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Current status of Instrumentation, Control and Automation in Wastewater Treatment Operations

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Abstract

Control is everywhere: in the pumping, the motors, the valves as well as in the operation in relation to oxygen supply, nitrogen conversions, chemical precipitation and hydraulic operation. The instrumentation development has made on-line control feasible in a lot of operational aspects of water and wastewater systems. Information technology, measurement processing, instrumentation, communication, real-time computing and operational management are brought together in automation systems. This paper aims to illustrate this development and to show that instrumentation, control and automation (ICA) is a concept that penetrates practically every aspect of water and wastewater treatment operation. There are three major driving forces for ICA: keep the plant running, satisfy (at all times) the effluent requirements despite disturbances and variable loads, and minimize the costs.

Key Words : Wastewater treatment, operation, ICA, instrumentation, control, automation

1. Introduction

Instrumentation, control and automation (ICA) are not new in water and wastewater treatment. ICA as an essential element of water systems has been recognized within the International Water Association (IWA) and its predecessors for more than three decades, as documented in the last ICA conference in 2001 (Olsson *et al.*, 2002a), in textbooks (Ingildsen & Olsson, 2001, Olsson & Newell, 1999) and in a recent IWA state-of-the-art book (Olsson *et al*., 2004). During that time wastewater treatment plants have been upgraded from being relatively simple mechanical/biological plants for removal of organic matter and suspended solids to being complex mechanical/chemical/biological plants for treatment of nearly any type of wastewater—and with very high effluent quality standards. Today the better knowledge of fundamental mechanisms produces an increased understanding of the processes and the possibility to control them. It is generally acknowledged that the introduction of ICA during the last decades has increased the capacity of biological nutrient removing (BNR) wastewater treatment plants by 10–30%. If these possibilities are further exploited by intelligent use of measurements and information technology, the improvements due to ICA will have a significant impact during the next decade. It has the potential to reduce operating costs—such as electrical energy, chemicals, sludge disposal, and in some countries green taxes—and to keep the effluent quality consistently acceptable, despite load variability and plant disturbances. Furthermore, ICA can make the plant meet increasing load demands. For apparent reasons ICA has to be integrated already in the plant design process. It is expected that ICA will have an even larger impact on both the performance and economy of wastewater treatment systems in the coming decade.

Information technology is now a mature technology and most treatment plants have several computers installed, but they are still under-utilized in plant operation outside of SCADA and PLC systems. Offline computers are generally used for little more than simple calculations and data visualization using spreadsheets and report preparation using word processors, largely because of the wide familiarity

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with this software.

Is the wastewater treatment process different from other industrial processes? The answer is both *no* and *yes*. *No*, all processes can be controlled to perform better. It is the process knowledge, the sensor technology and the way the plants have been designed and built that limit what can be achieved today. *Yes*, wastewater treatment processes do have some unique features: the flow rates, the disturbances, the small concentrations, the organisms, the separation and the fact that all the "raw material" has to be accepted and treated. Of course, other processes have their unique features, too. What are different are the attitudes in the different industries. The attitudes often depend on the incentives. In wastewater treatment, the incentives to put in the groundwork that, for instance, the oil industry started to do in the 1970s have not existed until today. But now the use of automation will progress much faster, thanks in part to industries like the oil industry. Other reasons for this change may be attributed to structural issues, such as stricter effluent standards, higher demands on operational efficiency, looser links between treatment industry (providers of treatment services) and authorities (the enforcers of effluent standards), etc. Yet another important reason is the increase in the plant complexity due to new and enhanced treatment technologies.

As the technology progresses it is apparent that more emphasis has to be placed on human aspects in order to make the best use of the plants and facilities and the human perspective is so often forgotten. Any great technology will fail if the operators and other people are not involved in the whole work, from planning, design to implementation and execution. Keeping and improving the competence at all levels will be an urgent question to deal with.

The paper presents the current availability of instrumentation and its combination with monitoring, control and automation. Some examples are presented where advanced instrumentation and control have been used to enhance the operation of a full-scale nutrient removal plant.

2. Automation Today in Wastewater Treatment

Automation of industrial processes involves a number of system components (Olsson & Newell, 1999). The natures of three of these components are specific for wastewater treatment operation: instrumentation, process monitoring and process control. In addition to these three, other automation components such as communication and database handling are also crucial for efficient operation. However, these components are less specific for wastewater treatment operations and can be considered as standard ingredients of the automation systems. Several factors have made the progress of automation in wastewater treatment possible (Olsson, 2002):

1. *Instrumentation technology* is today much more mature. Complex instruments like on-line *in-situ* nutrient sensors and respirometers are now regularly used in the field.
2. *Actuators* have improved over the years. Today variable speed drives in pumps and compressors are commonly used to allow a better controllability of the plant.
3. *Data collection* is no longer a great obstacle. Software packages are available for data acquisition and plant supervision. Benefits of such systems are no longer questioned.
4. *Computing power* can be considered almost "free".
5. *Advanced dynamical models* of many unit processes have been developed and there are commercial *simulators* available to condense the knowledge of plant dynamics.
6. *Control theory* and *automation technology* offer powerful tools.
7. *Operators and process engineers* are today much more educated in instrumentation, computers and control technology. However, there is still a great need for more education.

It is quite apparent that good operation must rely on functioning equipment. Automation is not only control algorithms or computer displays. All the links in the chain have to be working to obtain a good operational system. The hardware includes not only the instrumentation, but also all the various actuators, such as compressors, pumps, motors and valves. Communication systems are getting increasingly important in plant control systems. The software relies not only on proper control algorithms, but includes databases, communication systems, data acquisition systems and human friendly displays. Most important of all: people. Any well-intended and functioning control system can be a total failure if the operating people do not trust it. Therefore people involvement and education are a crucial part of a successful system.

2.1 Objectives for automation

The objectives for automation in wastewater treatment can be summarized in the key objectives discussed below.

Keep the plant running: Make sure that the equipment is functioning, that the pumps, valves and motors are operating, that the instruments are calibrated and maintained and that the signals are properly communicated to the control system. This includes the “low level controls” that are not immediately connected to the effluent quality. Most of these control actions are traditional process control loops, such as air pressure, liquid level, and flow rate control.

Satisfy the effluent requirements: It is not sufficient to keep the physical parameters correct, but other variables have to be controlled. It includes variables of different unit processes, such as dosage control for chemical precipitation, dissolved oxygen (DO) control, return sludge control or sludge retention time (SRT) control. Typically, there is one or a few simple control loops for each unit process.

Minimize the cost: In each one of the unit processes, the control scheme may be more elaborate so that resources like energy are saved. One example is DO control, where the DO setpoint is variable, not only along the aeration basin, but also variable in time. The ultimate goal at this level is to optimize the unit process operation.

Integrate the plant operation: The ultimate purpose of this is also to satisfy the effluent requirement at minimum cost and/or to maximize the utilization of existing investments. By coordinating several processes it is possible to decrease the impact of disturbances to the plant. The combined operation of the processes may make it possible to optimally use the available volumes and the sludge for the best operation and for the least impact on the receiving water.

Despite almost universal acceptance, there is still a great amount of opportunity to further apply automation. Recent surveys have shown that approximately 50% of control loops are run in manual mode.

2.2 Constraints for automation

There are a number of limiting factors for successful implementation of automation in treatment operation. Depending on the country the main bottlenecks may vary, but they are often related to the economy, plant constraints, software, legislation and education. Many of these constraints were recognized early (Olsson, 1993) but are still valid.

Economy: Since the wastewater treatment industry is basically a non-profit industry, there have been quite unclear goals as to what automation could do. Automation has been considered costly and has not been part of the initial design. Instead, the design has been completed first, and then automation has been introduced. Therefor a proper balance between design and operation costs is often not achieved. An adequate use of control and automation may in fact be a crucial factor that can make a plant run consistently and economically.

Plant constraints: Today there are quite a few plants demonstrating the success of automation, but many designers are still conservative and design plants with large safety margins. One looks for tried methods. As a result too little flexibility and controllability are built into many plants. Many actuators, pumps, motors and valves are not designed for control. Variable speed control is a proven technology, and still this is not universally recognized. Poor actuator design can eliminate any effort of otherwise good control systems.

Software: Many software systems are proprietary which will prevent standardization. There is an educational problem to make the users competent in using the software. There is a need to make software more user-friendly and flexible, so that the specific needs of a plant operation can be met.

Legislation: In many countries there is a lack of a tight regulatory standard, which makes it unnecessary to tighten the control on plants. The enforcement of the effluent regulations is often quite inadequate. Many regulatory standards are not adapted to the need of the receiving water. Instead they are static and do not consider dynamic variations.

Education, training and understanding: In most countries, the public awareness has been small until recently. This has caused delayed investments in better treatment facilities. Operators are not always adequately educated to deal with on-line instrumentation and control. Most environmental engineers (including operating engineers as well as designing engineers) would need more basic education in dynamics to appreciate the need and potential for automation.

3. Instrumentation

To measure is to know. As already remarked two important facts are emphasized: (1) Instrumentation is no longer a bottleneck for the control of wastewater systems and can readily be employed in control systems (here we use the common terms *measuring instruments* or *instrumentation* for sensors, analysers and other measuring instruments). (2) Information needs to be properly extracted from the measured data. Thus instrumentation always has to be combined with adequate data screening, measurement processing and more or less sophisticated extraction of features from the measurements. To track the current process operational state via the instrumentation is called *monitoring*.

For a long time instrumentation was considered a major obstacle for on-line control. Developments during the last two decades have changed that (**Table 1**) and increased confidence in instrumentation is now driven by the fact that clear definitions of performance characteristics and standardised tests for instrumentation have become available (ISO 15839:2003). The development of online sensors is continuing, and new technologies are introduced, that also allows measuring new parameters (Lynggaard-Jensen & Harremoes, 1996, Fleischmann *et al*., 2003, Langergraber *et al.,* 2004). Obviously, the trend has been to design smaller sensors and make them function by direct measurement, i.e. online sensors are becoming increasingly similar to the more classical sensors such as oxygen and pH—at least with regard to size and application. Next to the more common measurements there are also other instrumentation available for control, such as respirometers, VFA and alkalinity sensors, see further Vanrolleghem & Lee (2003).

Standardisation of instrumentation specifications now makes it possible to specify, compare and select the most adequate instrumentation—not only in technical terms but also in economical terms through calculation of the cost of ownership (**Table 2**). The investment costs for the device itself are often a minor part of the costs during the lifetime of the instrumentation.

Measurements from the instrumentation shall be available 24 hours a day and 7 days a week. However, even reliable instrumentation can fail during operation, which can have serious consequences if the instrumentation is used in closed loop control. Therefore real time data validation is needed before using measurements for control purposes. Data validation can be performed by quite simple methods on measurements from a single instrument or as cross validation on measurements from more instruments if any correlation is expected (Lynggaard-Jensen & Frey, 2002). If confidence in a measurement decreases, it might be possible (on a short-term basis) to use an estimated value, but eventually control must be set to a default scheme until confidence in the measurement has been restored.

4. Process Monitoring

In a sophisticated treatment plant there is a huge data flow from the process. Unlike humans, computers are infinitely attentive and can detect abnormal patterns in plant data. The capability of computers to extract patterns (useful information) is rarely utilised beyond simple graphing. Information technology is not commonly used to encapsulate process knowledge, i.e. knowledge about how the process works and how to best operate it.

Most of the changes in WWTPs are slow when the process is recovering from an 'abnormal' state to a 'normal' state. The early detection and isolation of faults in the bio-

Table 1 Commonly used measurements performed by instrumentation on WWTPs

Flow rate	Conductivity	Ammonium
Level, pressure	Dissolved oxygen	Nitrate
Temperature	Turbidity	Phosphate
pH	Sludge concentration	Organic matter
Redox	Sludge blanket level	Biogas production

Table 2 Items (and examples) included in the instrumentation cost-of-ownership calculation

Instrumentation	Cost of the instrumentation itself
Conditioning	Cost of rig, building, pumps, pipes, pretreatment, ...
Installation	Time costs for project and skilled workers
Integration	Time costs for programming of SCADA, control loops, ...
Consumables	Costs of chemicals, power, etc.
Maintenance	Cost of service contract and time costs for calibration, cleaning, ...
Spare parts	Cost of spare parts

logical process are very effective because they allow corrective action to be taken well before the situation becomes unfavourable. Some changes are not very obvious and may gradually grow until they become a serious operational problem.

Several methodologies are already applied in the chemical and petroleum process industry but are seldom exploited in the water industry. Examples are time series analysis, multivariate analysis, cluster analysis, Fourier frequency analysis and wavelet time and frequency analysis. Noise confounds many signals and whereas it can be removed by filtering, so can information-carrying patterns. Sometimes the noise pattern itself can contribute to the detection of abnormal behaviour.

Sensors for ammonia, nitrate and phosphate provide essential information to control a biological nutrient removal plant. Monitoring the course of the nutrient concentrations over time gives insight into the magnitude of variations and can be the basis for both detection and control. **Fig. 1** depicts an example from a period where on-line *in situ* nitrate, ammonium and phosphate sensors were located towards the outlet of an anoxic zone in a pre-denitrification plant in Lund, Sweden.

The ammonium concentration at the outlet of the anoxic zone not only shows the variability but also can be used as a load and feedforward signal for better control of dissolved oxygen in the aerator. The nitrate is shown to disappear at certain periods, showing that the anoxic zones are not used to their full capacity at all times. The phosphate sensor indicates that biological phosphorous release takes place when the zone becomes anaerobic (nitrate is gone). This shows that even at this late stage VFA is available for biological phosphorous release. It should be noted that the phosphorous release starts immediately when the nitrate concentration has disappeared (applies only in the first half of the data series). Especially during this phase it is a great advantage that the sensor can be moved around to find the most suitable location.

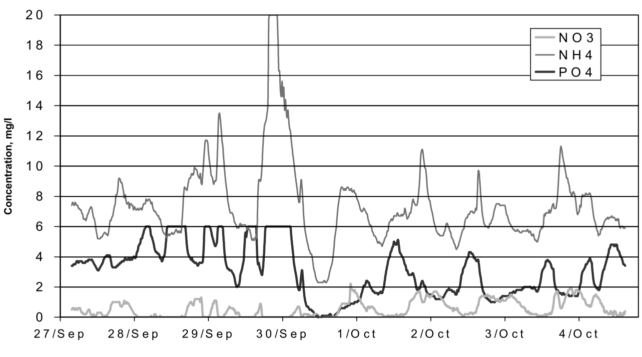

Fig. 1 Observation of the nutrients concentrations during one week at a location close to the outlet of the anoxic zone. The ammonia is the upper curve. The nitrate (the lowest curve) will go to zero at regular intervals, meaning that the denitrification has gone to completion. As soon as the nitrate reaches zero the reactor will turn anaerobic and we can see the phosphate rising quickly due to P release (from Ingildsen & Olsson, 2001).

4.1 Advanced signal processing

Multivariate statistical process control (MSPC), artificial neural networks (ANN), knowledge based system (KBS), fuzzy logic and wavelets are examples of signal processing and monitoring tools frequently found in the literature. Inspiration for this progress is generally coming from, for instance, chemical, pharmaceutical, and petrochemical industries. There are many similarities to other industrial fields but often adjustments must be done to adapt the methodologies to the requirements of wastewater treatment operation. Also, dynamic models, such as the Activated Sludge Model No 1 (Henze *et al.,* 2000), have been used to detect deviations and disturbances. However, it is tedious task to keep parameters updated according to the current operational conditions.

Knowledge on process performance indicators, such as respiration rate or nitrification rate is valuable for process monitoring and a lot of research is being carried out to find reliable and robust estimations methods. Biosensors and biological early warning systems are another research field for parameter estimation and process monitoring. These sensors and monitoring systems rely on immobilized microorganisms as well as higher organisms. The activity of the organisms are converted into signals and analyzed. The methodologies are often used to monitor toxicity, but can be used to determine other concentrations in the water stream.

Example: Using multivariate analysis for detection

This study is based on experiences from the Ronneby WWTP in Sweden, serving a population of about 15000. The plant is a pre-denitrification plant with two parallel lines and subsequent dissolved air flotation stage. The plant is operated at specific dissolved oxygen (DO) setpoints using DO controllers. A number of entities are measured on-line with no or negligible time delays. The measurements used in the case study originate from different stages in the process. A comprehensive description of multivariate methods for wastewater treatment monitoring is found in Rosen (2001).

Principal component analysis (PCA) is used to detect deviating measurements from a multivariate data set (Rosen, 2001) and Olsson *et al*., 2002b). PCA is today a standard tool for process monitoring in many industrial fields and is gaining recognition in WWT operation. PCA utilizes the fact that most industrial processes are driven by only a few underlying mechanisms that are ideally captured by principal components (latent variables). By plotting, for instance, the first component against the second component in a so-called score plot, the process changes can be viewed as a point moving around in the plane as new samples are added. Points that cluster represent similar process behaviour and, consequently, deviating points indicate process changes. This makes the score plot useful for classification purposes.

In this study a PCA model has been identified from a set of data containing 10^4 samples ($\approx$36 days) of process measurements. The variables range from influent flow rate and ammonia concentration to suspended solids concentrations in the biological reactors. The model is able to capture 50% of the variability using only two principal components. In **Fig. 2**(i), it is shown that the majority of the data are located in a cluster somewhat symmetrically located around the origin. The class boundary to the cluster below the main cluster has been determined empirically by manual inspection of data. Four classes are defined from the numerical characteristics of the data.

Some of the variables of the data used to identify the PCA model are shown in **Fig. 2**(ii). There are some events occurring during the training period: just before sample 2000 there are a few peaks in the influent flow rate (plot *d*) and in the air valve position (plot *c*); around samples 4400, 5800 and 6900 there are peaks in the suspended solids concentration (plots *a* and *b*); from samples 7000 to 7500 there is a period of rain increasing the influent flow significantly (plot *d*). All these events are represented by the different class memberships in the score plot. Normal, dry-weather conditions are covered by the class *a*. The peaks in flow rate together with the increased oxygen demand are represented by class *d*. Longer periods of high flow rate fall into class *b* while upsets in the suspended solids concentrations belong to class *c*. As shown in **Fig. 2**(i), different operating conditions appear as clusters or deviations in the score plot.

Next step is to investigate how the PCA model performs when applied to new (on-line) data. In **Fig. 3** the PCA model and its classes are used to classify a new set of data (10^4 samples). The majority of the data falls into the normal class (*a*), but there are some interesting deviations. Data are frequently classified as class *b* (high flow rate) and some times as class *d* (high oxygen demand).

There are also samples falling outside all the defined classes, somewhere between and below the classes *b* and *d*. In that case we have a situation not covered by the defined classes, and the set of classes may have to be updated for

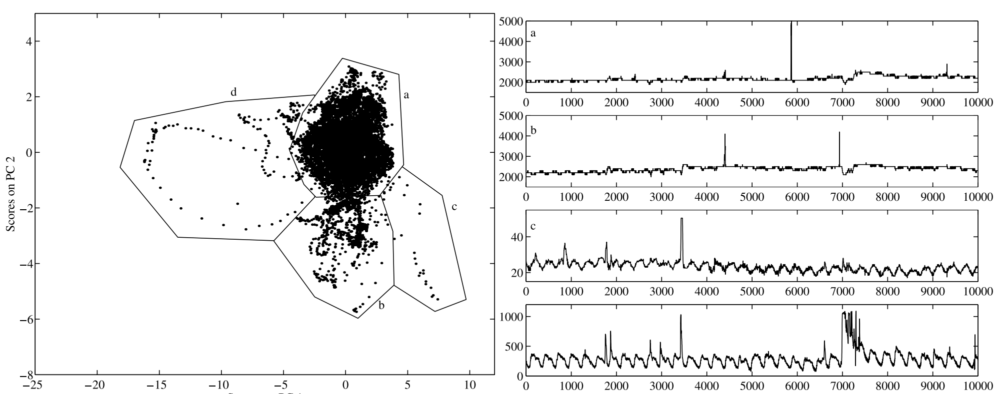

Fig. 2　(i) Score plot with classes manually defined from separate clusters and patterns in the plant. (ii) The original (measured) variables. Suspended solids concentration inline 1 (a) and in line 2 (b), air valve position (c) and influent flow rate (d).

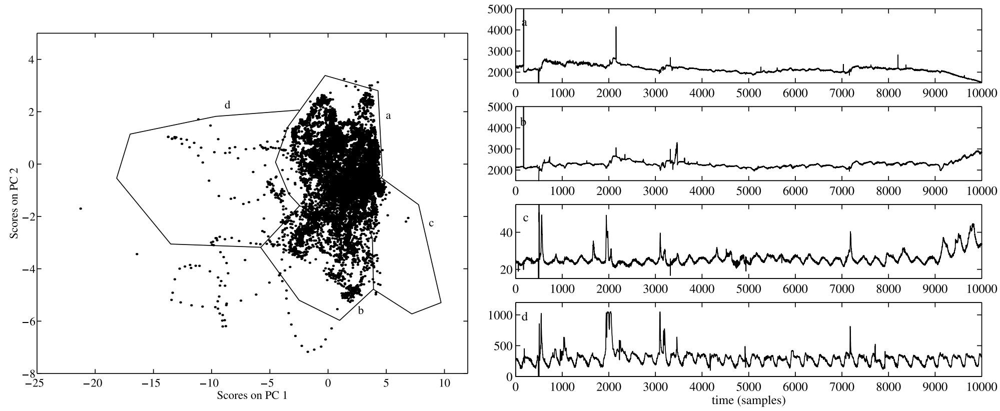

Fig. 3 (i) Score plot with classes from Fig. 2(i). (ii) The original (measured) variables. Suspended solids concentration in line 1 (a) and in line 2 (b). Air valve position (c) and influent flow rate (d).

future use. The data falling outside the defined classes range from samples 1937 to 1972 in the first event (the loop below class *d*) and from samples 3090 to 3100 in the second event (the loop below class *b*). By examining **Fig. 3**(ii), both events can be traced to an increase in both oxygen demand (plot *c*) and influent flow rate (plot *d*). This is not surprising as the events occur in between and below classes *b* and *d* in **Fig. 3**(i). The samples inside class *c* can be interpreted as an increase in the suspended solids concentration around samples 2150 and 3460. As a matter of fact, some samples fall outside the axis of the score plot and are not included for clarity reasons. An example of an event outside the score plot can be seen in **Fig. 3**(ii) around sample 500. It is obvious that something is wrong at that point in time.

The wastewater treatment industry has a lot to learn from other industrial fields. There are, however, a lot of work in progress within the field of process monitoring and operational support, albeit mostly in experimental stages. The introduction of new generations of SCADA and control systems will, together with current research and development, certainly affect the situation and operational personnel will, probably in a near future, have access to more sophisticated tools for process monitoring and evaluation. However, the integration of these tools with low level control loops in the process is yet to be explored and will provide an interesting topic for future research.

5. Control System Development

The purpose of control is to influence or govern a process (or other system), based on measurements, so that the process will reach the desired goal, despite disturbances. The state of the art in the control of wastewater treatment has developed significantly during the last decade. However, there is still a wide gap between the most advanced plants and the great majority of plants. For example, simple dissolved oxygen control is nowadays considered a proven technology, saving money and ensuring good process behaviour. Still it is not generally implemented. Today there is a deep understanding of the BNR mechanisms. Hence our ability to solve the control problems and to implement the solutions in software is so much better. Biological nitrogen removal has been studied extensively in the last decade and many control schemes have been developed. However, phosphorous removal mechanisms are still much less understood, and ICA will almost surely be a pre-requisite to operate these complex systems reliably. Sludge population optimization is another important challenge in control system design and the first steps in this direction are now being made (Yuan & Blackall, 2002).

There exists an enormous amount of literature today on control and much of it is adequate for water systems. Still, the real challenge in plant operation today is to *find suitable control structures*. With this we mean how to identify the most adequate measurement variables and instrument locations and how to connect these to the most appropriate manipulated variables. This also requires actuators that are sufficiently flexible and controllable.

Example: DO setpoint control based on ammonium measurements

The Källby WWTP in Lund, Sweden is a 100000 PE plant of a pre-denitrification type. In one of two parallel identical lines a DO setpoint controller (a simple PI controller) based on ammonium concentrations at the end of the aerated part of the plant was used. The DO concentration was controlled by means of DO sensor. The output from this controller was the airflow rate. The airflow rate was measured and manipulated by a PI controller opening or closing air valves. The resulting controller was a hierarchical structure of three PI controllers working in cascade by the master-slave principle. The controller performance is shown in **Fig. 4**, where it can be seen that besides periods of controller saturation the quite simple controller had a good performance. During the testing period aeration energy saving of 28% was reached compared to the parallel line where a constant DO setpoint was applied.

Example: Control of Post-Precipitation for Phosphorus Removal

At Källby WWTP in Lund, Sweden a post precipitation reactor has been used for the precipitation of phosphate. The traditional control is a flow proportional controller, where the dosage is proportional to the influent flow rate. It is often adjusted for rain events and the charges of the particles and the performance is checked by grab samples or 24-hour samples. Considering a typical phosphate concentration variation into the chemical step, **Fig. 5**, it is not trivial to obtain an average effluent phosphate concentration of 0.5 or 0.3 mg/l PO_4-P with such a plain strategy; it is necessary to use a quite high dosage.

A typical performance of load control is shown in **Fig. 6**. It is obvious that the influent phosphate concentration is increasing during the second half of the period, which seems to be the explanation for the increase in effluent phosphate concentration during the same period.

A feedback control strategy is then implemented where the dosage is controlled by means of PI controller that uses online and *in situ* measurements of phosphate in the flocculation chamber. By using online control the dosage can be reduced considerably and at the same time there is a confidence that the effluent concentration is acceptable regardless of events taking place upstream in the process, **Fig. 7**. For example if a phosphorous release takes place by accident, the controller increases the dosage correspondingly. As can be seen from **Fig. 7** it is possible to control the dosage to yield a quite constant effluent phosphate concentration, close to the target of 0.5 mg/l, in spite of variations in the influent phosphate concentration, **Fig. 5**. The standard

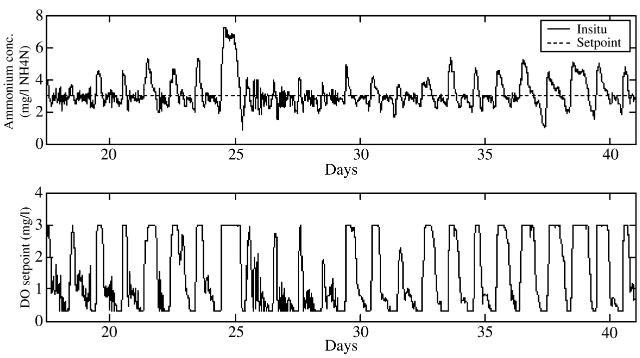

Fig. 4 Control performance. Upper plot shows the ammonium concentration at the end of the aerated part of the plant. The ammonium setpoint is 3 mg NH_4-N/l. The lower plot shows the DO setpoint during the same time. The DO setpoint is limited between 0.5 and 3 mg/l (from Ingildsen, 2002).

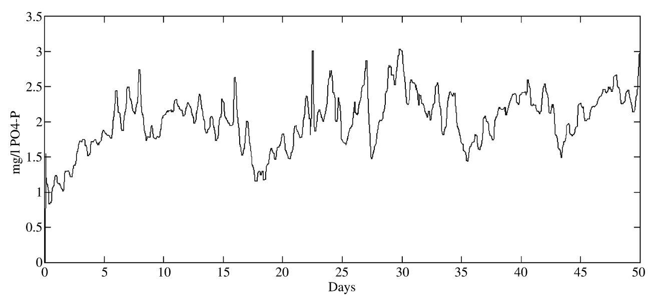

Fig. 5 Example of variation in PO_4 concentration into the chemical lines (from Ingildsen, 2002).

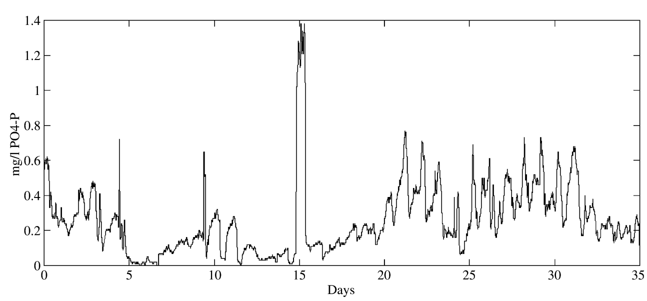

Fig. 6 Effluent phosphate concentration from flocculation chamber based on hydraulic load (from Ingildsen, 2002).

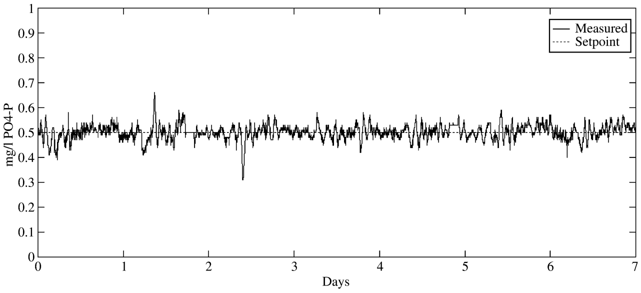

Fig. 7 Effluent phosphate from the flocculation chamber using sensor feedback (from Ingildsen, 2002).

deviation of the phosphate concentration from the flocculation chamber in **Fig. 7** is 0.031 mg/l PO_4-P. Furthermore, by simply adjusting the setpoint of the controller to 0.3 mg/l the controller could readily adjust the dosage with a similar performance.

6. Models for control

Mathematical models are becoming an essential part for design and operation of water and wastewater systems. The most sophisticated models available today, as the activated sludge model (Henze *et al.*, 2000) or anaerobic digester model (Batstone *et al.*, 2002), describe process dynamics in a highly detailed mechanistic way. However, the complexity of such models causes severe problems of identifiability and verifiability as they rely heavily on off-line analysis for calibration and identification. Usually, the models are derived from simpler unit operations and later combined to form large plant models. Although the qualitative behaviour is most probably the same, the identification and validation become an awkward task. A number of different parameter combinations can often explain the same dynamical behaviour (Dochain & Vanrolleghem, 2001). Also the time constants of the processes are very different and a treatment system suffers from long lag times and sudden, abrupt failures. In addition, there are a number of internal feedback loops within the system. The complete process is complex which is reflected in the modelling and it is also difficult to operate efficiently. This implies that the assistance of computer-based control systems is essential.

If a control system cannot perform well enough on measured information by direct feedback of observed variables, then one can seek to incorporate a model of the system in the controller. Such a model forms the basis for more sophisticated predictive control. Consequently, simplified dynamical models that allow all model parameters to be uniquely updated from available on-line measurements and with different predictive time horizons will prove useful. Naturally, the time scale of the models must also be related to the time scale in which the controlled variable can influence the process. The effectiveness to manage high process complexity by hierarchical and modular models has been demonstrated in numerous process industry applications. Consequently, it is suggested that future control systems for water and wastewater processes are based on similar principles.

To improve the reliability of a control system the need for fall-back control is essential. When severe problems occur, for example actuator or sensor failures, the control system should react on this and apply a robust control strategy that may not be optimal but will avoid significant process failures. Once the equipment functionality has been restored the control system can move the process back into a more efficient operating state. For any successful application of control it is also a necessity that the process is flexible enough to allow for a reasonable degree of freedom in terms of manipulation by the control system. Naturally, any new process should be designed for such flexibility rather than having to be subjected to costly re-constructions in the future. In many situations this is a major bottleneck for successful implementation of control in water and wastewater systems. A state-of-the-art book on control in wastewater treatment systems is currently published by IWA (Olsson *et al.*, 2004).

7. Automation

Automation is the method of making a process or a system operate automatically. *Uncertainty* in the process or in the environment around the process makes automation a great challenge. *Disturbances* are everywhere and are the main reason for control. Application of automation in wastewater treatment operation can be said to have two primary functions: information acquisition and process control. For the former function, the level of automation is relatively high. Many, often thousands of variables (there are plants with as much as 30000 variables), are today gathered on-line in the SCADA systems of treatment plants and more or less sophisticated data analyses are standard components of the treatment operation and quality monitoring. However, the latter function, process control, is less developed and often limited to a few unit process control loops. The potential of plant wide automation is to coordinate the various unit processes so that the overall performance requirements are better fulfilled.

Automation is not only control algorithms or computer displays. It is quite apparent that good operation must rely on functioning equipment. All the links in the chain have to be working to obtain a good operational system. Communication systems are getting increasingly important in plant control systems. The software relies not only on proper control algorithms, but includes databases, communication systems, data acquisition systems and human friendly displays. Most important of all: people. Any well-intended and functioning control system can be a total failure if the operating people do not trust it.

The development towards process/plant wide control approaches is still in its infancy. In the plant wide perspective many interactions have to be taken into consideration. If the sewer system is included into the controlled system, then the wastewater treatment plant flow rate becomes a controllable variable and not just an external disturbance. The interaction in the treatment plant due to internal recycle streams, both in the activated sludge process and between the sludge treatment and the wastewater treatment, are significant factors in the plant wide operation. There is also a downstream coupling in the treatment plant. The strong coupling between the aerator and the settler is well known. Another coupling is between pre-precipitation and the biological reactor. The chemical dosage will not only cause phosphates to precipitate. Other particulate material will be eliminated via the primary settler, so the carbon load to the bioreactors will be decreasing. The resource allocation, in particular energy utilization, is another important issue that has to be faced in plant wide control. A more detailed discussion and some full scale experiences are further explored in Olsson *et al.* (2004).

Automation has been accepted as a standard component of wastewater treatment plant operation. The control system includes a supervisory system that sends setpoints to the SCADA system with regard to for example DO setpoints, setpoints for the sludge concentration in the return sludge, chemical dosage setpoints, phases, start and stop of aeration tank settling, etc. Implementation of such plant-wide control systems has a good cost-benefit relationship with payback periods ranging from one to five years. However, to make the next step and to implement—at least some part of—control in the total system in reality proves to be a very tedious task. The present obstacles seem to have more to do with data (assessment, management, analysis) and administration than with control algorithm issues. Moreover, since the overall objective can still not be defined in concrete terms, the operators seem to be careful to embark on the idea of integrated control approaches. To make plant wide and integrated control come up on the agenda, it is needed to focus on a wider spectrum of problem areas. This includes structuring large control systems, organizing automation structures, and modularizing large control systems.

Future development will be exploiting the enormous capacity of data distribution that is possible today. Many SCADA systems are also applying the technology from the Internet, which gives an almost unlimited potential for remote data evaluation and decision. The distributed control room is already here. There is a limit of how much expertise a treatment plant can afford. However, given that plant data can be made available anywhere it is possible to utilize specialist competencies wherever they are located. However, there are several human and managerial aspects of how to distribute the responsibility and decision-making in various sectors. In the EU TELEMAC project a remote monitoring and control system is developed for use in wine wastewater treatment facilities, where one expert is remotely supervising some 20 small treatment plants. There is already commercial software available for this type of process monitoring and control. Naturally there has to be caution against publicizing sensitive data or against misuse of information. Also, there is a need to guarantee that data is correctly interpreted from each individual plant.

8. Challenges

The increasing incorporation of ICA in water treatment operation is not only driven by the impressive technical development of instrumentation and computer technology, modelling and control, and the progress in automation. It is motivated by economy and environmental obligations and turns out to be a necessary and worthwhile investment. It is already proven in several installations that ICA investments have paid off quickly and we will see that ICA will become an increasing part of the total investments.

Mounting evidence has become available demonstrating that the microbial populations and their properties are jointly determined by the wastewater composition and the design and operation of a treatment system. The impact of control systems on the microbial communities has not attracted much attention in the past, and sludge population optimization through on-line process control is still an emerging concept (Yuan & Blackall, 2002). Fundamental studies to understand how certain microorganisms are selected and how bacterial properties are influenced by particular plant designs and operations are of vital importance and need to be carried out in a systematic way. Modern molecular techniques such as Fluorescent In-Situ Hybridization (Amman *et al.*, 1995), which allow the identification and quantization of microorganisms present in a system, are indispensable tools for these studies. The most rapid fundamental advances will come from the incorporation of detailed micro-scale data into current mathematical models such that these models more closely represent the sludge processes, allowing model-based sludge population optimization. A great deal of effort from both microbiologists and engineers is still required for the practical application of these methods in the context of process control. The close collaboration between microbiologists and engineers cannot be over-emphasized.

ICA is often perceived as the *hidden technology*. You will notice it when it does *not* work. The complexity of modern WWTPs is often reflected in the ICA systems. Several specialities have to be synthesized into one system of process technology and automation. The *challenge of automation* is to comprehend the *system aspects from a unit process perspective* and to understand the *process aspects from a system perspective*. This challenge has profound consequences on the profession and on fundamental educational approaches, not the least in civil and environmental engineering curricula. One important implication is that process specialists have to be able to appreciate the implications of ICA. Likewise computer and control engineers have to understand the process controllability and its constraints. It further emphasizes the multi-disciplinary character of water operations. Such a challenge ought to inspire young people.

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下廃水処理における計装，制御，自動化（ICA）の現状

Gustaf Olsson

要　約

ポンプ，モータ，バルブ，あるいは，送風量，硝化・脱窒，凝集沈殿，水量の調節など，“制御”技術は，下廃水処理のあらゆる場面に導入されている．また，“計装”技術の発展によって，上下水道施設の運転管理の多くの分野において，リアルタイム制御の導入が現実的なものとなった．情報処理技術，計測技術，計装技術，通信技術，リアルタイムコンピューティング技術，そして運転管理技術などが，統合的に導入されることによって自動化システムが実現されているのである．本論文では，これらの技術の開発状況を概説し，“ICA”が，現実的な意味において，上下水道処理施設運転管理の全ての分野に浸透しつつある概念であると示すことを目指した．“ICA”の普及には3つの大きな目的がある．すなわち，施設の運転を維持すること，負荷変動などの外乱の影響を受けずに水質基準を（常に）満足すること，そして，諸コストの最少化である．

キーワード：下廃水処理，運転，ICA，計装，制御，自動化

（訳　後藤雅史）