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Industrial Electrical Engineering and Automation

Control strategy development implemented in the Benchmark Simulation Model No. 1 (BSM1)

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REPORT

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CONTENTS

1. INTRODUCTION

This is a modelling and simulation exercise as a part of the self-study course required for my PhD studies at IEA, LTH. The specific objective of this task is to develop, evaluate, and compare different control strategies for wastewater treatment plants (WWTPs) using the Benchmark Simulation Model No. 1 (BSM1) (Gernaey et al., 2014).

The BSM1 is a platform which can be used for objective comparison of different developed control strategies. The performance evaluation using the BSM1 is based on a reference simulation model consisting of a precise plant layout, well-defined controllers, performance criteria, and other test procedures.

2. METHODS

2.1. Plant Layout

The plant layout is shown in **Figure 1**, consisting of a biological reactor followed by a secondary clarifier. In the default configuration, the biological reactor is a five-compartment activated sludge unit wherein the first two tanks are anoxic while the last three are aerated. The biological processes are described using the Activated Sludge Model No. 1 (ASM1) (Henze et al., 1987). The secondary clarifier is a 10-layer non-reactive model and follows the double exponential settling vecity function by Takács et al. (1991).

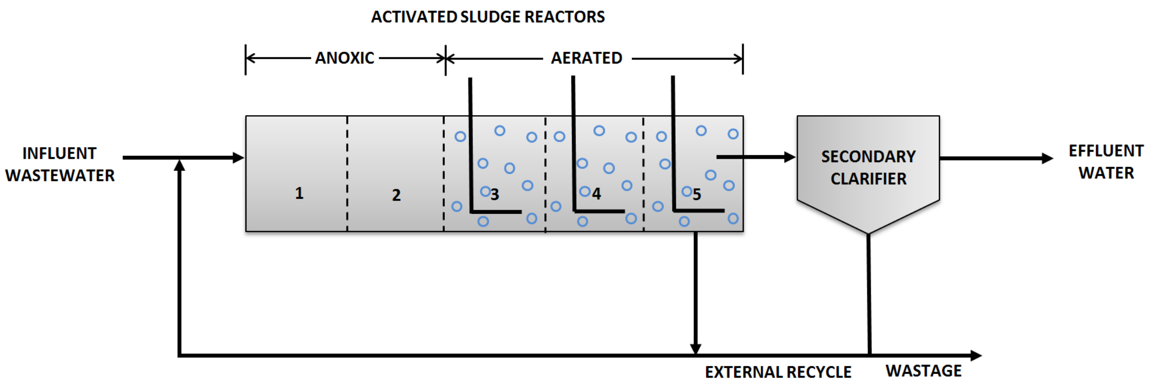


Figure 1. BSM1 plant layout (open loop).

2.2. Influent Data

The influent data used is that proposed by Vanhooren and Nguyen (1996) and used as standard BSM1 inputs. Data for dry weather, storm weather, and rain weather are provided.

2.3. Simulation

The plant was simulated in closed loop for 150 days to achieve quasi steady state using the

CONSTANT INPUT file (ideal sensors and actuators used). Then the DRY WEATHER file was used to simulate the closed loop dynamics during 14 days and set up the plant for the dynamic benchmark simulations (using active noise and delay on sensors and actuators). The results of this simulation was used as initial values for the actual plant performance calculations using the different dynamic input files, in this case, the dry weather input.

2.4. Default Controllers (D)

Two default controllers are given in BSM1. The first one is the controller for dissolved oxygen (DO) in tank 5 using a DO setpoint = 2 mg L^{-1} and by controlling the KLa in the same tank. The concentration of DO is measured using a sensor of class A taking into account measurement noise.

The other default controller is for the NO_3 level in tank 2. An NO_3 setpoint of 1 mg L^{-1} is used and the manipulated variable is the internal recirculation rate Q_{int}. The nitrate concentration in the same tank is measured using a sensor of class B_0 and again taking into account measurement noise.

2.5. New Control Strategies (S1, S2, S3)

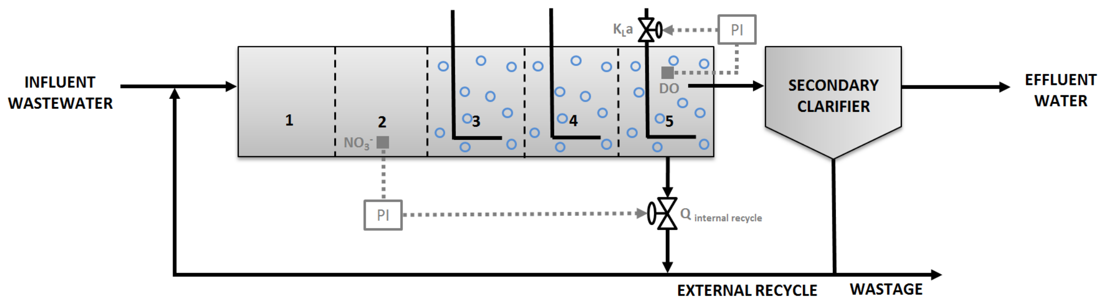
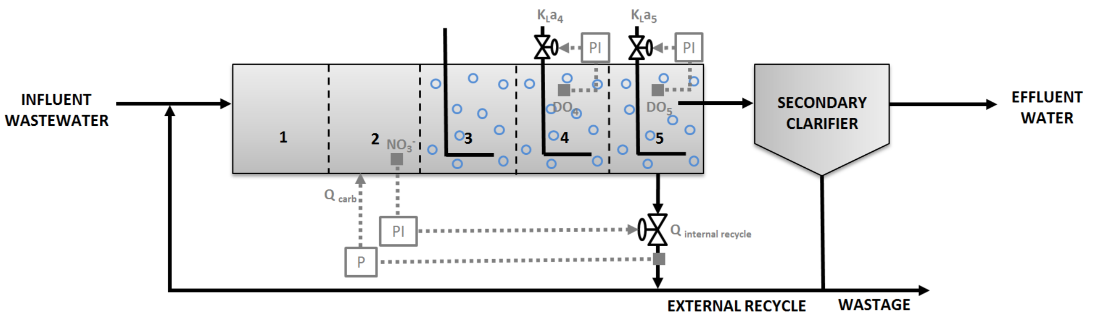
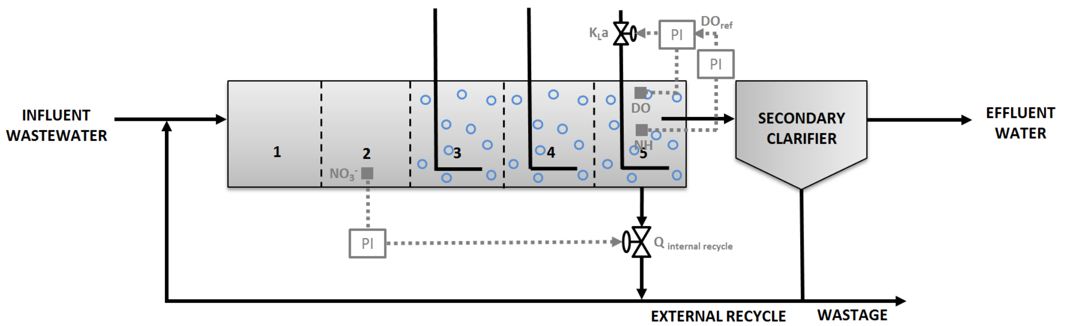
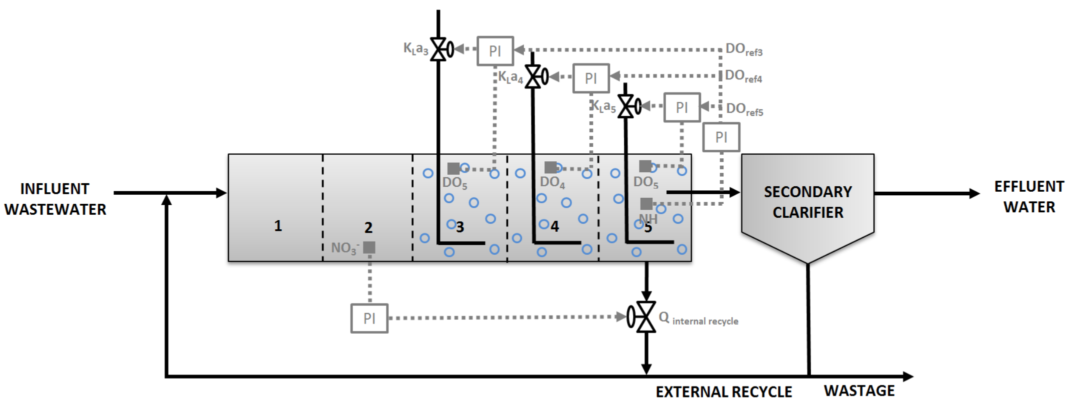
Three control strategies are evaluated in this task. In general, the goal is to reduce further the effluent ammonia (NH_3) or ammonium (NH_4^+) and/or nitrate (NO_3^-) concentrations by improving the denitrification and nitrification performance of the plant.

To lower the concentration of NO_3^- in the effluent, the internal flow recirculation rate from the secondary clarifier could be increased. If there is a high concentration of NO_3^- that needs to be converted to N_2 gas, denitrification should be improved. More carbon source should be provided for the denitrifiers to do well and this could be accomplished by adding an external carbon source. The downside of this is that there will be higher operational costs associated with the external carbon source and increase in pumping energy requirement.

On the other hand, to decrease the concentration of NH_3 and NH_4^+ nitrification should be improved. Sufficient O_2 concentrations in the three aerobic tanks should be provided by controlling the KLa values of the aerators in tanks 3, 4, and 5. The downside of this control strategy is that operational costs will be higher due to increase in aeration energy.

The proposed control strategies listed in **Table 1** are in addition to the default controllers already implemented in BSM1 as described in **Section 2.4** (unless otherwise stated).

Table 1. Proposed control strategies for NH_3/NH_4^+ and/or NO_3^- removal.

<table>
<tr><th></th><th>STRATEGY TO DECREASE NO_3^-</th><th>STRATEGY TO DECREASE NH_3/NH_4^+</th></tr>
<tr><td>O</td><td>-</td><td>-</td></tr>
<tr><td colspan="3">(See Figure 1.)</td></tr>
<tr><td>D</td><td>Control Q_{int} based on S_{NO} in tank 2</td><td>Control K_La in tank 5 based on DO in tank 5</td></tr>
<tr><td colspan="3">
</td></tr>
<tr><td>S1</td><td>Control Q_{carb} in tank 2 based on Q_{intr}</td><td>Control K_La in tank 4 based on DO in tank 4</td></tr>
<tr><td colspan="3">
</td></tr>
<tr><td>S2</td><td>-</td><td>Control K_La in tank 5 using O_2 ref. point set by S_{NH} controller in tank 5 (cascade control) – replaces the K_La controller in (D).</td></tr>
<tr><td colspan="3">
</td></tr>
<tr><td>S3</td><td>-</td><td>Control K_La in tanks 3, 4, 5 using O_2 reference points set by S_{NH} controller in tank 5 (cascade control) – replaces the K_La controller in (D).</td></tr>
<tr><td colspan="3">
</td></tr>
</table>

3. RESULTS AND DISCUSSIONS

The main objective of the proposed control strategies is to further decrease the ammonia concentration in the effluent. Note that it is only in S1 that an additional control strategy to also further decrease the nitrate concentration was included.

Table 2. Effluent N concentrations and performance indices for the various control strategies implemented in this study.

CONTROL STRATEGY	NO (mg N L^{-1})	NH (mg N L^{-1})	TN (mg N L^{-1})	IQI (kg poll units d^{-1})	EQI (kg poll units d^{-1})	OCI
O	8.8238	4.7589	15.5686	52081.3952	6690.1049	16148.0066
D	12.4199	2.5392	16.9245	52081.3952	6123.0182	16382.4026
S1	4.4871	3.0774	9.7105	52081.3952	5181.1906	25010.1834
S2	13.4285	2.1595	17.5439	52081.3952	6092.3749	16910.7486
S3	14.3443	1.7001	17.9922	52081.3952	6003.6409	17767.3214

S1 uses a P controller for the external carbon flow rate based on the internal recirculation flow rate. In addition, it also has a PI controller (same parameters used as in PI controller for K_La control in tank 5) for K_La control in tank 4 based on the ammonia concentration in the same tank. These two are control strategies in addition to that in the default BSM1 control. Among all the control strategies, this is able to further decrease the nitrate concentration because of the external carbon source. This resulted in the lowest effluent quality index. However, a much higher operational cost is expected due to the cost of the carbon source as well as the associated pumping as well as the aeration cost for tank 4.

S2, on the other hand, makes use of a cascade controller. The slave controller is for the K_La in tank 5 and the master controller defines the oxygen reference setpoint based on the ammonia measurement in the same tank. This strategy replaces the PI controller for K_La as used in the default BSM1 control.

S3 is also a cascade controller but uses the oxygen reference setpoint obtained from the master controller to control the K_La in tank 3 as well as in tanks 4 and 5. S_{NH} is measured in tank 5, and the setpoints for S_{NH} in tanks 3, 4 and 5 were chosen to be the same (2 g N m^{-3}). A PI controller then uses the S_{NH} error to define the oxygen setpoints in tanks 3, 4, and 5.

As expected, the three proposed control strategies resulted in a decrease in effluent ammonia concentration and the effluent water quality criteria but as a consequence increase the operational cost index, compared to the open loop simulation results (see **Table 2**, **Figure 2**). S1-S3 decrease the S_{NH} concentration in the effluent with an increase in the S_{NO} concentration except for the case when there is an additional control strategy for nitrate removal (S1). The decrease in EQI entails additional operational costs which thus increases the OCI.

The main contributors for the increase in OCI for strategy S1 are the carbon source addition cost and the pumping energy cost, both of which are due to the external carbon source addition to improve denitrification. The difference in the OCI between S2/S3 and the default control strategy is due to the aeration energy cost (see **Appendix A1**).

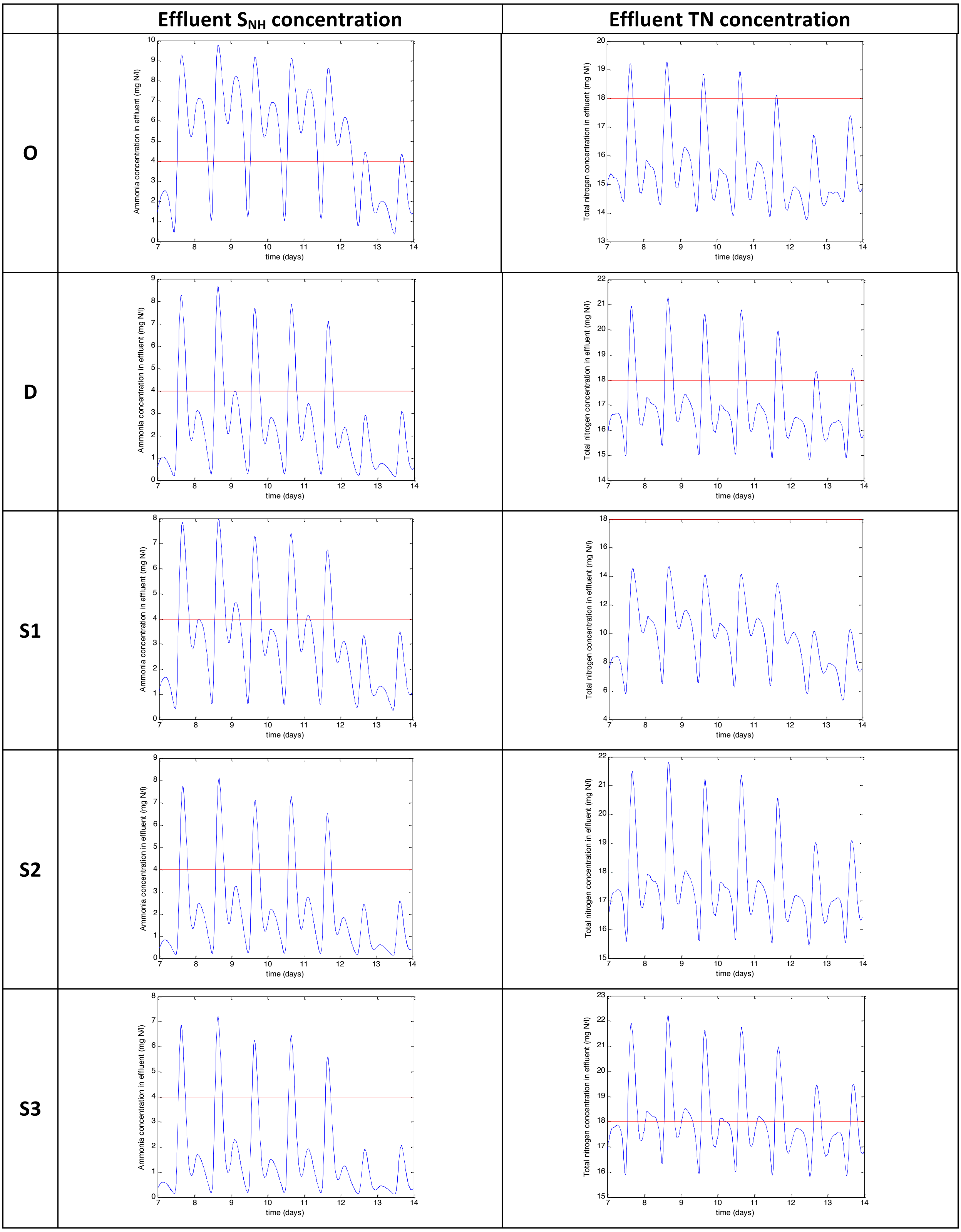


Figure 2. Effluent total ammonia and total nitrogen and their corresponding limit values for the different control strategies implemented in BSM1.

An observation from this study is that it is a challenge to both simultaneously decrease EQI and OCI. An important decision sometimes has to be made whether to prioritize ensuring a good effluent quality or saving costs. This predicament involves a lot of opportunitites to develop many other kinds of control strategies such as use of model-based control (e.g. model predictive controller). It should also be noted that associated with some control strategy implementations is an additional need for sensor/s which is not included in the potential costs.

It is also worthwhile to note that the available pumps and aeration system have limited capacity and therefore cannot be operated above their limits. This limitation is a reason why there is only a little to no effect in removing peak concentrations in the influent load. Studies by Jeppsson et al. (2007) have shown that control of storage tanks (e.g. in plant-wide BSM2) are often done to reduce peaks in the influent loads. Åmand (2011) has also indicated, based on a study of various control of aeration systems, that use of a combined feedback feedforward control was able to reduce (ammonia) peaks.

4. CONCLUSIONS

The implemented control strategies were able to decrease the average effluent ammonia concentration below the 4 mg N L^{-1} limit compared to the open loop result as seen in **Figure 2**. It is only in strategy S1 that effluent nitrate concentration was also lower compared to the open loop result due to the additional control strategy specific for improving denitrification, however the total nitrogen concentration is still below the 18 mg N L^{-1} limit. The results presented have shown an inverse relationship between the operational cost index and the effluent quality index, which means that if the objective was to obtain a good effluent quality then operational costs will have to increase and vice versa. Further analysis can be performed on fine-tuning the controllers used in this study.

5. REFERENCES

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Vanhooren, H. and Nguyen K. (1996). *Development of a simulation protocol for evaluation of respirometry-based control strategies*. Report University of Gent, Belgium and University of Ottawa, Canada.

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APPENDIX

A1. Operational Cost Index (OCI) for the different control strategies

Cost Indices	O	D	S1	S2	S3
Sludge production	12178.4499	12203.0282	14960.9371	12206.5642	12211.9898
Aeration energy	3341.3867	3698.3438	3789.9409	4238.3635	5097.331
Pumping energy	388.17	241.0305	532.5985	225.8209	218.0005
Carbon source addition	0	0	5486.707	0	0
Mixing energy	240	240	240	240	240
Updated Total OCI	**16148.0066**	**16382.4026**	**25010.1834**	**16910.7486**	**17767.3214**

A2. Performance evaluation of ASM3 bioP plant during dynamic simulation (dry weather data) – BSM1 open loop version (O)

```
Overall plant performance during time 7 to 14 days
**************************************************

Effluent average concentrations based on load
---------------------------------------------
Effluent average flow rate = 18061.3325 m3/d
Effluent average SI conc = 30 mg COD/l
Effluent average SS conc = 0.97352 mg COD/l
Effluent average XI conc = 4.5794 mg COD/l
Effluent average XS conc = 0.22285 mg COD/l
Effluent average XBH conc = 10.2208 mg COD/l
Effluent average XBA conc = 0.54217 mg COD/l
Effluent average XP conc = 1.7572 mg COD/l
Effluent average SO conc = 0.74639 mg (-COD)/l
Effluent average SNO conc = 8.8238 mg N/l
Effluent average SNH conc = 4.7589 mg N/l  (limit = 4 mg N/l)
Effluent average SND conc = 0.72901 mg N/l
Effluent average XND conc = 0.015691 mg N/l
Effluent average SALK conc = 4.4562 mol HCO3/m3
Effluent average TSS conc = 12.9917 mg SS/l  (limit = 30 mg SS/l)

Effluent average Kjeldahl N conc = 6.7448 mg N/l
Effluent average total N conc = 15.5686 mg N/l  (limit = 18 mg COD/l)
Effluent average total COD conc = 48.2958 mg COD/l  (limit = 100 mg COD/l)
Effluent average BOD5 conc = 2.7746 mg/l  (limit = 10 mg/l)

Effluent average load
---------------------
Effluent average SI load = 541.84 kg COD/day
Effluent average SS load = 17.583 kg COD/day
Effluent average XI load = 82.7093 kg COD/day
Effluent average XS load = 4.025 kg COD/day
Effluent average XBH load = 184.6007 kg COD/day
Effluent average XBA load = 9.7924 kg COD/day
Effluent average XP load = 31.7369 kg COD/day
Effluent average SO load = 13.4807 kg (-COD)/day
Effluent average SNO load = 159.3704 kg N/day
Effluent average SNH load = 85.9513 kg N/day
Effluent average SND load = 13.1668 kg N/day
Effluent average XND load = 0.28341 kg N/day
Effluent average SALK load = 80.4845 kmol HCO3/day
Effluent average TSS load = 234.6482 kg SS/day

Effluent average Kjeldahl N load = 121.8197 kg N/d
Effluent average total N load = 281.1902 kg N/d
Effluent average total COD load = 872.2873 kg COD/d
Effluent average BOD5 load = 50.1124 kg/d

Other effluent quality variables
--------------------------------
Influent Quality (I.Q.) index = 42042.8149 kg poll.units/d (original BSM1 version)
Effluent Quality (E.Q.) index = 7065.612 kg poll.units/d (original BSM1 version)
Influent Quality (I.Q.) index = 52081.3952 kg poll.units/d (updated BSM1 version)
Effluent Quality (E.Q.) index = 6690.1048 kg poll.units/d (updated BSM1 version)

Sludge production for disposal = 17049.8298 kg SS
Average sludge production for disposal per day = 2435.69 kg SS/d
Sludge production released into effluent = 1642.5377 kg SS
Average sludge production released into effluent per day = 234.6482 kg SS/d
Total sludge production = 18692.3675 kg SS
Total average sludge production per day = 2670.3382 kg SS/d

Total aeration energy = 45332.784 kWh (original BSM1 version)
Average aeration energy per day = 6476.112 kWh/d (original BSM1 version)
Total aeration energy = 23389.7067 kWh (updated BSM1 version)
Average aeration energy per day = 3341.3867 kWh/d (updated BSM1 version)

Total pumping energy (for Qintr, Qr and Qw) = 20767.32 kWh (original BSM1 version)
Average pumping energy per day (for Qintr, Qr and Qw) = 2966.76 kWh/d (original BSM1 version)
Total pumping energy (for Qintr, Qr and Qw) = 2717.19 kWh (based on BSM2 principles)
Average pumping energy per day (for Qintr, Qr and Qw) = 388.17 kWh/d (based on BSM2
principles)
```

```
Total mixing energy = 1680 kWh (based on BSM2 principles)
Average mixing energy per day = 240 kWh/d (based on BSM2 principles)

Total added carbon volume = 0 m3
Average added carbon flow rate = 0 m3/d
Total added carbon mass = 0 kg COD
Average added carbon mass per day = 0 kg COD/d

Operational Cost Index
----------------------
Sludge production cost index = 12178.4498 (using weight 5 for BSM1)
Aeration energy cost index = 6476.112 (original BSM1 version)
Updated aeration energy cost index = 3341.3867 (updated BSM1 version)
Pumping energy cost index = 2966.76 (original BSM1 version)
Updated pumping energy cost index = 388.17 (based on BSM2 principles)
Carbon source addition cost index = 0
Mixing energy cost index = 240 (based on BSM2 principles)
Total Operational Cost Index (OCI) = 21861.3218 (original BSM1 version)
Updated Total Operational Cost Index (OCI) = 16148.0065 (using new aeraration and pumping
costs)

Effluent violations
-------------------
95% percentile for effluent SNH (Ammonia95) = 8.8818 g N/m3
95% percentile for effluent TN (TN95) = 18.5332 g N/m3
95% percentile for effluent TSS (TSS95) = 15.7415 g SS/m3

The maximum effluent total nitrogen level (18 mg N/l) was violated
during 0.57292 days, i.e. 8.1845% of the operating time.
The limit was violated at 5 different occasions.

The maximum effluent ammonia nitrogen level (4 mg N/l) was violated
during 4.375 days, i.e. 62.5% of the operating time.
The limit was violated at 7 different occasions.

Qualitative criteria for settling problems
------------------------------------------
The plant has experienced high (>0.8) risk for the development of filamentous bulking due to N
deficiency
during 0 days, i.e. 0% of the operating time.
...and risk for the development of filamentous bulking due to N deficiency 100% of the
operating time.
average risk 0.00011765

The plant has experienced high (>0.8) risk for the development of aerobic (low DO) filamentous
bulking
during 0.57292 days, i.e. 8.1845% of the operating time.
...and risk for the development of aerobic (low DO) filamentous bulking 96.2798% of the
operating time.
average risk 0.32341
The most dangerous situation was between days 8.4479 and 8.5729

The plant has experienced severe (>0.8) risk for the development of low F/M filamentous
bulking
during 2.9688 days, i.e. 42.4107% of the operating time.
...and risk for the development of low F/M filamentous bulking 100% of the operating time.
average risk 0.74557
The most dangerous situation was between days 12.0104 and 12.4375

The plant has experienced high (>0.8) risk for the development of low F/M foaming
during 0 days, i.e. 0% of the operating time.
...and risk for the development of low F/M foaming 100% of the operating time.
average risk 0.53855

The plant has experienced high (>0.8) risk for the development of foaming due to high Ss/Xs
fraction
during 0 days, i.e. 0% of the operating time.
...and risk for the development of foaming due to high Ss/Xs fraction 99.256% of the operating
time.
average risk 0.025602

The plant has experienced high (>0.8) risk for the development of rising sludge
during 2.3854 days, i.e. 34.0774% of the operating time.
...and risk for the development of rising sludge 100% of the operating time.
average risk 0.68191
The most dangerous situation was between days 13.4688 and 13.8229
```

```
Overall risk
------------
The plant has experienced severe (>0.8) risk for (integrated) BULKING
during 3.5417 days, i.e. 50.5952% of the operating time.
...and risk for the development of (integrated) Bulking 100% of the operating time.
average risk 0.81015
The most dangerous situation was between days 12.0104 and 12.4375

The plant has experienced severe (>0.8) risk for (integrated) FOAMING
during 0 days, i.e. 0% of the operating time.
...and risk for the development of (integrated) Foaming 100% of the operating time.
average risk 0.54695

The plant has experienced high (>0.8) risk for the development of RISING SLUDGE
during 2.3854 days, i.e. 34.0774% of the operating time.
...and risk for the development of rising sludge 100% of the operating time.
average risk 0.68191
The most dangerous situation was between days 13.4688 and 13.8229

The plant has experienced OVERALL severe (>0.8) risk for OVERALL SETTLING PROBLEMS
during 4.5729 days, i.e. 65.3274% of the operating time.
...and risk for the development of OVERALL SETTLING PROBLEMS 100% of the operating time.
average risk 0.88848
The most dangerous situation was between days 8.3958 and 13.4375
```

A3. Performance evaluation of ASM3 bioP plant during dynamic simulation (dry weather data) – BSM1 default control strategy (D)

```
Overall plant performance during time 7 to 14 days
**************************************************

Effluent average concentrations based on load
---------------------------------------------
Effluent average flow rate = 18057.8774 m3/d
Effluent average SI conc = 30 mg COD/l
Effluent average SS conc = 0.88177 mg COD/l
Effluent average XI conc = 4.5728 mg COD/l
Effluent average XS conc = 0.20084 mg COD/l
Effluent average XBH conc = 10.2314 mg COD/l
Effluent average XBA conc = 0.57803 mg COD/l
Effluent average XP conc = 1.7553 mg COD/l
Effluent average SO conc = 1.9881 mg (-COD)/l
Effluent average SNO conc = 12.4199 mg N/l
Effluent average SNH conc = 2.5392 mg N/l  (limit = 4 mg N/l)
Effluent average SND conc = 0.70651 mg N/l
Effluent average XND conc = 0.01442 mg N/l
Effluent average SALK conc = 4.0409 mol HCO3/m3
Effluent average TSS conc = 13.0038 mg SS/l  (limit = 30 mg SS/l)

Effluent average Kjeldahl N conc = 4.5046 mg N/l
Effluent average total N conc = 16.9245 mg N/l  (limit = 18 mg COD/l)
Effluent average total COD conc = 48.2201 mg COD/l  (limit = 100 mg COD/l)
Effluent average BOD5 conc = 2.7568 mg/l  (limit = 10 mg/l)

Effluent average load
---------------------
Effluent average SI load = 541.7363 kg COD/day
Effluent average SS load = 15.923 kg COD/day
Effluent average XI load = 82.5745 kg COD/day
Effluent average XS load = 3.6267 kg COD/day
Effluent average XBH load = 184.7574 kg COD/day
Effluent average XBA load = 10.438 kg COD/day
Effluent average XP load = 31.6976 kg COD/day
Effluent average SO load = 35.9017 kg (-COD)/day
Effluent average SNO load = 224.2771 kg N/day
Effluent average SNH load = 45.8525 kg N/day
Effluent average SND load = 12.7581 kg N/day
Effluent average XND load = 0.26039 kg N/day
Effluent average SALK load = 72.9708 kmol HCO3/day
Effluent average TSS load = 234.8206 kg SS/day

Effluent average Kjeldahl N load = 81.3429 kg N/d
Effluent average total N load = 305.6201 kg N/d
Effluent average total COD load = 870.7534 kg COD/d
Effluent average BOD5 load = 49.7823 kg/d

Other effluent quality variables
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Influent Quality (I.Q.) index = 42042.8149 kg poll.units/d (original BSM1 version)
Effluent Quality (E.Q.) index = 7552.3603 kg poll.units/d (original BSM1 version)
Influent Quality (I.Q.) index = 52081.3952 kg poll.units/d (updated BSM1 version)
Effluent Quality (E.Q.) index = 6123.0182 kg poll.units/d (updated BSM1 version)

Sludge production for disposal = 17084.2395 kg SS
Average sludge production for disposal per day = 2440.6056 kg SS/d
Sludge production released into effluent = 1643.744 kg SS
Average sludge production released into effluent per day = 234.8206 kg SS/d
Total sludge production = 18727.9835 kg SS
Total average sludge production per day = 2675.4262 kg SS/d

Total aeration energy = 50689.5466 kWh (original BSM1 version)
Average aeration energy per day = 7241.3638 kWh/d (original BSM1 version)
Total aeration energy = 25888.4069 kWh (updated BSM1 version)
Average aeration energy per day = 3698.3438 kWh/d (updated BSM1 version)

Total pumping energy (for Qintr, Qr and Qw) = 10467.5555 kWh (original BSM1 version)
Average pumping energy per day (for Qintr, Qr and Qw) = 1495.3651 kWh/d (original BSM1 version)
Total pumping energy (for Qintr, Qr and Qw) = 1687.2136 kWh (based on BSM2 principles)
```

Average pumping energy per day (for Qintr, Qr and Qw) = 241.0305 kWh/d (based on BSM2 principles)

Total mixing energy = 1680 kWh (based on BSM2 principles)
Average mixing energy per day = 240 kWh/d (based on BSM2 principles)

Total added carbon volume = 0 m3
Average added carbon flow rate = 0 m3/d
Total added carbon mass = 0 kg COD
Average added carbon mass per day = 0 kg COD/d

Operational Cost Index

Sludge production cost index = 12203.0282 (using weight 5 for BSM1)
Aeration energy cost index = 7241.3638 (original BSM1 version)
Updated aeration energy cost index = 3698.3438 (updated BSM1 version)
Pumping energy cost index = 1495.3651 (original BSM1 version)
Updated pumping energy cost index = 241.0305 (based on BSM2 principles)
Carbon source addition cost index = 0
Mixing energy cost index = 240 (based on BSM2 principles)
Total Operational Cost Index (OCI) = 21179.7571 (original BSM1 version)
Updated Total Operational Cost Index (OCI) = 16382.4026 (using new aeraration and pumping costs)

Effluent violations

95% percentile for effluent SNH (Ammonia95) = 7.3902 g N/m3
95% percentile for effluent TN (TN95) = 20.2693 g N/m3
95% percentile for effluent TSS (TSS95) = 15.7663 g SS/m3

The maximum effluent total nitrogen level (18 mg N/l) was violated
during 1.2813 days, i.e. 18.3036% of the operating time.
The limit was violated at 7 different occasions.

The maximum effluent ammonia nitrogen level (4 mg N/l) was violated
during 1.1979 days, i.e. 17.1131% of the operating time.
The limit was violated at 5 different occasions.

Qualitative criteria for settling problems
--
The plant has experienced high (>0.8) risk for the development of filamentous bulking due to N deficiency
during 0 days, i.e. 0% of the operating time.
...and risk for the development of filamentous bulking due to N deficiency 100% of the operating time.
average risk 0.00011765

The plant has experienced high (>0.8) risk for the development of aerobic (low DO) filamentous bulking
during 0.57292 days, i.e. 8.1845% of the operating time.
...and risk for the development of aerobic (low DO) filamentous bulking 97.4702% of the operating time.
average risk 0.33851
The most dangerous situation was between days 8.4479 and 8.5729

The plant has experienced severe (>0.8) risk for the development of low F/M filamentous bulking
during 3 days, i.e. 42.8571% of the operating time.
...and risk for the development of low F/M filamentous bulking 100% of the operating time.
average risk 0.73513
The most dangerous situation was between days 13 and 13.4375

The plant has experienced high (>0.8) risk for the development of low F/M foaming
during 0 days, i.e. 0% of the operating time.
...and risk for the development of low F/M foaming 100% of the operating time.
average risk 0.53998

The plant has experienced high (>0.8) risk for the development of foaming due to high Ss/Xs fraction
during 0 days, i.e. 0% of the operating time.
...and risk for the development of foaming due to high Ss/Xs fraction 99.7024% of the operating time.
average risk 0.025851

The plant has experienced high (>0.8) risk for the development of rising sludge
during 4 days, i.e. 57.1429% of the operating time.
...and risk for the development of rising sludge 100% of the operating time.

```
average risk 0.70072
The most dangerous situation was between days 9.4479 and 10.1563

Overall risk
------------
The plant has experienced severe (>0.8) risk for (integrated) BULKING
during 3.5729 days, i.e. 51.0417% of the operating time.
...and risk for the development of (integrated) Bulking 100% of the operating time.
average risk 0.81085
The most dangerous situation was between days 13 and 13.4375

The plant has experienced severe (>0.8) risk for (integrated) FOAMING
during 0 days, i.e. 0% of the operating time.
...and risk for the development of (integrated) Foaming 100% of the operating time.
average risk 0.5489

The plant has experienced high (>0.8) risk for the development of RISING SLUDGE
during 4 days, i.e. 57.1429% of the operating time.
...and risk for the development of rising sludge 100% of the operating time.
average risk 0.70072
The most dangerous situation was between days 9.4479 and 10.1563

The plant has experienced OVERALL severe (>0.8) risk for OVERALL SETTLING PROBLEMS
during 6.5625 days, i.e. 93.75% of the operating time.
...and risk for the development of OVERALL SETTLING PROBLEMS 100% of the operating time.
average risk 0.97423
The most dangerous situation was between days 8.0313 and 12.4375
```

A4. Performance evaluation of ASM3 bioP plant during dynamic simulation (dry weather data) – BSM1 control strategy 1 (S1)

```
Overall plant performance during time 7 to 14 days
**************************************************

Effluent average concentrations based on load
---------------------------------------------
Effluent average flow rate = 18075.0383 m3/d
Effluent average SI conc = 29.9926 mg COD/l
Effluent average SS conc = 0.97795 mg COD/l
Effluent average XI conc = 4.1653 mg COD/l
Effluent average XS conc = 0.26381 mg COD/l
Effluent average XBH conc = 12.0902 mg COD/l
Effluent average XBA conc = 0.4698 mg COD/l
Effluent average XP conc = 2.0939 mg COD/l
Effluent average SO conc = 1.9913 mg (-COD)/l
Effluent average SNO conc = 4.4871 mg N/l
Effluent average SNH conc = 3.0774 mg N/l  (limit = 4 mg N/l)
Effluent average SND conc = 0.74676 mg N/l
Effluent average XND conc = 0.018807 mg N/l
Effluent average SALK conc = 4.6446 mol HCO3/m3
Effluent average TSS conc = 14.3123 mg SS/l  (limit = 30 mg SS/l)

Effluent average Kjeldahl N conc = 5.2234 mg N/l
Effluent average total N conc = 9.7105 mg N/l  (limit = 18 mg COD/l)
Effluent average total COD conc = 50.0536 mg COD/l  (limit = 100 mg COD/l)
Effluent average BOD5 conc = 3.1992 mg/l  (limit = 10 mg/l)

Effluent average load
---------------------
Effluent average SI load = 542.1168 kg COD/day
Effluent average SS load = 17.6765 kg COD/day
Effluent average XI load = 75.2885 kg COD/day
Effluent average XS load = 4.7684 kg COD/day
Effluent average XBH load = 218.5313 kg COD/day
Effluent average XBA load = 8.4917 kg COD/day
Effluent average XP load = 37.8477 kg COD/day
Effluent average SO load = 35.9931 kg (-COD)/day
Effluent average SNO load = 81.1052 kg N/day
Effluent average SNH load = 55.6248 kg N/day
Effluent average SND load = 13.4977 kg N/day
Effluent average XND load = 0.33993 kg N/day
Effluent average SALK load = 83.9519 kmol HCO3/day
Effluent average TSS load = 258.6956 kg SS/day

Effluent average Kjeldahl N load = 94.4124 kg N/d
Effluent average total N load = 175.5177 kg N/d
Effluent average total COD load = 904.7207 kg COD/d
Effluent average BOD5 load = 57.8265 kg/d

Other effluent quality variables
--------------------------------
Influent Quality (I.Q.) index = 42042.8149 kg poll.units/d (original BSM1 version)
Effluent Quality (E.Q.) index = 5048.1182 kg poll.units/d (original BSM1 version)
Influent Quality (I.Q.) index = 52081.3952 kg poll.units/d (updated BSM1 version)
Effluent Quality (E.Q.) index = 5181.1905 kg poll.units/d (updated BSM1 version)

Sludge production for disposal = 20945.3119 kg SS
Average sludge production for disposal per day = 2992.1874 kg SS/d
Sludge production released into effluent = 1810.8694 kg SS
Average sludge production released into effluent per day = 258.6956 kg SS/d
Total sludge production = 22756.1812 kg SS
Total average sludge production per day = 3250.883 kg SS/d

Total aeration energy = 51877.9002 kWh (original BSM1 version)
Average aeration energy per day = 7411.1286 kWh/d (original BSM1 version)
Total aeration energy = 26529.5864 kWh (updated BSM1 version)
Average aeration energy per day = 3789.9409 kWh/d (updated BSM1 version)

Total pumping energy (for Qintr, Qr and Qw) = 30877.3125 kWh (original BSM1 version)
Average pumping energy per day (for Qintr, Qr and Qw) = 4411.0446 kWh/d (original BSM1
version)
Total pumping energy (for Qintr, Qr and Qw) = 3728.1893 kWh (based on BSM2 principles)
```

Average pumping energy per day (for Qintr, Qr and Qw) = 532.5985 kWh/d (based on BSM2 principles)

Total mixing energy = 1680 kWh (based on BSM2 principles)
Average mixing energy per day = 240 kWh/d (based on BSM2 principles)

Total added carbon volume = 32.0058 m3
Average added carbon flow rate = 4.5723 m3/d
Total added carbon mass = 12802.3163 kg COD
Average added carbon mass per day = 1828.9023 kg COD/d

Operational Cost Index

Sludge production cost index = 14960.937 (using weight 5 for BSM1)
Aeration energy cost index = 7411.1286 (original BSM1 version)
Updated aeration energy cost index = 3789.9409 (updated BSM1 version)
Pumping energy cost index = 4411.0446 (original BSM1 version)
Updated pumping energy cost index = 532.5985 (based on BSM2 principles)
Carbon source addition cost index = 5486.707
Mixing energy cost index = 240 (based on BSM2 principles)
Total Operational Cost Index (OCI) = 32509.8172 (original BSM1 version)
Updated Total Operational Cost Index (OCI) = 25010.1834 (using new aeraration and pumping costs)

Effluent violations

95% percentile for effluent SNH (Ammonia95) = 7.0936 g N/m3
95% percentile for effluent TN (TN95) = 13.8814 g N/m3
95% percentile for effluent TSS (TSS95) = 17.1155 g SS/m3

The maximum effluent ammonia nitrogen level (4 mg N/l) was violated
during 1.6771 days, i.e. 23.9583% of the operating time.
The limit was violated at 7 different occasions.

Qualitative criteria for settling problems

The plant has experienced high (>0.8) risk for the development of filamentous bulking due to N deficiency
during 0 days, i.e. 0% of the operating time.
...and risk for the development of filamentous bulking due to N deficiency 100% of the operating time.
average risk 0.00011765

The plant has experienced high (>0.8) risk for the development of aerobic (low DO) filamentous bulking
during 1.1458 days, i.e. 16.369% of the operating time.
...and risk for the development of aerobic (low DO) filamentous bulking 98.2143% of the operating time.
average risk 0.42363
The most dangerous situation was between days 8.4479 and 8.6458

The plant has experienced severe (>0.8) risk for the development of low F/M filamentous bulking
during 2.0208 days, i.e. 28.869% of the operating time.
...and risk for the development of low F/M filamentous bulking 100% of the operating time.
average risk 0.72522
The most dangerous situation was between days 12.0833 and 12.4167

The plant has experienced high (>0.8) risk for the development of low F/M foaming
during 0 days, i.e. 0% of the operating time.
...and risk for the development of low F/M foaming 100% of the operating time.
average risk 0.50824

The plant has experienced high (>0.8) risk for the development of foaming due to high Ss/Xs fraction
during 0 days, i.e. 0% of the operating time.
...and risk for the development of foaming due to high Ss/Xs fraction 99.8512% of the operating time.
average risk 0.025648

The plant has experienced high (>0.8) risk for the development of rising sludge
during 0 days, i.e. 0% of the operating time.
...and risk for the development of rising sludge 100% of the operating time.
average risk 0.42338
Overall risk

The plant has experienced severe (>0.8) risk for (integrated) BULKING

```
during 3.1667 days, i.e. 45.2381% of the operating time.
...and risk for the development of (integrated) Bulking 100% of the operating time.
average risk 0.80715
The most dangerous situation was between days 12.0833 and 12.4167

The plant has experienced severe (>0.8) risk for (integrated) FOAMING
during 0 days, i.e. 0% of the operating time.
...and risk for the development of (integrated) Foaming 100% of the operating time.
average risk 0.51286

The plant has experienced OVERALL severe (>0.8) risk for OVERALL SETTLING PROBLEMS
during 3.1667 days, i.e. 45.2381% of the operating time.
...and risk for the development of OVERALL SETTLING PROBLEMS 100% of the operating time.
average risk 0.80715
The most dangerous situation was between days 7.4896 and 12.4167
```

A5. Performance evaluation of ASM3 bioP plant during dynamic simulation (dry weather data) – BSM1 control strategy 2 (S2)

```
Overall plant performance during time 7 to 14 days
**************************************************

Effluent average concentrations based on load
---------------------------------------------
Effluent average flow rate = 18053.694 m3/d
Effluent average SI conc = 30 mg COD/l
Effluent average SS conc = 0.85587 mg COD/l
Effluent average XI conc = 4.5728 mg COD/l
Effluent average XS conc = 0.19424 mg COD/l
Effluent average XBH conc = 10.2335 mg COD/l
Effluent average XBA conc = 0.58456 mg COD/l
Effluent average XP conc = 1.7567 mg COD/l
Effluent average SO conc = 3.9463 mg (-COD)/l
Effluent average SNO conc = 13.4285 mg N/l
Effluent average SNH conc = 2.1595 mg N/l  (limit = 4 mg N/l)
Effluent average SND conc = 0.69667 mg N/l
Effluent average XND conc = 0.014014 mg N/l
Effluent average SALK conc = 3.9418 mol HCO3/m3
Effluent average TSS conc = 13.0063 mg SS/l  (limit = 30 mg SS/l)

Effluent average Kjeldahl N conc = 4.1154 mg N/l
Effluent average total N conc = 17.5439 mg N/l  (limit = 18 mg COD/l)
Effluent average total COD conc = 48.1976 mg COD/l  (limit = 100 mg COD/l)
Effluent average BOD5 conc = 2.7507 mg/l  (limit = 10 mg/l)

Effluent average load
---------------------
Effluent average SI load = 541.6108 kg COD/day
Effluent average SS load = 15.4516 kg COD/day
Effluent average XI load = 82.5557 kg COD/day
Effluent average XS load = 3.5067 kg COD/day
Effluent average XBH load = 184.7519 kg COD/day
Effluent average XBA load = 10.5535 kg COD/day
Effluent average XP load = 31.7147 kg COD/day
Effluent average SO load = 71.2457 kg (-COD)/day
Effluent average SNO load = 242.4336 kg N/day
Effluent average SNH load = 38.9873 kg N/day
Effluent average SND load = 12.5774 kg N/day
Effluent average XND load = 0.25301 kg N/day
Effluent average SALK load = 71.164 kmol HCO3/day
Effluent average TSS load = 234.8119 kg SS/day

Effluent average Kjeldahl N load = 74.2983 kg N/d
Effluent average total N load = 316.732 kg N/d
Effluent average total COD load = 870.1449 kg COD/d
Effluent average BOD5 load = 49.6598 kg/d

Other effluent quality variables
--------------------------------
Influent Quality (I.Q.) index = 42042.8149 kg poll.units/d (original BSM1 version)
Effluent Quality (E.Q.) index = 7773.7279 kg poll.units/d (original BSM1 version)
Influent Quality (I.Q.) index = 52081.3952 kg poll.units/d (updated BSM1 version)
Effluent Quality (E.Q.) index = 6092.3749 kg poll.units/d (updated BSM1 version)

Sludge production for disposal = 17089.1899 kg SS
Average sludge production for disposal per day = 2441.3128 kg SS/d
Sludge production released into effluent = 1643.6832 kg SS
Average sludge production released into effluent per day = 234.8119 kg SS/d
Total sludge production = 18732.8731 kg SS
Total average sludge production per day = 2676.1247 kg SS/d

Total aeration energy = 60416.2451 kWh (original BSM1 version)
Average aeration energy per day = 8630.8922 kWh/d (original BSM1 version)
Total aeration energy = 29668.5447 kWh (updated BSM1 version)
Average aeration energy per day = 4238.3635 kWh/d (updated BSM1 version)

Total pumping energy (for Qintr, Qr and Qw) = 9402.8803 kWh (original BSM1 version)
Average pumping energy per day (for Qintr, Qr and Qw) = 1343.2686 kWh/d (original BSM1 version)
Total pumping energy (for Qintr, Qr and Qw) = 1580.746 kWh (based on BSM2 principles)
```

Average pumping energy per day (for Qintr, Qr and Qw) = 225.8209 kWh/d (based on BSM2 principles)

Total mixing energy = 1680 kWh (based on BSM2 principles)
Average mixing energy per day = 240 kWh/d (based on BSM2 principles)

Total added carbon volume = 0 m3
Average added carbon flow rate = 0 m3/d
Total added carbon mass = 0 kg COD
Average added carbon mass per day = 0 kg COD/d

Operational Cost Index

Sludge production cost index = 12206.5642 (using weight 5 for BSM1)
Aeration energy cost index = 8630.8922 (original BSM1 version)
Updated aeration energy cost index = 4238.3635 (updated BSM1 version)
Pumping energy cost index = 1343.2686 (original BSM1 version)
Updated pumping energy cost index = 225.8209 (based on BSM2 principles)
Carbon source addition cost index = 0
Mixing energy cost index = 240 (based on BSM2 principles)
Total Operational Cost Index (OCI) = 22420.725 (original BSM1 version)
Updated Total Operational Cost Index (OCI) = 16910.7486 (using new aeraration and pumping costs)

Effluent violations

95% percentile for effluent SNH (Ammonia95) = 6.7806 g N/m3
95% percentile for effluent TN (TN95) = 20.8836 g N/m3
95% percentile for effluent TSS (TSS95) = 15.776 g SS/m3

The maximum effluent total nitrogen level (18 mg N/l) was violated
during 1.6354 days, i.e. 23.3631% of the operating time.
The limit was violated at 8 different occasions.

The maximum effluent ammonia nitrogen level (4 mg N/l) was violated
during 1.0729 days, i.e. 15.3274% of the operating time.
The limit was violated at 5 different occasions.

Qualitative criteria for settling problems
--
The plant has experienced high (>0.8) risk for the development of filamentous bulking due to N deficiency
during 0 days, i.e. 0% of the operating time.
...and risk for the development of filamentous bulking due to N deficiency 100% of the operating time.
average risk 0.00011765

The plant has experienced high (>0.8) risk for the development of aerobic (low DO) filamentous bulking
during 0.57292 days, i.e. 8.1845% of the operating time.
...and risk for the development of aerobic (low DO) filamentous bulking 97.1726% of the operating time.
average risk 0.33949
The most dangerous situation was between days 8.4479 and 8.5729

The plant has experienced severe (>0.8) risk for the development of low F/M filamentous bulking
during 3.0104 days, i.e. 43.006% of the operating time.
...and risk for the development of low F/M filamentous bulking 100% of the operating time.
average risk 0.73607
The most dangerous situation was between days 13 and 13.4375

The plant has experienced high (>0.8) risk for the development of low F/M foaming
during 0 days, i.e. 0% of the operating time.
...and risk for the development of low F/M foaming 100% of the operating time.
average risk 0.54047

The plant has experienced high (>0.8) risk for the development of foaming due to high Ss/Xs fraction
during 0 days, i.e. 0% of the operating time.
...and risk for the development of foaming due to high Ss/Xs fraction 99.5536% of the operating time.
average risk 0.025762

The plant has experienced high (>0.8) risk for the development of rising sludge
during 3.5729 days, i.e. 51.0417% of the operating time.
...and risk for the development of rising sludge 100% of the operating time.

```
average risk 0.62915
The most dangerous situation was between days 7.4583 and 8.1354

Overall risk
------------
The plant has experienced severe (>0.8) risk for (integrated) BULKING
during 3.5833 days, i.e. 51.1905% of the operating time.
...and risk for the development of (integrated) Bulking 100% of the operating time.
average risk 0.81097
The most dangerous situation was between days 13 and 13.4375

The plant has experienced severe (>0.8) risk for (integrated) FOAMING
during 0 days, i.e. 0% of the operating time.
...and risk for the development of (integrated) Foaming 100% of the operating time.
average risk 0.54936

The plant has experienced high (>0.8) risk for the development of RISING SLUDGE
during 3.5729 days, i.e. 51.0417% of the operating time.
...and risk for the development of rising sludge 100% of the operating time.
average risk 0.62915
The most dangerous situation was between days 7.4583 and 8.1354

The plant has experienced OVERALL severe (>0.8) risk for OVERALL SETTLING PROBLEMS
during 6.3125 days, i.e. 90.1786% of the operating time.
...and risk for the development of OVERALL SETTLING PROBLEMS 100% of the operating time.
average risk 0.96153
The most dangerous situation was between days 8.1146 and 12.4375
```

A6. Performance evaluation of ASM3 bioP plant during dynamic simulation (dry weather data) – BSM1 control strategy 3 (S3)

```
Overall plant performance during time 7 to 14 days
**************************************************

Effluent average concentrations based on load
---------------------------------------------
Effluent average flow rate = 18051.9149 m3/d
Effluent average SI conc = 30 mg COD/l
Effluent average SS conc = 0.83934 mg COD/l
Effluent average XI conc = 4.5722 mg COD/l
Effluent average XS conc = 0.19001 mg COD/l
Effluent average XBH conc = 10.2333 mg COD/l
Effluent average XBA conc = 0.59238 mg COD/l
Effluent average XP conc = 1.7576 mg COD/l
Effluent average SO conc = 3.9778 mg (-COD)/l
Effluent average SNO conc = 14.3443 mg N/l
Effluent average SNH conc = 1.7001 mg N/l  (limit = 4 mg N/l)
Effluent average SND conc = 0.68821 mg N/l
Effluent average XND conc = 0.013753 mg N/l
Effluent average SALK conc = 3.8436 mol HCO3/m3
Effluent average TSS conc = 13.0091 mg SS/l  (limit = 30 mg SS/l)

Effluent average Kjeldahl N conc = 3.6479 mg N/l
Effluent average total N conc = 17.9922 mg N/l  (limit = 18 mg COD/l)
Effluent average total COD conc = 48.1848 mg COD/l  (limit = 100 mg COD/l)
Effluent average BOD5 conc = 2.7472 mg/l  (limit = 10 mg/l)

Effluent average load
---------------------
Effluent average SI load = 541.5574 kg COD/day
Effluent average SS load = 15.1518 kg COD/day
Effluent average XI load = 82.5362 kg COD/day
Effluent average XS load = 3.4301 kg COD/day
Effluent average XBH load = 184.7308 kg COD/day
Effluent average XBA load = 10.6936 kg COD/day
Effluent average XP load = 31.728 kg COD/day
Effluent average SO load = 71.8066 kg (-COD)/day
Effluent average SNO load = 258.9423 kg N/day
Effluent average SNH load = 30.6893 kg N/day
Effluent average SND load = 12.4235 kg N/day
Effluent average XND load = 0.24827 kg N/day
Effluent average SALK load = 69.3838 kmol HCO3/day
Effluent average TSS load = 234.839 kg SS/day

Effluent average Kjeldahl N load = 65.8508 kg N/d
Effluent average total N load = 324.7932 kg N/d
Effluent average total COD load = 869.8279 kg COD/d
Effluent average BOD5 load = 49.5931 kg/d

Other effluent quality variables
--------------------------------
Influent Quality (I.Q.) index = 42042.8149 kg poll.units/d (original BSM1 version)
Effluent Quality (E.Q.) index = 7934.5559 kg poll.units/d (original BSM1 version)
Influent Quality (I.Q.) index = 52081.3952 kg poll.units/d (updated BSM1 version)
Effluent Quality (E.Q.) index = 6003.6409 kg poll.units/d (updated BSM1 version)

Sludge production for disposal = 17096.7858 kg SS
Average sludge production for disposal per day = 2442.398 kg SS/d
Sludge production released into effluent = 1643.8732 kg SS
Average sludge production released into effluent per day = 234.839 kg SS/d
Total sludge production = 18740.659 kg SS
Total average sludge production per day = 2677.237 kg SS/d

Total aeration energy = 79103.1443 kWh (original BSM1 version)
Average aeration energy per day = 11300.4492 kWh/d (original BSM1 version)
Total aeration energy = 35681.317 kWh (updated BSM1 version)
Average aeration energy per day = 5097.331 kWh/d (updated BSM1 version)

Total pumping energy (for Qintr, Qr and Qw) = 8855.4584 kWh (original BSM1 version)
Average pumping energy per day (for Qintr, Qr and Qw) = 1265.0655 kWh/d (original BSM1
version)
Total pumping energy (for Qintr, Qr and Qw) = 1526.0038 kWh (based on BSM2 principles)
```

Average pumping energy per day (for Qintr, Qr and Qw) = 218.0005 kWh/d (based on BSM2 principles)

Total mixing energy = 1680 kWh (based on BSM2 principles)
Average mixing energy per day = 240 kWh/d (based on BSM2 principles)

Total added carbon volume = 0 m3
Average added carbon flow rate = 0 m3/d
Total added carbon mass = 0 kg COD
Average added carbon mass per day = 0 kg COD/d

Operational Cost Index

Sludge production cost index = 12211.9898 (using weight 5 for BSM1)
Aeration energy cost index = 11300.4492 (original BSM1 version)
Updated aeration energy cost index = 5097.331 (updated BSM1 version)
Pumping energy cost index = 1265.0655 (original BSM1 version)
Updated pumping energy cost index = 218.0005 (based on BSM2 principles)
Carbon source addition cost index = 0
Mixing energy cost index = 240 (based on BSM2 principles)
Total Operational Cost Index (OCI) = 25017.5045 (original BSM1 version)
Updated Total Operational Cost Index (OCI) = 17767.3214 (using new aeraration and pumping costs)

Effluent violations

95% percentile for effluent SNH (Ammonia95) = 5.9261 g N/m3
95% percentile for effluent TN (TN95) = 21.2385 g N/m3
95% percentile for effluent TSS (TSS95) = 15.7827 g SS/m3

The maximum effluent total nitrogen level (18 mg N/l) was violated
during 2.75 days, i.e. 39.2857% of the operating time.
The limit was violated at 11 different occasions.

The maximum effluent ammonia nitrogen level (4 mg N/l) was violated
during 0.875 days, i.e. 12.5% of the operating time.
The limit was violated at 5 different occasions.

Qualitative criteria for settling problems
--
The plant has experienced high (>0.8) risk for the development of filamentous bulking due to N deficiency
during 0 days, i.e. 0% of the operating time.
...and risk for the development of filamentous bulking due to N deficiency 100% of the operating time.
average risk 0.00011765

The plant has experienced high (>0.8) risk for the development of aerobic (low DO) filamentous bulking
during 0 days, i.e. 0% of the operating time.
...and risk for the development of aerobic (low DO) filamentous bulking 95.3869% of the operating time.
average risk 0.065728

The plant has experienced severe (>0.8) risk for the development of low F/M filamentous bulking
during 3.0104 days, i.e. 43.006% of the operating time.
...and risk for the development of low F/M filamentous bulking 100% of the operating time.
average risk 0.7362
The most dangerous situation was between days 13 and 13.4375

The plant has experienced high (>0.8) risk for the development of low F/M foaming
during 0 days, i.e. 0% of the operating time.
...and risk for the development of low F/M foaming 100% of the operating time.
average risk 0.54089

The plant has experienced high (>0.8) risk for the development of foaming due to high Ss/Xs fraction
during 0 days, i.e. 0% of the operating time.
...and risk for the development of foaming due to high Ss/Xs fraction 99.4048% of the operating time.
average risk 0.025644

The plant has experienced high (>0.8) risk for the development of rising sludge
during 3.5313 days, i.e. 50.4464% of the operating time.
...and risk for the development of rising sludge 100% of the operating time.
average risk 0.62169

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The most dangerous situation was between days 7.4583 and 8.1354

Overall risk
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The plant has experienced severe (>0.8) risk for (integrated) BULKING
during 3.0104 days, i.e. 43.006% of the operating time.
...and risk for the development of (integrated) Bulking 100% of the operating time.
average risk 0.74727
The most dangerous situation was between days 13 and 13.4375

The plant has experienced severe (>0.8) risk for (integrated) FOAMING
during 0 days, i.e. 0% of the operating time.
...and risk for the development of (integrated) Foaming 100% of the operating time.
average risk 0.54973

The plant has experienced high (>0.8) risk for the development of RISING SLUDGE
during 3.5313 days, i.e. 50.4464% of the operating time.
...and risk for the development of rising sludge 100% of the operating time.
average risk 0.62169
The most dangerous situation was between days 7.4583 and 8.1354

The plant has experienced OVERALL severe (>0.8) risk for OVERALL SETTLING PROBLEMS
during 6.2708 days, i.e. 89.5833% of the operating time.
...and risk for the development of OVERALL SETTLING PROBLEMS 100% of the operating time.
average risk 0.95761
The most dangerous situation was between days 8.125 and 12.4375
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