A tool for optimum design of WWTPs under uncertainty: Estimating the Probability of Compliance

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Abstract: This paper presents a prototype tool for design of Wastewater Treatment Plants (WWTPs). It is a model-based approach that explicitly accounts for both temporal variability and uncertainty. It evaluates a set of WWTP designs for a pre-defined configuration and estimates the probability of compliance (POC) given some sources of uncertainty. The proposed tool uses two nested loops: the outer loop tests different scenarios looking for the optimal combination of the design variables; the inner loop uses a Monte Carlo simulation propagating the uncertain model inputs to obtain the POC. The Benchmark Simulation Model no.1 was used as basic plant configuration. The design variables were: total volume of the plant; aerobic fraction; waste flow rate; recycle flow rate; and internal recirculation flow rate. The sources of uncertainty included parameters related to the biochemical model and the secondary clarifier settling. A set of 100 designs was evaluated by comparing the distributions of the average and maximum concentrations of NH_4, TN and TSS with respect to typical effluent requirements. It was found that the effect of the sources of uncertainty is quite important to evaluate the performance of the plant. For example, while the BSM1 plant fulfills some effluent requirements using the default parameter values, it was shown that it only can guarantee them with a POC below 0.85 when considering the uncertainty. This is an example of the potential that this tool has for better informing the engineering firms about their design proposals.

Keywords*: design; Monte Carlo; uncertainty analysis; wastewater treatment plants.*

1   INTRODUCTION

The design of Wastewater Treatment Plants (WWTPs) has generally been performed by using design guidelines such as Metcalf & Eddy, ATV, Grady, HSA principles, etc. These guidelines can be seen as steady state models where the design variables (total volume, secondary settler dimensions, oxygen requirements, etc.) are obtained from mass balances of COD, nitrogen and phosphorous (Alex et al., 2007). They are easy to use and they summarize considerable experience in WWTP design practise. However, the limitation of these methods is twofold: they do not consider the dynamics of the system; the uncertainty about the plant performance is tackled by the use of safety factors which represent the lack of knowledge about the influent load and its composition, the biochemical behaviour of the system, possible hydraulic short-circuits, etc.

The use of dynamic simulation models can provide a much more comprehensive framework for WWTP design (Bixio et al., 2002; Rivas et al., 2008). In this context, the dynamic behaviour of the plant can be represented, and the effect of most of

the uncertainties in the system can be quantified by performing an uncertainty analysis. Several examples of uncertainty analysis for wastewater treatment plant performance evaluation can be found in the literature. For example, Sin et al. (2009) made a critical discussion of uncertainty analysis applications; Flores-Alsina et al. (2008) or Benedetti et al. (2010) evaluated different control strategies under uncertainty; and Sala-Garrido et al. (2012) analysed the economics related to WWTP management in an uncertain context.

This paper proposes a prototype tool for the design of wastewater treatment plants within an uncertainty framework. The main purpose of the paper is not to provide a full methodology for wastewater treatment plant design, but to present the potential that the use of dynamic models and uncertainty analysis might have to evaluate the behaviour of a WWTP in a design phase. The proposed tool will enable the design engineers to estimate the probability of compliance (POC) with respect to the effluent requirements (Corominas et al., 2010).

2   MATERIALS AND METHODS

2.1   Plant layout, simulation strategy and plant performance evaluation

The *Benchmark Simulation Model No.1* or BSM1 was proposed as a tool for evaluating activated sludge wastewater control strategies (Copp, 2001). It is a pre-denitrification system for nitrogen removal (see Figure 1). The activated sludge unit, modelled using the activated sludge model no. 1 (ASM1, Henze et al., 2000) consists of five compartments, in which the first two are anoxic and the last three are aerated. The settling unit, modelled using the Takács settling model (Takács et al., 1991), is a non-reactive secondary settler subdivided into 10 layers. The default plant layout uses an anoxic volume of 2000 m^3 and an aerobic volume of 4000 m^3 which yields a SRT of 10 days with an HRT of approximately 15 h. For further details on the BSM1 the reader is referred to the IWA Task Group on Benchmarking of Control Strategies for WWTPs (http://www.benchmarkwwtp.org/) and Copp (2001).
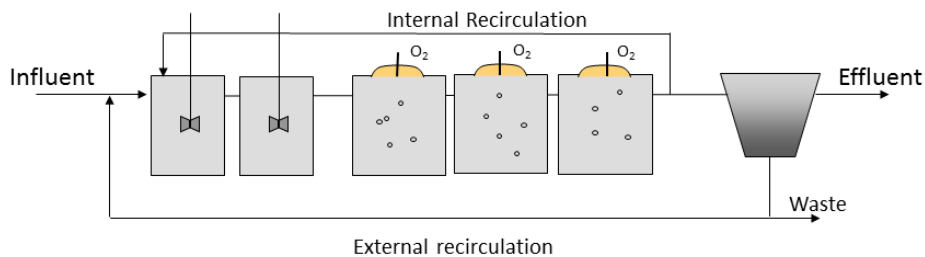

Figure 1. BSM1 plant configuration

The model of the BSM1 layout was implemented and simulated in the WEST (www.mikebydhi.com) simulation platform. The simulations were performed for a temperature of 15 °C. To simulate the BSM1, the following strategy was used: 150 days using constant dry weather influent load (steady-state load) to obtain a steady-state, followed by two times 14 days of dynamic simulations using a dynamic dry weather influent load profile. The last 14 days of the dynamic simulations were considered for the plant performance evaluations. The performance of the designs was assessed with respect to the maximum and average values of the ammonium (NH_4), total nitrogen (TN) and total suspended solids (TSS) concentrations in the effluent. The simulated results were compared with typical effluent requirements (Table 1).

Table 1. Effluent Requirements to evaluate the plant designs under uncertainty

Variable	Unit	Maximum	Average
NH_4	mgN/l	6	3
TN	mgN/l	20	18
TSS	mg/l	20	18

2.2 Evaluation of designs under uncertainty

On the basis of the default parameter values in the BSM1 model, different designs were evaluated in terms of the effluent quality; and taking into account the main sources of uncertainty.

The design assessment is basically performed by completing two simulation loops (Figure 2): the inner one evaluates the uncertainty for a certain design (Monte Carlo loop); the outer changes the design variables. For a given design setup, the MC loop evaluates the effluent quality by means of a set of histograms (TSS maximum, TSS average, NH_4 maximum, NH_4 average, etc.) represented by Graph 1 (Figure 2). This operation is repeated over a sufficiently large selection of model designs; and all the histograms obtained are summarized by their percentile distribution, represented by Graph 2 (Figure 2). For a certain design and given the sources of uncertainty considered, we can estimate the Probability of Compliance (POC) with respect to each effluent criterion (TSS maximum, TSS average, NH_4 maximum, NH_4 average, etc.).
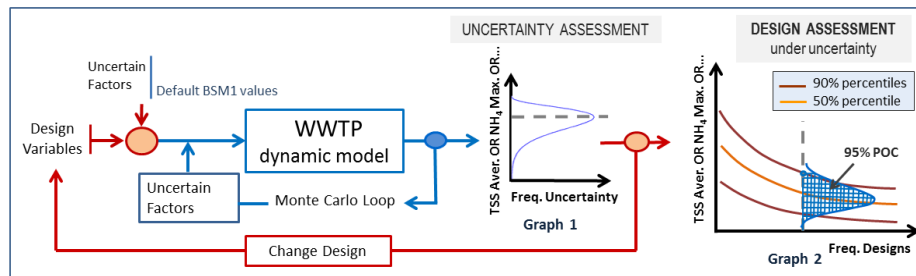

Figure 2. Simulation scheme followed for design assessment under uncertainty

For this first test of the prototype tool, we evaluated 100 designs by considering random values of five design variables (Figure 1): total volume of the plant; aerobic fraction; waste flow rate; recycle flow rate; and internal recirculation flow rate. Latin Hypercube Sampling was used to achieve a representative sample of the design space (Table 2).

Table 2. Default values and Reasonable ranges of the design variables

Variable	Unit	Default	Min	Max
Total volume	m^3	6000	4600	7600
Aerobic fraction	-	0.667	0.5	0.75
Waste flow rate	$m^3 \, day^{-1}$	385	280	600
Recycle flow rate	$m^3 \, day^{-1}$	18831	14000	23000
Internal recirculation flow rate	$m^3 \, day^{-1}$	55338	40000	70000

The uncertainty analysis is also performed using Latin hypercube sampling. This time, 200 parameter sets were found enough to converge to the desired distribution of results. The uncertainty analysis concerned parameters related to the biochemical model (Henze et al., 2000) and the Takács settling model (Takács et al., 1991). The uncertainty analysis was performed on the most important parameters (Table 3) according to previous results obtained from global sensitivity analysis (Sin et al., 2011; Ramin et al., 2011). In sum, 100x200 dynamic model simulations were performed using the Uncertainty Analysis tool of WEST2011 (www.mikebydhi.com). This simulation tool was very useful since the 20,000 simulations were performed by only preparing 100 simulation setups.

Table 3. Uncertainty of the most important biochemical and settling parameters

Parameter	Unit	Default	Min	Max
Biochemical model				
X_{ITSS}	gTSS (gCOD)$^{-1}$	0.75	0.70	0.95
K_{NH}	gN m^{-3}	1.00	0.50	1.50
K_{OA}	gCOD m^{-3}	0.40	0.30	0.50
b_A	day^{-1}	0.05	0.04	0.06
i_{XB}	gN (gCOD)$^{-1}$	0.08	0.04	0.12
μ_A	day^{-1}	0.50	0.48	0.53
Settling model				
SVI	-	100	75	105
f_{NS}	-	0.00228	0.001	0.005
V_0	m^3 day^{-1}	474	427	521

3   RESULTS AND DISCUSSION

Figure 3 shows the time series (only evaluation period) of two designs: one in which the denitrification-nitrification is achieved (Working Design or WD) and another one in which it is not (Non-Working Design or NWD). The daily and weekly pattern is clearly observed. The main difference between the two designs corresponds to the ammonium concentration; the TN concentration (although not so different) is still lower in the WD (in consequence of the low ammonium) while the TSS is higher due to the biomass generated in the biological processes.
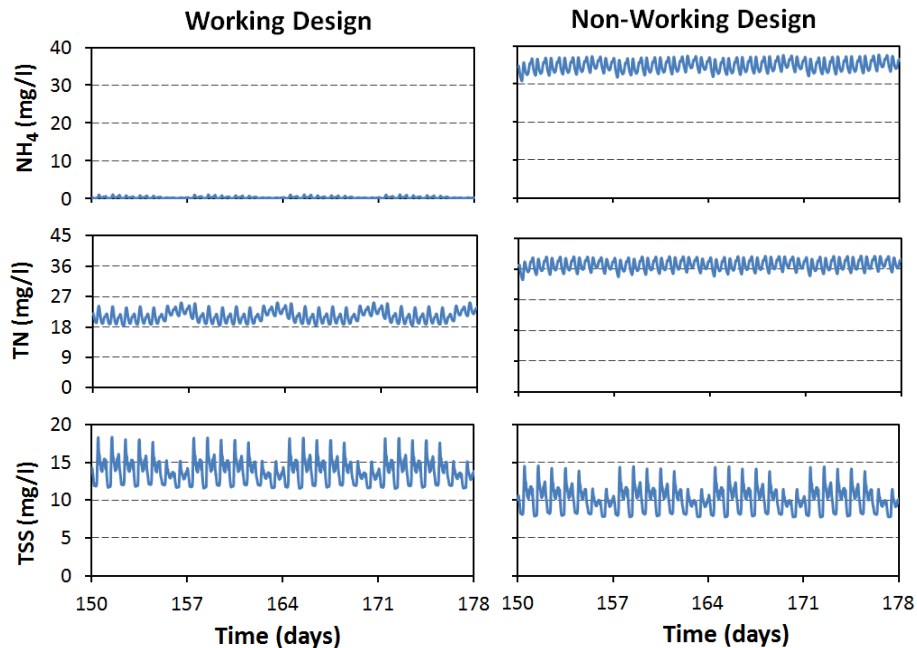

Figure 3. Time Series results along the 14-day evaluation period of two design proposals (a working and a non-working design).

For the working and non-working designs in Figure 3 we analyse the effect of considering uncertainty. Figure 4 shows the histograms of the NH$_4$, TN and TSS average values in the effluent. The uncertainty in the outputs is in general lower in the WD than in the NWD. The standard deviations (sd) of the average NH$_4$ concentration is around 0.14 mg/l in the WD and 3.70 mg/l in the NWD. For the TSS the sd is 1.30 mg/l in the WD and 3.17 mg/l in the NWD. This tendency is not observed for TN with a sd of 3.59 mg/l in the WD and a sd of 1.90 mg/l in the NWD (the variability induced by the solids seems to be higher than the variation provoked

by the ammonium). With respect to the normality of the distributions, the Lilliefors test rejects the null hypothesis (that the distributions are normal) at a 5% significance level in the case of the NH_4 and TN concentrations but not for the TSS histograms (closer to normality since they are the result of different aggregating processes).
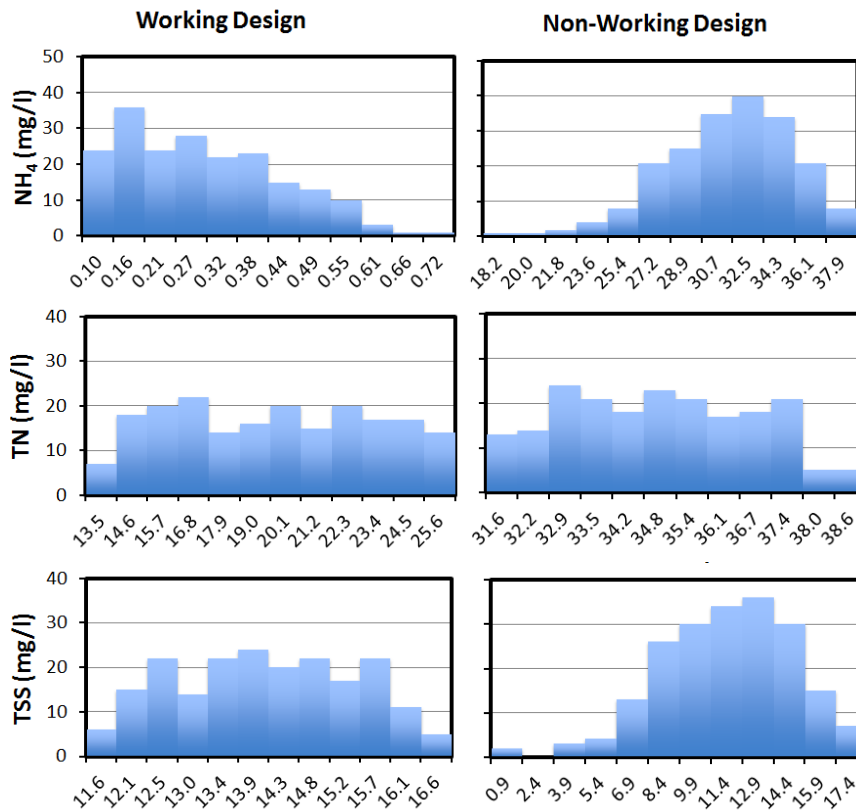

Figure 4. Histograms of the average values of NH_4, TN and TSS in the effluent for a Working Design (WD) and a Non-Working Design (NWD).

Figure 5 shows the distribution of the maximum (on the left) and average (on the right) values of the NH_4, TN and TSS in the effluent by means of their median (50% percentile) and 90% percentiles along the 100 design scenarios. The percentiles are plotted together with the effluent requirements (Table 1). Note that the design scenarios are sorted in descending order of their 50% percentile (for each of the effluent parameters considered), and therefore a certain design appears with different abscissa value at each graph. For example, a design with a high ammonium removal performance may have a high "design scenario number" for the NH_4 effluent values (both maximum and average) while it may have a medium value in the TN graphs and a low "design scenario number" for the TSS.

These results (Figure 5) show that in terms of NH_4 and TN effluent values, the effect due to varying the design scenario is much higher than the effect of the uncertainty. On the contrary, in the case of TSS the uncertainty causes higher variation than the changes in design. This may be due to the uncertainty in the settling parameters (Table 3). These sources of uncertainty might be inducing a higher impact in the TSS effluent than considering a variety of designs even when including some plants that nitrify and others that do not. Given the proximity of the maximum and average percentiles, in the following all the results will be discussed in terms of the average results.
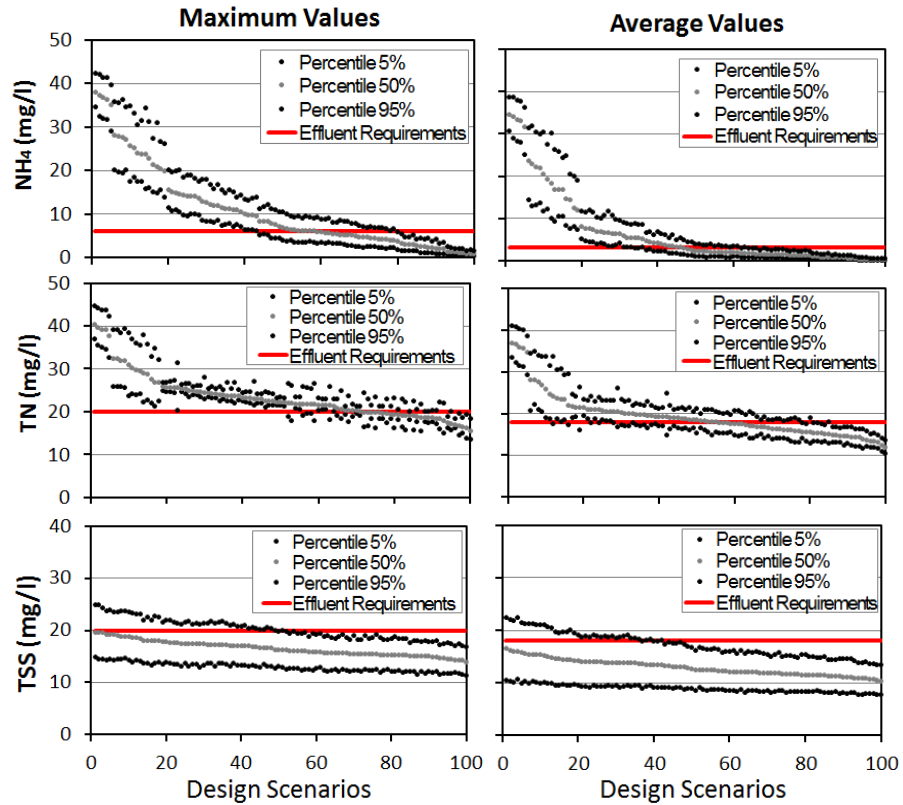
Figure 5. Median and 90% percentiles of the maximum and average values of the NH$_4$, TN and TSS effluent concentrations for 100 plant designs.

Figure 6 helps to understand the relationships between the output variables by analysing the distributions of the 100 average values of NH$_4$, TSS and TN at their 85% percentile and their 95% percentile. The correlation between the TSS and NH$_4$ in the effluent is not very strong (r^2=0.2) although it can be seen that in general low ammonium concentrations are related to high concentration of total solids. In contrast, the ammonium and total nitrogen are quite closely related (r^2=0.75): while keeping a very strong correlation for high NH$_4$ and TN values (NWD), their relationship is fuzzier for high nitrogen removal rates (WD). The reason is that the total nitrogen is the sum of the organic (nitrogen in the biomass) and inorganic nitrogen, and therefore, in the WD the nitrogen contained in the solids leads to some variability in the TN results. Finally, the relationship between the total nitrogen and the total solids is quite weak (r^2=0.16) and the only conclusion is that high nitrogen concentrations (NWD) are related to low concentrations of total solids.

The designs that fulfil the effluent criteria (Table 1) are those below the "Effluent Requirements" lines in Figure 5. Since the designs appear with different abscissa value for the different criteria (Figure 5), we found that only 2 out of the 100 evaluated designs met all the effluent requirements at 0.95 POC. These two designs compared to the BSM1 design values (Figure 7) are: 119% and 126% in terms of volume; and 117% and 112% in terms of waste flow rate. In the case that a POC of 0.85 could be accepted (a higher risk of not complying with the effluent requirements is assumed), 8 designs out of 100 are eligible (Figure 7). All these plants have larger volumes than in the default BSM1 model but might have lower or higher values of waste flow rate. It seems that for the complying designs the volumes and flow rate values of the WDs are not correlated (Figure 7).
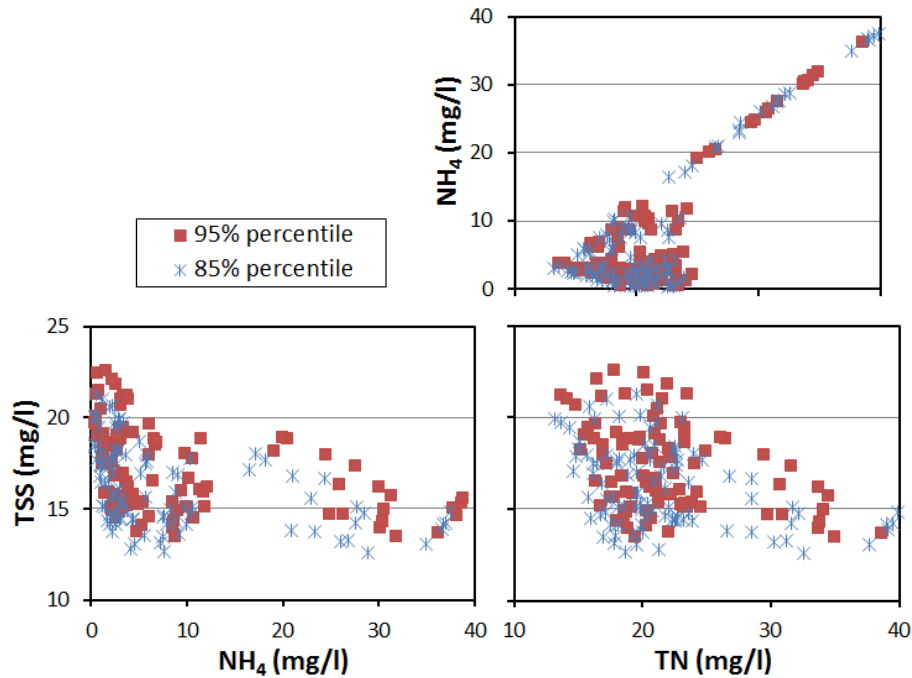
Figure 6. Relationships between the output variables expressed as 95% and 85% percentiles of the average values of NH_4, TN and TSS in the effluent.
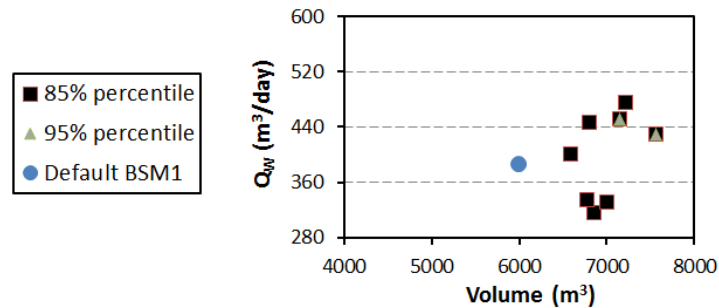

Figure 7. Relationship of the volumes and waste flow rates of the designs that fulfil the effluent requirements with a 95% and 85% probability of compliance

4   CONCLUSIONS

The potential of a new tool for design of WWTPs under uncertainty has been shown. For that aim, the design of a nitrification-denitrification wastewater treatment plant has been analysed assuming the BSM1 plant configuration and taking into account the most important sources of uncertainty with respect to the modelling of the biochemical processes and settling mechanisms. The main findings are:

- Taking into account the sources of uncertainty is important when tackling a design problem. In this example, they have caused an output uncertainty (measured by the standard deviation) of 0.14 mg/l in the average effluent concentration of ammonium (49% of its mean value), 3.59 mg/l in the total nitrogen (18% of its mean value), and 1.30 mg/l in the total solids (9% of its mean value).
- While the BSM1 plant fulfills some effluent requirements using the default parameter values, it has been shown how the design variables need to change (higher volumes) to guarantee a probability of compliance of 0.95.

The main advantage of using this methodology in comparison with the traditional design guidelines is that it allows estimating the probability of compliance of a certain design. In consequence, the engineering firm, the end-user (city) or consultancy will be better informed about the risks assumed and will therefore be able to adopt more robust design solutions.

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