The Inclusion of Variability and Uncertainty Evaluations in WWTP Design by Means of Stochastic Dynamic Modeling: The Case of Eindhoven

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ABSTRACT

This paper illustrates how a dynamic model can be used to evaluate a plant upgrade using post-upgrade performance data. The case study is that of the Eindhoven WWTP upgrade completed in 2006. As a first step, the design process was analyzed and the choices regarding variability and uncertainty (i.e. safety factors) were made explicit. As a second step, a dynamic model of the plant was set up, able to reproduce the anticipated variability. The third step was to define probability density functions for the parameters assumed to be uncertain, and propagate that uncertainty with the dynamic model by means of Monte Carlo simulations. The last step was the statistical evaluation of the simulation results. This work should be regarded as a "learning exercise" increasing the understanding of how and to what extent variability and uncertainty are currently incorporated in design guidelines and how model-based post-project appraisals could be performed.

KEYWORDS: Design guidelines; probabilistic design; plant reliability.

INTRODUCTION

Inputs and outputs of WWTPs are neither steady nor perfectly known (Belia *et al.*, 2009). WWTP influent and operation are the result of both environmental and anthropogenic phenomena, which are both variable (changing over time) and uncertain (we cannot predict them with complete certainty).

The dynamic simulators currently available can capture the impact of a variable influent by using time series as inputs. To evaluate uncertainty most engineers use scenario analysis, whereby one model input (influent, model parameter) or a combination of model inputs is varied for each simulation. A more quantitative way to evaluate the ability of a plant to meet a given effluent permit when looking into the future (conditions of uncertainty) is the combination of dynamic simulation with Monte Carlo (MC) analysis.

Design guidelines (government, literature or in house) are typically static in nature. Variability in the influent or the response of the biomass or even the reliability of a process is often accounted for through the use of specific safety factors and combinations of key design parameters such as temperature, flows, loads, etc. The selection of the safety factors and the combination of the design parameters are meant to make sure that the selected volumes, surface areas, aeration system, etc, can produce the desired effluent under all expected conditions (except force majeure) evaluated under steady-state conditions (i.e. fixed influent).

The Eindhoven WWTP was used as case study to investigate how variability and uncertainty can be incorporated in design guidelines and how to perform model-based post-project appraisals. The Eindhoven treatment plant is operating at its design load which allows for a direct comparison of the design assumptions with plant performance data. The original retrofit project investigated the extension of the Eindhoven WWTP – UCT process implemented as concentric circular tanks – which was required because of more stringent N- and P- removal limits, the need to meet the standards of the urban water directive and the need to extend the hydraulic capacity of the biological train. The upgrades were completed in March 2006. To evaluate the performance of the upgraded plant for the design horizon foreseen in the upgrade, the plant model was tested for all of the key parameters identified by the design engineers as highly variable or uncertain. A detailed description of the plant can be found in Cierkens *et al.* (2012). More details on this work can be found in Benedetti *et al.* (2012) and Belia *et al.* (2012).

MATERIAL AND METHODS

If a dynamic model is to be used to evaluate the reliability of a design, the dynamic model simulating the treatment plant has to account for the same variability and uncertainty as the design engineers anticipated in their approach. The former, i.e. the variability of these key design parameters can be easily captured in the dynamic model through the use of long-term (e.g. one year) time series as inputs. For the latter, a method of quantifying the uncertainty of other design parameters would be to describe the parameters with probability density functions (PDF), and to incorporate them in the modeling results through the use of MC simulations.

Dynamic model set-up

The model originally set up in a previous project (Benedetti *et al.*, 2010; Nopens *et al.*, 2010) was used as the starting point for this study. The 2010 model – implemented in WEST (www.mikebydhi.com) – was modified to run long-term simulations by implementing controllers as substitutes for measured inputs of operational variables like airflow and recycle flows, as those data were available only for limited periods of time. To reproduce a typical model-based evaluation of a design, the model (of the upgraded plant) was built and simulated with input data from the year 2000 (pre-upgrade) producing the output that would have been obtained and evaluated by the modeler at the time of the design. That output was then compared to process and effluent data from 2008 (post-upgrade) to make an ex post evaluation of the actual quality of the translation of the steady-state design into the dynamic model-based design framework. The evaluation was made by comparing model results and plant data on the basis of yearly averages and cumulative curves, not time series, as the plant influent and effluent were from two different years (2000 and 2008), and hence not directly comparable.

The input data used covered the period of 1 February 2000 to 31 January 2001 and included:

- influent flow measurements with 5-minute frequency, averaged in 30-minute intervals to reduce the measurement noise;
- daily composite samples (60 points per year) with concentrations of COD, TKN and PO_4;
- daily average temperature in the tanks (365 points per year).

Uncertainty

The sources of uncertainty and variability mentioned in the design documents were identified and translated in the framework of dynamic modeling and MC simulation. The majority of the sources was linked to influent and process temporal variability and was dealt with dynamic simulations with adequate input frequency and duration. Some sources were identified, but not accounted for in the design, therefore the values of model parameters linked to these sources were fixed at their default values during the MC simulation. The remaining three sources were quantified and incorporated in the MC simulation, by means of defining a PDF for the model parameters corresponding to the uncertainty source. These were:

- Non-settleable fraction of solids in primary settler (removal efficiency).
- Certainty factor: this factor accounted for non-ideal conditions for pH, toxic compounds and dissolved oxygen (DO) in some parts of the system; it multiplies the aerobic residence time.
- Overall peak factor: the determined oxygen input is multiplied by this factor to account for all unaccounted uncertainties.

Five hundred (500) Monte Carlo (with Latin Hypercube Sampling) 1-year simulations were run in WEST with the model of the plant calibrated for year 2000 and fed by data of year 2000, to conduct the uncertainty analysis of the designed plant upgrade (Benedetti *et al.*, 2011). The results of the MC simulations were evaluated by comparing them with cumulative curves of NH_4 and NO_3 in the effluent from off-line daily composite samples in year 2008. If the accounted variability and uncertainty in the dynamic model is sufficient, one would (with some quantified confidence) expect the year 2008 data to be included in the uncertainty bands of the model prediction. The uncertainty analysis was performed for the daily composite ammonia time series, since this was used as one of the criteria on the basis of which the plant compliance is judged (not to exceed 3 $mgNH_4$-N/l on a daily average basis).

RESULTS AND DISCUSSION

Dynamic model results

The simulation results of the calibrated dynamic model fed with year 2000 data were compared to measurements from on-line sensors or off-line analyses of daily composite samples (52 points per year) of year 2008 data. For each water quality component, the simulation output and plant data cumulative curves were compared. As already stated, the input data used for the simulation were from 2000 (pre-upgrade), while the measured process and effluent data were from 2008 (post-upgrade). All simulated cumulative curves for the above components reproduce the on-line data (see Figure 1 for two examples) and recycles (predicted by controllers) reasonably well. The observed deviations may be due to model structure and calibration issues. However, in this particular case another reason is apparent, i.e. the loading in the two years (2000 and 2008) is significantly different, with a decrease of 14% for annual averaged NH_4 and 22% for annual averaged COD between 2000 and 2008. Despite these deviations, it is believed that the model can serve as a good basis for the intended exercise. Nevertheless, it is suggested to further investigate the correctness of the model structure and the implementation of all controllers, to be able to better reproduce the observed variability. However, this is outside the scope of this work.

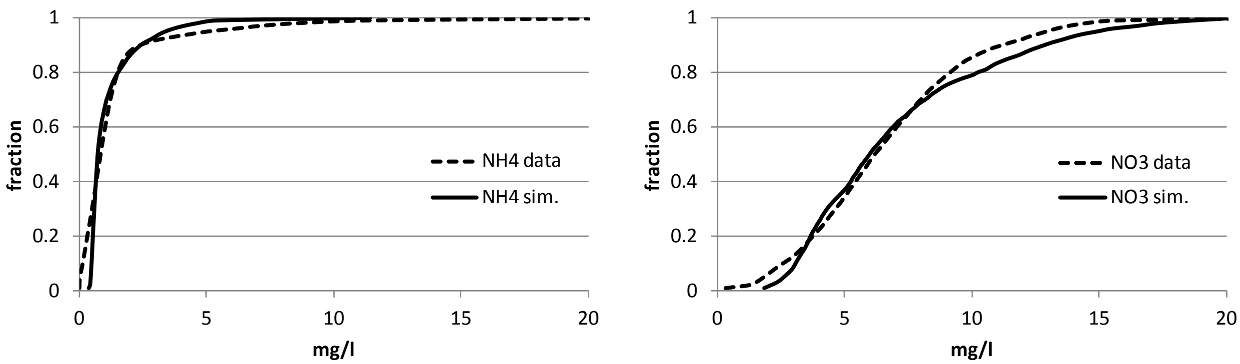

Figure 1. Cumulative curves for on-line measured (dashed lines) and simulated 30-minute data (full lines) for NH4 and NO3 concentrations at the end of the outer ring.

Dynamic model results including uncertainty evaluations

At this stage, the dynamic model is now applied including the uncertainty translated from the design safety factors (as was discussed earlier). Again, cumulative curves have to be used for comparison as input and output time series are from different periods and cannot be directly compared. Figure 2 shows the cumulative curves from the available measurements and those from the MC simulations (showing the median and 5^{th} and 95^{th} percentiles). As can be seen in Figure 2, the 90% confidence interval (CI), i.e. the region lying in between the outer percentiles (dotted lines), includes the NH_4 measurements (i.e. the solid line lies inside the 90% CI region) as of the value 2.5 $mgNH_4$-N/l and higher. This was considered a positive outcome since this concentration range is in this case the most important for plant compliance. The model predicted that the effluent limit of 3 $mgNH_4$-N/l will not be exceeded between 75% and 95% of the time during the evaluation period (1 year), and this with a 90% confidence. At lower concentrations there is an overestimation of the simulation results compared to the measurements (i.e. the simulated CDF is located consistently at higher NH_4 values compared to the measured one). This suggests a need of further improvements in the model (currently under investigation), and the inclusion of uncertainty in influent data, as the TKN load in year 2008 was significantly lower than in year 2000, while the influent load to the treatment plant during the upgrade study was considered constant (catchment growth negligible). The observed load decrease falls in the category of “unknown unknowns” or “total ignorance” (Belia *et al.*, 2009) as a source of uncertainty.

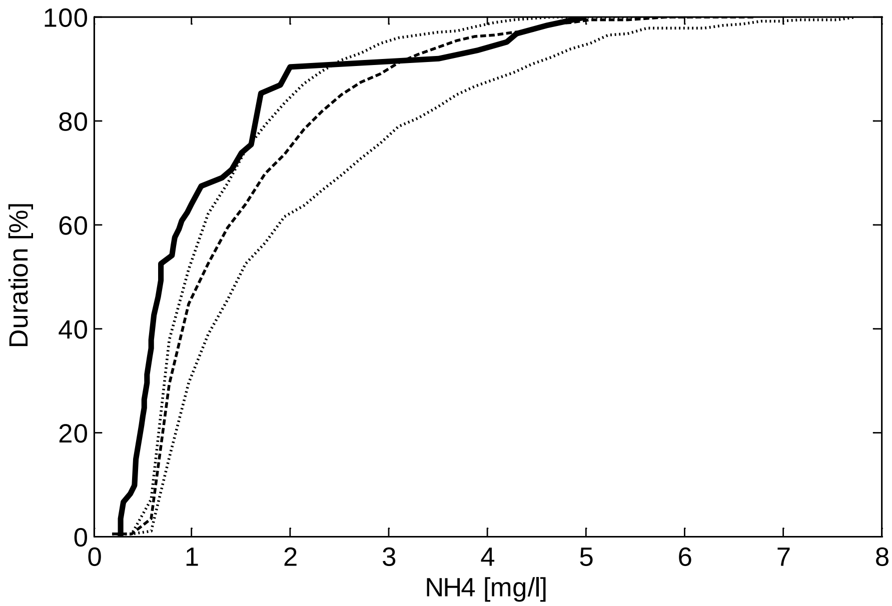

Figure 2. Cumulative curves for effluent NH_4 concentration; solid line: daily composite samples (2008 data); dashed line: 50^{th} percentile of MC simulations; dotted lines: 5^{th} and 95^{th} percentiles of MC simulations.

CONCLUSIONS AND PERSPECTIVES

The following points summarize the main outcomes of the method implemented in this study; they are specific to the Eindhoven plant and upgrade study:

- all "safety factors" that were used to account for uncertainty in the design phase were listed and interpreted;
- a translation method of the design, the safety factors and the uncertainties into a dynamic model with Monte Carlo simulations was outlined;
- the uncertainty analysis proved to be reliable for the variable of interest for plant compliance (effluent daily composite samples of NH_4 at 3 mg/l and above) but not for some other variables;
- the two main sources of uncertainty which require further attention are the influent loading and the plant operation and control.

This project can be viewed as a "learning exercise" increasing the understanding of how variability and uncertainty are currently incorporated in design guidelines and how model-based post-project appraisals could be performed. A follow-up project will investigate further the quantification of the sources of uncertainty identified in the guidelines and the relevance of their decomposition and inclusion in the calibrated model. It is hoped that knowledge acquired in this project will contribute to the development of a comprehensive probabilistic design methodology that makes use of stochastic dynamic models.

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