sludge from the post-settler into the deox tanks.

The Mantis model was written as a C-file and implemented as a system-function (S-function) in Simulink. One S-function block represents one perfectly mixed tank in the activated sludge basin as seen in Figure 2.2. As state variables and input/output to the S-function the components in the Petersen matrix in Table 2.2, the flow rate, airflow rate and the temperature are used. The states of the S-function are the components in the Petersen matrix, and the change in each component is calculated using the process rate and coefficients as in Equations 2.7 and 2.8.

The three parts of the activated sludge basins, i.e. anoxic, mixed and aerobic, are in the blocks AS1, AS2 and AS3 in Figure 2.3. The aerobic part is shown in Figure 2.4.

Tanks 1-4, in Figure 2.2, are implemented in AS1, tanks 5 and 6 in AS2 and tanks 7 and 8 in AS3.

The deoxidation tanks is modelled as ten reaction tanks connected in series. These tanks effectively removes all S_O from the wastewater.

A very simple model of the trickling filters is used. The model simply converts all ammonia nitrogen (S_{NH}) to nitrate and nitrite nitrogen (S_{NO}).

The post-settler is also modelled as ideal, removing all suspended solids.

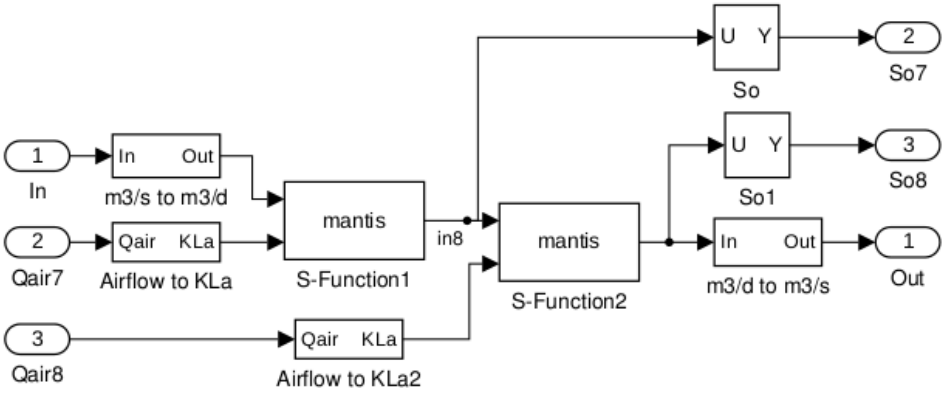

Figure 2.4: Simulink model of two aerated tanks (AS3).

The components used in the model are listed in Table 2.4, the composite variables in Table 2.5. the stoichiometric parameters in Table 2.6 and the kinetic parameters in Table 2.7. All values for the different parameters are from the Morya 2010 project [4].

To verify the model, simulations where executed with identical inputs as the GPS-X model used in the Morya 2010 project. The output, were nearly identical.

2.2.3 The influent

A two month summer period measurement series from Ryaverket are used as input to the simulations. Temperature ($Temp$), flow (Q), chemical oxygen demand (COD), S_{NH} and S_{NO} are considered as measured in the simulations. All these variables used in

Table 2.4: Components

Inorganic Suspended Solids		
X_{II}	inert inorganic suspended solids	g/m^3
Organic Variables		
S_I	soluble inert organic material	$gCOD/m^3$
S_S	readily biodegradable substrate	$gCOD/m^3$
X_I	particulate inert organic material	$gCOD/m^3$
X_S	slowly biodegradable substrate	$gCOD/m^3$
X_{BH}	active heterotrophic biomass	$gCOD/m^3$
X_{BA}	active autotrophic biomass	$gCOD/m^3$
X_U	unbiodegradable particulate matter from cell decay	$gCOD/m^3$
Dissolved Oxygen		
S_O	dissolved oxygen	gO_2/m^3
Nitrogen compounds		
S_{NH}	free and ionized ammonia	gN/m^3
S_{ND}	soluble biodegradable organic nitrogen	gN/m^3
X_{ND}	particulate biodegradable organic nitrogen	gN/m^3
S_{NO}	nitrate and nitrite nitrogen	gN/m^3
S_{NN}	dissolved dinitrogen	gN/m^3
Alkalinity		
S_{ALK}	alkalinity	$mole/m^3$

Mantis are not measured directly. By using COD fractions in the same way that is used in the Morya 2010 project [4] the measured COD is divided into the different variables.

Most of the data are daily averages and since the aeration process has a time response in less than a day a variation is added. Therefore, the variation from a set of test data taken from the COST simulation benchmark described by Copp [7], was scaled to have the same daily average as the collected measurement series, i.e.

$$\tilde{S_S}(t) = \hat{S_S}(t) + \hat{S_S}(t) \cdot \frac{COST_{S_S}(T) - \frac{1}{N}\sum_{i=0}^{N}(COST_{S_S}(i))}{\frac{1}{N}\sum_{i=0}^{N}(COST_{S_S}(i))}, \tag{2.12}$$

where $\tilde{S_S}(t)$ is the measured mean value with added variations at time t, $\hat{S_S}(t)$ is the measured mean value at time t, $COST_{S_S}(T)$ is a value from the COST data series at

Table 2.5: Composite variables

Organic Matter (COD, BOD, TSS)		
S_{COD}	filtered COD	$gCOD/m^3$
X_{COD}	particulate COD	$gCOD/m^3$
COD	total COD	$gCOD/m^3$
S_{BOD}	filtered carbonaceous BOD_5	gO_2/m^3
X_{BOD}	particulate carbonaceous BOD_5	gO_2/m^3
BOD	total carbonaceous BOD_5	gO_2/m^3
S_{BOD_U}	filtered ultimate carbonaceous BOD	gO_2/m^3
X_{BOD_U}	particulate ultimate carbonaceous BOD	gO_2/m^3
BOD_U	total ultimate carbonaceous BOD	gO_2/m^3
VSS	volatile suspended solids	g/m^3
X	total suspended solids	g/m^3
Inorganic Matter		
X_{ISS}	inert inorganic suspended solids	g/m^3
Nitrogen compounds		
S_{TKN}	filtered TKN	gN/m^3
X_{TKN}	paticulate TKN	gN/m^3
TKN	total TKN	gN/m^3
TN	total nitrogen	gN/m^3

the T'th part of a day divided in N parts. The daily mean measurements are linearly interpolated to get data points between each daily measurement. The result for the component of readily biodegradable soluble substrate (S_S) is shown in Figure 2.5, where we can note that the daily variations are the same from one day to another.

Table 2.6: Stoichiometric parameters at 20 °C

Composite Variable Stoichiometry			
Organic Fractions			
i_{CV}	$XCOD/VSS$	1.480	$gCOD/gVSS$
f_{BOD}	BOD_5/BOD_U ratio	0.660	-
Nutrient Fractions			
i_{bhn}	N content of active biomass	0.068	$gN/gCOD$
i_{uhn}	N content of endogenous/inert mass	0.068	$gN/gCOD$
Model Stoichiometry			
Active Heterotrophic Biomass			
Y_H	heterotrophic yield	0.666	$gCOD/gCOD$
f_{UH}	heterotrophic endogenous fraction	0.080	$gCOD/gCOD$
Active Autotrophic Biomass			
Y_A	autotrophic yield	0.240	$gCOD/gN$
f_{UA}	autotrophic endogenous fraction	0.080	$gCOD/gCOD$

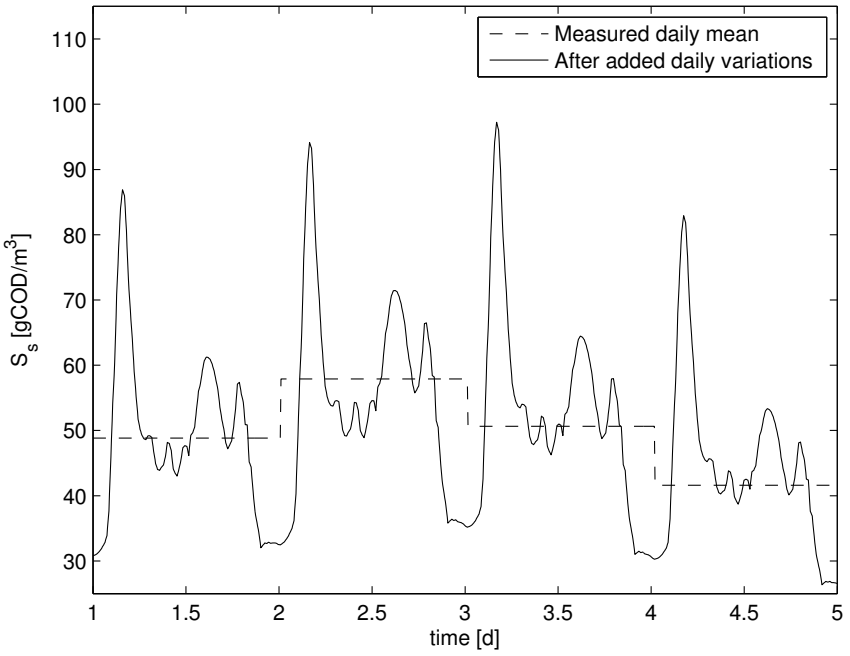

Figure 2.5: The measured daily mean of readily biodegradable soluble substrate (S_S) and the same variable with daily variation from Copp [7].

Table 2.7: Kinetic parameters at 20 °C

Active Heterotrophic Biomass		
μ_H	heterotrophic maximum specific growth rate	3.20 $1/d$
K_{SH}	readily biodegradable substrate half saturation coefficient	5.00 $gCOD/m^3$
K_{OH}	aerobic oxygen half saturation coefficient	0.20 gO_2/m^3
K_{AD}	anoxic oxygen half saturation coefficient	0.20 gO_2/m^3
η_g	anoxic growth factor	0.50 -
K_{NO}	nitrate half saturation coefficient	0.10 gN/m^3
K_{NH}	ammonia (as nutrient) half saturation coefficient	0.05 gN/m^3
b_H	heterotrophic decay rate	0.62 $1/d$
K_{ALK}	alkalinity half saturation coefficient	0.10 $mole/m^3$
Active Autotrophic Biomass		
μ_A	autotrophic maximum specific growth rate	0.90 $1/d$
K_{NA}	ammonia (as substrate) half saturation coefficient	0.70 gN/m^3
K_{OA}	oxygen half saturation coefficient	0.25 gO_2/m^3
b_A	autotrophic decay rate	0.17 $1/d$
K_{ALKA}	alkalinity half saturation coefficient for autotrophic growth	0.50 $mole/m^3$
Hydrolysis		
K_h	maximum specific hydrolysis rate	3.00 $1/d$
K_X	slowly biodegradable substrate half saturation coefficient	0.10 $gCOD/gCOD$
η_h	anoxic hydrolysis factor	0.60 -
Ammonification		
K_a	ammonification rate	0.08 $m^3/gCOD/d$

In simulations used for optimization a constant input is required to keep the number of variables at a minimum. In these scenarios a mean value of the whole dry summer period is used.

2.2.4 The effluent

The parts of the effluent that are affected by aeration and regulated by restrictions is total nitrogen (TKN) and biochemical oxygen demand (BOD). Both have an upper limit for the yearly average of 10 mg/l [8].

3

Control strategy

The carbon source is a cost that should be minimized. Therefore it is preferred that as much as possible of the nitrate is removed in the activated sludge basins rather than in the post-denitrification basins.

The control currently in use at Ryaverket are PI controllers that keep the dissolved oxygen at a given set point, usually 2 mg/l [4]. Only the last 40 % of the activated sludge basins are aerated. The concentration of dissolved oxygen is continually measured in tank 6, 7 and 8. These measured values are used as feedback signals to the PI controllers, having the set point value as input and the airflow into the basins as controller output.

If the dissolved oxygen (S_O) is too low, unwanted bacteria has a tendency to increase and disturb the post-settler because of poor settling properties. Usually this is prevented by keeping the dissolved oxygen above 2 mg/l in the last tank [9]. However, a study at Ryaverket showed no significant change in the quality of the effluent after a short period with an oxygen concentration of 1 mg/l [10].

3.1 Lambda tuning

To tune the PI-controller in this study the Lambda method is used, which is a method widely used in the process industry to tune PI controllers [11].

The part of the tank that is aerated using a PI controller is approximated as a first order process described by

$$G(s) = K_p \frac{e^{-sL}}{1 + sT}, \tag{3.1}$$

where K_p is the static gain, L is the dead time and T is the time constant of the process $G(s)$. These parameters are approximated by a step response.

A PI controller has the transfer function

$$G_c(s) = K_c \frac{1 + sT_i}{sT_i} \tag{3.2}$$

where K_c is the controller gain and T_i is the integral time. The closed loop transfer function is specified as

$$G_{cl}(s) = \frac{e^{-sL}}{1 + sT_{cl}} \tag{3.3}$$

where T_{cl} is the time constant of the closed loop.

Using (3.2) to control (3.1) the closed loop system can be written as

$$G_{cl}(s) = \frac{GG_c}{1 + GG_c} = \frac{K_c K_p (1 + sT_i) e^{-sL}}{(1 + sT)sT_i + K_p K_c (1 + sT_i) e^{-sL}} \tag{3.4}$$

Choosing $T_i = T$ in (3.4) to cancel the pole at $1/T$ gives

$$G_{cl}(s) = \frac{K_c K_p e^{-sL}}{sT + K_p K_c e^{-sL}} = \frac{e^{-sL}}{\frac{sT}{K_p K_c} + e^{-sL}} \tag{3.5}$$

Using $1 - sL$ as an approximation for e^{-sL} in the denominator of (3.5) we get

$$G_{cl}(s) = \frac{e^{-sL}}{1 + s\left(\frac{T}{K_p K_c} - L\right)} \tag{3.6}$$

By comparing (3.3) with (3.6) we get

$$K_c = \frac{T}{K_p (T_{cl} + L)} \tag{3.7}$$

$$T_i = T \tag{3.8}$$

The desired time constant for the closed loop system, T_{cl}, is related to the process using

$$T_{cl} = \lambda T \tag{3.9}$$

if $T > L$ and

$$T_{cl} = \lambda L \tag{3.10}$$

if $L > T$, where λ usually is chosen between 0.5 and 3.0. A smaller λ results in a fast response and a larger λ gives a slow system that is less sensitive to parameter variations.

3.2 Optimal airflow

The criteria to minimize the aeration cost is, according to the staff at Ryaverket, approximately the same as minimizing the total airflow into the activated sludge basins.

By choosing the current values, $BOD_{current}$ and $NO_{current}$, as maximal values allowed in the optimizations, no impairment is possible. The problem is described by

$$\begin{array}{lllll} \text{minimize} & q_{O_2,6} + q_{O_2,7} + q_{O_2,8} & & & \\ \text{subject to} & BOD & \leq & BOD_{current} & \\ & NO & \leq & NO_{current} & \\ & q_{O_2,X} & \leq & q_{O_2,X,max} & X \in [6,7,8] \\ & S_{O,8} & \geq & 1 & \end{array} \tag{3.11}$$

where $q_{O_2,6}$, $q_{O_2,7}$ and $q_{O_2,8}$ are the airflows into tank 6, 7 and 8. As can be seen, the airflows ($q_{O_2,X}$) also has an upper limit ($q_{O_2,X,max}$) due to the capacity of the compressors. Also, the dissolved oxygen concentration in the last tank should not be less than 1 mg/l.

The relationships between the airflows and BOD and NO are complex, involving the Petersen matrix in Table 2.2, the mass balances over the tanks and (2.9) and (2.11) for the oxygen transfer. Clearly, the problem is not linear.

3.3 Same airflow

In Equation (2.11) for the mass transfer coefficient (K_La) it is seen from the term $(1 - e^{-k_2 \cdot q_{O_2}})$ that an increase in airflow is more effective at lower airflows and becomes less and less effective the higher the airflow is. By aerating as large part as possible of the activated sludge basins, the aeration should therefore be more effective since a lower total airflow will result in the same oxygen transfer as a higher airflow in a smaller part.

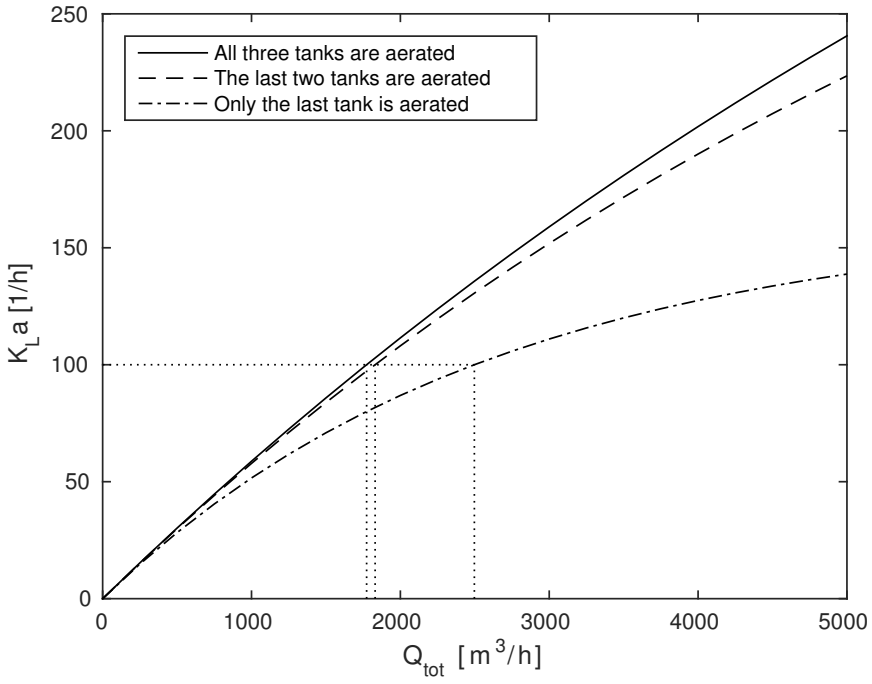

Figure 3.1: Mass transfer coefficient (K_La) depending on total airflow ($q_{O_2,tot}$) for one, two and three tanks aerated.

Indeed, as seen in Figure 3.1, the same (total) mass transfer coefficient, K_La, is achieved using less total airflow, $q_{O_2,tot}$, as a larger part of the activated sludge basins are aerated.

Aerating a larger part of the basins, however, results in a smaller anoxic part. This can result in a lower reduction of nitrate and nitrite, NO, since denitrification is slower at higher concentrations of S_O.

4

Simulation

4.1 Finding the optimal airflow

To find the optimal airflow, the Matlab command *fmincon* is used. By keeping the influent concentration constant and changing the airflow, the effect on BOD and NO, i.e. nitrite and nitrate, can be studied. Since *fmincon* only finds a local minimum, a good guess of where the optimal solution is located has to be found and used as a starting point. To study how BOD and NO depend on the aeration, a grid of solutions is calculated, and the minimum of these solutions is used as starting point. The three tanks that can be aerated, are aerated in steps of a tenth of the practical upper limit. The practical upper limit is found by studying Figure 4.1. When the graph has a low slope the aeration is almost saturated. Since a higher concentration than 4 mg/l dissolved oxygen doesn't results in any significant increase of reaction rate, this is chosen as an upper limit for the grid. The resulting optimal aeration is used to compare the currently used set point control and the variations considered in this thesis.

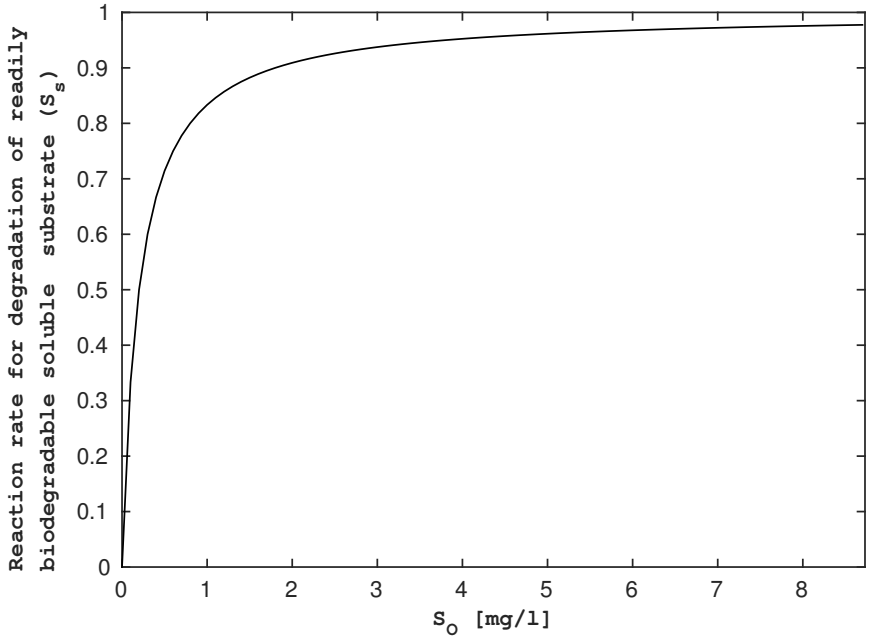

Figure 4.1: Reaction rate for the degradation of S_S at different concentrations of S_O.

4.2 The current setup

A scenario that uses a set point is simulated. This is similar to the currently used control of the aeration at the plant at Ryaverket. Simulations are run with 40 % of the activated sludge basins aerated. A PI controller keeps the dissolved oxygen concentration at a level of 2 mg/l.

The controller is given a set point as input and compares that to the outgoing dissolved oxygen concentration of an activated sludge tank. The difference is used as input to a PI controller that controls the airflow of the tank. The activated sludge block is given the airflow, q_{O_2}, as an input.

4.2.1 Lambda tuning

Tanks 6 to 8 in the model are each subject to a step on the input that results in a change of S_O from 2.0 to 2.1 mgO_2/l. The result of the step is shown in Figure 4.2 and Table 4.1.

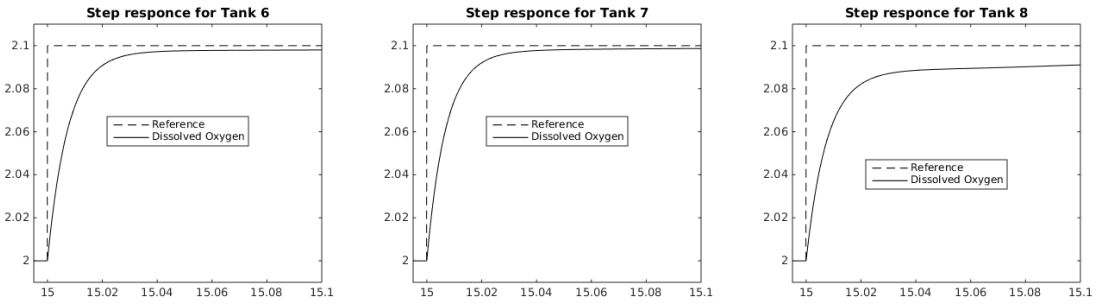

Figure 4.2: Oxygen concentration responses to steps in the aeration in tanks 6-8.

Table 4.1: First order process parameters for tanks 6-8 approximated using step responses.

	Tank 6	Tank 7	Tank 8
K_p	0.0029	0.0026	0.0025
L	0	0	0
T	0.0078	0.0073	0.0095

The resulting controller parameters using $\lambda = 0.5$ are shown in Table 4.2.

Table 4.2: PI-controller parameters.

	Tank 6	Tank 7	Tank 8
K_c	680	773	788
T_i	0.0078	0.0073	0.0095

4.3 Same airflow across all tanks

This model is very similar to the current setup above, but instead of controlling each tank separately, only the last outgoing dissolved oxygen concentration is measured and all the tanks are given the same airflow. Simulations are run with both 40 % and 60 % aeration of the basins.

$$\begin{aligned} \sum_{X=6}^{8} q_{O_2,X} &= \sum_{X=6}^{8} q_{O_2,current,X} \\ q_{O_2,X} &= q_{O_2,Y} \qquad X,Y \in [7,8] \textit{ or } [6,7,8], \end{aligned}$$

where $q_{O_2,current,X}$ is the airflow in tank X used in simulations of the currently used setup.

4.4 Minimum *BOD*, same total airflow as current

$$\begin{array}{lllll} \text{minimize} & BOD & & & \\ \text{subject to} & \sum_{X=6}^{8} q_{O_2,X} & = & q_{O_2,current,total} & \\ & q_{O_2,X} & \leq & q_{O_2,X,max} & X \in [6,7,8] \\ & S_{O,8} & \geq & 1 & \end{array} \tag{4.1}$$

Keeping the total airflow constant, at the same level that is currently used, and minimizing BOD, the optimal strategy for the distribution of aeration in the tanks can be determined.

4.5 Minimum *NO*, same total airflow as current

$$\begin{array}{lllll} \text{minimize} & NO & & & \\ \text{subject to} & \sum_{X=6}^{8} q_{O_2,X} & = & q_{O_2,current,total} & \\ & q_{O_2,X} & \leq & q_{O_2,X,max} & X \in [6,7,8] \\ & S_{O,8} & \geq & 1 & \end{array} \tag{4.2}$$

Same approach as in the previous scenario, but now minimizing NO instead of BOD to investigate an optimal strategy to distribute the airflow over the tanks to keep NO at a minimum, while keeping the aeration constant.

4.6 Minimum total airflow, same *BOD* as current

$$\begin{array}{lllll} \text{minimize} & \sum_{X=6}^{8} q_{O_2,X} & & & \\ \text{subject to} & BOD & = & BOD_{current} & \\ & q_{O_2,X} & \leq & q_{O_2,X,max} & X \in [6,7,8] \\ & S_{O,8} & \geq & 1 & \end{array} \tag{4.3}$$

Here, a constraint is added to optimizes the airflow while keeping the same BOD as achieved by the currently used control. This result should show how to aerate the different basins in order to minimize the airflow without increasing the BOD-concentration in the effluent.

4.7 Minimum total airflow, same *NO* as current

$$\begin{aligned} \text{minimize} \quad & \sum_{X=6}^{8} q_{O_2,X} \\ \text{subject to} \quad & NO = NO_{current} \\ & q_{O_2,X} \leq q_{O_2,X,max} \quad X \in [6,7,8] \\ & S_{O,8} \geq 1 \end{aligned} \tag{4.4}$$

Here, the constraint is changed to optimize the airflow while keeping the same NO as achieved by the currently used control. This result show how to aerate the different basins in order to minimize the airflow without increasing the NO-concentration in the effluent.

4.8 Simulations using variable influent

The set points produced from the optimizations above are then simulated for a variable influent. The variations of BOD and NO over time are shown in Figures 4.3 and 4.4.

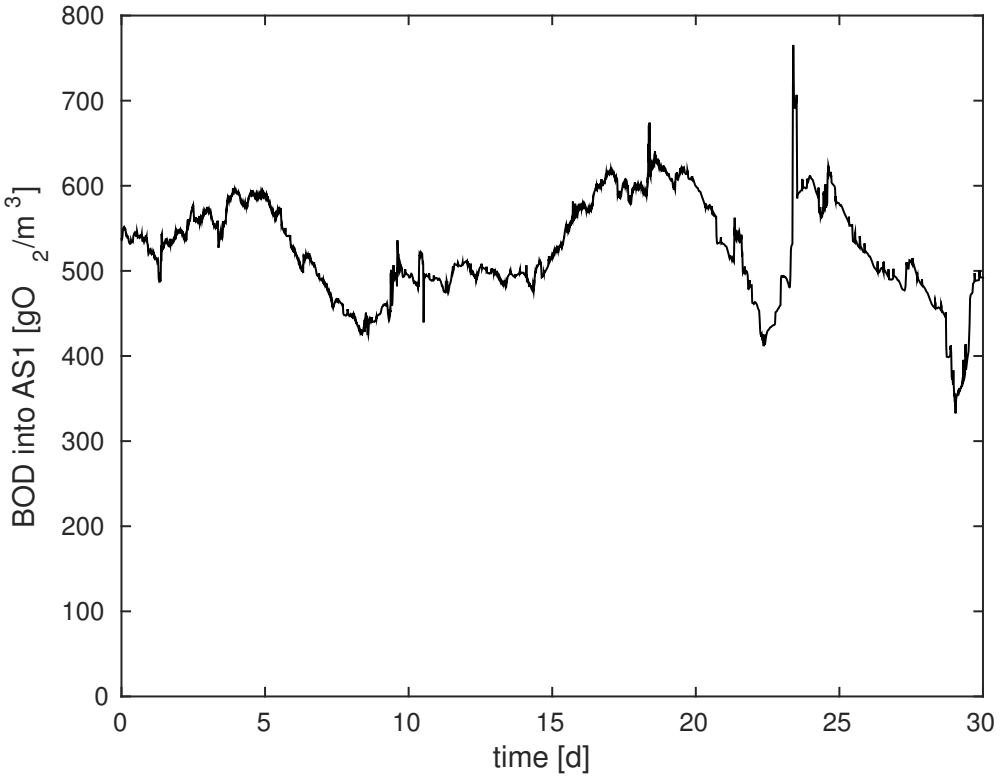

Figure 4.3: Concentration of BOD in the influent to the activated sludge basin.

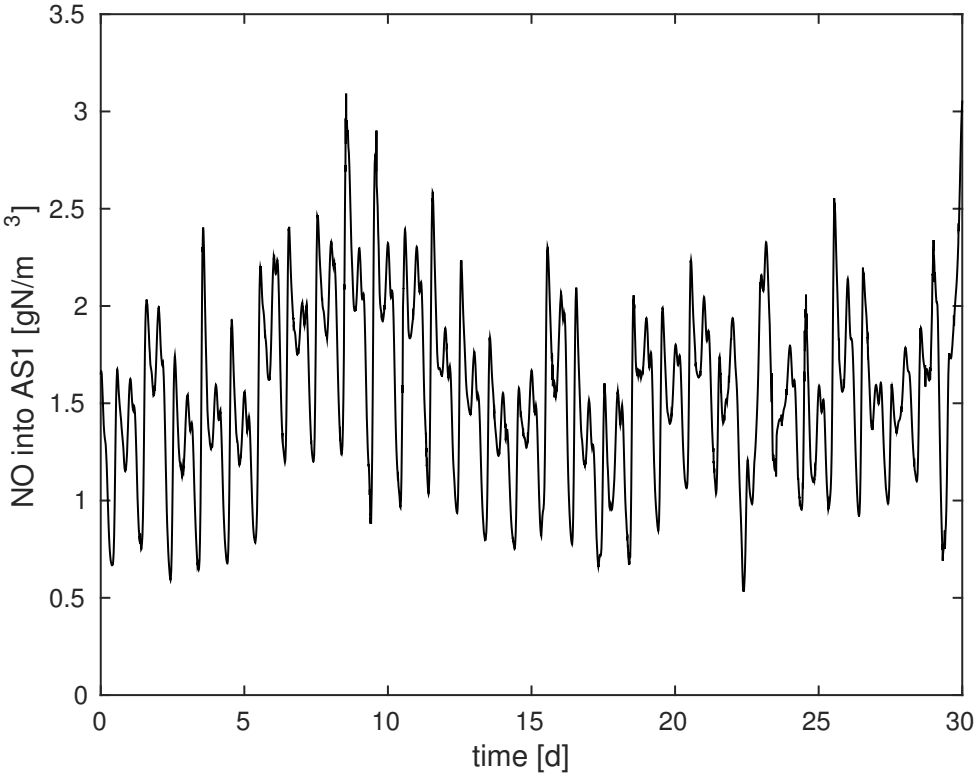

Figure 4.4: Concentration of NO in the influent to the activated sludge basin.

5

Results

To keep the number of variables to a minimum in the simulations used for optimization, the influent was constant and the steady state variables of the effluent was used as results.

To investigate that the results also are "valid" for variable influent, the same set points found in the optimizations were used in simulations with variable influent.

In both cases the simulation periods were 60 days and the effluent used in the comparisons in the case with variable influent was the mean value over the last 30 days.

5.1 The current setup

This result is used as a benchmark for the different control strategies investigated. The results are shown in Figure 5.1 and this simulation is used as a reference point for the effectiveness of the other simulations illustrated in Figure 5.2.

5.2 Same airflow across all tanks

As seen by Figure 5.2, the effect of distributing the airflow evenly over 40 % of the basins compared to the current setup is very small. Keeping the same total airflow but distributing the air over 60 % has a large positive effect on the reduction of BOD but considerably less NO is removed.

5.3 Minimum BOD, same total airflow as current

This result is similar to the one with the same airflow over 60 % above. As seen in Figure 5.1, the aeration in this scenario is almost evenly distributed among the tanks. This results in a larger part of the basins with high concentrations of S_O and good BOD removal properties. The set points are shown in Table 5.1.

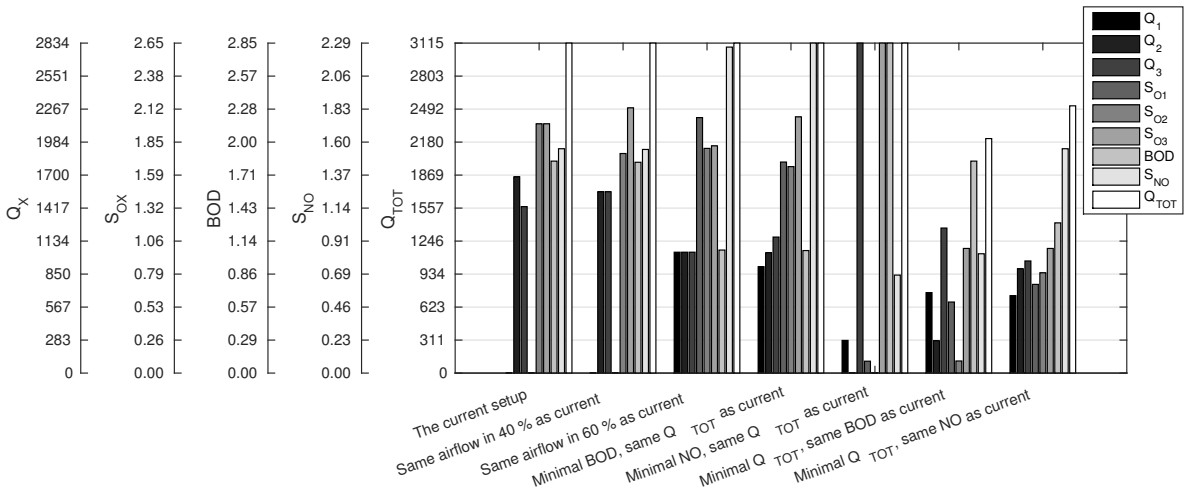

Figure 5.1: Results from simulation over 60 days with constant inflow variables.

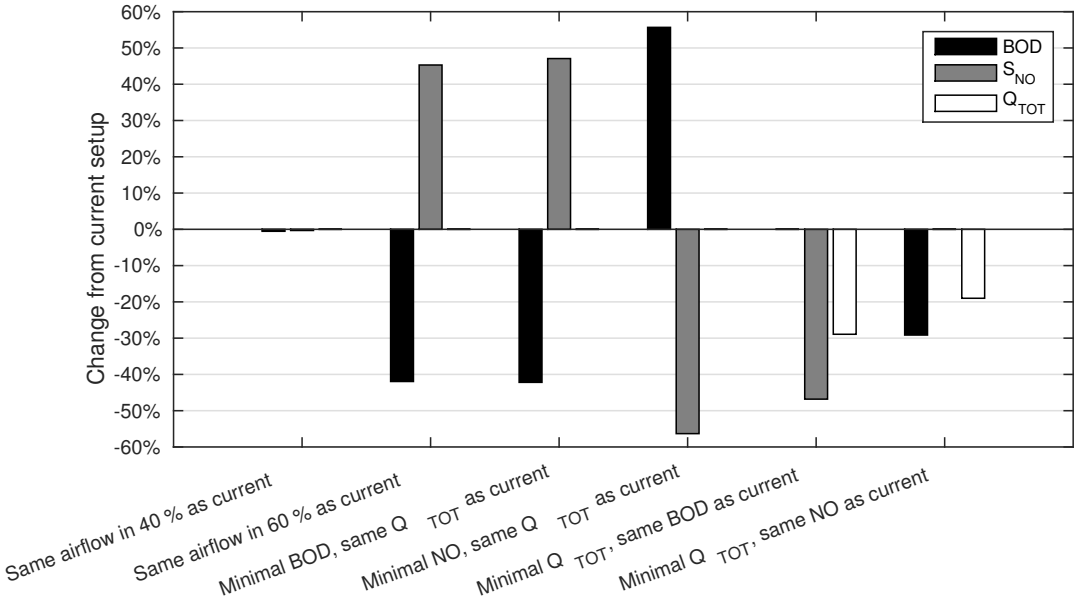

Figure 5.2: Change in percent from the currently used control in simulations over 60 days with constant inflow variables.

Table 5.1

$SP_{S_{O,6}}$	$1.69\,\mathrm{gO_2/m^3}$
$SP_{S_{O,7}}$	$1.66\,\mathrm{gO_2/m^3}$
$SP_{S_{O,8}}$	$2.06\,\mathrm{gO_2/m^3}$

5.4 Minimum *NO*, same total airflow as current

In this scenario more NO is reduced but much less BOD is removed, as seen in Figure 5.2. By studying Figure 5.1 and Table 5.2, it is found that nearly all air is pumped into the last tank. This is expected, since less concentration of S_O in Tanks 6 and 7 extends the anoxic zone and hence a better reduction of NO is achieved.

Table 5.2

$SP_{S_{O,6}}$	$0.10\,\mathrm{gO_2/m^3}$
$SP_{S_{O,7}}$	$0.00\,\mathrm{gO_2/m^3}$
$SP_{S_{O,8}}$	$2.65\,\mathrm{gO_2/m^3}$

5.5 Minimum total airflow, same *BOD* as current

Minimizing the total airflow and keeping BOD at the same level as in the currently used setup results in a better reduction of NO and a lower total airflow, as seen in Figure 5.2. The optimal distribution of air is controlled by the set points shown in Table 5.3.

Table 5.3

$SP_{S_{O,6}}$	$0.57\,\mathrm{gO_2/m^3}$
$SP_{S_{O,7}}$	$0.10\,\mathrm{gO_2/m^3}$
$SP_{S_{O,8}}$	$1.00\,\mathrm{gO_2/m^3}$

In Tank 8 the lowest allowed concentration of S_O is used and that is why Tank 7 has such a low set point.

When an optimization without the lower bounds on the concentration of S_O is executed, all air is in Tank 6 and 7, as seen in Table 5.4.

Table 5.4

$SP_{S_{O,6}}$	$0.82\,\mathrm{gO_2/m^3}$
$SP_{S_{O,7}}$	$0.52\,\mathrm{gO_2/m^3}$
$SP_{S_{O,8}}$	$0.00\,\mathrm{gO_2/m^3}$

This explains the odd composition of the set points.

5.6 Minimum total airflow, same *NO* as current

Keeping NO at the same level as the currently used setup and at the same time minimizing the total airflow results in a higher reduction of BOD as well as a lower total airflow (see Figure 5.2).

The resulting oxygen set points are shown in Table 5.5.

Table 5.5

$SP_{S_{O,6}}$	$0.71\,\mathrm{gO_2/m^3}$
$SP_{S_{O,7}}$	$0.80\,\mathrm{gO_2/m^3}$
$SP_{S_{O,8}}$	$1.00\,\mathrm{gO_2/m^3}$

5.7 Simulations using variable influent

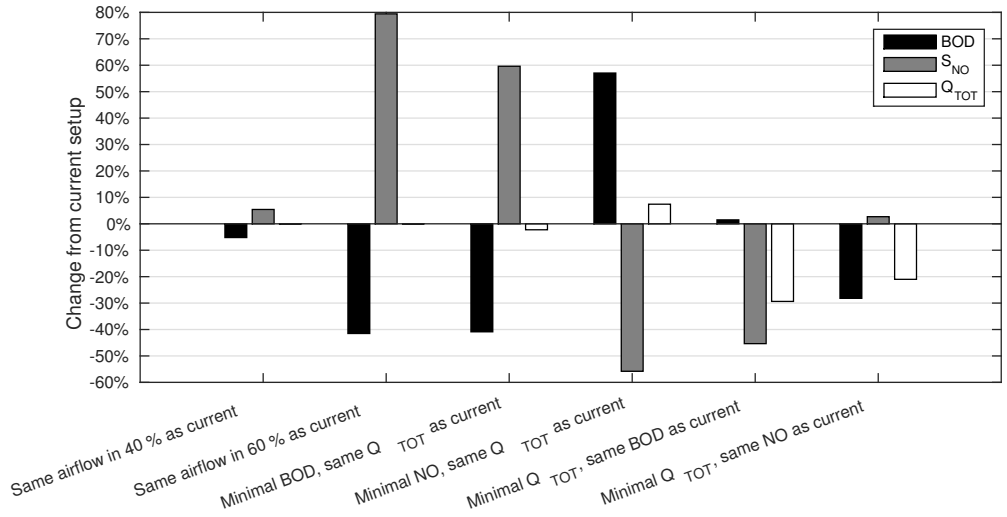

Figure 5.3: Change in percent from the currently used control in simulations of 60 days with variable inflow variables.

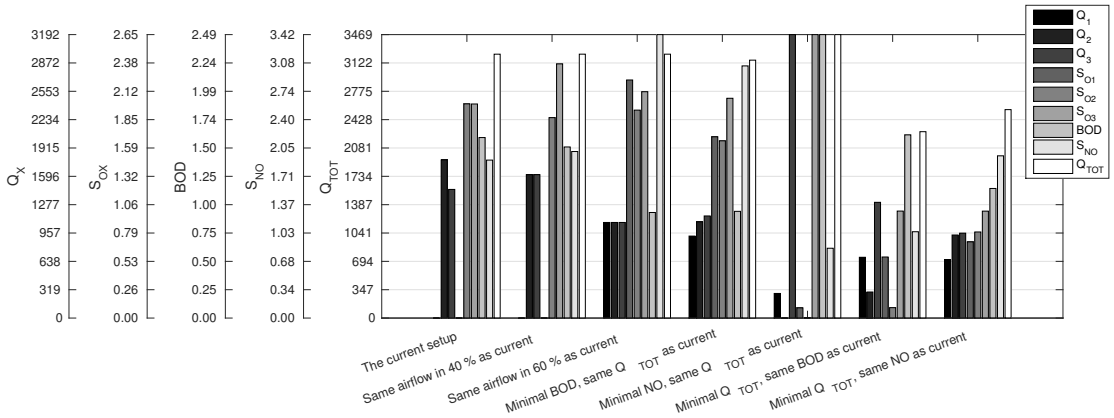

Figure 5.4: Results from simulation of 60 days with variable inflow variables.

Simulations are performed using variable influent and the set points for S_O from the optimizations using constant influent. As seen in Figures 5.3 and 5.4, the results are similar to the results for constant influent shown in Figures 5.2 and 5.1. There are small differences between the simulations with constant and variable influent. But the important differences remains. The results from minimizing the airflow and keeping BOD or NO constant are still an improvement of the currently used control.

More details for these results are given in Appendix A.

6

Discussion

As seen in Figures 5.1 and 5.4 the best reductions of BOD and NO are achieved when a larger part is aerated with lower concentrations of S_O. In the scenarios with lowest NO, most air is pumped into the last tank. In the scenarios with low BOD the aeration is more evenly distributed.

Depending on which of the two pollutants, BOD or NO, that is more important to reduce at the moment, the set points for S_O should be adjusted accordingly. During high concentrations of NO in the influent the set point configuration shown in Table 5.3 should be used and when BOD concentrations are high the configuration shown in Table 5.5 should be used.

In general, the simulations shows that less is more. In the scenarios that reduces BOD without increasing NO, and vice versa, the total airflow is also reduced. The reason is that more of the activated sludge basins are aerated. To aerate 60 % instead of 40 % at a lower S_O concentration reduces the cost of aeration at the same time as the reduction of BOD and NO are higher.

It might not be possible to have as low set points as suggested in this report due to growth of undesired bacteria. But the simulations clearly indicates that expanding the aeration volume with only a moderate reduction of aeration can reduce costs and pollutions considerably. The cost of aeration can be lowered by as much as 30 % without increasing BOD or NO in the effluent. According to Neth [4], the annual cost of aeration is approximately 3 700 000 SEK/year which gives a potential maximum saving of over 1 000 000 SEK/year. In reality this number is most likely much smaller, but there is potential to save a significant sum each year.

Since Table 5.3 has such a low set point in Tank 7 the air may not be enough to mix the tank properly. To fully use this control strategy at site, it may be necessary to install a stirrer for the affected parts of the basins.

The accuracy of the model is as good as the parameters used. Further work should investigate also the dynamics of the plant and tune relevant parameters. The parameters

used in the model have only been tested and validated under normal operation and not at as low concentrations of S_O as suggested here.

The parts of the model that includes the settler and the trickling filters are extremely simplified. As long as the process is working in a similar state in the different scenarios the results should be good enough to evaluate the advantages and disadvantages of the different control strategies discussed here.

The control strategies in this thesis is of a constant nature, where a set of set points are used to control the aeration of the basins. Further studies that investigates the possibility to control the aeration using input from an NO-sensor should be preformed. By aerating smaller parts of the basins when the concentration of NO is high, more NO can be removed while still having a good reduction of BOD when the concentration of NO is low.

7

Conclusion

By aerating a larger part of the activated sludge basins, 60 % instead of 40 %, both cost and effluent concentrations of BOD and NO are reduced. Depending on if BOD or NO is the compound that is most important to reduce, the airflow should be distributed differently between the tanks.

There is a risk of growth of unwanted bacteria if the concentration of S_O is low. Since the concentrations recommended in this thesis is considerably lower than the concentrations used today, the concentration of S_O could be lowered in small steps during a long period of time, at the same time as the quality of the effluent is closely monitored.

Strategies to reduce either BOD or NO, and at the same time lower the cost of aeration, have been found. The potential of saving money on the reduced aeration is also found to be significant.

A

Tables

Table A.1: Results from simulations with constant influent.

	$S_{O,6}$	$S_{O,7}$	$S_{O,8}$	$q_{O_2,6}$	$q_{O_2,7}$	$q_{O_2,8}$	BOD	S_{NO}	$q_{O_2,total}$
The current setup	0.00	2.00	2.00	0	1402	1012	3.78	0.56	2414
Same airflow in 40 % as current	0.00	1.55	2.22	0	1207	1207	3.78	0.55	2414
Same airflow in 60 % as current	0.77	1.16	1.56	805	805	805	2.10	0.73	2414
Minimal BOD, same $q_{O_2,tot}$ as current	0.44	0.04	2.46	639	95	1681	3.54	0.38	2414
Minimal NO, same Q_{TOT} as current	0.10	0.00	2.65	281	0	2834	2.85	0.68	3115
Minimal $q_{O_2,tot}$, same BOD as current	0.30	0.11	1.00	540	277	916	3.78	0.34	1732
Minimal $q_{O_2,tot}$, same NO as current	0.41	0.76	1.00	624	741	716	2.51	0.56	2081

Table A.2: Results from variable influens simulations.

	$S_{O,6}$	$S_{O,7}$	$S_{O,8}$	$q_{O_2,6}$	$q_{O_2,7}$	$q_{O_2,8}$	BOD	S_{NO}	$q_{O_2,total}$
The current setup	0.00	2.00	2.00	0	1781	1448	1.59	1.91	3229
Same airflow in 40 % as current	0.00	1.87	2.37	0	1615	1615	1.50	2.01	3229
Same airflow in 60 % as current	2.22	1.94	2.11	1076	1076	1076	0.93	3.42	3229
Minimal BOD, same Q_{TOT} as current	1.69	1.66	2.05	923	1083	1150	0.94	3.04	3156
Minimal NO, same Q_{TOT} as current	0.10	0.00	2.65	277	0	3192	2.49	0.84	3469
Minimal Q_{TOT}, same BOD as current	0.57	0.10	1.00	684	293	1303	1.61	1.04	2281
Minimal Q_{TOT}, same NO as current	0.71	0.80	1.00	659	935	956	1.14	1.96	2551

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