A quantitative risk analysis tool for design/simulation of wastewater treatment plants

D. Bixio*, G. Parmentier*, D. Rousseau, F. Verdonck***, J. Meirlaen***, P.A. Vanrolleghem*** and C. Thoeye***

* Aquafin nv, Technology Department, Dijkstraat 8, B-2630 Aartselaar, Belgium
(E-mail: *davide.bixio@aquafin.be*)

** Department of Applied Ecology and Environmental Biology, Ghent University, J.Plateaustraat 22, B-9000 Gent, Belgium

*** Biomath Department, Ghent University, Coupure Links 653, B-9000 Gent, Belgium

Abstract Uncertainty is a central concept in the decision-making process, especially when dealing with biological systems subject to large natural variations. In the design of activated sludge systems, a conventional approach in dealing with uncertainty is implicitly translating it into above-normal safety factors, which in some cases may even increase the capital investments by an order of magnitude. To obviate this problem, an alternative design approach explicitly incorporating uncertainty is herein proposed. A probabilistic Monte Carlo engine is coupled to deterministic wastewater treatment plant (WWTP) models. The paper provides a description of the approach and a demonstration of the general adequacy of the method. The procedure is examined in an upgrade of a conventional WWTP towards stricter effluent standards on nutrients. The results suggest that the procedure can support the decision-making process under uncertainty conditions and that it can enhance the likelihood of meeting effluent standards without entailing above-normal capital investments. The analysis led to reducing the capital investment by 43%, producing savings of more than 1.2 million euro.

Keywords Activated sludge; design; modelling; nutrient removal; risk assessment

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Introduction

Aquafin NV is a private company responsible for pre-financing, design, construction and long-term operation of the collectors, pumping stations and municipal wastewater treatment plants (WWTPs) in Flanders (the northern region of Belgium) and is currently operating more than 180 WWTPs.

In terms of the EU Directive 271/91 on Urban Wastewater Treatment, the whole Flemish region was designated as a sensitive area. This meant the implementation of nutrient removal for all treatment works in agglomerations of more than 10,000 population equivalents (PE). The large capital investment and the need to build at a rapid pace imposed a systematic approach for the construction of new infrastructures and the upgrading of the existing ones. Key tools for a quick and economically sound implementation of the program were standardisation for new WWTPs and extended use of dynamic modelling for retrofitting existing WWTPs (Ockier *et al*., 2001). On the one hand dynamic modelling offered potential for substantial savings (e.g. Bixio *et al*., 2000; Boonen *et al*., 2000); on the other hand the complexity in the analysis was increased and the footprint reduction of the biological reactors implied reduced safety margins. Since the calculations upon which the simulations are based require estimates of a large set of parameters, and since in practice only limited information is acquirable, the evaluation of risk plays a central role in the analysis.

An innovative procedure is herein reported. The aim of this procedure is to quantify the causal link between the level of uncertainty and its determinants. The risk analysis approach and its management philosophy will be illustrated with an actual renovation of a WWTP. Results are contrasted with those obtained by conventional approaches.

Materials and methods

The quantification of the uncertainty of the system as a whole is carried out by the following steps.

1. Assigning information about the probability distribution of each input parameter and variable in the system.
2. For every calculation, the simulation uses a value for each input parameter randomly selected by the Monte Carlo engine from the probability density function for that variable. Over multiple calculations, the Monte Carlo engine produces a range of values for the input parameters and variables that reflect the probability density function of each input parameter and variable. The set of samples ("shot") is entered into the deterministic model.
3. The deterministic model is then solved for each shot, as it would be for any deterministic analysis.
4. The model results are stored and the process is repeated until the specified number of model iterations is completed.

These steps are set out schematically in Figure 1.

The probabilistic simulation takes into account both input and parameter uncertainty, such as dealing with the difficulties in estimating model parameters and taking into account the inherent uncertainty in specific phenomena. The Monte Carlo engine, however, does not account for model uncertainty.

This iterative process generates a probability density function or cumulative density function of the output (Rousseau *et al.*, 2001). Based on the distribution of the output, a risk level representing the high end (e.g. 95th percentile), central tendency (median or mean), or any other desired level of probability can be identified. It is therefore possible to represent uncertainty in the output of a model by generating sample values for the model inputs, and running the model repetitively. Instead of obtaining a discrete number for model outputs as in a deterministic simulation, a set of output samples is obtained (Cullen and Frey, 1999).

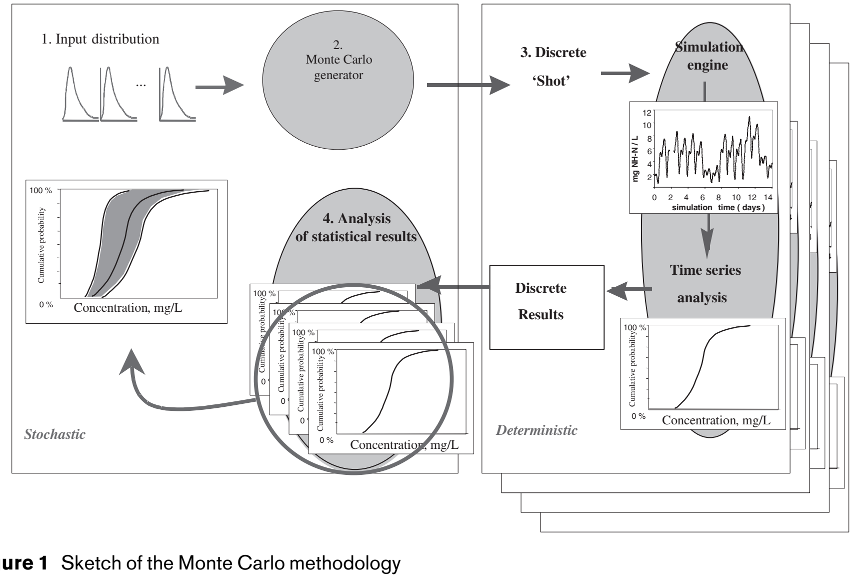

Figure 1 Sketch of the Monte Carlo methodology

Case study: renovation of the WWTP Hove (Belgium)

Definition of the issue

The proposed methodology was applied in the upgrading of a typical conventional activated sludge system to nutrient removal standards.

The municipal WWTP at Hove serves a community of 28,000 population equivalents (PE). Primary treatment consists of fine screens, an aerated sandtrap and rectangular primary clarifiers (Figure 2). Secondary treatment is achieved by a conventional single-stage activated sludge system. Phosphorus is removed by simultaneous chemical precipitation. The excess sludge is aerobically digested, thickened by gravitation and mechanically dewatered; the sludge is then transported to a nearby facility for further treatment.

The WWTP must be upgraded to comply with the new EU standards on nutrient removal. As little or no development of the urban drainage system is expected and 98% of the inhabitants are connected to the sewer system, the available information is considered representative for the scenario analysis. The main determinants and the new effluent consent are summarised in Table 1.

The boldface values in Table 1 refer to figures upon which the environmental performance is judged. At present, the WWTP does not meet the nitrogen effluent consent.

One important feature to achieve an optimal allocation of resources in the renovation project is maximizing the reuse of the existing reactors. Most of the existing process units are nearly twenty years old, but generally in good condition. Moreover, extra land to be acquired is situated in an area designated for agricultural use (and is expensive!). With the

LEGEND

1. screw pump pit
2. main building
2.1 blower basement
3. fine screen
4. sandtrap
4.1. sandtrap basement
5. sand silos
6. Prime sedimentation tanks (PST and stormwater
7. aeration
8. secondary sedimentation tanks
9. effluent
10. recirculation building
11. recirculation channel
12. sludge oxidation tanks (SOT)
12.1. SOT and PST basement
13. Thickener
14. FeCl3 tank
15. Sludge building
16. container lime milk
20. conveyor belts
21. gates

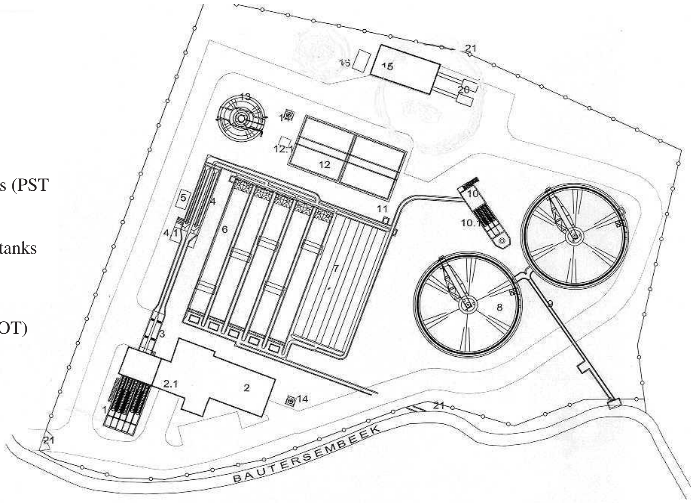

Figure 2 Layout of the WWTP Hove

Table 1 Influent loading and effluent quality during 1996–2000: 280 measurements

	Loading, kg.d^{-1}			Effluent in 2000, mg.l^{-1}			Consent,
	AVG	STDEV	Extra load	MIN	AVG	95%ile	mg.l^{-1}
BOD	924	696	174	<3	5	**8**	**25***
COD	2.625	1.705	330	25	47	**79**	**125***
SS	1.384	1.379	296	<2	12	**24**	**35***
TN	319	157	25	6,6	**18,9**	34,2	**15****
TP	51	28	8	0,4	**1,2**	2,0	**2****

* 95th percentile; ** Annual Mean

premises that primary clarification has a negative impact on the life cycle costs (data not shown), a solution converting (a) primary clarification and stormwater tanks to predenitrification and (b) the aerobic sludge digestion tanks to intermittent aeration tanks, was selected as possible alternative in the feasibility study.

The existing bioreactor capacity of this alternative (4.924 m^3) is approximately 20% smaller than the one calculated by the ATV 131 guidelines (ATV, 1991). However, such a nominal capacity is the result of static calculations with non-site-specific safety factors. Reducing the safety factors to match the available volume would result in savings of more than 1.2 million euro (or 43% of the total investment cost). But what are the most likely consequences of a more critical design?

With the premise that in this case study the major consequences are an increased risk of non-compliance with the effluent nitrogen consent, the analysis will specifically focus on the risk of failure on the nitrogen consent.

Results

In the evaluation of the risk, first conditions such as "optimally operated WWTP", representative influent load variations, and "representative rainfall" year were analysed (data not shown). The first set of simulations were run under a set of very restrictive explicit assumptions such as: (a) on-line MLVSS set-point control at 2,5 g/L; (b) optimal on-line control of the intermittent aeration; (c) "representative" rainfall distribution; (d) process temperature distribution between 9°C and 20°C; (e) load probability distributions of a standard year; (f) no mechanical failure or human error. In these conditions, the simulations show that the annual effluent results are virtually not affected by the expansion (data not shown). Figure 3 shows the expected yearly results for the alternative without expansion (from now on: alternative 1).

In Figure 3, the horizontal axis depicts the level of effluent concentration and the vertical axis shows the cumulative effluent distribution. The variability due to time is captured in the cumulative distribution curve. The uncertainty due to model input uncertainty is visualized as a gray band around the variability distribution. For each level of cumulative probability, the 5th percentile, 50th percentile and 95th percentile uncertainty curves are traced (full lines).

To explain the meaning of these figures, the actual results of the WWTP for the year 2000 are also reported (dotted line), and described below. We can say that in 2000 more

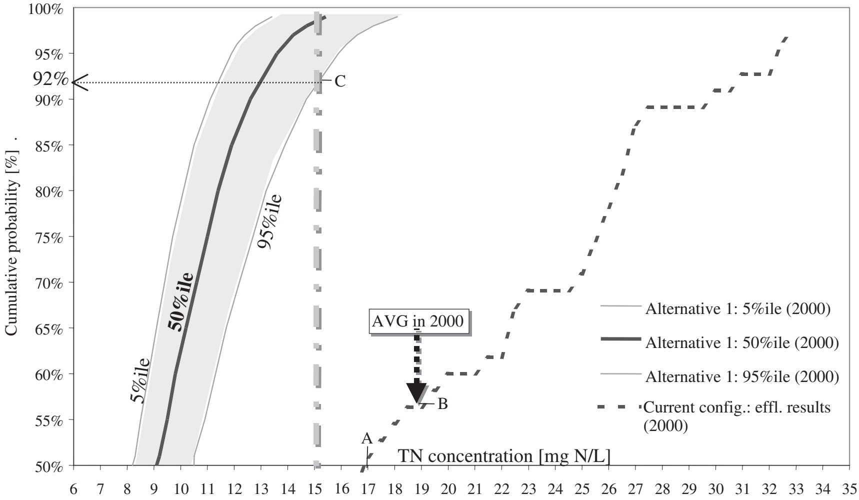

Figure 3 Alternative 1: simulated effluent nitrogen results for a representative year

than 50% of the TN measurements in the effluent were over the limit of 15 mg/L, the median being 17.0 mg N/L (point A). In fact, the mean corresponds in this case to the 57%ile (point B). Since this curve stems from observations and not from model predictions, no uncertainty curves are drawn (actually, one could also construct an uncertainty band on the observations e.g. based on measurement error). Now passing to the analysis of the results of alternative 1, we may say with 95% certainty that 92% of the expected results will be below the consent (point C). A total of 100 shots were run to build the effluent confidence interval as illustrated in Figure 3. The results of each shot are indicative of the distribution of 365 24 h composite samples.

The second step in the analysis was a keen evaluation of the margin of safety available. In other terms, the analysis focused on the evaluation of the process vulnerability when the restrictive simulation assumptions are not met.

The behaviour of the nitrification capacity when the MLVSS set-point of 2.5 g VSS/L cannot be reached, is reported as an example. Figure 4 compares the winter performance of the nitrification through the cumulative probability distribution of the effluent ammonia concentration for the alternative without expansion (dotted lines: alternative 1), and the one with expansion (full lines: alternative 2), during a cold winter and a biomass concentration of 2.3 g VSS/L. It is worth noting that a reduction of the MLVSS set-point of 0.2 g VSS/L corresponds to a reduction of the MLSS concentration of 0.3–0.5 g MLSS/L. Cold winter here means that the process temperature remains 9°C for more than two sludge ages.

The distributions of the effluent ammonia concentrations depicted in Figure 4 are indicative of critical conditions for the nitrification process. Thanks to a proper quantification of the uncertainty, we can say with 50% certainty that nitrifiers will be kept in the system for both alternatives on the one hand, and that only the alternative with expansion can assure the same condition with 95% certainty on the other.

This is a relevant issue because a wash-out of nitrifiers can endanger the annual consent on effluent total nitrogen (data not shown). The question is then: what is the risk, in winter, of a MLVSS equal or lower than 2.3 g/L (2.3 g VSS/L corresponding with 3.4 g/L ≤ MLSS ≤ 4.0 g/L) for more than, say, half a sludge age?

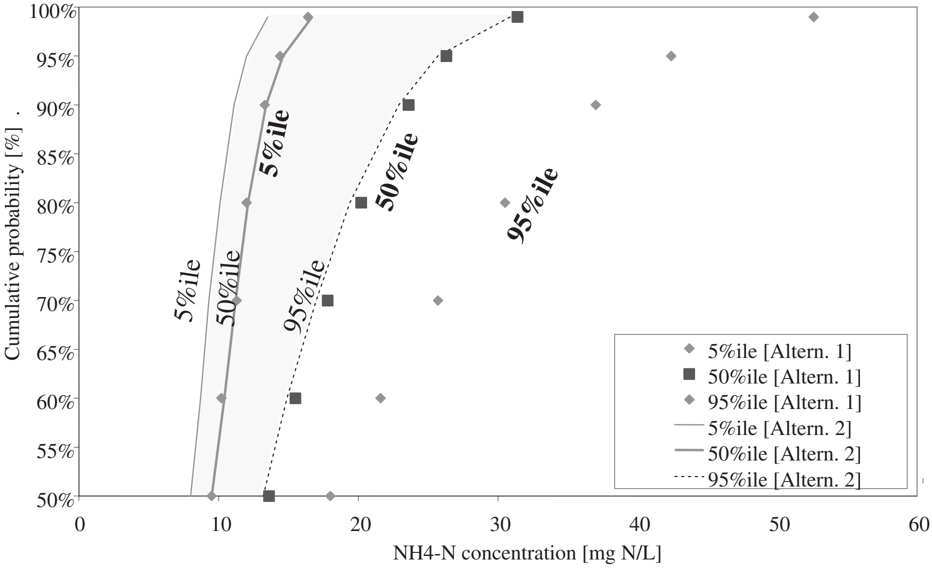

Figure 4 Simulated cold winter distribution of the NH4-N in the effluent: VSS control at 2.3 g/L

Discussion

Based on the proposed methodology, the risk manager no longer perceives the possible harmful effect based on arbitrarily defined generic safety factors, but puts the accent on where the ignorance/indeterminacy actually is.

Because the method provides an explicit way of calculating the probability distributions of the level of risk, it avoids the problems of compounding conservative values of input variables.

A clearly enunciated acceptable level of risk would provide a concise focus for evaluating how well resources are spent, saving the high-level management, regulatory agencies, public interest organisations or general public the need to understand the laborious details of the technical processes creating those risks. With risk analysis it is possible to determine that a particular risk represents the 50th, 90th, 95th percentile or any other percentile level of risk, or conversely, to select a level of risk that corresponds to the desired level of protection.

However, it is worth noting that the acceptability of a risk cannot be defined in isolation. A less risky course of action might be preferred to a riskier course of action, if that could be done at reasonable cost. For example, in the case study a reduction of 21% of the conventionally dimensioned volume yields a 43% reduction of the total investment costs (data not shown). Instead, if no existing infrastructures were available, ie if the WWTP could be built from scratch in a more suitable area, a 21% volume reduction would have yielded total savings of less than 6% (data not shown). Depending on the risk-aversion propensity of the decision-makers, the risks might be considered acceptable in the first but not in the second case. This holds particularly true when considering that the benefits enjoyed today by the risk-taking action imply higher investments in the future (increase of the overall general costs of the project plus necessity of extra piping when compared with alternative 2), if corrective actions will be necessary. Thus, acceptability of risk should be defined in terms of the risk-benefit tradeoffs.

The consequences of what happens should the outcome turn out to be bad have to be carefully evaluated from the beginning. For example, in winter the risk of having an MLVSS in the aeration basin equal or lower than 2.3 g/L for more than half a sludge age, is dependent on the dimensioning of the clarifier and the settling characteristics of the sludge. With the premise that the estimation of the latter is subject to a large degree of uncertainty, the analysis led to the following.

1. Precautionary actions such as design of an anoxic selector. Moreover, it is worth noting that for the case study the dimensioning of the secondary clarification unit is based on a semi-dynamic design, in which conventional safety factors are applied. The risk-based tool was used only to verify the results of the dimensioning. Technical judgement and experience were applied for the assignment of the settling properties of the sludge.
2. Investment in on-line control to minimise the vulnerability of the system to site-specific process disturbances such as first flush phenomena and industrial discharge.
3. Budget for stand-by aerators to be installed in the anoxic tank in case of necessity. This budget will only be used if analysis of the results from the start-up of the upgraded system proves that corrective actions are needed (phased approach).

Conclusions

Because of the possible savings when compared to costly extension of the plant volume, extensive plant optimisation through process analysis is a very interesting option.

Because the uncertainty can be reduced (at a cost!) but not eliminated, proper quantitative information about the causal link of the uncertainty can enhance the probability of optimal allocation of resources, reducing the disbursement of capital in excess of what is required. The proposed approach informs the designer about the causal link by explicitly incorporating uncertainty and variability in the analysis.

The acceptability of risk cannot be defined in isolation. A risk-cost benefit concept is more appropriate. At WWTP Hove, this approach helped to reduce the dimensioning of the biological reactors by 21%. A larger risk taking was accepted because of the 43% investment cost reduction.

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