INTEGRATING RISK ANALYSIS IN THE DESIGN/SIMULATION OF ACTIVATED SLUDGE SYSTEMS

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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 in 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, a useful demonstration of the general adequacy of the method and clarifies areas of strength and weakness.

The methodology has been used as a support of decision making in an upgrade of a conventional WWTP towards strict nutrient removal consents. The analysis led to reducing the capital investment by 43%, producing savings of more than 1,000,000 $.

The results suggest that the proposed methodology can enhance the likelihood of meeting effluent standards not entailing above-normal capital investment in a transparent, robust and tailor-made way.

BACKGROUND

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 the transposition of the EU Directive 271/91 on Urban Wastewater Treatment, the whole Flemish region was designated 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 WWTP's (Ockier et al., 2000). 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 it has introduced complexity in the analysis and implicitly reduced safety margins by decreasing the footprint of the biological reactors. 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.

GENERAL OBJECTIVE

Conventional design approaches account for risk management by deliberately calculating a conservative or high-end point estimate of risk. Such high-end point estimates result from the multiplication of high-end values for input parameters and variables. The larger the number of multiplied variables for which high-end values are selected, the higher the resulting safety factor (e.g.: combination of winter temperature, daily peaks, poor settling characteristics, etc.). This may in some instances be far above any realistic estimates. These approaches may lead to dissatisfactory allocation of the resources. The following question then arises:

How should engineers best integrate risk analysis into model-based design of activated sludge systems?

An alternative approach based on the combination of probabilistic modelling techniques with the available deterministic models may give a satisfactory answer. The aim of such a procedure is to quantify the causal link between the level of uncertainty and its determinants. It provides a way of explicitly incorporating uncertainty in the model-based process analysis.

In the first place, a research project was developed coupling a probabilistic Monte Carlo engine to the IWA (formerly IAWQ) activated sludge model (ASM) No. 1 (Henze et al., 1987). With the premise that nutrient removal in activated sludge is adequately understood (IWA, 2000), Monte Carlo simulation techniques can be satisfactory for this task, provided that:

- ⇨ Consistent high-quality data are available for a series of years.
- ⇨ Calculation capacity of desktop computers is powerful enough to solve the sophistication of the mathematical analysis within the practical timeframe of real-life projects.

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.

METHODOLOGY

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 fig. 1.

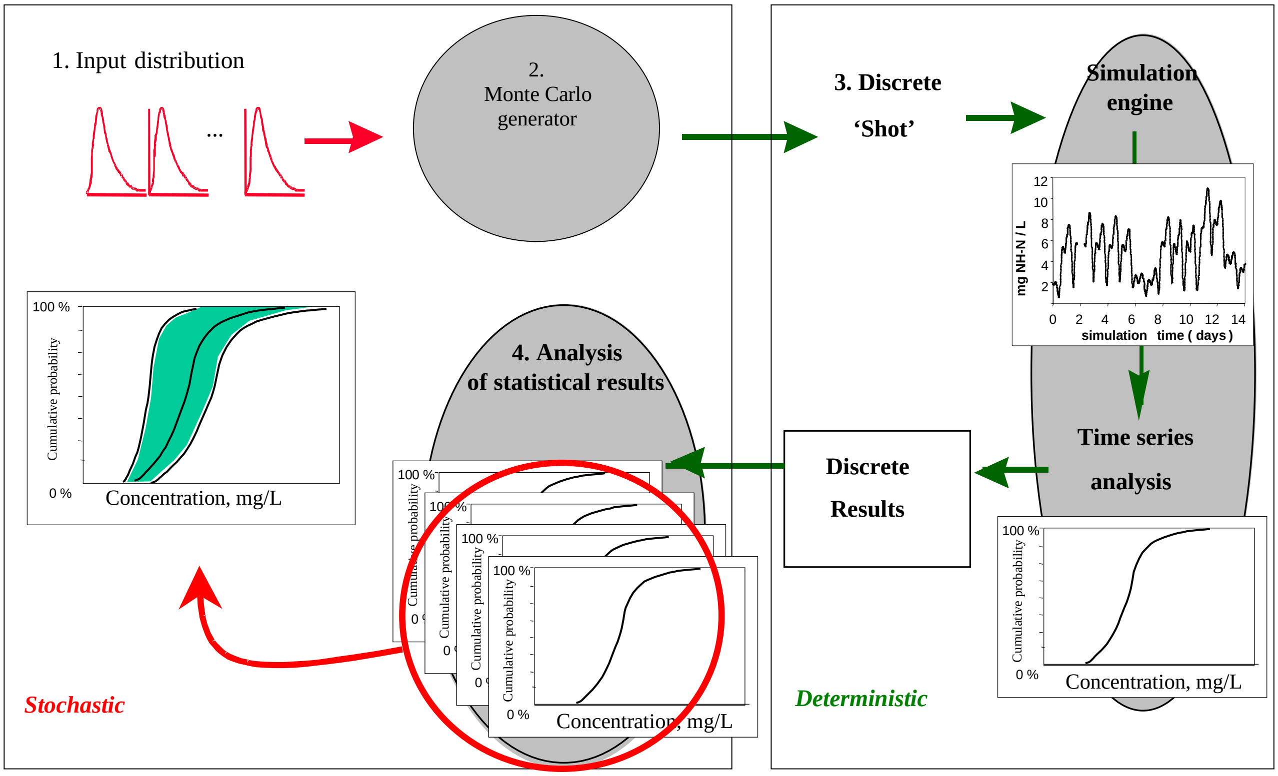

Figure 1. Layout of the Monte Carlo methodology

The probabilistic simulation takes into account both input and parameter uncertainty, in this way dealing with the difficulties in estimating model parameters and taking into account the inherent uncertainty in specific phenomena. The Monte Carlo engine, it is worth to note, does not account for model uncertainty.

A distinction ought to be made between uncertainty and inherent variability. Variability represents heterogeneity or diversity, which cannot be reduced through further measurement or study. Uncertainty represents ignorance about a poorly characterised phenomenon, which can sometimes be reduced through further measurement or study. In the current status of the project, the variability is assumed completely captured via the dynamic simulations and uncertainty is captured via the Monte Carlo simulation. Therefore, there is no need for a second order Monte Carloanalysis that would simulate variability and uncertainty in two loops, as illustrated in Grum & Aaldenberg (1999).

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 & Frey, 1999).

CASE STUDY: RENOVATION OF THE WWTP OF THE TOWN OF HOVE (BELGIUM)

The proposed methodology has been assessed in the context of a typical conventional activated sludge system that had to be upgraded for nutrient removal standards.

Description of the WWTP

The municipal WWTP of Hove serves a community of 28,000 inhabitants and has a capacity of 64,800 m³/d (17.1 MGD). A flow of approx. 21,600 m³/d (5.7 MGD) is treated biologically; the remainder only receives primary treatment.

Primary treatment consists of fine screens, an aerated sandtrap and rectangular primary clarifiers (fig. 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.

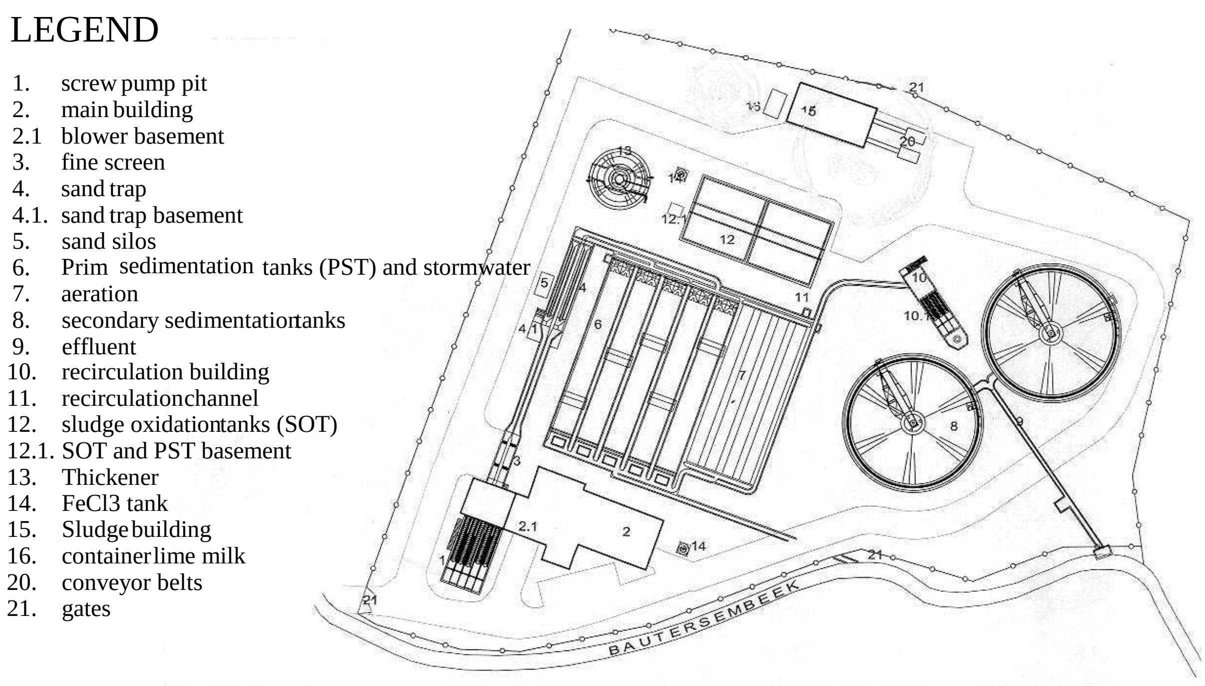

Figure 2. Layout of the WWTP Hove

The WWTP must be upgraded to comply with the new EU standards on nutrient removal and to provide secondary treatment to 6 Q14 (43,700 m³/d or 11.5 MGD).

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 effluent consent are summarised in table 1.

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

	Loading, kg.d^{-1}			**Effluent in 2000, mg.l^{-1}**			**EU consent, mg.l^{-1}**
	AVG	*STDEV*	*Extra load*	*MIN*	*AVG*	*95%ile*	
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

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

WWTP renovation: process configuration alternatives

One important feature for meeting an optimal allocation of resources in the renovation project is maximising the reuse of the existing reactors. Most of the existing process units are nearly twenty years old, but generally in good condition. Secondly, land must be acquired in an area designated for agricultural use (and is expensive !). With the premises that primary clarification has a negative impact on the life cycle costs (data not shown), a solution converting (a) primary clarification and storm water tanks to pre-denitrification and (b) the aerobic sludge digestion tanks to intermittent aeration tanks, was selected as possible alternative in the feasibility study (fig. 3). (alternative 1 for future reference). Other alternatives were also considered, but rejected in the analysis.

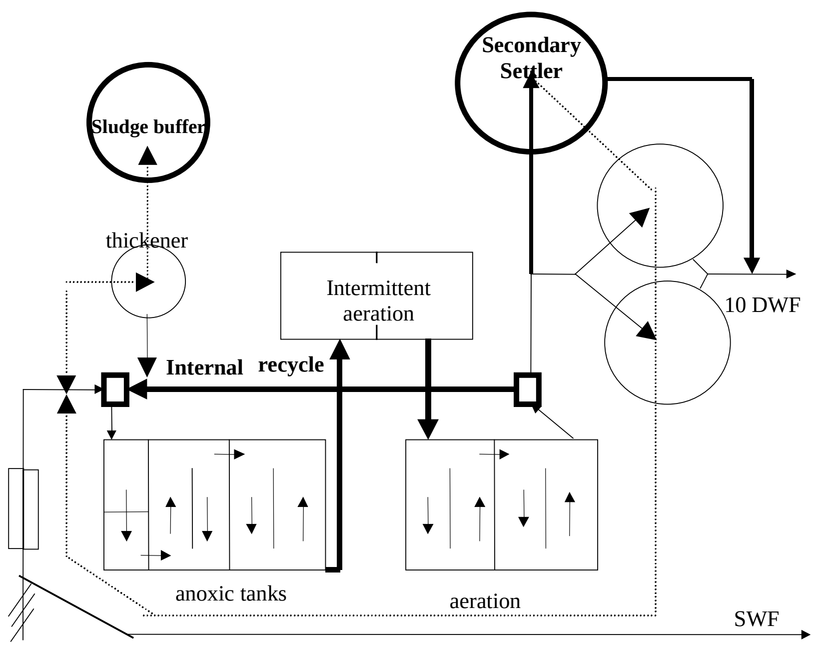

Figure 3. One process alternative for the renovation of the WWTP of Hove (in bold: new infrastructures)

The existing bioreactor capacity of the process alternative illustrated in figure 3 is 4,924 m³. The estimated renovation costs for this configuration are approx. 1,500,000 $.

Conventional design approach

The ATV guidelines A131 are used as a reference for conventional design (ATV, 1991). A process temperature of 10°C and the average pollutant load defined in Table 1 are introduced into the model; this selection yields a peak factor of 1.6 and a nominal bioreactor volume of approx. 6,000 m³ (fig. 4). The peak factor is derived from the size of the WWTP and the sludge age and it should implicitly reflect considerations over the daily variation of the pollutants.

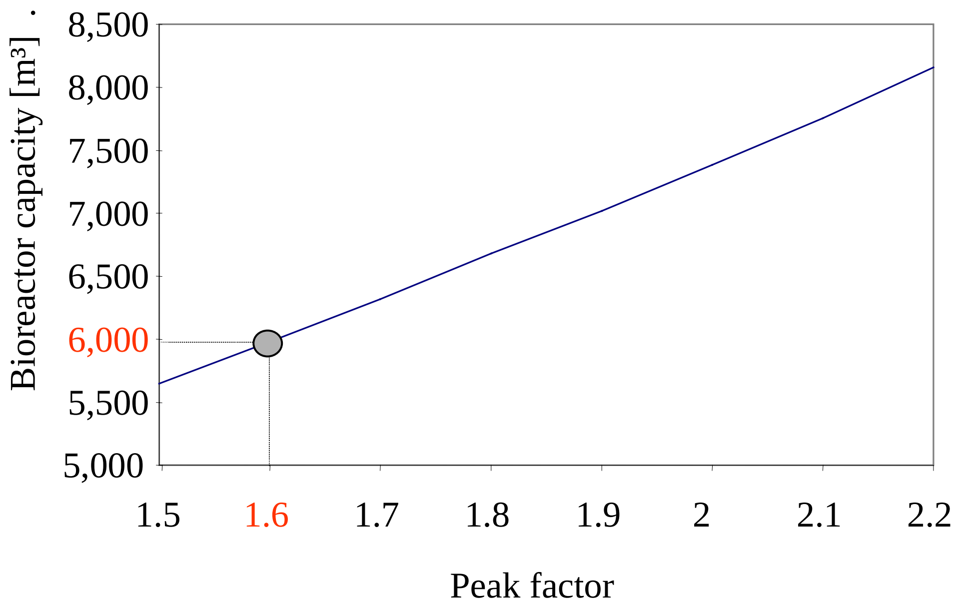

Figure 4. Static design: bioreactor capacity versus ATV ‘peak factor’, 10°C

The renovation cost with the required expansion of the bioreactor (alternative 2 for future reference) is approx. 2,500,000 $. Specifically to the bioreactor expansion, the following extra costs must be considered:

(a) A bioreactor expansion of over 1,000 m³, or 20% of the existing capacity	$ 290,000
(b) Provision of fine bubble aeration in the new bioreactor	210,000
(c) The secondary clarifiers must be dismantled to allow for the expansion	150,000
(d) Acquisition of new land	670,000
(e) Two new secondary clarifiers	260,000
(f) Extra piping	10,000
	$ 1,590,000

Thus, while the bioreactor itself costs 500,000 $, the overall cost of the bioreactor expansion rises by over 300%. These are situations often encountered in renovation projects in urban areas.

Proposed design approach

The proposed design approach consists of three stages (Bixio et al., 2000). The first two stages deal with data collection and preparation, the third step deals with the actual scenario analysis.

- ***Stage 1****: preliminary desk analysis.*

The calculations upon which the simulations are based require estimates of a large set of parameters. On the other hand, since budget and time limitations play a major role, only limited information is acquirable. Many estimates, however inaccurate they are, do not affect the effluent prediction; some parameters vary slightly from plant to plant. At this stage the evaluation of risk plays a central role in directing the engineer to rationalise the acquisition of the information. This can be done in a number of ways. One of which is a sensitivity analysis with the not yet-calibrated model, where best guesses for the probability distributions of the parameters and variables are assigned.

Relevant and immediately available in-depth information of the historical data series could be used. Historical records such as inflow, influent and effluent BOD_5, COD, SS, TN, KjN, NH_4-N, NOx-N, TP, settleable solids, and process data such as water temperature, sludge production, O2 profiles, SVI, etc. are available for a number of years. A statistical analysis brought some order to a seemingly amorphous (cfr standard deviations in table 1) and confusing time series. The application of cluster analysis helped to identifying a daily pattern, a weekly pattern as well as intense peaks associated to first flush phenomena. By dividing the time series in different mutually distinct classes and by applying filters to the different clusters the dispersion of the data has been reduced; in other words, a stronger correlation between different variables, given specified conditions, was identified. The latter is an important feature because direct observation is either not available for each relevant process variable or it is available but with different time scales. While very detailed information about flow rate measurements is available (on-line measurements), the effluent quality is measured once or twice a day, the influent quality once a week, etc. It is therefore worthwhile to find relationships between high- and low- frequency measurements. A regression relationship between the influent ammonium-nitrogen concentration versus the daily flow is set out in Figure 5.

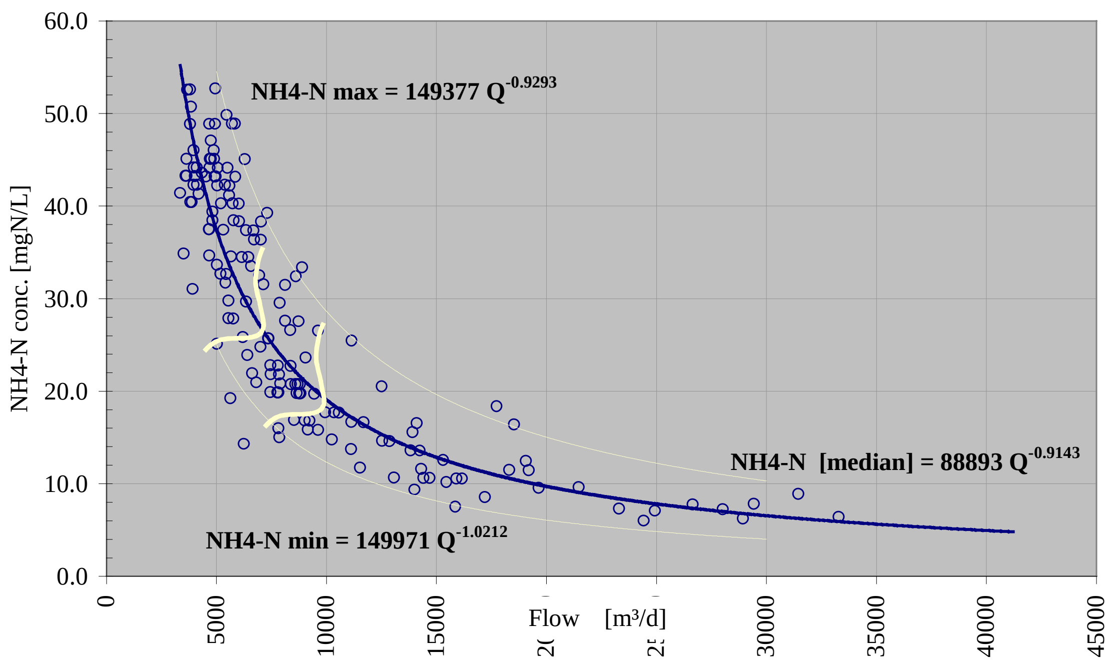

Figure 5. Influent NH4-N concentration vs daily flow: period 1/1/1997-31/12/2000

It is worth noting that the Monte Carlo engine can retain information about low-boundary, median and high-boundary regression curves, as well as their probability distribution (cfr. Figure 5).

- ***Stage** 2: field testing*

A measuring campaign has provided the basis for validation/rejection of the arbitrary assumption set-up in the previous stage, for the reduction of uncertainty and for complementation and further valorisation of the relevant historical data. This can be done in many different ways but a simple example can illustrate the basic features.

The COD fractionation of the raw wastewater is very sensitive to the estimation of the effluent results/footprint of the reactors; especially in light of a sub-optimal BOD/N and with a presumably high recalcitrant COD fraction (cfr. Table 1). An acceptable estimate of the COD fractionation for municipal wastewater can be obtained by physical-chemical methods (e.g.: Roeleveld and Kruit, 1998). With these methods, it is essential to know the particulate and dissolved COD fraction. However, this information was not available in the historical data series and the uncertainty related to expert judgement was sensitive to retaining decisions on investment. The measuring campaign could help in settling this issue in an acceptable manner. Figure 6 shows results concerning the dry weather flow.

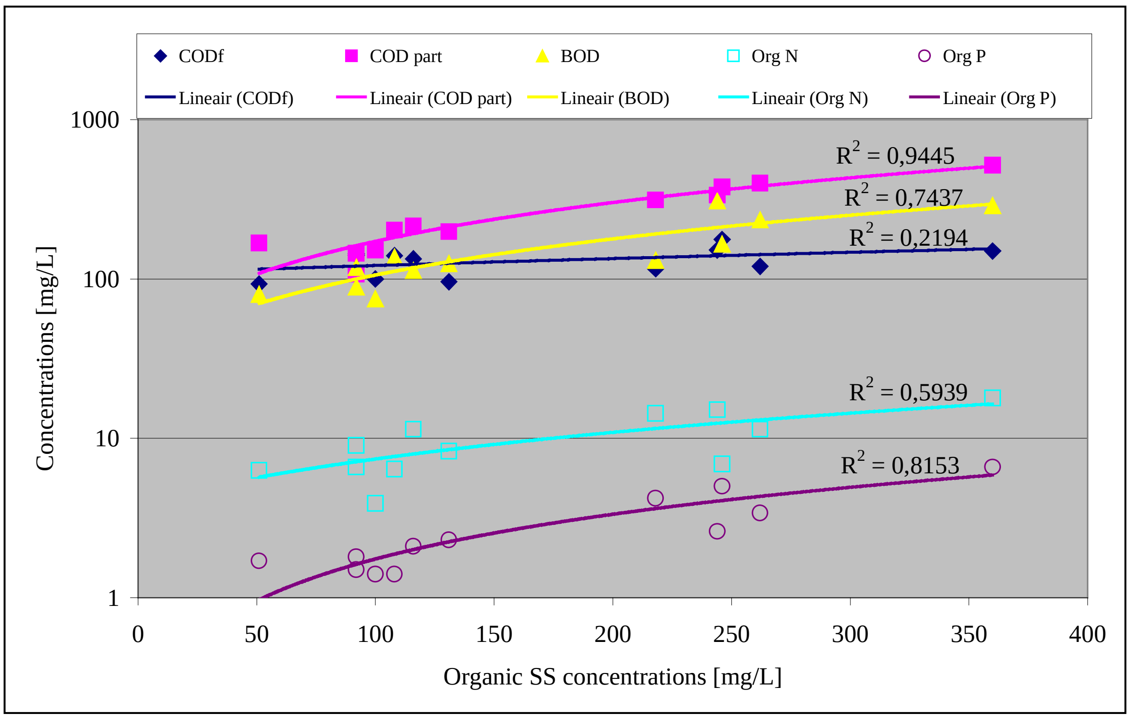

Figure 6. Influent organic SS conc. vs S_{COD}, X_{COD} , BOD_5, organic N and organic P: dry weather flow

The horizontal axis depicts the influent organic SS concentrations and the vertical axis shows the influent concentrations of several other parameters; among others, dissolved (S_{COD}) and particulate (X_{COD}). As it was expected, particulate COD and organic SS were found significantly positively correlated; moreover, the dry weather flow inorganic SS fraction was negligible (data not shown). Thus, the assumption of SS ≅ OSS in dry weather flow was applied to the historical time series. With this assumption it was possible to assign a correlation coefficient - and its confidence boundary - between SS (which is available in the historical series), and the particulate COD (which is not available). From this, an estimation of the dissolved COD could be derived (S_{COD}=COD-X_{COD}). This in conjunction with other evidence could construct a better estimation of the dry weather flow COD fractionation. Redundant available information such as that derived from the sludge production of the WWTP could verify the validity of the assumptions.

- ***Stage** 3: scenario analysis*

The cumulative distribution of the expected effluent annual nitrogen concentration in the year 2000 for alternative 1 (ie: without expansion) is illustrated in Figure 7. Since the effluent consent is expressed in annual average concentration and since the dilution is a stochastic factor, which may have a large influence on the effluent results, it is worth noting that it is important to specify which 'year' we are referring to. The analysis is performed not only for 'representative years', but also for extreme years (ie very dry or wet years), each of which has its peculiarities. While some are evident, some others are less evident (e.g. the effect of dilution on the settling characteristics).

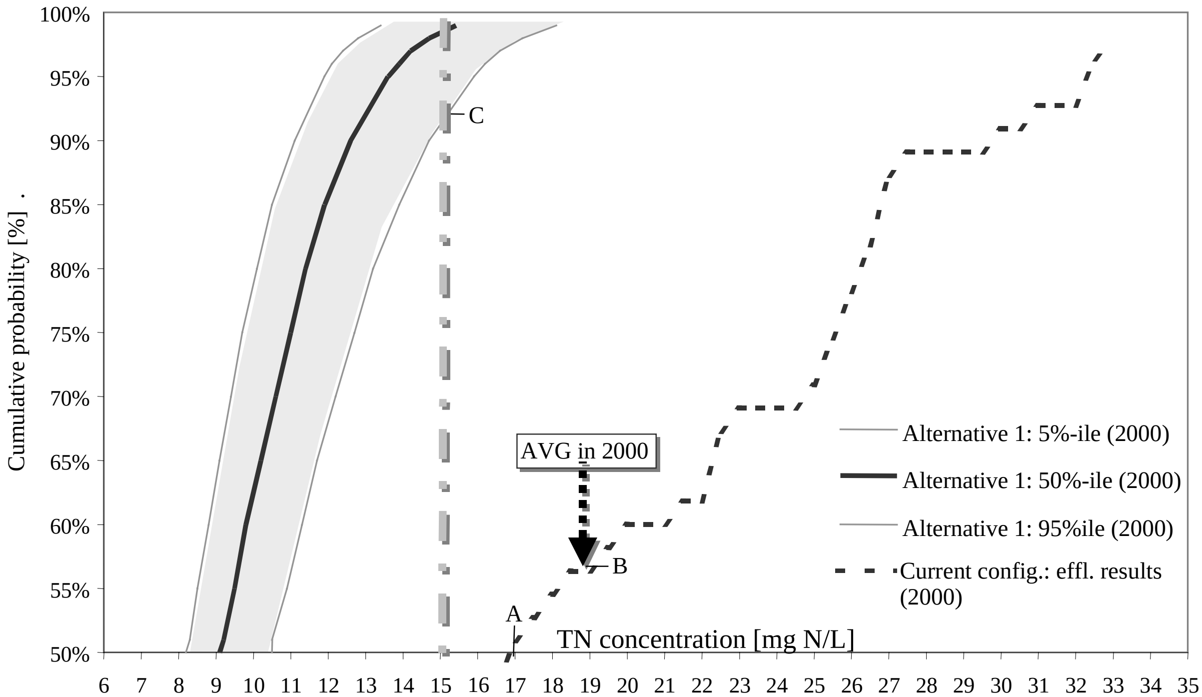

Figure 7. Alternative 1: simulated effluent nitrogen results for year 2000 (under optimal WWTP operation)

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 thick (half) S-shaped curve. The uncertainty due to model input uncertainty is visualised as a grey 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 in the first place. We can say that in 2000 more 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). It is worth noting that when the mean is 18.9 mg/L (cfr. Table 1) and the median is 17.0 mg/L then the distribution is significantly skewed. 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. (remark: 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). The results of each shot refer to 365 24h composite samples (as for the consent). Each shot is run with a combination of input variables and parameters and produces one cumulative distribution curve; by running a large number of shots with different input combinations, the generated input probability distribution leads to the effluent confidence interval as illustrated in Figure 7. The rather restrictive assumption of (log)normal distribution of the data is made.

The simulated annual effluent results of BOD, COD and SS are also with 95% certainty below the consent (data not shown). As concerns phosphorus, it is today below the consent (cfr. table 1), and both the current process configuration and that proposed in the alternative 1, all use chemical P-precipitation. Under the thus far simulated conditions, alternative 1 is expected to meet the effluent consents with 95% certainty.

How safe is the conventional design approach?

The question can now be reversed. Namely, if 4,924 m³ (alternative 1) can meet the norms with 95% certainty, how safe is the design with 6,000 m³ (alternative 2)? The simulations show that, based on annual results, the effluent results are virtually not affected by the expansion. This implicitly implies that when the WWTP is optimally operated (**!**) both alternatives have enough spare capacity for large part of the year. For instance Figure 8 compares the nitrification capacity through the cumulative probability distribution of the effluent ammonia concentration for the alternative 1 (dotted lines), and 2 (full lines) '*ceteris paribus'* (the Latin for 'other things being equal'). The difference in nitrification capacity appears to be only marginal.

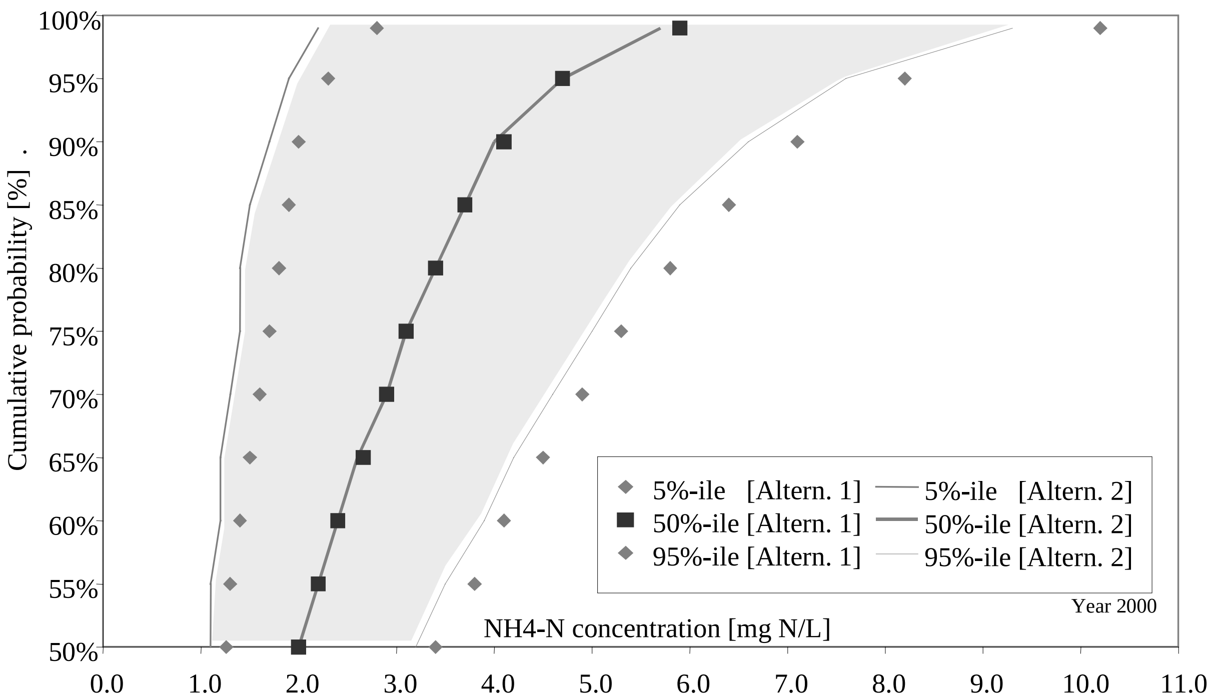

Figure 8. Comparison of alternatives 1 and 2: simulated NH4-N effluent results (optimal WWTP operation)

It is worth noting that simulations thus far have been focused on the calculation of an optimally operated WWTP, which is an optimistic IDEAL situation. The results may be quite different in case of sub-optimal operation or 'unexpected' events ('unexpected' here means out of the simulation assumptions). In some situations (e.g.: loss of nitrification), this may endanger the REAL results to meet the effluent limits. It is clear that a keen evaluation of the margin of safety available is needed. The scenario analysis includes a final stage, where a detailed event tree analysis is performed, which provides an explicit means of examining the process configuration vulnerability to sub-optimal operation or unexpected conditions. The event tree analysis evaluates the set of very restrictive explicit assumptions initially made in the model-based analysis. Namely: (a) MLVSS set-point control at 2.4 g/L; (b) optimal on-line control of the intermittent aeration, ie governed by a reliable and optimally operated on-line NH4-N analyser; (c) 'representative' rainfall distribution; (d) process temperature distribution between 10°C and 20°C; (e) load probability distributions as defined in the previous stages; (f) no mechanical failure or human error. This task is underway.

DISCUSSION

Degree of objectivity displayed

The degree of objectivity depends upon three factors, each of which is considered briefly.

- *An analysis based on fundamental principles relatively well understood.*

In our experience and from literature, the processes described in the ASM No. 1 model have an acceptable predictive power if the activated sludge system receives municipal wastewater and the models are ‘properly’ used. ‘Properly’ here means that their theoretical limitations must be recognised and assumptions and constraints kept in mind in the analysis. The situation is quite different for the sludge separation process, where the current settling models are well descriptive but not predictive. This point will be treated later on. It is also worth noting that the probabilistic Monte Carlo simulation does not account for model uncertainty.

- *Decisions are made with a healthy understanding of the factors that will influence that decision.*

Despite evident advantages such as simplicity and requirement of limited information, many engineers are uncomfortable with the prospect of depending upon the convenient but unrealistic paradigm of process steadiness made in conventional design. The assumption that all complex dynamics of flow, pollutant load, microorganisms and the operating conditions are at “equilibrium” hampers in itself a proper evaluation of the risk. This approach is now replaced by a more realistic paradigm of controlled non-steadiness. Many real-life situations such as supportive on-line measurements, coping with transient but intense first flush events, etc. can be evaluated in their merits and a causal link between variability plus uncertainty and margin of safety can be made. The calculation of break-even points, e.g.: levels of uncertainty or sub-optimal operating conditions in which the consent will be at stake, is of evident significance in that it defines the operating margins of each process alternative.

- *It appeals directly to empirical evidence.*

The measure of the risk of a particular course of action is grounded on a rational analysis of the available imperfect information. In the conventional approach, the poor link between the cause-effect relationship of risk and uncertainty makes it necessary to calculate a conservative or high-end point estimate of input variables and/or parameters. The uncertainty of each input variable and parameter can now be explicitly introduced into the model-based analysis.

On the one hand the available informative content of data of present and past events plays a central role, this reducing the space for arbitrary judgement. On the other hand, this also implies that the effective use of the Monte Carlo simulation techniques depends heavily upon such information being available. In the case of projects such as WWTP renovations where a large amount of relevant informative data is available, this makes perfect sense. If factors, external to the control of the designer, are changing (among others the influent composition and its effect on the activated sludge characteristics) then a probability drawn from past or present experience may no longer be applicable. In that case, 'subjective' probabilities are considered; these are based on the decision-maker's own expectations, preferences, experience and judgement about the future. These expectations can provide some assistance, but it is clear that subjective probabilities assigned over the uncertainty can be a dangerous guide in decision-making.

Conditions for the success

- *The willingness and possibility of the engineer to invest time and resources searching for current valid and relevant information.*

It is clear that in principle the concepts introduced in this paper are potentially of great significance in the process of decision making. However, the risk analysis is basically a mathematical tool and can only be of practical application if quantitative estimates can be made of the probability distribution of the sensitive input parameters and variables. We have seen that the designer may wish to reduce uncertainty of a particular situation by gathering additional information. This implies a reallocation of the investment resources, implying higher costs for monitoring and personnel in the very early phase of the project. On the one hand, this is justified by potentially substantial return on investment. The designer can justify the potential value of acquiring additional information based on an objective utility function. On the other hand, institutional factors like local tendering rules, incentives for the decision makers, etc. will play a major role in the actual reallocation of the resources. The authors recognise that the proposed design methodology makes perfect sense in the Flemish region, but it may be unpractical in others.

- *Expert judgement is an essential part of the effective use of risk analysis.*

Although this methodology can serve as a more objective basis for decision making in risk management, this does not mean that expert judgement is abandoned altogether! On the contrary, expert input is more than ever required and should heavily contribute to the setting of an acceptable level of risk. This procedure does not eliminate risks, it helps managers identify and deal with imperfect information. Because of the increased level of complexity and the assumptions, this approach should never be applied in a mechanistic fashion, and any conclusions it suggests must be carefully considered in light of sound technical judgement and experience.

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 have been applied for the assignment of the settling properties of the sludge. This assignment is not only relevant for the dimensioning of the secondary clarifier and the effluent SS, but also for the quantification of effluent compliance of - among others - total nitrogen. Other precautionary courses of action, such as the design of an anoxic selector, have been undertaken (cfr. Fig. 3).

Challenges to its practicality

Perhaps the most obvious practical problem with this approach, at least to date, is that the calculation step cannot be performed in the blink of an eye. While this approach can theoretically handle virtually unlimited difficult and large configurations, in practice the extent of system complexity is limited by the computation time. For instance, as a compromise between complexity and speed of the delivery, in this study we had to step back from a preferred 12 tank-in-series plug-flow system to a 3 tank-in-series complete-mix configuration. Table 2 summarises the calculation time required to run a 1-year shot on three different PCs now commercially available for the 3 tank-in-series configuration.

Table 2 Computation time versus computer characteristics for the studied configuration

Computer Type	specifications	Simulation time for 1 shot*
Compaq Professional workstation AP 500	PROC.: Intel PIII 500 MHz RAM: MB 192 @ 100 Mhz	1h21 – 1h46 (≅ 5.9 days per scenario)
Clone PC (no brand)	PROC.: Intel PIII 1 GHz RAM: MB 256 @ 133 Mhz	0h51 - 1h05 (≅ 3.8 days per scenario)
Fujitsu Siemens Scenic	PROC.: Intel P4 1.4 GHz RAM: MB 128 @ 133 Mhz	0h40 – 0h57 (≅ 3.2 days per scenario)

***1 shot = time series of 1 year**

To overcome/minimise the calculation problem, a project has been developed to linearise the IWA activated sludge models.

CONCLUSIONS

Because of the high investment costs involved in renovating WWTPs, extensive plant optimisation through advanced process analysis is a very interesting option, because of the potential savings compared to costly extension of the plant volume.

The proposed approach illuminates the designer about the degree of conservatism that would otherwise result from the compounding of conservative assumptions employed in conventional renovation/design projects and proposes a way to avoid it in a robust and transparent way. This can enhance the probability of optimal allocation of resources, reducing the disbursement of capital in excess of what is required.

Risk analysis is not necessarily successful. Risk analysis is a decision supporting tool which needs to be fed with the proper information; in practical terms, this means higher costs of monitoring and skilled personnel for analysis. These costs can often be justified by substantial return on investment. The cost-benefit-risk analysis for the renovation of the WWTP of the town of Hove yielded savings of over 1,000,000 $ or 43% compared to conventional static design. Savings of such an order are not accidental; they are rather the direct results of careful planning.

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