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. However, many developments have not been addressed here, such as sewer control, drinking water treatment and water distribution control. It is hoped that this review can stimulate new attempts to more effectively apply control and automation in water systems in the coming years.

Key words | modelling, monitoring, sensors, simulation, wastewater, water

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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 International Association on Water Pollution Research (IAWPR), 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 up to the 11th IWA conference on ICA in Narbonne (France). A comprehensive review is impractical but it is worth critically assessing 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

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on the discussion of wastewater treatment, as this has been the dominating theme in 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. However, 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 worth identifying the driving forces in ICA research and development, and we recognize both sticks and carrots. The technology development – computers, instrumentation, power electronics, control theory, process knowledge and modelling – has many ICA implications. We now need to closely examine whether we have been fully utilizing 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 mainstream. Many professionals are now 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, in keeping with control-integrated design. Inflexible or underdimensioned designs cannot be improved by control alone.

The first ICA applications in the 1970s were made in activated sludge processes for organic matter removal. The effluent requirements were mostly for biochemical oxygen demand (BOD) and suspended solids, while neither nitrogen nor phosphorus 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:

- Currently, 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 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 (aeration tank settling operation).
- More recirculation streams 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 biological phosphorus removal (Bio-P).
- External carbon can be added to control denitrification.

Energy is now the single largest operating expense in plants so it makes economic sense to reduce those costs wherever 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 have taken place towards sludge treatment and waste-to-value conversion processes, which has led to the renaming of wastewater treatment plants (WWTPs) to water resource recovery facilities (WRRFs).

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 realization 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 & Olsson (2012). As discussed below, system-wide aspects will also become increasingly important.

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 whether the data are 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 database (Hauduc *et al.* 2010).

Too often, the amount of data is overwhelming and the relevant information is not extracted. 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 (University 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 plant equipment 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 realized 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 biological oxygen demand (BOD), ammonia, nitrate and phosphate. Furthermore, a central location for gathering and dispensing information on instrumentation testing was recognized as being 'of considerable assistance'.

Today, there are numerous sensors available on the market. According to a recent – but not public – industrial market 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 in nutrient sensors has taken place in the last two decades, from automated laboratory analyzers that had to be protected from the measured system to *in situ* sensors that can be placed directly into the liquid to be monitored. On-line *in situ* nutrient sensors are becoming more common place and affordable, e.g. ion-selective electrode probes for ammonia and UV probes for nitrate and nitrite (Rieger *et al.* 2004). 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 dissolved oxygen (DO) measurements that require less maintenance compared with membrane-based sensors.

Ingildsen (2002) showed how a phosphate *in situ* sensor could significantly improve chemical dosage control; however, robust *in situ* phosphate sensors remain high on the wish list. Sludge blanket sensors were used for secondary clarifier control decades ago, but more reliable sensors are now available. An on-line 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 Plósz *et al.* (2007). Now that so many sensors have been developed, it is important to unlock and disseminate the information from them.

There is still a huge potential for using 'sensor networks'. They consist of a group of sensors with a communications infrastructure with the purpose of monitoring 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 being adopted for remote monitoring in wastewater treatment systems. The possibility was mentioned in Olsson *et al.* (2005), Chapter 1. A real application of remote monitoring is described in Lee *et al.* (2004), describing a centralized control system using the Internet to remotely control small decentralized plants in Korea's rural communities.

Actuators

In the last few decades, there has been a revolution in the development of power electronics. Power electronic devices like insulated-gate bipolar transistors are now generally available for currents up to 1,200 A and voltages up to 3,000 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. One example is the air valve opening in an aeration system. This approach enables the control of the DO according to 'the most open valve' control method (Olsson & 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 only for recording, despite being installed for the purpose of control. The monitoring system could also assist in diagnosis and advice, or aid in the simulation of operational adjustment consequences. Several tools have been developed to aid in process monitoring and data management.

Statistical analysis, for example 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 & Newell (1999), Thomann et al. (2002) and Thomann (2008). This is the basis for fault detection. A standardized method to process sensor data at treatment plants is presented in Irizar et al. (2008), where sampled data are 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 & Olsson 1998). The most well-known method to reduce the dimensionality of the data cloud is principal component analysis (PCA) (Jolliffe 2005). 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 composition (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 & Lennox (2001) and Lennox & 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 & 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 are 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 recognize the shape of the sensor profiles (Kim et al. 2012).

Plant operators obtain a lot of valuable information from their own senses. This includes heuristic knowledge such as qualitative observations (including vision, smell and hearing) and specific experiences which may help to diagnose problems in settling, aeration systems and many other operational problems. Human sensing is a valuable input to control systems and is considered part of knowledge based systems, which are discussed below.

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 channeled to the water profession via the IWA Task Group (1982) on Activated Sludge Modelling with Mogens Henze, Les Grady, Willi Gujer, Gerrit v. R. 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 (ASMs) (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 & Draper 1987).

It is important to keep in mind that there may be a whole spectrum of models. The ASM models are detailed descriptions of the biological treatment and are used both for process understanding and for plant design. To ensure that such a model is valid for a specific plant during its whole lifetime requires model updating and verification when the plant design is changed. There are no easy shortcuts for such model verifications.

Other kinds of models are used for model predictive control (MPC) and are significantly simpler. They usually describe the relationship between only one measurement and one control variable. They need to be updated in real time in timescales anywhere from fractions of hours to months, as the process dynamics are typically not the same over time. Often this requires automatic parameter estimation based upon on-line sensor information (Olsson & Newell 1999). On-line model adaptation algorithms are described in detail in Dochain & Vanrolleghem (2001), Chapter 7.

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 majority of the process control problems in wastewater treatment (Olsson & Newell 1999). This is also true 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) 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 (P) or PI controllers. Highly non-linear dynamics – 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. In most cases there are only insignificant cross-couplings between several inputs and outputs. Therefore, most process parts can be favorably decoupled and thus controlled by single-input-single-output controllers.

The dynamics in wastewater treatment is truly stiff with a 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). However, 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.

The control of wastewater treatment systems is certainly not limited by the available control theory. Rather, the challenge is to have a comprehensive understanding of the process and its limitations, the control authority of the actuators, the reliability of and information from the sensors and also 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 & 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 & Larsen 1995) and SSSP (Bidstrup & 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 & 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 on-line 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 & 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.

Twenty 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. The potential of soft sensors and estimation techniques to test sensor information has not yet 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 considerable potential for using on-line simulation for operator support. This is proven 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 standardized procedure, it is possible to efficiently evaluate numerous strategies through dynamic computer simulations. The unlimited number of simulation permutations makes the need for a standardized protocol important if different strategies are to be objectively compared.

The idea to produce a standardized 'simulation benchmark' was first suggested by Bengt Carlsson (Uppsala University, Sweden) at the 1993 ICA Conference in Hamilton, Canada, 20 years and five 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 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*. (2014). 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 criticized as only academically applicable and providing limited benefit to the applied modelling community. However, even though the work was aimed at the control community to evaluate control strategies, for modellers in general 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 for measurement. Ammonia measurements are now being used to calculate variable DO setpoints. Some practitioners are sceptical about the long-term reliability of ammonia sensors even if they fully accept the measurement principle. Denitrification can be optimized by controlling the internal recirculation flow rate, using nitrate sensors. Phosphate analyzers 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 DO control, driven by the desire to reduce the costs induced by this energy consuming process (Olsson 2012). The state-of-the-art until 2005 was summarized in Olsson *et al.* (2005). A review of aeration control with emphasis on the 21st century is found in Åmand *et al.* (2013).

In the early 1980s Nielsen *et al.* (1981) showed how nitrogen removal could be favorably controlled based on measurements of DO, ammonia and nitrate. The control was implemented in an alternating process using the phase length and the DO setpoint as control variables.

The thesis by Lindberg (1997) is an example of an outcome from a Swedish national research initiative 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. As a result, one of the first strategies for ammonium feedback control was suggested. 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.

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 MPC, but far fewer have actually been implemented in full scale.

MPC has attracted much interest within many applications of automatic control over the last 20 years. Using the available ASM models for the purpose of on-line control in an MPC context has been done in simulations (Steffens & Lant 1999; Stare *et al.* 2007). The limitation of the performance of these models, and thereby their controllers, in a full scale on-line setting is not the model quality per se, but rather the data quality. Much is required from a multi-variable model-based controller with several inputs in terms of sensor and data quality.

Vrečko *et al.* (2011) was one of the first attempts at MPC in a real nitrogen removing process (pilot-plant moving bed biofilm reactor, MBBR). Even though evaluation was performed over a relatively short period of time, the paper summarizes what was learned from full-scale control studies: 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 analyzed in Rieger *et al.* (2012, 2013).

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

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

The integration of knowledge-based systems with automatic control systems enables not only sensor information but also operator observations as inputs to control. In this way, so-called environmental decision support systems (EDSS) appear as a paradigm to deal with the inherent complexity of decision making in wastewater management. Such a system can integrate mathematical models and control algorithms, using numerical computations, with knowledge-based techniques, using human-kind reasoning aspects. This is done in a hierarchical architecture and can include the human element in the control loop. EDSS represents a further step for the planning, design and operation of wastewater treatment systems (Poch *et al.* 2004).

Many plants in many countries around the world have adopted ICA. Nevertheless, from an operational point of view, it seems difficult to reap all the benefits of the instrumentation, process models and knowledge. It appears that the information provided is not always adequately understood or acted upon. Better ways to provide information – for example by visualization (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 standardization. There are too many one-off controllers. Often researchers in academia work 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 ongoing (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 water and wastewater operation.

CONTROL-INTEGRATED DESIGN

There is an important coupling between design and operation. Many plants are designed using a steady-state worst-case approach without properly 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 frequent 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 of controlling 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 of controlling the aerobic volume, the control authority can be used to better utilize 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 & Jeppsson (1994). For example, in many systems even the control of air flow rate is a challenge, either because the system is too large or there is a lack of controllability.

THE SYSTEM-WIDE PERSPECTIVE

At the first 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, Ohio 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 currently 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, especially in the chemical engineering field, 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 & Beck (1974). The problem was emphasized 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 plant. The interactions demand that we look at the global effects of the chosen disturbance rejection strategies, with a particular emphasis on recycle streams (Olsson & Newell 1999). System-wide control is still a topic for advanced research almost 40 years after its 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.'

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). Knowledge-based representation techniques also complement standard deterministic models for risk assessment of microbiology-related operational problems, such as filamentous bulking in activated sludge processes or foaming in anaerobic digesters. These issues cannot be described with standard deterministic models due to the lack of fundamental knowledge to precisely describe how the mechanisms for the phenomena are related to the plant operational parameters. Typical examples are the excess growth or death of filamentous organisms. In many cases only cause-effect relationships are known (Comas *et al.* 2008). Some examples of practical implementations of EDSS in full scale WWTPs are found in www.sisltech.net.

These approaches also recognize the need for an integrated perspective of the urban water systems. The performance indices have to include not only technical, environmental and economic criteria but, although 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 integrated water systems.

OUTLOOK

Even if the need for ICA is no longer called into question, ICA is still perceived as the 'hidden technology' and it is only noticed when it does not work. Certainly, the need for ICA in water and wastewater systems is clear. A recent ARC Advisory Group study (ARC 2013) 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, East Asia and others, existing water and wastewater systems are rapidly aging and require significant investment to ensure efficient water supply with improved infrastructure. Emerging economies, such as 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) recognized 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 are 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 has 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 the following.

- *Design:* Including ICA as part of the design process.
- *Instrumentation:* Making use of new sensors and instruments being developed for biological wastewater treatment, for anaerobic digestion, sewers and other parts of a wider water system. The challenge is to implement adequate maintenance plans on-site and to

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, soft sensors, fault 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 testing 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 decentralized wastewater systems. Here, advanced use of communication technology, local networks and Internet will be extremely important (Olsson 2013). One aspect is the access to competent operating personnel, even for small plants. Another aspect is coordinated, system-wide control in large plants.
  - 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 water quality.
  - Extending the focus to drinking water treatment, industrial water treatment, wastewater recycling, removal of micropollutants in WWTPs and efficient resource recovery. 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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