Modelica project - Group 14

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ABSTRACT

This Modelica/Dymola project in the course TTK4130 Modeling and Simulation at NTNU has been given for the first time in the spring semester of 2018. The goal of the project was to introduce the Modelica language and the Dymola software for the students. The software and language are powerful tools for modeling and simulating systems in a variety of physical, chemical, biological and electrical branches of science. The tool is capable of modeling and simulating complex systems over a wide range of time spans. This project is based on the "Benchmark Simulation Model no. 1 (BSM1)" by J. Alex et al. (2008) [Ale08] of a complete Wastewater Treatement Plant with varying complexity. The students were to modify and adjust several parts and parameters of the plant and observe the changes introduced.

INTRODUCTION

Wastewater is water in any form that has been contaminated by domestic or commercial processes, this including sewage and byproducts of large-scale industries. Letting enormous volumes of wastewater into lakes, rivers and oceans has a very negative effects on the biological environment. [Wri14]

The composition of wastewater may include chemical and biological pollutants. Wastewater usually contains high concentrations of nitrogen and among others phosphorous and potassium in the form of nitrates, ammonia and organic pollutants. A high amount of nitrates and nitrites will cause excess algae growth in streams and rivers. The excess algae growth depletes oxygen, which results in death of fish and other important organisms. A vast amount of organic pollutants can cause toxicity and create high oxygen demand with following damage to the ecological system. By cleaning the water through a wastewater treatment, the pollutants in the water can be removed or lowered to non-damaging levels. Wastewater also contains large amounts of solids which can be sedimented and removed. One rather problematic paradox is that the wastewater often actually contains too much water compared to the concentrations of organic matter. This is especially true when a lot of rainwater etc. is passed through the treatment plants.

Biological nitrification in wastewater treatment is the process of oxidizing the ammonia to remove nitrogen from wastewaters. Ammonia originate mostly from organic matter containing nitrogen e.g. proteins (meat and blood) and urea, releasing ammonia when bio-degrading. The process is illustrated in the following equation.

$$2\,NH_4{}^+ + 3\,O_2 \longrightarrow 2\,NO_2{}^- + 4\,H^+ + 2\,H_2O \qquad (1)$$

The autotrophic process (1) is followed by oxidation of nitrite ions to nitrate in equation (2).

$$2\,NO_2{}^- + O_2 \longrightarrow 2\,NO_3{}^- \qquad (2)$$

After the nitrification step, follows a denitrification process when nitrate (NO_3) is reduces to nitrogen gas (N_2) by a facultative hetrophic bacteria. The process occurs when oxygen levels are depleted(anoxic conditions) and nitrate becomes the primary oxygen source for microorganisms. When bacteria break apart nitrate($NO_3{}^-$) to gain the oxygen (O_2), the nitrate is reduced to nitrous oxide (N_2O), and then down to nitrogen gas (N_2) [**W.P.Company**].

The wastewater model on Figure 2 illustrates the different stages in a benchmark plant. Treatment plants are large non-linear systems, and hence to develop a suitable controller a standardized benchmark plant is developed. The plant has several different subsystems with changing properties and responses. Some parts of the plant should be controlled relatively fast, within minutes, while others takes days to react to changes. The sludge reactor consist of five active compartments, two anoxic tanks and three aerobic tanks. In the anoxic section oxygen is only available in bounded form in the water. In the aerobic tanks oxygen is continuously introduced using airbubbles. The concentrations must be precisely regulated so that the microorganisms in the tanks perform the oxidizing of ammonia.

To describe and analyze the biological process in the treatment reactor, the Activated Sludge Model no. 1 [**ASM1**] is often selected. In Figure 3 you find a general overview of the ASM1 model. The process roughly occurs in two units: an aerated biological reactor, where bacteria are used to degrade pollutants, and a settling unit(also called clarifier), in which the activated sludge settles to the bottom of the unit. Activated sludge is recycled from the bottom of the clarifier into the biological reactor [Nel09]. S is indicated in Figure 3 as soluble organic material, while the particulate organic material is denoted letter X.

METHODS AND THEORY

The control of active sludge reactors is often based on maintaining a constant concentration of dissolved oxygen within the reactor. Therefore it is common to treat the dissolved oxygen concentration as an adjustable parameter [Com87].

In our model many of the parameters are simplified. For instance the temperature dependence of the reactions in the tanks are neglected. The controllers used to automatically regulate the reactions are also deleted. The system is therefore uncontrolled and only run in open loop. To see changes in the output we must adjust parameters of the inputs and do a new simulation. Changes can be made in among others; the influent contents, oxygen concentration in the aerobic tanks, return and recycle pumping power for the sludge.

ASSIGNMENT 1 - IMPLEMENTATION OF WASTEWATER TREATMENT PLANT SIMULATION

In the first assignment we familiarized ourselves with the wastewater treatment package, by following the steps given in the project discription and assignment text, and running the benchmark example in ASM1.

Next, we aimed to develop a simulation model for the BSM1 benchmark, which is based on the report "Benchmark Simulation Model no. 1 (BSM1)". We used the ASM1 benchmark as a basis, and made a changes as stated in the assignment text. After making these changes, we tested the dynamical model on different process conditions. We used the same initial conditions as in the script file of ASM1, and ran simulations for a 14 day period. This first task, albeit very simple, required quite thorough understanding of the task, model and program. At first we did not understand what was to be expected and ended up having to redo the first task later.

ASSIGNMENT 2 - DYNAMIC OPEN-LOOP SIMULATIONS

To verify our previous simulations, a dynamic open-loop simulation was conducted. The simulation of the plant was done by removing active controllers and disregarding process noise. The simulation data will then always be identical for the same conditions.

We used the script file of ASM1 to set the initial values of the different units. Since steady-state values are invariant of the initial conditions, the initial values can be set arbitrarily. We added another WWSource with constant output as given in Table 5 of the BSM1 report [Ale08], and ran the open-loop dynamic simulation for 100 days. The results of the simulation is shown in Figure 4. As one can see, the simulation reached steady-state values within a few days and the 100 days used gives a very calm system. By comparison one can see that the results of the simulations perfectly matches those given in the file "Verificationdata.pdf". The file with the simulation results were saved as a .mat file, so that we could use is to initialize later simulations.

The next simulation was initialized using the previously saved .mat file, and ran for 14 days using the influent data contained in the file ”Infdry.txt” for ASM1. The original WWSource was again used for this task.

Our next step was to reformulate our system of equations in tank 5 such that it changes the value of Kla automatically. We want Kla to be set such that the output concentration of dissolved oxygen SO is exactly $2g(COD).m^{-3}$. After changing Kla from parameter to variable in tank 5, and adding an extra equation, we were able to plot the variation of Kla against time for this tank. This can be seen in figure 11. We can observe that Kla is adjusting based on the influent to keep SO at the desired value.

ASSIGNMENT 3 - PERFORMANCE INDICATORS I

The performance indicators given in section 6 was implemented to gauge the performance of the wastewater treatment plant. The following performance indices: EQ, PE, AE and IQ was calculated over the full time period from the first day to the 14th day. That is, $t_0 = 1$ and $t = 14$ in the formulas below.

- Effluent quality (EQ) is averaged over the period of observation T, based on a weighting of the effluent loads of compounds that have a major influence on the quality of the receiving water and that are usually included in regional legislation. It is defined as:

$$\frac{1}{T \cdot 1000} \int_{t_0}^{t} \begin{pmatrix} B_{SS} \cdot SS_e(t) + B_{COD} \cdot COD_e(t) + B_{Nkj} \cdot S_{Skj,e}(t) \\ + B_{NO} \cdot SNO, e(t) + B_{BOD5} \cdot BOD_e(t)) \end{pmatrix} Q_e(t) \cdot \mathrm{dt}$$

- Pumping energy (PE) depends on how the various tanks can be arranged on the available space. In BSM1 the pumping energy is calculated as:

$$\frac{1}{T} \int_{t_0}^{t} \left(0.004 \cdot Q_a(t) + 0.008 \cdot Q_r(t) + 0.05 \cdot Q_w(t)\right) \cdot \mathrm{dt}$$

- Aeration energy (AE) should take into account the plant peculiarities (type of diffuser, bubble size, depth of submersion, etc.) and is calculated from the K_La according to the following relation:

$$\frac{S_O^{(sat)}}{T \cdot 1.8 \cdot 1000} \int_{t_0}^{t} \left(\sum_{i=1}^{5} V_i \cdot K_L a_i(t) dt\right)$$

- Influent quality (IQ) index can be defined as:

$$\frac{1}{T \cdot 1000} \int_{t_0}^{t} \begin{pmatrix} B_{SS} \cdot SS_0(t) + B_{COD} \cdot COD_e(t) + B_{Nkj} \cdot S_{Skj,0}(t) \\ + B_{NO} \cdot SNO, 0(t) + B_{BOD5} \cdot BOD_0(t)) \end{pmatrix} Q_0(t) \cdot \mathrm{dt}$$

All these indicators were created using a sensor as template, the O_2 sensor was much used. The required equations, inputs and outputs were then added to the sensor with the Modelica text view, and if needed adjusted in the Icon and Diagram view.

ASSIGNMENT 4 - PERFORMANCE INDICATORS II

The performance indicators ME and SP from section 6 was also implemented and calculated over the full time period from the first day to the 14th day.

- The compartments in anoxic state should be mixed to avoid settling. Mixing energy (ME) is a function of the compartment volume:

$$\frac{24}{T}\int_{t_0}^{t}\sum_{i=1}^{i=5}\begin{bmatrix}0.005\cdot V_i \text{ if } K_L a_i(t) < 20d^{-1}\\ 0 \text{ otherwise}\end{bmatrix}\cdot dt$$

- Sludge production (SP) is calculated from the total solid flow from wastage and the solid accumulated in the system over the period of time:

$$\frac{1}{T}\Big(TSS(14days) - TSS(7days) + 0.75\Big)\cdot \int_{t_0}^{t}(X_{S,w} + X_{I,u} + X_{B,H,w} + X_{B,A,w})\cdot Q_w(t)\cdot dt$$

These indicators was again created from sensor templates with the required equations, inputs and outputs.

We ensured that our performance indicators from Assignment 3 and 4 gave reasonable values, by comparing them to the values given in the table on page 35 of the BSM1 report. Then, we combined all the quality indicators for the overall cost index (OCI):

$$OCI = AE + PE + 5\cdot SP + 3\cdot EC + ME$$

The OCI will be used in the following tasks as a quality assessment when changing the system.

ASSIGNMENT 5 - OPEN-LOOP SENSITIVITY ANALYSIS I

To investigate the effects of different key process parameters on the efficiency if the wastewater treatment plant, we employ the simulation set-up developed in Assignment 1, 2 ,3 and 4. A constant value Kla for tank5 was used for the nominal case given in section 4 of the BSM1 report to carry out this analysis. The file *"Inf dry.txt"* was utilized for the influent data for ASM1 initialized at steady-state. The following parameters was measured on the plant using the performance indices developed previously:

- Volumetric flow-rates of the pumps
- Y_A and Y_H

We see from the figure 5, that when we increase the max rate of the pumps, we also increase the total flow rate in the system. There is a linear relation between the flow rate and the max settings of the pumps. We have not considered if this indicates that the system is always working with the maximum allowed rates.

Changing the parameters Y_a and Y_h in the Stoichiometry settings, does not affect the pumping energy. We see from the equations in the BSM1 report that these parameters only affect the different soluble organic materials S in the sewage. Readily biodegradable substrate S_S together with S_O, S_{NO}, S_{NH} and S_{ALK}. See figures 6, 7 and 8. We can observe that S_O and S_S are the parameters that are most affected. An increase in Y_a and Y_h reduce S_O and S_S and therefore seems to give a better treatment of the sewage.

ASSIGNMENT 6 - OPEN-LOOP SENSITIVITY ANALYSIS II

As in previous assignment, the effect of the following parameters on the plant was measured using the performance indices developed in assignment 3:

- Kla values of the aeration tanks
- SO_{sat}

a) We change Kla in tanks 3 through 5 and simulate. See plots 9

We can observe that the different parameters affected by Kla react differently. For instance is S_{NH} decreasing with increasing Kla, while S_O is increasing. This seems reasonable considering that the reduction of ammonia is dependant on the oxygen concentration in the tanks. The aeration energy (AE) will also increase due to increased air injection

b) We again fixate Kla to standard values and change the So_{sat} values in the aeration tanks and simulate. See figure 10.

Here we observe that by limiting the So_{sat} the Overall Cost Index (OCI) increase. This seems to primarily be affected by an increase in sludge production (SP). The same effect can not be seen by increasing So_{sat}.

ASSIGNMENT 9 - PERFECT SETTLER MODELLING AND IMPLEMENTATION

In this assignment we implemented a new settler in our plant. See figure 14. The settler is used to remove sludge produced in the bioreactors for recycling and disposal. We wanted the settler to remove all particles, which means that the effluent stream contains no biomass. In order to model the settler, we used the equations presented in the assignment text.

Using the "settler initital.mos" script for initialization, we verified the settler by running the "infdry" input for 14 days. The settler behaved as expected. Then, we ran the settler for the constant input for 100 days. The new steady-state values of the variables in the verification data can be seen in Table 2. They do not differ much from the steady-state values for the previous settler, except for Effluent.In.Xbh which is now zero. These input variables is given by the new script file: *settler_initial.mos*

ASSIGNMENT 10 - SETTLER DESIGN

In this assignment we wanted to determine a sensible value for the surface area of the settler in the previous assignment, in order to allow for perfect separation. We did so by using the following equations:

$$T = \frac{Ah}{Q} \text{ and } T = \frac{h}{v} ,$$

where T is time spent in the settler, A is the surface area of the settler, h is the settler's height, Q is the inflow rate. v is the velocity of a particle, and is given by:

$$v = \frac{g(\rho_p - \rho_f)d^2}{18\mu} ,$$

where g is the gravitational constant, ρ_p and ρ_f is the density of respectively the particle and the liquid, d is the particle's diameter, and μ is the viscosity of the liquid.

We made a new model, and extended the settler from the previous assignment. We defined the variables needed to use the equations above, and ran the model. The calculated surface area needed for the perfect settling varied similarly to the inflow rate Q, which is to be expected. The maximum surface area is approximately 344m^2. Adding 60% margin for safety gives us a surface area of 550m^2. Assuming a width of 4m, the required length of the settler for perfect separation would be 138m. See plot 13

CONCLUSION

This assignment in the Modeling and Simulation course TTK4130, have required the students to learn how to use the Dymola software and to some degree the Modellica language. It has also given an understanding in how wastewater treatment plants function and what challenges they face with different environmental and weather conditions etc.

A deep and full understanding of the complete plant, with control and regulation of parameters and how the different components are affected by changes in conditions, are not to be expected. The complete plant is very large and have several nonlinearities which is challenging to fully comprehend from this small assignment.

All in all the Modelica Project assignment have given a good starting point for learning how to use Dymola and Modelica for modeling and simulating systems. This will likely prove important in future courses and work.

References

[Com87] The Water Planet Company. *Nitrification and Denitrification*. 1987. URL: https://ac.els-cdn.com/0043135487900583/1-s2.0-0043135487900583-main.pdf?_tid=561829a4-f241-4bbb-ab18-358d517d4927&acdnat=1520024496_2928fd4d1e146583257352edfe64a78d (visited on 03/02/2018).

[Ale08] J. Alex. *Benchmark Simulation Model no. 1 BSM1*. 2008. URL: http://apps.ensic.inpl-nancy.fr/benchmarkWWTP/Pdf/Description_BSM1_20080619.pdf (visited on 02/27/2018).

[Nel09] M.I. Nelson. *Analysis of the activated sludge model*. 2009. URL: https://www.sciencedirect.com/science/article/pii/S0893965908002528 (visited on 03/02/2018).

[Wri14] S. Wright. *The Importance of Wastewater Treatment*. 2014. URL: http://marinesciencetoday.com/2014/02/13/the-importance-of-wastewater-treatment/ (visited on 02/27/2018).

APPENDICES

Tables and figures on the following pages:

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_{NH}
Alkalinity	S_{ALK}

Table 1. Nomenclature

Variable (steady-state)	Value	Unit
Effluent.In.Salk	4.12558	mmol/l
Effluent.In.Si	30.0	mg/l
Effluent.In.Snd	0.68828	mg/l
Effluent.In.Xbh	9.78153	mg/l
tank5.aeration	630.761	
tank4.aeration	1337.07	
tank3.aeration	1507.59	
Settler.Waste.Salk	4.12558	mmol/l
Settler.Waste.Snd	0.68828	mg/l
Settler.Waste.Snh	1.73333	mg/l
Settler.Waste.Sno	10.4152	mg/l
Settler.Waste.Xbh	5004.65	mg/l
Settler.Xf	3269.84	mg/l

Fig. 1: Verificationdata

Variable (steady-state)	Value	Unit
Effluent.In.Salk	4.08619	mmol/l
Effluent.In.Si	30	mg/l
Effluent.In.Snd	0.677059	mg/l
Effluent.In.Xbh	0	mg/l
tank5.aeration	630.62	
tank4.aeration	1368.11	
tank3.aeration	1547.98	
Settler.Waste.Salk	4.08619	mmol/l
Settler.Waste.Snd	0.677059	mg/l
Settler.Waste.Snh	1.27605	mg/l
Settler.Waste.Sno	10.5094	mg/l
Settler.Waste.Xbh	5254.01	mg/l

Table 2. New steady-state values in assignment 9

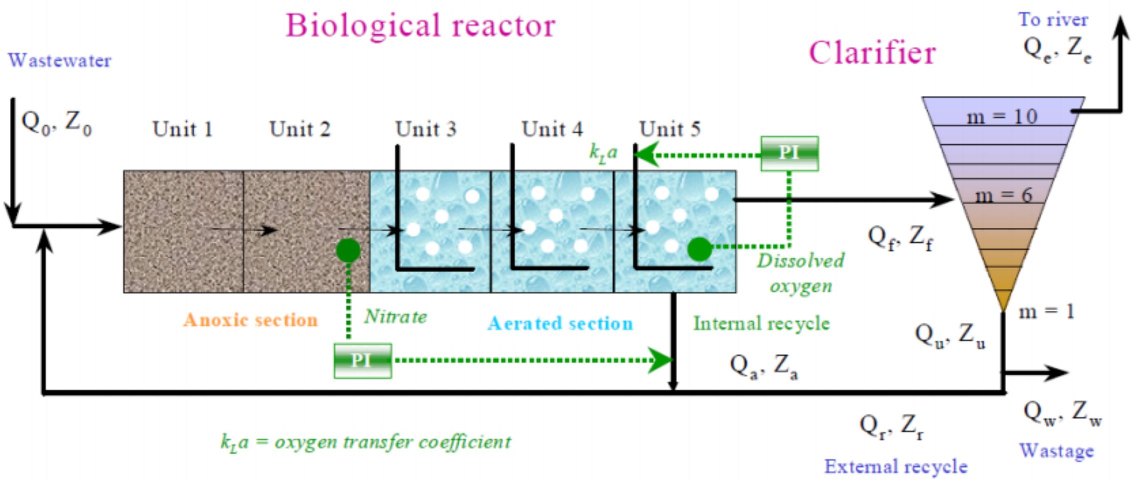

Fig. 2: Wastewater treatment plant from "Benchmark Simulation Model no 1 (BSM1)" by J. Alex et al. (2008) [Ale08]

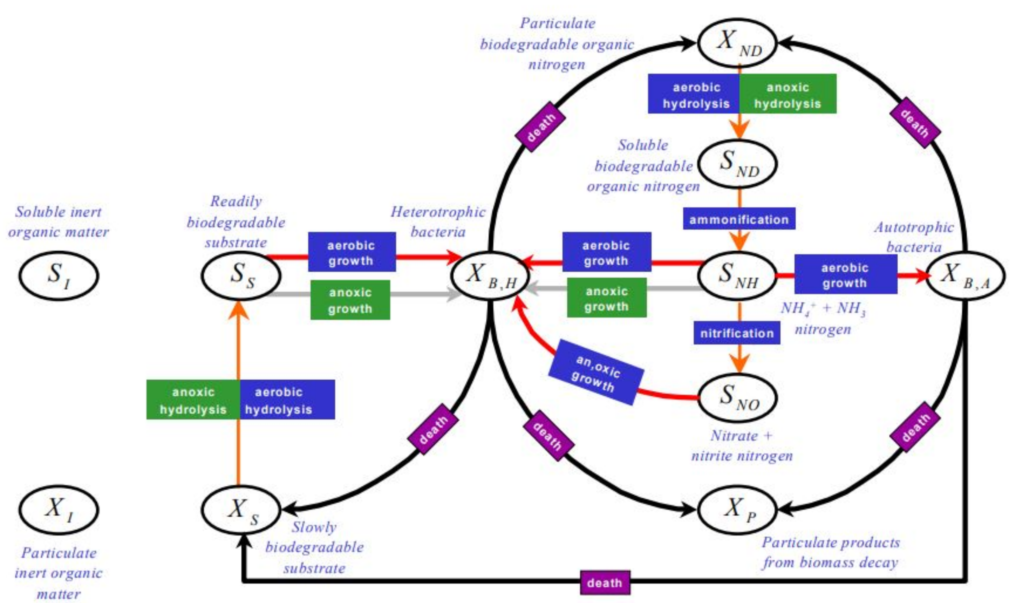

Fig. 3: Overview of ASM1

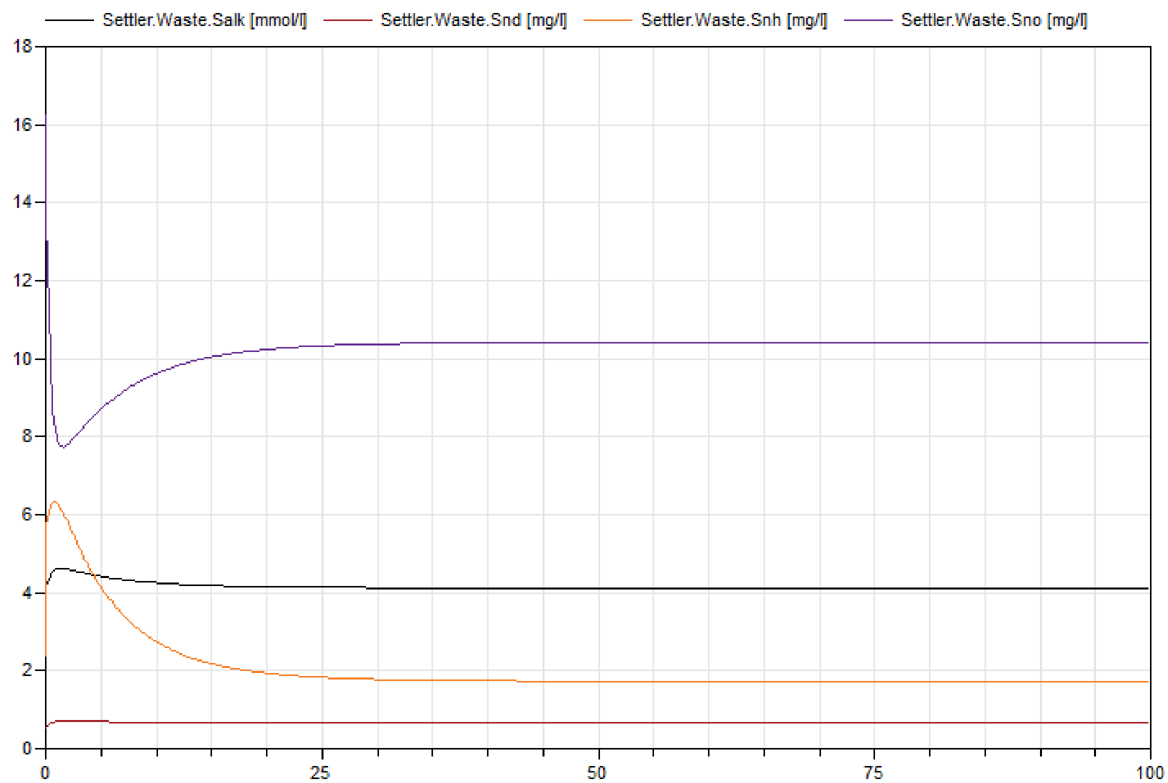

Fig. 4: Simulation of Settler for 100 days [Ale08]

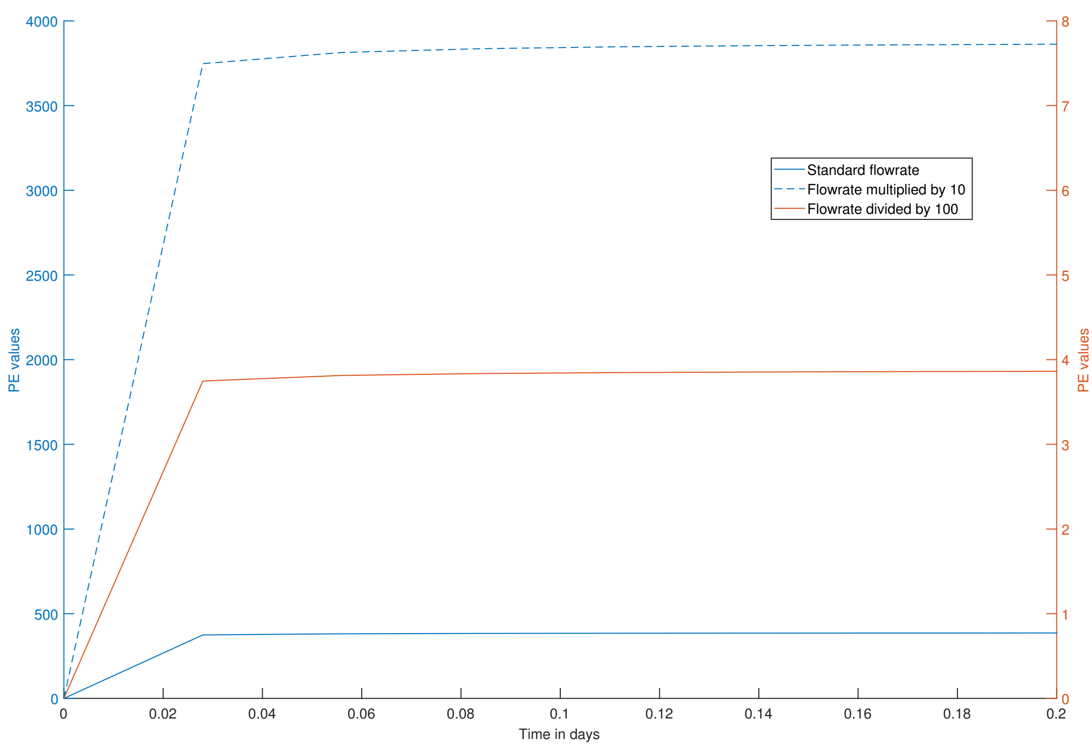

Fig. 5: Plot with Pumping Energy given different max flows from pumps

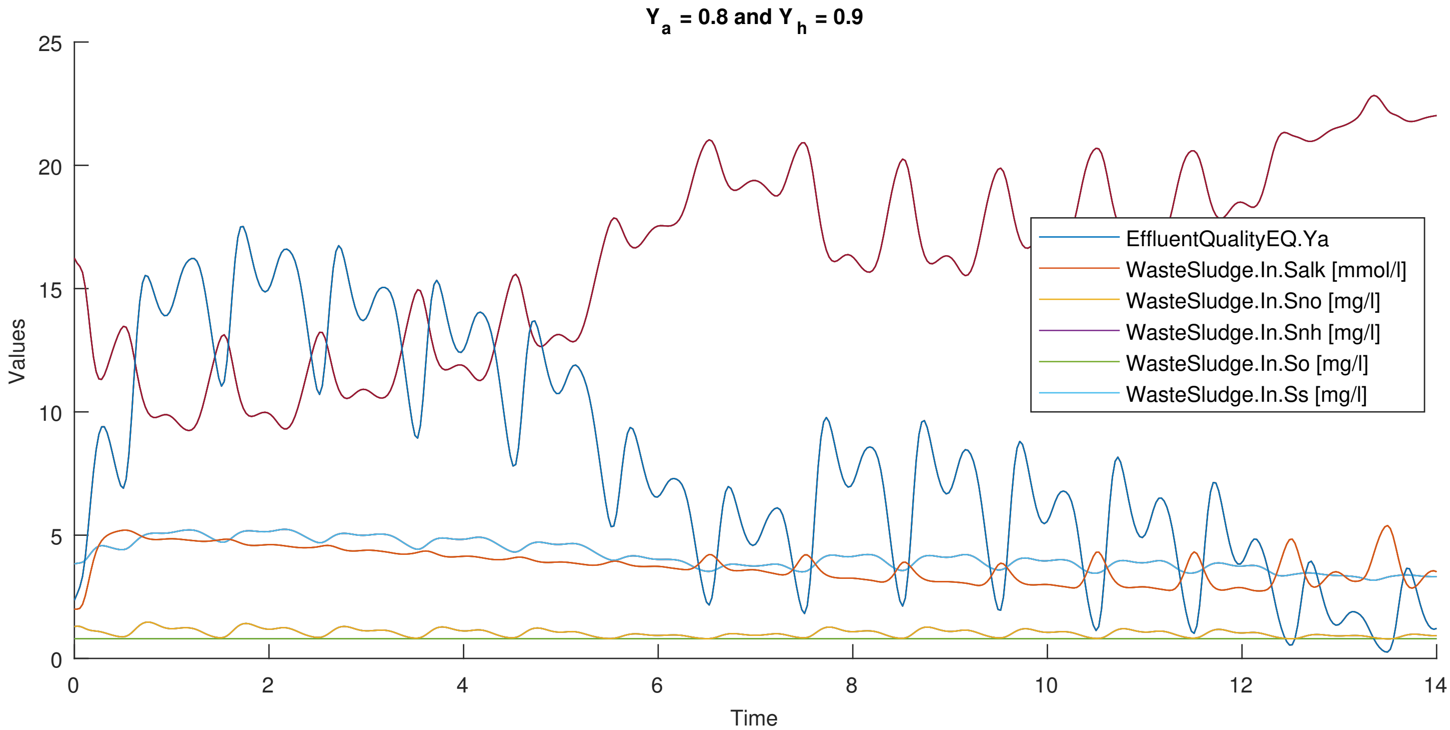

Fig. 6: $Y_a = 0.8$ and $Y_h = 0.9$

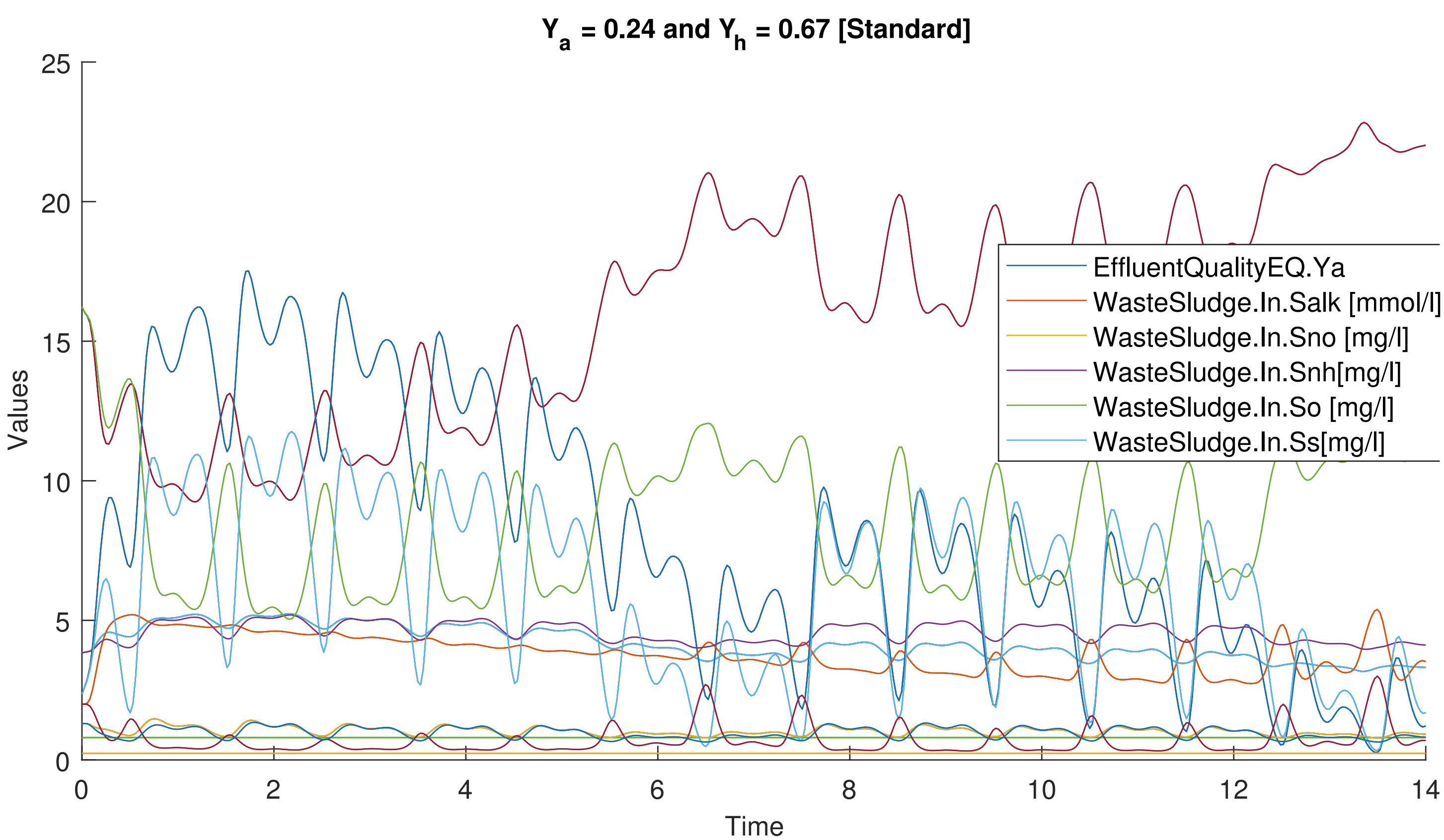

Fig. 7: $Y_a = 0.24$ and $Y_h = 0.67$

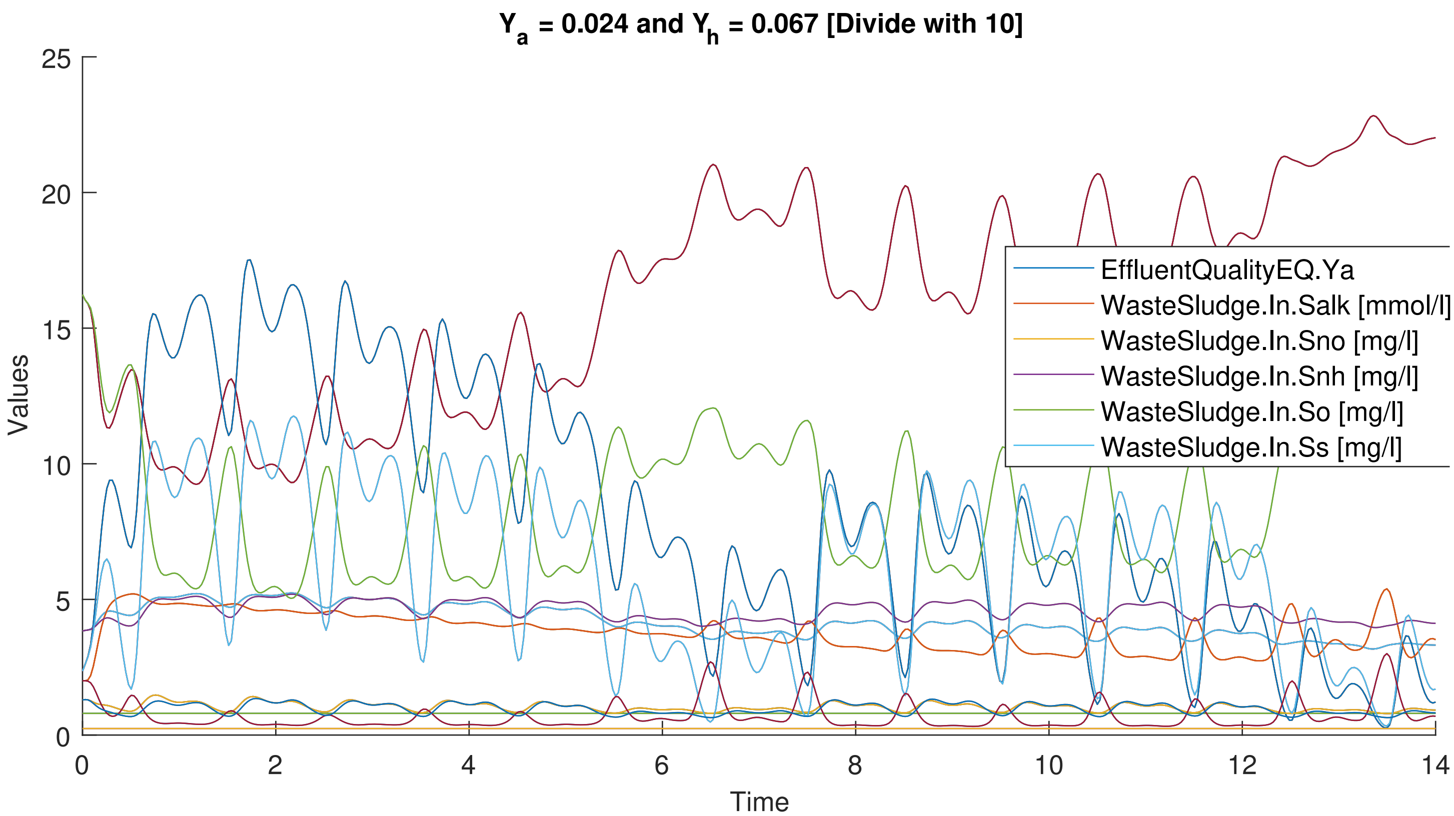

Fig. 8: $Y_a = 0.024$ and $Y_h = 0.067$

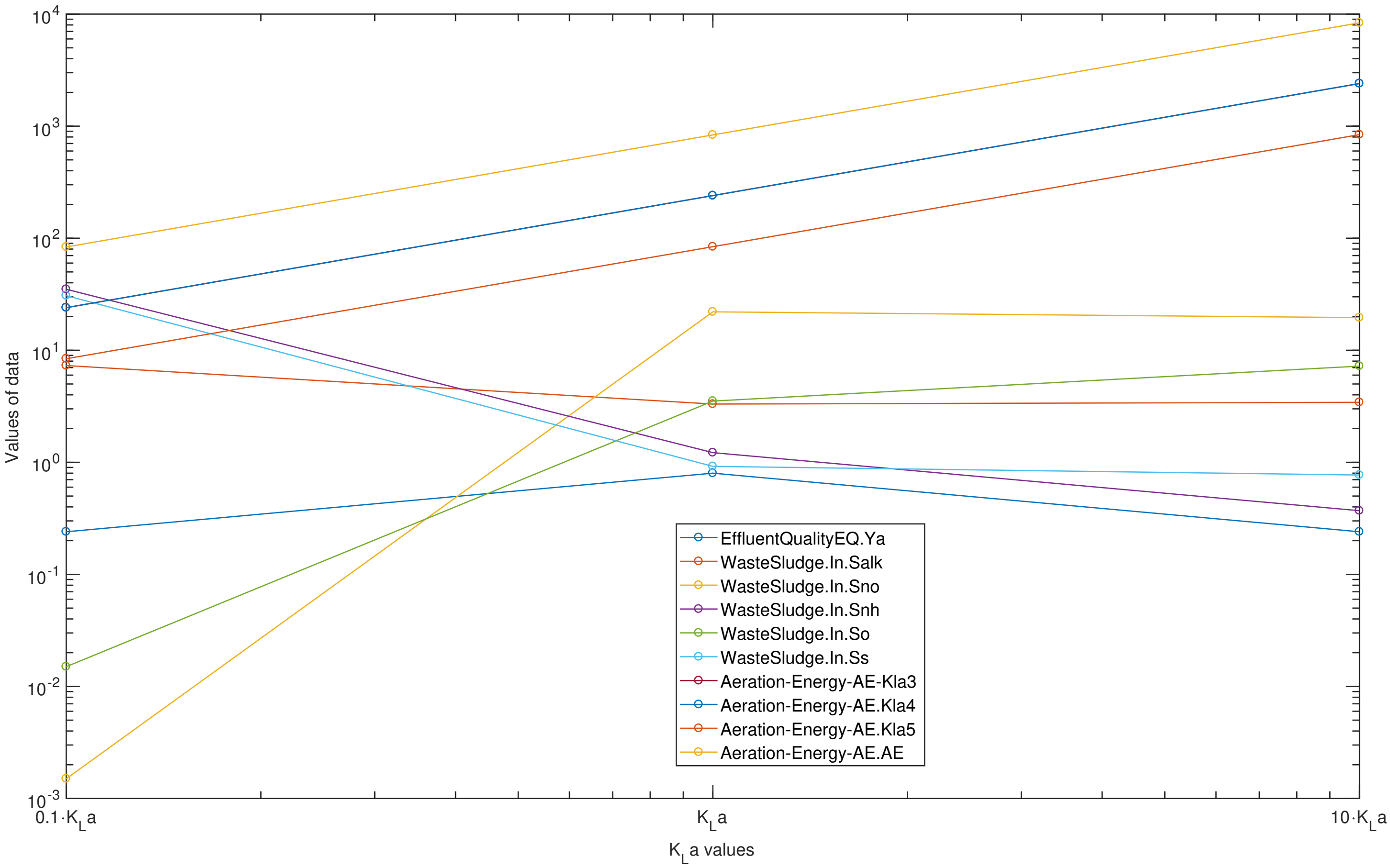

Fig. 9: Plots of parameters with different values of Kla, Standard values for Kla (84 for tank 3,4 and 240 for tank 5), compared with Kla divided by 10 and multiplied by 10. Both axis are logarithmic.

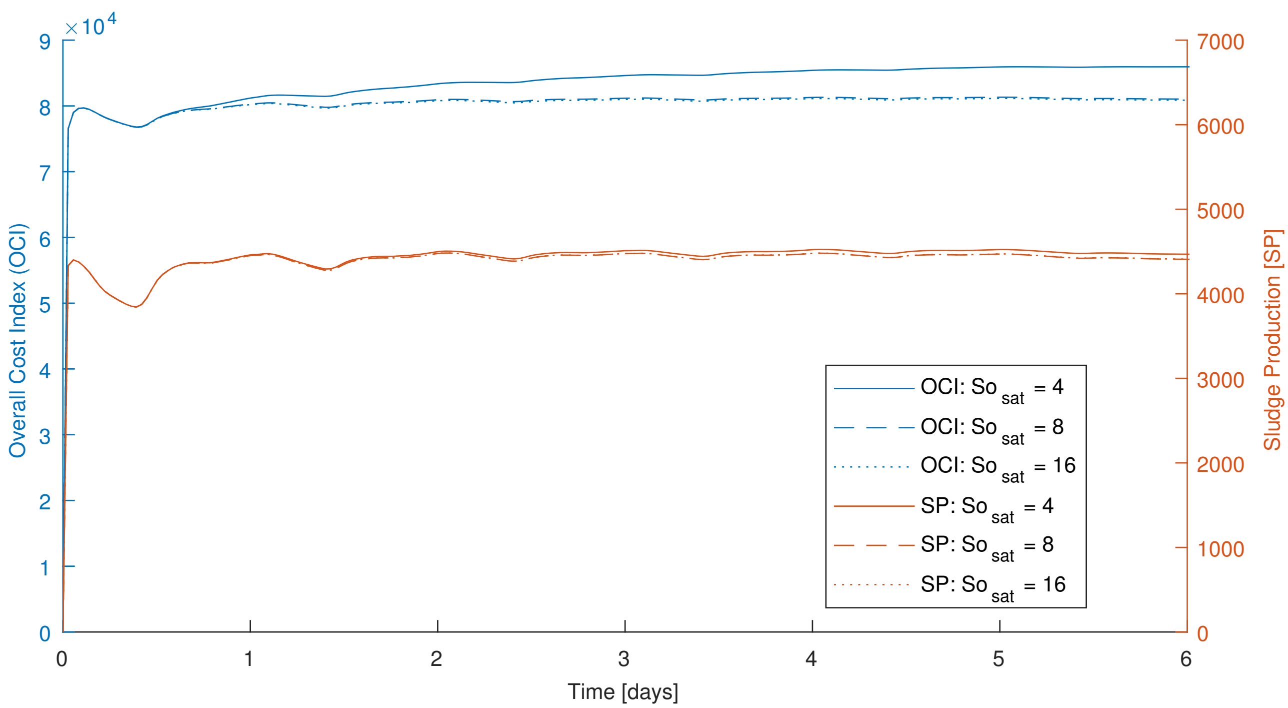

Fig. 10: Plot of OCI and SP against time with different values on So_{SAT}

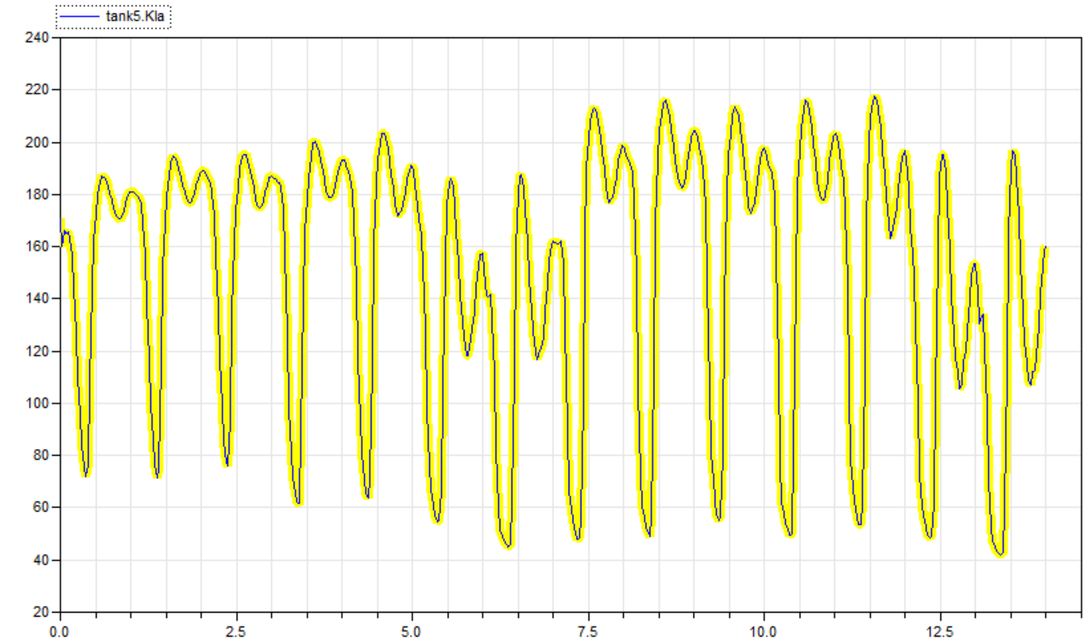

Fig. 11: Plot of tank5 with variation of Kla against time

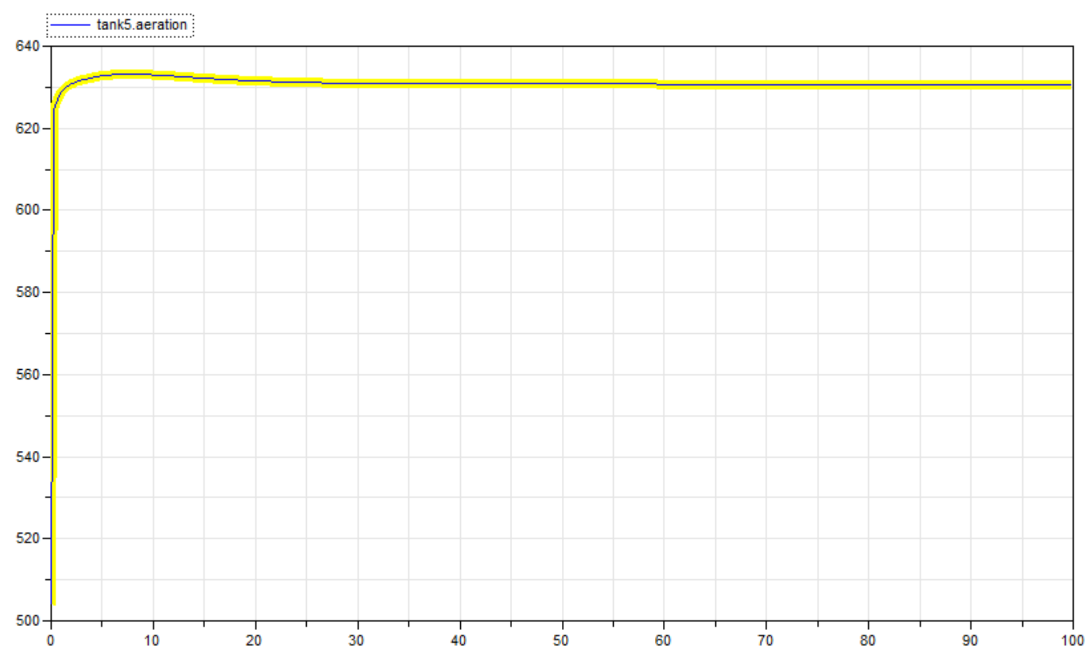

Fig. 12: Plot of tank5 with variation of Aeration against time

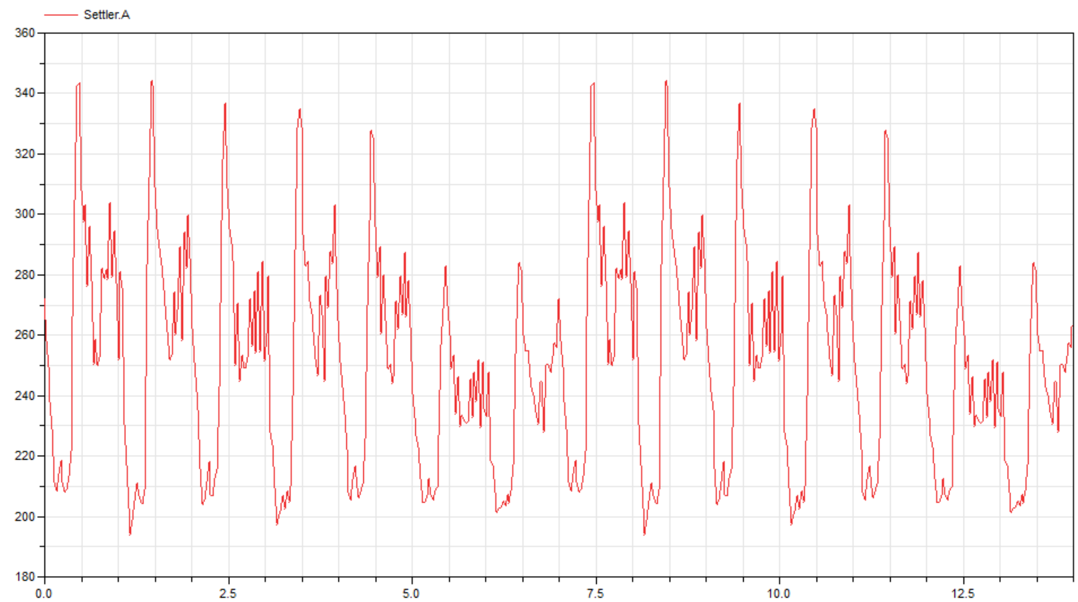

Fig. 13: Plot of the necessary area needed for perfect settling of solids, with variations in input from script against time

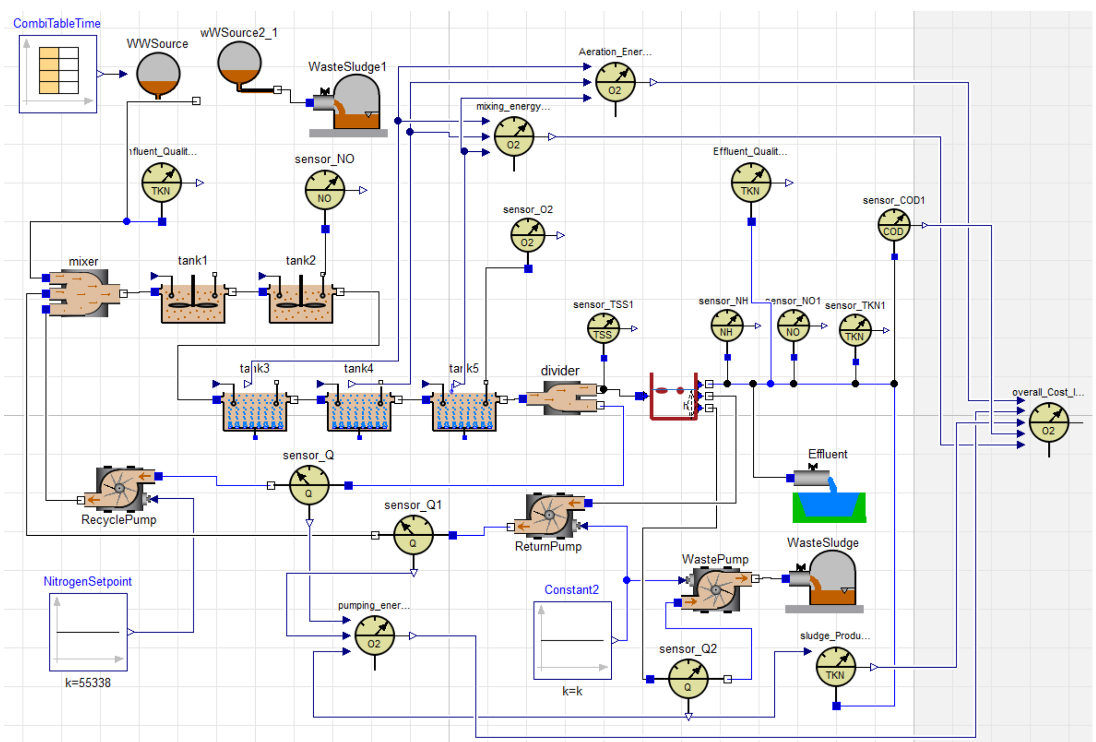

Fig. 14: The final model layout in Task 10