

# SIMULATION OF ACTIVATED SLUDGE PROCESSES

Computer lab in Wastewater Treatment – W4

Nitrogen removal using an activated sludge process

**Preparation exercises:**

1. Read the lab instruction carefully
2. Page 9 Exercise 3.2 a
3. Page 16-17 Exercise 4.2 a-b

Name	Comments by supervisor
Program      Year entering the program	
Date	
Lab passed      Sign	

## Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
<b>2</b>	<b>Simulation of an activated sludge process</b>	<b>2</b>
2.1	Process layout . . . . .	2
2.1.1	Volumes, flows and composition of the wastewater . . . . .	2
2.1.2	The sedimentation unit . . . . .	3
2.2	The graphical user interface (GUI) . . . . .	3
2.3	Running the simulator . . . . .	5
2.3.1	Starting the simulator . . . . .	5
2.3.2	Plotting and presenting data . . . . .	5
2.3.3	Changing the process . . . . .	6
2.3.4	Controlling the process . . . . .	7
2.3.5	Resetting the simulator . . . . .	8
<b>3</b>	<b>Exercises - Pre denitrification process</b>	<b>8</b>
<b>4</b>	<b>Exercises - Post denitrification process</b>	<b>16</b>
<b>A</b>	<b>Appendix 1</b>	<b>21</b>
A.1	A Short Java Introduction . . . . .	21
A.2	Overview of the simulation program . . . . .	21
<b>B</b>	<b>Appendix 2</b>	<b>23</b>
<b>C</b>	<b>Appendix 3</b>	<b>24</b>
<b>D</b>	<b>Appendix 4</b>	<b>26</b>

## 1 Introduction

Modeling and simulation studies become more and more common also in the wastewater treatment area. Since, a wastewater treatment plant is a very dynamic process, static rules of thumb may not be sufficient in the design and operation of the plant.

In all simulation studies it is of fundamental importance to be aware of model approximations and the validity of the model. Note that different needs often lead to different requirements of the accuracy of the underlying model.

In this laboratory work, a simulator based on the Activated Sludge Model No 1 (ASM1), will be used to simulate an activated sludge process. The simulator is written in *JAVA* and was made as a master thesis work. In Appendix 1 a short overview of *JAVA* and the simulator program is given. In the lab you will run the simulator using the *Netscape Communicator*. The purpose of the laboratory work is to study different aspects of nutrient removal in the activated sludge process. Two different alternatives for nitrogen removal in an activated sludge process will be considered:

- Pre denitrifying process
- Post denitrifying process

## 2 Simulation of an activated sludge process using the ASM1 and a graphical process simulator

### 2.1 Process layout

In the default version of the simulator program, the modeled activated sludge process uses pre denitrification for nitrogen removal with the possibility to add an external carbon source in compartment 1. It is also possible to choose the setup for simulating a post denitrifying system, see Section 4. A schematic layout of the process is shown in Figure 1 (lower half).

#### 2.1.1 Volumes, flows and composition of the wastewater

The simulated process consists of a basin divided in 10 completely mixed compartments and a settler. The (default) configuration of the compartments is given in Table 1.

Compartment No.	Volume (m <sup>3</sup> )	Operation
1	235	Anoxic
2	235	Anoxic
3	235	Anoxic
4	235	Anoxic
5	235	Anoxic
6	235	Aerobic
7	235	Aerobic
8	235	Aerobic
9	235	Aerobic
10	235	Aerobic

Table 1: The basin consists of 10 compartments, compartments 1 to 5 are non-aerobic (anoxic) and compartments 6-10 are aerobic.

The nominal flow rates used in the simulator are given in Table 2.

Flow	Rate [m <sup>3</sup> /h]
Influent	250
Excess sludge	4
Return sludge	250
Internal recirculation	0
External carbon flow rate	0

Table 2: Nominal values of the flow rates in the the simulation model.

Each compartment is modeled with the ASM1. The values of the parameters and concentrations in the model can be changed. The default concentrations of different compounds in the influent wastewater are given in Table 3.

Standard abbrev.	Abbrev. in simulator	Variable	Conc. (mg/l)
$X_{B,H}$	Xbh	Heterotrophic biomass	0
$X_{B,A}$	Xba	Autotrophic biomass	0
$X_S$	Xs	Slowly biodegradable substrate	82
$X_I$	Xi	Part. inert org. matter	43
$X_{N,D}$	Xnd	Part. biodegradable org. nitrogen	5.8
$S_{N,H}$	Snh	$NH_4-NH_3$ nitrogen	23.5
$S_{N,D}$	Snd	Soluble biodegradable org. nitrogen	2.1
$S_{N,O}$	Sno	Nitrate and nitrite nitrogen	1
$S_I$	Si	Soluble inert org. matter	37
$S_O$	So	Oxygen	0.1
$S_S$	Ss	Readily biodegradable substrate	80

Table 3: Influent wastewater composition. The values approximately correspond to the composition of pre sedimented wastewater at the main municipal plant in Uppsala.

### 2.1.2 The sedimentation unit

The sedimentation unit is modeled as a traditional one-dimensional layer model with 10 vertical layers. The equations describing the sedimentation model is given in Appendix 3.

The excess sludge is removed at the bottom of the sedimentation basin. The sludge age is calculated as

$$\theta_s = \frac{V * X}{Q_w * X_{rec} + Q_{eff} * X_{eff}} \quad [days] \quad (1)$$

where  $V$  is the volume of the aerobic compartment,  $X$  is the mean sludge concentration in the aeration basin,  $Q_w$  is the excess sludge flow rate (expressed in  $m^3/day$ ),  $X_{rec}$  is the concentration of the sedimented sludge,  $Q_{eff}$  is the effluent biomass flow rate (expressed in  $m^3/day$ ) and  $X_{eff}$  is the concentration of the effluent biomass. The sludge age presented in the simulator is calculated using (1).

## 2.2 The graphical user interface (GUI)

The simulator is operated with a GUI where also the status of the plant is shown in real time. As seen from Figure 1, the plant is schematically drawn in the GUI. The simulated flow rates of the pumps are changed by clicking of the pump symbol and alter the desired flow rate in the window that appears. Note that the cursor must be located inside the "value box" before a value can be entered. To the right in the GUI, the simulation time is presented during the simulation. Note, that some changes may take hours or days before they are fully observable.

Important process parameters can also be shown in the GUI. For example, if the field *Sludge Properties* is clicked, a window that shows the sludge age, the sludge concentration and the excess sludge flow appears. The sludge concentration is here defined as the average concentration of particulate compounds in the aerobic compartments.

To further improve the presentation of the status of the plant, three bar diagrams are used. Each diagram shows the concentration of a selectable compound in incoming water, all compartments, return sludge and the effluent water. In these diagrams, the numerical values of the concentrations are also shown. In the GUI an ordinary graph is also used. Here, the concentrations of two compounds in a specific compartment can be plotted versus time.

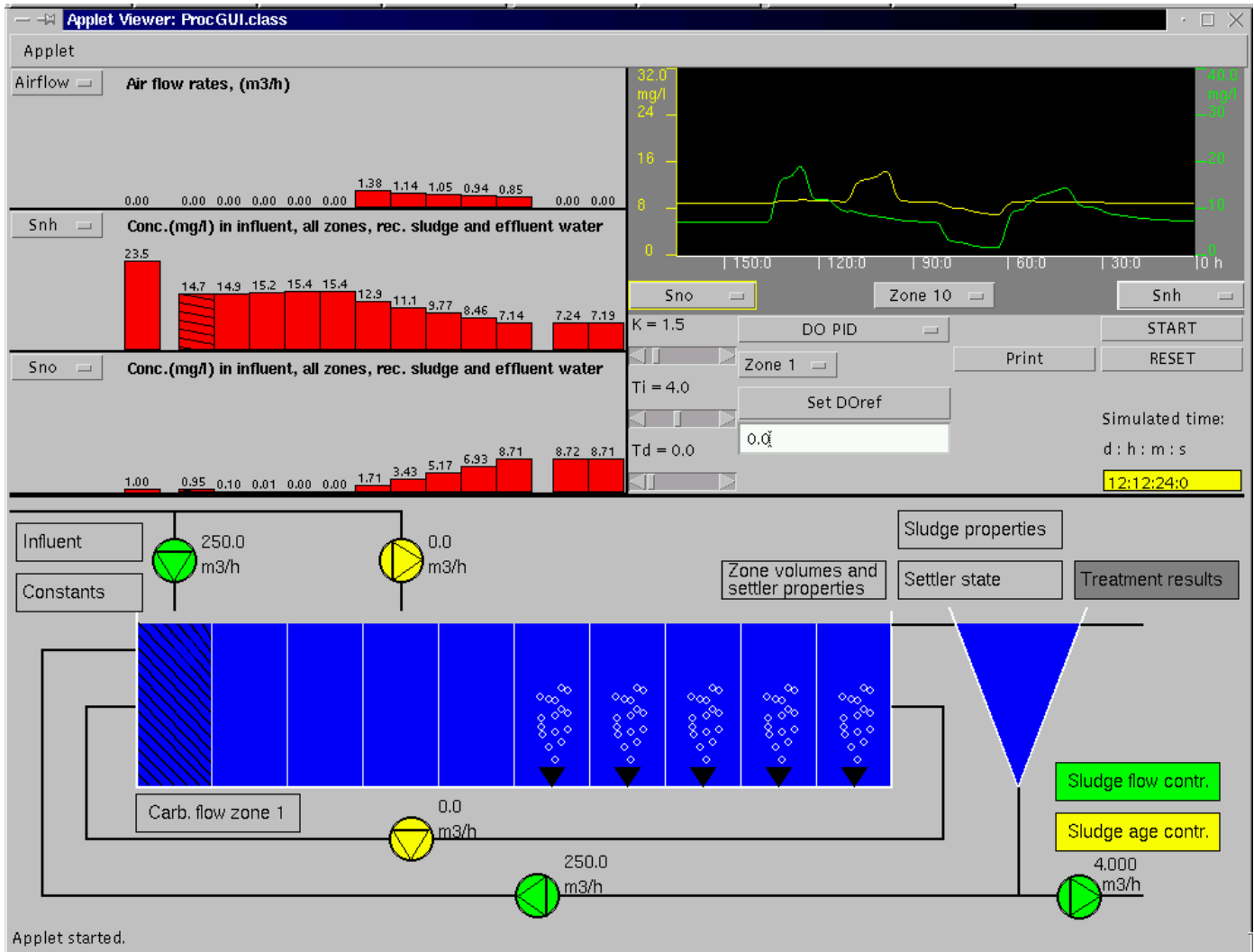


Figure 1: An The graphical user interface in the simulator.

## 2.3 Running the simulator

To start the simulator (wait until you have started reading Section 3 before you actually do this), do the following:

### 2.3.1 Starting the simulator

1. Start *Netscape Communicator*
2. Load the actual URL, see Section 3 for details.
3. As you may notice, the GUI is a little bit too big for your screen. This can be adjusted by choosing *hide* on the first three items in the menu *view* in the Communicator.
4. Click on the *START* button in the GUI.

### 2.3.2 Plotting and presenting data

5. To choose a certain component to plot in the bar diagrams, use the menu bar to the left of a bar diagram. For instance, to plot the concentration of dissolved oxygen, choose  $S_O$ . The oxygen concentrations in influent water, all compartments, return sludge and effluent water are then displayed.
6. In the scrolling graph it is possible to plot the concentrations of two components at the same time. Three menu bars are located under the graph. In the middle menu bar it can be chosen whether to plot concentrations from influent water, any of the compartments, return sludge or the effluent water. Two components may then be selected from the menu bars to the left and to the right.
7. The simulated time is presented in two ways. First, it can be seen approximately from the timescale of the graph, secondly it is presented in a separate text field to the right in the GUI.
8. When the field *Sludge properties* is clicked, a window presenting the actual sludge age, the excess sludge flow and the sludge concentration of the plant appears.
9. The state of the settler is shown when the field *Settler state* is clicked. Here the particulate concentration in the effluent is presented. Also the particulate concentration profile in the settler is shown, see Figure 2. When a sludge overflow occurs, a warning message appears in the window.
10. When the field *Treatment results* is clicked, a window illustrating the concentrations of COD, BOD, total N, ammonium (Snh), nitrate (Sno) and Total Suspended Solids (TSS) in influent and effluent of the plant appears. The reduction percentage is also shown in the window, see further Appendix 4.

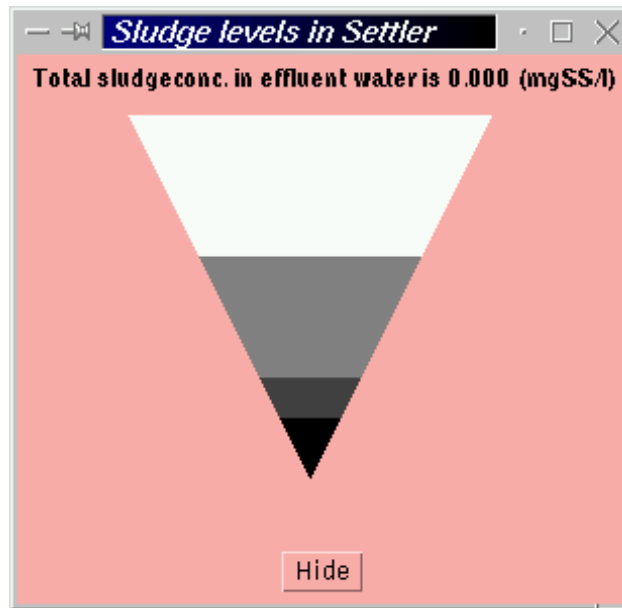


Figure 2: The particulate concentration profile of the settler. The darkness of the colour is proportional to the sludge concentration.

### 2.3.3 Changing the process

11. To change a flow rate, click on the corresponding pump symbol in the process image and enter a new value in the appearing window. An active pump will be colored green, and an inactive yellow. Also external carbon (ethanol) can be added by clicking on *Carb. flow zone 1*.
12. To change ASM1 process parameters, click on the field *Constants* (upper left corner) in the process image. A new window where the new parameters may be entered is shown. Here, it is also possible to choose the simulated temperature of the water. To make the text fields writeable, they must be clicked with the cursor. When a new value has been chosen, push the *ok* button in the window. The new values are then used in the process, and the window closes. If the button *Cancel* is chosen, no changes in the process are done and the window disappears. The window is depicted in Figure 3.
13. To change concentrations of the components in the influent water, click in the field *Influent*. A window similar to the one described above appears, and new values can be entered in the same way.
14. By clicking in the field *Zone volumes and settler properties*, a window appears where the volumes of all compartments can be changed. Here, it is also possible to change the settler parameters such as settler area, settler height and settling velocity.



	20C	Actual temp.
Yh, heterotroph. yield	0.67	0.67
Ya, autotroph. yield	0.24	0.24
fp	0.08	0.08
lxb	0.086	0.086
lxp	0.06	0.06
myh	0.25	0.25
Ks	20.0	20.0
Koh	0.2	0.2
Kno	0.5	0.5
Bh	0.026	0.026
etah	0.4	0.4
etag	0.8	0.8
Knh	1.0	1.0
Koa	0.4	0.4
Ba	0.00833	0.00833
Kh	0.125	0.125
Kx	0.03	0.03
Ka	0.0033	0.0033
mya	0.033	0.033
Temp., C	20.0	

Figure 3: The window for changing the ASM1 process parameters.

### 2.3.4 Controlling the process

- During simulation, it is possible to choose between running the simulator with a fixed excess sludge flow or with a fixed sludge age. In the default setup, the simulator is running with a fixed sludge flow. By clicking in the field *Sludge age control* and enter a desired fixed sludge age in the appearing window, the simulator will run with a fixed sludge age instead. Clicking on the field *Sludge flow control* and enter a desired flow value will change the mode back, so that the simulations again run with a fixed excess sludge flow.
- To change the reference values of dissolved oxygen, go to the panel under the scrolling graph (located under the menu bar *DO PID*). Here it is chosen in what compartment to change the reference value. Enter a value in the text field and then push the *Set DOref* button. Note that the air bubbles in the compartment will disappear when  $DO_{ref} = 0$  is chosen.

17. When the option *DO setpoint controller* is chosen from the menu bar *DO PID* under the graph, it is possible to run a supervisory control of the DO controllers. The user may then enter a set-point for the ammonium concentration in the last aerated compartment. When the button *Set Snhref* is selected, the supervisory control starts. Once the option *DO PID* is chosen in the menu bar again, the supervisory control stops.
18. When the option *C controller* is chosen from the menu bar *DO PID* under the graph, it is possible to automatically control the flow rate of external carbon source. The user may enter the set-point of nitrate in the last anoxic compartment.

### 2.3.5 Reseting the simulator

19. In case the simulator needs to be reseted, press the button *RESET* followed by *shift+reload* in the Communicator view menu (Netscape).

## 3 Exercises - Pre denitrification process

You will here study the effect on the process when changing different process parameters. Some supporting calculations will also be done.

### Exercise 3.1, Preparations

First, start Netscape and go to the following URL:

<http://www.syscon.uu.se/JASS>

and select the link Lab versions: *Lab 1*. Push the *start* button to start the simulations.

When you have started the simulator it may be a good idea to select some variables to plot. A reasonable default selection is to choose air flow rate in bar diagram 1 (this gives a quantitative measure on the respiration rate), ammonium in bar diagram 2 and nitrate in bar diagram 3. The treatment result window gives some important information about influent and effluent concentrations and the percentage reduction of different compounds.

After you have done this, check that:

- The flow of the incoming water=250 m<sup>3</sup>/h, the internal recirculation=0 m<sup>3</sup>/h, the excess sludge flow=4 m<sup>3</sup>/h and the return sludge flow = 250 m<sup>3</sup>/h.
- The oxygen concentrations should be around 2 mg/l in the last five compartments and zero in the first five. This is checked by choosing *So* in one of the bar diagrams.

Let the simulator reach steady state values (this may take 5-10 days) and check:

- Effluent ammonium = ..... mg/l
- Effluent nitrate = ..... mg/l
- Nitrate in last anoxic compartment = ..... mg/l
- Percentage reduction of ammonium = .....
- Percentage reduction of total N = .....
- Percentage reduction of COD = .....
- Percentage reduction of BOD = .....

### Exercise 3.2, Effect of internal recirculation rate

An increase of the internal recirculation rate reduces the effluent nitrate concentration if the denitrification is complete or almost complete.

Assume we have complete denitrification ( $S_{NO} = 0$  in the last anoxic compartment), the influent flow is  $Q$ , internal recirculation is  $rQ$ , return sludge is  $sQ$ , and when  $x$  mg ammonium nitrogen is nitrified  $x$  mg nitrate nitrogen is obtained. To derive the effluent nitrate concentration from the last aerobic compartment, the following mass balance is valid

$$Q S_{NH,in} = (Q + rQ + sQ) S_{NO,eff} \quad (2)$$

which can be written as

$$S_{NO,eff} = \frac{1}{1 + r + s} S_{NH,in} \quad (3)$$

a) If  $s = 1$  and  $r = 0$  in the beginning and then the internal recirculation is increased to  $r = 1$ , by how many percent is the effluent nitrate reduced?

**ANSWER:**

b) Increase the internal recirculation to  $250 \text{ m}^3/\text{h}$  ( $r = 1$ ). Write down the values of the nitrate concentration and the percentage reduction of the effluent concentrations, after the change in internal recirculation. Comment on the result and compare with (3).

- Effluent ammonium = ..... mg/l
- Effluent nitrate = ..... mg/l
- Nitrate in last anoxic compartment = ..... mg/l
- Percentage reduction of ammonium = .....
- Percentage reduction of total N = .....
- Percentage reduction of COD = .....
- Percentage reduction of BOD = .....

**ANSWER:**

c) Now, increase the internal recirculation in steps until the flow rate is about  $1000 \text{ m}^3/\text{h}$ . Is expression 3 still valid? Try to explain the result.

**ANSWER:**

### Exercise 3.3, Effect of incoming biodegradable substrate

a) Now, set the internal recirculation back to zero and change the concentration of easily degradable carbon  $S_S$  in the influent water to  $25 \text{ mg/l}$ . Wait for the process to reach steady state.

Note the effluent levels of ammonium and nitrate and the percentage reduction of the effluent concentrations.

- Effluent ammonium = ..... mg/l
- Effluent nitrate = ..... mg/l
- Percentage reduction of ammonium = .....
- Percentage reduction of total N = .....
- Percentage reduction of COD = .....
- Percentage reduction of BOD = .....

What can you say about the ammonium and nitrate levels compared to the first case in Exercise 3.1?

**ANSWER:**

b) Which biological process is most sensitive to lack of easily biodegradable substrate in the influent water?

**ANSWER:**

c) Now, increase the internal recirculation to  $250 \text{ m}^3/\text{h}$ . What happens with the nitrate levels?

- Effluent nitrate = ..... mg/l
- Nitrate in last anoxic compartment = ..... mg/l

Compare the result with Exercise 3.2 a-b. Is an increase of the internal recirculation the right way to solve the problem? Motivate!

**ANSWER:**

#### **Exercise 3.4, Adding an external carbon source**

A common way of getting a higher denitrification rate when there is a lack of easily degradable organic matter in the anoxic compartments is to add external carbon (ethanol our case) in the first anoxic compartment. Do this by clicking in the field *Carbon Zone 1* and enter a ethanol flow rate (l/h) in the window that appears. Try to make the nitrogen removal as good as possible (around 0.5-1 mg/l in last anoxic compartment) without adding more carbon than is needed to get almost complete denitrification in the last anoxic compartment ( a good start value of the ethanol flow rate may be in the interval 5-10 (l/h). Leave other flowrates unchanged from the previous task. Write down your values of ammonium and nitrate in effluent water and in the last anoxic compartment below. You may also study the percentage reduction of the concentrations.

- Effluent ammonium = ..... mg/l
- Effluent nitrate = ..... mg/l
- Nitrate in last anoxic compartment = ..... mg/l
- Percentage reduction of ammonium = .....
- Percentage reduction of total N = .....
- Percentage reduction of COD = .....
- Percentage reduction of BOD = .....

Comment on your results! Compare your results with Exercise 3 a-b.

**ANSWER:**

### Exercise 3.5, Changing the DO levels

a) First of all, turn off the external carbon flow and set the concentration of  $S_s$  back to 80 mg/l. Wait for the simulations to reach steady state. Write down values of air flow rates and ammonium and nitrate concentrations.

- Air flow rates in compartment 6....., 7....., 8....., 9....., 10.....
- Effluent ammonium = ..... mg/l
- Effluent nitrate = ..... mg/l

b) The dissolved oxygen concentration has a large impact on the activated sludge process. By default, it is set to 2 mg/l in all the five aerobic compartments. Change the DO set-point (the reference value of dissolved oxygen) to 1.5 mg/l in all these compartments and study the effect on the ammonium and nitrate concentrations. How to do this is described in Section 2.3. Write down the values of: air flow rates, nitrate concentrations, and effluent ammonium after you have changed DO set-point.

- Air flow rates in compartment 6....., 7....., 8....., 9....., 10.....
- Effluent ammonium = ..... mg/l
- Effluent nitrate = ..... mg/l

Comment on the results.

ANSWER:

**Exercise 3.6, Increase of influent ammonium.**

First, change all five (compartment 6-10) oxygen reference values back to 2.0 mg/l. Let the simulator reach steady state values (this may take 5-10 days).

Increase the ammonium concentration by 4.5 mg/l (to 28 mg/l) and study the effect in ammonium, nitrate concentrations, and air flow rates. Choose  $S_o$  and  $S_{nh}$  in compartment 10 in the time graph. Try to explain what you see (Compare to Exercise 3.5).

- Air flow rates in compartment 6....., 7....., 8....., 9....., 10.....
- Effluent ammonium = ..... mg/l
- Effluent nitrate = ..... mg/l

ANSWER:

**Exercise 3.7, Supervisory control of the DO**

First of all, reset the simulator. (How to do this is described in section 2.3). Change the internal recirculation to 250 m<sup>3</sup>/h. Choose  $S_o$  and  $S_{nh}$  in the time graph and select to study compartment 10. In the bar diagram you should choose to study the Airflow,  $S_{nh}$  and  $S_{no}$ . Select the option *DO setpoint controller* from the menu bar *DO PID* under the graph. This supervisory controller controls the ammonium level in the last aerated compartment, by adjusting the set point of the DO controllers in the aerated compartments.

a) Change the ammonium set-point (in compartment 10) to be the same as the effluent ammonium concentration you obtained in Exercise 3.5a. When the ammonium concentration has settled, increase the influent ammonium concentration by 4.5 mg/l (to 28 mg/l).

Explain what happens and compare the result with Exercise 3.6b.

**ANSWER:**

b) Now, set the influent ammonium concentration back to 23,5 mg/l. Study the effect on  $S_{nh}$ ,  $S_{no}$ ,  $S_o$  and airflow when you decrease the ammonium concentration by 6.5 mg/l (to 17 mg/l). Can you draw any conclusions about the advantages and the drawbacks with a supervisory DO controller compared to a constant DO?

**ANSWER:**

### **Exercise 3.8, Increase of excess sludge flow**

The amount of biomass in the bioreactor affects the whole process. The most critical process to maintain is usually the nitrification process, why? Switch over to constant DO controlling (option *DO PID* in the menu bar) and set the influent ammonium concentration back to 23,5 mg/l. Change the excess sludge flow rate to 40 m<sup>3</sup>/h and study the ammonium conc. nitrate conc. and air flow rates. Explain what you see.

**ANSWER:**

Now you have made a wash-out! Be thankful it was only done in a simulator.



**Exercise 3.9, Decrease of the temperature - optional task**

Reload and restart the simulator. Set the internal recirculation flow rate to  $250\text{m}^3/\text{h}$ , and wait for the process to reach steady state. The activated sludge process is affected by the temperature, some processes more than others. Change the simulated temperature to  $10\text{ }^\circ\text{C}$ . This is done by clicking the area *Constants* and enter the value in the temperature field. Note how this affects the process parameters. What seem to happen when the temperature is decreased? What process is most affected? Motivate this by checking the process parameters!

**ANSWER:**

As you can see the temperature decrease leads to high ammonium levels in the effluent water. A way of dealing with this problem is to aerate more compartments. When more compartments are aerated you may not have complete denitrification in the last anoxic compartment anymore, and the nitrate removal may therefore be increased by adding external carbon to the first compartment. Your task is now to make the nitrogen removal of the plant to work as good as possible. The internal recirculation may *not* be increased to more than  $300\text{ m}^3/\text{h}$ . For instance, aerate compartment 4 and compartment 5 (i.e set the oxygen reference values in these compartments to about  $2.0\text{ mg/l}$ ) and wait for simulations to reach steady state (note that this takes quite a while). When you add carbon to the first compartment, try not to add more than is needed to get an almost complete denitrification in your last anoxic compartment (a reasonable initial guess may be in the order  $1\text{-}10\text{ l/h}$ ). You can also try to use the supervisory DO controller. Describe and explain your results below.

**ANSWER:**

## 4 Exercises - Post denitrification process

First of all, a version of the simulator that simulates a post denitrification process should be loaded. This simulator is found on the URL

<http://www.syscon.uu.se/JASS>

and select the link Lab versions: *Lab 2*.

Start the simulations in the same way as before. The simulator has the same influent concentrations, process constants, and volumes as the previous one.

### Exercise 4.1, Preparations

After you have started the simulator, let it reach steady state values (this may take 5-10 days) and check:

- Effluent ammonium = ..... mg/l
- Effluent nitrate = ..... mg/l
- Percentage reduction of ammonium = .....
- Percentage reduction of total N = .....
- Percentage reduction of COD = .....
- Percentage reduction of BOD = .....

What can you say about the levels of ammonium and nitrate in the effluent water and the percentage reduction of ammonium and total N, compared with Exercise 3.1. Explain the differences! What can you do to improve the nitrogen removal?

**ANSWER:**

### Exercise 4.2, Calculation of external carbon dosage

In many cases, it is of value to calculate the (approximate) amount of external carbon needed. A simplified approach is to be carried out below.

a) Consider a completely mixed reactor which is described by the ASM1 using the following assumptions:

- The dissolved oxygen  $S_o = 0$ . (completely anoxic)
- The hydrolysis process is ignored.
- The decay rate is zero.
- Only heterotrophic biomass  $X_{B,H}$  is considered

- An (adapted) external carbon flow rate with COD value  $S_c$  and flow rate  $u$  is added.
- The dilution rate is  $D = Q/V$ .

The model then becomes (make sure you can derive this model from the ASM1 matrix and basic bioreactor modeling):

$$\frac{dX_{B,H}}{dt} = \mu(\theta)X_{B,H} + D(X_{B,H,in} - X_{B,H}) \quad (4)$$

$$\frac{dS_S}{dt} = -\frac{1}{Y_H}\mu(\theta)X_{B,H} + D(S_{S,in} - S_S) + \frac{S_C}{V}u \quad (5)$$

$$\frac{dS_{NO}}{dt} = -\frac{1 - Y_H}{2.86Y_H}\mu(\theta)X_{B,H} + D(S_{NO,in} - S_{NO}) \quad (6)$$

where  $\mu(\theta)$  is the specific growth rate which depends on several variables (denoted  $\theta$ ).

Consider (4) - (6) during *steady state*. Derive an expression for the necessary stationary flow rate of external carbon  $u$  using the following steps. First, assume  $S_{S,in} = 0$  (i.e. no internal organic matter available for denitrification) and  $S_S = 0$  (all external carbon is used). Then solve for  $u$  in (5) and solve for  $\frac{1}{Y_H}\mu(\theta)X_{B,H}$  in (6). Insert the last expression in the first one. Finally, let  $\Delta S_{NO} = S_{NO,in} - S_{NO}$  and you should end up with a neat expression for how much carbon flow rate is needed in order to remove  $\Delta S_{NO}$  mg/l nitrate.

**ANSWER:**

b) Calculate the desired flow rate of external carbon (transformed to l/h) for the case

$$Y_H = 0.67$$

$$Q = 250 + 250 = 500 \text{ m}^3/\text{h}$$

$$S_C = 1200000 \text{ mg/l}$$

$$\Delta S_{NO} = 4 \text{ mg/l}$$

**ANSWER:**

**Exercise 4.3, Adding an external carbon source**

First set  $Kh = 0$  (we assumed no hydrolysis), this parameter is found after clicking on the *Constants* text field. External carbon (ethanol) will be added in order to improve the denitrification and reduce the nitrate level in the anoxic compartments. The ethanol will be added in compartment 6 (first anoxic compartment). To add ethanol, just click on the pump symbol above the compartment and enter a value of the flow rate (unit l/h).

Set the flow rate calculated in Exercise 4.2b Let the process, reach steady state and check the nitrogen removal  $\Delta S_{NO} = S_{NO}^{zone5} - S_{NO}^{zone10}$ .

Note that since we have a recycle of nitrate we can not state that the nitrate level in the effluent is decreased with 4 mg/l, what we *may* say is that the reduction in the anoxic compartments should be 4 mg/l.

However, you may find that  $S_{NO}^{zone5} - S_{NO}^{zone10}$  is less than 4. Try to explain why. Hints: Is all assumptions made in Exercise 4.2a fulfilled? Is all external carbon used for denitrification?

*Optional:* Try to find a way to adjust the process so that the assumptions made in Exercise 4.2a are better fulfilled.

**ANSWER:**

**Exercise 4.4, Effect of hydrolysis**

Set  $Kh = 0.125$  and continue to add external carbon. Now, the nitrogen removal should increase. Try to explain why.

**ANSWER:**

In the long run, manual control of the external carbon source is not a very cost efficient way of getting a good nitrate removal In the next two tasks you will run an automatic carbon flow rate controller. The key idea of the control strategy is to adjust the flow rate so that the nitrate level in the last anoxic zone is kept at a

selected set point. The controller is designed<sup>1</sup> to achieve fast disturbance rejection. Disturbance rejection in this case means that the controller should equalize changes in flow rates and variations in concentrations of the influent water.

#### Exercise 4.5, Automatic control of the external carbon source

The purpose with this exercise is to illustrate a control strategy for controlling the ethanol flow rate.

Go to the menu bar *DO PID* and select *C controller* instead. The panel with oxygen PID regulators is now replaced with a external carbon source regulator. To switch to automatic carbon control, push the *ok* button. To give a new reference value of the nitrate level in the effluent water, write your new value in the text field to the right of the text *No3 ref zone 10:* and push the *set* button. By pushing the button *manual*, the control of the ethanol is switched back to the manual mode.

Try different reference values (set points) for the nitrate level and study how the controller reacts.

**ANSWER:**

#### Exercise 4.6, Control of the external carbon when influent ammonium concentration is changed

Set the nitrate level setpoint in compartment 10 to 6.0 mg/l.

When the system has reached steady state, increase the concentration of influent ammonium to 40 mg/l. Study how the effluent nitrate is affected. Can you see any differences in the nitrate levels when the disturbance is applied?

Write down the steady state concentration of the effluent nitrate when the influent ammonium is 40 mg/l: .

- Effluent nitrate = ..... mg/l

Decrease the influent ammonium to 23 mg/l and wait for steady state. Switch the carbon controller to manual mode and then increase the influent ammonium to 40 mg/l. What happens?

- Effluent nitrate = ..... mg/l

Summarize and comment on the result below.

<sup>1</sup>More about this in the course “Modellering och styrning av MTP”, periode 43.

ANSWER:

#### Exercise 4.7, Sludge overflow in the sedimentation unit

a) Reload the simulator. Before you restart, double both the influent flow rate and the return sludge flow rate to  $500 \text{ m}^3/\text{h}$  each, also increase the influent concentration to  $X_s = 160 \text{ mg/l}$  and  $X_i = 90 \text{ mg/l}$ . This can be regarded as a storm with sewer flush-out simulation. Start the simulation and look at the state of the sedimentation unit by clicking at the field *Settler state*. Note that the height of the sludge blanket is increasing (the layers with black color). How long time did it take until you reached sludge overflow (40 mg/l suspended solids concentration i effluent water)?

What is the reason for the deteriorated sedimentation? You may try to explain by drawing a sketch.

**Hint:** Think of the solid flux model.

ANSWER:

b) Try to stop the sludge overflow by increasing the excess flow rate by small stepwise changes. Did you manage to decrease the sludge overflow? What are the drawbacks when the sludge blanket and the effluent suspended solids concentration are controlled by the excess flow rate?

*Optional:* Set the excess flow rate back to  $4 \text{ m}^3/\text{h}$  and try to control the sludge blanket with the return sludge flow. Did you manage to decrease the sludge overflow? What are the drawbacks and the advatages when the sludge blanket and the effluent suspended solids concentration are controlled by the return sludge flow rate?

ANSWER:

## A Appendix 1

### A.1 A Short Java Introduction

Java is an *object-oriented* programming language. For the programmer, this means that the focus is on the data in the application and methods to manipulate that data, rather than thinking in terms of procedures. In an object oriented language, a class is collection of data and methods that operate on that data. All put together, the data and the methods describe the state and behaviour of an object. Classes are arranged in a hierarchy, so that subclasses can inherit behaviour from a superclass. This is good to know since Java has a large amount of predefined superclasses that handles graphics, networking etc.

Java is an *interpreted* language: The Java compiler generates architecture neutral byte codes for the Java Virtual Machine (the interpreter and run-time system), rather than native machine code. To run a Java program, the computer uses the interpreter to execute the compiled byte-codes. Because of the architecture neutrality and platform independency of the byte-codes, Java programs can run on any computer that the Java Virtual Machine has been ported to. Of course, the interpretation makes Java slower than programs compiled to machine-code, but for many applications, the speed of Java is completely sufficient.

A running Java interpreter can load and create instances of any Java class at any time, therefore Java is said to be a *dynamic* language. The high-level support for networking also makes Java a *distributed language*.

A thing that the programmer appreciate with Java is the simplicity of the language. From the start, Java was designed to be easy to learn and to look familiar to a majority of programmers. Java reminds a lot of C and C++, but many features that causes a lot of trouble in these languages (for instance pointers) has been removed and Java is therefore quite robust.

A big strength with Java is its built-in functions for *multithreading*. In many applications it is advantageous to execute different tasks at the same time, and compared to in C/C++, multi threading is very easy.

All-together, writing software in Java feels quite comfortable, and it is easy to write robust software even when it comes to large programs with many interacting parts.

### A.2 Overview of the simulation program

This section of the manual has the purpose to help the interested student to get a picture of the program structure in the simulator. Some fundamentals are that the program is running in two separate threads, first we have the thread initiated in the ProcGUI class. The main task of this thread is to handle different kind of events (communication between user and program). The second thread is the simulation thread initiated in the Simulator class that handles the solving of the differential equations of the ASM1. To illustrate the program threads, a block scheme with the most important program interactions is given in Figure 1. All classes that are part of the program are listed in Table 1. This table may useful to get an idea of the program structure.

Name of class	function
ProcGUI	Starts up the program, defines the GUI
AWTContainer	Contains global declarations of graphic objects
ImageCanvas	Draws the process image
RTView	Draws the scrolling graph
Bar	Draws a bar diagram
SettlerView	Draws the settler
Settlerlevel	Draws layer concentrations in the settler
UpdContainer	Contains other global class declarations
FlowInUpdate	Class for changing flows and substance concentrations
SludgeDialog	Class for showing some sludge parameters
CarFlowDialog	Class for entering an external carbon flow
ProcessDialog	Class for changing process constants
VolumeDialog	Class for entering new zone volumes
SludgeAgeDialog	Class for entering a desired value of the sludgeage
Iaw	Contains properties and equation solvers of a compartment
IawSetta	Contains properties and equation solvers of a one-dimensional layer settler
Simulator	Starts up the actual simulation

Table 4: The code of the simulator consists of 15 classes. The main purpose of each class is described in the right column.

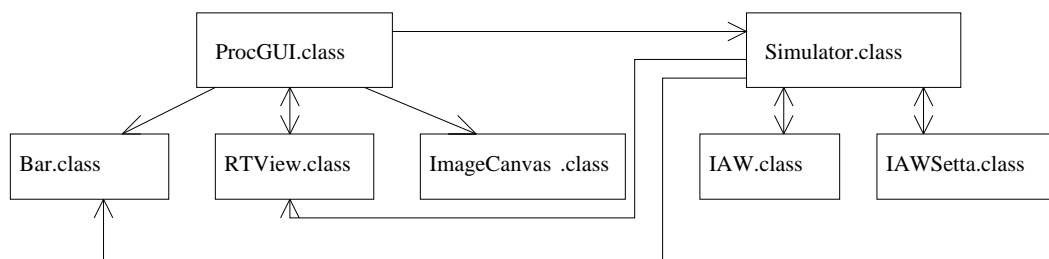


Figure 4: The main interactions in the program.



## B Appendix 2

Constants in model

deltaT = 0.0100

alfa = 5.000000

KCs = 8.6370000

--- \*\*\* ASM1 constants

--- stoichiometric constants :

Yh = 0.6700

Ya = 0.2400

fp = 0.0800

Ixb = 0.0860

Ixp = 0.0600

--- kinetic constants for heterotrophic bacteria:

mytH = 0.25

bh = 0.026

Ks = 20.000

Koh = 0.2000

Kno = 0.5000

etaG = 0.8000

--- kinetic constants for autotrophic bacteria:

mytA = 0.0330

ba = 0.0083

Knh = 1.0000

Koa = 0.4000

Ka = 0.00330

--- kinetic constants for hydrolysis:

Kh = 0.125

Kx = 0.0300

etaH = 0.4000

## C Appendix 3

### Secondary settler

- Geometry:
  - A: Area = 500 m<sup>2</sup>
  - $z_m = 1$  to 10: Height of layer m (all equal)
  - Height = 4 m
  - Settler volume = 2000 m<sup>3</sup>
- Solid flux due to gravity sedimentation  $J_s$ :

$$J_s = v_s(X)X$$

where X is the total sludge concentration

- Double-exponential settling velocity function:

$$\max \left[ 0, \min \left\{ v'_0, v_0 \left( e^{-r_h(X-X_{min})} - e^{-r_p(X-X_{min})} \right) \right\} \right]$$

$$X_{min} = f_{ns}X_f$$

Maximum settling velocity	$v'_0$	m/h	8.7
Maximum Vesilind settling velocity	$v_0$	m/h	18
Hindered zone settling parameter	$r_h$	m <sup>3</sup> /gSS	0.00057
Flocculant zone settling parameter	$r_p$	m <sup>3</sup> /gSS	0.00286
Maximum settling velocity	$f_{ns}$		0.00128

- Mass balances for the sludge:

– For the feed layer:

$$\frac{dX_m}{dt} = \frac{\frac{Q_f X_f}{A} + J_{clar,m+1} - (v_{up} + v_{dn})X_m - \min(J_{s,m}, J_{s,m-1})}{z_m}$$

where  $Q_f$  is the flowrate from the last bioreactor and  $X_f$  is the sludge concentration from the last bioreactor.

– For the intermediate layers below the feed layer:

$$\frac{dX_m}{dt} = \frac{v_{dn}(X_{m+1} - X_m) + \min(J_{s,m}, J_{s,m+1}) - \min(J_{s,m}, J_{s,m-1})}{z_m}$$

– For the bottom layer:

$$\frac{dX_1}{dt} = \frac{v_{dn}(X_2 - X_1) + \min(J_{s,2}, J_{s,1})}{z_1}$$

– For the intermediate clarification layers above the feed layer:

$$\frac{dX_m}{dt} = \frac{v_{up}(X_{m-1} - X_m) + J_{clar,m+1} - J_{clar,m}}{z_m}$$

where

$$J_{clar,j} = \begin{cases} \min(v_{s,j}X_j, v_{s,j-1}X_{j-1}) \\ v_{s,j}X_j \text{ if } X_{j-1} \leq X_t \end{cases}$$

– For the top layer:

$$\frac{dX_{10}}{dt} = \frac{v_{up}(X_9 - X_{10}) - (J_{clar,10})}{z_1}$$

with

$$J_{clar,10} = \begin{cases} \min(v_{s,10}X_{10}, v_{s,9}X_9) \\ v_{s,10}X_{10} \text{ if } X_9 \leq X_t \end{cases}$$

The threshold concentration  $X_t$  is equal to 3000 mg/l

• For the soluble components:

– For the feed layer:

$$\frac{dZ_m}{dt} = \frac{\frac{Q_f Z_f}{A} - (v_{up} + v_{dn})Z_m}{z_m}$$

– For the intermediate layers below the feed layer:

$$\frac{dZ_m}{dt} = \frac{v_{dn}(Z_{m+1} - Z_m)}{z_m}$$

– For the feed layer and the layers above the feed layer:

$$\frac{dZ_m}{dt} = \frac{v_{up}(Z_{m-1} - Z_m)}{z_m}$$

where

$$v_{dn} = \frac{Q_r + Q_w}{A}$$

$$v_{up} = \frac{Q_{eff}}{A}$$

## D Appendix 4

### Quality parameters in effluent

The total suspended solids is calculated as

$$TSS = 0.75(X_{s_{eff}} + X_{i_{eff}} + X_{p_{eff}} + X_{bh_{eff}} + X_{ba_{eff}}).$$

The total nitrogen concentration is calculated as

$$totalN = S_{no_{eff}} + S_{NKj,eff}$$

where

$$S_{NKj,eff} = S_{nh_{eff}} + S_{nd_{eff}} + X_{nd_{eff}} + I_{xb}(X_{bh_{eff}} + X_{ba_{eff}}) + I_{xp}(X_{i_{eff}} + X_{p_{eff}}).$$

Biochemical oxygen demand is calculated as

$$BOD = 0.25(S_{s_{eff}} + X_{s_{eff}} + (1 - fp)((X_{bh_{eff}} + X_{ba_{eff}})$$

and chemical oxygen demand as

$$COD = S_{s_{eff}} + S_{i_{eff}} + X_{s_{eff}} + X_{i_{eff}} + X_{p_{eff}} + X_{bh_{eff}} + X_{ba_{eff}}.$$