Estimating costs and benefits of advanced control for wastewater treatment plants – the MAgIC methodology

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Abstract This paper discusses a methodology to estimate the costs and benefits of advanced control for wastewater treatment plants. The methodology has been applied to four wastewater treatment plants, representing four standard types of plants built in Flanders, Belgium. The paper outlines the methodology and illustrated results from one of the four design cases. General results are shown and contrasted with full-scale experience. The methodology appears to give realistic results and will be used for further refinement of default control algorithms for certain types of plants. A preliminary analysis indicates that on-line control can become cost-effective for plant sizes above 50,000 population equivalents.

Keywords Benchmarking; cost−benefit analysis; full-scale plant control; on-line process control; sensors

Introduction

Aquafin is responsible for the design, construction, prefinancing and operation of the municipal wastewater infrastructure of Flanders, the northern region of Belgium. Aquafin currently manages 199 wastewater treatment plants, 791 pumping stations and 3,838 km of sewers. Since 1998, Aquafin has gradually been introducing advanced on-line control (i.e. control based on on-line nutrient analysers) into the design (Boonen *et al.*, 1999; Bixio *et al.*, 2000) and operation of its treatment plants (Devisscher *et al.*, 2002; Devisscher and Parmentier, 2003). Currently, on-line ammonia measurements have been installed in 12 plants, nitrate is measured on-line in 46 plants and phosphate analysers are installed in 10 plants. The effective coupling of the sensors to on-line control algorithms is now operational in 10 plants, and is imminent in two more. Most implementations are a consequence of specific operational or infrastructural demands.

On the basis of the acknowledged tangible benefits of on-line control, a project was carried out to extend the application of on-line control over a wider range of plants. Aquafin plants are designed according to a design matrix (Ockier *et al.*, 2001). Such a matrix of standard plant layouts lends itself perfectly for implementing control algorithms on a broad basis, by designing standard algorithms for these standard plants. The main design goal is to establish for which classes of the design matrix, on-line control is beneficial by default, i.e. due to its design size rather than for reasons of operational specifics.

A methodology has been developed to estimate costs and benefits of control using modelling and simulation. The approach is largely inspired by the now widely accepted IWA/COST benchmark approach (Spanjers *et al.*, 1998; Copp, 2002), and is built on the basis of an internal benchmarking study (Ghermandi *et al.*, 2004). The methodology is designed such that the evaluation should be possible from existing data, and is backed up

with full-scale data and implementations. The methodology is called the MAgIC methodology, an acronym for matrix for advanced instrumentation and control.

Methodology

As has been pointed out, the Flemish plants are designed according to a matrix, in which a certain range of design loading rates determines the plant layout. From each of the design classes under study, an existing plant was selected, based on the following criteria: (1) if possible, the design size should be in the middle of the class range; (2) the plant should be in operation for at least 2 years, in order to have a sufficient amount of data; and (3) no specific operational problems or exceptional conditions should be reported for the plant.

The analysis is then carried out on these existing plants, that are assumed representative for each matrix class. This cost/benefit analysis is performed following the scheme illustrated in Figure 1.

In the following text, each of the blocks is described in more detail.

Treatment plant modelling

The layout of the plant is implemented in Simulink®, interfacing to a C++ model library developed in-house. The modelling framework is based on ASM1 (Henze *et al.*, 1986), with a Takacs settling model (Takacs *et al.*, 1991) and extended with features from ASM2d (Henze *et al.*, 1999), more specifically ammonia and phosphorous growth limitation, chemical phosphorous precipitation and redissolution, growth related P-uptake and decay related P-release, and the notion of total solids. The total solids also considers a non-COD containing inorganic fraction (e.g. minerals).

These models were extended with cost models. The main cost categories considered are: (1) aeration energy; (2) pumping energy; (3) mixing energy; (4) chemicals; and (5) sludge treatment and disposal. For aeration energy, an in-house formula was used, that takes into account the type of aerator to link K_La to energy. Pumping energy was estimated using an integration over time of power according to:

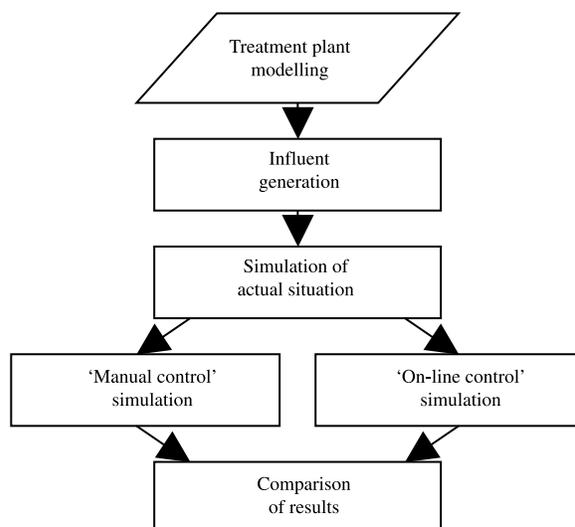$$P = \frac{\rho \times g \times Q \times H}{\eta}$$

Figure 1 Outline of the MAgIC methodology

in which P represents pumping power, ρ is the density of mixed liquor (taken to be 1,100 kg/m^3), Q the flow rate, H the total pump head and η the efficiency of the pump. This formula was chosen since it is easily adaptable to different pump heads (which can vary considerably) and different types of pumps. For mixing energy, the total installed power for mixing equipment is summed together.

According to Petersen *et al.* (2002), a steady state fit to 1 year's plant data was carried out for each of the models.

Influent generation

Few quantitative data are available for influent composition (weekly or twice a week, depending on plant size), whereas daily flow rate data are abundant. For this reason, a software synthetic influent generator was built, taking into account typical aspects of the Flemish situation, including a decreased load during weekends, and the effect of rain events either in the form of first flush or dilution, depending on the period before the rain event. In addition, a daily pattern with variable amplitude is added to the flow rate data.

The approach taken can be summarised as follows. If sufficient daily measured flow rate values are available, they are used directly, and classified into dry and wet days. Given the scarcity of quality data, load is computed from seasonal averages, disregarding the 5th and 95th percentile margins. This load is redistributed on a day-by-day basis according to a normal distribution. To this synthetic daily sequence, factors are applied to account for weekends, or for first flush events (identified by checking whether a rain event appears after a number of dry days or another rain day). A daily pattern is applied to the flow rate (without affecting the mean daily value), and concentrations are calculated from load and flow rate. If daily flow rate values are not available, they are generated from a seasonal Poisson distribution, after which they undergo the same treatment as the flow rate values taken from data.

These generated data are still expressed in 'classical parameters', i.e. total suspended solids, ammonia, total nitrogen, total phosphorous. They are transformed to ASM1 parameters using transformations based on STOWA (1996).

Simulation of actual situation

This first simulation attempts to reproduce the behaviour of the plant over 1 year of operation. For this simulation, operational data are taken from the daily reports of the plant and are applied to the model. These data consist of daily incoming flow rates, and operational settings such as oxygen set-points, waste flow rates, recirculation fractions and denitrification percentages. This simulation is considered a reference scenario, and is used to check the output of the model against real data.

Simulation of manual control

This simulation aims at estimating what can potentially be achieved with manual control. This is simulated by running discrete PI controllers (tuned manually) with a sampling period of 2 days, mimicking an operator basing his decisions on grab samples. Such manual control loops are present for: (1) MLSS control; (2) phosphorous removal control; and (3) nitrogen removal control. The MLSS controller adapts the waste flow rate as a function of the TS measurement in the aeration tank. The phosphorous controller adjusts the dosage rate of ferric solution based on phosphate measurements in the effluent. The nitrogen removal controller varies the %DN fraction based on ammonia concentration in the effluent. (Note: most of the Flemish plants have intermittent aeration systems; the %DN is the percentage of denitrification time in such an intermittent mode of operation.)

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Simulation of on-line control

In this simulation, the manual phosphorous removal and nitrogen removal controllers are replaced by the default on-line control algorithms of Aquafin (tuned manually). All other parameters are kept equal to the manual control case.

For both the manual and on-line control case, 11 scenarios are simulated to take the influence of variability and actual load into account. The impact of these factors in the scenario's is detailed in Table 1.

The effect of variability within a day is achieved by varying the amplitude of the daily pattern. For high variability, the amplitude is doubled; for low variability the amplitude is halved. The effect of interdaily variability is simulated by adapting the variance of the normal load distribution in the influent generation process. Again, it is doubled or halved for high and low variability. Overload/underload conditions are simulated by adapting concentration or flow rate, or both, to simulate different types of overload or underload.

Comparison of results

After simulation, comparisons are made to evaluate the effect of on-line control on the various cost factors (aeration, wastage, iron dosage, mixing, pumping) and the effluent quality (the notion of effluent quality from the IWA/COST benchmark is used).

Results

First, validation of various components of the methodology will be discussed. After this, a typical output of the methodology will be given for one example plant. Finally, results in terms of total cost reductions for the four studied plant layouts will be presented.

Validation steps of the methodology

Modelling framework. The C++ simulation library was first validated by running a pure ASM1 simulation against the IWA/COST benchmark steady state simulation, and gave identical results.

Cost functions. To evaluate the usefulness of the cost functions used, a treatment plant with detailed cost information was modelled, and simulated costs were compared to actual costs. Results of this comparison are given in Table 2. In addition, the IWA/COST formulae were added to the comparison.

As can be seen from the table, all costs are underestimated (within reason). This means that, for calculating savings, the estimates are conservative. For pumping energy, the IWA/COST formulae are slightly more accurate than the one quoted above. Nevertheless, the latter has been used in this study since actual pump heads vary significantly, and are clearly of influence for the required energy. In addition, this formula can be adapted to different types of pumps by changing the efficiency.

For recycle energy, an important underestimation can be noticed. This can be explained by the fact that the recycle flow rate is controlled proportionally with the influent flow rate.

Table 1 Overview of simulated scenario's

	1	2	3	4	5	6	7	8	9	10	11
Daily variability	–	H	L	–	–	–	–	–	–	–	–
Interdaily variability	–	–	–	H	L	–	–	–	–	–	–
Ratio actual/design concentration	–	–	–	–	–	H	L	H	L	–	–
Ratio actual/design flow	–	–	–	–	–	–	–	H	L	H	L

H, high; L, low; –, normal

Table 2 Evaluation of cost functions (energy in kWh; iron dosage in EUR)

	Influent pumping energy	Recycle pumping energy	Aeration energy	Mixing energy	Iron dosage
Actual data	220,000	125,000	475,000	179,000	3,300
Calculated	185,000	55,000	439,000	136,000	2,600
Calculated (IWA/COST)	195,000	82,000	426,000	NA	NA

In practice, the ranges in which these pumps can be controlled are limited. Most frequency controllers cannot run below 30% of the range. In addition, it is often the case that one of the screw pumps keeps running continuously.

For aeration energy, the internal formula yields nearly equivalent results as the IWA/COST formula, but is adaptable for different types of aerators, and is therefore preferred.

Influent generation. The goal of the influent generator is to provide synthetic data to fill the gaps in experimental records. To evaluate the synthetic influent generator, real influent values were compared with synthetic influent data, generated from a seasonal population with statistical properties that were based on these data. The goal is, of course, not to reproduce the actual data, but rather to create supplemental data with features that are coherent with the data. As an example, Figure 2 shows a comparison for flow rate and ammonia data. The figure shows that the patterns of real and synthetic data are comparable.

Example of output

The treatment plant under study has a design capacity of 28,000 PE (population equivalents), and is actually operating at 27,700 PE. The simulation of the actual situation results in an energy cost of 53,000 EUR per year, while the actual energy cost is 63,000 EUR. A similar underestimation is observed in all cases. It is probably caused by an underestimation of pump costs (due to the nature of screw pumps, they can be allowed to keep running, even dry) and the neglect of various other energy costs at the plant (e.g. energy for the service buildings).

The results of the comparisons between actual and manual or on-line scenarios are given in Figure 3. In each case the reference is scaled to 1. On the left, the manual scenario is compared to the actual, so results are normalised such that actual results are 1; on the right graph, the manual scenario is scaled to 1.

As can be seen from this figure, the manual controller is able to reduce iron flow rate compared to the actual situation, without worsening the effluent quality correspondingly. This effect is most likely caused by the reduction of safety factors in operation. Indeed, a PI controller does not anticipate future peak loads as an operator would.

A more interesting comparison is the one between the manual control and the on-line control algorithm. This is an assessment of the advantages of on-line control, with its short response time, over an ideal manual control situation. It becomes clear that the on-line controller decreases aeration energy and iron flow rate even further, while at the same time improving the effluent quality.

The effects look quite different when considered as absolute cost values (Figure 4). In this figure, the absolute differences from the actual scenario are shown, expressed as Euros/year. It appears that the relatively small effects on sludge production and aeration have an important monetary effect. In this respect, it should be pointed out that local sludge disposal costs are quite high, since the sludge cannot be land spread.
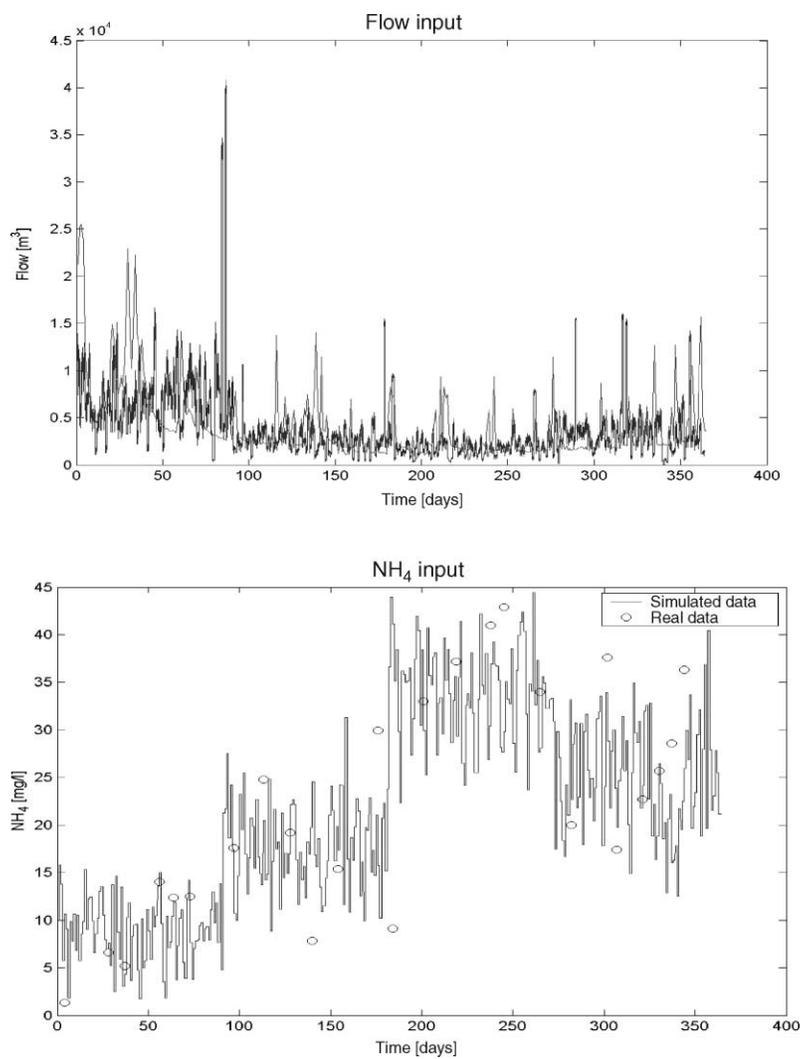
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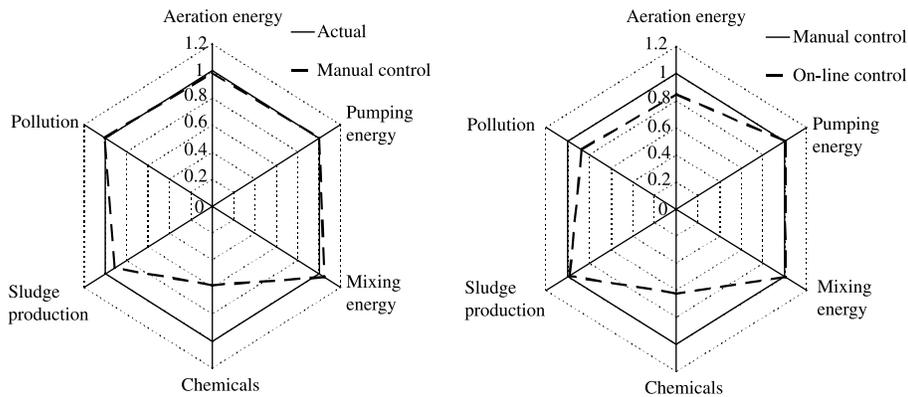**Figure 2** Example of a synthetically generated influent series versus real data

Figure 3 Effect of manual (left, actual is taken as a reference) and on-line control (right, manual is reference)
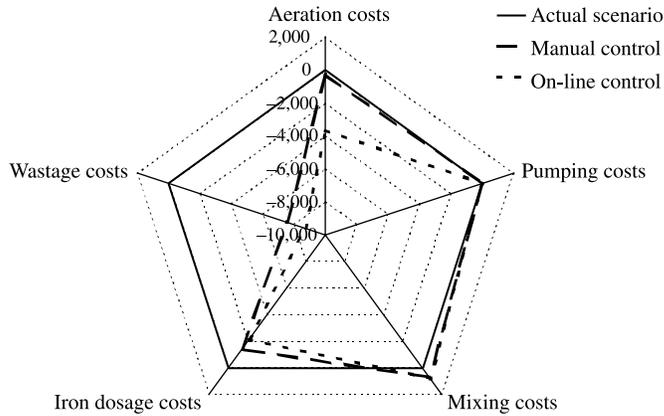
Figure 4 Effect of manual and on-line control expressed as absolute values

The effect of interdaily and daily variability on the comparison is not shown in this contribution. The results obtained are very hard to interpret and no general conclusions can be drawn at this stage. This conclusion holds for all studied plants. Importantly, however, the effects of variability, are small. Therefore, the effect of differences in the random generation of the load scattering proves more important than the effect of the variability. More research is needed to improve the evaluation of variability.

The effect of overload or underload (of both flow rate and concentration) is shown in Figure 5. In the overload situation, the on-line controller results in a better effluent for a slightly increased aeration effort, and some savings in dosage, while the underload situation, pollution is reduced, but there is more room for savings in aeration energy and chemical dosage.

General results

Up to now, four categories of the Aquafin design matrix have been investigated using the methodology outlined above. The total absolute cost reductions achieved by on-line control in function of the plant size are given in Figure 6a. Relative savings in aeration and chemical dosage are given in Figure 6b.

For the plant of 21,000 PE, the data are most probably incorrect. Indeed, during calibration, no parameter set could be found such that with the reported dosage rates, the predicted effluent phosphorous was below consent, as was the case in the actual plant.
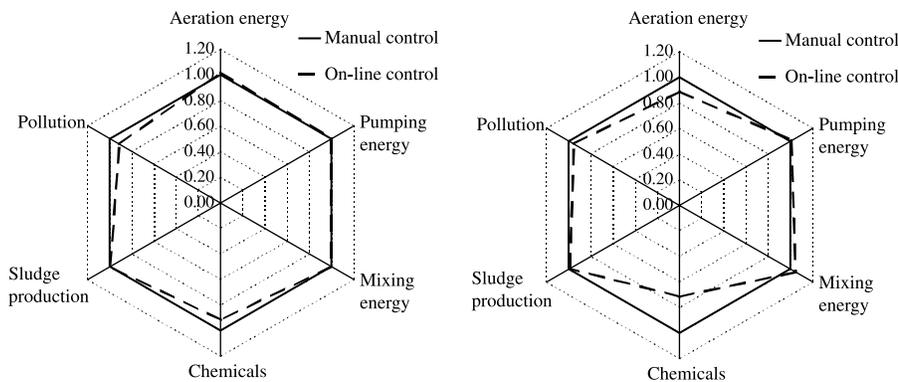

Figure 5 Effect of overload (left) and underload (right) situations. Manual control is taken as a reference.
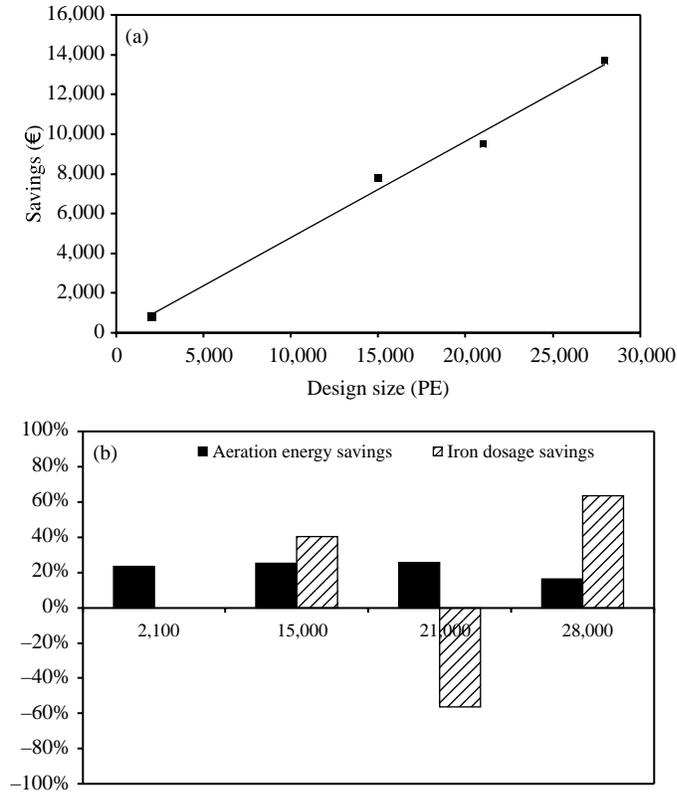
Figure 6 Cost reductions in function of plant size: total savings (a), relative savings (b)

Discussion

The relative reductions found by the methodology can be compared with full-scale data. Savings in aeration energy by implementation of advanced control in the Flemish plants range from 10 to 20%, although these estimates are difficult to establish. Savings in chemicals dosing can reach 30%. At first sight, the methodology appears to overestimate these savings. However, as has been pointed out, most full-scale implementations up to now have occurred to answer a specific demand, mostly plant overload. From the discussion above, it appeared that overload situations give less room for savings. Therefore, the observed (overload) savings should be at the lower end of what can be expected.
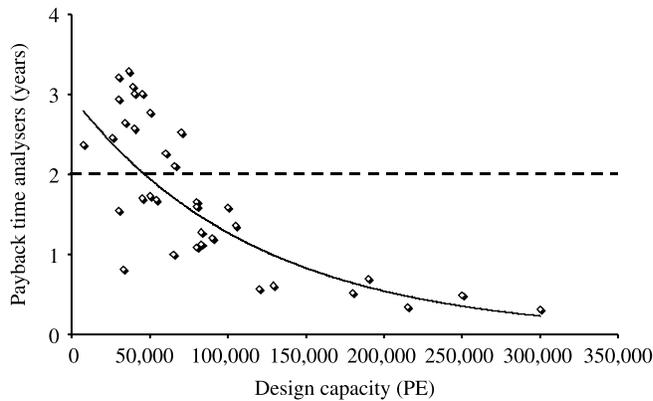

Figure 7 Calculated payback time for implementation of on-line control to Aquafin plants

Although on-line control is seldom implemented for economical reasons exclusively, it is interesting to balance possible savings against costs for all Aquafin plants. Assuming that aeration results in 15% savings and chemicals dosage can be reduced by 20%, an analysis of payback period was made, taking into account actual expenses for the plants, and current prices for investment and maintenance in analyser assemblies. From this analysis, shown in Figure 7, on-line control would become cost-effective at plant sizes above 50,000 PE, if a payback period shorter than 2 years is required.

Conclusions

A methodology was developed to estimate costs and benefits of on-line control for wastewater treatment. The methodology, which enables the designer to apply different control structures to various types of treatment processes, has been used to estimate the savings that can be achieved by applying automatic controllers to a collection of typical Flemish wastewater treatment plants. By verifying different steps in the methodology, and comparing them with full-scale data, the results appear realistic. The methodology will now be used to fine-tune control algorithms for standard wastewater treatment plant layouts.

Acknowledgements

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