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Benchmark Simulation Model No 2: finalisation of plant layout and default control strategy

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ABSTRACT

The COST/IWA Benchmark Simulation Model No 1 (BSM1) has been available for almost a decade. Its primary purpose has been to create a platform for control strategy benchmarking of activated sludge processes. The fact that the research work related to the benchmark simulation models has resulted in more than 300 publications worldwide demonstrates the interest in and need of such tools within the research community. Recent efforts within the IWA Task Group on "Benchmarking of control strategies for WWTPs" have focused on an extension of the benchmark simulation model. This extension aims at facilitating control strategy development and performance evaluation at a plant-wide level and, consequently, includes both pretreatment of wastewater as well as the processes describing sludge treatment. The motivation for the extension is the increasing interest and need to operate and control wastewater treatment systems not only at an individual process level but also on a plant-wide basis. To facilitate the changes, the evaluation period has been extended to one year. A prolonged evaluation period allows for long-term control strategies to be assessed and enables the use of control handles that cannot be evaluated in a realistic fashion in the one week BSM1 evaluation period. In this paper, the finalised plant layout is summarised and, as was done for BSM1, a default control strategy is proposed. A demonstration of how BSM2 can be used to evaluate control strategies is also given.

Key words | benchmarking, BSM2, control, evaluation criteria, plant-wide modelling, simulation, wastewater treatment

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INTRODUCTION

The use of a benchmark for assessment of process performance, control system evaluation, etc. is well established within chemical engineering and research. The success of the COST/IWA Benchmark Simulation Model No 1 (BSM1, e.g. Spanjers *et al.* 1998; Copp 2002; Jeppsson & Pons 2004) for control strategy development and evaluation clearly indicates the usefulness of such a tool for the wastewater research community.

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During the last decade the importance of integrated and plant-wide control has been emphasised by the chemical engineering research community (Downs & Skogestad 2009), and the wastewater industry is starting to realise the benefits of such an approach. A WWTP should be considered as a unit, where primary/secondary clarification units, activated sludge reactors, anaerobic digesters, thickeners, dewatering systems, etc. are linked together and need to be operated and controlled not only on a local level as individual processes but by supervisory systems taking into account all the interactions between the processes. Otherwise, sub-optimal performance will be an unavoidable outcome leading to reduced effluent quality and/or higher operational costs.

Recently proposed extended benchmark systems like BSM1_LT (Rosen *et al.* 2004) and BSM2 (Jeppsson *et al.* 2006) were developed to take the issues stated above into account.

Jeppsson *et al.* (2007) performed exploratory test studies to evaluate the behaviour of the proposed BSM2. That study concluded that both evaluation criteria and system loading required additional work. This paper addresses the shortcomings stipulated by Jeppsson *et al.* (2007) and describes the finalised plant layout for BSM2. Moreover, as was done for BSM1, a default control strategy is proposed and a demonstration is given on how the BSM2 can be used to evaluate control strategies.

FINALISATION OF THE BSM2 PLANT LAYOUT AND PERFORMANCE CRITERIA

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 WWTPs. The on-going research and development of BSM2 is being performed within the framework of the IWA Task Group on Benchmarking of Control Strategies for WWTPs, established in 2005 (see www.benchmarkwwtp.org). 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). Since then, the development has continued and a more complete version was presented at Watermatex2007 (Jeppsson *et al.* 2007). That paper included about 15 simple demonstration cases, both with and without active controllers, and was aimed at investigating how the evaluation criteria captured various operational conditions. It was revealed that (1) the evaluation criteria were not very sensitive to the different tested cases and (2) the very highly loaded system, which was deliberately adopted, limits what can be accomplished by active control. Indeed, the study showed that active control has its limitations and will not be able to significantly improve the performance of a highly overloaded plant. One reason for this high overloading is the extra nitrogen (N) load coming from the reject water, which was not present or accounted for in the BSM1 case.

Based on the above findings, some modifications to the plant layout and evaluation criteria were adopted for the BSM2.

Final modifications of the plant layout

To overcome the problem related to the overloading of the plant (as defined by $g\,d^{-1}\,m^{-3}$ of aeration volume) and make the BSM2 more interesting from a control perspective, the load on the activated sludge process was decreased. Two actions were undertaken to decrease it. First, the incoming wastewater nitrogen load was reduced by 15% (approximately offsetting the load from the recycled reject water in BSM2). The second action involved re-evaluating the tank volumes. To do this, the design guidelines from both the German Association for Water Economy, Wastewater and Waste (ATV A131 2000) and US Environmental Protection Agency (Harris *et al.* 1982) were used. Both guidelines suggested that the aerobic volume should be increased by approximately a factor 2.5. The investigation led to an agreement on an increase of the tank volumes. Anoxic tanks were increased from 1,000 m^3 to 1,500 m^3, aerobic tanks from 1,333 m^3 to 3,000 m^3, resulting in a total plant volume increase from 6,000 m^3 to 12,000 m^3. Owing to these changes also some flow rates had to be updated to maintain a reasonable sludge residence time (SRT): the recycle flow rate Q_r was changed to 20,648 $m^3\,d^{-1}$ (i.e. the same as the average incoming flow rate); the internal recirculation rate was changed to 3 times the average incoming flow (61,944 $m^3\,d^{-1}$). These changes also resulted in changes in certain plant specifications. The hydraulic residence time (HRT) of the primary clarifier decreased from 1.2 h to 1 h, whereas the overall (aerobic + anoxic) HRT of the biological reactors was increased from 8 h to 14 h while the sludge loading to the secondary clarifier increased from 0.5 $m\,h^{-1}$ to 0.6 $m\,h^{-1}$. The volume changes also required an update of the K_La coefficients in the aerobic tanks. These were modified to 120 d^{-1} for tanks 3 and 4 and to 60 d^{-1} for tank 5. Keen observers will note that these changes also caused a drop in the SRT of the anaerobic digester from 20 to 19 d. The final plant layout including these changes is depicted in Figure 1.

The main simulation platforms in which a ring-tested BSM2 implementation is available to date are SIMBA®, WEST®, FORTRAN and MATLAB®/SIMULINK®. The ring test was performed in a series of steps. In the first step, the different unit process models (primary clarifier, BSM1 system, thickener, ASM2ADM interface, digester, ADM2ASM interface and dewatering unit) were implemented and tested in isolation. Once the accurate implementation of the individual models was verified, the entire BSM2 was successfully ring tested at steady state, both verifying the outputs of the different unit processes and the EQI and OCI criteria (see below). The implementations were then tested dynamically in open loop (without controllers) using an evaluation period of one year followed by a closed-loop evaluation using the same one year period. As was expected, dynamic differences larger than the ones of the steady state verification were observed between the platforms, but these differences were still in an acceptable range. Detailed results of the ring test will be made available in the upcoming IWA Scientific and Technical Report on benchmarking (Gernaey *et al.* in preparation).

Final modifications of the performance criteria

Two issues arose with regard to the Effluent Quality Index (EQI) and the Operational Cost Index (OCI): (1) originally, there was no difference between the contribution of nitrate and ammonium (OCI), although it is known that the latter is more harmful for the environment (Camargo & Alonso 2006) and (2) aeration was found to dominate the OCI, which has a significant impact on the evaluation process.

For the handling of the first issue, the EQI equation is reproduced for the reader's sake:

$$EQI = \frac{1}{1000 t_{obs}} \int_{t_{start}}^{t_{end}} [PU_{TSS}(t) + PU_{COD}(t) + PU_{BOD}(t) + PU_{TKN}(t) + PU_{NO}(t)] Q_e(t)\, dt,$$

where t_{obs} represents the total evaluation time and the pollution units PU_{xxx} are calculated as the product of

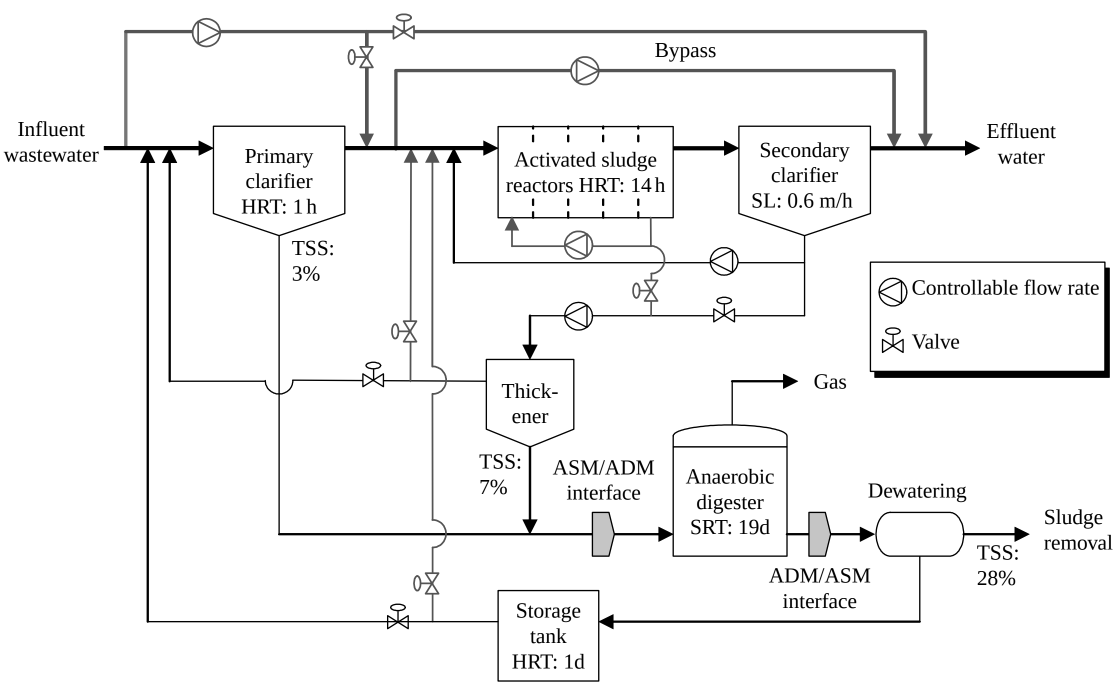

Figure 1 | New finalised plant layout for BSM2.

weights β_{xxx} and the concentration of compound XXX at time (t). The weights β_{xxx} were determined based, in part, on empirical effluent component weightings from a paper by Vanrolleghem *et al.* (1996). Jeppsson *et al.* (2007) showed that the original criterion (EQI) does not reward–from an environmental perspective–any effort to go below the effluent limits for ammonium (i.e. identical β for TKN and nitrate nitrogen (S_{NO}) = 20). Therefore, for better agreement with ecological aspects related to discharge of ammonium (S_{NH}) versus S_{NO}, the weights in the EQI-expression were changed from 20 to 30 for TKN and from 20 to 10 for S_{NO}. Finally, the BOD of any bypassed water is computed as 65% of the biodegradable COD, whereas that in the settler effluent only contains 25% BOD_5.

For the handling of the second issue, the OCI equation is reproduced:

$$OCI = AE + PE + 3\cdot SP + 3\cdot EC + ME - 6\cdot MP + HE^{net}$$

where AE represents aeration energy, PE is pumping energy, SP is sludge production for disposal, EC is external carbon addition, ME is mixing energy, MP represents methane production and HE^{net} is the net heating energy needed to heat the sludge in the anaerobic digester (normally zero thanks to available heat generated by the electricity production from methane). AE, PE and ME are calculated based on specific sub-models.

To address the aforementioned dominating impact of aeration, the expression to compute the contribution of aeration was changed from the original empirical equation that directly related the oxygen transfer coefficient (K_La) to aeration energy (AE) into a widely accepted expression that physically describes the Oxygen Transfer Rate (OTR) and relates the latter to power consumption based on engineering understanding. The OTR [$kg\,O_2\,d^{-1}$] is defined as:

$$OTR = V\cdot K_La_{15}(S_{Osat,15} - 0)/1000$$

Assuming a transfer efficiency of 1.8 kg oxygen per kWh used, the new AE [$kWh\,d^{-1}$] becomes:

$$AE = \frac{S_{Osat,15}}{t_{obs}\cdot 1.8\cdot 1000}\int_{t_{start}}^{t_{end}}\sum_{i=1}^{5} V_{as,i}\cdot K_La_{i,15}(t)\,dt$$

For reasons of completeness and the reader's sake, evaluation criteria that were not changed include the percentages of time when effluent limits are violated. The effluent limits are defined as: $N_{tot,e} < 18\,g\,N\,m^{-3}$, $COD_e < 100\,g\,COD\,m^{-3}$, $S_{NH,e} < 4\,g\,N\,m^{-3}$, $TSS_e < 30\,g\,TSS\,m^{-3}$ and $BOD_{5,e} < 10\,g\,BOD_5\,m^{-3}$. 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 those S_{NH}, N_{tot} and TSS effluent concentrations that are exceeded during 5% of the evaluation time. A detailed description of all BSM2 evaluation criteria can be found in Gernaey *et al.* (2010).

SIMULATION PROCEDURE

The simulation procedure for BSM2 is described in detail in Jeppsson *et al.* (2007) and will not be repeated here as no changes to the procedure were made.

BSM2 OPEN-LOOP PERFORMANCE

In order to evaluate these changes to the plant and the evaluation criteria, the new open loop case (referred to as new OL), i.e. without any control actions was simulated and compared to the one without the previously described modifications (referred to as old OL). The results are summarised in Table 1. First, the impact of the modified EQI, AE and OCI can be seen from the bracketed values which indicate the values obtained with the old expressions. The EQI drops by about 900 PU due to the change in weights of TKN and S_{NO}. AE is about half using the new expression, which decreases its contribution in the OCI from 56 to 43% for the new OL case.

Results show that the new plant design performed significantly better in open-loop compared to the old open loop. The Effluent Quality Index (EQI) decreased by 44%, mainly because of better TN removal. Effluent S_{NH} ($S_{NH,e}$) violations, being the percentage of time $S_{NH,e}$ exceeds $4\,g\,N\,m^{-3}$, are reduced by 85% and the average effluent S_{NH} is reduced as well. Moreover, this improvement does not deteriorate the level of $S_{NO,e}$ as was observed to be the trade-off (either sacrifice on $S_{NH,e}$ or on $S_{NO,e}$) in Jeppsson *et al.* (2007). Furthermore, the increased anoxic volume

Table 1 | Simulation results for different open loop (OL) and closed loop (CL) cases

	Unit	Old OL	New OL	Def CL	CL1	CL2
EQI	–	*10027 (11000)**	*5661 (6435)**	*5577*	*5447*	*5274*
Av $S_{NH,e}$	$g\,N.m^{-3}$	6.24	1.65	0.47	0.48	1.11
Av $S_{NO,e}$	$g\,N.m^{-3}$	13.33	7.47	11.05	10.40	7.85
Av TSS_e	$g\,COD.m^{-3}$	17.16	15.90	15.17	15.17	14.92
Av TN_e	$g\,N.m^{-3}$	21.94	11.20	13.53	12.89	10.94
Av $COD_{tot,e}$	$g\,COD.m^{-3}$	51.94	50.06	49.02	49.03	48.78
Av $BOD_{5,e}$	$g\,BOD.m^{-3}$	3.67	2.77	2.79	2.79	2.74
OCI	–	*9085 (13368)**	*9208 (11727)**	*9450*	*9348*	*8052*
SP	$kg{\cdot}d^{-1}$	3143	2980	3021	3021	2961
AE	$kWh{\cdot}d^{-1}$	4266 (8548)*	4000 (6519)*	4225	4121	3848
ME	$kWh{\cdot}d^{-1}$	648	768	768	770	1039
PE	$kWh{\cdot}d^{-1}$	398	442	445	445	445
MP	$kg\,CH_4{\cdot}d^{-1}$	1165	1059	1085	1085	1073
EC	$kg\,COD\,d^{-1}$	800	800	800	*800*	*400*
S_{NH} violation	% of time	56.54	8.27	0.41	0.29	0.23
av. $S_{O,as,5}$	$g\,(\text{-COD}){\cdot}m^{-3}$	2.54	1.21	1.57	1	0.18
min $S_{O,as,5}$	$g\,(\text{-COD}){\cdot}m^{-3}$	0.43	0.10	0.49	0.38	0.02
max $S_{O,as,5}$	$g\,(\text{-COD}){\cdot}m^{-3}$	5.99	4.40	2.57	1.58	3.23

*The values between brackets represent the values calculated using the obsolete expressions for EQI, AE and OCI as specified in Jeppsson et al. (2007).

improves denitrification. The OCI does not change significantly although it can be seen that this is a combination of different effects brought about by the volume changes: lower sludge production, lower aeration energy, higher mixing energy (due to larger anoxic volumes), higher pumping energy and less methane production. Especially the reduced percentage of S_{NH} violations opens perspectives for control.

Time series of DO in the 4th tank and the effluent ammonia are illustrated in Figure 2 for the new OL. It shows that the oxygen concentration in the bioreactor is not adequate, poor during daytime when the plant is highly loaded (with DO decreasing below 1 $g.m^{-3}$) and excessive at night (DO reaching concentration of almost 4 $g.m^{-3}$). Moreover, it is highly inefficient in nitrification.

BSM2 DEFAULT CONTROL STRATEGY

To illustrate the use of BSM2, a default control strategy has been developed with the aim to demonstrate the potential for control actions to improve plant performance. It should be stressed that this proposed control strategy does not represent the best strategy available. It is intended to provide a simple example of how the benchmark can be used to develop novel plant-wide control strategies.

The default closed-loop configuration (def CL) of BSM2 consists of a Proportional-Integral (PI) dissolved oxygen (DO) controller that controls the DO set point in tank 4 to $2\,g\,O_2\,m^{-3}$ by manipulating K_La_3, K_La_4 and K_La_5 with K_La_5 set to half the value of K_La_3 and K_La_4. Controller parameters are not reported as they differ between platforms depending on the controller implementation (as was the case for BSM1 as well). The control loop is shown in Figure 3. In all cases (including open loop) an external carbon source is fed into the first anoxic reactor at a constant flow rate of $2\,m^3\,d^{-1}$ (COD concentration $= 400.000\,g\,m^{-3}$) except for CL2 where this flow rate is reduced to $1\,m^3\,d^{-1}$. Moreover, for all closed-loop cases a timer based control is active for the recycled sludge flow rate to adapt the plant to seasonal variations. When the temperature of the influent wastewater is below 15°C, Q_w is set to $300\,m^3\,d^{-1}$ (i.e. for $t = 0-181$ days and $t = 364-454$ days), and when the temperature is

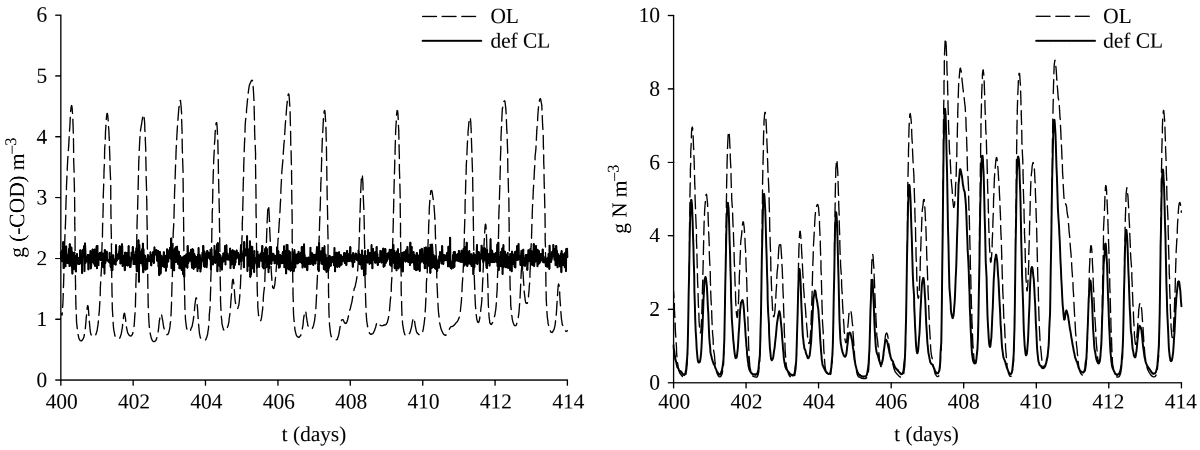

Figure 2 | Dynamics of DO in tank 4 (left) and effluent ammonia concentration (right) for the BSM2 open-loop (new OL) and default control strategy (def CL).

above 15 °C, Q_w is set to 450 m^3 d^{-1} (i.e. for the remaining time periods).

The results for the BSM2 default control strategy are summarised in Table 1. It can be seen that the strategy leads to a slightly better EQI compared to the new open-loop case. This is mainly related to the decrease in effluent S_{NH}. However, this improvement requires additional aeration, which increases the calculated OCI. From Table 1, it can be seen that, on average, more DO is supplied in the "def CL" system (average S_O in tank 5 = 1.57 g m^{-3} versus 1.21 g m^{-3} for new OL).

To illustrate the effect of this simple control strategy on process variables compared to the new open-loop case, time series of the DO in the 4th tank and the effluent ammonia concentration are presented in Figure 2. The addition of a DO controller, ensures constant DO and thus decreases the peaks in effluent ammonia concentration.

TESTING OF ALTERNATIVE CONTROL STRATEGIES USING BSM2

In order to further test BSM2 and to provide an example of how to use the new benchmark some other simple control strategies were tested. The first control strategy that was evaluated (CL1) consists of a combination of two PI DO-controllers. The first one controls the DO set point in tank 4 to 2 g m^{-3} by manipulating K_La_3 and K_La_4. The second one controls the DO set point in tank 5 to 1 g m^{-3} by manipulating K_La_5. The control loop is shown in Figure 4.

This strategy aims at reducing the excessive amount of oxygen used in tank 5 for the default closed-loop case (max $S_{O,as,5}$ of 2.57 g m^{-3}). The results for this strategy are also shown in Table 1. It can be seen that the strategy further reduces the EQI. Due to better control of the DO in tank 5 (see Table 1) and, hence, less DO recycled to the anoxic tank, denitrification is improved. Also, the effluent S_{NH} violations (% of time) decreased slightly as compared to the default control case. The decoupled DO control also results in a lower OCI, mainly due to reduced aeration costs (tighter DO range and lower average DO in tank 5). However, the OCI is still higher than the open-loop case.

The second control strategy that was evaluated (CL2) consists of a PI DO-controller and a cascade S_{NH}-DO controller. The former is exactly the same as in case CL1. The latter uses a PI S_{NH}-controller to control the DO set point instead of using a fixed set point ($DO_{sp,min}$ = 0 g m^{-3}; $DO_{sp,max}$ = 3 g m^{-3}). The set point for S_{NH} in tank 5 was chosen to be 1.5 g N m^{-3}. A PI DO-controller uses this

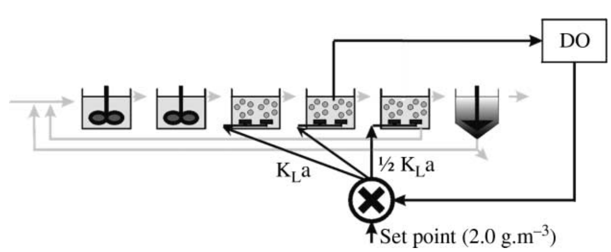

Figure 3 | Control loop used in the default BSM2 control strategy (def CL).

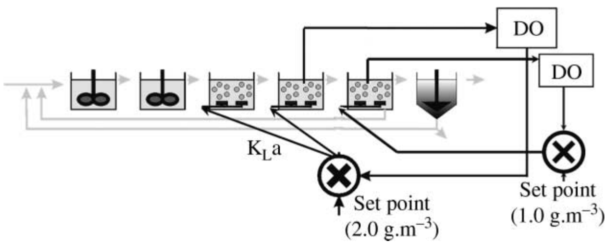

Figure 4 | Control loop used in control strategy CL1.

set point to control K_La_5. The control loop is shown in Figure 5. Moreover, as mentioned before, the carbon dosage is reduced to 1 m^3 d^{-1}.

This strategy directly controls S_{NH} instead of DO. The previous cases show that by controlling DO nitrification is essentially complete and the effluent ammonia is well below the effluent requirement. This in turn means more than necessary S_{NO} production (and carbon dosage required to keep TN below its limit) occurred and more oxygen was consumed than necessary. The strategy aims to limit this excess nitrification. Results of the strategy are also shown in Table 1. The CL2 strategy further decreases the EQI by drastically reducing S_{NO}. The results further show that the increase in average effluent S_{NH} does not lead to more violations. In this case the OCI is significantly reduced, which is a combination of different factors, but mostly driven by reduced aeration, reduced carbon dosage and reduced sludge production. Indeed, although the range of DO is broader compared to the previous two cases, the average DO is significantly reduced. This is a nice example of how control can assist in improving plant performance at no increase in cost.

It is noteworthy to acknowledge that in the BSM framework the potential costs related to effluent discharge

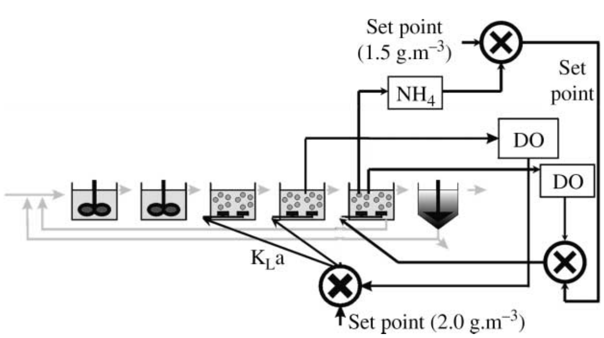

Figure 5 | Control loop used in control strategy C2.

and implementation of control loop equipment are not included. The reason for this is the regional variation in these specific costs. However, based on the computed variables, a user could easily perform these calculations based on his/her location-specific costs.

CONCLUSIONS

The finalisation of the Benchmark Simulation Model no. 2 has addressed some shortcomings in interim versions of the model. With respect to the performance indices, the weights used in the computation of the EQI were adjusted to reflect ecological considerations. The over-prediction of the aeration contribution in the total operating cost (OCI) was addressed by using a new expression. The overloading of the originally proposed plant was addressed by reducing the N-load coming to the plant (to compensate for the high N-content of the reject water) and increasing the volume of the activated sludge tanks.

These amendments resulted in an open-loop case that is more realistic for a properly designed plant with on-site sludge treatment. The EQI has been reduced by a better N_{tot} removal and the OCI remained similar as a result of several positive and negative effects that balanced out. A default control strategy has been proposed using single DO-control of tank 4. A clear improvement in EQI and S_{NH} violations was established, but at the expense of an increased OCI. Finally, two other control strategies were described to illustrate the use of BSM2. These additional case studies identified a control strategy that could reduce EQI and S_{NH} violations at significantly reduced operating cost compared to the OL case, clearly demonstrating the usefulness of control and BSM2 as an evaluation tool.

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