Feasibility of automatic chemicals dosage control – a full-scale evaluation

M. Devisscher, H. Bogaert, D. Bixio, J. Van de Velde and C. Thoeye
Aquafin NV, Dijkstraat 8, 2630 Aartselaar, Belgium. (E-mail: *Martijn.Devisscher@aquafin.be*)

Abstract This contribution discusses the feasibility of automatic control for chemicals dosing in activated sludge systems. The evaluation is made on the basis of a full-scale implementation at the Lommel WWTP (Belgium) of an on-line controlled dosage system for iron chloride and external carbon source. The control laws are very simple and allow intuitive adaptation by the plant operators. The control system results in a significant reduction of the chemicals dosage, better effluent results and a lower sludge production. The implementation is furthermore cost-efficient.
Keywords Control; denitrification; external carbon source; on-line; phosphorus removal; wastewater

Water Science and Technology **Vol 45 No 4–5 pp 445–452**

Introduction

In Flanders (Belgium), all municipal wastewater treatment plants (WWTPs) serving conglomerations of more than 10,000 p.e. must comply with a consent on nutrient removal (nitrogen and phosphorus). In many installations, phosphorus must necessarily be removed with the aid of chemicals because of the too low carbon/phosphorus ratio of the influent. In a number of installations, denitrification is helped by external carbon source dosage because of the too low carbon/nitrogen ratio of the influent. Process disturbances such as large variations in flow (10 dry weather flows must be pumped to the WWTP), pollutant load (first flushes, industrial discharge, . . .) and temperature (high seasonal gradient), and the often diluted wastewater are in general so large that the use of the convenient operating paradigm that all complex dynamics of flow, pollutant load, micro-organisms and the operating conditions are at "equilibrium" is far from the reality. In order to optimise the ever increasing capital investment, operation and management costs of wastewater treatment, the convenient but unrealistic paradigm of steady state processes is being replaced by a more realistic paradigm of controlled non-steadiness with supportive on-line measurements.

The significance of on-line automatic control of external carbon source dosage and chemicals for phosphorus precipitation in activated sludge systems is largely recognised in the literature; especially for the reduction of the effluent quality, not entailing an unnecessary increase of the operating costs linked to sludge production (e.g. Aspegren *et al.*, 1992; Bogaert *et al.*, 1999). Moreover, today several reliable and accurate on-line analysers are in our experience commercially available. However, documentation is mainly limited to control theories, process technology, pilot plant experiments, simulation-based evaluations or furnished by manufacturers. Still few full-scale WWTP applications are found in the literature.

Several types of existing and/or innovative controller systems were developed and/or tested at full-scale in Flemish municipal WWTPs (e.g. Yuan *et al.*, 1996), and thereafter gradually used in the day-to-day wastewater treatment practice. In this paper the implementation of a straightforward control system on full scale is illustrated. Two separated loops systems, one for dosage of external carbon source in the predenitrification tanks, and another for the dosage of $FeClSO_4$ for simultaneous phosphorus precipitation, are described. Cost-efficiency and operational feasibility of this automatic control (maintenance requirements, reliability, additional workload for the operators, . . .) are evaluated over a long term period.

The results are contrasted with the conventional approach which implies daily off-line measurements of the effluent quality.

Description of the plant

The Lommel WWTP serves 35,000 p.e. and has a nominal capacity of 1,890 kg BOD/d (5,250 m^3/d). It treats a mixture of domestic and industrial wastewater. It has been adapted for nutrient removal by the inclusion of an anoxic zone for denitrification and by the installation of a $FeClSO_4$ dosage system for phosphorus removal. While BOD load is not far from design capacity, the industrial component in the influent makes the N and P load highly exceed it: the actual nutrient load amounts to approximately 60,000 p.e. (600 kg N/d) in terms of nitrogen and 90,000 p.e. (180 kg P/d), in terms of phosphorus. This results in an unfavourable fingerprint for both nitrogen and phosphorus removal. Therefore, to aid denitrification, a carbon source is added. Both chemicals are added to the anoxic zone.

Although quite constant on a long term average basis, the N and P loading rates are quite variable in a short time frame: within one-week measuring campaigns, the standard deviation of the daily flow-proportional samples is about 20,000 p.e. for P and 10,000 p.e. for N. There are also important daily variations (see Figure 1).

On-line control

To respond to the variability in N and P loads, and to reduce several problems associated with overdosing (as discussed further on), on-line control of the chemicals dosage was investigated.

The dosage is performed by two independent loops. A first loop controls the addition of the carbon source based on on-line measurements of nitrate and ammonia. A second one controls the addition of $FeClSO_4$ based on on-line phosphate measurements.

For these measurements, a cabin was installed at the plant. The sample is taken at the start of the aerobic zone and passed through an ultrafiltration unit. This filtered stream is then analysed on-line for nitrate (UV absorption), ammonia and phosphate (colorimetric measurements). Figure 2 illustrates schematically the implantation of the controller at the plant.

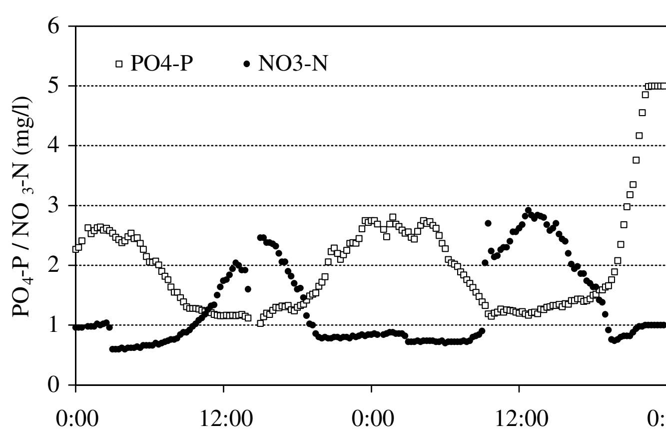


Figure 1 Example of daily variability: nitrate and phosphate concentration in the aeration tank during two consecutive days

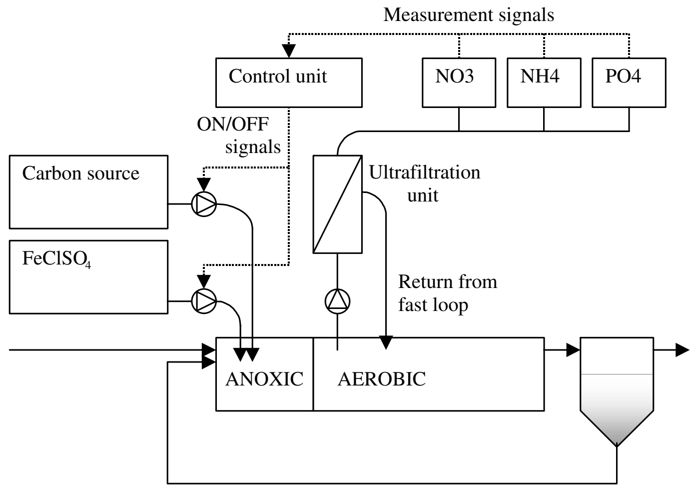


Figure 2 Implantation of the control strategy at the plant

The pumps are controlled by timers. The timers have a cycle of 12 minutes. In this period, they are switched on for a number of seconds, and are off for the remainder of the period. On the basis of the measurements, the controller determines the "on" time of the timers for the dosage pumps. It can be varied between a certain minimum (for a certain minimal nutrient concentration) and the full 12 minutes (for a certain maximal concentration). For intermediate levels, the "on" time is proportional to the concentration of nitrate, respectively phosphate in the mixed liquor. The minimal value is set to ensure removal even when the sensors transmit an erroneous low value.

The general principle of the controllers is summarised in Figure 3.

For the N-loop, an additional rule is implemented: the dosage is stopped when the ammonia concentration reaches a certain level.

The flow rate corresponding with the 12 minute "on" state corresponds of course with the fixed flow rate at which the pump is working. This fixed flow rate, i.e. the maximal dosage rate, can be manipulated by the operators. In this way, the adaptation of the controllers is handled in an intuitive manner at the site itself. If the operators notice too high levels of the nutrients, they can increase the flow rate of the pumps. Alternatively, it can be decreased when no benefit can be gained from additional dosage.

An additional "alarm" state was also foreseen: when a general failure alarm was received from the analyser in question, the dosage rates are set to a dosing at 50% of the maximal dosage flow rate.

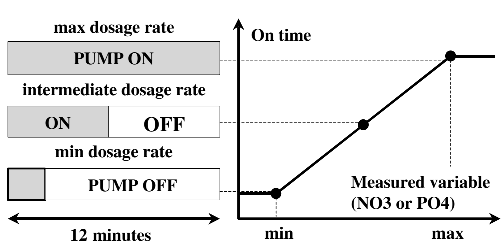


Figure 3 Principle of the proportional controllers

Results and discussion

It is not a trivial task to perform a detailed cost-benefit analysis for this on-line control strategy. While some results are directly measurable, such as improved effluent results and reduced chemicals use, some have to be calculated, such as sludge production and oxygen demand, and others are very hard to quantify, such as reliability and operator acceptance.

Effluent results

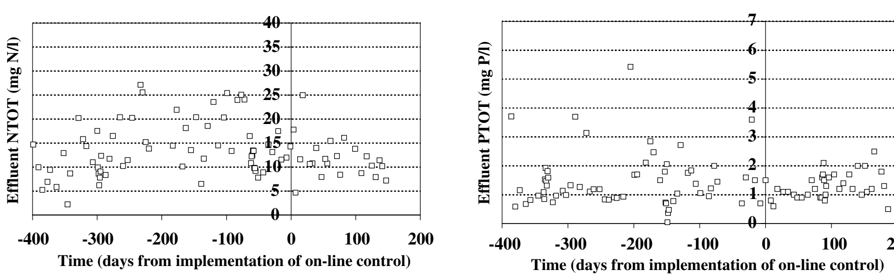
The effect of the on-line control on effluent results is summarised in Figure 4. The time axis is rescaled to have the time of implementation of the control strategy at 0. In vertical axis, effluent concentrations are shown.

The figure clearly indicates, for both chemicals, a better compliance with the norms (15 mg N/l and 2 mg P/l, respectively) compared to manual dosage. With manual dosing (at the left of vertical axis), several peaks are observed in effluent values. This is because a piecewise constant dosing, based on daily measurements, cannot respond sufficiently fast to variations in the load that occur faster than the time scale of the measurements, i.e. at best daily. Controlled dosage, on the other hand, responds almost immediately.

Chemicals dosing

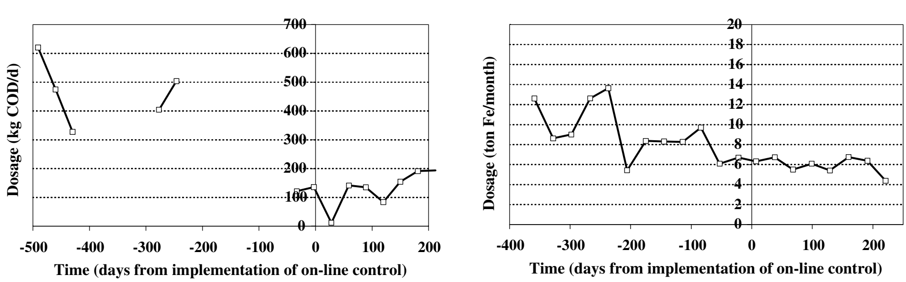
The effect on chemicals dosing is shown in Figure 5. The figure shows monthly averages of the daily dosed amounts. The axis is rescaled as in Figure 4.

The figure shows that the dosage of both the carbon source and the iron chloride have significantly decreased since the automation. This can be explained by the following. The dosage needed to keep the effluent consent is lower in a piecewise constant regime than in a controlled regime. Indeed, a constant dosing rate needs to deliver the amount needed to accomodate the higher peaks in the constantly varying demand, and is therefore mostly overdosing. A controlled dosage on the other hand will keep the addition in proportion to the actual demand in the plant, and will only dose these large amounts when required.



a. Effluent total nitrogen *b. Effluent total phosporous*

Figure 4 Effect of on-line control on effluent results



a. Carbon source dosage *b. Iron chloride dosage*

Figure 5 Effect of on-line control on chemicals dosing

For carbon dosage, it can be noticed that for some months no data were available. This is due to nitrification problems. Obviously, in the absence of nitrification, dosing of a carbon source is a pure waste and the dosing was therefore turned off. The presence in the control strategy of the ammonia measurement allowed one to automatically take this into account, such that there was no need to completely switch off the dosing.

In fact, since the implementation of the control strategy, nitrification problems have reduced. This can, at least partially, be explained by the following. The lower dosage rates attained in the controlled case, result in a lower sludge production (see next paragraph). This results in a higher SRT, which reduces washout of nitrifiers at low temperatures.

Sludge production

A factor which should not be neglected when evaluating chemical dosage is the sludge production associated with it. In Flanders, sludge handling and disposal is one of the major costs of WWTP operation and maintenance. They account generally for 35–50% of the total operation and maintenance costs.

The actual sludge production resulting from chemicals dosing is very hard to measure in a cheap and reliable way. Therefore, the sludge production has been estimated using practical rules. Sludge production due to carbon dosage has been calculated assuming a yield of 0.272 kg VSS/kg COD. This yield value is representative for anoxic growth (McClintock *et al.*, 1988). It is used here in order to produce *conservative* estimates. In other terms, the effective sludge production might well be higher in reality, because the carbon overdosed is not necessarily metabolised in anoxic conditions, certainly in the case of overdosing. Sludge production from iron dosage has been calculated using the generally accepted simplification (Maurer and Boller, 1999; Henze *et al.*, 1999) that phosphorus is precipitated as $FePO_4$ and the remaining iron precipitates as $Fe(OH)_3$.

The results of these calculations are shown in Table 1. It should be stressed that these values are indicative, and do not result from targeted experimentation.

Aeration

Over-dosing of carbon source brings about an additional oxygen demand. Indeed, the carbon that is not oxidised by the nitrate in the anoxic zone shunts to the aerobic zone and causes an additional oxygen demand. Calculations yielded an additional oxygen demand of about 50 tons/year for manual dosage.

Sedimentation

Since the implementation of the control strategy, SVI has reduced from around 100 ml/g to about 80 ml/g. A possible explanation can be found in the optimised dosing. This will avoid spill of readily biodegradable matter to the aeration tank, and reduce phosphorous limitation, which are known causes for bulking (Jenkins *et al.*, 1993). However, no experiments were performed to verify this.

Maintenance demands

Long-term day-to-day practice showed that a daily maintenance of 45 minutes is sufficient

Table 1 Estimated annual sludge production due to chemicals dosing (in tons DM per year)

	Iron chloride	Carbon source
Manual dosage	260	40
Controlled dosage	190	12

to ensure adequate functioning of the measuring cabin. The daily routine includes a thorough inspection of the analysers, and a cleaning of the ultrafiltration unit. Every week to two weeks, measurements are verified by lab analysis, and tubing in the analysers are cleaned. Reagents have to be replaced, depending on the analyser, from every two weeks to two months. Most of the maintenance time was taken up by the ultrafiltration unit: automated cleaning would significantly reduce maintenance requirements.

Reliability

Given the thorough maintenance described above, the system can be called very reliable. In the fourteen months of operation, only two failures occured, namely one melted fuse and a broken valve.

Acceptance

It is still common belief that one of the major bottlenecks for implementation of control strategies is the lack of acceptance and/or skills by plant operators. Our experience has shown the contrary. It is thanks to the motivation and interest of the operators that this control strategy has become a success since the very beginning.

A much-neglected factor for the success of automatic control is the need for simplicity. Indeed, to ensure an efficient functioning, the control strategy should allow easy adaptation by the operators, and advantage should be taken of their expertise. Thanks to the simplicity of this control strategy and the strong motivation of the crew, the necessary skills were easily acquired and tuning could be left to the plant operators.

Cost efficiency

The above results were used to quantify the actual costs and benefits that are due to the implementation of the control strategy. The result of these calculations is given in Table 2.

Investment costs are composed of the sensors, the ultrafiltration unit, automation boards and housing. Working costs can be attributed to reagents, parts, personnel costs and expert maintenance. The savings are gained from reduced aeration, sludge production and chemicals. The relative distribution of the savings is illustrated in Figure 6.

The cost-efficiency calculation has been done in two ways. In a first analysis the calculations are split up for the carbon source and the iron chloride dosage. This is possible since they are in essence two independent loops. A second analysis regards the total system, i.e. including both control loops.

Table 2 Breakdown of costs and benefits from the implementation of the control strategy

Type	Iron chloride	Carbon source	Combined
Investment costs (EU)	29,000	45,200	59,200
Working costs (EU/y)	6,500	9,200	13,800
Savings (EU/y)	55,000	19,500	74,500
Payback period	7 months	> 2 years	12 months

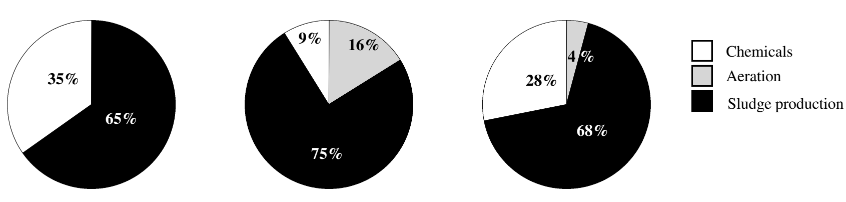


Figure 6 Distribution of the savings made with the implementation of controllers

A first conclusion appearing from this analysis is that the control loop for iron chloride dosage is cost efficient. The payback period is approximately 7 months. It is remarkable that most of the savings are not realised in the chemicals, but in the reduction of sludge treatment costs associated with it.

This conclusion can also be made for the carbon dosage loop. It appears furthermore that the carbon dosage control is not cost-efficient in itself (payback period > 2 years). This has several causes. First, the carbon source used is a cheap industrial product, and the savings that can be made are therefore rather low. As an additional exercise, the calculations were repeated using the price of acetic acid as a carbon source. This resulted in a pay-back period of 8 months.

Another cause of the low cost-efficiency can be pointed out. Since there are nitrification problems at the plant, there was need for an ammonia analyser. This requires housing and ultrafiltration and therefore explains the high investment cost. Without the ammonia analyser, the investment cost drops to about 20,000 EU, and the payback period reduces to approximately 15 months.

The implementation of the combined setup is again cost-efficient. The housing, ultrafiltration and automation can be used for both loops, resulting in a relatively lower investment cost. The payback period for the total system is about 1 year.

Conclusions

Feasibility of a control strategy is not quantifiable in a simple figure. Some benefits occur as directly measurable quantities; some have to be estimated and other important factors, such as ecological benefits and acceptance cannot easily be quantified. The evaluation of feasibility somehow remains a question of experience and is quite plant-specific.

From a purely financial point of view, the implementation of both control loops at the same time appear cost-efficient, and the implementation is called a success. A separate evaluation of the two loops indicated that, while the iron dosage loop is clearly cost efficient, the carbon dosage loop in itself is not. The cause of this is the low price of the carbon source.

However, aspects other than purely financial ones justify implementation of the carbon source control loop. The loss of nitrification was no longer observed with automatic controlled dosage. The loss of nitrifying biomass may even be caused by the overdosing with manual dosage. Indeed, the overdosing results in increased heterotrophic sludge inventory, and eventually washout of autotrophs. Also, effluent results are more consistently below consents.

A thorough maintenance scheme assures a reliable functioning of these control loops. The major maintenance demand is required by the ultrafiltration system. Currently, this system is cleaned manually. An automated cleaning would certainly reduce personnel effort and costs.

The simplicity of the control loops assures a good understanding with the plant personnel, and tuning of the controller is done in an intuitive manner. This stimulates the motivation of the crew, and is certainly a main factor in the success of the implementation.

In general, the implementation of this control strategy is a success, in both financial, ecological, and social terms.

Acknowledgements

Acknowledgements are due to Pieter Baudewijn and Erik Claes of the Aquafin R&D Analyser team (internally known as the A-Team) and the entire crew of RWZI Lommel, in particular Roger Strackx and Marcel Jaeken.

References

Aspegren, H., Nyberg, U., la Cour Jansen, J. and Andersson, B. (1992). Model and Sensor Optimisation of Nitrogen Removal at the Klagshamn Plant. *Wat. Sci. Tech.* **26**(5–6), 1315–1323.

Bogaert, H., Yuan, Z., Leten, J. and Verstraete, W. (1999). Intelligent Biocontroller for Activated Sludge Wastewater Treatment Plants. Aquafin Technological Study TE (93)07; Aartselaar, Belgium.

Henze, M., Gujer, W., Mino, T., Matsuo, T., Wentzel, M.C., Marais, G.v.R. and Van Loosdrecht, M.C.M. (1999). Activated sludge model no. 2D, ASM2D. *Water Science and Technology*, **39**(1), 165–182.

Jenkins, D., Richard, M.G. and Daigger, G.T. (1993). *Manual on the causes and control of activated sludge bulking and foaming*. Lewis publishers, Michigan, USA.

Maurer, M. and Boller, M. (1999). Modelling of phosphorus precipitation in wastewater treatment plants with enhanced biological phosphorus removal. *Water Science and Technology*, **39**(1), 147–163.

McClintock, S.A., Sherrard, J.H., Novak, J.T. and Randall, C.W. (1988). Nitrate versus oxygen respiration in the activated sludge process. *Journal of the Water Pollution Control Federation*, **60**(3), 342–350.

Yuan, Z., Bogaert, H., Vanrolleghem, P., Thoeye, C., Vansteenkiste, G. and Verstraete, W. (1996). Carbon Dosage Control for Predenitrification Processes. In: Proc. Workshop Modelling, Monitoring and Control of Wastewater Treatment Plants. Med. Fac. Landbouww. Univ. Gent, 61/4a: pp. 1733–1743. Ghent, Belgium.