Benchmark Simulation Model no. 1 (BSM1)

J. Alex, L. Benedetti, J. Copp, K.V. Gernaey, U. Jeppsson,
I. Nopens, M.N. Pons, J.P. Steyer and P. Vanrolleghem

Summary

The present document presents in details the final state of Benchmark Simulation Model no. 1 (BSM1). The model equations to be implemented for the proposed layout, the procedure to test the implementation and the performance criteria to be used are described, as well as the sensors and control handles. Finally open-loop and closed-loop results obtained with a Matlab-Simulink and a FORTRAN implementations are proposed.

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1. INTRODUCTION

Wastewater treatment plants (WWTPs) are large non-linear systems subject to large perturbations in influent flow rate and pollutant load, together with uncertainties concerning the composition of the incoming wastewater. Nevertheless these plants have to be operated continuously, meeting stricter and stricter regulations.

Many control strategies have been proposed in the literature but their evaluation and comparison, either practical or based on simulation is difficult. This is due to a number of reasons, including: (1) the variability of the influent; (2) the complexity of the biological and biochemical phenomena; (3) the large range of time constants (varying from a few minutes to several days); (4) the lack of standard evaluation criteria (among other things, due to region specific effluent requirements and cost levels).

It is thus difficult to judge the particular influence of an applied control strategy on reported plant performance increase, as the reference situation is often not properly characterized. Due to the complexity of the systems it takes much effort to develop alternative controller approaches and, as a consequence of that, a fair comparison between different control strategies is only seldom made. And even if this is done, it remains difficult to conclude to what extent the proposed solution is process or location specific.

To enhance the acceptance of innovating control strategies, the performance evaluation should be based on a rigorous methodology including a reference simulation model, a precise plant layout, well-defined controllers, performance criteria and test procedures.

From 1998 to 2004, the development of benchmark tools for simulation-based evaluation of control strategies for activated sludge plants has been undertaken in Europe by Working Groups of COST Action 682 and 624 (Alex *et al*., 1999). This development work is now continued under the umbrella of the IWA Task Group on Benchmarking of Control Strategies for WWTPs.

The benchmark is a simulation environment defining a plant layout, a simulation model, influent loads, test procedures and evaluation criteria. For each of these items, compromises were pursued to combine plainness with realism and accepted standards. Once the user has validated the simulation code, any control strategy can be applied and the performance can be evaluated according to a defined set of criteria. The benchmark is not linked to a particular simulation platform: direct coding (C/C++, Fortran) as well as commercial WWTP simulation software packages (such as Simba®, WEST®, GPS-X®) can be used. For this reason, the full set of equations and all the parameter values are available in the present document.

The first layout (BSM1) is relatively simple. The benchmark plant is composed of a five-compartment activated sludge reactor consisting of two anoxic tanks followed by three aerobic tanks. The plant thus combines nitrification with predenitrification in a configuration that is commonly used for achieving biological nitrogen removal in full-scale plants. The activated sludge reactor is followed by a secondary clarifier. A basic control strategy is proposed to test the benchmark: its aim is to control the dissolved oxygen level in the final compartment of the reactor by manipulation of the oxygen transfer coefficient and to control the nitrate level in the last anoxic tank by manipulation of the internal recycle flow rate.

The purpose of the present document is to describe in details the BSM1 benchmark, as depicted in Figure 1. Further information to facilitate the implementation on various platforms can be found in Copp (2002). However, some slight changes have been made since then and a careful reading of the present document is required for an up-to-date use of BSM1.

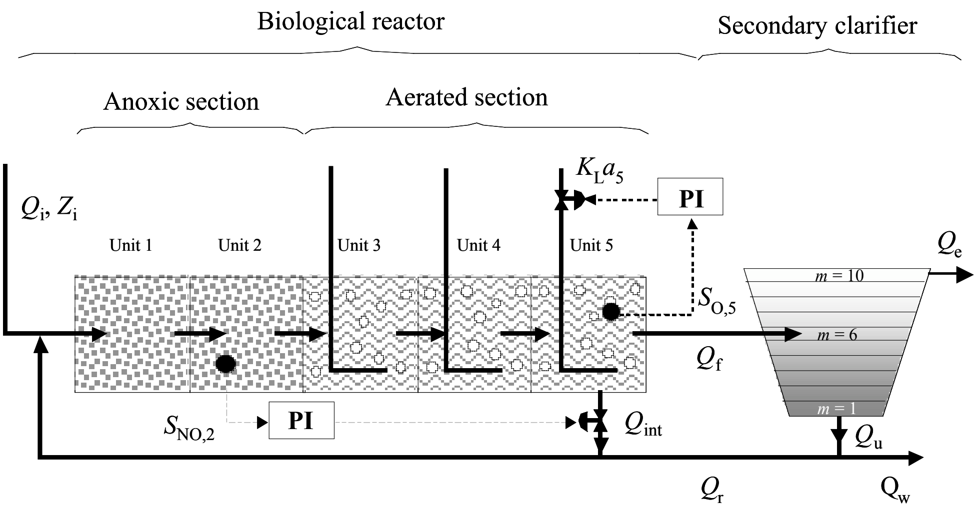

Figure 1: General overview of the BSM1 plant

2. SIMULATION MODEL

2.1. General characteristics

The plant is designed for an average influent dry-weather flow rate of 18,446 $m^3.d^{-1}$ and an average biodegradable COD in the influent of 300 $g.m^{-3}$. Its hydraulic retention time (based on average dry weather flow rate and total tank volume – i.e. biological reactor + secondary clarifier – of 12,000 m^3) is 14.4 hours. The biological reactor volume and the settler volume are both equal to 6,000 m^3. The wastage flow rate equals 385 $m^3.d^{-1}$. This corresponds to a biomass sludge age of about 9 days (based on the total amount of biomass present in the system).

The influent dynamics are defined by means of files for three different weather conditions: dry weather, rain weather (a combination of dry weather and a long rain period) and storm weather (a combination of dry weather with two storm events).

2.2. Bioprocess model

The Activated Sludge Model no. 1 (ASM1; Henze *et al.*, 1987) has been selected to describe the biological phenomena taking place in the biological reactor (Figure 2).

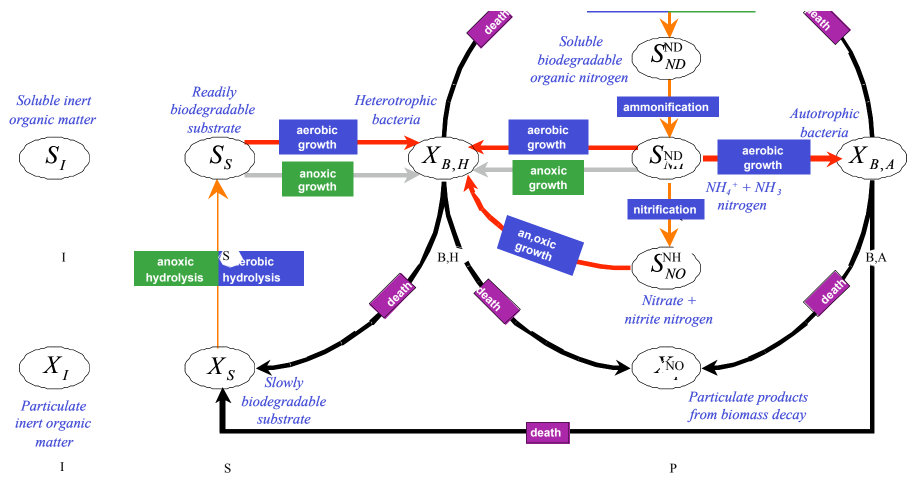

Figure 2: General overview of ASM1

2.2.1. List of variables

A list of state variables, with their definition and appropriate notation, is given in Table 1.

Table 1: List of ASM1 variables

Definition	Notation
Soluble inert organic matter	S_I
Readily biodegradable substrate	S_S
Particulate inert organic matter	X_I
Slowly biodegradable substrate	X_S
Active heterotrophic biomass	$X_{B,H}$
Active autotrophic biomass	$X_{B,A}$
Particulate products arising from biomass decay	X_P
Oxygen	S_O
Nitrate and nitrite nitrogen	S_{NO}
$NH_4^+ + NH_3$ nitrogen	S_{NH}
Soluble biodegradable organic nitrogen	S_{ND}
Particulate biodegradable organic nitrogen	X_{ND}
Alkalinity	S_{ALK}

2.2.2. List of processes

Eight basic processes (ρ_k, k = 1 to 8) are used to describe the biological behavior of the system.

- $j = 1$: Aerobic growth of heterotrophs

$$\rho_1 = \mu_H \left(\frac{S_S}{K_S + S_S}\right)\left(\frac{S_O}{K_{O,H} + S_O}\right) X_{B,H} \tag{1}$$

- $j = 2$: Anoxic growth of heterotrophs

$$\rho_2 = \mu_H \left(\frac{S_S}{K_S + S_S}\right)\left(\frac{K_{O,H}}{K_{O,H} + S_O}\right)\left(\frac{S_{NO}}{K_{NO} + S_{NO}}\right)\eta_g X_{B,H} \tag{2}$$

- $j = 3$: Aerobic growth of autotrophs

$$\rho_3 = \mu_A \left(\frac{S_{NH}}{K_{NH} + S_{NH}}\right)\left(\frac{S_O}{K_{O,A} + S_O}\right) X_{B,A} \tag{3}$$

- $j = 4$: Decay of heterotrophs

$$\rho_4 = b_H X_{B,H} \tag{4}$$

- $j = 5$: Decay of autotrophs

$$\rho_5 = b_A X_{B,A} \tag{5}$$

- $j = 6$: Ammonification of soluble organic nitrogen

$$\rho_6 = k_a S_{ND} X_{B,H} \tag{6}$$

- $j = 7$: Hydrolysis of entrapped organics

$$\rho_7 = k_h \frac{X_S/X_{B,H}}{K_X + \left(X_S/X_{B,H}\right)}\left[\left(\frac{S_O}{K_{O,H} + S_O}\right) + \eta_h \left(\frac{K_{O,H}}{K_{O,H} + S_O}\right)\left(\frac{S_{NO}}{K_{NO} + S_{NO}}\right)\right] X_{B,H} \tag{7}$$

- $j = 8$: Hydrolysis of entrapped organic nitrogen

$$\rho_8 = k_h \frac{X_S/X_{B,H}}{K_X + \left(X_S/X_{B,H}\right)}\left[\left(\frac{S_O}{K_{O,H} + S_O}\right) + \eta_h \left(\frac{K_{O,H}}{K_{O,H} + S_O}\right)\left(\frac{S_{NO}}{K_{NO} + S_{NO}}\right)\right] X_{B,H}\left(X_{ND}/X_S\right) \tag{8}$$

2.2.3. Observed conversion rates

The observed conversion rates (r_k) result from combinations of the basic processes: $r_k = \sum_j \nu_{kj}\rho_j$

- S_I ($k = 1$)

$$r_1 = 0 \tag{9}$$

- S_S (k= 2)

$$r_2 = -\frac{1}{Y_H}\rho_1 - \frac{1}{Y_H}\rho_2 + \rho_7 \tag{10}$$

- X_I (k = 3)

$$r_3 = 0 \tag{11}$$

- X_S (k = 4)

$$r_4 = (1 - f_P)\rho_4 + (1 - f_P)\rho_5 - \rho_7 \tag{12}$$

- $X_{B,H}$ (k = 5)

$$r_5 = \rho_1 + \rho_2 - \rho_4 \tag{13}$$

- $X_{B,A}$ (k = 6)

$$r_6 = \rho_3 - \rho_5 \tag{14}$$

- X_P (k = 7)

$$r_7 = f_P\rho_4 + f_P\rho_5 \tag{15}$$

- S_O (k = 8)

$$r_8 = -\frac{1 - Y_H}{Y_H}\rho_1 - \frac{4.57 - Y_A}{Y_A}\rho_3 \tag{16}$$

- S_{NO} (k = 9)

$$r_9 = -\frac{1 - Y_H}{2.86\,Y_H}\rho_2 + \frac{1}{Y_A}\rho_3 \tag{17}$$

- S_{NH} (k = 10)

$$r_{10} = -i_{XB}\rho_1 - i_{XB}\rho_2 - \left(i_{XB} + \frac{1}{Y_A}\right)\rho_3 + \rho_6 \tag{18}$$

- S_{ND} (k = 11)

$$r_{11} = -\rho_6 + \rho_8 \tag{19}$$

- X_{ND} (k = 12)

$$r_{12} = (i_{XB} - f_P i_{XP})\rho_4 + (i_{XB} - f_P i_{XP})\rho_5 - \rho_8 \tag{20}$$

- S_{ALK} (k = 13)

$$r_{13} = -\frac{i_{XB}}{14}\rho_1 + \left(\frac{1 - Y_H}{14 \cdot 2.86\,Y_H} - \frac{i_{XB}}{14}\right)\rho_2 - \left(\frac{i_{XB}}{14} + \frac{1}{7Y_A}\right)\rho_3 + \frac{1}{14}\rho_6 \tag{21}$$

2.2.4. Biological parameter values

The biological parameter values used in BSM1 correspond approximately to a temperature of 15°C. The stoichiometric parameters are listed in Table 2 and the kinetic parameters in Table 3.

Table 2: Stoichiometric parameters

Parameter	Unit	Value
Y_A	g cell COD formed.(g N oxidized)$^{-1}$	0.24
Y_H	g cell COD formed.(g COD oxidized)$^{-1}$	0.67
f_P	dimensionless	0.08
i_{XB}	g N.(g COD)$^{-1}$ in biomass	0.08
i_{XP}	g N.(g COD)$^{-1}$ in particulate products	0.06

Table 3: Kinetic parameters

Parameter	Unit	Value
μ_H	d^{-1}	4.0
K_S	g COD.m^{-3}	10.0
$K_{O,H}$	g (-COD).m^{-3}	0.2
K_{NO}	g NO_3-N.m^{-3}	0.5
b_H	d^{-1}	0.3
η_g	dimensionless	0.8
η_h	dimensionless	0.8
k_h	g slowly biodegradable COD.(g cell COD.d)$^{-1}$	3.0
K_X	g slowly biodegradable COD.(g cell COD)$^{-1}$	0.1
μ_A	d^{-1}	0.5
K_{NH}	g NH_3-N.m^{-3}	1.0
b_A	d^{-1}	0.05
$K_{O,A}$	g (-COD).m^{-3}	0.4
k_a	m^3 (g COD.d)$^{-1}$	0.05

2.3. Detailed plant layout

2.3.1. Bioreactor (General characteristics)

According to Figure 1, the general characteristics of the bioreactor for the default case are:

Number of compartments: 5
Non-aerated compartments: compartments 1-2
Aerated compartments:

- compartments 3-4, with a fixed oxygen transfer coefficient (K_La = 10 h^{-1} = 240 d^{-1})
- compartment 5: the dissolved oxygen concentration (S_O) is controlled at a level of 2 g (-COD).m^{-3} by manipulation of the K_La

For each compartment, the following variables have been defined (k = 1 to 5):

- Flow rate: Q_k
- Concentration: $Z_{as,k}$
- Volume:
  Non-aerated compartments: $V_{as,1} = V_{as,2}$ = 1,000 m^3
  Aerated compartments: $V_{as,3} = V_{as,,4} = V_{as,5}$ = 1,333 m^3
- Reaction rate: r_k

2.3.2. Reactor mass balances (general formula)

The general equations for mass balancing are as follows:

- For k = 1 (unit 1)

$$\frac{dZ_{as,1}}{dt} = \frac{1}{V_{as,1}}\left(Q_{int}Z_{int} + Q_rZ_r + Q_iZ_i + r_{Z,1}V_{as,1} - Q_1Z_{as,1}\right) \tag{22}$$

$$Q_1 = Q_{int} + Q_r + Q_i \tag{23}$$

- For k = 2 to 5

$$\frac{dZ_{as,k}}{dt} = \frac{1}{V_{as,k}}\left(Q_{k-1}Z_{as,k-1} + r_{Z,k}V_{as,k} - Q_kZ_{as,k}\right) \tag{24}$$

$$Q_k = Q_{k-1} \tag{25}$$

- Special case for oxygen ($S_{O,as,k}$)

$$\frac{dS_{O,as,k}}{dt} = \frac{1}{V_{as,k}}\left(Q_{k-1}S_{O,as,k-1} + r_{Z,k}V_{as,k} + (K_L a)_k V_{as,k}\left(S_O^* - S_{O,as,k}\right) - Q_k S_{O,as,k}\right) \quad (26)$$

where the saturation concentration for oxygen is S_O^* = 8 g.m^{-3}.
$r_{Z,k}$ stands for the appropriate conversion rate, depending upon the state variable considered (cf §§ 2.2.3).

- Miscellaneous

$$Z_{int} = Z_{as,5} \quad (27)$$

$$Z_f = Z_{as,5} \quad (28)$$

$$Z_w = Z_r \quad (29)$$

$$Q_f = Q_e + Q_r + Q_w = Q_e + Q_u \quad (30)$$

where Q_u is the underflow of the secondary clarifier.

2.3.3. Secondary clarifier

The secondary clarifier is modeled as a 10 layer non-reactive unit (i.e. no biological reaction). The 6th layer (counting from bottom to top) is the feed layer. The secondary clarifier has an area (A) of 1,500 m^2. The height of each layer m (z_m) is equal to 0.4 m, for a total height of 4 m. The secondary clarifier volume is therefore equal to 6,000 m^3.

The solid flux due to gravity is $J_s = v_s(X_{sc})X_{sc}$ where X_{sc} is the total sludge concentration. A double-exponential settling velocity function (Takács *et al.,* 1991) has been selected:

$$v_s(X_{sc}) = \max\left[0, \min\left\{v_0', v_0\left(e^{-r_h(X_{sc}-X_{min})} - e^{-r_p(X_{sc}-X_{min})}\right)\right\}\right] \quad (31)$$

with $X_{min} = f_{ns}X_f$. X_f is the total solid concentration from the biological reactor. The parameter values for the settling velocity function are given in Table 4.

Table 4: Settling parameters

	Parameter	Units	Value
Maximum settling velocity	v_0'	m.d^{-1}	250.
Maximum Vesilind settling velocity	v_0	m.d^{-1}	474
Hindered zone settling parameter	r_h	m^3.(g SS)$^{-1}$	0.000576
Flocculant zone settling parameter	r_p	m^3.(g SS)$^{-1}$	0.00286
Non-settleable fraction	f_{ns}	dimensionless	0.00228

The upward (v_{up}) and downward (v_{dn}) velocities are calculated as:

$$v_{dn} = \frac{Q_u}{A} = \frac{Q_r + Q_w}{A} \quad (32)$$

$$v_{up} = \frac{Q_e}{A} \quad (33)$$

According to these notations, the mass balances for the sludge are written as:
For the feed layer (m = 6):

$$\frac{dX_{sc,m}}{dt} = \frac{\frac{Q_f X_f}{A} + J_{sc,m+1} - (v_{up} + v_{dn})X_{sc,m} - \min(J_{s,m}, J_{s,m-1})}{z_m} \quad (34)$$

For the intermediate layers below the feed layer (m = 2 to m = 5):

$$\frac{dX_{\mathrm{sc,m}}}{dt}=\frac{v_{\mathrm{dn}}\left(X_{\mathrm{sc,m+1}}-X_{\mathrm{sc,m}}\right)+\min\left(J_{s,\mathrm{m}},J_{s,\mathrm{m+1}}\right)-\min\left(J_{\mathrm{s,m}},J_{\mathrm{s,m-1}}\right)}{z_{\mathrm{m}}} \tag{35}$$

For the bottom layer (m = 1):

$$\frac{dX_{\mathrm{sc,1}}}{dt}=\frac{v_{\mathrm{dn}}\left(X_{\mathrm{sc,2}}-X_{\mathrm{sc,1}}\right)+\min\left(J_{\mathrm{s,2}},J_{\mathrm{s,1}}\right)}{z_1} \tag{36}$$

For the intermediate clarification layers above the feed layer (m = 7 to m = 9)

$$\frac{dX_{\mathrm{sc,m}}}{dt}=\frac{v_{\mathrm{up}}\left(X_{\mathrm{sc,m-1}}-X_{\mathrm{sc,m}}\right)+J_{\mathrm{sc,m+1}}-J_{\mathrm{sc,m}}}{z_{\mathrm{m}}} \tag{37}$$

$$J_{\mathrm{sc,j}}=\begin{cases}\min\left(v_{s,\mathrm{j}}X_{\mathrm{sc,j}},v_{s,\mathrm{j-1}}X_{\mathrm{sc,j-1}}\right) \; if \;\; X_{\mathrm{sc,j-1}}>X_{\mathrm{t}}\\ \text{or}\\ v_{s,\mathrm{j}}X_{\mathrm{sc,j}} \quad if \quad X_{\mathrm{sc,j-1}}\le X_{\mathrm{t}}\end{cases} \tag{38}$$

For the top layer (m = 10)

$$\frac{dX_{\mathrm{sc,10}}}{dt}=\frac{v_{\mathrm{up}}\left(X_{\mathrm{sc,9}}-X_{\mathrm{sc,10}}\right)-J_{\mathrm{sc,10}}}{z_{10}} \tag{39}$$

$$\text{with } J_{\mathrm{sc,10}}=\begin{cases}\min\left(v_{\mathrm{s,10}}X_{\mathrm{sc,10}},v_{\mathrm{s,9}}X_{\mathrm{sc,9}}\right) \; if \;\; X_{\mathrm{sc,9}}>X_{\mathrm{t}}\\ \text{or}\\ v_{\mathrm{s,10}}X_{\mathrm{sc,10}} \quad if \quad X_{\mathrm{sc,9}}\le X_{\mathrm{t}}\end{cases} \tag{40}$$

The threshold concentration X_{t} is equal to 3,000 g.m^{-3}

For the soluble components (including dissolved oxygen), each layer represents a completely mixed volume and the concentrations of soluble components are calculated accordingly.

For the feed layer (m = 6)

$$\frac{dZ_{\mathrm{sc,m}}}{dt}=\frac{\frac{Q_{\mathrm{f}}Z_{\mathrm{f}}}{A}-\left(v_{\mathrm{dn}}+v_{\mathrm{up}}\right)Z_{\mathrm{sc,m}}}{z_{\mathrm{m}}} \tag{41}$$

For the layers m = 1 to 5

$$\frac{dZ_{\mathrm{sc,m}}}{dt}=\frac{v_{\mathrm{dn}}\left(Z_{\mathrm{sc,m+1}}-Z_{\mathrm{sc,m}}\right)}{z_{\mathrm{m}}} \tag{42}$$

For the layers m = 7 to 10

$$\frac{dZ_{\mathrm{sc,m}}}{dt}=\frac{v_{\mathrm{up}}\left(Z_{\mathrm{sc,m-1}}-Z_{\mathrm{sc,m}}\right)}{z_{\mathrm{m}}} \tag{43}$$

The concentrations in the recycle and wastage flow are equal to those of the first layer (bottom layer):

$$Z_{\mathrm{u}}=Z_{\mathrm{sc,1}} \tag{44}$$

Calculation of the sludge concentration is straightforward from the concentrations in compartment 5 of the activated sludge reactor:

$$X_{\mathrm{f}} = \frac{1}{fr_{\mathrm{COD-SS}}}\left(X_{\mathrm{S,as,5}} + X_{\mathrm{P,as,5}} + X_{\mathrm{I,as,5}} + X_{\mathrm{B,H,as,5}} + X_{\mathrm{B,A,as,5}}\right)$$
$$= 0.75\left(X_{\mathrm{S,as,5}} + X_{\mathrm{P,as,5}} + X_{\mathrm{I,as,5}} + X_{\mathrm{B,H,as,5}} + X_{\mathrm{B,A,as,5}}\right) \quad (45)$$

given a COD to SS conversion factor, $fr_{\mathrm{COD\text{-}SS}}$, equal to 4/3. The same principle is applied for X_{u} (in the secondary clarifier underflow) and X_{e} (at the plant exit).

To calculate the distribution of particulate concentrations in the recycle and the wastage flows, their ratios with respect to the total solid concentration are assumed to remain constant across the secondary clarifier:

$$\frac{X_{\mathrm{S,as,5}}}{X_{\mathrm{f}}} = \frac{X_{\mathrm{S,sc,1}}}{X_{\mathrm{u}}} \quad (46)$$

Similar equations hold for $X_{\mathrm{P,sc,1}}$, $X_{\mathrm{I,\ sc,1}}$, $X_{\mathrm{B,H,sc,1}}$, $X_{\mathrm{B,A,\ sc,1}}$ and $X_{\mathrm{ND,\ sc,1}}$. Note that this assumption means that the dynamics of the fractions of particulate concentrations in the inlet of the secondary clarifier will be directly propagated to the secondary clarifier underflow and overflow, without taking into account the normal retention time in the secondary clarifier.

In the steady-state case, the sludge age calculation is based on the total amount of biomass present in the system, i.e. the reactor and the secondary clarifier:

$$SRT = \frac{TX_{\mathrm{as}} + TX_{\mathrm{sc}}}{\phi_{\mathrm{e}} + \phi_{\mathrm{w}}} \quad (47)$$

where TX_{as} is the total amount of biomass present in the reactor:

$$TX_{\mathrm{as}} = \sum_{k=1}^{k=n}\left(X_{\mathrm{B,H,as,k}} + X_{\mathrm{B,A,as,k}}\right)V_{\mathrm{as,k}} \text{ with } n = 5 \quad (48)$$

TX_{sc} is the total amount of biomass present in the secondary clarifier:

$$TX_{\mathrm{sc}} = \sum_{j=1}^{j=m}\left(X_{\mathrm{B,H,sc,j}} + X_{\mathrm{B,A,sc,j}}\right)z_{\mathrm{j}} \cdot A \text{ with } m = 10 \quad (49)$$

ϕ_{e} is the loss rate of biomass in the secondary clarifier overflow:

$$\phi_{\mathrm{e}} = \left(X_{\mathrm{B,H,sc,m}} + X_{\mathrm{B,A,sc,m}}\right)Q_{\mathrm{e}} \quad (50)$$

and ϕ_{w} is the loss rate of biomass in the wastage flow.

$$\phi_{\mathrm{w}} = \left(X_{\mathrm{B,H,sc,1}} + X_{\mathrm{B,A,sc,1}}\right)Q_{\mathrm{w}} \quad (51)$$

In real plants, the sludge age is measured based on the total amount of solids present in the system:

$$SRT_{\mathrm{meas}} = \frac{TSS_{\mathrm{as}} + TSS_{\mathrm{sc}}}{\psi_{\mathrm{e}} + \psi_{\mathrm{w}}} \quad (52)$$

where TSS_{as} is the total amount of solids present in the reactor:

$$TSS_{\mathrm{as}} = \sum_{k=1}^{k=n} TSS_{\mathrm{as,k}} \cdot V_{\mathrm{as,k}} \quad (53)$$

with $n = 5$ and $TSS_{\mathrm{as,k}} = \frac{1}{fr_{\mathrm{COD-SS}}}\left(X_{\mathrm{S,as,i}} + X_{\mathrm{P,as,i}} + X_{\mathrm{I,as,i}} + X_{\mathrm{B,H,as,i}} + X_{\mathrm{B,A,as,i}}\right)$ (54)

TSS_{sc} is the total amount of solids present in the secondary clarifier:

$$TSS_{\mathrm{sc}} = \sum_{j=1}^{j=m} TSS_{\mathrm{sc,j}} \cdot z_{\mathrm{j}} \cdot A \quad (55)$$

with $m = 10$ and $TSS_{\mathrm{sc,j}} = \frac{1}{fr_{\mathrm{COD-SS}}}\left(X_{\mathrm{S,sc,j}} + X_{\mathrm{P,sc,j}} + X_{\mathrm{I,sc,j}} + X_{\mathrm{B,H,sc,j}} + X_{\mathrm{B,A,sc,j}}\right)$ (56)

ψ_{fe} is the loss rate of solids in the secondary clarifier overflow:

$$\psi_{\mathrm{e}} = TSS_{\mathrm{sc},m} \cdot Q_{\mathrm{e}} \quad (57)$$

with $TSS_{\mathrm{sc,m}} = \frac{1}{fr_{\mathrm{COD-SS}}}\left(X_{\mathrm{S,sc,m}} + X_{\mathrm{P,sc,m}} + X_{\mathrm{I,sc,m}} + X_{\mathrm{B,H,sc,m}} + X_{\mathrm{B,A,sc,m}}\right)$ (58)

with $m = 10$.
ψ_w is the loss rate of solids in the wastage flow:

$$\psi_w = TSS_{sc,1} \cdot Q_w \tag{59}$$

$$\text{with } TSS_{sc,1} = \frac{1}{fr_{COD-SS}} \left(X_{S,sc,1} + X_{P,sc,1} + X_{I,sc,1} + X_{B,H,sc,1} + X_{B,A,sc,1} \right) \tag{60}$$

2.3.4. Effluent composition

In BSM1, the plant effluent composition is the same as the secondary clarifier overflow. For any composition state variable:

$$Z_e = Z_{sc,10} \tag{61}$$

2.4. Influent data

The influent data were initially proposed by Vanhooren and Nguyen (1996). The time is given in days, the flow rate is given in $m^3.d^{-1}$ and the concentrations are given in $g.m^{-3}$. The data are given in the following order:

$$t \;\; S_I \;\; S_S \;\; X_I \;\; X_S \;\; X_{B,H} \;\; X_{B,A} \;\; X_P \;\; S_O \;\; S_{NO} \;\; S_{NH} \;\; S_{ND} \;\; X_{ND} \;\; S_{ALK} \;\; Q_i$$

In any influent: $S_O = 0$ g (-COD).m^{-3}; $X_{B,A} = 0$ g COD.m^{-3}; $S_{NO} = 0$ g N.m^{-3}; $X_P = 0$ g COD.m^{-3}; $S_{ALK} = 7$ mole.m^{-3}

2.4.1. Dry weather

The influent file "Inf_dry_2006.txt" can be downloaded from the CD. This file contains two weeks of dynamic dry weather influent data (Figure 3).

2.4.2. Storm weather

The influent file "Inf_strm_2006.txt" can be downloaded from the CD This file contains one week of dynamic dry weather influent data and two storm events superimposed on the dry weather data during the second week (Figure 4).

2.4.3. Rain weather

The influent file "Inf_rain_2006.txt" can be downloaded from the CD. This file contains one week of dynamic dry weather data and a long rain event during the second week (Figure 5).

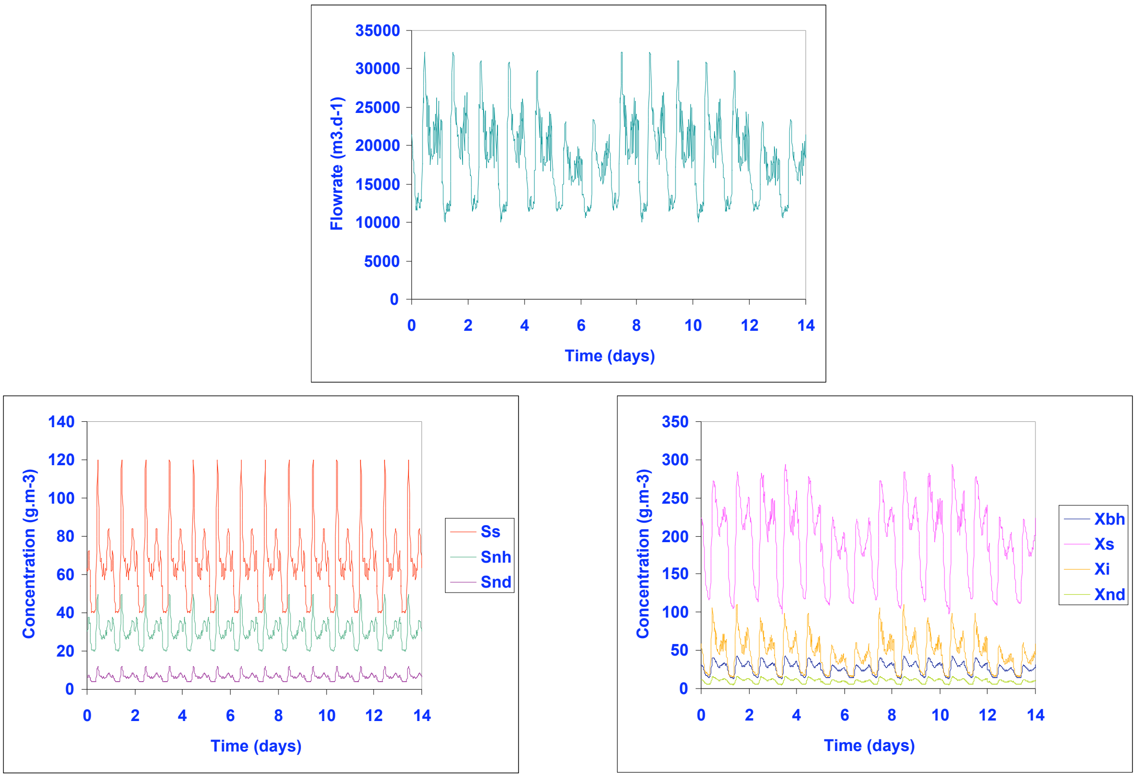

Figure 3: Dry weather influent

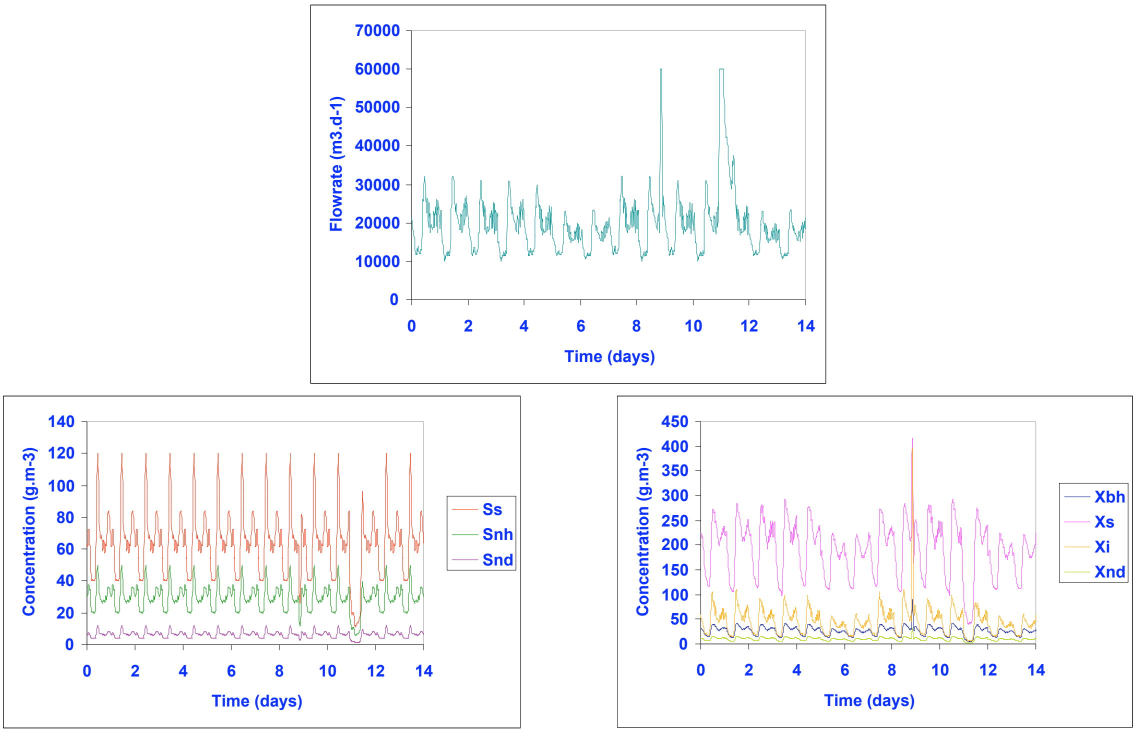

Figure 4: Storm weather influent

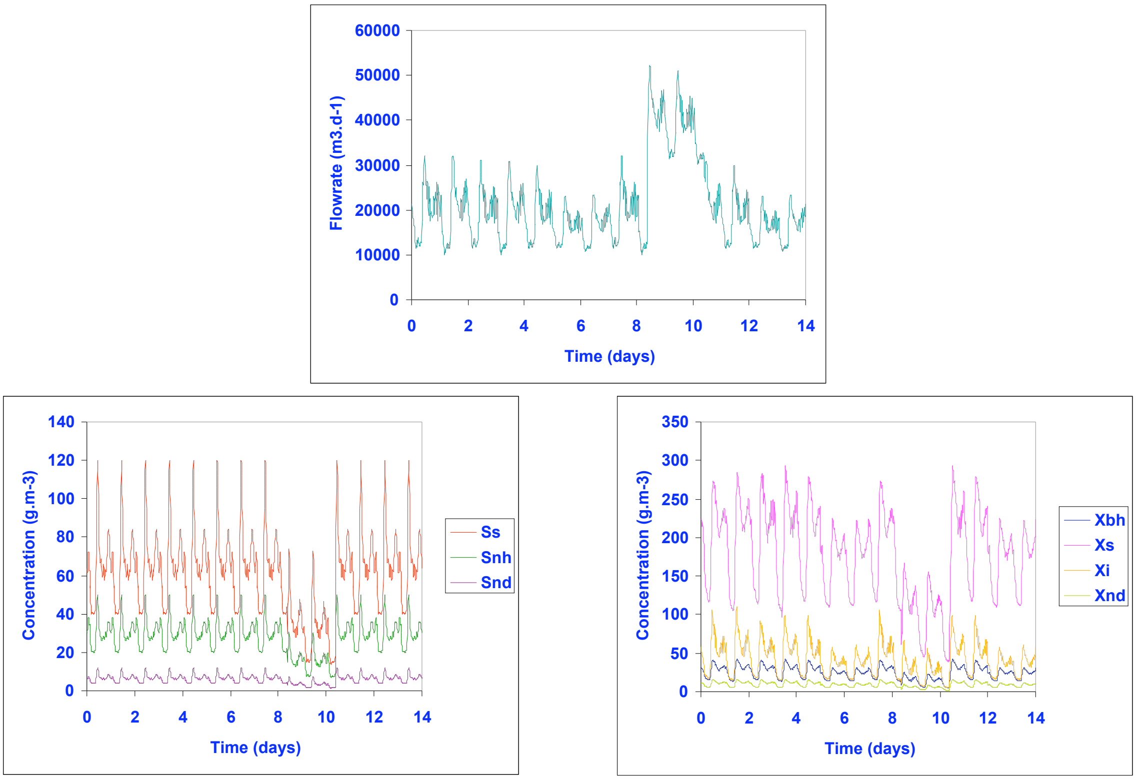

Figure 5: Rain weather influent

3. INITIALIZATION

Initial values can be selected by the user. A 100-day period of stabilization in closed-loop using constant inputs (average dry weather flow rate and flow-weighted average influent concentrations) (see Table 5) with no noise on the measurements has to be completed before using the dry weather file (14 days) followed by the weather file to be tested. Noise on measurements should be used with the dynamic files (see Section 7).

Table 5: Load averages for the stabilization period

Variable	Value	Unit
$Q_{i,stab}$	18 446	$m^3.d^{-1}$
$S_{S,stab}$	69.50	g $COD.m^{-3}$
$X_{B,H,stab}$	28.17	g $COD.m^{-3}$
$X_{B,A,stab}$	0	g $COD.m^{-3}$
$X_{S,stab}$	202.32	g $COD.m^{-3}$
$X_{I,stab}$	51.20	g $COD.m^{-3}$
$S_{NH,stab}$	31.56	g $N.m^{-3}$
$S_{I,stab}$	30.00	g $COD.m^{-3}$
$S_{ND,stab}$	6.95	g $N.m^{-3}$
$X_{ND,stab}$	10.59	g $N.m^{-3}$
$S_{ALK, stab}$	7.00	$mole.m^{-3}$
$S_{O,stab}$	0	g(-COD).m^{-3}
$S_{NO,stab}$	0	g $N.m^{-3}$

The system is stabilized if the steady state for these conditions is reached. A simulation period of 10 times the sludge age suffices for that. If for a specific control strategy, the sludge age is influenced, the stabilization period must be adjusted accordingly but in principle the wastage flow rate should not be manipulated for the short-term evaluation of BSM1.

4. OPEN-LOOP ASSESSMENT

In order for users to verify their implementations, open-loop results for the dry weather situation are available on the website. The procedure to assess the open-loop case is similar to the closed-loop one: simulate the plant for a stabilization period of 100 days before using the dry weather file. For open-loop assessment, the default case control variables (see section 5 for full description) have the following constant values: Q_{int} = 55,338 $m^3.d^{-1}$ and $K_La(5)$ = 3.5 h^{-1} (or 84 d^{-1}). The steady state values after 100 days (Tables 6 to 8) will be found in the text file "Steady.txt" and the first day of the weather file in the text file "First_day.txt" (results with 15 minutes sampling interval) on the CD. The steady-state and first-day values have been provided by Ulf Jeppsson and were obtained by implementing the benchmark in Matlab/Simulink. A comparison of the steady-state results obtained on three platforms (Matlab/Simulink, GPS-X and FORTRAN code) can be found in Pons *et al.* (1999).

For evaluation of the simulation results over a fixed period of time ($t_{\text{obs}} = t_f - t_0$), average values are to be calculated as follows (The user should be aware that all the integrals for performance assessment are calculated by rectangular integration with a time step of 15 min):

- Flow rate ($m^3.d^{-1}$): $$\overline{Q} = \frac{\int_{t_0}^{t_f} Q(t)\cdot dt}{t_{\text{obs}}} \qquad (62)$$

- Concentration for compound Z_k (mass.m^{-3}) in flow Q must be flow proportional:

$$\overline{Z}_k = \frac{\int_{t_0}^{t_f} Q(t)\cdot Z(t)_k \cdot dt}{\int_{t_0}^{t_f} Q(t)\cdot dt} \qquad (63)$$

Table 6: Biological reactor steady-state (open-loop)

	influent	k	1	2	3	4	5	Unit
$S_{I,stab}$	30	$S_{I,as,k}$	30	30	30	30	30	g $COD.m^{-3}$
$S_{S,stab}$	69.5	$S_{S,as,k}$	2.81	1.46	1.15	0.995	0.889	g $COD.m^{-3}$
$X_{I,stab}$	51.2	$X_{I,as,k}$	1149.	1149.	1149.	1149.	1149.	g $COD.m^{-3}$
$X_{S,stab}$	202.32	$X_{S,as,k}$	82.1	76.4	64.9	55.7	49.3	g $COD.m^{-3}$
$X_{B,H,stab}$	28.17	$X_{B,H,as,k}$	2552.	2553.	2557.	2559.	2559.	g $COD.m^{-3}$
$X_{B,A,stab}$	0	$X_{B,A,as,k}$	148.	148.	149.	150.	150.	g $COD.m^{-3}$
$X_{P,stab}$	0	$X_{P,as,k}$	449.	450.	450.	451.	452.	g $COD.m^{-3}$
$S_{O,stab}$	0	$S_{O,as,k}$	0.00430	0.0000631	1.72	2.43	0.491	g $(-COD).m^{-3}$
$S_{NO,stab}$	0	$S_{NO,as,k}$	5.37	3.66	6.54	9.30	10.4	g $N.m^{-3}$
$S_{NH,stab}$	31.56	$S_{NH,as,k}$	7.92	8.34	5.55	2.97	1.73	g $N.m^{-3}$
$S_{ND,stab}$	6.95	$S_{ND,as,k}$	1.22	0.882	0.829	0.767	0.688	g $N.m^{-3}$
$X_{ND,stab}$	10.59	$X_{ND,as,k}$	5.28	5.03	4.39	3.88	3.53	g $N.m^{-3}$
$S_{ALK,stab}$	7	$S_{ALK,as,k}$	4.93	5.08	4.67	4.29	4.13	$mole.m^{-3}$
TSS_{stab}		$TSS_{as,k}$	3285	3282	3278	3274	3270	g $SS.m^{-3}$
$Q_{i,stab}$	18446	Q_k	92230	92230	92230	92230	92230	$m^3.d^{-1}$

Table 7: Secondary clarifier steady-state – Concentration of solids and soluble components in the secondary clarifier layers (open-loop)

k	$TSS_{sc,k}$ g COD.m^{-3}	$S_{I,sc,k}$ g COD.m^{-3}	$S_{S,sc,k}$ g COD.m^{-3}	$S_{O,sc,k}$ g COD.m^{-3}	$S_{NO,sc,k}$ g N.m^{-3}	$S_{NH,sc,k}$ g N.m^{-3}	$S_{ND,sc,k}$ g N.m^{-3}	$S_{ALK,sc,k}$ mole.m^{-3}
10	12.5	30	0.889	0.491	10.4	1.73	0.688	4.13
9	18.1	30	0.889	0.491	10.4	1.73	0.688	4.13
8	29.5	30	0.889	0.491	10.4	1.73	0.688	4.13
7	69.0	30	0.889	0.491	10.4	1.73	0.688	4.13
6	356.	30	0.889	0.491	10.4	1.73	0.688	4.13
5	356.	30	0.889	0.491	10.4	1.73	0.688	4.13
4	356.	30	0.889	0.491	10.4	1.73	0.688	4.13
3	356.	30	0.889	0.491	10.4	1.73	0.688	4.13
2	356.	30	0.889	0.491	10.4	1.73	0.688	4.13
1	6394.	30	0.889	0.491	10.4	1.73	0.688	4.13

Table 8: Secondary clarifier steady-state: State variables at underflow and discharge (m = 10)

Underflow		Overflow		Unit
$S_{I,sc,1}$	30	$S_{I,sc,m}$	30	g COD.m^{-3}
$S_{S,sc,1}$	0.889	$S_{S,sc,m}$	0.889	g COD.m^{-3}
$X_{I,sc,1}$	2247	$X_{I,sc,m}$	4.39	g COD.m^{-3}
$X_{S,sc,1}$	96.4	$X_{S,sc,m}$	0.188	g COD.m^{-3}
$X_{B,H,sc,1}$	5005	$X_{B,H,sc,m}$	9.78	g COD.m^{-3}
$X_{B,A,sc,1}$	293.	$X_{B,A,sc,m}$	0.573	g COD.m^{-3}
$X_{P,sc,1}$	884.	$X_{P,sc,m}$	1.73	g COD.m^{-3}
$S_{O,sc,1}$	0.491	$S_{O,sc,m}$	0.491	g COD.m^{-3}
$S_{NO,sc,1}$	10.4	$S_{NO,sc,m}$	10.4	g N.m^{-3}
$S_{NH,sc,1}$	1.73	$S_{NH,sc,m}$	1.73	g N.m^{-3}
$S_{ND,sc,1}$	0.688	$S_{ND,sc,m}$	0.688	g N.m^{-3}
$X_{ND,sc,1}$	6.90	$X_{ND,sc,m}$	0.0135	g N.m^{-3}
$S_{ALK,sc,1}$	4.13	$S_{ALK,sc,m}$	4.13	mole.m^{-3}
$TSS_{sc,1}$	6394.	$TSS_{sc,m}$	12.50	g SS.m^{-3}
Q_r	18446	Q_e	18061	m^3.d^{-1}
Q_w	385			m^3.d$^-$

5. SET-UP OF DEFAULT CONTROLLERS

Default controllers are proposed so the closed-loop simulation and the implementation of the evaluation criteria can be tested before the user implements his/her own control strategy. The primary control objectives for the default strategies are (i) to maintain the NO_3-N concentration in the second compartment at a predetermined set point value (1 g.m^{-3}) and (ii) to maintain the dissolved oxygen concentration in the fifth compartment at a predetermined set point value (2 g (-COD).m^{-3}). The modeling principles of the sensors are given in Section 7 of this document.

5.1. Controller variables

The NO_3-N measurement in the second anoxic compartment is of class B_0 with a measurement range of 0 to 20 g N.m^{-3}. The measurement noise is equal to 0.5 g N.m^{-3}. The manipulated variable is the internal recycle flow rate from last aerated compartment back to the first compartment.

For the dissolved oxygen control in last aerated compartment, the probe is assumed to be of class A with a measurement range of 0 to 10 g (-COD).m^{-3} and a measurement noise of 0.25 g (-COD).m^{-3}. The manipulated variable is the oxygen transfer coefficient, K_La_5.

Constraints are applied on recirculation flows. The range for Q_{int} is 0 to 5 times $Q_{i,stab}$. The external recycle flow rate Q_r is maintained constant and is set to $Q_r = Q_{i,stab}$. There are also constraints on oxygen transfer in compartment 5: K_La can vary from 0 to 10 h^{-1}.

5.2. Controller types

Both suggested controllers are of the PI type. Their performance is assessed by (k = 1 for nitrate-PID and k = 2 for oxygen-PID):
- the Integral of Absolute Error (*IAE*)

$$IAE_{\mathrm{k}} = \int_{t_0}^{t_{\mathrm{f}}} |e_{\mathrm{k}}| \cdot dt \tag{64}$$

where e_{k} is the error:

$$e_{\mathrm{k}} = Z_{\mathrm{k}}^{\mathrm{setpoint}} - Z_{\mathrm{k}}^{\mathrm{meas}} \tag{65}$$

- the Integral of Squared Error (*ISE*)

$$ISE_{\mathrm{k}} = \int_{t_0}^{t_{\mathrm{f}}} e_{\mathrm{k}}^2 \cdot dt \tag{66}$$

- the maximal deviation from set point:

$$Dev_{\mathrm{k}}^{\max} = \max\{|e_{\mathrm{k}}|\} \tag{67}$$

- the error variance:

$$Var(e_{\mathrm{k}}) = \overline{e_{\mathrm{k}}^2} - \left(\overline{e_{\mathrm{k}}}\right)^2 \tag{68}$$

with

$$\overline{e_{\mathrm{k}}} = \frac{\int_{t_0}^{t_{\mathrm{f}}} e_{\mathrm{k}} \cdot dt}{t_{\mathrm{obs}}} \tag{69}$$

$$\overline{e_{\mathrm{k}}^2} = \frac{\int_{t_0}^{t_{\mathrm{f}}} e_{\mathrm{k}}^2 \cdot dt}{t_{\mathrm{obs}}} \tag{70}$$

- the variance of manipulated variable (u_k) variations:

$$Var(\Delta u_{\mathrm{k}}) = \overline{\Delta u_{\mathrm{k}}^2} - \left(\overline{\Delta u_{\mathrm{k}}}\right)^2 \tag{71}$$

with

$$\Delta u_{\mathrm{k}} = |u_{\mathrm{k}}(t + dt) - u_{\mathrm{k}}(t)| \tag{72}$$

$$\overline{\Delta u_{\mathrm{k}}} = \frac{\int_{t_0}^{t_{\mathrm{f}}} \Delta u_{\mathrm{k}} \cdot dt}{t_{\mathrm{obs}}} \tag{73}$$

and $$\overline{\Delta u_{\mathrm{k}}^2} = \frac{\int_{t_0}^{t_{\mathrm{f}}} \Delta u_{\mathrm{k}}^2 \cdot dt}{t_{\mathrm{obs}}} \tag{74}$$

These criteria can be generalized for any controller implemented on the benchmark.

6. PERFORMANCE ASSESSMENT

The flow-weighted average values of the effluent concentrations over the three evaluation periods (dry, rain and storm weather: 7 days for each) should obey the limits given in Table 9. Total nitrogen (N_{tot}) is calculated as the sum of $S_{\mathrm{NO,e}}$ and $S_{\mathrm{NKj,e}}$, where S_{NKj} is the Kjeldahl nitrogen concentration.

The *percentage of time* the effluent limits are not met must be reported, as well as the *number of violations*. The number of violations is defined as the *number of crossings* of the limit (from below to above the limit).

Table 9: Effluent quality limits

Variable	Value
N_{tot}	<18 g N.m^{-3}
COD_{tot}	<100 g COD.m^{-3}
S_{NH}	<4 g N.m^{-3}
TSS	<30 g SS.m^{-3}
BOD_5	<10 g BOD.m^{-3}

The performance assessment is made at two levels.
- The **first level** concerns the local control loops, assessed by *IAE* (Integral of the Absolute Error) and *ISE* (Integral of the Squared Error) criteria, by maximal deviation from set points, and by error variance. Basically, this serves as a proof that the proposed control strategy has been applied properly.
- The **second level** provides measures for the effect of the control strategy as such on plant performance and it can be divided into four sub-levels:

- the **effluent quality**: levies or fines are to be paid due to the discharge of pollution in the receiving water bodies. The Effluent Quality Index (*EQI*) (kg pollution unit.d^{-1}) is averaged over the period of observation t_{obs} (d) (i.e. the second week or 7 last days for each weather file) based on a weighting of the effluent loads of compounds that have a major influence on the quality of the receiving water and that are usually included in regional legislation. It is defined as:

$$EQI = \frac{1}{t_{\mathrm{obs}} \cdot 1000} \int_{t=7\,days}^{t=14\,days} \begin{pmatrix} B_{\mathrm{TSS}} \cdot TSS_{\mathrm{e}}(t) + B_{\mathrm{COD}} \cdot COD_{\mathrm{e}}(t) + B_{\mathrm{NKj}} \cdot S_{\mathrm{NKj,e}}(t) \\ + B_{\mathrm{NO}} \cdot S_{\mathrm{NO,e}}(t) + B_{\mathrm{BOD5}} \cdot BOD_{\mathrm{e}}(t) \end{pmatrix} Q_{\mathrm{e}}(t) \cdot dt \tag{75}$$

where

$$S_{\mathrm{NKj,e}} = S_{\mathrm{NH,e}} + S_{\mathrm{ND,e}} + X_{\mathrm{ND,e}} + i_{\mathrm{XB}}\left(X_{\mathrm{B,H,e}} + X_{\mathrm{X,A,e}}\right) + i_{\mathrm{XP}}\left(X_{\mathrm{P,e}} + X_{\mathrm{i,e}}\right) \tag{76}$$

$$TSS_{\mathrm{e}} = 0.75 \cdot \left(X_{\mathrm{S,e}} + X_{\mathrm{I,e}} + X_{\mathrm{B,H,e}} + X_{\mathrm{B,A,e}} + X_{\mathrm{P,e}}\right) \tag{77}$$

$$BOD_{5,\mathrm{e}} = 0.25 \cdot \left(S_{\mathrm{S,e}} + X_{\mathrm{S,e}} + (1 - f_{\mathrm{P}}) \cdot \left(X_{\mathrm{B,H,e}} + X_{\mathrm{B,A,e}}\right)\right) \tag{78}$$

$$COD_{\mathrm{e}} = S_{\mathrm{S,e}} + S_{\mathrm{I,e}} + X_{\mathrm{S,e}} + X_{\mathrm{I,e}} + X_{\mathrm{B,H,e}} + X_{\mathrm{B,A,e}} + X_{\mathrm{P,e}} \tag{79}$$

and the B_{i} are weighting factors for the different types of pollution to convert them into pollution units (Table 10). The concentrations are to be expressed in g.m^{-3}. The values for B_{i} have been deduced from Vanrolleghem *et al.* (1996).

Table 10: Weighting factors B_i values for calculation of the Effluent Quality Index (*EQI*)

Factor	B_{TSS}	B_{COD}	B_{NKj}	B_{NO}	B_{BOD5}
Value (g pollution unit.g^{-1})	2	1	30	10	2

The 95% percentiles of the effluent ammonia ($S_{\mathrm{NH,e95}}$), effluent total nitrogen ($N_{\mathrm{tot,e95}}$) and total suspended solids (TSS_{e95}) have to be shown as well. These percentiles represent the S_{NH}, N_{tot} and *TSS* effluent concentrations that are exceeded 5% of the time.

- the **cost factors for operation**

- the **sludge production to be disposed** *(SP)* (kg.d^{-1})

The sludge production, *SP*, is calculated from the total solid flow from wastage and the solids accumulated in the system over the period of time considered (7 days for each weather file).

$$SP = \frac{1}{t_{obs}} \left(TSS(14\ days) - TSS(7\ days) + 0.75 \cdot \int_{t=7\,days}^{t=14\,days} \left(X_{\mathrm{S,w}} + X_{\mathrm{I,w}} + X_{\mathrm{B,H,w}} + X_{\mathrm{B,A,w}}\right) Q_{\mathrm{w}}(t) \cdot dt \right) \tag{80}$$

where *TSS* (*t*) is the amount of solids in the system at time *t*, i.e.

$$TSS(t) = TSS_{\mathrm{as}}(t) + TSS_{\mathrm{sc}}(t) \tag{81}$$

TSS_{as} and TSS_{sc} are given respectively by equations 52 and 54.

- the **total sludge production** *(SP_{total})* (kg.d^{-1}) takes into account the sludge to be disposed and the sludge lost at the weir:

$$SP_{total} = SP + \frac{0.75}{t_{obs}} \int_{t=7\,days}^{t=14\,days} \left(X_{S,e} + X_{I,e} + X_{B,H,e} + X_{B,A,e} + X_{P,e}\right) Q_e(t)\,dt \tag{82}$$

- the **aeration energy** (AE) (kWh.d^{-1}) and the **pumping energy** (PE) (kWh.d^{-1}) (internal and external flow recycle pumps).

The pumping energy depends on how the various tanks can be arranged on the available space. Considering the state-of-the-art design rules an arrangement with two parallel lines, similar to the one shown in Appendix 1, can be proposed. In BSM1 the pumping energy is calculated as:

$$PE = \frac{1}{t_{obs}} \int_{t=7\,days}^{t=14\,days} \left(0.004 \cdot Q_{int}(t) + 0.008 \cdot Q_r(t) + 0.05 \cdot Q_w(t)\right) \cdot dt \tag{83}$$

with the flow rates expressed in m^3.d^{-1}. Explanation for the selection of the coefficients can be found in the Technical Report ?????

The aeration energy AE should take into account the plant peculiarities (type of diffuser, bubble size, depth of submersion, etc ...) and is calculated from the K_La according to the following relation, valid for Degrémont DP230 porous disks at an immersion depth of 4 m:

$$AE = \frac{S_O^{sat}}{t_{obs} \cdot 1.8 \cdot 1000} \int_{t=7\,days}^{t=14\,days} \sum_{k=1}^{5} V_{as,k} \cdot K_L a_k(t)\,dt \tag{84}$$

with K_La given in d^{-1} and k referring to the compartment number.

- the **consumption of external carbon source** (EC) (kg COD.d^{-1}) that could be added to improve denitrification (see Section 7 on control and handles)

$$EC = \frac{COD_{EC}}{t_{obs} \cdot 1000} \int_{t=7\,days}^{t=14\,days} \left(\sum_{k=1}^{k=n} Q_{EC,k}\right) \cdot dt \tag{85}$$

where $Q_{EC,k}$ is the flow rate of external carbon added to compartment k and COD_{EC} = 400,000 g COD.m^{-3} is the concentration of readily biodegradable substrate in the external carbon source.

- the **mixing energy** (ME) (kWh.d^{-1})

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

$$ME = \frac{24}{t_{obs}} \int_{t=7\,days}^{t=14\,days} \sum_{k=1}^{k=5} \begin{bmatrix} 0.005 \cdot V_{as,k} \;\; if \;\; K_L a_k(t) < 20 \;\; d^{-1} \\ 0 \; otherwise \end{bmatrix} \cdot dt \tag{86}$$

- controller output variations

The maximum values and the variance of the manipulated variables variations should be given. This will provide an indication on peak loads and the wear of the pumps and aeration devices.

Furthermore, for comparison with the Effluent Quality Index, an Influent Quality Index (IQI) index can be defined as:

$$IQI = \frac{1}{t_{obs} \cdot 1000} \int_{t=7\,days}^{t=14\,days} \begin{pmatrix} B_{TSS} \cdot TSS_i(t) + B_{COD} \cdot COD_i(t) + B_{NKj} \cdot S_{NKj,i}(t) \\ + B_{NO} \cdot S_{NO,i}(t) + B_{BOD5} \cdot BOD_{5,i}(t) \end{pmatrix} Q_i(t)\,dt \tag{87}$$

with:

$$S_{NKj,i} = S_{NH,i} + S_{ND,i} + X_{ND,i} + i_{XB}\left(X_{B,H,i} + X_{X,A,i}\right) + i_{XP}\left(X_{P,i} + X_{i,i}\right) \tag{88}$$

$$TSS_i = 0.75 \cdot \left(X_{S,i} + X_{I,i} + X_{B,H,i} + X_{B,A,i} + X_{P,i}\right) \tag{89}$$

$$BOD_{5,i} = 0.65 \cdot \left(S_{S,i} + X_{S,i} + (1 - f_P) \cdot \left(X_{B,H,i} + X_{B,A,i}\right)\right) \tag{90}$$

$$COD_i = S_{S,i} + S_{I,i} + X_{S,i} + X_{I,i} + X_{B,H,i} + X_{B,A,i} + X_{P,i} \tag{91}$$

- Finally an **Overall Cost Index** (*OCI*) is calculated:

$$OCI = AE + PE + 5 \cdot SP + 3 \cdot EC + ME \tag{92}$$

Tests of performance assessment, in open and closed-loop, under dry weather conditions, can be found in Appendices 2 and 3, respectively.

7. SENSORS AND CONTROL HANDLES

7.1. Introduction

To test your own control strategy on the BSM1 plant, appropriate sensors and actuators must be selected. To avoid unrealistic control behaviour, the dynamic behaviour of sensors and actuators (control handles) as well as additional measurement noise must be considered. To allow for a wide range of different strategies to be tested (within the confinement of the physical plant layout), a significant number of sensors and control handles are available. Their mathematical descriptions focus on simplicity rather than completely accurate reproductions of their true behaviour.

The principle for any good control strategy implies that the number of sensors and control actions should be minimised within the framework of the selected control strategy, due to the investment and maintenance costs, etc (Rieger *et al.*, 2003).

For initialisation purposes, first test of control concepts, or evaluation of the theoretical potential of control options it is of course a valid option to use ideal sensors (no noise, no delay). For internal flow rates (e.g. return sludge, internal recycle) which are basically control handles it can be assumed that the flow rates are known or can be measured without errors and delays. For such an ideal sensor, no specific sensor model is required. But the usage of ideal sensors should be reported when discussing a specific control strategy.

7.2. Sensors

The aim of the sensor classification is to describe different sensor types but also to limit the number of sensor classes in order to ease the comparison of the simulation results. The benchmark deals with control strategies, therefore only a few related criterions are used and only one minimal measuring interval of 5 minutes is taken into account. It is not intended to define a user configurable class, since this would make it difficult to compare different benchmark studies. Should it nevertheless be impossible to choose a class, the benchmark model user is requested to describe the specific sensor in detail.

The main parameter to describe the sensor dynamics of the sensor classes is the “Response time”. This parameter is defined in an ISO norm (ISO 2003) and characterises the sensor dynamics based on a step response as presented in Figure 6.

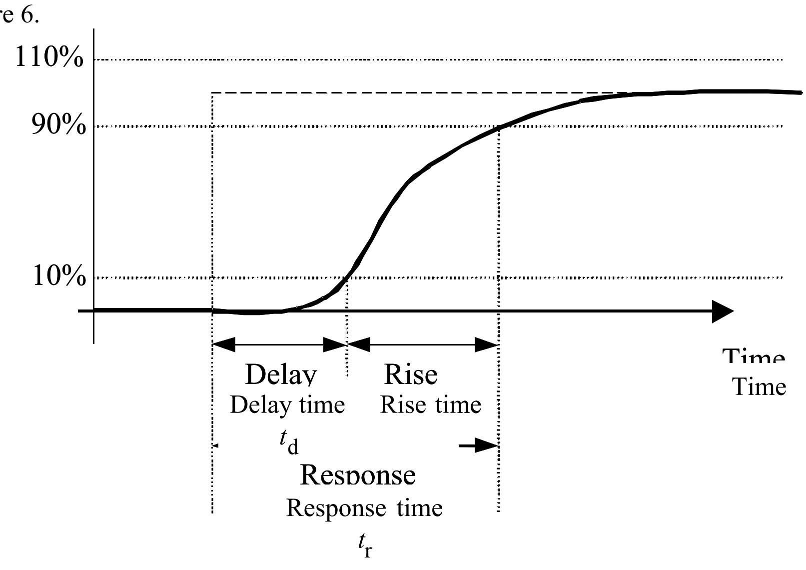

Figure 6: Definition of response time

In the norm the response time is the sum of the delay and the rise (or fall) time. The delay is defined as the time to reach 10% of the final value of a step response (t_d). Thus, the delay time in this context is not exactly the same as a transport delay time or dead-time defined in control engineering. The overall time to reach (and not to leave) a band from 90% - 110% of the final value of the step response is introduced as response time (here t_r). To describe the dynamics of a sensor it is assumed that the two values delay time and response time (as defined by Figure 6) are given.

For the definition of the benchmark sensor classes a response time (t_r) is proposed. The six sensor classes are shown in Table 11 and a list of typical sensors is provided in Table 12.

Table 11: Sensor classes. A measuring interval equal to 0 means continuous measurement

Sensor classes	Response time (t_r) [min]	Measuring interval (t_i) [min]	Examples
Class A	1	0	Ion sensitive, optical without filtration
Class B_0	10	0	Gas sensitive + fast filtration
Class B_1	10	5	Photometric + fast filtration
Class C_0	20	0	Gas-sensitive + slow filtration
Class C_1	20	5	Photometric + slow filtration or sedimentation
Class D	30	30	Photometric or titrimetric for total components

The response time includes the whole system with filtration unit and measuring system. Class A is a more or less ideal sensor; the response time of 1 minute is chosen in order to prevent unrealistic control applications. Class B contains mainly classical on-line analyzers with a fast filtration and short sample loops. In Class C, analyzers with a slow filtration or sedimentation unit are described. Class D includes all batch measurements like respirometer and sensors for total components. To take into account continuously and discontinuously measuring sensors, the classes B and C are divided into two subclasses. Five minutes is selected as the measuring interval, which is a typical minimum value for photometric analyzers. Longer intervals are not useful for control actions and are therefore neglected.

Additional to choosing the sensor class, the user has to define the measuring range for each sensor. Depending on the chosen measurement range, the standard deviation is assumed to be 2.5% of the maximum measurement value (see sensor model description).

Real measurement signals always include measurement noise, which can lead to unwanted control actions or slow down the reaction. Therefore, noise is included in the sensor model. The idea is not to model noise exactly, but to take into account some of its effects. In order to get comparable benchmark simulation results, the noise signal is defined. Choice of a random signal would have required running each benchmark simulation a large number of times in order to eliminate the influence of the random signal. The noise signal is chosen with a standard deviation of 1, which is multiplied with the defined noise level (2.5% of the maximum measurement value). The noise is white zero-mean normally distributed noise. Other types of noise would be too specific and the sensors within one class would not be comparable.

As an illustration, the oxygen and nitrate sensors described for the default closed-loop test case can very easily be described as:
- oxygen sensor: Class A, measurement range: 0-10 g (-COD).m^{-3}, measurement noise _ = 0.25 g (-COD).m^{-3}.
- nitrate sensor: Class B_0 with a measurement range 0-20 g N.m$^{-3,}$ measurement noise _ = 0.5 g N.m^{-3}.

7.3. Sensor model description

To ensure identical implementation and behaviour of the sensor models, it is necessary to describe the model in detail. The following description is the result of a Simulink implementation and takes into account a number of performance issues which are similar for most of the simulation systems.

The proposed sensor classes contain a set of continuous (A, B_0, C_0) and time-discrete sensor models (B_1, C_1, D). Continuous models are preferred to time-discrete ones for implementing the continuous sensors for performance reasons. The discontinuous sensors B_1 and C_1 are modelled in a similar way but include an output sample and hold function. Sensor class D is modelled only in discrete form.

7.3.1. Continuously measuring sensors

For the sensor classes A, B_0 and C_0 the approach is shown in Figure 7:

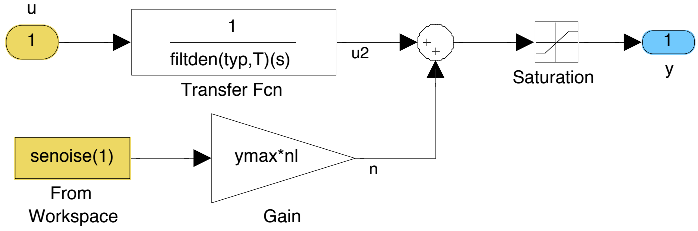

Figure 7: Simulink model of sensor class A, B_0 and C_0

The original sensor signal u is transformed by a linear transfer function (block Transfer Fcn). This transfer function is used to implement the expected time response of the sensor. Real time behaviour of sensors is typically a combination of transport+delay time behaviour (or dead time) caused by sample transport and preparation and a first or higher order dynamics (time constants) caused by different reasons, e.g. a mixing tank.

To have a sensor model with the same response time, a series of equal first order delay transfer functions is assumed. The number of first order transfer functions in series (n) determines the ratio of delay time and response time (as defined in Figure 6). Table 13 shows the parameters for the response-time modelling (see specific sensor model) of the continuously operating sensors.

For the sensor class A a response time (t_r) of 1 min and a system order of n = 2 is suggested. The assumed transfer function is:

$$G_S(s) = \frac{1}{1+\tau s} \quad \frac{1}{1+\tau s} \tag{93}$$

The problem is to find τ such as t_r = 1 min, using either SIMULINK or the time-domain function:

$$y = 1 - \left(1 + \frac{t}{\tau}\right) exp\left(-\frac{t}{\tau}\right) \tag{94}$$

with $\tau = 0.257 = t_r/3.89$, $R_{td/tr}$= 0.133. Thus the transfer function is only a small fraction of the response time as typical for this sensor class.

For the sensor classes B and C a system order of n = 8 is assumed. For class B a response time of 10 min and for class C of 20 min is selected. The transfer function is

$$G_S(s) = \frac{1}{1+\tau s} \quad \frac{1}{1+\tau s} \quad \frac{1}{1+\tau s} \quad \frac{1}{1+\tau s} \quad \frac{1}{1+\tau s} \quad \frac{1}{1+\tau s} \quad \frac{1}{1+\tau s} \quad \frac{1}{1+\tau s} \tag{95}$$

with $\tau = t_r / 11.7724$.

This will lead to a ratio of the delay time to the response time of $R_{td/tr}$ = 0.392. In this case the delay time is approximately 40% of the response time. This is assumed to consider the significant effect of the transport of the sample for the sensor classes B and C. The step responses for the classes A, B_0 and C_0 are presented in Figure 8.

Table 12: Typical sensor characteristics within the proposed classification scheme

Measured variable	Sensor types	t_d (min)	t_i (min)
MLSS ($g.m^{-3}$)	A	0	0
Turbidity (FNU or $gTSS.m^{-3}$)	A	0	0
S_{NH4} (ion sensitive)	A	0	0
S_{NOx} (ion sensitive)	A	0	0
S_{NOx} (UV)	A	0	0
C_{COD}, S_{COD} (UV/Vis)	A	0	0
Flow rate ($m^3.d^{-1}$)	A	0	0
Water level (m)	A	0	0
Temperature (°C)	A	0	0
pH	A	0	0
S_O (g (-COD).m^{-3})	A	0	0
Sludge blanket heigth (m)	A	0	0
S_{NH4} (gas sensitive + normal filtration)	B_0	10	0
S_{NOx} (UV + normal filtration)	B_0	10	0
S_{NH4} (photometric + normal filtration)	B_1	10	5
S_{NO3} (photometric + normal filtration)	B_1	10	5
S_{NO2} (photometric + normal filtration)	B_1	10	5
S_{PO4} (photometric + normal filtration)	B_1	10	5
S_{NH4} (gassensitive + slow filtration or sedimentation)	C_0	20	0
S_{NOx} (UV + slow filtration or sedimentation)	C_0	20	0
S_{NH4} (photometric + slow filtration or sedimentation)	C_1	20	5
S_{NO3} (photometric + slow filtration or sedimentation)	C_1	20	5
S_{NO2} (photometric + slow filtration or sedimentation)	C_1	20	5
S_{PO4} (photometric + slow filtration or sedimentation)	C_1	20	5
C_{COD} (thermal chemical oxidation + photometric)	D	30	30
TOC (thermal oxidation + IR detector)	D	30	30
C_N (thermal oxidation + IR detector or chemoluminescence detector)	D	30	30
C_P (thermal chemical oxidation + photometric)	D	30	30
Respirometer	D	30	30
Titration biosensor (alkalinity)	D	30	30

Table 13: Parameters for response time modelling

Sensor class	t_r (min)	n	τ (min)	$R_{td/tr}$
A	1	2	0.257	0.133
B_0	10	8	0.849	0.392
C_0	20	8	1.699	0.392

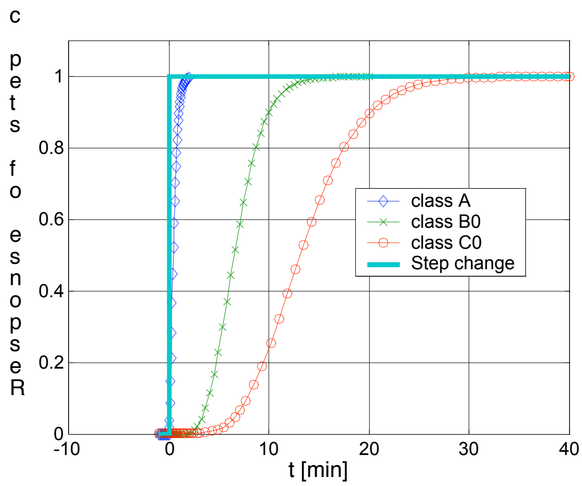

Figure 8: Step response of classes A, B_0, C_0.

The noise is modelled with a constant noise level *nl*. In the SIMULINK model presented in Figure 9, the noise signal (white noise with a standard deviation _=1) is multiplied by the noise level *nl* and the maximum value of the measurement interval y_{max}. A normal distributed (standard deviation 1), frequency limited noise signal has been created and provided as an ASCII file ("sennoise.asc") on the CD to allow the reproduction of results. The signal was created using a sample time of 1 min. The file must be interpolated using linear interpolation to provide a continuous noise signal. Using the sample time of 1 min together with the linear interpolation will limit the frequency spectrum of the noise (cut-of of high frequencies - pink noise). The file contains 25 columns of independent noise data for 14 days. For different sensors, also different noise columns should be used to avoid correlated noise on different sensor signals.

In the Simulink model presented in Figure 7, the block 'From Workspace' should read the ASCII file using linear interpolation. The noise signal is multiplied by the noise level *nl* and the maximum value of the measurement interval y_{max}. The noise level is defined as nl = 0.025 for all benchmark sensor classes (= 2.5% of the maximum measurement value). The resulting noise signal will have a standard deviation of $nl*y_{max}$. The noise will be added to the delayed measurement signal (*u2*) and the resulting value will be limited to the measurement interval (0, y_{max}). This is performed using the 'Saturation' block for the example implementation in Figure 7.

The noise is added to the delayed measurement signal and limited to the measurement interval (0, y_{max}).

7.3.2. Discontinuously measuring sensors

Sensor classes B_1, C_1 and D are operated discontinuously using a sampling interval t_i. An example of an implementation using a SIMULINK model is presented in Figure 9. The implementation is similar to that used in the model for the continuously measuring sensors but includes an additional output sample and hold function.

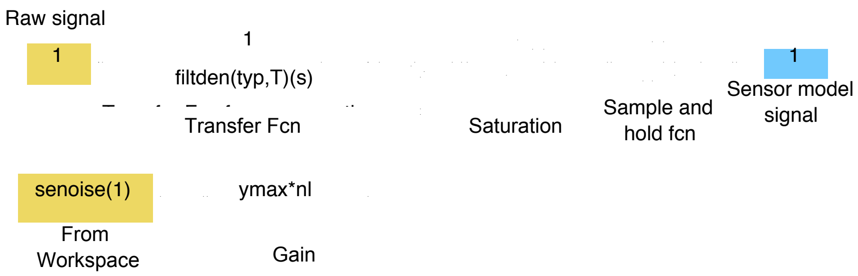

Figure 9: Simulink implementation class B_1, C_1.

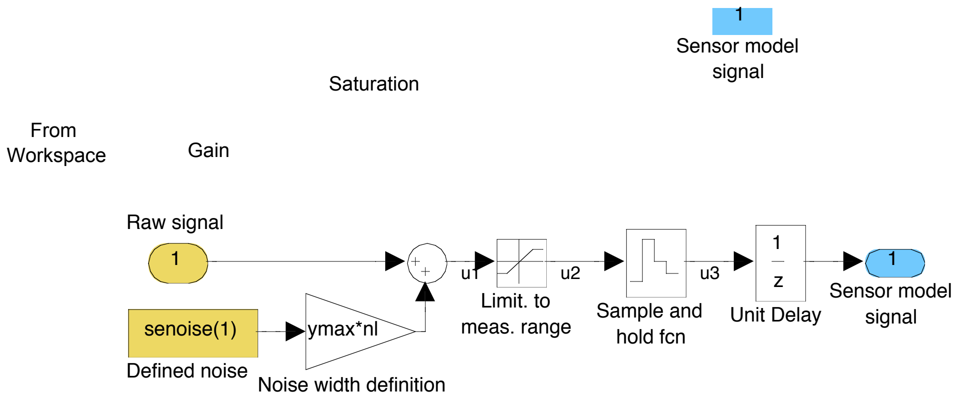

Figure 10: Simulink implementation class D.

Sensor class D represents batch-type reactors, for which any of the continuous delay times are negligible, compared to the batch operation of the measurement. An appropriate SIMULINK implementation is demonstrated in Figure 10. This model adds noise to the original signal, limits the sum to the measuring range (0, $y_{\max}$) and uses a sample and hold function followed by a unit delay ($y(k) = u_3(k-1)$). Figure 11 shows examples of the output signal for all sensor classes.

7.3.3. Conclusions

Table 14 summarizes the recommended sensor parameter values for BSM1. Except for the plant influent flow rate, all the other flows are not explicitly measured but can be considered as known for simplicity.

7.4. Control handles

For reasons of simplicity, all available control handles are considered to be ideal with regard to their behaviour. In the closed-loop test case, only two control handles are used: the internal recirculation flow rate (Q_{int}) and the oxygen transfer rate in reactor number 5 (K_La_5). The following control handles are considered to exist for the implementation of new control strategies on the benchmark plant:

- internal flow recirculation rate (Q_{int});
- return sludge flow rate (Q_r);
- wastage flow rate (Q_w);
- anoxic/aerobic volume – all five biological reactors are equipped with both aerators and mechanical mixing devices, i.e. in a discrete fashion the volumes for anoxic and aerobic behaviour can be modified;
- aeration intensity individually for each reactor (K_La_1, K_La_2, K_La_3, K_La_4, K_La_5), taking into account the dynamics of the aeration system;
- external carbon source flow rate (Q_{EC1}, Q_{EC2}, Q_{eEC3}, Q_{EC4}, Q_{EC5}) where the carbon source is considered to consist of readily biodegradable substrate, i.e. COD_{EC};
- influent distribution by use of step feed (fractions of the influent flow to each of the five biological reactors: $f_{Qi1}, f_{Qi2}, f_{Qi3}, f_{Qi4}, f_{Qi5}$);
- distribution of internal flow recirculation (fractions of the internal recirculation flow to each of the five biological reactors: $f_{Qint1}, f_{Qint2}, f_{Qint3}, f_{Qint4}, f_{Qint5}$);
- distribution of return sludge flow (fractions of the return sludge flow to each of the five biological reactors: $f_{Qr1}, f_{Qr2}, f_{Qr3}, f_{Qr4}, f_{Qr5}$)

The above selection gives about 30 individual control handles to manipulate the defined benchmark plant and dramatically increases its flexibility. Such a number of available control handles may not be realistic for a real plant but is defined for the benchmark plant in order to allow for basically any type of general control strategy. The defined limitations for the different control handles are given in Table 15.

The non-ideal aeration system (K_La_1- K_La_5) is defined with significant dynamics. A response time of t_r = 4 min is considered (see Rieger *et al.*, 2005). A second order time delay function gives a reasonable model of this process. The time constant of each of the two identical first order delays is $\tau = t_r /3.89 = 1.03$ min.

Table 14: Recommended BSM1 sensor parameters

Measured variable	Class	Measurement range	Measurement noise (_)
Flow rate ($m^3.d^{-1}$) high range	A	0-100 000	2500
Water level (m)	A	0-5	0.125
Temperature (°C)	A	5-25	0.5
pH	A	5-9	0.1
S_O (g (-COD).m^{-3})	A	0-10	0.25
Sludge blanket level (m)	A	0-5	0.125
S_{NO} (g N.m^{-3})	B_0	0-20	0.5
S_{NH} (g N.m^{-3}) low range	B_0	0-20	0.5
S_{NH} (g N.m^{-3}) high range	B_0	0-50	1.25
S_{ALK} (mole HCO_3.m^{-3})	B_0	0-20	0.5
Mixed-liquor suspended solids (g.m^{-3})	A	0-10 000	250
Effluent total suspended solids (g.m^{-3})	A	0-200	5
COD_{tot} (g COD.m^{-3})	D	0-1 000	25
OUR (g (-COD).$m^{-3}d^{-1}$)	D	0-2 000	50

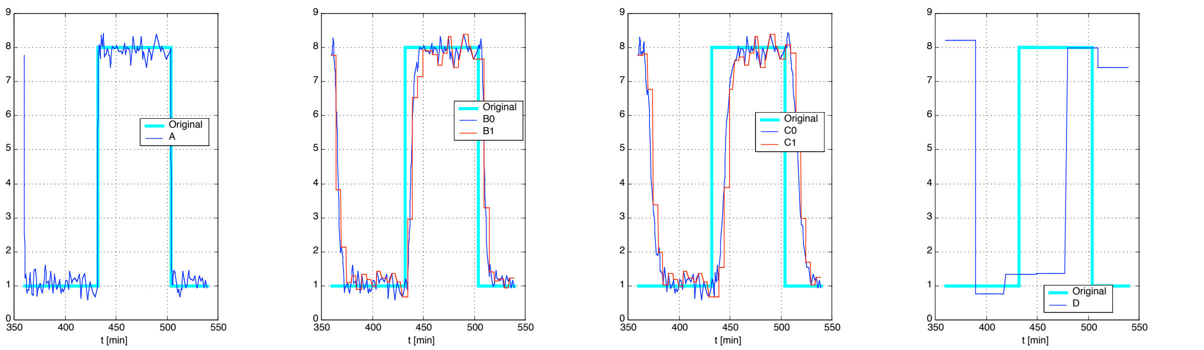

Figure 11: Pulse response of sensor classes.

7.5. Alternative description

To clarify the sensor and actuator models, a presentation in form of differential and difference equations is also presented in this section. The notations are summarized in Table 16.

7.5.1 Model for sensor class A and actuator model

$$\frac{d\, x_1(t)}{dt} = \frac{1}{\tau}u(t) - \frac{1}{\tau}x_1(t) \tag{96}$$

$$\frac{d\, u_2(t)}{dt} = \frac{1}{\tau}x_1(t) - \frac{1}{\tau}u_2(t) \tag{97}$$

$$y_1(t) = u_2(t) + y_{\max} nl\ n(t) \tag{98}$$

$$y(t) = \begin{cases} y_1(t) > y_{\max} : y_{\max} \\ y_{\min} \le y_1(t) \le y_{\max} : y_1(t) \\ y_1(t) < y_{\min} : y_{\min} \end{cases} \tag{99}$$

7.5.2. Model for sensor class B_0 and C_0

$$\frac{d\, x_1(t)}{dt} = \frac{1}{\tau}u(t) - \frac{1}{\tau}x_1(t) \tag{100}$$

$$\frac{d\,x_{k+1}(t)}{dt} = \frac{1}{\tau} x_k(t) - \frac{1}{\tau} x_{k+1}(t); \quad k = 1 \; to \; 6 \tag{101}$$

$$\frac{d\,u_2(t)}{dt} = \frac{1}{\tau} x_7(t) - \frac{1}{\tau} u_2(t) \tag{102}$$

$$y_1(t) = u_2(t) + y_{\max} nl\ n(t) \tag{103}$$

$$y(t) = \begin{cases} y_1(t) > y_{\max} : y_{\max} \\ y_{\min} \le y_1(t) \le y_{\max} : y_1(t) \\ y_1(t) < y_{\min} : y_{\min} \end{cases} \tag{104}$$

Table 15: Available control handles and their limitations

Control handle	Minimum value	Maximum value	Comments
Q_{int} ($m^3.d^{-1}$)	0	92230	Max = 500% of $Q_{0,stab}$
Q_r ($m^3.d^{-1}$)	0	36892	Max = 200% of $Q_{0,stab}$
Q_w ($m^3.d^{-1}$)	0	1844.6	Max = 10% of $Q_{0,stab}$
K_La_1 (d^{-1})	0	360	Reactor 1
K_La_2 (d^{-1})	0	360	Reactor 2
K_La_3 (d^{-1})	0	360	Reactor 3
K_La_4 (d^{-1})	0	360	Reactor 4
K_La_5 (d^{-1})	0	360	Reactor 5
Q_{EC1} ($m^3.d^{-1}$)	0	5	Reactor 1 Carbon source conc. 400,000 g $COD.m^{-3}$ available as COD_S (e.g. 25% ethanol solution)
Q_{EC2} ($m^3.d^{-1}$)	0	5	Reactor 2 Otherwise same as above
Q_{EC3} ($m^3.d^{-1}$)	0	5	Reactor 3 Otherwise same as above
Q_{EC4} ($m^3.d^{-1}$)	0	5	Reactor 4 Otherwise same as above
Q_{EC5} ($m^3.d^{-1}$)	0	5	Reactor 5 Otherwise same as above
f_{Qi1}, f_{Qi2}, f_{Qi3}, f_{Qi4}, f_{Qi5}	0	1	Part of the influent flow rate distributed to each biological reactor Note: the sum of all five must always equal one
f_{Qint1}, f_{Qint2}, f_{Qint3}, f_{Qinta4}, f_{Qint5}	0	1	Part of the internal recirculation flow rate distributed to each biological reactor Note: the sum of all five must always equal one
f_{Qr1}, f_{Qr2}, f_{Qr3}, f_{Qr4}, f_{Qr5}	0	1	Part of the sludge return flow rate distributed to each biological reactor Note: the sum of all five must always equal one

Table 16: Variables used in the sensor models

Variable	Definition
$u(t)$	ideal measurement signal from process
$x_1(t)..x_7(t)$	internal states for dynamic part of sensor model
$u_2(t)$	delayed measurement signal (intermediate variable)
$y_1(t), y_2(t), y_3(k), y_4(k)$	intermediate signals
$y(t)$	real measurement signal from sensor (delayed, noisy, limited)
τ	time constant for one first order time delay
t_i	sampling interval for discontinuous sensor models

7.5.3. Model for sensor class B_1 and C_1

$$\frac{d\,x_1(t)}{dt} = \frac{1}{\tau}u(t) - \frac{1}{\tau}x_1(t) \tag{105}$$

$$\frac{d\,x_{k+1}(t)}{dt} = \frac{1}{\tau}x_k(t) - \frac{1}{\tau}x_{k+1}(t); \quad k = 1 \text{ to } 6 \tag{106}$$

$$\frac{d\,u_2(t)}{dt} = \frac{1}{\tau}x_7(t) - \frac{1}{\tau}u_2(t) \tag{107}$$

$$y_1(t) = u_2(t) + y_{\max}\cdot nl\cdot n(t) \tag{108}$$

$$y_2(t) = \begin{cases} y_1(t) > y_{\max} : y_{\max} \\ y_{\min} \le y_1(t) \le y_{\max} : y_1(t) \\ y_1(t) < y_{\min} : y_{\min} \end{cases} \tag{109}$$

$$y_3(k)=y_2(t,\ t = k\cdot t_i) \tag{110}$$

$$y(t)=y_3(k,\ k = \mathrm{floor}(t/\ t_i)) \tag{111}$$

7.5.4. Model for sensor D

$$y_1(t) = u(t) + y_{\max}\cdot nl\cdot n(t) \tag{112}$$

$$y_2(t) = \begin{cases} y_1(t) > y_{\max} : y_{\max} \\ y_{\min} \le y_1(t) \le y_{\max} : y_1(t) \\ y_1(t) < y_{\min} : y_{\min} \end{cases} \tag{113}$$

$$y_3(k)=y_2(t,\ t = k\cdot t_i) \tag{114}$$

$$y_4(k)=y_3(k-1) \tag{115}$$

$$y(t)=y_4(k,\ k = \mathrm{floor}(t/t_i)) \tag{116}$$

8. CONCLUSIONS

The document has described in details the implementation of BSM1. To further help the user, Appendices 2 to 5 contains open-loop and closed-loop results obtained with a Matlab-Simulink and a FORTRAN implementations.

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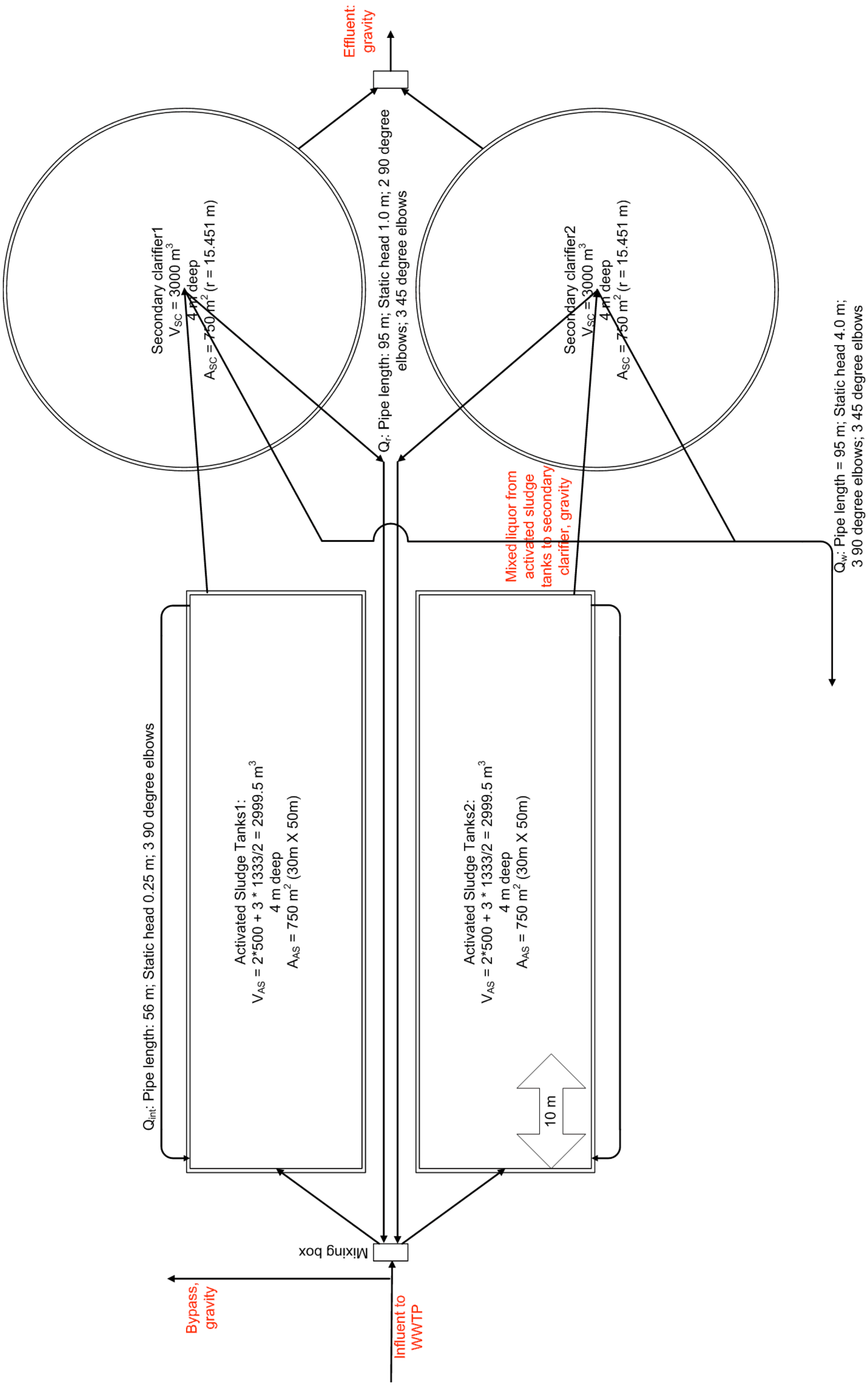
Appendix 1: Practical BSM1 plant layout



Appendix 2: Open-loop performance (summary)

Effluent average concentrations based on load		
Variable	Unit	FORTRAN
Effluent average flow rate	$m^{-3}.d$	18055.2
Effluent average S_I concentration	g $COD.m^{-3}$	30.
Effluent average S_S concentration	g $COD.m^{-3}$	0.9725
Effluent average X_I concentration	g $COD.m^{-3}$	4.58
Effluent average X_S concentration	g $COD.m^{-3}$	0.2231
Effluent average $X_{B,H}$ concentration	g $COD.m^{-3}$	10.22
Effluent average $X_{B,A}$ concentration	g $COD.m^{-3}$	0.5421
Effluent average X_P concentration	g $COD.m^{-3}$	1.757
Effluent average S_O concentration	g $(-COD).m^{-3}$	0.7462
Effluent average S_{NO} concentration	g $N.m^{-3}$	8.801
Effluent average S_{NH} concentration (limit = 4 g $N.m^{-3}$)	g $N.m^{-3}$	4.794
Effluent average S_{ND} concentration	g $N.m^{-3}$	0.7308
Effluent average X_{ND} concentration	g $N.m^{-3}$	0.01571
Effluent average S_{ALK} concentration	mol $HCO_3^-.m^{-3}$	4.46
Effluent average *TSS* concentration (limit = 30 g $SS.m^{-3}$)	g $SS.m^{-3}$	12.99
Effluent average Kjeldahl N concentration	g $N.m^{-3}$	6.782
Effluent average total N concentration (limit = 18 g $N.m^{-3}$)	g $N.m^{-3}$	15.58
Effluent average total COD concentration (limit = 100 g $COD.m^{-3}$)	g $COD.m^{-3}$	48.30
Effluent average BOD_5 concentration (limit = 10 $g.m^{-3}$)	$g.m^{-3}$	2.775

Effluent average load		
Variable	**Unit**	FORTRAN
Effluent average S_I load	kg $COD.d^{-1}$	541.656
Effluent average S_S load	kg $COD.d^{-1}$	17.558682
Effluent average X_I load	kg $COD.d^{-1}$	82.692816
Effluent average X_S load	kg $COD.d^{-1}$	4.02811512
Effluent average $X_{B,H}$ load	kg $COD.d^{-1}$	184.524144
Effluent average $X_{B,A}$ load	kg $COD.d^{-1}$	9.78772392
Effluent average X_P load	kg $COD.d^{-1}$	31.7229864
Effluent average S_O load	kg $(-COD).d^{-1}$	13.47279024
Effluent average S_{NO} load	kg $N.d^{-1}$	158.9038152
Effluent average S_{NH} load	kg $N.d^{-1}$	86.5566288
Effluent average S_{ND} load	kg $N.d^{-1}$	13.19474016
Effluent average X_{ND} load	kg $N.d^{-1}$	0.283647192
Effluent average S_{ALK} load	kmol $HCO_3^-.d^{-1}$	80.526192
Effluent average *TSS* load	$kg.d^{-1}$	234.537048
Effluent average Kjeldahl N load	kg $N.d^{-1}$	122.4503664
Effluent average total N load	kg $N.d^{-1}$	281.300016
Effluent average total COD load	kg $COD.d^{-1}$	872.06616
Effluent average BOD_5 load	$kg.d^{-1}$	50.10318

Effluent violations		
Variable	Unit	Value (FORTRAN)
95% percentile of effluent S_{NH} ($S_{\mathrm{NH,e95}}$)	g N.m^{-3}	8.9175
95% percentile of effluent total N ($N_{\mathrm{tot,e95}}$)	g N.m^{-3}	18.535
95% percentile of effluent TSS (TSS_{e95})	g COD.m^{-3}	15.8
Maximum effluent total N limit (18 g N.m^{-3}) was violated		
during:	d	0.5761
% of total evaluation time:	%	8.23
number of violations:		5
Maximum effluent total COD limit (100 g COD.m^{-3}) was violated		
during:	d	0
% of total evaluation time:	%	0
number of violations:		0
Maximum effluent total ammonia limit (4 g N.m^{-3}) was violated		
during:	d	4.403
% of total evaluation time:	%	62.9
number of violations:		7
Maximum effluent total TSS limit (30 g SS.m^{-3}) was violated		
during:	d	0
% of total evaluation time:	%	0
number of violations:		0
Maximum effluent total BOD_5 limit (10 g.m^{-3}) was violated		
during:	d	0
% of total evaluation time:	%	0
number of violations:		0

Other output quality variables		
Variable	Unit	Value (FORTRAN)
Influent quality (*IQI*) index	kg poll.units.d^{-1}	52100
Effluent quality (*EQI*) index	kg poll.units.d^{-1}	6700
Sludge production for disposal	kg SS	17052
Average sludge production for disposal per day	kg SS.d^{-1}	2436
Sludge production released into effluent	kg SS	1631
Average sludge production released into effluent per day	kg SS.d^{-1}	233
Total sludge production	kg SS	18683
Total average sludge production per day	kg SS.d^{-1}	2669

'Energy' related variables		
Variable	Unit	Value (FORTRAN)
Average aeration energy	kWh.d^{-1}	3341
Average pumping energy	kWh.d^{-1}	388.2
Average carbon source dosage	kg COD.d^{-1}	0
Average mixing energy	kWh.d^{-1}	240

Operational cost index		
Variable	Unit	Value (FORTRAN)
Sludge production cost index	-	12180
Aeration energy cost index	-	3341
Pumping energy cost index	-	388.2
Carbon source dosage cost index	-	0
Mixing energy cost index	-	240
Total Operational Cost Index (*OCI*)	-	16150

Appendix 3: Closed-loop performance (summary)

Effluent violations		
Variable	Unit	Value (MATLAB)
95% percentile of effluent S_{NH} ($S_{NH,e95}$)	g N.m^{-3}	7.3902
95% percentile of effluent total N ($N_{tot,e95}$)	g N.m^{-3}	20.2693
95% percentile of effluent TSS (TSS_{e95})	g COD.m^{-3}	15.7663
Maximum effluent total N limit (18 g N.m^{-3}) was violated		
during:	d	1.2813
% of total evaluation time:	%	18.3036
number of violations:		7
Maximum effluent total COD limit (100 g COD.m^{-3}) was violated		
during:	d	0
% of total evaluation time:	%	0
number of violations:		0
Maximum effluent total ammonia limit (4 g N.m^{-3}) was violated		
during:	d	1.1979
% of total evaluation time:	%	17.1131
number of violations:		5
Maximum effluent total TSS limit (30 g SS.m^{-3}) was violated		
during:	d	0
% of total evaluation time:	%	0
number of violations:		0
Maximum effluent total BOD_5 limit (10 g.m^{-3}) was violated		
during:	d	0
% of total evaluation time:	%	0
number of violations:		0

Other output quality variables		
Variable	Unit	Value (MATLAB)
Influent quality (*IQI*) index	kg poll.units.d^{-1}	52081.3952
Effluent quality (*EQI*) index	kg poll.units.d^{-1}	6123.0182
Sludge production for disposal	kg SS	17084.2397
Average sludge production for disposal per day	kg SS.d^{-1}	2440.6057
Sludge production released into effluent	kg SS	1643.7439
Average sludge production released into effluent per day	kg SS.d^{-1}	234.8206
Total sludge production	kg SS	18727.9836
Total average sludge production per day	kg SS.d^{-1}	2675.4262

'Energy' related variables		
Variable	Unit	Value (MATLAB)
Average aeration energy	kWh.d^{-1}	3698.3438
Average pumping energy	kWh.d^{-1}	241.0305
Average carbon source dosage	kg COD.d^{-1}	0
Average mixing energy	kWh.d^{-1}	240

Operational cost index		
Variable	Unit	Value (MATLAB)
Sludge production cost index	-	12203.0284
Aeration energy cost index	-	3698.3438
Pumping energy cost index	-	241.0305
Carbon source dosage cost index	-	0
Mixing energy cost index	-	240
Total Operational Cost Index (*OCI*)	-	16382.4027

Controller performance		
Nitrate controller	Unit	Value (MATLAB)
Controller type		continuous PI with K=10000 $m^3.d^{-1}.(g\ N.m^{-3})^{-1}$, τ_i=0.025 d, τ_t=1.015 d
Set point $S_{NO,2}$	$g\ N.m^{-3}$	1
Average of e_{NO3}	$g\ N.m^{-3}$	-0.0021211
Average of $\|e_{NO3}\|$	$g\ N.m^{-3}$	0.20497
IAE e_{NO3}	$g\ N.m^{-3}d$	1.4348
ISE e_{NO3}	$(g\ N.m^{-3})^2d$	0.56897
Max e_{NO3}	$g\ N.m^{-3}$	0.91782
Standard deviation of e_{NO3}	$g\ N.m^{-3}$	0.28509
Variance of e_{NO3}	$(g\ N.m^{-3})^2$	0.081276
Max deviation of Q_{int}	$m^3.d^{-1}$	45734.3965
Max deviation of Q_{int} in 1 sample	$m^3.d^{-1}$	18918. 9397
Average value of Q_{int}	$m^3.d^{-1}$	18610.0823
Standard deviation of Q_{int}	$m^3.d^{-1}$	4078.4756
Variance of Q_{int}	$(m^3.d^{-1})^2$	16633963.24

Controller performance		
Dissolved oxygen controller		
Controller type	Unit	continuous PI with antiwindup, K=25 $d^{-1}.(g\ (-COD).m^{-3})^{-1}$, τ_i=0.002 d, τ_t=0.001 d
Set point $S_{O,5}$	$g\ (-COD).m^{-3}$	2
Average of e_{SO5}	$g\ (-COD).m^{-3}$	-0.00039763
Average of $\|e_{SO5}\|$	$g\ (-COD).m^{-3}$	0.084044
IAE e_{SO5}	$g\ (-COD).m^{-3}.d$	0.58831
ISE e_{SO5}	$(g\ (-COD).m^{-3})^2 \cdot d$	0.083975
Max e_{SO5}	$g\ (-COD).m^{-3}$	0.39631
Standard deviation of e_{SO5}	$g\ (-COD).m^{-3}$	0.10953
Variance of e_{SO5}	$(g\ (-COD).m^{-3})^2$	0.011996
Max deviation of K_La_5	d^{-1}	242.2831
Max deviation of K_La_5 in 1 sample	d^{-1}	47;8828
Average value of K_La_5	d^{-1}	144.1219
Standard deviation of K_La_5	d^{-1}	9.5682
Variance of K_La_5	$(d^{-1})^2$	91.5507

Appendix 4: Open loop results under Matlab-Simulink

```
STEADY STATE RESULTS FOR BSM1 OPENLOOP
(Results from Matlab/Simulink implementation by Dr Ulf Jeppsson, IEA, Lund
University, Sweden, March 27 2008)

Influent characteristics
************************
   SI =  30 mg COD/l
   SS =  69.5 mg COD/l
   XI =  51.2 mg COD/l
   XS =  202.32 mg COD/l
   XBH = 28.17 mg COD/l
   XBA = 0 mg COD/l
   XP =  0 mg COD/l
   SO =  0 mg -COD/l
   SNO = 0 mg N/l
   SNH = 31.56 mg N/l
   SND = 6.95 mg N/l
   XND = 10.59 mg N/l
   SALK = 7 mol HCO3/m3
   TSS = 211.2675 mg SS/l

Flow conditions
***************
   Influent flow to WWTP = 18446 m3/d
   Influent flow to AS = 92230 m3/d
   Internal recirculation = 55338 m3/d
   Secondary clarifier feed flow = 36892 m3/d
   Returned sludge flow = 18446 m3/d
   Wastage sludge flow = 385 m3/d
   Effluent flow = 18061 m3/d

Input to AS
***********
   SI =  30 mg COD/l
   SS =  14.6116 mg COD/l
   XI =  1149.1183 mg COD/l
   XS =  89.3302 mg COD/l
   XBH = 2542.1684 mg COD/l
   XBA = 148.4614 mg COD/l
   XP =  448.1754 mg COD/l
   SO =  0.39275 mg -COD/l
   SNO = 8.3321 mg N/l
   SNH = 7.6987 mg N/l
   SND = 1.9406 mg N/l
   XND = 5.6137 mg N/l
   SALK = 4.7005 mol HCO3/m3
   TSS = 3282.9402 mg SS/l

Reactor 1
*********
   SI =  30 mg COD/l
   SS =  2.8082 mg COD/l
   XI =  1149.1183 mg COD/l
   XS =  82.1349 mg COD/l
   XBH = 2551.7631 mg COD/l
   XBA = 148.3886 mg COD/l
   XP =  448.8459 mg COD/l
   SO =  0.0042984 mg -COD/l
   SNO = 5.3699 mg N/l
   SNH = 7.9179 mg N/l
```

```
   SND = 1.2166 mg N/l
   XND = 5.2849 mg N/l
   SALK = 4.9277 mol HCO3/m3
   TSS = 3285.188 mg SS/l

Reactor 2
*********
   SI =  30 mg COD/l
   SS =  1.4588 mg COD/l
   XI =  1149.1182 mg COD/l
   XS =  76.3862 mg COD/l
   XBH = 2553.3824 mg COD/l
   XBA = 148.3083 mg COD/l
   XP =  449.5167 mg COD/l
   SO =  6.3132e-05 mg -COD/l
   SNO = 3.6619 mg N/l
   SNH = 8.3445 mg N/l
   SND = 0.88207 mg N/l
   XND = 5.0291 mg N/l
   SALK = 5.0802 mol HCO3/m3
   TSS = 3282.5339 mg SS/l

Reactor 3
*********
   SI =  30 mg COD/l
   SS =  1.1495 mg COD/l
   XI =  1149.1182 mg COD/l
   XS =  64.8549 mg COD/l
   XBH = 2557.1288 mg COD/l
   XBA = 148.9404 mg COD/l
   XP =  450.4123 mg COD/l
   SO =  1.7184 mg -COD/l
   SNO = 6.5408 mg N/l
   SNH = 5.548 mg N/l
   SND = 0.82889 mg N/l
   XND = 4.3924 mg N/l
   SALK = 4.6748 mol HCO3/m3
   TSS = 3277.841 mg SS/l

Reactor 4
*********
   SI =  30 mg COD/l
   SS =  0.99532 mg COD/l
   XI =  1149.1182 mg COD/l
   XS =  55.694 mg COD/l
   XBH = 2559.18 mg COD/l
   XBA = 149.5262 mg COD/l
   XP =  451.3087 mg COD/l
   SO =  2.4289 mg -COD/l
   SNO = 9.299 mg N/l
   SNH = 2.9674 mg N/l
   SND = 0.76679 mg N/l
   XND = 3.879 mg N/l
   SALK = 4.2935 mol HCO3/m3
   TSS = 3273.6203 mg SS/l

Reactor 5
*********
   SI =  30 mg COD/l
   SS =  0.88949 mg COD/l
   XI =  1149.1182 mg COD/l
   XS =  49.3056 mg COD/l
   XBH = 2559.341 mg COD/l
```

```
   XBA = 149.7963 mg COD/l
   XP =  452.2051 mg COD/l
   SO =  0.49094 mg -COD/l
   SNO = 10.4152 mg N/l
   SNH = 1.7334 mg N/l
   SND = 0.68828 mg N/l
   XND = 3.5272 mg N/l
   SALK = 4.1256 mol HCO3/m3
   TSS = 3269.8246 mg SS/l

Secondary clarifier underflow
*****************
   SI =  30 mg COD/l
   SS =  0.88949 mg COD/l
   XI =  2247.0367 mg COD/l
   XS =  96.4143 mg COD/l
   XBH = 5004.6489 mg COD/l
   XBA = 292.9183 mg COD/l
   XP =  884.2618 mg COD/l
   SO =  0.49094 mg -COD/l
   SNO = 10.4152 mg N/l
   SNH = 1.7334 mg N/l
   SND = 0.68828 mg N/l
   XND = 6.8972 mg N/l
   SALK = 4.1256 mol HCO3/m3
   TSS = 6393.9599 mg SS/l

Settler effluent
****************
   SI =  30 mg COD/l
   SS =  0.88949 mg COD/l
   XI =  4.3918 mg COD/l
   XS =  0.18844 mg COD/l
   XBH = 9.7815 mg COD/l
   XBA = 0.57251 mg COD/l
   XP =  1.7283 mg COD/l
   SO =  0.49094 mg -COD/l
   SNO = 10.4152 mg N/l
   SNH = 1.7334 mg N/l
   SND = 0.68828 mg N/l
   XND = 0.01348 mg N/l
   SALK = 4.1256 mol HCO3/m3
   TSS = 12.4969 mg SS/l

Settler internal (1 is top layer)
*********************************
   TSS1 = 12.4969 mg SS/l
   TSS2 = 18.1132 mg SS/l
   TSS3 = 29.5402 mg SS/l
   TSS4 = 68.9779 mg SS/l
   TSS5 = 356.0738 mg SS/l
   TSS6 = 356.0738 mg SS/l
   TSS7 = 356.0738 mg SS/l
   TSS8 = 356.0738 mg SS/l
   TSS9 = 356.0738 mg SS/l
   TSS10 = 6393.9599 mg SS/l

Other variables
***************
   Trad. sludge age (XS + XP + XI + XBH + XBA in reactors) = 7.3155 days
   Spec. sludge age (XBH + XBA in reactors and settler) = 9.1436 days
   Total hydraulic retention time = 15.6118 hours
   Reactor hydraulic retention time = 7.8053 hours
```

```
   Thickening factor at bottom of settler (TSSu/TSSfeed) = 1.9554
   Thinning factor at top of settler (TSSeff/TSSfeed) = 0.0038219

Dimensions
**********
   Reactor 1 is anoxic
   Volume reactor 1 = 1000 m3
   Reactor 2 is anoxic
   Volume reactor 2 = 1000 m3
   Reactor 3 is aerobic
   Volume reactor 3 = 1333 m3
   Reactor 4 is aerobic
   Volume reactor 4 = 1333 m3
   Reactor 5 is aerobic
   Volume reactor 5 = 1333 m3
   Settler height = 4 m
   Settler area = 1500 m2
   Settler volume = 6000 m3
```

DYNAMIC RESULTS FOR BSM1 OPENLOOP
(Results from Matlab/Simulink implementation by Dr Ulf Jeppsson, IEA, Lund University, Sweden, March 27 2008)

```
SUMMARY OF PLANT PERFORMANCE
****************************
The plant was simulated in openloop for 150 days to achieve steady state
using the CONSTANTINPUT file.
Then the DRYWEATHER file was used to simulate the dynamics during 14 days
and set up the plant for the dynamic simulations.
The results of this simulation was used as initial values for the actual
plant performance calculations using the different dynamic input files.


*******************
* DRYWEATHER FILE *
*******************

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 = 31.7368 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 = 121.8198 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 = 52081.3952 kg poll.units/d
Effluent Quality (E.Q.) index = 6690.1066 kg poll.units/d

Sludge production for disposal = 17049.8309 kg SS
Average sludge production for disposal per day = 2435.6901 kg SS/d
Sludge production released into effluent = 1642.5375 kg SS
Average sludge production released into effluent per day = 234.6482 kg SS/d
Total sludge production = 18692.3684 kg SS
Total average sludge production per day = 2670.3383 kg SS/d

Total aeration energy = 23389.7067 kWh
Average aeration energy per day = 3341.3867 kWh/d

Total pumping energy (for Qintr, Qr and Qw) = 2717.19 kWh
Average pumping energy per day (for Qintr, Qr and Qw) = 388.17 kWh/d

Total mixing energy = 1680 kWh
Average mixing energy per day = 240 kWh/d

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
----------------------
Aeration energy cost index = 3341.3867
Pumping energy cost index = 388.17
Carbon source addition cost index = 0
Mixing energy cost index = 240
Total Operational Cost Index (OCI) = 16148.0073

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.
```

```
********************
* RAINWEATHER FILE *
********************

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

Effluent average concentrations based on load
---------------------------------------------
Effluent average flow rate = 23808.1776 m3/d
Effluent average SI conc = 22.8388 mg COD/l
Effluent average SS conc = 1.1349 mg COD/l
Effluent average XI conc = 5.6339 mg COD/l
Effluent average XS conc = 0.34502 mg COD/l
Effluent average XBH conc = 12.8584 mg COD/l
Effluent average XBA conc = 0.64114 mg COD/l
Effluent average XP conc = 2.0654 mg COD/l
Effluent average SO conc = 0.84653 mg (-COD)/l
Effluent average SNO conc = 6.9493 mg N/l
Effluent average SNH conc = 5.0085 mg N/l  (limit = 4 mg N/l)
Effluent average SND conc = 0.81596 mg N/l
Effluent average XND conc = 0.023611 mg N/l
Effluent average SALK conc = 5.1458 mol HCO3/m3
Effluent average TSS conc = 16.1579 mg SS/l  (limit = 30 mg SS/l)

Effluent average Kjeldahl N conc = 7.39 mg N/l
Effluent average total N conc = 14.3394 mg N/l  (limit = 18 mg COD/l)
Effluent average total COD conc = 45.5175 mg COD/l  (limit = 100 mg COD/l)
Effluent average BOD5 conc = 3.4749 mg/l  (limit = 10 mg/l)

Effluent average load
---------------------
Effluent average SI load = 543.7504 kg COD/day
Effluent average SS load = 27.0204 kg COD/day
Effluent average XI load = 134.1321 kg COD/day
Effluent average XS load = 8.2142 kg COD/day
Effluent average XBH load = 306.1353 kg COD/day
Effluent average XBA load = 15.2645 kg COD/day
Effluent average XP load = 49.1729 kg COD/day
Effluent average SO load = 20.1542 kg (-COD)/day
Effluent average SNO load = 165.4509 kg N/day
Effluent average SNH load = 119.244 kg N/day
Effluent average SND load = 19.4266 kg N/day
Effluent average XND load = 0.56215 kg N/day
Effluent average SALK load = 122.511 kmol HCO3/day
Effluent average TSS load = 384.6892 kg SS/day

Effluent average Kjeldahl N load = 175.943 kg N/d
Effluent average total N load = 341.3939 kg N/d
Effluent average total COD load = 1083.6897 kg COD/d
Effluent average BOD5 load = 82.7306 kg/d

Other effluent quality variables
--------------------------------
Influent Quality (I.Q.) index = 52081.3952 kg poll.units/d
Effluent Quality (E.Q.) index = 8951.3288 kg poll.units/d

Sludge production for disposal = 16471.0731 kg SS
Average sludge production for disposal per day = 2353.0104 kg SS/d
Sludge production released into effluent = 2692.8242 kg SS
Average sludge production released into effluent per day = 384.6892 kg SS/d
Total sludge production = 19163.8973 kg SS
```

```
Total average sludge production per day = 2737.6996 kg SS/d

Total aeration energy = 23389.7067 kWh
Average aeration energy per day = 3341.3867 kWh/d

Total pumping energy (for Qintr, Qr and Qw) = 2717.19 kWh
Average pumping energy per day (for Qintr, Qr and Qw) = 388.17 kWh/d

Total mixing energy = 1680 kWh
Average mixing energy per day = 240 kWh/d

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
----------------------
Aeration energy cost index = 3341.3867
Pumping energy cost index = 388.17
Carbon source addition cost index = 0
Mixing energy cost index = 240
Total Operational Cost Index (OCI) = 15734.6089

Effluent violations
-------------------
95% percentile for effluent SNH (Ammonia95) = 9.4978 g N/m3
95% percentile for effluent TN (TN95) = 17.8121 g N/m3
95% percentile for effluent TSS (TSS95) = 21.6824 g SS/m3

The maximum effluent total nitrogen level (18 mg N/l) was violated
during 0.32292 days, i.e. 4.6131% of the operating time.
The limit was violated at 3 different occasions.

The maximum effluent ammonia nitrogen level (4 mg N/l) was violated
during 4.4375 days, i.e. 63.3929% of the operating time.
The limit was violated at 7 different occasions.
```

```
********************
* STORMWEATHER FILE *
********************

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

Effluent average concentrations based on load
---------------------------------------------
Effluent average flow rate = 20658.1004 m3/d
Effluent average SI conc = 26.2999 mg COD/l
Effluent average SS conc = 1.1194 mg COD/l
Effluent average XI conc = 5.5746 mg COD/l
Effluent average XS conc = 0.32571 mg COD/l
Effluent average XBH conc = 11.9054 mg COD/l
Effluent average XBA conc = 0.57344 mg COD/l
Effluent average XP conc = 1.8527 mg COD/l
Effluent average SO conc = 0.75549 mg (-COD)/l
Effluent average SNO conc = 7.3707 mg N/l
Effluent average SNH conc = 5.681 mg N/l  (limit = 4 mg N/l)
Effluent average SND conc = 0.80749 mg N/l
Effluent average XND conc = 0.022846 mg N/l
Effluent average SALK conc = 4.9038 mol HCO3/m3
Effluent average TSS conc = 15.1739 mg SS/l  (limit = 30 mg SS/l)

Effluent average Kjeldahl N conc = 7.9553 mg N/l
Effluent average total N conc = 15.326 mg N/l  (limit = 18 mg COD/l)
Effluent average total COD conc = 47.6511 mg COD/l  (limit = 100 mg COD/l)
Effluent average BOD5 conc = 3.2314 mg/l  (limit = 10 mg/l)

Effluent average load
---------------------
Effluent average SI load = 543.3052 kg COD/day
Effluent average SS load = 23.1245 kg COD/day
Effluent average XI load = 115.16 kg COD/day
Effluent average XS load = 6.7285 kg COD/day
Effluent average XBH load = 245.9427 kg COD/day
Effluent average XBA load = 11.8463 kg COD/day
Effluent average XP load = 38.2733 kg COD/day
Effluent average SO load = 15.6069 kg (-COD)/day
Effluent average SNO load = 152.2652 kg N/day
Effluent average SNH load = 117.3594 kg N/day
Effluent average SND load = 16.6812 kg N/day
Effluent average XND load = 0.47195 kg N/day
Effluent average SALK load = 101.3031 kmol HCO3/day
Effluent average TSS load = 313.4631 kg SS/day

Effluent average Kjeldahl N load = 164.3417 kg N/d
Effluent average total N load = 316.6069 kg N/d
Effluent average total COD load = 984.3805 kg COD/d
Effluent average BOD5 load = 66.7547 kg/d

Other effluent quality variables
--------------------------------
Influent Quality (I.Q.) index = 54061.497 kg poll.units/d
Effluent Quality (E.Q.) index = 8197.7197 kg poll.units/d

Sludge production for disposal = 18252.4352 kg SS
Average sludge production for disposal per day = 2607.4907 kg SS/d
Sludge production released into effluent = 2194.2416 kg SS
Average sludge production released into effluent per day = 313.4631 kg SS/d
Total sludge production = 20446.6768 kg SS
Total average sludge production per day = 2920.9538 kg SS/d
```

```
Total aeration energy = 23389.7067 kWh
Average aeration energy per day = 3341.3867 kWh/d

Total pumping energy (for Qintr, Qr and Qw) = 2717.19 kWh
Average pumping energy per day (for Qintr, Qr and Qw) = 388.17 kWh/d

Total mixing energy = 1680 kWh
Average mixing energy per day = 240 kWh/d

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
----------------------
Aeration energy cost index = 3341.3867
Pumping energy cost index = 388.17
Carbon source addition cost index = 0
Mixing energy cost index = 240
Total Operational Cost Index (OCI) = 17007.0104

Effluent violations
-------------------
95% percentile for effluent SNH (Ammonia95) = 10.1872 g N/m3
95% percentile for effluent TN (TN95) = 18.9449 g N/m3
95% percentile for effluent TSS (TSS95) = 20.7485 g SS/m3

The maximum effluent total nitrogen level (18 mg N/l) was violated
during 0.64583 days, i.e. 9.2262% of the operating time.
The limit was violated at 4 different occasions.

The maximum effluent ammonia nitrogen level (4 mg N/l) was violated
during 4.625 days, i.e. 66.0714% of the operating time.
The limit was violated at 7 different occasions.
```

Appendix 5: Closed-loop results under Matlab-Simulink

```
STEADY STATE RESULTS FOR BSM1 CLOSEDLOOP
i.e. constant input file and ideal sensors/actuators, control strategy
according to BSM1 description
(Results from Matlab/Simulink implementation by Dr Ulf Jeppsson, IEA, Lund
University, Sweden, March 28 2008)

Influent characteristics
************************
   SI =  30 mg COD/l
   SS =  69.5 mg COD/l
   XI =  51.2 mg COD/l
   XS =  202.32 mg COD/l
   XBH = 28.17 mg COD/l
   XBA = 0 mg COD/l
   XP =  0 mg COD/l
   SO =  0 mg -COD/l
   SNO = 0 mg N/l
   SNH = 31.56 mg N/l
   SND = 6.95 mg N/l
   XND = 10.59 mg N/l
   SALK = 7 mol HCO3/m3
   TSS = 211.2675 mg SS/l

Flow conditions
***************
   Influent flow to WWTP = 18446 m3/d
   Influent flow to AS = 53377.6074 m3/d
   Internal recirculation = 16485.6074 m3/d
   Settler feed flow = 36892 m3/d
   Returned sludge flow = 18446 m3/d
   Wastage sludge flow = 385 m3/d
   Effluent flow = 18061 m3/d

Input to AS
***********
   SI =  30 mg COD/l
   SS =  24.5463 mg COD/l
   XI =  1149.1683 mg COD/l
   XS =  113.7148 mg COD/l
   XBH = 2533.1267 mg COD/l
   XBA = 151.7894 mg COD/l
   XP =  445.766 mg COD/l
   SO =  1.3088 mg -COD/l
   SNO = 8.8506 mg N/l
   SNH = 11.3461 mg N/l
   SND = 2.8366 mg N/l
   XND = 6.8699 mg N/l
   SALK = 4.924 mol HCO3/m3
   TSS = 3295.1738 mg SS/l

Reactor 1
*********
   SI =  30 mg COD/l
   SS =  3.2439 mg COD/l
   XI =  1149.1683 mg COD/l
   XS =  98.6029 mg COD/l
   XBH = 2552.1095 mg COD/l
   XBA = 151.6721 mg COD/l
   XP =  446.9249 mg COD/l
   SO =  0.0076964 mg -COD/l
```

```
   SNO = 3.5133 mg N/l
   SNH = 11.8312 mg N/l
   SND = 1.3621 mg N/l
   XND = 6.1775 mg N/l
   SALK = 5.3399 mol HCO3/m3
   TSS = 3298.8582 mg SS/l

Reactor 2
*********
   SI =  30 mg COD/l
   SS =  1.6707 mg COD/l
   XI =  1149.1683 mg COD/l
   XS =  91.7032 mg COD/l
   XBH = 2552.3711 mg COD/l
   XBA = 151.5303 mg COD/l
   XP =  448.0839 mg COD/l
   SO =  6.0271e-05 mg -COD/l
   SNO = 1 mg N/l
   SNH = 12.5482 mg N/l
   SND = 0.78899 mg N/l
   XND = 5.9537 mg N/l
   SALK = 5.5706 mol HCO3/m3
   TSS = 3294.6425 mg SS/l

Reactor 3
*********
   SI =  30 mg COD/l
   SS =  1.2195 mg COD/l
   XI =  1149.1683 mg COD/l
   XS =  69.6594 mg COD/l
   XBH = 2560.2025 mg COD/l
   XBA = 152.6873 mg COD/l
   XP =  449.6336 mg COD/l
   SO =  1.635 mg -COD/l
   SNO = 6.2289 mg N/l
   SNH = 7.3197 mg N/l
   SND = 0.8307 mg N/l
   XND = 4.7131 mg N/l
   SALK = 4.8236 mol HCO3/m3
   TSS = 3286.0133 mg SS/l

Reactor 4
*********
   SI =  30 mg COD/l
   SS =  0.97326 mg COD/l
   XI =  1149.1683 mg COD/l
   XS =  54.4484 mg COD/l
   XBH = 2563.3104 mg COD/l
   XBA = 153.7108 mg COD/l
   XP =  451.1853 mg COD/l
   SO =  2.4745 mg -COD/l
   SNO = 11.0693 mg N/l
   SNH = 2.7825 mg N/l
   SND = 0.75276 mg N/l
   XND = 3.8403 mg N/l
   SALK = 4.1538 mol HCO3/m3
   TSS = 3278.8674 mg SS/l

Reactor 5
*********
   SI =  30 mg COD/l
   SS =  0.80801 mg COD/l
   XI =  1149.1683 mg COD/l
```

```
   XS =  44.4828 mg COD/l
   XBH = 2562.8514 mg COD/l
   XBA = 154.163 mg COD/l
   XP =  452.7367 mg COD/l
   SO =  2 mg -COD/l
   SNO = 13.5243 mg N/l
   SNH = 0.67193 mg N/l
   SND = 0.6645 mg N/l
   XND = 3.2605 mg N/l
   SALK = 3.8277 mol HCO3/m3
   TSS = 3272.5516 mg SS/l

Settler underflow
*****************
   SI =  30 mg COD/l
   SS =  0.80801 mg COD/l
   XI =  2247.1365 mg COD/l
   XS =  86.9837 mg COD/l
   XBH = 5011.5176 mg COD/l
   XBA = 301.4575 mg COD/l
   XP =  885.3022 mg COD/l
   SO =  2 mg -COD/l
   SNO = 13.5243 mg N/l
   SNH = 0.67193 mg N/l
   SND = 0.6645 mg N/l
   XND = 6.3757 mg N/l
   SALK = 3.8277 mol HCO3/m3
   TSS = 6399.2981 mg SS/l

Settler effluent
****************
   SI =  30 mg COD/l
   SS =  0.80801 mg COD/l
   XI =  4.39 mg COD/l
   XS =  0.16993 mg COD/l
   XBH = 9.7905 mg COD/l
   XBA = 0.58893 mg COD/l
   XP =  1.7295 mg COD/l
   SO =  2 mg -COD/l
   SNO = 13.5243 mg N/l
   SNH = 0.67193 mg N/l
   SND = 0.6645 mg N/l
   XND = 0.012455 mg N/l
   SALK = 3.8277 mol HCO3/m3
   TSS = 12.5016 mg SS/l

Settler internal (1 is top layer)
*********************************
   TSS1 = 12.5016 mg SS/l
   TSS2 = 18.1183 mg SS/l
   TSS3 = 29.548 mg SS/l
   TSS4 = 69.0015 mg SS/l
   TSS5 = 356.2825 mg SS/l
   TSS6 = 356.2825 mg SS/l
   TSS7 = 356.2825 mg SS/l
   TSS8 = 356.2825 mg SS/l
   TSS9 = 356.2825 mg SS/l
   TSS10 = 6399.2981 mg SS/l

Other variables
***************
   Trad. sludge age (XS + XP + XI + XBH + XBA in reactors) = 7.3273 days
   Spec. sludge age (XBH + XBA in reactors and settler) = 9.139 days
```

```
   Total hydraulic retention time = 15.6118 hours
   Reactor hydraulic retention time = 7.8053 hours
   Thickening factor at bottom of settler(TSSu/TSSfeed) = 1.9554
   Thinning factor at top of settler (TSSeff/TSSfeed) = 0.0038201

Dimensions
**********
   Reactor 1 is anoxic
   Volume reactor 1 = 1000 m3
   Reactor 2 is anoxic
   Volume reactor 2 = 1000 m3
   Reactor 3 is aerobic
   Volume reactor 3 = 1333 m3
   Reactor 4 is aerobic
   Volume reactor 4 = 1333 m3
   Reactor 5 is aerobic
   Volume reactor 5 = 1333 m3
   Settler height = 4 m
   Settler area = 1500 m2
   Settler volume = 6000 m3
```

DYNAMIC RESULTS FOR BSM1 CLOSEDLOOP BSM1
(Results from Matlab/Simulink implementation by Dr Ulf Jeppsson, IEA, Lund University, Sweden, March 28 2008)

```
SUMMARY OF PLANT PERFORMANCE
****************************
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 DRYWEATHER 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.

Default controllers:
controller for DO in tank 5, DOsetpoint=2mg/l, Sensor model A, Actuator
model used, Noise data from file column 1;
controller for NO3-N in tank 2, NO3setpoint=1mg/l, Sensor model B0,  Noise
data from file column 2.

Evaluation is based on data every 15 minutes and uses zero-order hold
(forward Euler) for integration between measurements.



*******************
* DRYWEATHER FILE *
*******************

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
--------------------------------
Influent Quality (I.Q.) index = 52081.3952 kg poll.units/d
Effluent Quality (E.Q.) index = 6123.0182 kg poll.units/d

Sludge production for disposal = 17084.2397 kg SS
Average sludge production for disposal per day = 2440.6057 kg SS/d
Sludge production released into effluent = 1643.7439 kg SS
Average sludge production released into effluent per day = 234.8206 kg SS/d
Total sludge production = 18727.9836 kg SS
Total average sludge production per day = 2675.4262 kg SS/d

Total aeration energy = 25888.4069 kWh
Average aeration energy per day = 3698.3438 kWh/d

Total pumping energy (for Qintr, Qr and Qw) = 1687.2136 kWh
Average pumping energy per day (for Qintr, Qr and Qw) = 241.0305 kWh/d

Total mixing energy = 1680 kWh
Average mixing energy per day = 240 kWh/d

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 = 12203.0284
Aeration energy cost index = 3698.3438
Pumping energy cost index = 241.0305
Carbon source addition cost index = 0
Mixing energy cost index = 240
Total Operational Cost Index (OCI) = 16382.4027

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.

Performance of active controllers during time 7 to 14 days
************************************************************

Nitrate controller for second anoxic reactor
============================================

PI controller with anti-windup: K = 10000 m3/d/(g N/m3)
                                Ti = 0.025 days
                                Tt = 0.015 days

Controlled variable - SNO (tank 2), setpoint = 1 mg N/l
-------------------------------------------------------
Average value of error (mean(e)) = -0.0021211 (mg N/l)
Average value of absolute error (mean(|e|)) = 0.20497 (mg N/l)
Integral of absolute error (IAE) = 1.4348 (mg N/l)*d
Integral of square error (ISE) = 0.56897 (mg N/l)^2*d
Maximum absolute deviation from nitrate setpoint (max(e)) = 0.91782 mg N/l
Standard deviation of error (std(e)) = 0.28509 mg N/l
Variance of error (var(e)) = 0.081276 (mg N/l)^2

Manipulated variable (MV), Qintr
--------------------------------
Maximum absolute variation of MV (max-min) = 45734.3965 m3/d
Maximum absolute variation of MV in one sample (max delta) = 18918.9397
m3/d
Average value of MV (mean(Qintr)) = 18610.0822 m3/d
Standard deviation of MV (std(Qintr)) = 4078.4756 m3/d
Variance of MV (var(Qintr)) = 16633963.2296 (m3/d)^2


Oxygen controller for last aerobic reactor
==========================================

PI controller with anti-windup: K = 25 1/d/(g (-COD)/m3)
                                Ti = 0.002 days
                                Tt = 0.001 days

Controlled variable - SO (tank 5), setpoint = 2 mg (-COD)/l
-----------------------------------------------------------

Average value of error (mean(e)) = -0.00039763 (mg (-COD)/l)
Average value of absolute error (mean(|e|)) = 0.084044 (mg (-COD)/l)
```

```
Integral of absolute error (IAE) = 0.58831 (mg (-COD)/l)*d
Integral of square error (ISE) = 0.083975 (mg (-COD)/l)^2*d
Maximum absolute deviation from oxygen setpoint (max(e)) = 0.39631 mg (-
COD)/l
Standard deviation of error (std(e)) = 0.10953 mg (-COD)/l
Variance of error (var(e)) = 0.011996 (mg (-COD)/l)^2

Manipulated variable (MV), KLa (tank 5)
---------------------------------------
Maximum absolute variation of MV (max-min) = 242.2831 1/d
Maximum absolute variation of MV in one sample (max delta) = 47.8828 1/d
Average value of MV (mean(KLa5)) = 144.1219 1/d
Standard deviation of MV (std(KLa5)) = 9.5682 1/d
Variance of MV (var(KLa5)) = 91.5507 (1/d)^2
```

```
********************
* RAINWEATHER FILE *
********************

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

Effluent average concentrations based on load
---------------------------------------------
Effluent average flow rate = 23806.8789 m3/d
Effluent average SI conc = 22.8353 mg COD/l
Effluent average SS conc = 1.0294 mg COD/l
Effluent average XI conc = 5.6285 mg COD/l
Effluent average XS conc = 0.31107 mg COD/l
Effluent average XBH conc = 12.8824 mg COD/l
Effluent average XBA conc = 0.68536 mg COD/l
Effluent average XP conc = 2.0617 mg COD/l
Effluent average SO conc = 1.9918 mg (-COD)/l
Effluent average SNO conc = 9.1649 mg N/l
Effluent average SNH conc = 3.226 mg N/l  (limit = 4 mg N/l)
Effluent average SND conc = 0.78728 mg N/l
Effluent average XND conc = 0.021515 mg N/l
Effluent average SALK conc = 4.8606 mol HCO3/m3
Effluent average TSS conc = 16.1768 mg SS/l  (limit = 30 mg SS/l)

Effluent average Kjeldahl N conc = 5.5816 mg N/l
Effluent average total N conc = 14.7465 mg N/l  (limit = 18 mg COD/l)
Effluent average total COD conc = 45.4337 mg COD/l  (limit = 100 mg COD/l)
Effluent average BOD5 conc = 3.4557 mg/l  (limit = 10 mg/l)

Effluent average load
---------------------
Effluent average SI load = 543.6382 kg COD/day
Effluent average SS load = 24.5064 kg COD/day
Effluent average XI load = 133.9972 kg COD/day
Effluent average XS load = 7.4056 kg COD/day
Effluent average XBH load = 306.6892 kg COD/day
Effluent average XBA load = 16.3163 kg COD/day
Effluent average XP load = 49.0825 kg COD/day
Effluent average SO load = 47.4177 kg (-COD)/day
Effluent average SNO load = 218.1877 kg N/day
Effluent average SNH load = 76.8013 kg N/day
Effluent average SND load = 18.7426 kg N/day
Effluent average XND load = 0.5122 kg N/day
Effluent average SALK load = 115.7154 kmol HCO3/day
Effluent average TSS load = 385.118 kg SS/day

Effluent average Kjeldahl N load = 132.8813 kg N/d
Effluent average total N load = 351.069 kg N/d
Effluent average total COD load = 1081.6353 kg COD/d
Effluent average BOD5 load = 82.2692 kg/d

Other effluent quality variables
--------------------------------
Influent Quality (I.Q.) index = 52081.3952 kg poll.units/
Effluent Quality (E.Q.) index = 8184.7263 kg poll.units/d

Sludge production for disposal = 16503.104 kg SS
Average sludge production for disposal per day = 2357.5863 kg SS/d
Sludge production released into effluent = 2695.8261 kg SS
Average sludge production released into effluent per day = 385.118 kg SS/d
Total sludge production = 19198.9302 kg SS
Total average sludge production per day = 2742.7043 kg SS/d
```

```
Total aeration energy = 25699.4632 kWh
Average aeration energy per day = 3671.3519 kWh/d

Total pumping energy (for Qintr, Qr and Qw) = 1996.8482 kWh
Average pumping energy per day (for Qintr, Qr and Qw) = 285.264 kWh/d

Total mixing energy = 1680 kWh
Average mixing energy per day = 240 kWh/d

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 = 11787.9314
Aeration energy cost index = 3671.3519
Pumping energy cost index = 285.264
Carbon source addition cost index = 0
Mixing energy cost index = 240
Total Operational Cost Index (OCI) = 15984.5473

Effluent violations
-------------------
95% percentile for effluent SNH (Ammonia95) = 8.0395 g N/m3
95% percentile for effluent TN (TN95) = 19.1429 g N/m3
95% percentile for effluent TSS (TSS95) = 21.6967 g SS/m3

The maximum effluent total nitrogen level (18 mg N/l) was violated
during 0.77083 days, i.e. 11.0119% 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 1.8958 days, i.e. 27.0833% of the operating time.
The limit was violated at 8 different occasions.



Performance of active controllers during time 7 to 14 days
************************************************************

Nitrate controller for second anoxic reactor
============================================

PI controller with anti-windup: K = 10000 m3/d/(g N/m3)
                                Ti = 0.025 days
                                Tt = 0.015 days

Controlled variable - SNO (tank 2), setpoint = 1 mg N/l
-------------------------------------------------------
Average value of error (mean(e)) = 0.002672 (mg N/l)
Average value of absolute error (mean(|e|)) = 0.24784 (mg N/l)
Integral of absolute error (IAE) = 1.7349 (mg N/l)*d
Integral of square error (ISE) = 0.79436 (mg N/l)^2*d
Maximum absolute deviation from nitrate setpoint (max(e)) = 0.92134 mg N/l
Standard deviation of error (std(e)) = 0.33686 mg N/l
Variance of error (var(e)) = 0.11347 (mg N/l)^2

Manipulated variable (MV), Qintr
--------------------------------
Maximum absolute variation of MV (max-min) = 84374.4066 m3/d
```

```
Maximum absolute variation of MV in one sample (max delta) = 18678.4397
m3/d
Average value of MV (mean(Qintr)) = 29608.9372 m3/d
Standard deviation of MV (std(Qintr)) = 4110.5486 m3/d
Variance of MV (var(Qintr)) = 16896609.8904 (m3/d)^2


Oxygen controller for last aerobic reactor
==========================================

PI controller with anti-windup: K = 25 1/d/(g (-COD)/m3)
                                Ti = 0.002 days
                                Tt = 0.001 days

Controlled variable - SO (tank 5), setpoint = 2 mg (-COD)/l
-----------------------------------------------------------

Average value of error (mean(e)) = -0.00046529 (mg (-COD)/l)
Average value of absolute error (mean(|e|)) = 0.079532 (mg (-COD)/l)
Integral of absolute error (IAE) = 0.55672 (mg (-COD)/l)*d
Integral of square error (ISE) = 0.074733 (mg (-COD)/l)^2*d
Maximum absolute deviation from oxygen setpoint (max(e)) = 0.38505 mg (-
COD)/l
Standard deviation of error (std(e)) = 0.10332 mg (-COD)/l
Variance of error (var(e)) = 0.010676 (mg (-COD)/l)^2

Manipulated variable (MV), KLa (tank 5)
---------------------------------------
Maximum absolute variation of MV (max-min) = 227.3181 1/d
Maximum absolute variation of MV in one sample (max delta) = 47.8828 1/d
Average value of MV (mean(KLa5)) = 139.5768 1/d
Standard deviation of MV (std(KLa5)) = 9.2235 1/d
Variance of MV (var(KLa5)) = 85.0722 (1/d)^2
```

```
*********************
* STORMWEATHER FILE *
*********************

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

Effluent average concentrations based on load
---------------------------------------------
Effluent average flow rate = 20654.9629 m3/d
Effluent average SI conc = 26.2982 mg COD/l
Effluent average SS conc = 0.9995 mg COD/l
Effluent average XI conc = 5.6341 mg COD/l
Effluent average XS conc = 0.28755 mg COD/l
Effluent average XBH conc = 11.9051 mg COD/l
Effluent average XBA conc = 0.63091 mg COD/l
Effluent average XP conc = 1.9072 mg COD/l
Effluent average SO conc = 1.9905 mg (-COD)/l
Effluent average SNO conc = 10.553 mg N/l
Effluent average SNH conc = 3.0622 mg N/l  (limit = 4 mg N/l)
Effluent average SND conc = 0.77656 mg N/l
Effluent average XND conc = 0.02043 mg N/l
Effluent average SALK conc = 4.4897 mol HCO3/m3
Effluent average TSS conc = 15.2737 mg SS/l  (limit = 30 mg SS/l)

Effluent average Kjeldahl N conc = 5.3146 mg N/l
Effluent average total N conc = 15.8676 mg N/l  (limit = 18 mg COD/l)
Effluent average total COD conc = 47.6626 mg COD/l  (limit = 100 mg COD/l)
Effluent average BOD5 conc = 3.205 mg/l  (limit = 10 mg/l)

Effluent average load
---------------------
Effluent average SI load = 543.1883 kg COD/day
Effluent average SS load = 20.6447 kg COD/day
Effluent average XI load = 116.372 kg COD/day
Effluent average XS load = 5.9394 kg COD/day
Effluent average XBH load = 245.8993 kg COD/day
Effluent average XBA load = 13.0314 kg COD/day
Effluent average XP load = 39.3935 kg COD/day
Effluent average SO load = 41.1136 kg (-COD)/day
Effluent average SNO load = 217.9728 kg N/day
Effluent average SNH load = 63.2503 kg N/day
Effluent average SND load = 16.0398 kg N/day
Effluent average XND load = 0.42198 kg N/day
Effluent average SALK load = 92.7345 kmol HCO3/day
Effluent average TSS load = 315.4767 kg SS/day

Effluent average Kjeldahl N load = 109.7725 kg N/d
Effluent average total N load = 327.7453 kg N/d
Effluent average total COD load = 984.4686 kg COD/d
Effluent average BOD5 load = 66.2001 kg/d

Other effluent quality variables
--------------------------------
Influent Quality (I.Q.) index = 54061.497 kg poll.units/d
Effluent Quality (E.Q.) index = 7220.7241 kg poll.units/d

Sludge production for disposal = 18238.4311 kg SS
Average sludge production for disposal per day = 2605.4902 kg SS/d
Sludge production released into effluent = 2208.337 kg SS
Average sludge production released into effluent per day = 315.4767 kg SS/d
Total sludge production = 20446.7681 kg SS
Total average sludge production per day = 2920.9669 kg SS/d
```

```
Total aeration energy = 26046.4214 kWh (updated BSM1 version)
Average aeration energy per day = 3720.9173 kWh/d (updated BSM1 version)

Total pumping energy (for Qintr, Qr and Qw) = 1856.3886 kWh
Average pumping energy per day (for Qintr, Qr and Qw) = 265.1984 kWh/d

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 = 13027.4508
Aeration energy cost index = 3720.9173
Pumping energy cost index = 265.1984
Carbon source addition cost index = 0
Mixing energy cost index = 240
Total Operational Cost Index (OCI) = 17253.5665

Effluent violations
-------------------
95% percentile for effluent SNH (Ammonia95) = 7.8033 g N/m3
95% percentile for effluent TN (TN95) = 20.1257 g N/m3
95% percentile for effluent TSS (TSS95) = 20.7886 g SS/m3

The maximum effluent total nitrogen level (18 mg N/l) was violated
during 1.0938 days, i.e. 15.625% 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 1.8854 days, i.e. 26.9345% of the operating time.
The limit was violated at 7 different occasions.

The maximum effluent total suspended solids level (30 mg SS/l) was violated
during 0.020833 days, i.e. 0.29762% of the operating time.
The limit was violated at 2 different occasions.



Performance of active controllers during time 7 to 14 days
************************************************************

Nitrate controller for second anoxic reactor
============================================

PI controller with anti-windup: K = 10000 m3/d/(g N/m3)
                                Ti = 0.025 days
                                Tt = 0.015 days

Controlled variable - SNO (tank 2), setpoint = 1 mg N/l
-------------------------------------------------------
Average value of error (mean(e)) = 0.0051026 (mg N/l)
Average value of absolute error (mean(|e|)) = 0.23979 (mg N/l)
Integral of absolute error (IAE) = 1.6785 (mg N/l)*d
Integral of square error (ISE) = 0.78797 (mg N/l)^2*d
Maximum absolute deviation from nitrate setpoint (max(e)) = 1.2014 mg N/l
Standard deviation of error (std(e)) = 0.33547 mg N/l
Variance of error (var(e)) = 0.11254 (mg N/l)^2
```

```
Manipulated variable (MV), Qintr
--------------------------------
Maximum absolute variation of MV (max-min) = 83663.6739 m3/d
Maximum absolute variation of MV in one sample (max delta) = 18489.0489
m3/d
Average value of MV (mean(Qintr)) = 24623.036 m3/d
Standard deviation of MV (std(Qintr)) = 4141.7466 m3/d
Variance of MV (var(Qintr)) = 17154064.5203 (m3/d)^2


Oxygen controller for last aerobic reactor
==========================================

PI controller with anti-windup: K = 25 1/d/(g (-COD)/m3)
                                Ti = 0.002 days
                                Tt = 0.001 days

Controlled variable - SO (tank 5), setpoint = 2 mg (-COD)/l
-----------------------------------------------------------

Average value of error (mean(e)) = -0.00038723 (mg (-COD)/l)
Average value of absolute error (mean(|e|)) = 0.080854 (mg (-COD)/l)
Integral of absolute error (IAE) = 0.56598 (mg (-COD)/l)*d
Integral of square error (ISE) = 0.078876 (mg (-COD)/l)^2*d
Maximum absolute deviation from oxygen setpoint (max(e)) = 0.37924 mg (-
COD)/l
Standard deviation of error (std(e)) = 0.10615 mg (-COD)/l
Variance of error (var(e)) = 0.011268 (mg (-COD)/l)^2

Manipulated variable (MV), KLa (tank 5)
---------------------------------------
Maximum absolute variation of MV (max-min) = 244.5373 1/d
Maximum absolute variation of MV in one sample (max delta) = 47.8829 1/d
Average value of MV (mean(KLa5)) = 147.9338 1/d
Standard deviation of MV (std(KLa5)) = 9.3809 1/d
Variance of MV (var(KLa5)) = 88.0009 (1/d)^2
```