Verification of WWTP design guidelines with activated sludge process models

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ABSTRACT
There is significant interest in using process models for WWTP design to complement the traditional design guidelines. However, transparent quantification of the differences in the design results obtained with the two approaches has not been done yet. The objective of this paper is to define a methodology to evaluate the expected performance of a designed WWTP. The use of this methodology will enable to identify inherent safety incorporated in design guidelines by verification with dynamic process models. The methodology includes two parts: first, multiple designs are made using a design guideline for different combinations of influent characteristics, effluent requirements, safety factors and operating preferences. Second, the results of the designs (e.g. reactor volumes) are applied in a process model that emulates WWTP behaviour. The effluent concentrations predicted by the process model are then compared to the effluent requirements which were imposed for the designs. The methodology is illustrated using the Metcalf & Eddy design guidelines for a nitrogen-removing process and the ASM1 process model.

KEYWORDS: Activated sludge models Design, Monte Carlo, Nitrogen removal, Uncertainty, Wastewater treatment

INTRODUCTION

The use of activated sludge models (ASM) (Henze *et al*., 2000) is common practice within the field of wastewater treatment (Copp *et al.*, 2009; Phillips *et al.*, 2009). These models have been widely used for learning, design and process optimisation purposes (Gernaey *et al*., 2004). Focusing on the design applications these ASM-type models have been helpful to evaluate different alternatives for designing and upgrading wastewater treatment plants (WWTP) (Daigger and Nolasco, 1995; Hao *et al.*, 2001; Salem *et al.*, 2002; Larrea *et al.*, 2007), to optimize the design exercises (Rivas *et al*., 2008), to evaluate costs (Vanrolleghem *et al*., 1996), to extract knowledge (Flores *et al*., 2006), to evaluate the production of Green-house gases (Johnson and Hiatt, 2009) and to study uncertainty related to the process design (Sin *et al*., 2009).

Guidelines traditionally used for design (Metcalf & Eddy, ATV, Grady, Ten State Standards, HSA principles) are based on simplified system descriptions. In recent years there is a growing interest in applying the dynamic ASM-type (chemical-biological) process models to complement the traditional design guidelines. For instance, the HSG group in Germany presented a study (Spering et *al.*, 2008) where the ASM3 model parameters were adjusted to obtain similar design results compared to the ATV design guidelines. However, there is no clear methodology to evaluate the performance of traditional design guidelines using the ASM-type models.

The objective of this paper is to develop a methodology that is able to estimate the reserve capacity inherent in a design guideline. The methodology is based upon comparing the results of a certain guideline to a reference. In this case it is proposed to use the ASM1 model as reference. The methodology developed in this paper should be applicable to other design guidelines.

METHODOLOGY

The methodology suggested for assessing the reserve capacity inherent in a design guideline is presented in Figure 1 and explained below.

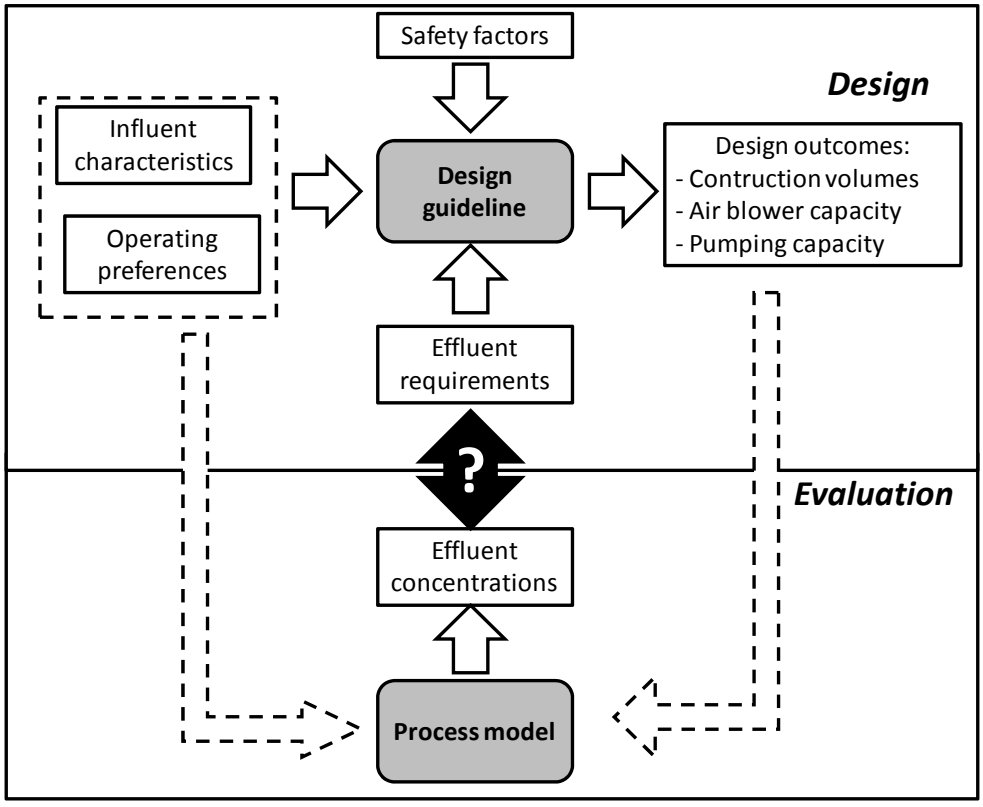

Figure 1. Methodology for design guideline evaluation

Multiple designs generation using guidelines

Designs for a given guideline are determined by defining influent wastewater characteristics, specifying operating preferences (e.g. DO and MLSS concentration in the reactors), selecting safety factors (SF) and setting the effluent requirements. The design outcomes are the reactor volumes, air blower capacity and pumping capacity. A full exploration of the «design space» of a

guideline is conducted by repeating this exercise for many possible combinations of these design conditions. This is achieved by selecting a range of values for the design conditions, in this study through uniform probability density functions. The Monte Carlo (MC) simulation technique using efficient Latin Hypercube sampling (LHS) is applied to propagate the ranges of the design conditions to the design outcomes.

Evaluation of the design guideline using dynamic process models

The lower part of Figure 1 shows the evaluation step. The same inputs used for the designs (influent characteristics and operating preferences, e.g. DO and MLSS concentration in the reactors) together with the design outcomes obtained from the guideline are used as inputs to the process model. The predicted effluent concentrations obtained with the process model are then compared to the effluent requirements which were imposed for the designs. This enables to investigate whether the guidelines lead to optimal designs or to over- or under-sized plants. It is important to stress that the same criteria used for the design requirements (e.g. weekly average of effluent concentrations) are applied in the evaluation step.

Case study

In this case study, the Metcalf & Eddy guidelines (Tchobanoglous *et al*., 2003) are used to size a modified Ludzack-Ettinger plant for nitrogen removal. In order to explore the «design space», 1000 design configurations are created by random sampling from uniform probability density functions for the influent fractions, the effluent requirements, the safety factors and the dissolved oxygen operating concentration. The uniform probability density functions are characterised by the lower and upper values in Table 1.

Table 1. Range of values of design conditions expressed as uniform distributions characterised by default, upper and lower values

Design conditions	Symbol	Default	Lower value	Upper value	Units
Influent fractions					
Undegradable soluble	f_S_U	0.09	0.05	0.14	-
Biodegradable soluble	f_S_B	0.16	0.08	0.24	-
Undegradable particulates	$f\_X_{U,inf}$	0.12	0.06	0.18	-
Biodegradable particulates	f_X_B	0.52	0.35	0.72	-
Heterotrophic biomass	f_X_{OHO}	0.11	0.06	0.17	-
Effluent requirements (weekly average)					
Effluent ammonium	S_{NHx}	2	0.5	6	$gN \cdot m^{-3}$
Effluent nitrate	S_{NOx}	6	5	10	$gN \cdot m^{-3}$
Safety factors					
Aerobic section	SF_{AER}	1.25	1	1.5	-
Anoxic section	SF_{ANOX}	1.25	1	1.5	-
Operational conditions					
Dissolved oxygen (aerobic zone)	S_{O2}	2	0.5	4	$(-gCOD) \cdot m^{-3}$

The time series of influent characteristics and the parameter values for the dynamic simulations are taken from Copp (2002) which considers an average influent dry-weather flow rate of 18446 $m^3 \cdot d^{-1}$, an average biodegradable COD of 300 g $COD \cdot m^{-3}$ and an average ammonium

concentration of 50 g NH_4-N·m^{-3}. Taking this influent data as starting point 1000 influent files are generated applying different coefficients for the influent fractionation of the organic matter. The total COD load profile is the same for the 1000 influent files, but the fractions of inorganic soluble (f_S_U), organic biodegradable (f_S_B), undegradable particulates ($f\_X_{U,inf}$) and the heterotrophic biomass (f_X_{OHO}) fractions are randomly sampled according to Table 1. For each of the files the mass balance is closed by assigning the rest of COD to the fraction of the organic particulates X_B ($f\_X_B = 1\text{-}f\_S_U - f\_S_B - f\_X_{U,inf} - f\_X_{OHO}$).

Effluent requirements are defined as average weekly concentrations and the ranges are assumed to cover values that would typically be envisaged by regulators.

The process model used to evaluate the designs includes the biokinetic Activated Sludge Model nº1 (ASM1, Henze *et al*., 2000) and the settler model defined in Takács *et al*. (1991). A dissolved oxygen controller in the aerobic reactor and a MLSS controller for all reactors have been implemented in order to impose the operating preferences of the design on the dynamic process model simulations. The simulation procedure is based on 150 days of steady-state simulation, followed by 14 days of dynamic simulation and another final 14 days of dynamic simulation. The evaluation of the simulation results is based on the average of the last 7 days of dynamic simulation. This simulation procedure is conducted for each of the designs obtained with the guideline (the overall balance is 1000 simulations).

RESULTS AND DISCUSSION

Designs obtained with Metcalf & Eddy guideline

The results presented in this paper focus on the design of the aerobic reactor. The histogram of the 1000 designed volumes presented in Figure 2 is skewed with values ranging between 4000 m^3 and 17000 m^3. This range of values is quite large, demonstrating that a wide range of design possibilities has been explored.

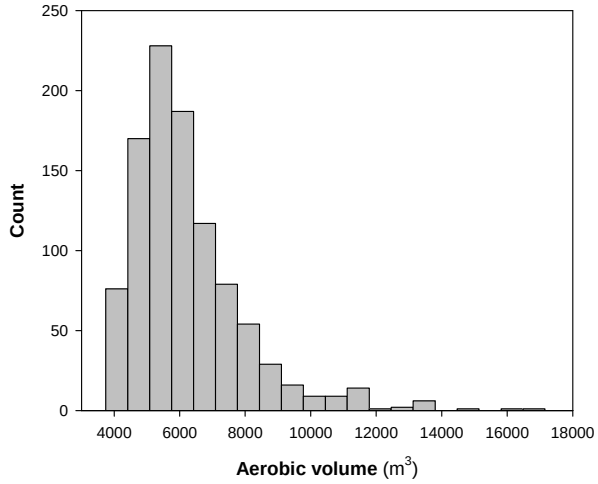

Figure 2. Histograms of the aerobic volumes for the 1000 designs using the Metcalf & Eddy guideline

The variation of the aerobic volume with respect to design conditions (DO set-point and effluent ammonia) (see Table 1) is presented in Figure 3. It can be observed that the design volume is

sensitive to the desired effluent ammonia. This was validated with a sensitivity analysis presented in Flores-Alsina *et al*. (2010) where the effluent ammonia concentration was found to be the most influential input with respect to the aerobic volume. The influence of the safety factors on the volume can also be seen in Figure 3. The higher the safety factors the lower the volumes obtained.

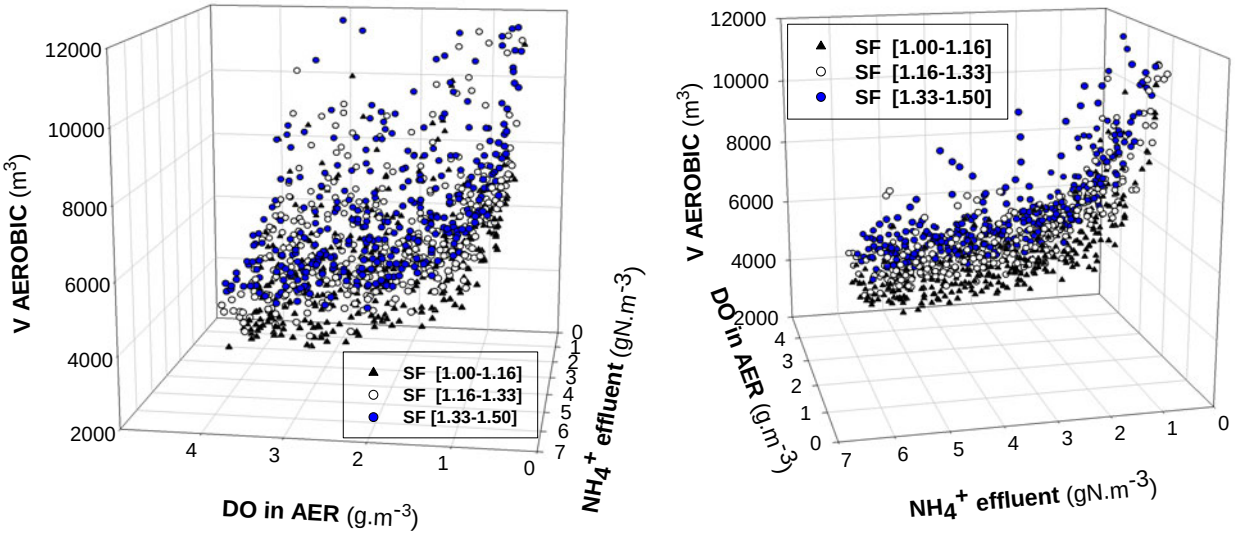

Figure 3. Results of the sizing of the aerobic reactor for the 1000 designs using the Metcalf & Eddy guideline

Evaluation of designs with a dynamic process model

The goal of this study is the evaluation of a design guideline with an ASM1-based process model. In order to evaluate the design results for the aerobic volume, the effluent NH_4^+ requirements for each design are plotted against the predicted concentration (effluent NH_4^+) obtained from the process model, as presented in Figure 4.

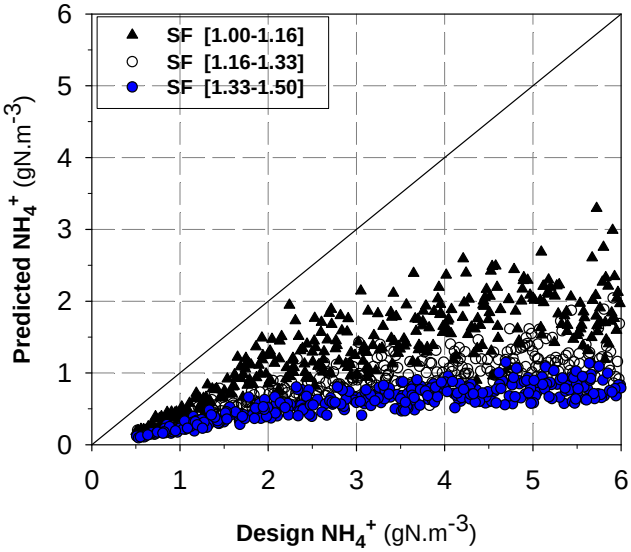

Figure 4. Predicted concentrations obtained with the ASM1 process model vs. the Metcalf & Eddy design effluent requirement for the 1000 designs.

It can be observed that there is a monotonous increasing relationship between the imposed effluent requirements for the Metcalf & Eddy designs and the concentrations predicted with the process model. Figure 4 indicates that the aerobic reactor volumes, obtained with the Metcalf & Eddy guideline, are oversized i.e. the predicted ammonia concentration values (from the dynamic simulations) are (significantly) below the concentration requirements imposed for the design. Even the use of low safety factors leads to overdesign.

Discussion of differences observed

In order to understand the differences obtained for the design and predicted effluent ammonia several factors have to be taken into account.

1) Predicted SRTs with the BSM1 model are higher than the chosen SRTs during the designs (see Figure 5). In fact, the design allows selecting two important characteristics of the treatment plant: the MLSS concentration in the bioreactor and the SRT. However, it is impossible to impose both on the dynamic process model. Both options were tested and it turned out that imposing the design MLSS concentration on the dynamic simulations led to a less extreme sludge production (see Figure 6). By imposing an MLSS concentration, the BSM1 simulations result in higher SRTs and therefore higher nitrification capacities are obtained, explaining the lower ammonium concentration in the effluent. The differences in the SRTs can be explained by the different model structures of both models (see equation 1 and equation 2) that do not allow fixing the MLSS and the SRT of the system at the same time. Note that fixing the SRTs (and leaving the MLSS to evolve to lower values) would make that the effluent ammonia concentrations would come closer to the values the plant was designed for, but the sludge production results become quite extreme (results not shown).

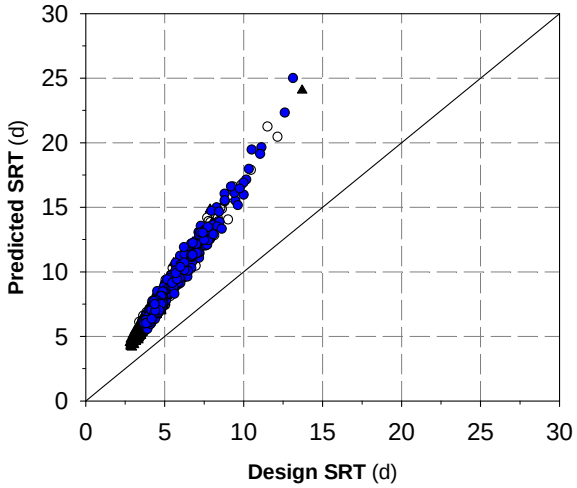

Figure 5. Design vs simulated SRT for the 1000 design exercises

SRT calculation Metcalf & Eddy (Eq 1)	SRT calculation BSM1 (Eq 2)
$SRT_{Metcalf} = \frac{1}{\mu_{ANO}}$ $\mu_{ANO} = \mu_{ANO,Max} \cdot \frac{S_{NHx}}{K_{NHx,ANO} + S_{NHx}} \cdot \frac{S_{O2}}{K_{O2,ANO} + S_{O2}}$	$SRT_{BSM1} = \frac{V * X}{Q_w * X_w + Q_e * X_e}$

2) Sludge production is much higher in the BSM1 model simulations compared to the expected sludge production from the Metcalf & Eddy design (Figure 6).

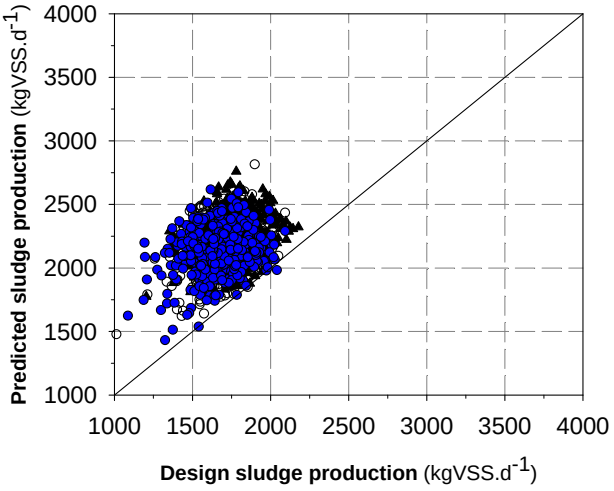

Figure 6. Design vs simulated sludge production for the 1000 design exercises

This difference can be explained by the more detailed BSM1 model structure, coupled to different default kinetic and stoichiometric parameters for both Metcalf & Eddy guidelines and BSM1 (see Table 2). An example of this is the death-regeneration concept that is considered in the ASM1 models, that leads to different meaning for the decay rates and the undegradable particulates (X_U) generated in biomass decay. However, for these parameters it is well-known how to make decay rates and the fraction of undegradable particulates comparable for the two model structures (see equation 3 and equation 4 where parameters with a prime are the Metcalf & Eddy parameters).

Table 2. Parameter values used in the Metcalf & Eddy design (values at 15ºC). Notation taken from Corominas et al. (2010)

Parameter	Symbol	Metcalf & Eddy	BSM1
Maximum growth rate of X_{OHO}	$\mu_{OHO,Max}$	4.27	4
Half-saturation coefficient for S_B	$K_{SB,OHO}$	20	10
Decay rate for X_{OHO}	b'_{OHO}	0.098	0.115 (b_{OHO}=0.3)
Maximum growth rate of X_{ANO}	$\mu_{ANO,Max}$	0.3813	0.5
Half-saturation coefficient for S_{O2}	$K_{O2,ANO}$	0.5	0.2
Half-saturation coefficient for S_{NHx}	$K_{NHx,ANO}$	0.4415	1
Decay rate for X_{ANO}	b'_{ANO}	0.0658	0.019 (b_{ANO}=0.05)
Yield for X_{OHO} growth	Y_{OHO}	0.4	0.67
Yield of X_{ANO} growth per S_{NOx}	Y_{ANO}	0.12	0.24
Fraction of X_U generated in biomass decay	$f'_{XU\_Bio,lys}$	0.15	0.20 ($f_{XU\_Bio,lys}$=0.08)

$$b_{OHO} = \frac{b'_{OHO}}{1 - Y_{OHO} * (1 - f_{XU\_Bio,lys})} \quad \text{Eq 3} \qquad f_{XU\_Bio,lys} = \frac{f'_{XU\_Bio,lys}}{1 - Y_{OHO} * (1 - f_{XU\_Bio,lys})} \quad \text{Eq 4}$$

On the other hand, for other parameters it is not that simple. For instance, the observed yields in Metcalf & Eddy cannot be compared to the yield used in the BSM1 model.

The sensitivity of the Metcalf & Eddy volumes to the kinetic and stoichiometric parameters will be explored in future work by following the methodology described in Flores *et al*. (2010).

Evaluation of the design guideline verification methodology

The proposed methodology can be used to quantify the reserve capacity inherent in a design guideline, e.g. by how much can the reactor volume be reduced until the predicted effluent concentrations reach the design effluent requirements. Such calculation is conducted by selecting several designs and for each of them running different dynamic simulations applying gradual changes in the volume of the aerobic reactors. An example for one of the 1000 designs is presented in Figure 7. For this specific case, the ASM-type model shows that the aerobic volume could be reduced by 35% compared to the design of Metcalf & Eddy. When removing the safety margins included in the dimensioning guidelines the plant size can be reduced significantly. In Benedetti et al. (2010) the volumes obtained with ATV design guidelines were reduced up to 60% of its original volume when using a dynamic model.

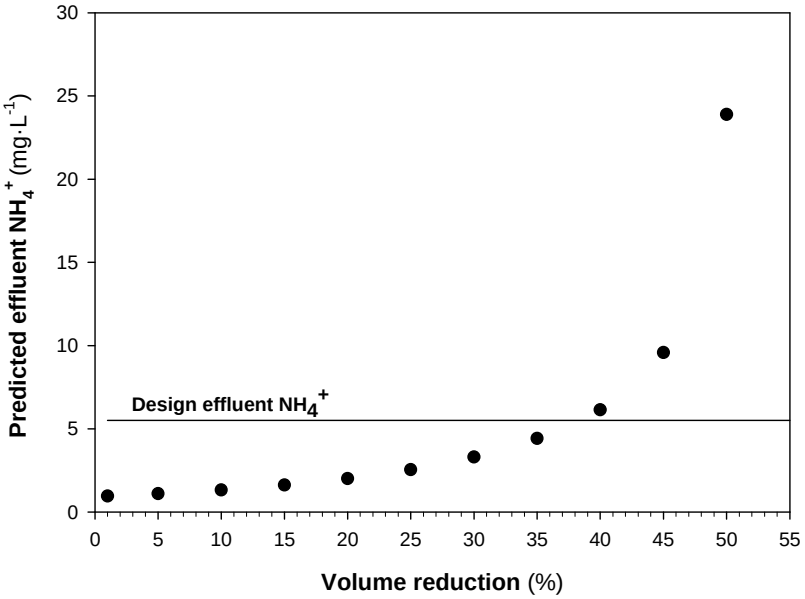

Figure 7. Predicted effluent ammonia at different volume reductions for one design exercise (SF=1.33; DO set-point = 2.87 $mgO_2 \cdot L^{-1}$; effluent ammonia = 5.5 $mgN \cdot L^{-1}$; Aerobic volume = 4830 m^3)

The guideline verification methodology proposed here can be applied to different influent characteristics, operating preferences, safety factors, effluent requirements and kinetic and stoichiometric parameters in order to explore a full range of design options. This is conducted by performing a large number of design verifications (1000 Metcalf & Eddy designs and 1000 dynamic simulations in this illustrative case). This methodology is also complemented with a sensitivity analysis of the results obtained with the design guideline.

With this study the authors also want to make the point that modifying the ASM-type models to describe the results obtained by a specific guideline as performed by Spering *et al.* (2008) will not improve the design guidelines themselves. Both design guidelines and dynamic process model simulations have their role to play. One should only be aware of the differences and get some idea on the inherent reserve capacity present.

This study demonstrates that the verification of design guidelines is a complex issue and there is still further work to do. Ongoing research focuses on studying the underlying mechanisms that are behind the different model structures and to find the best approaches for objective comparison. The proposed methodology will also be applied to other design guidelines for cross-comparison of inherent safety.

CONCLUSIONS

A methodology is proposed and validated to verify the results obtained from different design guidelines by using ASM-type model simulations. The methodology suggests i) to perform multiple design exercises for a given guideline applying different ranges for design conditions and influent wastewater fractionation, ii) to run multiple ASM-type dynamic model simulations using the outcomes of the design exercises as inputs and iii) to compare the resulting effluent ammonia, sludge production, etc. The results show that the Metcalf & Eddy guidelines give over-sized aerobic reactors compared to the BSM1 simulations due to the differences in the model structure and their default model parameters. The different structures of the models make the verification of the design guidelines with a dynamic model a complex problem. For this reason, the verification has to be conducted by checking different criteria, including, for the illustrative case, the effluent ammonia, the SRTs and the sludge production obtained with the different approaches.

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