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Industrial Electrical Engineering and Automation

Self-study course on modelling and simulation of wastewater systems

Magnus Arnell

Division of Industrial Electrical Engineering and Automation
Faculty of Engineering, Lund University

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MAGNUS ARNELL
Doktorand, IEA, Lunds University
E–mail: magnus.arnell@iea.lth.se

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1. Course content

I have recently started PhD. studies at IEA, LTH in modelling and simulation of wastewater systems and in particular Wastewater treatment plants, WWTP. In order to familiarise myself with the subject, I have conducted a comprehensive self-study course containing literature studies and exercises.

The literature studies have included books and articles. Below are listed the publications that I read in full and in depth. In addition, many sources have been sought for references etc. I got a valuable opportunity to become familiar with research in general, the research front by date and meet the research fellows from around the world when I attended the Watermatex 2011 conference i San Sebastian, Spain. From the many exciting publications there a sample was selected and studied and summarised in subsection 2.2 below. Those are not included in the reference list but after each author is the reference to the proceedings given (Oral Presentations, OP).

Since much of the hands on work will include implementation of models and simulations with the *Benchmark Simulation Model* (BSM) system in Matlab/Simulink some exercises were also made. See appendices.

2. Methods

2.1. Literature review

WWTP models There can be many different objectives for WWTP-modelling. The books of Olsson and Newell (1999) and Makinia (2010), describe in detail the basics of modelling and different types of models. There are a great number (and increasing) of publications of models and submodels for WWT processes. A selection has been read in order to grasp the most important parts of the system, i.e. Henze et al. (2000), Gernaey et al. (2006), Takács et al. (1991). Of particular interest is the area of nitrous oxide modelling. These models are still under development and the influence of different pathways for N_2O formation is discussed. A uniform model including all processes independently is not available. Hiatt et al. (2008), Mampaey et al. (2011), Ni et al. (2011), Ni et al. (2012).

Simulation and BSM Since simulation and the BSM-systems will be an important part of my studies I made quite some effort to get to know it well. The official BSM documentation has been read in deapth and consulted frequently during the exercises, Alex et al. (2008a), Alex et al. (2008b). Some of the published articles have been studied for reference and understanding of the common knowledge in the area, Jeppsson et al. (2007), Nopens et al. (2009), Nopens et al. (2010), Rosen et al. (2006). Also application of simulations for case evaluation has been of interest, Ayesa et al. (2006).

Climate impact Of personal interest and great importance for the future research are the understanding of the over-all climate debate and how the water and wastewater services influence the climate change. Olsson (2012) gives a broad overview of the water and energy linkage. Publications from IPCC (Forster et al. , 2007, chap. 2.10) and others, such as Shine et al. (2005) and Wiedmann et al. (2005) have provided a good understanding of the different measures for GHG emissions and climate impact and how they can be used. Some specific references on WWTP GHG emissions have been studied, e.g. Flores-Alsina et al. (2011), Gori et al. (2011) and also publications on LCA of WWTPs (Lim and Park , 2009; Pasqualino et al. , 2009; Høibye et al. , 2008).

2.2. Watermatex 2011

A GENERIC ALGORITHM FOR REAL TIME CONTROL OF URBAN DRAINAGE SYSTEMS - APPLIED IN PRACTICE

Schütze M. et. al., OP II p. 461 - 467

This paper describes an algorithm for real time control of urban drainage systems. The aim of the authors has been to simplify the often complicated model-based control strategies in order to encourage implementation in real drainage systems, a goal I think they have reached. The control algorithm is based on the fact that many sewer networks have a number of storage-tanks that already have local control based on control of the flow out from the tank based on for example the level in the tank. They refer to earlier work that have shown the applicability and potential of implementing an overarching control strategy for all of the system.

Their proposed algorithm is basically just controlling the flow upstream based on the situation downstream. The strategy is tested in a number of case-studies with varying results but always a significant reduction of overflow volumes.

My remarks are:

- The work is done in an area of great importance for the industry but from a research point of view it is quite basic.
- The work focuses on the practical aspects as ease of implementation and that is good.

- The overall structure of the control is well described but I miss a more detailed description of the actual control set up for tank volumes etc.
- Finally the paper collects a good list of references and gives good suggestions on future work.

A MULTI-LAYER MODELING SOFTWARE FRAMEWORK SUPPORTING THE DESIGN OF AUTOMATIC CONTROL SOLUTIONS IN WWTPS

Maiza M. et. al., OP I p. 208 - 215

This paper addresses the fact that most existing WWTP-models and software implementations of them are not built to be totally realistic in all aspects. The authors' work has been to implement more realistic models for a number of sensors and actuators as pumps and blowers but also to add a supervisory control layer reflecting the behaviour of a SCADA-system for control of the plant. The implementation in WEST/Matlab is described and also two case studies were the concept is tested. The work is ambitious and succeed to a great extent with the objective of the study but the amount of results from the case-study is scarce and hard to evaluate.

My remarks are:

- It is a good idea to add more realism to the simulation-tools available.
- The modelling of pumps and blowers are new in this context but for sensors it has been presented and widely used elsewhere which also is acknowledged.
- I really do not understand the idea with the hierarchical structure other than for communication of the concept. But to also implement it that way and even use different simulation platforms for the different tasks seems unnecessarily complicated.

SUGGESTION OF A MULTI-OBJECTIVE CONTROL STRATEGY ON MAXIMIZATION OF CH_4-PRODUCTION AND MINIMIZATION OF EFFLUENT NUTRIENTS IN BSM2

Kim M.J. et. al., OP I p. 127 - 134

The work of the authors addresses an important problem in practical operation of WWTPs, to apply the best control-strategy for conflicting multi-objective operational goals. In this case they have chosen a common one namely to minimize the effluent nitrogen and at the same time maximizing the gas-production.

The paper is very well written with a good background description of the complicated situation and what problems single loop or single objective control strategies can give rise to. They describe the method for achieving a multi-objective strategy *Multi Objective Generic Algorithm, MOGA,* in a clear and easily understandable way. For me it seems like they have chosen the right method to solve the problem and the results they present support that they found a good solution for the problem.

My remarks are:

- A well written paper that is easy to read and understand.
- The method to find a control strategy for multi objectives and often conflicting situations should be general and possible to apply in other cases.
- I do not miss anything but own knowledge in the field. Therefore I can not really say if this is truly new or mostly common knowledge.

INTEGRATED SIMULATION OF MASS AND ENERGY FOR OPTIMIZING OPERATIONAL STRATEGIES IN WWTPS

Fernández T. et. al., OP I p. 101 - 110

This paper claims to suggest and use an expanded Plant Wide Model, based on complete mass- and energy-balances. Both sets of equations include all media and boundary-interactions. For mass-balances that is water, gas-flow and head-space gas, for energy a complete enthalpy-balance of the parameters above plus for enthalpy-conversions at boundaries and from actuators. This gives rise to a large set of equations to solve and the model is quite well described in the paper.

The proposed model is tested on a WWTP according to the BSM2 set-up modified with a pretreatment of the sludge before digestion. The results show that they indeed can interpret the integrated behaviour of mass and energy conversion in especially the aerobic digestion pretreatment.

My remarks are:

- Generally the paper is well written and easy to follow. I like that the model is well described.
- The work of the authors really intends to increase the detail and accuracy of the models. This is an obvious idea and in this case as far as I can determine also well performed.
- As I understand it this is of large importance in cases where the reactions (biological or chemical) produce or use a lot of energy or the

actuators such as blowers or pumps significantly contribute to the energy balance.

- I do not feel that my efforts in calculation energy-consumption of the whole plant operation need to go into this detail.

TOWARDS A BENCHMARKING TOOL FOR MINIMIZING WASTEWATER UTILITY GREENHOUSE GAS FOOTPRINTS

Porro J. et al, OP II p. 507 - 517

In this paper the standard BSM2-platform has been extended both in spatial conditions to include the sewer network and in scope of evaluation with a model for determination of N_2O, methane production in sewers and slip from digestion and carbon emissions that arise from energy usage. For all new processes existing and published models are used, they are only roughly described in the paper but numerous references lead to more detailed descriptions for the interested reader. The new system-wide benchmark is tested with three scenarios and different control strategies to evaluate the effect on GHG-emissions. The results are interesting and show among other things that the methane-production in the sewers account for about 8 % of the total, that sometimes when aeration is lowered in order to save energy and reduce CO_2-emissions the net benefit is negative due to increasing N_2O-emissions. They also show that the N_2O-emissions in the dynamic simulation exceed the steady-state case by 11 %, which show that the dynamics have to be considered.

My remarks are:

- This is directly related to what I would like to do. I will follow up the references and learn more about their work.
- It will be interesting to see the comparison with other models.

LCA OF WASTEWATER TREATMENT SYSTEMS: INTRODUCING A NET ENVIRONMENTAL BENEFIT APPROACH

Godin D. et. al., OP I p. 159 - 167

The authors have identified that the standard (ISO 14040) for LCA does not fit very well for analyzing WWTP:s since it associates the discharged treated wastewater with the treatment plant without taking into account neither the fact that the pollutant origins from somewhere else nor that the alternative to discharge the wastewater without treatment would be far worse. In this paper it is therefore proposed to use *Life Cycle Impact Assessment, LCIA,* taking into account the net environmental benefit that the treatment of the wastewater makes. They describe the method and the major differences to traditional LCA and also test it on a small WWTP in Canada. Even though my skills in LCA are not good enough I can see that this approach has a great potential.

My remarks are:

- I think this is a really good idea and think it could be used in several different applications, not the least in evaluation of new advanced far reaching treatment technologies.
- The paper is well written and easy to follow.
- In the case study I am a bit skeptical to three facts: *i)* the sampling of heavy metals can hardly be representative for the whole life cycle; *ii)* the fact that they do not give the sludge any credits as fertilizer is probably wrong and thereby gives rise to a major error since other studies have showed that this effect is significant; *iii)* even if the sludge does not act as a fertilizer it is still transported to agricultural lands and spread there and therefore the transport for that should be included. The last remark probably has a minor impact.

TOWARDS A STANDARD METHOD FOR LIFE CYCLE ASSESSMENTS OF WASTEWATER TREATMENT

Corominas Ll., OP I p. 168 - 175

This paper presents the results of a literature review of 41 papers dealing with LCA and wastewater treatment. It examines the applied LCA-method for each study and identifies the similarities and differences between them. It highlights that there is a need for a standard for LCA of WWT beyond the ISO-standard in order to provide comparability. Some new research also needs to be conducted in order to get useful data. No real suggestions for a standard method is propsed.

My remarks are:

- The article shows the problems with LCA today and a future standard would be good.
- The reference list is extensive and useful.

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A. Benchmark Simulation Model no. 1 - a control exercise

Benchmark Simulation Model no. 1 - a control exercise

Magnus Arnell
PhD student, IEA, Lund University
E–mail: magnus.arnell@iea.lth.se

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1. Introduction

As a part of my PhD-studies in benchmarking and control of wastewater systems at IEA, I started a literature review to learn about both basic, general and specific topics of concern for the subject. Part of this work is also to learn and get familiar with the Benchmark Simulation Model no. 1 and. 2 (BSM1 resp. BSM2) and more specific the Matlab/Simulink implementation of BSM1 and BSM2. In order to do that I have tried to implement a control strategy in each of the systems. This report describes the work in BSM1.

2. Method

2.1. The BSM1 protocol

The simulation platform used for this exercise is the BSM1 as described by [1] implemented in Matlab.

Plant and Model description

The plant consists of five biological reactors in series. In the default set up the first two are non-aerated with a volume of 1 000 m^3each and compartment number three to five are aerated, volume = 1 333 m^3each. The biological model is the Activated Sludge Model no. 1, ASM1 [3].

The bioreactors are followed by a settler, modelled as a 10-layer unit without biological reactions with an area of 1500 $m^2$and a depth of 4 m (0.4 m/layer). The influent enters at layer 6 from the bottom. The model described by [4] is chosen for the sedimentation processes.

The BSM1 package includes a series of control handles and sensor types in order to make it easy for each and every one to implement their own control strategy and evaluate it against others.

Default control strategy

The main objectives for the default control strategy is to *i)* maintain the NO_3-N-concentration at a pre set value of 1 mg NO_3-N/l and *ii)* maintain the oxygen concentration in the last reactor, no. 5, at 2 mg O_2/l. This is achieved by implementing two PI-controllers with NO_3-N and O_2-sensors that manipulates the recirculation rate of RAS for the NO_3-N-control and the $K_\mathrm{L}a$ 5 for the oxygen-control.

Simulation protocol

The simulation procedure is carried out in three steps: *i)* The system is initialized by performing a 100 days simulation with constant influent to reach steady state. This is used as the starting point for the dynamic simulations; *ii)* a 28 days dynamic simulation including the proposed control strategy, first 14 d dry weather influent followed by dry, rain or storm weather. Measurement noise is applied; *iii)* performance assessment with the built in calculations of: Effluent quality Index, EQI, Operational Cost Index, OCI, permit violations, risks and much more. See [1] for a detailed description.

2.2. Control strategy

The proposed control strategy is based on the fact that some treatment-plants have permits that prioritize a low effluent concentration of total nitrogen but not necessarily an extremely low ammonia-concentration. In that case a larger portion of the activated sludge reactor volume can be used for denitrification. To facilitate that the BSM1 plant configuration allows to alternate any of the 5 reactors between aerated or non-aerated/mixed conditions. But to just increase the number of non-aerated tanks from two to three would reduce the nitrification capacity way too much and violate the ammonia-criteria not just temporarily but also as an average.

In order to propose a control strategy to handle this in a cost effective way the following is proposed:

- in bioreactor 3 the aeration is regulated intermittently with an on/off-controller;
- the length of the aerated and non-aerated periods respectively is based on the ammonia-concentration at the outlet of the last bioreactor;
- the $K_{\mathrm{L}}a$ 3 (i.e. the airflow to the third bioreactor) is fixed to 240 during the aerated periods;
- The ammonia-level for switching state is chosen to 2 mg NH_4-N/l.

This way the average effluent ammonia-concentration is sure to be kept below the limit of 4 mg NH_4-N/l and at the same time using the maximum possible reactor volume for denitrification. To measure the ammonia concentration a ammonia sensor is introduced.

IMPLEMENTATION

The control strategy is applied in the Matlab/Simulink standard BSM1 implementation. The Simulink scheme is shown in figure 1. The sensor chosen for detection of ammonia in the effluent of tank 5 is a sensor with slow filtration and gas sensitive probe, model sensor type C0. The output signal is connected to a switch which changes the $K_{\mathrm{L}}a$ between 0 and $K_{\mathrm{L}}a$ 3 at the selected ammonia value.

The simulations were made according to the standard protocol for BSM1 as described above with the dry weather influent.

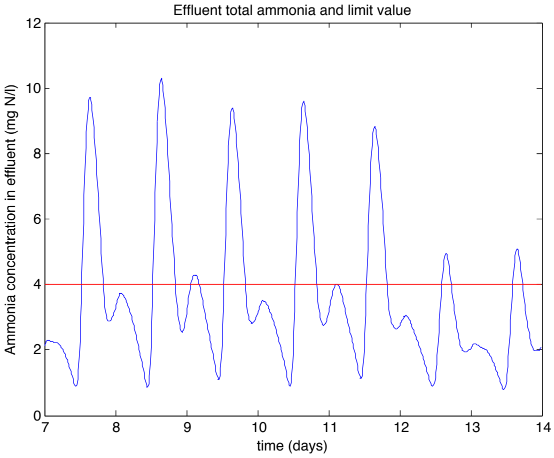

Figure 2. SNH in effluent for the proposed control strategy.

3. Results

The primary results are presented in table 1. The dynamic output for the most important parameters are shown in figures 2 to 8.

Table 1. Primary results in comparison with the default control strategy

	On/Off $K_{\mathrm{L}}a$ 3	Default
EQI [kg poll.units/d]	6369	6096
OCI	16121	16366
SNH in effl. [mg N/l]	3.6798	2.4783
SNO in effl. [mg N/l]	10.0941	12.4459
TN in effl. [mg N/l]	15.8175	16.8908
SNH violation [%]	27.6786	16.8155

4. Discussion

General performance The overall performance of the treatment plant is summarized in the EQI. For the proposed control strategy the value is 6369 which is higher than for the default case (EQI=6096). This is because the rise in ammonia increases the value more than

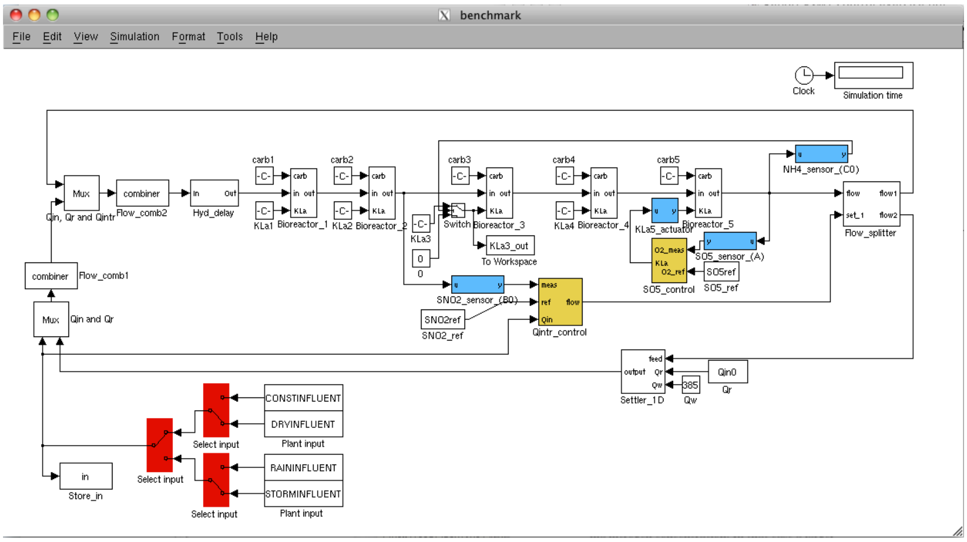

Figure 1. Implementation of control strategy in Simulink.

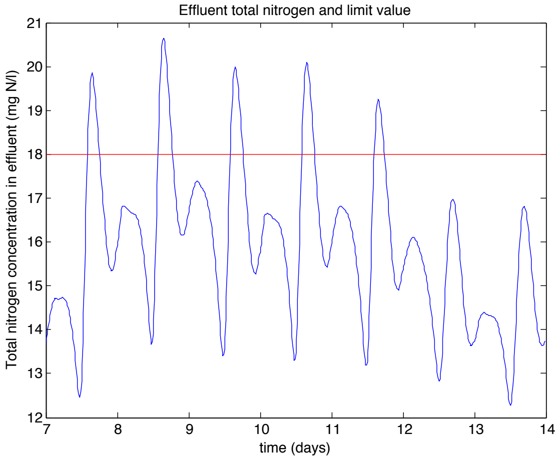

Figure 3. TN in effluent for the proposed control strategy.

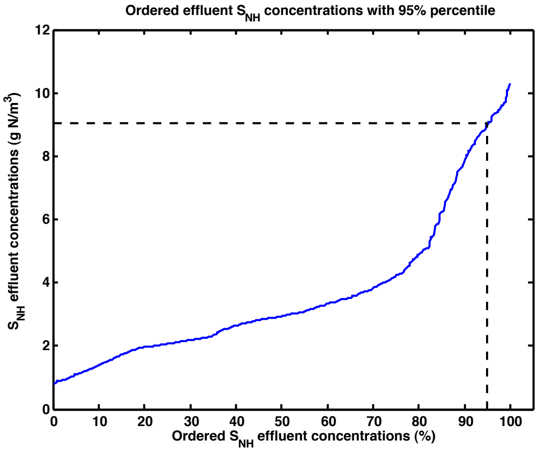

Figure 4. Ordered SNH in effluent for the proposed control strategy.

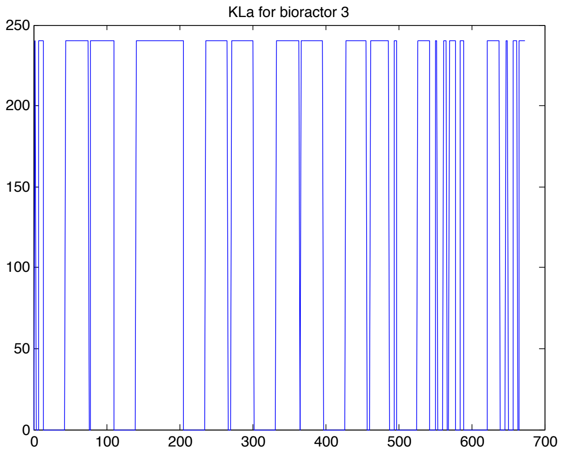

Figure 5. K_La 3 for the proposed control strategy.

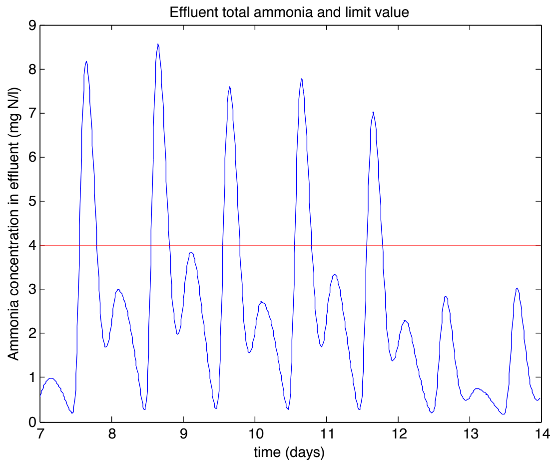

Figure 6. SNH in effluent for the default control strategy.

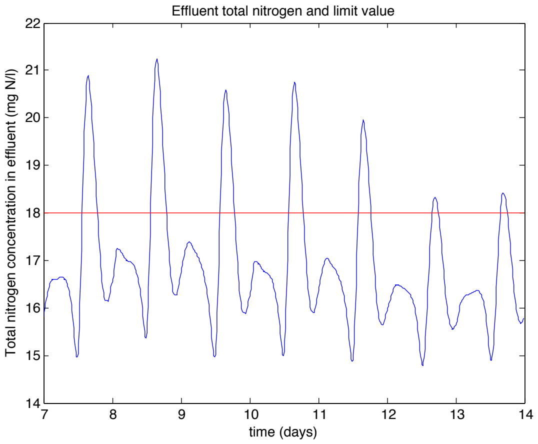

Figure 7. TN in effluent for the default control strategy.

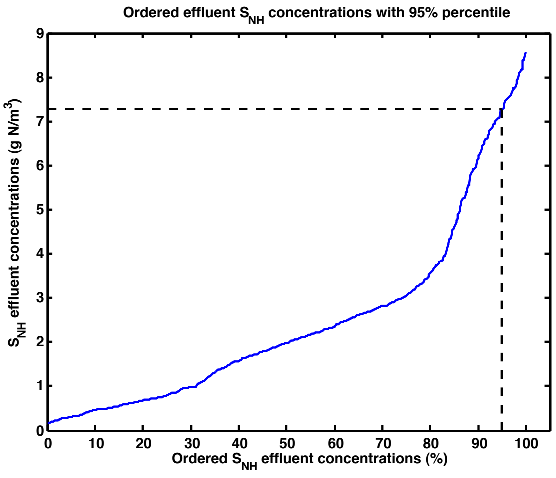

Figure 8. Ordered SNH in effluent for the default control strategy.

the decrease from lowered total nitrogen, TN. This is of course correct for most receiving waters.

Nitrogen removal In this example, to lower the TN was prioritized over an extremely low SNH. For that case a control strategy was chosen that allowed an increase in SNH in order to lower the overall TN. The results show that this goal is reached. The TN has decreased from 16.89 mg N/l as an average down to 15.81 mg N/l. At the same time the SNH has increased from 2.45 to 3.68 mg N/l as an average. As the benchmark protocol is set up with a SNH limit of 4 mg N/l the violation of that limit is increased with just above 10 % of the total evaluation time of 7 days.

Costs for implementation The total operating cost for the plant, OCI, has decreased from 16 366 to 16 121 since not as much ammonia is nitrified. The cost for a real implementation would be small, only one sensor has to be installed.

5. Conclusions

Although the decrease in TN is relatively small, 1 mgN/l or 6.5 %, the goal for the control strategy is fulfilled. The rise in SNH is just as small in absolute numbers, about 1 mgN/l, which corresponds to an increase of 49 % of effluent ammonia concentration. If this trade-off is net positive depends of course of the specific case. In the case with the plant in BSM1 it was not worth it since the EQI increased significantly.

On the other hand the cost for implementation and operation is small or profitable. The most obvious alternative to decrease the TN without increasing SNH would be to add a dosage of carbon-source. That would cost more to install with tanks, pumps etc. and give rise to a large operating cost.

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B. Benchmark Simulation Model no. 2 - a case study

Benchmark Simulation Model no. 2 - a case study

MAGNUS ARNELL
PhD student, IEA, Lund University
E–mail: magnus.arnell@iea.lth.se

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1. Introduction

As a part of my PhD-studies in benchmarking and control of wastewater systems at IEA, I started a literature review to learn about both basic, general and specific topics of concern for the subject. Part of this work is also to learn and get familiar with the Benchmark Simulation Model no. 1 and 2 (BSM1 resp. BSM2) and more specific the Maltlab/Simulink implementation of BSM1 and BSM2. In order to do that I have implemented a number of control strategies in each of the systems. The strategies were not chosen specifically or optimized to beat the default strategy or claim to be the best available choice but rather to give good and reasonable exercises. This report describes the work in BSM2.

2. Method

2.1. The BSM2 protocol

The platform used for the simulations in this study is the Benchmark Simulation Model no. 2, BSM2 [1]. It is a plant-wide model for simulation of a wastewater treatment plant (WWTP) that can be used for evaluating performance of for example control strategies.

PLANT AND MODEL DESCRIPTION

The BSM2 is a complete simulation platform for comparison of control strategies for WWTP:s. It consists of a plant layout, appointed dynamic models for the unit processes and implementation of them, influent loads, test procedures and evaluation criteria. The platform is not based on any specific simulation program and have been implemented in several platforms (Matlab, Fortran etc.) and even a few commercial platforms made for specific WWTP simulations (WEST, GPS-X Simba etc.). For this study the Matlab/Simulink implementation by Ulf Jeppsson has been used.

The plant layout as shown in figure 1 consists of,

- a primary clarifier,
- a 5 reactor activated sludge treatment with pre-denitrification, modelled with the original ASM1-model [3].
- a secondary settling tank modelled with the wide spread 10 layer Tacács model [5].
- a mesophilic anaerobic digester for primary- and thickened secondary sludge and followed by dewatering of the digested sludge. The dewatering unit is modelled as ideal separation and the digester with the ADM 1 [2]. To be able to interact with the ASM 1 model the digester implementation also includes two interfaces (one before and one after the digester) for converting the states between the two models [4].
- a storage tank for the decant from the sludge dewatering.

Apart from the unit processes the plant layout offers a large number of control handles ranging from different bypasses to process parameters such as airflow and pumping rates.

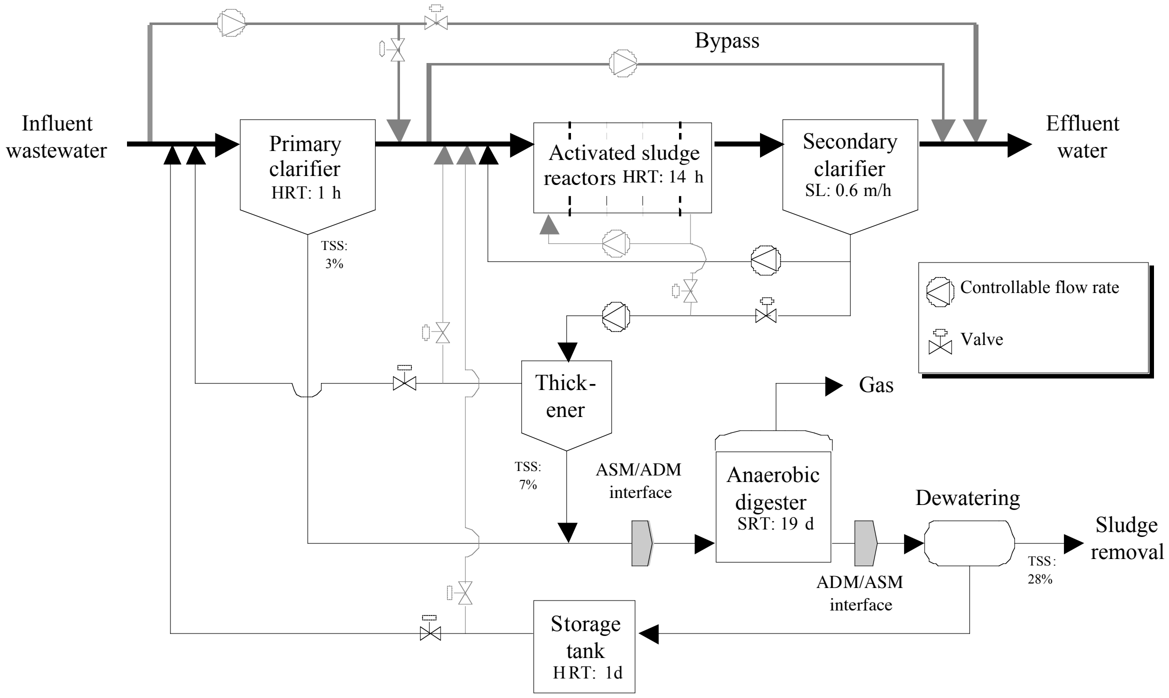

Figure 1. Principle plant layout in BSM2

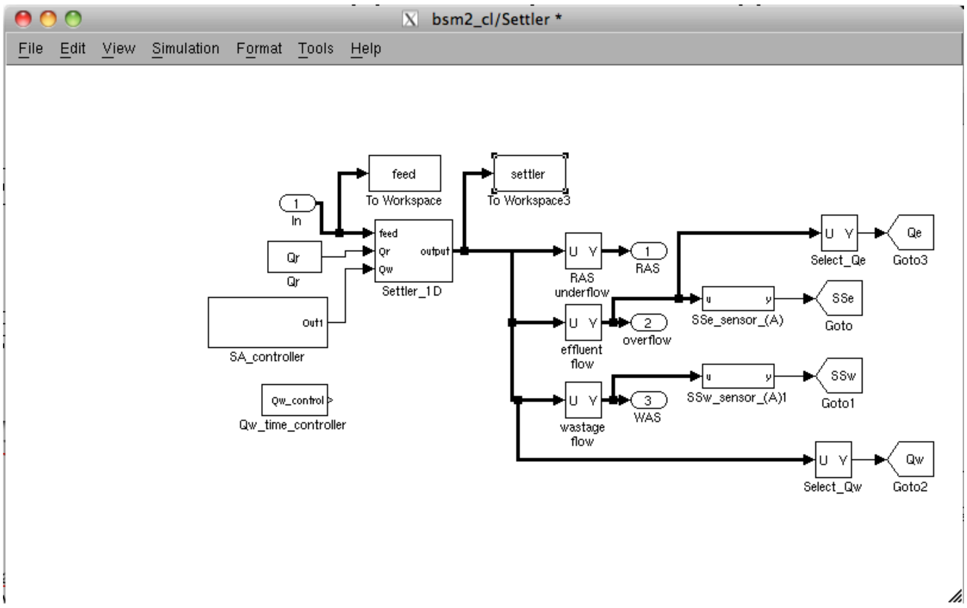

Figure 2. Settler subsystem for sludge age control in Simulink implementation

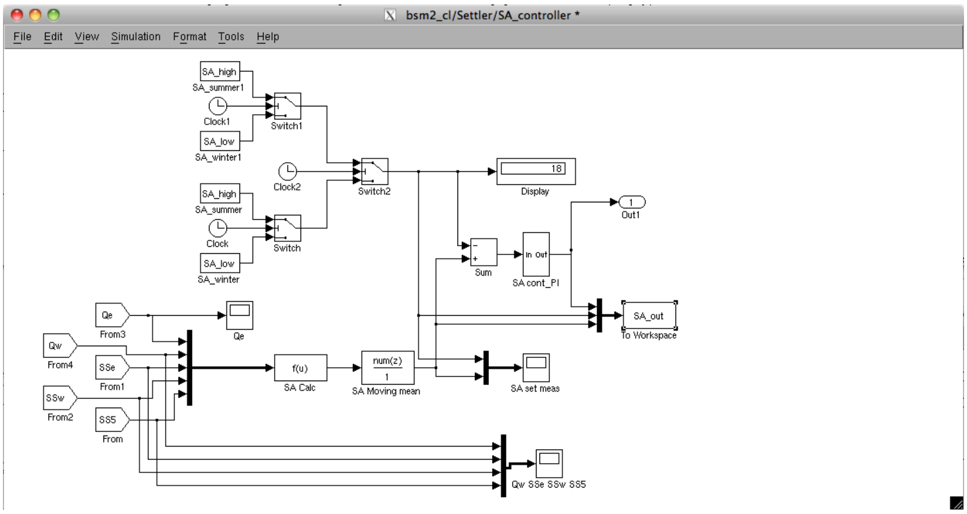

Figure 3. Sludge age control in Simulink implementation

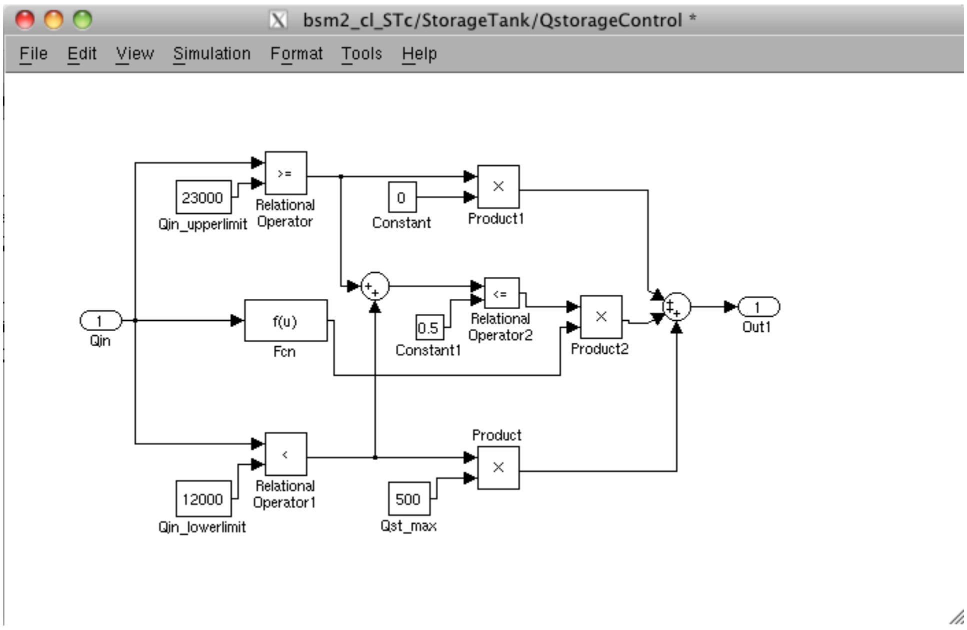

Figure 4. Storage tank control in Simulink implementation

SIMULATION PROTOCOL

The simulation procedure is carried out in three steps; *i)* The system is initialized by performing a 1000 days simulation with constant influent to reach steady state. This is used as the starting point for the dynamic simulations; *ii)* a 609 days dynamic simulation including the proposed control strategy, dynamic influent and with noise on sensors and actuators; *iii)* Performance assessment of the last 364 days with the built in calculations of: Effluent Quality Index, EQI, Operational Cost Index, OCI, permit violations, risks and much more. See [1] for a detailed description.

2.2. Control strategies

Three control strategies are proposed and tested in this exercise. Each of them is implemented separately in order to evaluate the specific effects. Explicitly that means that three model implementations and simulations are made and evaluated.

SLUDGE AGE CONTROL

In the default BSM2 setup the sludge withdrawal from the activated sludge step is done by a simple time control of the flow rate of Waste Activated Sludge, WAS. It is kept at 450 m^3/h during summer and lowered to 300 m^3/h during winter (between day 0 and 189 and between 364 and 546). This is to ensure sufficient nitrification during the cold period.

The basic idea with the proposed control strategy is to gain stability to the biological processes in the activated sludge treatment and to secure the nitrification during the cold period. The most important thing for stability is to give the bacteria constant conditions with as little variation as possible in ambient conditions. In an environment like a WWTP, where the incoming wastewater is totally out of control and varies all the time, this is of course very hard. One of the most crucial parameters is the sludge retention time in the system, also called the Sludge Age, SA, as it is an approximate value of how long each microorganism is retained in the system. If this value drops below the growth rate of the desired microorganisms they will be washed out. For organisms like nitrifies that only grow under aerobic conditions it's only the aerobic SA that counts, below the aerobic SA is referred to as SA. The SA is calculated with equation 1.

$$SA = \frac{TSS_{\mathrm{R5}} V_{\mathrm{R\,3,4,5}}}{TSS_{\mathrm{effluent}} Q_{\mathrm{effluent}} + TSS_{\mathrm{WAS}} Q_{\mathrm{WAS}}} \tag{1}$$

TSS is the *Total Suspended Solids* in the different streams in g/m^3 and Q denotes the flows in m^3/h, WAS is short for Waste Activated Sludge. Two things are obvious to each and everyone: *i)* the Q_{was} is the only possible control handle for the sludge age; *ii)* the sludge age will be in order of several days and the variation of the parameters in the equation is in order of minutes or hours. The last point means that the instantaneous calculation will vary a lot more and faster than the actual sludge age.

A sludge age estimator is implemented according to the following, se figures 2 to 3.

- TSS-sensors of class A0 are applied at bioreactor 5, WAS and the settler effluent.
- The instantaneous sludge age for the aerated volume is calculated according to equation 1, followed by a discrete FIR filter with one day sampling and a non weighted 15 day moving average. This is to get a more realistic behaviour and smoother control.
- The set-point for the sludge age control is a simple timer arrangement similar to the Q_{was}-control in the original BSM2-setup.
- A PI controller taking the error of the sludge age and manipulating the Q_{WAS}. The controller parameters are presented in table 1.

STORAGE TANK CONTROL

The reject water from the dewatering unit is lead to a storage tank (ST) before it is pumped back to the main plant. This offers several control options. The flow rate can be controlled and the position for return to the plant can be chosen. In the default strategy the set-point for reject flow rate from the tank, Q_{st}, is set to zero, which means that the tank will go full and thereby the recycle flow rate is equal to the reject water production from the dewatering unit.

Table 1. Parameters for the sludge age PI-controller.

Parameter	Value
SA setpoint winter	18
SA setpoint summer	8
KSA	7.5
TiSA	2.5
TtSA	1
SAintstate	0
SAaestate	0
Qwoffset	300
Qw_max	1500
useantiwindupSA	1

The recycled reject water adds an internal load to the main treatment that accounts for 58.8 tons of nitrogen per year or almost 18 % extra nitrogen, mostly ammonium, each year. This is due to mineralization of particulate nitrogen in the digester that has to be recycled and treated in the water train. The basic idea and goal for this control strategy is to equalize the load variations a bit by controlling the reject flow in order to recycle less during high load periods (daytime and high flow periods) and vice versa during low loaded periods (nighttime).

For the implementation in the Matlab model a Simulink sub model to the Storage tank model was built (figure 4) to produce a dynamic set-point for the pumping rate of reject from the tank. The model in figure 4 produces a proportional function limited at both high and low Q_{in}. A schematic graph is shown in figure 5. The main behaviour of this function / control is:

- When $Q_{in} < 12000$ $Q_{st} = 500$ m^3/d. That is a high pumping rate to pump most produced reject water and also empty the tank during low loaded periods.
- When $12000 < Q_{in} < 23000$ $Q_{st} = -0.04545Q_{in} + 1045.35$ m^3/d. A linear function gives less reject pumped with increased inflow.
- When $Q_{in} > 23000$ $Q_{st} = 0$ m^3/d. That means that the reject will go to the tank and when it is full it will be bypassed to the inlet.

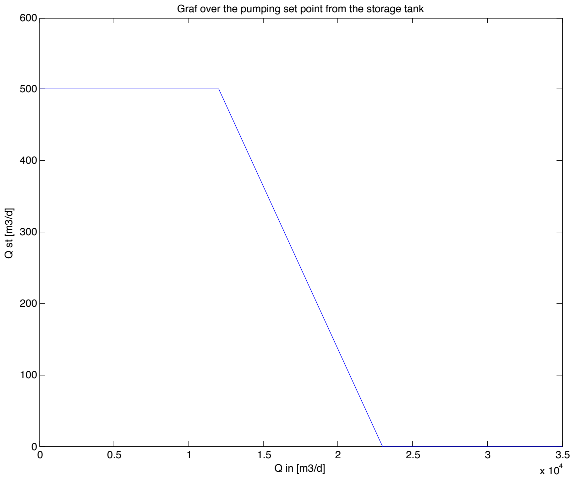

Figure 5. Function for the set-point of pumping rate from the storage tank.

SLUDGE LEVEL CONTROL

One control strategy that is often promoted as beneficial is controlling the RAS pumping rate reversed proportional to the hydraulic load on the biological treatment. This is a good idea from two perspectives, firstly, and most important, the variations in surface load on the clarifier is minimized since this avoids putting a maximum RAS-flow on top of a maximum inflow, secondly it brings back as much sludge as possible to the aerated tank during low loaded periods which is good for the growth of nitrifying organisms, i.e. it becomes a sort of bioaugmentation. The drawback of this control strategy is that during long periods with high hydraulic load the RAS-pumping goes on a minimum and a lot of the sludge is accumulated in the settler where it first of all make little or no use and secondly risks to escape. To prevent this the reversed proportionality must be flipped to direct proportional control during long periods with high inflow.

One way to do that is to look at what is really interesting, i.e. to prevent sludge loss. By measuring the sludge level in the settler and setting a limiting maximum value it can be used as a breakpoint for when to change the control of RAS-pumping. Important is that it often is the fluffier part of the

Table 2. Primary results in comparison with the default control strategy. EQI [kg poll.units/d], SNH in effl. [mg N/l], TN in effl. [mg N/l], TSS in effl. [mg TSS/l], SNH violation [%] and TSS violation [%]

	SA contr.	ST contr.	Default
EQI	6220	5577	5577
OCI	9305	9468	9447
SNH in effl.	0.40	0.39	0.47
TN in effl.	13.75	13.72	13.53
TSS in effl.	20.7	15.1	15.2
SNH violation	0.34	0.42	0.41
TSS violation	1.73	0.34	0.34

sludge that escapes first and can account for large proportions of the sludge. This without that the more compact sludge blanket rises very much.

To test the viability of this strategy a sludge blanket sensor has been implemented in the Matlab/Simulink version of BSM2.

3. Results and Discussion

The simulations were run according to the predefined BSM2 protocol for 609 days with noise added to actuators and sensors. For comparison a simulation was done with the default setup as well. The plant evaluation was done from day 245 to day 609.

The primary results are presented in table 2. Below the results are discussed for each strategy separately.

3.1. Sludge Age Control

The dynamic output for the most important parameters are shown in figures 6 to 9 including some comparisons with the default case for key parameters.

The implementation of the sludge age control was successful in the perspective that it kept the sludge age close to the set-point at all times. This held the nitrification capacity stable and therefore the ammonia concentration was also lower than the default strategy and gave rise to less violations. But in total the EQI got slightly higher. This is due to increased TSS concentration in the effluent. This is of course caused by temporarily too low Q_{WAS} but this has to be analyzed further to make any real conclusions. Partly because the settler-model in BSM2 is not very good to predict effluent concentrations. It is also clear that the PI-controller is not optimized and further tuning would be beneficial.

3.2. Storage Tank Control

As can be seen from table 2 the storage tank control is very close to the default strategy in almost all parameters and specially for the aggregated indices EQI and OCI. This means that the overall performance for the plant have not improved significantly. However looking at the key parameter that the control strategy was meant to affect, ammonium nitrogen, the effluent concentration is lowered from 0.47 to 0.39.

Figures 10 and 11 show a few parameters plotted for 8 days. As can be seen in figure 10 the Q_{st} behaves as expected with low set-point at high values of Q_{in}. During the dry period, day 257 to 262, reject is pumped at the maximum rate of 500 m^3/d and little or no reject is pumped during daytime. The signal is quite spiky due to a noisy behaviour of the measured Q_{in} even though the Q_{in}-signal is filtered with an exponential filter. During the period 262.5 to 264 the Q_{st} is zero due to high inflow. Looking at figure 11 we can se that the actual flow rate Q_{rej} is not zero during the same period because the storage tank goes full and the produced reject is bypassed. The graph over the volume in the storage tank, V_{st}, shows that during the dry period it is really emptied during nighttime but the buffer volume is only partly used during daytime. That implicates that the function for Q_{st} could be trimmed further. It is also obvious that while the tank is empty the behaviour of the control is very flickering. The actuator is forced to go on/off with a maximum set-point about 2 times per hour which might be undesirable but not a real problem from an operational point of view.

3.3. Sludge Level Control

As stated above no real control has been implemented but only a sensor for measurement of the sludge blanket level, h_{sb}. This is for reasons that

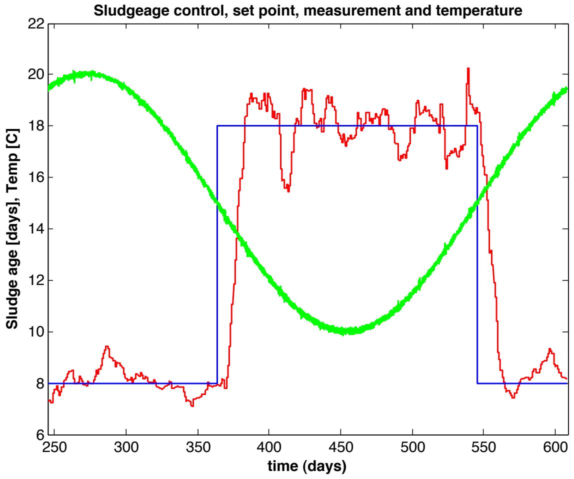

Figure 6. Calculated running average for sludge age (red) and its setpoint (blue) vs. effluent temperature (green) with sludge age control.

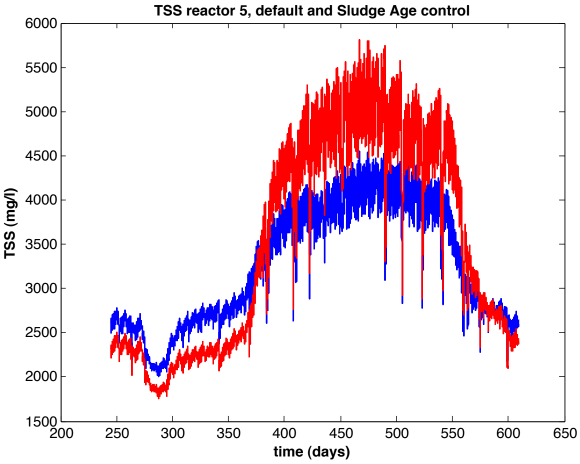

Figure 8. TSS in reactor 5 in default- (blue) and SA control-strategy (red).

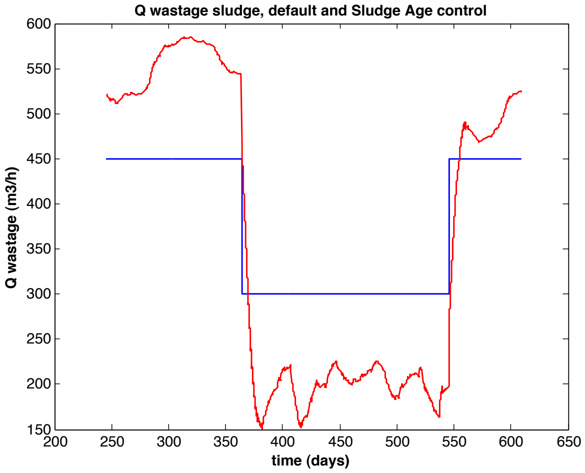

Figure 7. Flow rate of WAS in default- (blue) and SA control-strategy (red).

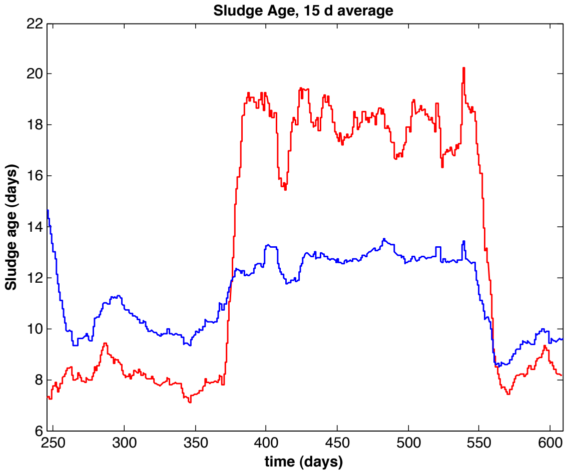

Figure 9. Sludge age for default strategy (blue) and Sludge Age control (red).

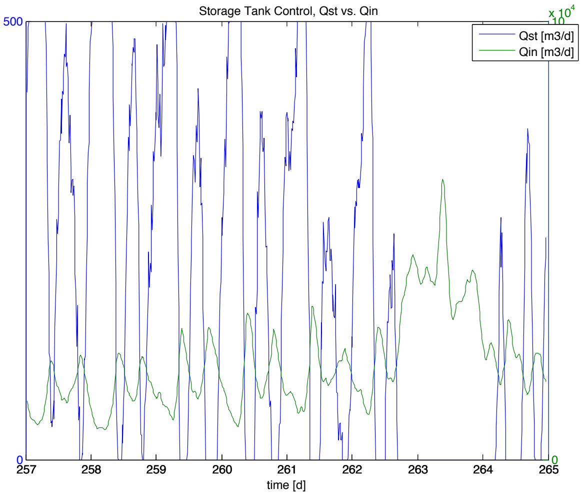

Figure 10. Setpoint for Reject pumping flow from the tank, Q_{st} and incoming flow Q_{in}.

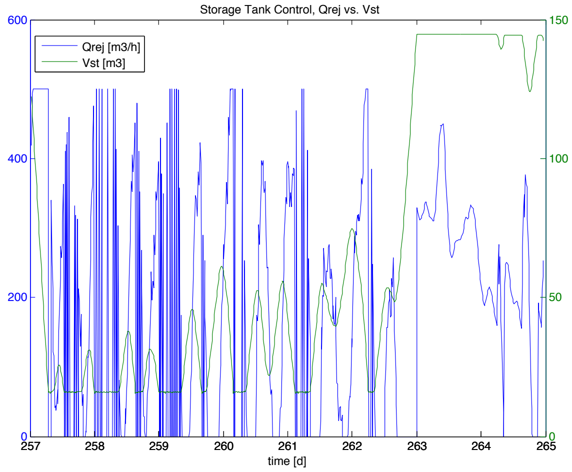

Figure 11. Actual reject flow, Q_{rej}, and Volume in storage tank, V_{st}.

will become obvious. The simulation is therefore merely a standard simulation of the default strategy, the raw measurement of h_{sb} can be found in figure 12. Two observations can be made from that, first that the total variation of h_{sb} is small, about 1.5 m, and the settler is never close to be totally filled up. The second observation is that the level tends to increase during the cold period. Probably due to lower RAS-flow.

To evaluate if this measured sludge blanket level can be used for control purposes two figures are presented with comparison of h_{sb}, $TSS_{\text{s,effl}}$ and Q_{AS}, one for warm conditions and one for cold conditions. In both periods h_{sb} correlates good with Q_{AS} in such respect that the h_{sb} increases when Q_{AS} increases a lot. Still the general increase during winter makes the peaks in h_{sb} during summer stay below or at the same level as the baseline during wintertime. The $TSS_{\text{s,effl}}$ also correlates good to h_{sb}. But the $TSS_{\text{s,effl}}$ never increases dramatically and for these two periods it does not even exceed the maximum limit of 30 g/m^3. This is good if it is true but since the settler model is known to poorly predict effluent concentrations it might also be wrong.

The conclusion is that good correlation between the measured variable, h_{sb} and the desired control variable $TSS_{s,effl}$ exists. Still the sludge blanket level will not work as a good variable for control since the small changes and natural variations make it hard to define distinct set-points. The question is also if the BSM2-model can be used to minimize effluent TSS as long as the settler model can not predict it accurately.

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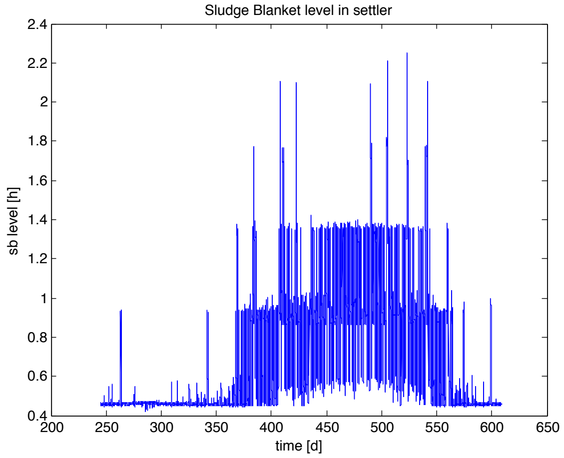

Figure 12. Sludge blanket level for the entire evaluation period.

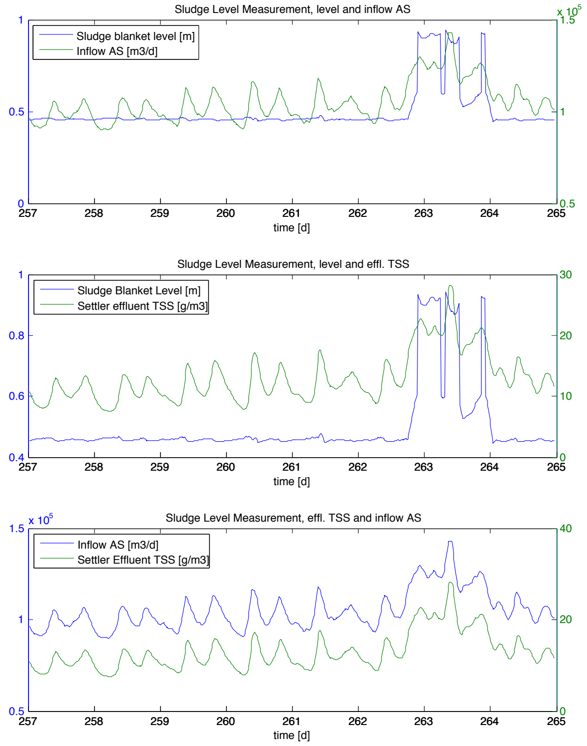

Figure 13. Comparison of different variables during one week in warm climate.

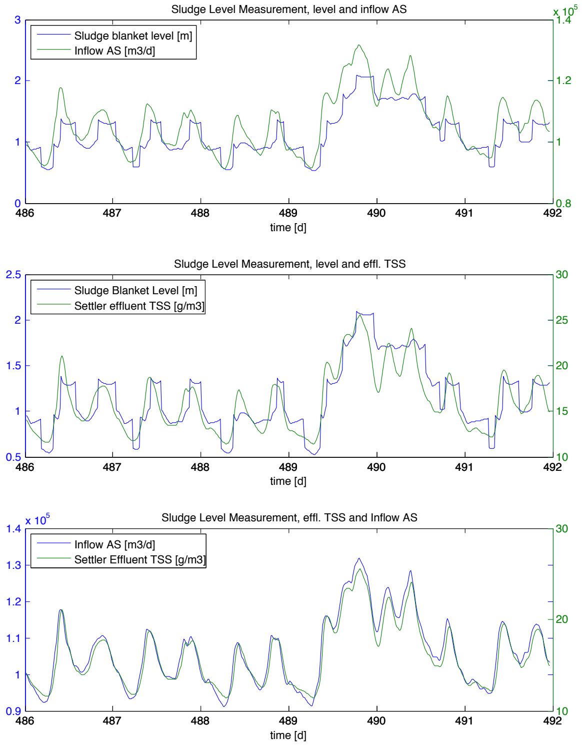

Figure 14. Comparison of different variables during one week in cold climate.

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