Benchmark simulation model no 2: general protocol and exploratory case studies

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Abstract Over a decade ago, the concept of objectively evaluating the performance of control strategies by simulating them using a standard model implementation was introduced for activated sludge wastewater treatment plants. The resulting Benchmark Simulation Model No 1 (BSM1) has been the basis for a significant new development that is reported on here: Rather than only evaluating control strategies at the level of the activated sludge unit (bioreactors and secondary clarifier) the new BSM2 now allows the evaluation of control strategies at the level of the whole plant, including primary clarifier and sludge treatment with anaerobic sludge digestion.

In this contribution, the decisions that have been made over the past three years regarding the models used within the BSM2 are presented and argued, with particular emphasis on the ADM1 description of the digester, the interfaces between activated sludge and digester models, the included temperature dependencies and the reject water storage. BSM2-implementations are now available in a wide range of simulation platforms and a ring test has verified their proper implementation, consistent with the BSM2 definition. This guarantees that users can focus on the control strategy evaluation rather than on modelling issues. Finally, for illustration, twelve simple operational strategies have been implemented in BSM2 and their performance evaluated. Results show that it is an interesting control engineering challenge to further improve the performance of the BSM2 plant (which is the whole idea behind benchmarking) and that integrated control (i.e. acting at different places in the whole plant) is certainly worthwhile to achieve overall improvement.

Keywords Benchmarking; BSM2; control; evaluation criteria; simulation; wastewater treatment; whole plant modelling

Introduction

The Benchmark Simulation Model No 2 (BSM2) is a detailed protocol for implementing, analysing and evaluating the impact and performance of both existing and novel control strategies applied to wastewater treatment plants (WWTPs). The on-going research and development of BSM2 is being performed within the framework of the *IWA Task Group*

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on Benchmarking of Control Strategies for WWTPs, established in 2005 (see www.benchmarkwwtp.org). This Task Group (TG) is also developing an associated benchmark system that focuses on long-term monitoring performance evaluation (i.e. BSM1_LT, Rosen *et al.* (2004)), but this will not be discussed in this paper. The final outcome of the TG's efforts will be an IWA Scientific and Technical Report, which is planned to appear by the end of 2008. BSM2 has been under development for several years with the preliminary concepts first introduced to a general audience at IWA's Watermatex2004 symposium (Jeppsson *et al.*, 2006) with the aim of getting feedback on the BSM2 from the research community. Since then the development has continued and a more complete version is presented in this paper. The focus of this paper has been placed on the more recent developments and modifications to the system that have been incorporated over the last three years. To demonstrate how BSM2 can be used to investigate the effects of different control strategies, the results from a number of simple and exploratory test cases are presented.

Availability and purpose

The use of benchmark systems for assessment of process performance, control system evaluation and similar purposes is well established. The success of the first COST/IWA benchmark simulation model (BSM1) (e.g. Copp, 2002; Jeppsson and Pons, 2004; Spanjers *et al.*, 1998) for activated sludge (AS) control strategy development and evaluation clearly indicated the usefulness of such a tool for the wastewater community, both for research and more practical applications. BSM1 is used by numerous research groups around the world for various purposes and is available as a predefined software tool in several commercial WWTP simulator packages – GPS-X™, SIMBA® and WEST® – as well as in stand-alone FORTRAN and C++ implementations and for the general MATLAB®/SIMULINK® platform. Implementations with varying success also have been achieved in STOAT™, BioWin™, AQUASIM, JASS, SciLab and EFOR™. For the BSM2 development the main strategic platforms to date are GPS-X™, SIMBA®, WEST®, STOAT™, FORTRAN and MATLAB®/SIMULINK®.

During the last decade the importance of integrated and plant-wide control has been emphasised by the research community and the wastewater industry is now starting to realise the benefits of such an approach. A WWTP should be thought of as one completely integrated system, where primary/secondary clarification units, activated sludge reactors, anaerobic digesters, thickeners, dewatering systems and other sub-processes are linked together and are operated and controlled not only on a local level as individual processes but by supervisory control systems taking into account all the interactions between the processes. In case the interactions between WWTP units are not considered, sub-optimal plant operation will be an unavoidable outcome leading to 'lower than possible' effluent quality and/or higher operational costs. It is the main purpose of BSM2 to take these issues into account. Consequently, wastewater pre-treatment and the sludge train have been included in BSM2 (BSM1 encompassed only the activated sludge and secondary clarification stages). To allow for a more thorough evaluation than provided for in BSM1 and additional control handles operating on longer time-scales, the benchmark evaluation period has been extended to one year (compared to one week in BSM1). The slow dynamics of anaerobic digestion (AD) processes – a unit process present in the sludge train – also necessitated a pro-longed evaluation period. With this extended evaluation period, seasonal effects on the WWTP in terms of temperature variations and changing influent flow rate patterns have been included.

It should be noted that the purpose of BSM2 is to provide a tool and procedure that is useful for evaluating the performance of proposed control strategies (often based on relative comparisons) rather than simulating all possible details of a real WWTP and associated behaviour. Consequently, the benchmark plant is not defined by any national standards or design principles but aims at describing an activated sludge plant with an influent load of 100,000 PE (80,000 from households and 20,000 from industrial origin) including many of the main processes that are often found at large-scale WWTPs around the world.

As a special remark, BSM2 also provides an excellent starting point for other types of investigations where specialized processes are added to the existing system and the consequences analysed using the principles of the BSM2 protocol. Examples of such applications have been recently presented by Volcke *et al.* (2006) for high-performance reject water treatment and by Benedetti *et al.* (2006) for general WWTP upgrade analysis. Obviously, evaluations based on the true BSM2 and the above types of extended or modified systems cannot be immediately compared in an objective benchmarking perspective but the applications demonstrate other potential uses and benefits of the BSM2 effort.

BSM2 protocol

The Benchmark Simulation Model No 2 protocol consists of a complete model representing a general WWTP, an associated control system, a benchmarking procedure and a set of evaluation criteria. The main components of the plant model (see also Figure 1) are:

- *Primary clarification,*
  - based on Otterpohl and Freund (1992) and Otterpohl *et al.* (1994)
  - 50% solids removal efficiency
  - no biological activity;
- *Five-reactor nitrogen removal activated sludge system,*
  - based on ASM1 (Henze *et al.*, 1987);
- *Secondary clarification,*
  - based on Takács *et al.* (1991)
  - no biological activity;
- *Gravity thickening,*
  - ideal and continuous process
  - 98% solids removal efficiency
  - no biological activity;
- *Anaerobic digestion,*
  - based on ADM1 (Batstone *et al.*, 2002);

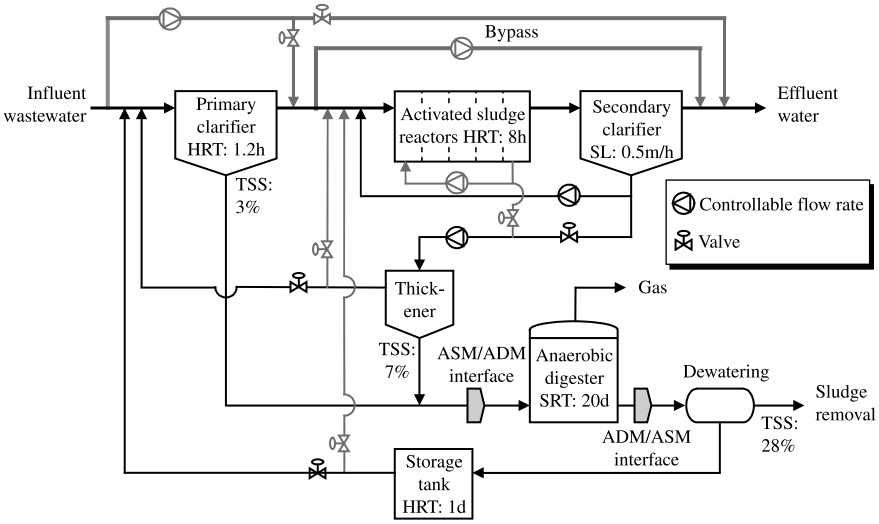

Figure 1 Plant layout for BSM2

- *Dewatering,*
    - ideal and continuous process
    - 98% solids removal efficiency
    - no biological activity;
- *AD/AS model interfaces,*
    - based on Nopens *et al.* (2007);
- *Storage tank,*
    - continuous process
    - controllable output pumping capacity
    - no biological activity;
- *Influent wastewater characteristics,*
    - based on Gernaey *et al.* (2005; 2006)
    - 609-day dynamic influent data file (data every 15 minutes).

Although considerable flexibility is provided so as to allow creative user-defined control strategies to be tested, only specified control handles and sensors are to be used for defining a control system. This stipulation is included to allow for objective and relative comparisons of suggested control strategies. More than 60 control handles are available for BSM2 and these include:

- More or less all *flow rates*:
    - primary clarifier and/or activated sludge system bypass or a combination of both
    - step feed
    - recycling of thickener effluent and reject water to the inlet of the primary clarifier or to the inlet of the AS system or a combination of both
    - wastage sludge withdrawn from the last AS reactor
    - internal flow combinations within the AS system;
- Addition of an *external carbon source* to any of the AS reactors;
- Any combination of *mixing and aeration* in the five AS reactors;
- *Reject water flow rate control* by the use of a storage tank.

All actuators (control handles) are considered ideal except the aeration system, which is described using a simple model creating a delay of the K_La inputs (the BSM systems provide K_La as a direct input rather than air flow rate), and the reject water storage tank, which requires a somewhat more complex model. As BSM2 does not include biological phosphorus removal, chemical precipitation, biological activity outside the AS and AD reactors or variable sludge characteristics, the defined control handles should allow most control strategies within the confinements of the BSM2 plant layout.

Sensors to be used for proposed control strategies have dynamic properties, which need to be taken into account. For BSM2, sensors are modelled based on the principles of Rieger *et al.* (2003). A number of sensor classes have been defined from which a benchmark user selects the ones most appropriate (recommendations are given by the TG). Noise level, time response, delay time, signal saturation levels and sampling time are sensor characteristics defined by the various classes, but ideal sensors also may be used when developing and testing a strategy. To allow for a more realistic reproduction and verification of a control strategy predefined noise should to be used.

It must be emphasized that documentation and verification examples exist, so the normal procedure would be that the TG provides the user with all the required models (or that the system is predefined in a commercial simulator). This approach guarantees that the implementation is correct, and will thus save a potential user a significant amount of time and effort and allows BSM2 to be used by a much wider audience. Moreover, this approach enables the user to focus on the overall purpose of BSM2 – control strategy development.

The simulation procedure for BSM2 is straightforward. The system is first simulated using predefined constant influent data of 200 days to reach a steady state. The constant influent represents the average values of the full 609-day dynamic input data. The steady state values obtained in this first simulation are subsequently used as initial values for simulations using the dynamic influent. From this starting point, BSM2 is simulated for 63 days (9 weeks, from $t = 0$ d to $t = 63$ d) with controls active to achieve a quasi or pseudo steady state based on the dynamic input data. This period is followed by 182 days of dynamic simulation (26 weeks, from $t = 63$ d to $t = 245$ d) in order to allow, for example, adaptive or model-based controllers enough time to adapt, estimate internal parameters or in some other way train the control algorithms. Finally, BSM2 is simulated for an additional 364 days (52 weeks, from $t = 245$ d to $t = 609$ d) and the output data generated during this last period (stored at 15-minute intervals) are used for plant performance evaluation. Obviously, the most difficult period during which to maintain good behaviour of the plant is during the cold season, which was the motivation for defining the coldest temperatures in the middle of the one-year evaluation period.

To assess the performance of the plant and control strategy, evaluation criteria are necessary. These criteria aim to condense the simulation output into a few indices and/or key variables that represent the system and controller performance. This approach simplifies the large output dataset into a manageable number of comparable numbers. In BSM2, the system performance is partly evaluated according to an effluent quality index (*EQI*, in kg pollution units d^{-1}):

$$EQI = \frac{1}{T \cdot 1000} \int_{t=245\text{ days}}^{t=609\text{ days}} \begin{pmatrix} \beta_{\mathrm{TSS}} \cdot TSS_{\mathrm{e}}(t) + \beta_{\mathrm{COD}} \cdot COD_{\mathrm{e}}(t) + \beta_{\mathrm{TKN}} \cdot S_{\mathrm{TKN,e}}(t) \\ + \beta_{\mathrm{NO}} \cdot S_{\mathrm{NO,e}}(t) + \beta_{\mathrm{BOD5}} \cdot BOD_{5,\mathrm{e}}(t) \end{pmatrix} \cdot Q_{\mathrm{e}}(t) \cdot \mathrm{d}t \qquad (1)$$

in which the subscript e denotes the effluent, T is the total evaluation period and all concentrations are expressed in mg/L units. The weighting factors for different effluent concentrations are: $\beta_{TSS} = 72$, $\beta_{COD} = 1$, $\beta_{TKN} = 20$, $\beta_{NO} = 20$ and $\beta_{BOD5} = 2$. The second main criterion is the operational cost index (*OCI*):

$$OCI = AE + PE + 3 \cdot SP + 3 \cdot EC + ME - 6 \cdot MP + \max(0, HE^{net}) \qquad (2)$$

where *AE* represents aeration energy (kWh/d), *PE* is pumping energy (kWh/d), *SP* is sludge production for disposal (average kg TSS/d), *EC* is external carbon addition (average kg COD/d), *ME* is mixing energy (kWh/d), *MP* stands for methane production (average kg CH_4/d) and HE^{net} is the net heating energy needed to heat the sludge in the anaerobic digester. The *AE*, *PE* and *ME* are in turn calculated based on more specific models. Influent pumping is not included in the *PE* as this value would be identical for any control strategy. A gas motor (or micro turbine) is assumed to be available for immediate electricity and heat production (in turn used to heat the AD) from the available methane. The *PE* has been considerably modified from the BSM1 definition and now assigns individual energy consumption for different pumps/flows. *ME*, *MP* and HE^{net} did not exist in BSM1.

Further evaluation criteria include the percentages of time when effluent limits are violated. The effluent limits are defined as: $N_{tot,e} < 18\,\mathrm{g\ N/m^3}$, $COD_e < 100\,\mathrm{g\ COD/m^3}$, $S_{NH,e} < 4\,\mathrm{g\ N/m^3}$, $TSS_e < 30\,\mathrm{g\ TSS/m^3}$ and $BOD_{5,e} < 10\,\mathrm{g\ BOD_5/m^3}$. Finally, the 95th percentiles of the effluent ammonia $S_{NH,e95}$, total nitrogen $N_{tot,e95}$ and total suspended solids TSS_{e95} concentrations should be reported. These percentiles represent the S_{NH}, N_{tot} and *TSS* effluent concentrations that are exceeded 5% of the evaluation time. A detailed description of all BSM2 evaluation criteria can be found in Vrecko *et al.* (2007).

BSM2 modifications

Essentially all proposals and concepts for extending the BSM1 into BSM2 presented at Watermatex2004 (Jeppsson *et al.*, 2006) have now been realized, implemented and verified in accordance with the plan. Some clarifications and updates related to the BSM2 protocol were presented in the previous section and below some special attention is given to a few concepts that have changed in a more fundamental way.

ADM1 for BSM2

The anaerobic digester of BSM2 is modelled using the ADM1 of Batstone *et al.* (2002). However, due to the computational burden of simulating a large model such as BSM2, the original ADM1 has been modified to optimize the simulation performance. An important difference between the ADM1 of Batstone *et al.* (2002) and the ADM1 for BSM2 is the introduction of continuous inhibition functions for pH to avoid simulation problems related to discontinuities. Also, an effort regarding the fate of nitrogen and COD in order to completely close the mass balances for the model has been made. In Batstone *et al.* (2002), it is suggested that the ADM1 is implemented as a differential algebraic system, with algebraic equations for the acid-base equilibrium (although differential equations are also given in the report). This is, however, not sufficient to remove the stiffness of the system while it has been discovered that the hydrogen state is much faster than the remaining states. Therefore, an algebraic solution of the hydrogen state has been implemented. This is important since at least some simulation platforms need to use non-stiff solvers to handle the noise and discrete events introduced for realism in BSM2. Detailed descriptions of the BSM2 implementation of ADM1 are given in Rosen *et al.* (2006) and Rosen and Jeppsson (2006).

ASM1/ADM1 model interfaces

Interfacing the state variables in the activated sludge system models with the ones of the anaerobic digester models and vice versa has been an important issue to resolve when coupling both systems. The interfacing problem has seen considerable attention in recent years and several proposals for consistent interfaces have been proposed, focusing on guaranteeing mass continuity. In BSM2, the original interface proposed by Copp *et al.* (2003) has been adopted after some important modifications that are reported in detail in Nopens *et al.* (2007). These modifications allow the interface to deal with the differences in primary and secondary sludge composition (and the concomitant differences in biogas yields), to guarantee charge continuity, to reduce the accumulation of inerts in the system. It means that (i) X_S and biomass fractions are treated differently, (ii) mapping no longer leads to composite material (X_C) in ADM1 but rather directly into lipids, carbohydrates and proteins, omitting the disintegration step and (iii) inorganic carbon can be calculated directly at this so-called modified Copp-interface (Nopens *et al.*, 2007).

Temperature dependency

Temperature is included as an additional state in the influent model (Gernaey *et al.*, 2005; 2006). Two types of temperature phenomena are modelled. The seasonal temperature variations are implemented as a sine wave with a period of 364 days, an average value of 15 °C and an amplitude of 5 °C. The minimum influent temperature is reached around 30 January, the maximum influent temperature is reached around 30 July. A diurnal influent temperature profile is also included, and is implemented as a sine wave with a period of 1 day and an amplitude of 0.5 °C. As a result of the diurnal influent temperature variations, the influent temperature is lowest in the early morning and highest in the late afternoon.

The effect of temperature on the biological kinetics is taken into account as described in Henze *et al.* (1987). The oxygen transfer coefficient varies with temperature according to the following equation:

$$K_La(T) = 1.024^{(T-15)} \cdot K_La(15\,^\circ C) \tag{3}$$

with K_La in d^{-1} and T in °C. Solubility of oxygen decreases with decreasing temperature. The semi-empirical function proposed in Lide *et al.* (2004), based on the van't Hoff equation is used. The oxygen equilibrium constant K ($\mathrm{M.bar}^{-1}$) varies with temperature as

$$K(T) = S_{O,\mathrm{liq}}/S_{O,\mathrm{gas}} = 56.12e^{A+B/T^*+C\ln T^*} \tag{4}$$

where $T* = (T + 273.15)/100$, $A = -66.7354$, $B = 87.4755$ $C = 24.4526$. This gives finally, after normalization to maintain consistency with BSM1 (i.e. $S_O^{\mathrm{sat}} = 8\,\mathrm{mg.L}^{-1}$ at 15 °C) the following relation for S_O^{sat}(in mg/L):

$$S_O^{\mathrm{sat}}(T) = (8/10.5) \cdot 6791.5 \cdot K(T) \tag{5}$$

Temperature dynamics in each reactor with a defined volume are finally modelled by a first-order system based on the 'heat' content ($T \cdot V$) of the wastewater and assuming completely mixed conditions, except for the digester, for which the temperature is fixed at 35 °C.

Reject water storage tank

A storage tank for process water (nitrogen-rich supernatant from sludge dewatering) has been added to allow for dosage of this influent source to the biological step (either to the inlet of the primary clarifier or the inlet to the AS system). The tank is modelled as a completely mixed tank reactor (CSTR) without describing any biological or settling processes. A pump is utilized to transport the water from the storage tank to the biological step. Special measures to deal with improper operation like the complete emptying or overflowing of the tank are part of the model. The volume of the storage tank represents a hydraulic retention time of one day based on the average supernatant flow rate and the maximum pump capacity is defined to ten times this flow rate. The role of storage tank is to be an available control handle rather than a part of a specialized supernatant treatment system. The main role of such a manipulated variable is to reduce peak ammonia loads to the AS system.

Ring test verification

All models of BSM2 have now been extensively and successfully tested and verified by independent implementations using several simulation platforms. Every individual process model was first verified in stand-alone tests and results evaluated based on statistical measures and comparisons of absolute values. The complete BSM2 system including the evaluation criteria calculations was then verified for both steady state and dynamic conditions (open loop as well as closed loop simulations). For the purpose of objective comparisons of control strategies it is essential that the benchmark results are not in any way platform dependent and that all model implementations can be trusted.

Case study

To investigate how the evaluation criteria capture various operational conditions, the complete BSM2 protocol has been applied and the system simulated for 20–25 simple cases, both with and without active controllers. Twelve of these cases are presented below. Although based on a preliminary version of BSM2, Vrecko *et al.* (2006) presented an initial study of two base cases, and in Flores *et al.* (2007) eleven control strategies are evaluated using a more recent BSM2 version and the results are further analysed using multivariable statistical techniques. In Gernaey *et al.* (2007), the BSM1 system behaviour is investigated using more than ten different test cases with a focus on potential differences between one-week and one-year evaluation periods. The purpose of this evaluation is not to describe or present any relevant control strategies but to determine advantages and weaknesses in the BSM2 protocol in general and in the defined evaluation criteria in particular. Consequently, the operational strategies are only briefly described and no details of the controllers are specified.

The selected reference case is the following strategy (standard nomenclature, $R_x =$ AS reactor no x): $Q_w = 210\,\mathrm{m^3/d}$ (constant, from settler), $Q_{intr} = 60{,}000\,\mathrm{m^3/d}$ (constant, from R_5 to R_1), $Q_r = Q_{in}$ (proportional, into R_1), $Q_{carb} = 1\,\mathrm{m^3/d}$ (constant into R_1, COD source of 400,000 mg/l), no bypassing or step feed, no use of reject water storage tank (direct flow through), thickener effluent and reject water return to primary clarifier, aeration control based on a DO sensor in R_4 (set point 2 mg/l) and identical K_La input into R_3 and R_5. In Table 1, only the differences in comparison with the reference case are given for the other test cases.

S11 is often referred to as the BSM2 open loop reference case and is added for comparison. In Table 2, values for the main evaluation criteria are given for all cases and also the yearly average effluent concentrations of ammonia, nitrate and total nitrogen are included.

It is clear that none of the presented cases is capable of maintaining the effluent limits at all times (based on measurements every 15 minutes and not on average values). The correlation between *SP* and *MP* is strong for the above cases – more gas is produced as a result of higher sludge input to the AD leading to more sludge to be disposed of. The value for *EC* will be highly dependent on each specific control strategy. *ME* and *PE* are fairly constant but *PE* will to some extent depend on the applied control (*ME* will be constant unless a switch of anoxic/aerobic volumes is made or extremely low level aeration is utilized). The dominating factor determining the overall *OCI* is clearly the aeration energy. By reducing *AE* (cases S4 and S10) the *OCI* can be significantly reduced while still maintaining a fairly good *EQI* (ranking 3 and 2, respectively). If only *OCI* and *EQI* are considered most readers would suggest that S10 is the best overall strategy – and it probably is – among the simple cases shown here (see also Figure 2, left). However, looking also at the yearly average effluent concentrations of ammonia, nitrate and total nitrogen a potential problem becomes apparent. The 'best' strategies all release significantly more ammonia. As the weights in the *EQI* calculation (see Equation 1) are identical for Kjeldahl nitrogen and

Table 1 Overview of presented operational strategies

Strategy	Description
RC	Reference case (see above)
S1	Sludge age control by manipulating Q_w (based on wastewater temperature and look-up table)
S2	Individual reactor DO control (3DO, set points 2, 2 and 1.5 mg/l, respectively)
S3	Combination of S1 and S2
S4	Individual reactor DO control (3DO, set points 1, 1 and 1 mg/l, respectively) and S1
S5	25% of influent wastewater flow bypassed primary clarifier at all times
S6	25% of influent wastewater flow bypassed primary clarifier, active from 11 am to 20 pm every day
S7	Reject water storage tank emptied during day time
S8	Reject water storage tank emptied during night time
S9	Cascade: S_{NH} control in R_5 (set point 1 mg N/l) by manipulating DO set points in R_3, R_4 and R_5
S10	Cascade: S_{NH} control in R_5 (set point 6 mg N/l) by manipulating DO set points in R_3, R_4 and R_5
S11	$Q_{intr} = 55{,}338\,\mathrm{m^3/d}$; $Q_w = 300\,\mathrm{m^3/d}$; $Q_r = 18{,}446\,\mathrm{m^3/d}$; $Q_{carb} = 2\,\mathrm{m^3/d}$; $K_La_3 = K_La_4 = K_La_5 = 240$ 1/d

Table 2 Evaluation criteria results for presented test cases

Evaluation criteria	EQI (kg/d)	OCI (1/d)	AE (kWh/d)	PE (kWh/d)	SP (kgSS/d)	EC (kgCOD/d)	ME (kWh/d)	MP (kgCH$_4$/d)
RC	13,914	13,158	10,062	424	2,427	400	648	1,076
S1	13,678	13,389	9,756	430	2,608	400	648	1,078
S2	14,165	12,479	9,277	423	2,318	400	648	1,004
S3	13,304	12,762	9,129	430	2,608	400	648	1,078
S4	12,670	10,270	6,880	431	2,654	400	648	1,142
S5	15,192	13,263	9,962	421	2,191	400	648	924
S6	14,457	13,249	10,047	423	2,318	400	648	1,004
S7	13,900	12,469	9,329	423	2,427	400	648	1,069
S8	14,000	13,458	10,320	423	2,429	400	648	1,070
S9	13,009	12,559	9,408	424	2,446	400	648	1,077
S10	11,896	10,664	7,511	424	2,447	400	648	1,077
S11	10,996	13,347	8,548	398	2,783	800	648	1,166

Evaluation Criteria	TN_{e95} (gN/m^3)	$S_{NH,e95}$ (gN/m^3)	TSS_{e95} (g/m^3)	$T_{viol}TN_e$ (%)	$T_{viol}S_{NH,e}$ (%)	$T_{viol}TSS_e$ (%)	$S_{NH,e,av}$ (gN/m^3)	$S_{NO,e,av}$ (gN/m^3)	$TN_{e,av}$ (gN/m^3)
RC	31.2	11.2	53.9	97.1	26.7	11.0	3.1	18.6	25.8
S1	32.0	12.8	53.7	98.5	38.8	10.2	4.4	18.3	26.2
S2	30.7	13.3	69.4	92.0	33.7	15.5	4.0	15.7	24.6
S3	31.0	13.3	53.5	97.7	41.3	10.2	4.7	17.1	25.3
S4	30.3	18.3	38.6	97.2	59.5	7.6	7.5	14.2	23.7
S5	32.2	15.3	88.4	87.5	37.9	22.5	4.7	14.3	25.0
S6	31.4	12.7	69.5	94.5	31.9	15.5	3.7	16.6	25.3
S7	38.2	20.5	53.1	81.2	39.7	10.9	5.8	16.0	25.8
S8	35.9	8.8	54.1	80.7	16.2	11.0	2.3	19.6	25.9
S9	31.1	9.5	53.3	79.0	21.4	11.1	2.7	16.7	23.5
S10	31.3	17.8	52.2	77.8	100	10.7	6.9	9.8	20.8
S11	28.8	15.5	20.9	81.5	56.6	1.1	6.3	13.3	22.0

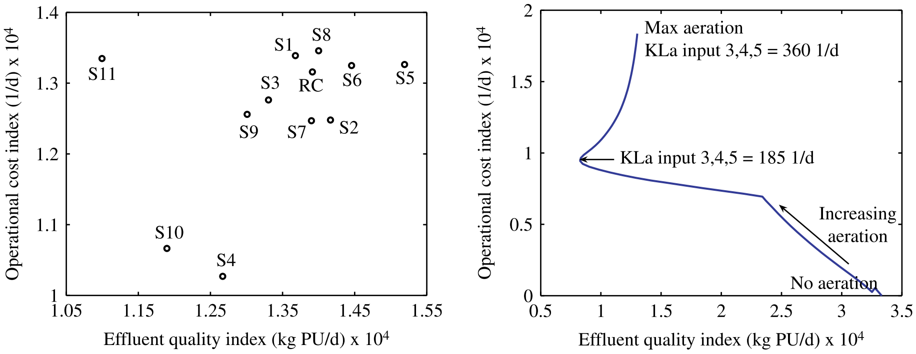

Figure 2 Operational strategy evaluation, *EQI* vs *OCI* for all test cases (left) and *EQI* vs *OCI* for the reference case as a function of aeration intensity (right)

nitrate, there is certainly no incentive to nitrify any more ammonia than can be reduced by denitrification, i.e. limited aeration and consequently a low *OCI*. If cases S9 and S10 are compared this is evident: S9 prioritizes nitrification and S10 almost minimizes 'unnecessary' nitrification, leading to considerably better *OCI* and *EQI* for S10.

To demonstrate the above issue further, Figure 2 (right) shows simulations using a constant influent wastewater (average of the one-year evaluation period) of the above reference case with one exception. The aeration input ($K_La_{3,4,5}$ set to constant values) varies from zero to its maximum value in small steps and for every simulation the *EQI* and *OCI* are calculated. As the input data are not identical to what was used previously the absolute values differs slightly but the effect is clearly visible. The *OCI* increases as a result of intensified aeration but the *EQI* demonstrates a clear optimum (keeping in mind that all other control handles remain unchanged). Any attempt to aerate the BSM2 system above this level would lead to higher operational costs and a reduced effluent quality (in terms of *EQI*). This effect will play a dominant role for any BSM2 control strategy.

There are many possibilities to slightly adjust the evaluation criteria to overcome this potential problem, if need be. One solution would be to require any valid control strategy to comply with the effluent limits on an hourly, weekly or yearly average (to comply 100% on a 15-minute basis may be impossible). However, this would lead to a situation where the optimum control strategy would imply remaining as close as possible to the effluent limits in the smartest possible way – which may certainly be realistic. Modifying the weights of the *EQI* to create an incentive for increased nitrification is another alternative, which may well be combined with the above effluent requirements to possibly promote control strategies reducing the ammonia concentration also below the effluent limit.

Another potential problem is related to the loading of the BSM2 plant. A decade ago, when development of BSM1 was initiated, it was decided that the most interesting case to analyse and control would be a high(over)-loaded AS plant. Also BSM2 is very highly loaded (the AS part) as it retains the features of BSM1. When a plant has too limited capacity there are limits of what can be accomplished by active control. The available actuators (e.g. pumps and aeration system) cannot be operated above their maximum capacity regardless of the controllers and very little can then be done, for example, to eliminate peaks in the influent load. At best, the control strategy will always be a compromise between effluent quality and operational costs since the performance of the high-loaded plant can basically only be improved by higher energy input, up to a certain limit. For a WWTP with some available capacity a good control strategy will instead focus on maintaining high effluent quality in the smartest possible way by utilizing the flexible control authority (as actuators are not saturated) and thereby maintaining high effluent quality while *reducing* operating costs. Due to the extensive testing of BSM1 and BSM2, the task group has also defined an extremely good (somewhat unrealistic) way to operate the plant without any control actions needed, which is shown in S11. It actually requires a significant effort simply to improve the BSM2 open loop reference case by using control. The above situation requires some further attention by the TG but may be resolved either by increasing the AS volume, modifying the reaction rates (not an attractive option at this stage), by reducing the predefined influent wastewater load or a combination of all. The above alternatives for slightly modifying BSM2 are currently being investigated and analysed by the task group. Potentially, both a high-loaded and a low(or normal)-loaded case could be made available.

What some of other cases show is that changing one control handle while maintaining all others intact, as done in this paper to simplify the strategy descriptions, does often not have much effect and may lead to worse overall performance of a plant. This is the problem of sub-optimization. It is essential to consider the entire plant and apply combinations of control. As no sophisticated plant-wide control strategy is applied here only limited effects of potential benefits can be found. However, case S8 demonstrates how a simple time-based pumping control of the reject water storage tank has significant effects of the effluent ammonia concentration (by reducing peak loads). This benefit does not show in *OCI* and *EQI* primarily because this strategy should be used in combination with other control modifications of the reference case. Many more detailed conclusions can be drawn but the intent of this case study is only to serve as a preliminary illustration.

Conclusions

The Benchmark Simulation Model No 2, which allows for the evaluation of plant-wide control strategies, is now essentially complete and will soon be available for wider distribution to interested groups within the wastewater community. BSM2 is implemented on a number of simulation platforms, which will enhance and simplify its future use. Some fine-tuning of the evaluation criteria and the influent wastewater characteristics may still be required but all main components of the system have now been verified and evaluated. The extended evaluation period offers a more realistic framework for analysing the impact on the plant performance over a much wider range of operating conditions. The inclusion of primary treatment as well as sludge treatment increases the complexity of the system but more importantly creates the necessary interactions between the different sub-processes, thereby requiring control strategies to consider the entire WWTP and promote the use of plant-wide control.

Although it is not difficult to identify new potential avenues for future BSM development, such as inclusion of chemical precipitation, enhanced biological phosphorus removal, biological activity in all sub-systems, new processes, adaptive sludge characteristics as a function of operational parameters, the main role of the TG will now be to consolidate and document its developments of BSM1, BSM1_LT and BSM2.

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