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Multi-criteria analysis of wastewater treatment plant design and control scenarios under uncertainty

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ABSTRACT

Wastewater treatment plant control and monitoring can help to achieve good effluent quality, in a complex, highly non-linear process. The Benchmark Simulation Model no. 2 (BSM2) is a useful tool to competitively evaluate plant-wide control on a long-term basis.

A method to conduct scenario analysis of process designs by means of Monte Carlo (MC) simulations and multi-criteria evaluation is presented. It is applied to the open loop version of BSM2 and to two closed loop versions, one with a simple oxygen controller and the other one with an ammonium controller regulating the set-point of the oxygen controller (cascade controller). The results show a much greater benefit of the cascade controller compared to the simple controller, both in environmental and economic terms. From an optimal process design point of view, the results show that the volume of the primary clarifier and the anoxic fraction of the reactor volume have an important impact on process performance.

The uncertainty analysis of the optimal designs, also performed with MC simulations, highlights the improved and more stable effluent under closed loop control.

1. Introduction

The biological, physical and chemical phenomena taking place in activated sludge systems are complex, interrelated and highly non-linear. Moreover, the operation of these systems should continuously meet effluent requirements, preferably at the lowest possible operational cost. In order to achieve this, monitoring and control of such plants can be very helpful but, given the complexity, this is not an easy task. Operators are often reluctant to test new control strategies on the real plant because of their possibly unexpected behaviour. Moreover, conventional controller design approaches do not provide objective ways of quantifying the risk involved in the decisions engineers take as they develop their designs. Process models can be used as tools for the identification and quantification of the different sources of uncertainty providing stakeholders with the ability to explicitly quantify uncertainties and include risk evaluations in their decision making process.

The Benchmark Simulation Model no. 1 (BSM1) was proposed in the nineties as a tool to foster the dissemination of control and monitoring strategies (Copp, 2002). This benchmark is a simulation environment defining a plant layout, simulation models for all process units, influent loads, test procedures and evaluation criteria. For each of these items, compromises were made to match model simplicity with reality and accepted standards. Once the user has verified the simulation code, any control strategy can be applied and the performance can be evaluated according to a well-defined set of criteria. Recently, the BSM2 (Jeppsson et al., 2007) was developed for plant-wide WWTP control strategy evaluation on a long-term basis, with a much more complex plant model, now also including a pre-treatment process and sludge treatment processes.

This paper shows the results of an uncertainty analysis (UA) performed on the BSM2 model in its open loop (without control) version and two closed loop (with control) versions, by means of Monte Carlo (MC) simulations (Benedetti et al., 2006, 2008a) and multi-criteria assessment. The parameters for which the uncertainty propagation is computed belong to the biochemical and physical models of the wastewater and sludge treatment processes.

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Five Pareto-optimal operation and design (OD) parameter sets (also found with MC simulations) for each of the three BSM2 configurations are compared based on modified BSM2 criteria and on the uncertainty of these criteria.

2. Methods

The following steps are suggested for conducting a thorough model-based evaluation of wastewater treatment alternatives, in this case applied to real-time control options:

1. Definition of alternatives
2. Definition of evaluation criteria
3. Selection of models
4. Definition of probability density functions (PDFs) for model parameters
5. Sensitivity analysis of evaluation criteria towards parameters (e.g. with MC simulations) and discard uninfluential parameters
6. Optimisation of influential OD parameters to find the best OD parameters for each alternative
7. Uncertainty analysis of optimal solution(s) for each alternative

2.1. The models

In this case, the models (step 3 of the above list) were already defined by the Benchmark Simulation Model no. 2 protocol (Jeppsson et al., 2007), which consists of a plant-wide (including wastewater and sludge treatment) model representing a general WWTP, a benchmarking procedure and a set of evaluation criteria.

The main components of the plant model (see Fig. 1) are (Jeppsson et al., 2007): primary clarification; five-reactor nitrogen removal activated sludge (AS) system, the first two anoxic and the last three aerobic; secondary clarification; gravity thickening; anaerobic digestion (AD); dewatering; AD/AS model interfaces; storage tank; influent wastewater characteristics, 609-day dynamic influent data file (data every 15 min).

The modelling and simulation software used in this work was WEST (MOSTforWATER, Kortrijk, Belgium) with its new numerical engine Tornado (Claeys et al., 2006).

2.2. Alternative process configurations

Three different configurations were tested (step 1), all with the first two of the five reactors in series set as anoxic: (1) the open loop (OL) version of BSM2, with kLa (oxygen transfer coefficient) for the three aerated tanks (kLa3, kLa4 and kLa5) respectively set to 120 d^{-1}, 120 d^{-1} and 60 d^{-1}; (2) the basic closed loop (C1) version, with kLa4 controlled to keep a set-point of Dissolved Oxygen (DO) of 2 mg/l, kLa3 set equal to kLa4 and kLa5 set to half of kLa4; (3) a more advanced closed loop (C2) version, with kLa3 and kLa4 set as in C1, but with kLa5 controlled in cascade with the DO set-point provided by a controller which sets NH_4 in Tank 5 to 1.5 mg/l.

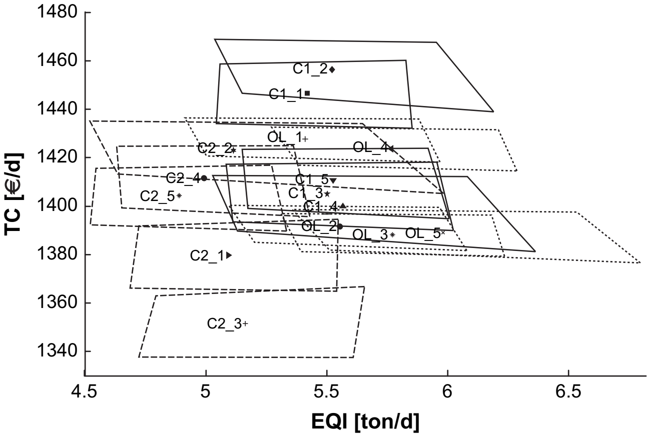

Fig. 2. Percentile polygons for EQI and TC of all optimal OL (dotted line), C1 (solid line) and C2 (dashed line) configurations.

2.3. Evaluation criteria

The five evaluation criteria (step 2) used in this work are: (1) the Effluent Quality Index (EQI), a weighted sum of effluent pollutant loads (in ton/d) with weight values set to 2 for BOD, 1 for COD, 2 for TSS, 30 for NH_4 and 10 for NO_3, reflecting the higher relative importance towards receiving water quality of nutrients, and the toxic and oxygen depleting properties of NH_4; (2) the fraction of time during which the effluent exceeds the limit of 4 mgNH_4/l, expressed as percentage of the whole evaluation period (one year, the last 365 of the 609 simulated days); (3) the OPEX of the plant; (4) the CAPEX of the plant; (5) the total cost (TC, sum of OPEX and CAPEX).

The operational expenditure of the plant (OPEX) is very similar to the Operating Cost Index (OCI) of BSM2 – taking into account aeration, pumping, mixing and heating energy, sludge disposal, C-source and energy recovery from methane (Jeppsson et al., 2007) – but it differs in the sense that it is actually calculated in monetary terms, to be able to compare it with the CAPEX. The latter is calculated from cost functions providing the total capital cost of a type of tank (aerated, anoxic, primary clarifier, and secondary clarifier) as function of its volume (Bohn, 1993; Günthert and Reicherter, 2001). Those values are then annualised with a given interest rate (4% per year) and service life for civil works (30 years) and mechanical equipment (15 years).

Both OPEX and CAPEX have been used in the optimisation (or scenario analysis) because by screening out parameter sets with performance worse than the median value (any other percentile would be appropriate, according to how many optimal sets are desired) for any of the five criteria, extreme solutions with very high or low OPEX or CAPEX were excluded, since it was thought not to be appropriate to have an extravagant OPEX/CAPEX ratio.

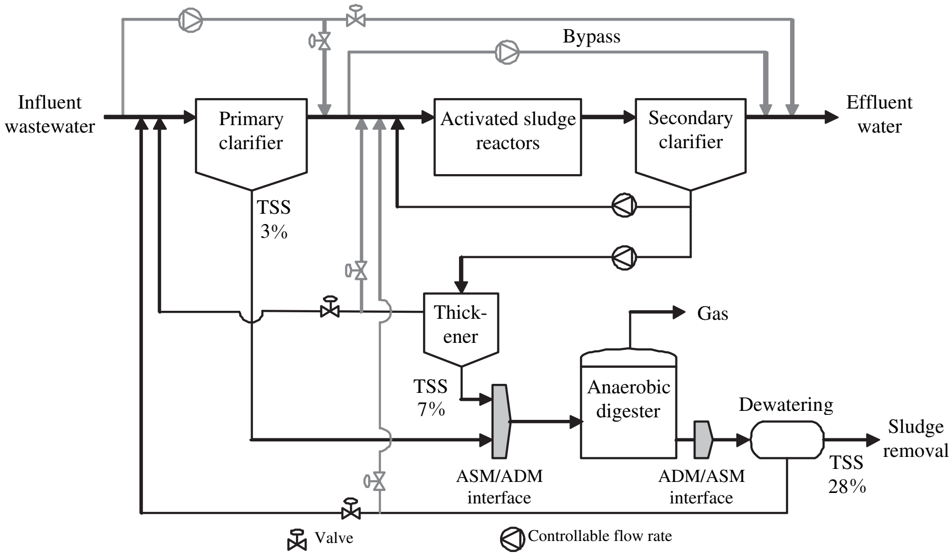

Fig. 1. Plant layout for BSM2 (adapted from Jeppsson et al., 2007).

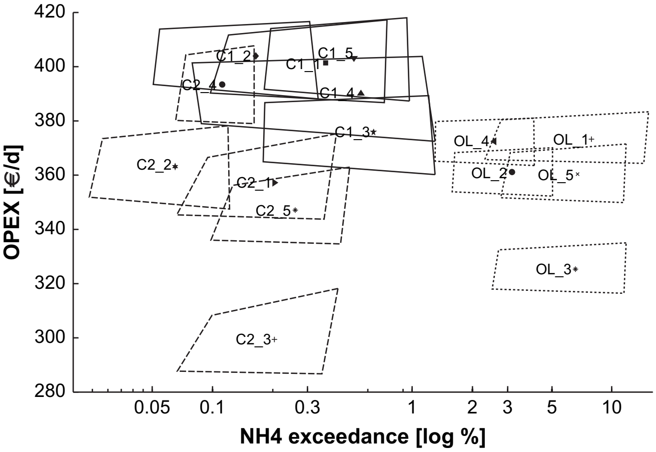

Fig. 3. Percentile polygons for NH_4 exceedance and OPEX of all optimal OL (dotted line), C1 (solid line) and C2 (dashed line) configurations.

As the CAPEX is not subject to uncertainty in this study, it has not been further considered in the uncertainty analysis (see Figs. 2 and 3).

2.4. Scenario and uncertainty analysis

Both the optimisation and the uncertainty analysis of the three configurations on the five BSM2 evaluation criteria were performed by means of MC simulations, which consist of performing multiple simulations with parameter values sampled (with Latin Hypercube Sampling) from Probability Density Functions (PDFs) of model parameters that are considered uncertain (step 4) (Benedetti et al., 2006, 2008a).

MC simulations are not an iterative optimisation algorithm; nevertheless they explore in good detail the parameter space with potentially less simulations than for example a multi-objective genetic algorithm (MOGA), for which the population size would be necessarily at least an order of magnitude smaller than the MC simulations conducted in this study. Even with iterative optimisation algorithms one cannot be sure that the optimum found is the real global optimum. Of course, an MOGA would more easily find the (hopefully global) minimum, but it is likely (intuitively, as it was not demonstrated, but it would be interesting research to conduct) that the difference by the solutions found with MC and with MOGA would not significantly differ when accounting for the uncertainties. Therefore, one can still consider this Monte Carlo procedure as a heuristic optimisation method which is robust, simple to implement and user friendly (there are no special algorithm settings to set, except deciding the size of the sample). Other advantages are: (1) it can be used as a preliminary step to locate interesting parameter spaces to be explored with other

Table 1
PDFs of the parameters; LB = lower bound, UB = upper bound, OD = operation and design, WT = wastewater treatment, ST = sludge treatment, T = triangular, U = uniform.

Parameter	Description or reference	Group	PDF	Median	LB	UB
AD.V_gas	Volume of gas in AD tank, in m^3	OD	U	–	240	360
AD.V_liq	Volume of liquid in AD tank, in m^3	OD	U	–	2720	4080
ASU3.Kla (only OL)	kLa in AS reactor no.3, in d^{-1}	OD	U	–	96	144
ASU4.Kla (only OL)	kLa in AS reactor no.4, in d^{-1}	OD	U	–	96	144
ASU5.Kla (only OL)	kLa in AS reactor no.5, in d^{-1}	OD	U	–	48	72
DO4_setpoint (C1 and C2)	Set-point for oxygen in Tank 4, in g/m^3	OD	U	–	1	3
kla_ratio (only C1)	Ratio of kLa5 on kLa4	OD	U	–	0.25	0.75
NH4_setpoint (only C2)	Set-point for NH_4 in Tank 5, in g/m^3	OD	U	–	0.75	2.25
C_source	C-source with COD = 400,000 g/m^3, in m^3/d	OD	U	–	1.6	2.4
dewatering.rem_perc	TSS removal fraction in dewatering	OD	U	–	0.96	1
dewatering.X_under	TSS underflow concentration, as fraction	OD	U	–	0.224	0.336
internal_rec	Internal mixed liquor recirculation, in m^3/d	OD	U	–	49,555.2	74,332.8
PC.f_PS	Primary settler underflow as ratio on inflow	OD	U	–	0.0056	0.0084
PC.Vol	Primary settler volume, in m^3	OD	U	–	800	1200
SC.A	Surface area of secondary settler, in m^2	OD	U	–	1200	1800
SC.H	Height of secondary settler, in m	OD	U	–	3.2	4.8
SC.Q_Under	Underflow of secondary settler, in m^3/d	OD	U	–	16,518.4	24,777.6
sec_sludge_to_AD	Secondary sludge to AD, in m^3/d	OD	U	–	240	360
thickener.rem_perc	TSS removal fraction in thickener	OD	U	–	0.96	1
thickener.X_under	TSS underflow concentration, as fraction	OD	U	–	0.056	0.084
Vol_aer	Volume of each aerated tank, in m^3	OD	U	–	2400	3600
Vol_anox	Volume of each anoxic tank, in m^3	OD	U	–	1200	1800
f_P	Henze et al. (1987)	WT	T	0.08	0.076	0.084
F_TSS_COD	TSS/COD ratio	WT	T	0.75	0.7125	0.7875
i_X_B	Henze et al. (1987)	WT	T	0.08	0.076	0.084
k_a	Henze et al. (1987)	WT	T	0.05	0.025	0.075
k_h	Henze et al. (1987)	WT	T	3	1.5	4.5
K_NH	Henze et al. (1987)	WT	T	1	0.5	1.5
K_NO	Henze et al. (1987)	WT	T	0.5	0.25	0.75
K_OA	Henze et al. (1987)	WT	T	0.4	0.2	0.6
K_OH	Henze et al. (1987)	WT	T	0.2	0.1	0.3
K_X	Henze et al. (1987)	WT	T	0.1	0.05	0.15
mu_A	Henze et al. (1987)	WT	T	0.5	0.4	0.6
mu_H	Henze et al. (1987)	WT	T	4	3.2	4.8
n_g	Henze et al. (1987)	WT	T	0.8	0.64	0.96
n_h	Henze et al. (1987)	WT	T	0.8	0.64	0.96
SC.f_ns	Takács et al. (1991)	WT	T	0.0023	0.0018	0.0027
SC.r_H	Takács et al. (1991)	WT	T	0.0006	0.0005	0.0007
SC.r_P	Takács et al. (1991)	WT	T	0.00286	0.00228	0.00343
SC.v0	Takács et al. (1991)	WT	T	474	379.2	568.8
Y_H	Henze et al. (1987)	WT	T	0.24	0.228	0.252
AD.khyd_ch	Batstone et al. (2002)	ST	T	0.8	0.5	1
AD.khyd_li	Batstone et al. (2002)	ST	T	1.1	0.7	1.5
AD.khyd_pr	Batstone et al. (2002)	ST	T	1.1	0.7	1.5
AD.Ks_ac_km_ac	Ks_ac/km_ac ratio, for correlation	ST	U	–	0.025	0.083
ASM2ADM.frxs	Nopens et al. (2009)	ST	T	0.646	0.612	0.68

Table 2
Operation and design parameters and evaluation criteria (yearly averages) for the original median parameter sets and the 5 optimal parameter sets for the OL configurations; in bold the best value, in italics the second best value.

	OL	OL_1	OL_2	OL_3	OL_4	OL_5
AD.V_gas	300	290	277	316	348	306
AD.V_liq	3000	3019	2863	3334	2788	3381
ASU3.Kla	120	106	117	97	116	132
ASU4.Kla	120	109	133	129	111	123
ASU5.Kla	60	64	63	61	55	70
SC.A	1500	1792	1519	1350	1501	1518
SC.H	4.00	3.31	3.47	3.82	3.69	3.70
SC.Q_Under	20,648	21,787	18,558	20,340	23,795	17,632
PC.Vol	900	969	1059	1130	1149	1118
PC .f_PS	0.0070	0.0062	0.0057	0.0065	0.0058	0.0075
sec_sludge_to_AD	300	266	276	301	308	249
internal_rec	61,944	59,975	58,616	49,782	70,187	51,150
Vol_aer	3000	3151	3023	3065	3329	2745
Vol_anox	1500	1389	1668	1748	1303	1421
dewatering.X_under	0.28	0.294	0.277	0.270	0.301	0.257
dewatering.rem_perc	0.98	0.968	0.975	0.991	0.983	0.960
C_source	2.00	2.01	1.73	1.68	1.84	1.93
thickener.X_under	0.070	0.060	0.074	0.069	0.073	0.057
thickener.rem_perc	0.98	0.991	0.978	0.969	0.991	0.974
EQI [ton/d]	5.63	**5.41**	5.58	5.82	5.86	5.97
NH_4 exceedance [%]	6.88	6.70	2.96	6.01	**2.18**	6.27
OPEX [€/d]	321	354	347	**317**	351	345
CAPEX [€/d]	1064	1054	1030	1063	1051	**1028**
TC [€/d]	1385	1409	*1378*	1380	1402	**1373**

methods and (2) the (multi-criteria) objective function does not need to be defined upfront, which allows to apply different functions to the same set of simulations, avoiding to re-run the optimisation each time the function is changed.

The BSM2 parameters were divided into three groups (see Table 1 for details): (1) operation and design (OD) parameters, including volumes, recirculation rates, etc.; (2) wastewater treatment (WT) parameters, including some parameters of the ASM1 and of the primary and secondary settler models; (3) sludge treatment (ST) parameters, including some parameters of the ADM1 and interface parameters.

A sensitivity analysis (step 5) allowed to discard some parameters that are not influential to the evaluation criteria (Benedetti et al., 2008b).

The PDFs of the 19 parameters regarding operation and design of the plant (Table 1) – used to explore the possibilities for optimisation of the performance of the configurations (step 6) with a scenario analysis – were defined as uniform with their mean set to the default value for BSM2 and boundaries set as +/−20% of the mean (+/−50% for the parameters of the controllers in C1 and C2). For the OD parameters, the PDFs do not have the purpose of representing the statistical properties of parameters, but of defining their range of variability for the optimisation of the configurations.

For each of the three configurations the number of MC simulations was chosen to be 50 times the number of parameters (950 simulations for OL and 900 for C1 and C2) to have as many combinations of options as feasible, given the large computational burden. For all simulations the five criteria were calculated and the Pareto-optimal parameter sets were selected. To further reduce the number of optimal sets, all sets with performance worse than the median value (any other percentile would be appropriate, according to how many optimal sets are desired) for any of the five criteria were excluded. This screening reduced the optimal sets from 900 to 10 for OL, to 8 for C1 and to 15 for C2. The best parameter set for each of the five criteria was selected for the uncertainty assessment. In case a set was the best for two criteria, also the second best for TC was selected, in order to have five different parameter sets for each configuration.

Table 3
Operation and design parameters and evaluation criteria (yearly averages) for the original median parameter sets and the 5 optimal parameter sets for the C1 configurations; in bold the best value, in italics the second best value.

	C1	C1_1	C1_2	C1_3	C1_4	C1_5
AD.V_gas	300	321	273	312	329	356
AD.V_liq	3000	2765	2988	3521	2912	2831
SC.A	1500	1584	1234	1745	1500	1662
SC.H	4.00	3.68	3.53	3.31	3.72	3.39
SC.Q_Under	20,648	23,955	23,653	21,488	22,259	17,878
DO4_setpoint	2.00	2.55	1.75	1.80	1.40	2.50
kla_ratio	0.50	0.36	0.41	0.65	0.70	0.46
PC .Vol	900	1112	1065	1075	833	1167
PC .f_PS	0.0070	0.0069	0.0075	0.0073	0.0066	0.0071
sec_sludge_to_AD	300	327	296	268	275	270
internal_rec	61,944	65,444	55,528	69,695	67,043	51,969
Vol_aer	3000	2964	3597	2579	2873	2704
Vol_anox	1500	1643	1630	1523	1505	1481
dewatering.X_under	0.28	0.294	0.269	0.323	0.236	0.240
dewatering.rem_perc	0.98	0.973	0.982	0.993	0.973	0.998
C_source	2.00	1.73	2.05	1.69	1.65	1.87
thickener.X_under	0.070	0.058	0.068	0.072	0.082	0.056
thickener.rem_perc	0.98	0.989	0.996	0.995	0.972	0.960
EQI [ton/d]	5.51	**5.63**	5.66	5.66	5.69	5.68
NH_4 exceedance [%]	0.33	0.31	**0.15**	0.51	0.41	0.50
OPEX [€/d]	347	338	347	**330**	335	336
CAPEX [€/d]	1054	1045	1052	1029	1009	**1007**
TC [€/d]	1411	1383	1400	1360	*1345*	**1343**

Table 4
Design and operational parameters and evaluation criteria (yearly averages) for the original median parameter sets and the 5 optimal parameter sets for the C2 configurations; in bold the best value.

	C2	C2_1	C2_2	C2_3	C2_4	C2_5
AD.V_gas	300	341	353	353	267	266
AD.V_liq	3000	2928	2856	3655	2745	3186
SC.A	1500	1397	1433	1376	1454	1723
SC.H	4.00	3.88	3.65	3.24	3.25	3.74
SC.Q_Under	20,648	24,748	22,784	20,065	19,494	23,608
DO4_setpoint	2.00	0.99	0.89	0.82	1.71	1.18
NH4_setpoint	1.50	1.13	1.09	1.33	2.20	1.06
PC .Vol	900	942	1173	1007	1068	1122
PC .f_PS	0.0070	0.0066	0.0065	0.0057	0.0070	0.0056
sec_sludge_to_AD	300	317	241	328	300	265
internal_rec	61,944	64,907	72,799	70,070	74,149	57,861
Vol_aer	3000	3186	3502	3373	3415	2866
Vol_anox	1500	1207	1278	1384	1325	1332
dewatering.X_under	0.28	0.309	0.273	0.318	0.318	0.251
dewatering.rem_perc	0.98	0.991	0.991	0.965	0.990	0.997
C_source	2.00	1.85	2.16	1.66	1.92	2.26
thickener.X_under	0.070	0.063	0.081	0.077	0.061	0.056
thickener.rem_perc	0.98	0.964	0.965	0.988	0.967	0.961
EQI [ton/d]	5.05	5.22	5.23	5.29	5.11	**4.97**
NH_4 exceedance [%]	0.20	0.17	**0.06**	0.18	0.11	0.24
OPEX [€/d]	321	287	300	**258**	320	293
CAPEX [€/d]	1063	1021	1059	1051	**1018**	1056
TC [€/d]	1384	**1309**	1360	1310	1339	1349

Concerning the influence of uncertainty in the choice of the best options, it can be said that the uncertainty can be significant, but scenarios away from that "compromise" space would not have overlapping percentile polygons. The uncertainty analysis is done, in this case, to discriminate (decide with more information) between scenarios closely performing.

The selection of the 19 WT and of the 5 ST model parameters for uncertainty analysis (step 7), see Table 1, was based on Benedetti et al. (2008b). The triangular PDFs of the ASM1 parameters were taken from Rousseau et al. (2001) and from Reichert and Vanrolleghem (2001), while for all the other parameters the PDFs were assumed to be triangular with median equal to the BSM2 default and boundaries at +/−20% of the median. The PDFs of the ADM1 parameters were mainly taken from Appendix A in Batstone et al. (2002), with additional information from Batstone et al. (2003, 2004) and Siegrist et al. (2002), while the AD/AS model interface parameters were assumed to be triangular with median equal to the BSM2 default and boundaries +/−20% of the median. For each of the optimal OD parameter sets, a number of simulations equal to 50 times the number of uncertain WT and ST parameters was run (1200 simulations).

The results of the uncertainty analysis are illustrated by means of percentile polygons (Benedetti et al., 2008a). One polygon summarises, for one OD parameter set, the yearly average values of two criteria for all 1200 simulations, by joining the 5th and 95th percentiles of the two criteria, calculated on the two principal axes. A marker shows the two 50th percentiles.

3. Results

3.1. Scenario analysis

The results of the scenario analysis are presented in Tables 2–4. For OL (Table 2), OL_2 appears to be a good option, improving the original OD parameter set in both environmental criteria at a lower total cost. The options with best EQI (OL_1) and best NH_4 exceedance (OL_4) entail a higher total cost. The option with the lowest TC shows a significantly higher EQI. Concerning the volumes, it looks like a good combination for cost saving is to have the primary clarifier and the anoxic fraction of reactor volume larger than in the original OL. Anyway, the improvements from the original OL are not substantial.

For C1 (Table 3) it can be said in general that the benefit of a simple control is clear from the low NH_4 exceedance, and that EQI shows little variation among the options. The original configuration has the best EQI but also the highest TC, while C1_2 has the best NH_4 exceedance but also a rather high TC. C1_4 and C1_5 have the lowest cost with a slightly worse EQI. Again, a relatively higher anoxic fraction and larger primary clarifier lower the TC.

The benefits of a more advanced control are very evident in C2 (Table 4), since all evaluation criteria are on average better than for OL and C1. This is due to the fact that having the oxygen set-point in Tank 5 controlled by the effluent NH_4 not only allows to lower the NH_4 peaks with higher oxygen supply, but especially to save aeration when it is not needed. This is the advantage of controlling directly the variable of interest rather than a proxy. Also in this case, the original set shows a low EQI but the highest TC. C2_1 and C2_3 have the lowest TC (much lower than the original) with an only slightly higher EQI. C2_5 is interesting since it has the lowest EQI at a lower TC than the original set, but giving up slightly on the NH_4 exceedance. For C2, a general property is that the optimal sets have an anoxic fraction of reactor volume much smaller than in the original set (in contrast to OL and C1) and a larger primary clarifier. Both for C1 and C2 the reduction that can be achieved for TC is around 5%, which can be considered a relevant saving.

In general for the three configurations, the major advantage of having a larger primary clarifier (10–30% more than the original volume) is the increased retention time offered which leads to increased removal efficiency in the tank and hence reduced organic and solids loading to the secondary/tertiary treatment stages.

3.2. Uncertainty analysis

The results of the uncertainty analysis are shown in Figs. 2–4. Looking at the two most comprehensive criteria – EQI for the environmental performance and TC for the economic performance – in Fig. 2, it is evident that the C2 configuration improves compared to the OL and C1 configurations. An interesting result is that the median TC for the control options is higher than the value resulting from the single simulation (with median parameter values) of the scenario analysis presented in Tables 1–3. This is particularly pronounced for C2, and as Fig. 3 shows, it is due to an increase in the OPEX (the CAPEX does not change in the uncertainty analysis). This behaviour is most likely due to the fact that the controllers (and C2 is a better controller than C1) "push" the EQI down in spite of the process variability. Fig. 3 also illustrates how C1

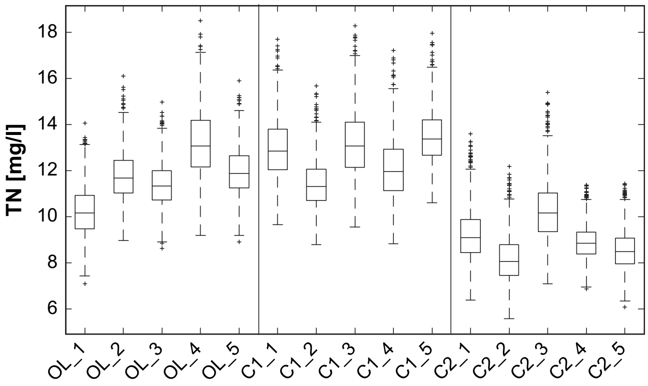

Fig. 4. Box plots for total nitrogen (TN) of all optimal OL, C1 and C2 configurations.

and especially C2 improve the NH_4 effluent and its stability. Note that the x-axis has a logarithmic scale, so the stability of the process, which is inversely proportional to the perimeter of the polygons, is much larger for C1 and especially C2 compared to OL. On the other hand, the OPEX (and as a consequence TC) varies more for C1 and C2 than for OL, since the action required by the controller to keep the set-point makes the aeration cost vary, while it is constant for OL. While the controllers induce smaller variations in NH_4, more variations are resulting in the other effluent concentrations. However, the overall variability of EQI (Fig. 2) is smaller with C1 and C2 than with OL. Fig. 4 illustrates the variability of total nitrogen (TN) for all the optimal OD configurations. It can be seen that C1 actually performs slightly worse than OL, since keeping oxygen higher (to lower NH_4 peaks) hampers denitrification. In C2, allowing lower oxygen in the last tank (which is recirculated to the anoxic tanks) when there is no need to nitrify, strongly improves denitrification. Furthermore, C2_4 (and to a lower degree C2_5) show a very good stability of TN.

4. Conclusions

A method to conduct scenario analysis by means of MC simulations and multi-criteria evaluation was presented. It was applied to the open loop version of BSM2 and to two configurations with closed loop control, one with a simple oxygen controller and the other one with an ammonium controller regulating the set-point of the oxygen controller (cascade controller).

The results show a much greater benefit of the cascade controller compared to the simple controller, both in environmental and economic terms. In general, optimal configurations have a large primary clarifier, which increases the primary sludge sent to the digester and therefore the biogas production, and reduces the load to be treated in the activated sludge. In the open loop and in the simple controller configurations, the anoxic fraction of the reactor volume is larger than in the cascade controller configuration. This can easily be explained by the fact that the cascade controller allows reduced oxygen concentration in the last tank before the recirculation to the anoxic tanks, allowing a same denitrification capacity in a smaller volume.

The uncertainty analysis performed on the optimal scenarios highlights the improved and more stable effluent with closed loop. It also appeared that the median OPEX of the uncertainty distributions is higher than the value from the single simulation of the optimal configuration with default parameters. This difference between the results is due to the non-linear nature of the system.

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