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Instrumentation, Control and Automation in wastewater– from London 1973 to Narbonne 2013

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Abstract: Key developments of instrumentation, control and automation (ICA) applications in wastewater systems during the past 40 years are highlighted in this paper. From the first ICA conference in 1973 through to today there has been a tremendous increase in the understanding of the processes, instrumentation, computer systems and control theory. Still many developments have not been addressed here, such as sewer control, drinking water treatment and water distribution control. It is the hope that this short review can stimulate new attempts to more effectively apply control and automation in water systems in the coming years.

Keywords: Monitoring, sensors, simulation, modelling, water, wastewater

INTRODUCTION

Instrumentation control and automation (ICA) integrates several branches within engineering to monitor and control operations in industrial processes and systems. The first ICA conference, under the sponsorship of the IWA predecessor IAWPR (International Association on Water Pollution Research), was held in London in 1973. In this paper we try to reflect on some of the ICA developments in wastewater systems that have taken place during the past 40 years until the 11th IWA conference on ICA in Narbonne. It is of course preposterous to give a comprehensive review but it is considered of interest to critically assess what the key developments have been. From this we hope to identify new challenges that should be addressed by the ICA community in the coming years and decades. This paper concentrates the discussion on wastewater treatment, as this has been the dominating theme in the ICA conferences. Control and automation of drinking water treatment and distribution as well as sewer operation and control have been excluded here due to space limitations. Still they are important parts of the system wide perspective and are briefly discussed in a separate section.

Four of the authors have been responsible for the scientific programs and the planning of the last four ICA conferences, since 1997. ICA developments have been reflected in the IWA Scientific and Technical Report No. 15 (Olsson *et al.,* 2005) and in Olsson (2012).

It is of interest to identify the driving forces in ICA research and development, and we recognise both sticks and carrots. The technology development – computers, instrumentation, power electronics, control theory, process knowledge and modelling – have many ICA implications. We now need to closely examine if we have been utilising available theory and tools for better operation and control. Regulatory drivers have forced the development of new processes for nutrient removal, and economic incentives have been created to improve the efficiency and reliability of operations. ICA is no longer a supplementary profession to the water and wastewater industry but has become main-stream. There are now lots of professionals implementing automation and process control in wastewater installations but unfortunately not always with the right education or the necessary process understanding to do so. The latter can be problematic, for example when it comes to identifying new opportunities resulting from implementing ICA tools.

DEMAND PULL

Regulatory requirements, economics and efficiency are important driving forces. Water quality is certainly a driver in plant design, but it is not typically the driver for ICA. Too often ICA is implemented to improve efficiency or reduce costs but only as a second step for existing plants. The coupling of design and operation ought to be improved, the so-called control-integrated design. Inflexible or under-dimensioned designs cannot be improved by control.

The first ICA applications in the 1970s were made in activated sludge processes for organic matter removal. The effluent requirements were mostly on BOD and suspended solids, while neither nitrogen nor phosphorous removal were considered. Since then more stringent effluent requirements, including nutrient removal, and more efficient operation have pushed the designs of wastewater treatment processes. This has given rise to many more manipulatable variables:

- Today a bioreactor has more zones; anaerobic, anoxic and aerobic. Some of them – the swing zones – can be both aerated and anoxic;
- Air supply systems are much more sophisticated. Aeration zones can be controlled separately, pressure losses can be minimized by variable pressure control and variable speed compressor control;
- More intermittent systems, such as sequential batch reactor (SBR) systems are being used and these are more flexible for control;
- Control systems have been developed where a portion of the aerated part of the plant has been used as a settler during high load situations (aerated tank settling operation);
- More recirculations are available, for example nitrate recirculation;
- Chemicals can be added for enhanced primary clarification as well as for chemical phosphorus removal;
- Volatile fatty acids can be added from the primary settler to enhance Bio-P;
- External carbon can be added to control denitrification.

Energy is now the single largest operating expense at the plant so it makes economic sense to reduce those costs where possible through good control. The vision of zero or even positive energy plants has already been realized in some cases (for example

Nowak *et al.,* 2011). Notably different energy forms have to be carefully defined, as electrical and thermal energy are not equivalent. While the traditional focus has been on the wastewater treatment process, a shift in emphasis may take place towards sludge treatment and waste-to-value conversion processes, leading to rename Wastewater Treatment Plants (WWTPs) into WRRFs, Water Resource Recovery Facilities.

It may be possible to address all of the driving forces together and show that with the right control strategies and settings the most efficient solution can be achieved. However, this means that better ways to deal with multi-criteria decisions will have to be developed. A lot of solutions are described in the literature but these are seldom applied in the water industry. A new IWA Working Group on Life Cycle Analysis is indicative of the realisation that efficient plant design and operation is the future. However, to achieve this, there is a need to get past the pure technical constraints and better understand the motivation of operators, as described by Rieger and Olsson (2012). As discussed below, system-wide aspects will become increasingly important as well.

TECHNOLOGY PUSH

Computers

With today's computer technology and on-line instrumentation we take it for granted that lots of data will be available, but we also know that data-rich is not the same as information-rich. Data have to be validated and interpreted. In 1973 a typical process computer was the Digital Equipment Corporation PDP8 with 28 kB of memory, supplied with nearly 100 analog inputs, some 200 digital outputs, and 15 analog outputs. Today we describe memory size in terms of GB and a plant often has more than 30,000 digital and analog signals. Historical data can be stored easily, so it is important to understand if the data is being used in a constructive way. We can easily simulate complicated non-linear models, but the challenge is still the verification and validation of the models and the underlying data base (Hauduc *et al*., 2010).

We are frequently drowning in data and lose sight of the forest from the trees. The human brain is a fantastic engineering tool, and - for the foreseeable future - cannot be substituted with even the smartest and most useful of algorithms. George Ekama (Univ. of Cape Town, South Africa) put this in a lucid way at the WWTmod conference in Quebec in 2010: "The main problem is to keep the main problem the main problem".

Instruments

Obtaining reliable measurements is the fundamental condition for control. In any plant operation we first have to make sure that the equipment of the plant is operating adequately. In other words: physical variables like flow rates, levels, and pressures have to be controlled by local controllers. The need for reliable instrumentation was realised from the very beginning. At a workshop in 1974 at Clemson University, S. Carolina, USA, the need for efficient and dependable sensors was discussed (Buhr *et al*., 1974). At the time, key variables included flow rate, sludge blanket level, settling velocity, respiration rate, suspended solids, short-term Biochemical Oxygen Demand, ammonia, nitrate and phosphate. Also a central location for gathering and dispensing information on instrumentation testing was recognised as being "of considerable assistance".

Today there are numerous sensors available on the market. According to a recent - but not public - industrial marketing analysis there are almost 100 sensor companies in the world working with water. These include a handful of large corporations dominating the market, but there is a variety of smaller companies developing new sensors that are of interest for treatment plants.

An important development of nutrient sensors has taken place in the last two decades, from automated laboratory analysers that had to be protected from the measured system to *in situ* sensors that can be placed directly in the liquid to be monitored. On-line *in-situ* nutrient sensors are becoming common and affordable (e.g. ion-selective electrodes (ISE) probes for ammonia and UV probes for nitrate and nitrite). This has eliminated long measurement delays and slow sensor dynamics, resulting in easier control and better performance. Relatively recent advancements include optical sensors based on luminescence techniques for DO measurements that require less maintenance compared to membrane-based sensors.

Ingildsen (2002) showed how a phosphate *in situ* sensor could significantly improve chemical dosage control, but still robust *in-situ* phosphate sensors are high up on the wish list. Sludge blanket sensors were used for secondary clarifier control decades ago, but more reliable sensors are now available. An online sludge settling velocity instrument could establish the crucial coupling between the biological reactor and the clarification. Such a settlometer was developed at Ghent University (Vanrolleghem *et al.,* 1996) and later commercialized. Its application is described in Plosz *et al.* (2007). Now that so many sensors have been developed, it is important to unlock and disseminate.

There is still a huge potential in using *sensor networks*. They consist of a group of sensors with a communications infrastructure with the purpose to monitor variables at diverse locations. Today there are several applications of networks measuring variables like temperature, rainfall intensity, chemical concentrations and pollutant levels.

The Internet is now ubiquitous and is slowly getting used for remote monitoring in wastewater treatment systems. The possibility was mentioned in Olsson *et al.* (2005), Chapter 1, and a real application of remote monitoring is described in Lee *et al.* (2004). A centralized control system using the Internet to remotely control small decentralized plants in Korea's rural communities was discussed in that publication.

Actuators

In the last few decades there has been a revolution in the development of power electronics. Power electronic devices like IBGT (Insulated-Gate Bipolar Transistors) are now generally available for currents up to 1200 A and voltages up to 3000 V with switching frequencies of more than 1 MHz. This makes frequency control of electric motors both affordable and reliable, from mW scale motors to MW drives. Variable speed control has a large influence on wastewater treatment operations in flow rate control as well as for air flow control. This has a profound influence on both the quality of the control action and on the energy efficiency of the various operations.

It should be kept in mind that it is important to measure the actuator action. For example, in an aeration system it is important to know the opening of an air valve. This enables the control of the DO according to "the most open valve" control method (Olsson and Newell, 1999; Åmand *et al.,* 2013). Furthermore, by monitoring the valve opening together with an air flow or a liquid flow it is possible to detect a pipe clogging or increased friction in the valve operation.

DATA QUALITY AND PROCESS MONITORING

A desirable ICA approach needs a monitoring system to gather, process and display the data, detect and isolate measurement faults or abnormal process situations. Too often instruments are used just for recording despite being installed for the purpose of control. The monitoring system could also assist in diagnosis and advice, and finally simulate the consequences of operational adjustments. Several tools have been developed to aid in process monitoring and data management.

Statistical analysis for i.e. outlier detection is seldom done at treatment plants today, although tools such as statistical mass-balances and control charts are available, as discussed by Olsson and Newell (1999), Thomann *et al.,* (2002) and Thomann (2008). A standardised method to process sensor data at treatment plants is presented in Irizar *et al.* (2008), where sampled data is filtered for noise reduction before it is stored. After storage, post-processing of data is made available. At the Rya WWTP in Sweden (Lumley, 2002) soft sensors were used to verify instrument readings. This included on-line mass balance calculations, where a calculated measurement was compared with the real measurement.

Multivariate analysis is a method to detect patterns and correlations in large data sets. It has been used for many years in the chemical process industry, but was only introduced into the wastewater industry in the late 1990s (Rosen and Olsson, 1998). The most well-known method to reduce the dimensionality of the data cloud is Principal Component Analysis (PCA). This technique is simple in the sense that the data can readily be projected onto a smaller dimension. However, PCA methods are insufficient to deal with data that are highly variable, such as influent flow rates and compositions (Rosen *et al*., 2003). Furthermore, the wide range of time constants in a wastewater treatment system makes it difficult to look at correlations of data in just one time scale. Various methods to extend the PCA were applied for monitoring wastewater treatment data by Rosen and Lennox (2001) and Lennox and Rosen (2002) as well as clustering and discriminant analysis. An operator decision support tool for wastewater treatment plant operation was also proposed by Moon *et al*. (2009). PCA has also been used in sequencing batch reactors for monitoring (Lee and Vanrolleghem, 2003; Villez *et al*., 2008) and as a basis for control of the phase length (Villez *et al*., 2010).

The multivariate methods have been successful in many applications, but have been much less useful in others. Rosen *et al*. (2003) give an insightful overview of why some of these methods have failed and also guide the reader on how the methods can be adapted for wastewater treatment operations. Many of the methods have been tested in the Benchmark Simulation Modelling efforts described below (Corominas *et al.,* 2011).

Another possibility to support the operator in decision making is to use data mining techniques for knowledge extraction from a historical database containing the disturbances and control actions and to match patterns to recognise the shape of the sensor profiles (Kim *et al*., 2012).

TOOLS FOR IMPROVED PROCESS UNDERSTANDING AND CONTROL

Process models

Impressive research efforts on nutrient removal were performed in particular at the University of Cape Town under the leadership of Prof. Gerrit v. R. Marais during the 1970s and 1980s. This was channelled to the water profession via the IWA Task Group (1982) on Activated Sludge Modelling with Mogens Henze, Les Grady, Willy

Gujer, Gerrit Marais and Tomonori Matsuo, later joined by Takashi Mino, Mark C. Wentzel and Mark van Loosdrecht. The understanding of the biological and related physico-chemical phenomena responsible for removal of organic carbon, nitrogen and phosphorus compounds has gradually been translated into the Activated Sludge Models (Henze *et al.*, 2000), the Anaerobic Digestion Model (Batstone *et al.*, 2002), and other models. The impact has been remarkable. Not only have these models increased understanding of key processes, but they have also provided a common language, verified implementations (Hauduc *et al.*, 2010) and nomenclature, recently updated (Corominas *et al.*, 2010).

Models of the equipment need to be added in order to design proper control systems. Therefore models of actuator dynamics – such as pumps, compressors and valves – and sensor dynamics have been developed for both the wastewater and other process industries (Rieger *et al.*, 2003).

The models provide platforms to perform plant-wide dynamic simulations with a time horizon up to several years, i.e. dynamic simulations where interactions between the activated sludge tanks, sedimentation, primary treatment and sludge treatment can be captured and evaluated for a number of sludge ages. This is a powerful tool in our search for improved control. However, one should be cautious and always keep the limitations of such models in mind. Experimental validation of control strategies developed on the basis of simulations with these models remains essential. As expressed by the statistician George E.P. Box (Box, 1979): “All models are wrong, but some are useful” (later he wrote: “Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful”; Box and Draper, 1987, p. 74).

Control theory

Control theory has had a truly extraordinary development during the last 40 years. Therefore, it is quite remarkable that the control theory that was available in the 1970s can still solve a vast majority of the process control problems in wastewater treatment (Olsson and Newell, 1999). This is true also in other process industries, like the pulp and paper industry, where some 95% of the controllers are PI (proportional-integral) regulators. The reason is that most of the processes can be described by low-order dynamics. Some non-linearities (like the Monod type ones) can be described as “smooth” non-linearities, i.e. the systems still behave linearly for small variations around the operating point. Others – like valve behaviour – can be compensated by cascade control, using simple proportional or PI controllers. Highly non-linear systems – like exothermic reactions – do not appear in wastewater treatment systems.

There are very few processes that are truly multivariable in the sense that a multivariable controller is necessary. Most process parts can be favourably decoupled and thus controlled by single-variable controllers. However, in monitoring using for example Principle Component Analysis – PCA – the multivariable character of measurements must be taken into account as some effects cannot be detected if the scores are monitored separately.

The wastewater treatment dynamics is truly stiff with a very large ratio between the fastest and the slowest response times, from seconds (air and liquid flow rates), to hours (concentration changes), days and months (microbial communities). Still, the system can be successfully decoupled in slow and fast control loops using simple controllers.

Any feedforward control requires a model of the system. With increased understanding of the process dynamics, such feedforward controllers have been applied.

Certainly many different kinds of controllers have been tested using simulation (see for example Weijers, 2000; Åmand *et al.,* 2013), including *rule-based control*, fuzzy logic control, linear quadratic control and model predictive control (MPC), but much fewer have actually been implemented in full scale.

The control of wastewater treatment systems is certainly not limited by the available control theory. Rather, the challenge is to have a good understanding of the process and its limitations, the control authority of the actuators, the reliability of and information from the sensors and the data management and monitoring strategies.

Simulator developments

With wastewater treatment models available it was natural to package the models in software. Early simulations were reported by Andrews and Graef (1971) and an early example of a model library was described in Olsson *et al*. (1985). Early simulators, used for model development, were developed, such as ASIM (Gujer and Larsen, 1995) and SSSP (Bidstrup and Grady, 1988). Research at McMaster University, Hamilton, Ontario, Canada led to the commercial package GPS-X from Hydromantis with Gilles Patry and Imre Takács as the key actors (Patry and Takács, 1990; GPS-X, 2013). Several other application specific simulator packages have appeared, such as Aquasim (Reichert, 1994; Aquasim, 2013), BioWin (Dold, 1990, 1992; Biowin, 2013), Simba (Developed at Ifak, Germany; Simba, 2013), STOAT (Stoat, 2013) and WEST (Vanhooren *et al.*, 2003; West, 2013). General purpose platforms like Matlab/Simulink are frequently used for simulation of wastewater treatment system control. An integrated examination of sewer systems, wastewater treatment plants and receiving waters is now possible using some of the commercially available simulators.

Some of the simulators can combine a process model with online real time modules, data filtering, sensor fault detection, parameter estimation, model parameter extraction from respirograms, uncertainty analysis, decision support modules and the software to make all these modules work together. The goal in the early 1990s was to use the system for automated, online model calibration, data validation, process diagnosis and control (Patry and Takács, 1994; Takács *et al*., 1995). An early way of using the simulator was to use one computer running a complex model representing the plant, with disturbances, and another computer connected to the "plant" running a simplified model identifying the disturbances, correcting for mass balance errors in the "data" and autocalibrating the model.

Today, 20 years later, we know that a fully integrated computer control system – including automatic model identification/calibration followed by an automated model-based control of a full plant – is still not achievable. The complexity of the plants is large. Sensor faults may not be detected unless there is sufficient sensor redundancy. Still the potential of soft sensors and estimation techniques to test sensor information has not been exhausted. However, the ideas of integrated control have helped the wastewater industry to see the vision of what could be achieved and what is required to move forward.

There is a large potential of using on-line simulation for operator support. This is a proven experience in some process industries. An early example in the wastewater industry is Printemps *et al.* (2004).

Control system benchmarking

From a practical standpoint, it is not reasonable to experimentally test and verify at full-scale the effectiveness of potential control strategies, and even though many control strategies have been proposed in the literature, the literature does not provide a clear basis for comparison of these strategies because of the many confounding influences that have an impact on the system. However, given a standardised procedure, it is possible to efficiently evaluate numerous strategies through dynamic computer simulations. The unlimited number of simulation permutations makes the need for a standardised protocol important if different strategies are to be objectively compared.

The idea to produce a standardised 'simulation benchmark' was first suggested by Bengt Carlsson (Uppsala University, Sweden) at the 1993 ICA Conference in Hamilton, Canada, exactly 20 years and 5 ICA conferences ago. This idea was developed by the first IAWQ Task Group on Respirometry-Based Control of the Activated Sludge Process (Spanjers *et al*., 1998) and subsequently modified by the European Co-operation in the field of Scientific and Technical Research (COST) 682/624 Actions in co-operation with the second IWA Respirometry Task Group (Pons *et al*., 1999; Copp, 2002; Copp *et al*., 2002). The benchmarking efforts are documented in Gernaey *et al*. (2013). As the benchmark plant models are simulation software independent, they provide an unbiased basis for comparing control strategies without reference to a particular facility.

The benchmark models have been criticised as only academically applicable and providing limited benefit to the applied modelling community. However, the work was aimed at the control community to evaluate control algorithms and the development of the benchmarks has provided a number of spin-off benefits, including the development of several applicable sub-models (Copp *et al.,* 2008). The benchmarks are a modelling toolbox and a platform on which modelling issues have been debated, experimented upon and tested. The benchmark simulation model development value lies in these individual modelling tools and the modular nature of those tools means that they are portable and can be used in isolation if the need arises. The hundreds of references in the literature to these benchmarks is a testament to their value both for control evaluation and modelling in general for now and the future.

PROCESS CONTROL

Several activated sludge manipulated variables have been the subject for feedback control, such as aeration, nitrate recirculation, external carbon dosage, chemical precipitation dosage, return sludge flow rate and waste sludge flow rate. Control strategies are improving thanks to improved possibilities to measure. Ammonia measurements are now being used to calculate variable DO setpoints. Denitrification can be optimised by controlling the internal recirculation flow rate, using nitrate sensors. Phosphate analysers have been used to control the dosage of chemicals for phosphorus removal as well as monitoring the biological phosphorus removal process.

Since the 1970s a huge amount of effort has been directed towards improving dissolved oxygen (DO) control, driven by the desire to reduce the costs induced by this energivorous process (Olsson, 2012). The state-of-the-art to 2005 was summarised in Olsson *et al*. (2005). A review of aeration control with emphasis on the 21st century is found in Åmand *et al*. (2013).

The thesis by Ingildsen (2002) played an important role in closing the gap between the theory of process control and real practice. Results in the thesis are still valid. Vrečko *et al*. (2011) is probably the first attempt at applying a model predictive controller (MPC) in a real nitrogen removing process (pilot-plant MBBR). Even though evaluation is performed over a relatively short period of time, the paper summarises what we have learned from full-scale control studies so far: feedforward-feedback or feedback control of ammonium is a powerful method to control aeration processes in nitrogen removal treatment plants. This is further described and analysed in Rieger *et al*. (2012, 2013).

The thesis by Lindberg (1997) is an example of an outcome from a Swedish national research initiative (suggested among others by Gustaf Olsson) in the early 1990s. Four different controllers for controlling the nitrate level using an external carbon source were evaluated using simulations and pilot plant experiments and one of the first strategies for ammonium feedback control was suggested.

A novel perspective was brought up by Yuan and Blackall (2002). They proposed that sludge population optimisation should be added as a new dimension to the control of biological wastewater treatment.

J.P. Steyer has written an excellent overview of the control of anaerobic digestion processes in Chapter 7 of Olsson *et al*. (2005) and in Steyer *et al*. (2006). It is essential to focus the attention on the lack of actuators in AD processes.

A lot of plants in many countries around the world have adopted ICA. Nevertheless, in operation it seems difficult to reap all the benefits of the instrumentation, process models and knowledge. It appears that the provided information is not always adequately understood or acted upon. Better ways to provide information – for example by visualisation (such as Wölle *et al.,* 2007) – and decision criteria for operations need to be developed. ICA professionals may not efficiently communicate their knowledge to colleagues. Sensors are located incorrectly, data analysis is not adequate, sampling frequencies are often unrealistic (mostly too fast), and controller settings are often not adequate.

One obstacle in controller implementation is the lack of standardisation. There are too many home-brewed controllers. Often we see researchers in academia working on “solutions looking for a problem”, and controller tuning is not always done properly. Many control systems do not include fall-back strategies; how to mitigate the risk of a broken or failing sensor. Work is on-going (for example in the IWA DOUT Task Group, Belia *et al*., 2009) to further look into how uncertainty will influence control (Alcaraz-Gonzalez *et al.*, 2005). There is a lot of theory developed for “control under uncertainty”, but much remains to be applied for the water and wastewater operations.

CONTROL-INTEGRATED DESIGN

There is an important coupling between design and operation. Many plants are designed using a steady-state worst-case approach without a proper accounting for the dynamics of the system. Without considering the dynamics it is unlikely that a proper control strategy design will be possible, which together with the often over-dimensioning of systems leads plants further away from optimal operation. If operational flexibility is not taken into consideration during the whole plant design phase then the control system may not manage to fulfil its requirements. Therefore, control engineers should be involved in the design. A poor design can only partially be improved by good control, and often a simple design improvement can replace a sophisticated control action. In an overloaded plant or in a plant with actuators without any control authority any control effort is meaningless.

The coupling between design and operation can be illustrated by one example; the possibility to control the aerobic volume (i.e. swing zones). Many plants are not designed to use available volumes in the best possible way. For example, the volumes for denitrification and nitrification are not typically changed during varying load conditions. However, with the possibility to control the aerobic volume, the control authority can be used to better utilise the plant capacity for both organic removal, and increased energy efficiency because the volumes are more appropriately sized for denitrification and nitrification dynamically. The issue of control authority was raised by Olsson and Jeppsson (1994). For example, in many systems even the control of air flow rate is a challenge, either due to a too large system or lack of controllability.

THE SYSTEM WIDE PERSPECTIVE

At the 1st ICA conference in 1973 the concept of system wide control was recognized. As stated by Kukudis (1973): "Even if we had the most sophisticated, automated plant in existence, it still would not be able to operate at maximum efficiency, because the designs of wastewater treatment plants are based on uniform combined sewer flow with consideration for periodic intensity due to storm flow or periodic lows during dry weather spells or hours of least demand. So, much of the time the flow into the plant is either above or below the maximum efficiency level." The sequential relationship between the sewer, the wastewater treatment plant and the receiving water is obvious and the need for control of flow in the sewers was recognized early. "We must speak of automation in the entire system -- the network of sewers and the plants". Sewer control was applied in Cleveland in the early 1970s (Kukudis, 1973). During dry periods flow equalization was used. During storm periods the system was designed to primarily capture and treat the first 20 minutes of flow during the storm period. This is what we today call the first flush, having the highest concentrations of pollutants. Any necessary bypassing after the first period would be of diluted effluent.

There are many definitions of "system wide". Some people call it "plant wide" (or "whole plant" in North America) and this starts with quite simple cascade controllers. Aeration control with ammonia, DO and air flow rate controllers in cascade is a typical example. The system boundaries may be limited to the wastewater treatment plant, or it may include the sewer system. Often, the ultimate goal of system wide control is the receiving water quality. The problem was well formulated by Young and Beck (1974). The problem was emphasised again 20 years later by Vanrolleghem (1994) in his PhD thesis. The many recycles make the complex couplings obvious, such as the return sludge, nitrate recycle or the recycling of the supernatant from the anaerobic digester to the influent of the wastewater treatment. The interactions demand that we look at the global effects of the chosen disturbance rejection strategies, with a particular emphasis on recycle streams (Olsson and Newell, 1999). System wide control is still a topic for advanced research almost 40 years after the formulation. This challenge was also described by Harremoës *et al*. (1993) and can still be our guiding principle in ICA today: "Wastewater management must be looked at in its totality and in close combination with the processes and quality aspects of the receiving waters. The system from the sink … to the ultimate consequential water quality in the environment has to be regarded as an entity."

Environmental decision support systems (EDSS) have appeared as a paradigm to deal with the inherent complexity of decision making in wastewater management. These systems, which integrate in a hierarchical architecture mathematical models and control algorithms (for numerical computations) with knowledge-based techniques (for human-kind reasoning aspects), are represented as a step further for planning, design and operation of wastewater treatment systems (Poch *et al*., 2004). Knowledge-based systems and other artificial intelligence techniques have been applied to systematically make use of heuristics, experience of practitioners and existing databases (Rodríguez-Roda *et al*., 2002). Besides, knowledge-based representation techniques also complement standard deterministic models for the risk assessment of microbiology-related operational problems (e.g. filamentous bulking in activated sludge processes or foaming in anaerobic digestion). These issues cannot be described with standard deterministic models due to the lack of fundamental knowledge to precisely describe the mechanisms for the phenomenon e.g. the excess growth or death of filamentous organisms with the plant operational parameters. In some of these cases, only cause-effect relationships are known (Comas *et al*., 2008).

These approaches also recognise the need for an integrated perspective of the urban water systems. Our performance indices have to include not only technical, environmental and economic criteria but, though more difficult to deal with, social aspects, for scenario assessment. Various scenarios have to be tested, including stricter legislation, extreme water-related events and resource recovery. This demands comprehensive understanding of Life Cycle Analysis in order to deal with the integrated water systems.

OUTLOOK

Even if the need for ICA is no longer called into question, ICA is still perceived as the *hidden technology*. It is noticed when it does *not* work. Certainly, the need for ICA in water and wastewater systems is huge. A recent ARC Advisory Group study (ARC, 2013) has found a fast-growing market for automation and field devices in wastewater treatment applications. ARC believes that the water and wastewater industry represents one of the greatest opportunities for the automation business through the next 20 years. The study further states that “the infrastructure needed to supply clean water and help protect water sources from human, industrial, and agricultural contaminants is sorely burdened on many different fronts. In the developed regions of North America, Europe, Japan and others, existing water & wastewater systems are rapidly aging and require significant investment to ensure efficient water supply with improved infrastructure. Emerging countries, especially the BRIC countries (Brazil, Russia, India and China), are expected to invest tens of billions of dollars each over the next several years. This is important to ensure that their water infrastructures can meet the needs of growing industrial activity and population.”

There are still major problems with process, control or instrumentation understanding. John Andrews (1930-2011) recognised the need for education at all levels when he noted in 1974 (Buhr *et al*., 1974): “A course in Process Dynamics and Control is commonly found in most chemical engineering curricula. We would be well advised to include a course in Dynamics and Control of Wastewater Treatment Systems in environmental engineering curricula.” This was a serious discussion in 1974. Still today, there is a need: engineers from all fields should be trained in process dynamics and modelling as well as in control theory and practice (Hug *et al*., 2009).

ICA is growing both in terms of the number of plants that apply ICA and the extent to which it is applied. A lot of research related to ICA is taking place in drinking water applications, in particular early warning systems for contaminants, variable pressure control in distribution networks, and leakage detection and localization systems. Applications of monitoring and control of wastewater quality and emissions in sewer networks are still emerging technologies. Real-life data and behaviour is not always easy to understand. However, the generation shift that is taking place among plant operators and engineers in many countries is a great opportunity. The new generation joining the water industry may have less practical process experience but generally have more computer experience and interest.

CONCLUSIONS

The complexity of modern wastewater treatment plants 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. Many challenges remain for the coming years, such as:

- *Design*: ICA has to be considered during the design process;
- *Instrumentation*: Making use of new sensors and instruments being developed, not only in the activated sludge process, but in anaerobic digestion, in sewers and in other parts of a wider water system. The challenge is to implement adequate maintenance plans on-site and develop Standard Operation Procedures for these sensors similar to what is available for laboratory measurements;
- *Computers*: Taking advantage of the enormous computing and storage capacity in real time computers in modern industrial control systems;
- *Signal treatment and monitoring*: Developing data validation tools and monitoring, detection and diagnosis methods to better integrate and re-use the huge amount of data and knowledge acquired and to better serve as operator support tools;
- *Process control*: Applying adequate control technology for the processes and test already developed process control ideas in full scale;
- *System-wide*: Extending the unit process and plant perspective to a wider system, fostering the receiving water as the main actor. Understanding how to formulate disparate objectives and performance criteria, finding out what is needed in terms of control variables, understanding the myriad of couplings in the complex systems and formulating user-friendly and appropriate control systems;
- *ICA in the whole water cycle:*
    - Developing ICA technology for non-conventional water systems, like decentralised wastewater systems. Making advanced use of network and communication technology;
    - Being ready to adopt ICA to new water structures, sometimes called “smart water grids” that can deliver water of different qualities to customers with varying needs for the water quality;
    - Extending the focus to drinking water treatment, industrial water treatment, wastewater recycling, removal of micropollutants in WWTPs. Emerging technologies such as membranes (UF/MF/NF/RO) and biofilms pose new exciting challenges and opportunities.
- *Dissemination*: Making sure that the results from the research community are adequately transferred and applied in plants all over the world.

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