doi: 10.2166/9781789060362_0667

15

Process control

Gustaf Olsson and Pernille Ingildsen

15.1 DRIVING FORCES AND MOTIVATIONS FOR CONTROL

Several driving forces motivate the control of wastewater treatment systems. Some of them are *demand pull* forces and others are *technology push* forces:

- Saving capital costs by optimising operations to reduce the need for additional capacity or to apply more load to a given system.
- Minimizing operational costs for energy, chemicals and sludge management, despite load changes and other disturbances.
- Keeping consistent operation to maintain effluent water quality.
- Understanding fluctuating processes, such as aeration, sludge thickening, and sludge generation.
- Detecting disturbances and giving early warning to counteract sudden events such as rain or toxicity.
- Gaining transparency into what is happening in the plant for trouble-shooting and post-analysis on detrimental events.

None of these aspects were fully understood when instrumentation, control and automation (ICA) attracted the attention of the water and wastewater industry in the early 1970s (Olsson *et al.,* 1973). Since then the technical development of new processes, sensor and instrumentation technology, computer performance, communication technology and the Internet of Things, detection methods, control theory and artificial intelligence has made ICA widespread in all kinds of water operations (Olsson, 2012). The emphasis is not only on more efficient wastewater treatment but on many aspects of early warning systems, plant monitoring, and operator guidance. There has also been major development towards understanding customer expectations, data-collection tools and the handling of 'big' data.

Too often ICA is implemented to improve efficiency or reduce costs but only as a second step for existing plants. Instead, the coupling of design and operation, known as control-integrated design, needs to be improved. Inflexible or under-dimensioned designs cannot be improved by control.

The chapter is from the book Biological Wastewater Treatment: Principles, Modelling and Design, Guanghao Chen, Mark C.M. van Loosdrecht, George A. Ekama and Damir Brdjanovic (Eds).

15.1.1 ICA system features

The ideal ICA is founded on some fundamental building blocks:

- The team (people-ware),
- Hardware (sensors, actuators),
- Communication-ware (information systems, hardware, communication protocols etc.),
- Software (the usual elements: PLC, SCADA, displays, and control algorithms).

Any water operation can be symbolized by three dimensions. Mass flows form one dimension: each component can be tracked by its mass balance in the system. Energy, the second dimension, describes the flow of electrical, chemical, and thermal energy. Energy is not only consumed, but the incoming water contains thermal and chemical energy that can be recovered as heat, biogas or nutrients. Energy balances in the wastewater system, in particular the possibility of the 'zero-energy' plant, are receiving increasing attention.

The ICA perspective represents the third dimension, the information flow. The fundamental concept of feedback can form the basis of the understanding of smart systems. Ingildsen and Olsson (2016) called it the 'MAD' approach: measure (M), analyse (A) and decide (D). This feedback concept can be practised at all levels, from simple component control to management and strategic decisions. The principle is illustrated in Figure 15.1.

To measure is to know: we need adequate data in space and in time. Measurement – the 'M' - includes not only signals from sensors and instruments, but also laboratory analysis results, observations and human communications. It comprises daily and monthly management reports and similar information that will form the basis for long-term decisions. Data must be checked, analysed, understood and interpreted – the 'A' – in order to become reliable information. The decision or control – the 'D' – does not need to be automatic as in a typical feedback controller. It can be manual in terms of decisions about plant operation or about more business-oriented operations. Finally, any decision will be turned into action using an 'actuator'.

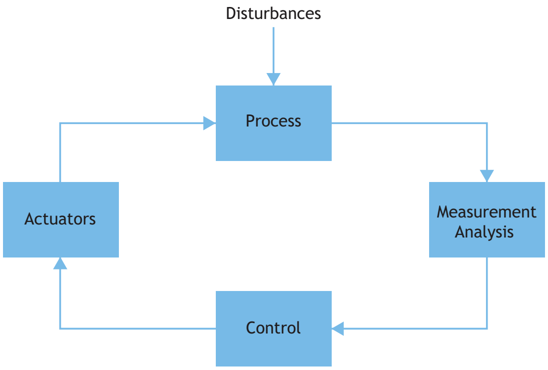

Figure 15.1 The feedback principle.

The word *smart* is used nowadays as a characteristic of devices, people and phenomena. It may mean clever, sharp or intelligent. Sometimes it is a synonym for elegant, stylish or neat. However, a smart water system is not the same as an elegant, glamorous or fashionable system. Instead it operates to fulfil the requirements of producing an acceptable product while keeping the energy and resource requirements at a minimum. Such a system should respond quickly and adequately to disturbances and recover rapidly after a major upset. The operation of the system must be sufficiently transparent so that people involved in the operation have enough information to make rational decisions. The goal is to integrate the complete urban water cycle: water supply, water distribution, urban drainage, wastewater treatment as well as the customer or demand side. The aim of our operations should be to adapt to, protect and preserve the natural water systems we depend on and operate within. Ultimately, our human water consumption should have no detrimental effects on nature.

A water operation can only be smart if people in all positions - not only the utility employees - get involved, so that they can see their respective role in the whole plant or system operation. It is crucial that the water users are engaged as well. For too long water utilities and operations have been invisible to the users, who take the perfect delivery of water and treatment of wastewater for granted. It should be recognized that most of the energy related to the water cycle is used in the home, not within utility operations. Therefore, passing information to the user is crucial. If customers can measure their water consumption and obtain information on how it relates to neighbours or what is 'normal', it can make them more aware of ways to be less wasteful.

The focus of control in most water systems today is on unit processes. In addition, the control of combined sewer overflow (CSO) for the benefit of receiving water quality has also been receiving increasing attention (Ahm *et al.*, 2016). CSO overflow structures are not primarily designed for measurement but to effectively discharge excess water. By using models and estimation it is possible to quantify the CSO discharge so that adequate mass balance calculations can be accomplished. CSO flow rates can be derived by using what are termed soft sensors, where the flow rates are estimated based on level measurements in the system.

Widening the perspective from single processes to a plant-wide view and further on to the entire urban water cycle is necessary in order to handle the increasing complexity of urban water systems. This transition requires system-thinking, where the multitude of couplings between processes and individual controllers are considered (Beck, 2005). Rodriguez-Roda *et al.* (2002) introduced a new way of thinking by describing the development and implementation of a knowledge-based supervisory system to operate a wastewater treatment plant. Their system structured the operation into data gathering, diagnosis and decision support and integrated the control by agent-based reasoning modules. Integrated control is further described in Section 15.10.

15.1.2 Driving forces

There are several driving forces to implement ICA in water systems. Some are demand pulls and others are technology pushes, as described in some detail in Olsson *et al*. (2014).

Key driving forces are more stringent regulatory requirements, financial considerations, and implementation efficiency. Others are growing urbanization and population which imply increasing water use and wastewater load. Climate change and associated extreme weather conditions further add to the operational challenges of urban water systems. However, although water quality is certainly a driver in plant design, it is not typically the main driver for ICA and is unfortunately not usually integrated with operational requirements. Also, despite the need for ICA being recognized decades ago (Vanrolleghem *et al*., 1996a), it has only been implemented as a second step for existing plants to improve efficiency or reduce costs, even though inflexible or under-dimensioned designs cannot be improved by control.

Process development has become increasingly sophisticated due to effluent requirements, and this has added to the demand for ICA. Bioreactors have more zones; anaerobic, anoxic and aerobic. More recirculation flows can be subject to control. Air supply systems are more sophisticated whereby aeration zones can be controlled separately, pressure losses can be minimized by variable pressure control, and compressors are supplied with variable speed control. Chemicals and external carbon can be added for control purposes.

The importance of actuators should also not be overlooked. In the last few decades there has been a revolution in the development of power electronics. Power electronic devices such as IBGT (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 to MW drives. Variable speed control has a large influence on wastewater treatment operations for flow-rate control as well as for air-flow control. This has a profound impact on both control action quality and on energy efficiency of various operations. All the major electric motor and pump vendors provide a large quantity of information on the internet. There are several short lectures available on www.youtube.com. Search for ‘electric drive systems’.

Energy is the single largest operating expense in water operations, so it makes economic sense to reduce these costs where possible through adequate control. The vision of zero or even positive-energy plants has already been realized in some cases (for example, Nowak *et al.,* 2011).

There has been a substantial technology push influencing ICA in water systems. Instrumentation and actuator development has been significant, contributing to making control more successful. Computing power is no longer any obstacle. The real challenge is to convert big data into useful information. The education level of operators and process engineers has been raised considerably over recent decades.

15.1.3 Outline of the chapter

The rest of the chapter is outlined as follows. Disturbances in wastewater treatment systems are significant and they are the reason for control, as explained in Section 15.2. The role of control is further described in Section 15.3. Instrumentation is the basis for advanced operation and its role in monitoring and control is discussed in Section 15.4. Wastewater systems are dynamic systems, implying that any correction needs time to be noticed in the system, as described in Section 15.5. To manipulate any system we need actuators, to translate decisions into mechanical actions, such as motors, pumps, compressors and valves, which is covered in Section 15.6. The following two sections, 15.7 and 15.8, are devoted to basic principles of control and some typical applications in wastewater treatment. Energy is closely related to water and wastewater treatment, and energy and other operating costs are discussed in Section 15.9. A wastewater treatment plant consists of many unit processes and their interaction has to be taken into consideration for more advanced control, which is in Section 15.10.

For the interested reader a comprehensive description of control in wastewater treatment systems is available in the textbook by Olsson and Newell (1999). An updated state-of-the-art description of control issues in wastewater systems is found in Olsson *et al.* (2005). In the more recent book by Ingildsen and Olsson (2016) the feedback principle is demonstrated not only for biological wastewater treatment but for all levels of water operation. In this chapter we limit the discussion to control systems in biological wastewater treatment.

15.2 DISTURBANCES IN WASTEWATER TREATMENT SYSTEMS

One of the incentives for control is the appearance of disturbances either about to enter or already within a plant. The impact of these disturbances should be compensated, but it is even better if the disturbances can be attenuated or best of all eliminated before they hit the plant. Compared to most other process industries, there are many external disturbances that a wastewater treatment plant can be subject to. The wastewater influent typically varies substantially both in terms of concentration of pollutants, composition and flow rate, with timescales ranging from hours to months. Discrete events such as rainstorms, toxic spills and peak loads also occur from time to time. Some disturbances are created within the plant due to process design, poor operation, inadequate equipment or process failures. As a result, a treatment plant is hardly ever in steady state but is subject to transient behaviour all the time.

Consistent performance must be maintained in the presence of these disturbances. The traditional method of reducing their effect has been to design plants with large volumes to attenuate large load disturbances. However, this solution incurs large capital costs. Online control systems, which have been demonstrated to cope well with most of these variations, are much more cost-effective and thus an attractive alternative. Eliminating disturbances is indeed one of the major incentives for introducing online process control to wastewater treatment systems.

Many disturbances are related to the plant influent flow. The influent changes both in terms of flow rate, concentration and composition, as illustrated in Figure 15.2. Any of these changes must be compensated for. If the result of the disturbance is measured within the plant, such as a change in the dissolved oxygen level, a rising sludge blanket, or a varying suspended solids concentration, the measured information is fed back to a controller that will activate a pump, a valve, or a compressor, so that the influence on the plant behaviour is minimized.

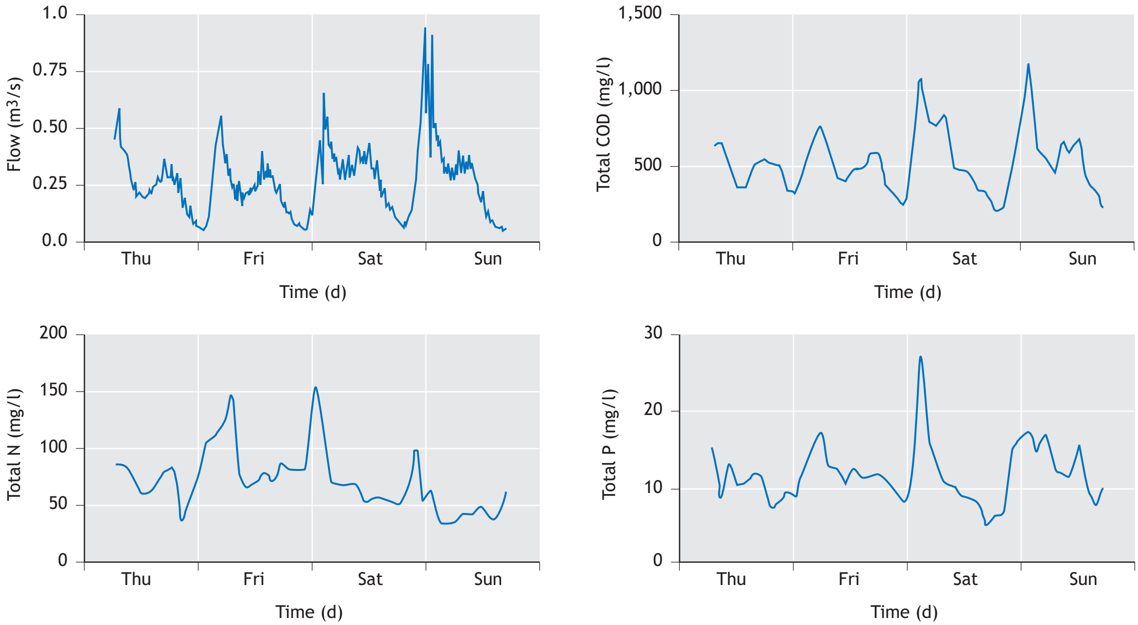

Figure 15.2 Typical dry weather diurnal variations in a municipality with mostly domestic wastewater. The data show variations from Thursday through Sunday (note the peak in P which is on Saturday).

Sometimes a load change can be measured upstream, before it has entered the plant. Then the information can be *fed forward* to prepare the plant. For example, the aeration can be increased before a load increase hits the plant. Another example is when the return sludge pumping can be increased to lower the sludge blanket in order to make the settler ready for an expected increase in the hydraulic load.

However, unfortunately, many disturbances are created within a plant due to inadequate operation. Often this is due to a lack of understanding of how various parts of a plant interact. Figure 15.3 shows such an example. The influent flow is pumped via three on-off pumps. This creates sudden changes of the flow rate, which will deteriorate the behaviour of both the clarification and the settling in the secondary sedimentation unit.

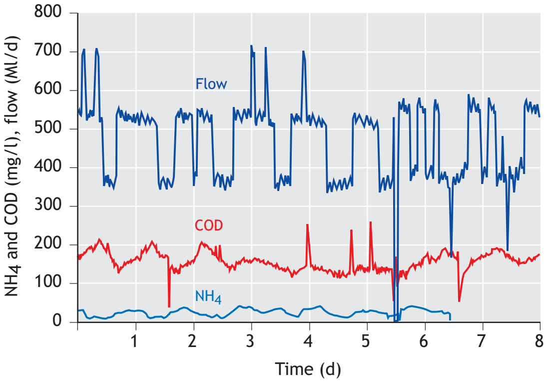

Figure 15.3 Influent variations in a large wastewater treatment plant having only on-off primary pumps, resulting in undesired sudden flow variations into the plant.

Filter backwashing can sometimes create huge operational problems. At one medium-sized plant the backwashing increased the influent flow rate by almost 50%, as illustrated in Figure 15.4.

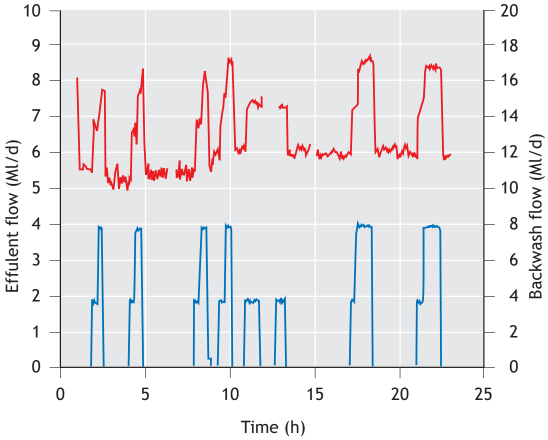

Figure 15.4 Filter backwashing (lower line) and its impact on the plant influent flow rate (upper line) and plant operation.

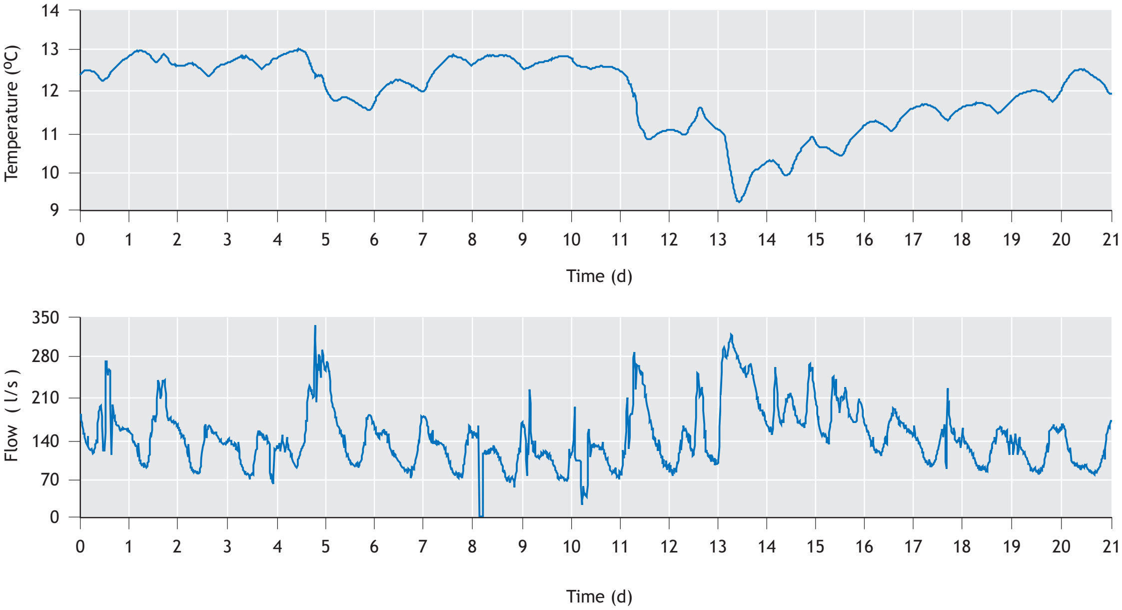

Figure 15.5 Influent flow rate variations during three weeks in the winter. The lower figure shows the daily variations and some rainy periods. The upper figure shows how the temperature decreases as a result of cold rain.

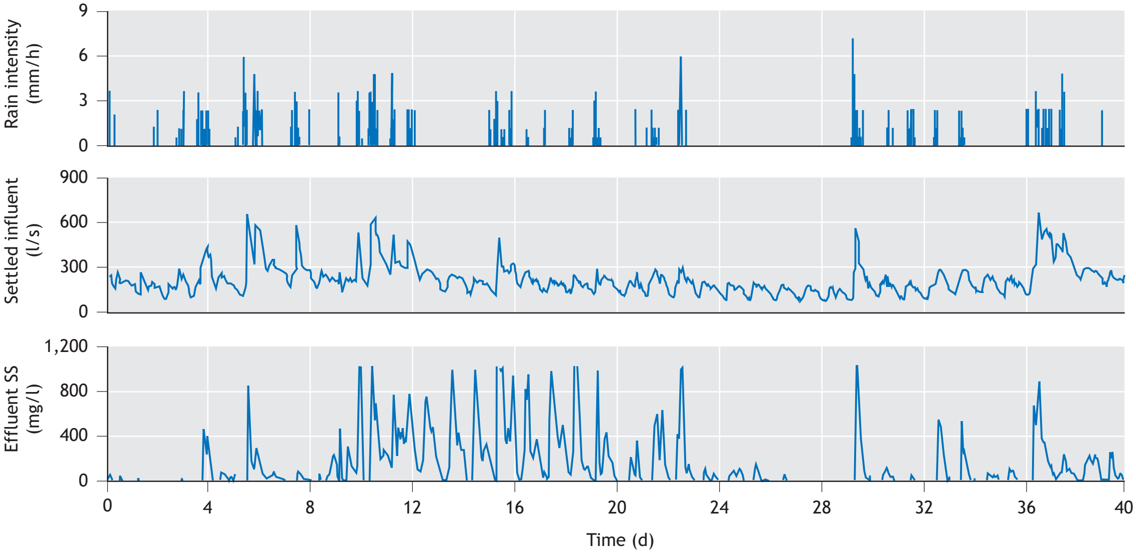

Figure 15.6 The relationship between large hydraulic disturbances and effluent quality. The upper figure shows the rain intensity during approximately 40 days and the middle figure is the corresponding influent flow rate to the municipal treatment plant. The lower figure shows the suspended solids concentration after the secondary settler; it clearly demonstrates that the clarifier is running close to its maximum capacity and is failing during large hydraulic peaks, resulting in large effluent suspended solids concentration values.

The nutrient removal plant had an anaerobic reactor as the first step. This reactor was hit not only by a large flow rate but also by oxygen-rich water, inhibiting the anaerobic reactions. The water propagated into the succeeding anoxic zone, still with some oxygen left. Obviously, the biological reactions suffered considerably and the effluent quality was unsatisfactory.

It transpired that pumping had to be performed differently, and the problem was readily solved, once the disturbance pattern was understood. Instead of pumping the backwash flow directly to the plant influent it was temporarily stored in an available volume and pumped gradually back to the plant input. This attenuated the flow rate change.

In a cold country the temperature of the influent water may change rapidly as a result of rain. Figure 15.5 is a data record over three weeks which shows how heavy rains during the winter will influence the water temperature, resulting in lower microbial activity as well as extra load for the clarifier and the settler. High flow rates will have a significant impact on the clarifier performance. This is illustrated in Figure 15.6.

If sludge supernatant is recycled to the plant influent during a high load, then the nitrogen load to the plant may be very large, as depicted in Figure 15.7. The figure shows how the oxygen uptake rate increases significantly as supernatant is recycled within the plant. It is crucial to identify the sources of the disturbances in order to obtain a high-performance operation of a plant. Then the control system can be structured so that these disturbances can be attenuated or even avoided.

Disturbances also arise from the shift of bacterial populations and changes in their microbial and physical properties. For example, it is not uncommon that a treatment system suffers from sludge settleability problems due to an outbreak of filamentous bacteria. The operations imposed by online control systems may themselves be a cause of a bacterial population shift. These disturbances must be properly dealt with in the control system design and evaluation. Further internal disturbances may be generated due to inadequate or inappropriate operations including human error, unsuitable or malfunctioning actuators, and/or sensor breakdowns, all of which may potentially cause major operational problems. Sudden flow shocks as a result of turning pumps on or off (without any variable speed control) or sudden backwashing of filters occur in many plants as well. Many of the internal disturbances can be avoided (or their impacts minimized) through introducing online control systems, particularly early warning systems.

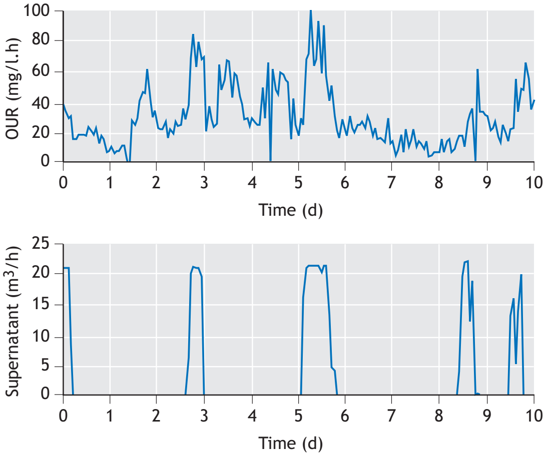

Figure 15.7 The effect of supernatant recycling in a plant during a 10-day period. The lower curve shows the supernatant flow rate (which is not very high but has a high concentration). The upper figure shows the oxygen uptake rate in the aerator (adapted from M.K. Nielsen, Denmark).

15.3 THE ROLE OF CONTROL AND AUTOMATION

ICA in wastewater treatment systems has come a long way and it is now an established and recognized area of technology in the profession. Several factors combined have made this progress possible:

- *Instrumentation technology* – to measure is to know – is today so much more mature. Complex instruments such as online in-situ nutrient sensors are now regularly used in the field. Instrumentation is no longer considered the major obstacle for wastewater treatment control.
- *Actuators* have improved over the years. Today variable speed drives in pumps and compressors are a proven technology and they allow better controllability and flexible operation of plants.
- *Computing power* can be considered almost free.
- *Data collection* is no longer a major obstacle. Software packages are available for data acquisition and plant supervision. The benefits of SCADA and process control systems are no longer questioned. Data analysis and monitoring software is commercially available. The obstacle is not the products but the competence to take full advantage of the available algorithms and software.
- *Control theory* and *automation technology* offer powerful tools. Benchmarking of different control methods is becoming recognized and tools for evaluating control strategy performance are available, such as costs, robustness and ‘performance images’.
- Advanced *dynamical models* of many unit processes have been developed and there are commercial *simulators* available to condense the knowledge of plant dynamics.
- *Operators and process engineers* are today much more educated in instrumentation, computers and control understanding. Naturally, with new water quality challenges the need for more education is apparent all the time.
- There are obvious *incentives* for ICA, not the least from an economic point of view. Plants are also becoming increasingly complex which necessitates automation and control.

The development towards process/plant-wide control approaches is still in its infancy, but their implementation is gaining momentum, which is further discussed in Section 15.10. ICA has been accepted as a standard element of wastewater treatment systems. Utilities are now highly dependent on ICA to minimize the resources needed to effectively operate facilities. However, despite almost universal acceptance, there is still a large opportunity to further apply ICA. Probably the biggest obstacle for better control is lack of process flexibility in many plants. Plant design and operation still need to be systematically integrated.

15.3.1 Setting the priorities

Any plant operator must set the priorities for an effective operation, and efficient performance must rely on functioning equipment. All the links in the chain must be working in order to get a satisfactory operational system. Hardware includes not only instrumentation, communication and computers but also actuators, such as compressors, pumps, motors and valves. Communication systems are becoming increasingly important in plant control systems. The software relies not only on proper control algorithms, but also databases, communication systems, data acquisition, and human-friendly displays. Most important of all: people. No control system can be presented to operators who have not been able to influence its design. So much of the performance is built on trust. Any well-intended and functioning control system can be (and has been!) a total failure if the operating people do not trust it. Therefore, people involvement and education is a crucial part of a successful system. So, what are the priorities?

- *Keep the plant running.* Before we even consider controlling the water quality it must be ensured that the plant equipment is working adequately. This includes meters of electric motor speeds, acoustic noise measurements, and indicators that can ensure that pumps and compressors are running. Simple level measurements or hydraulic measurement sensors can confirm that tank levels are within acceptable limits. Gas flow measurements indicate methane production in a digester, and conductivity sensors can detect changes in the influent composition. The whole idea of keeping the plant running is *not* to obtain accurate information of the plant state, but to ensure reliable basic operation. Most of the equipment control actions are traditional process control loops (Figure 15.1), such as air pressure control, liquid level control, and flow rate control.
- *Satisfy the effluent requirements*. It is not enough to keep the physical parameters correct. Other variables that are directly related to the effluent quality must be controlled. This is realized at this level. It involves manipulating the variables of different unit processes, such as dosage control for chemical precipitation, air flow rate control to keep the dissolved oxygen (DO) level satisfactory, and return sludge control or sludge retention time (SRT) control to manage the sludge content.
- *Minimize the cost.* In each unit process the control scheme may be more elaborate. One example is DO control, where the DO setpoint is variable, not only along the aeration basin, but also variable in time (see Section 15.8). The goal at this level is to optimize the unit process operation. All of this depends on suitable sensors and instruments. The cost can be influenced by decreasing the energy demand (for aeration or for mixing), or lowering the cost for dosage chemicals in phosphorous precipitation or in centrifuge operation. The cost is also related to the personnel. Many plants today are satisfactorily operated un-manned during evenings, nights and weekends.
- *Integrate the plant operation*. The purpose of integrating control is also to satisfy the effluent requirement at minimum cost. By coordinating several processes it is possible to decrease the impact of disturbances entering into or within the plant (compare figures 15.4 and 15.7). The combined operation of the processes may make it possible to optimally use the available volumes and the sludge for the best operation.

Present standard computer hardware and software and the growing availability of reliable real-time measurements (properly validated) for an increasing range of different parameters are enabling advanced closed-loop process control on wastewater treatment plants (WWTPs), resulting in increased operating safety and better operational economy. However, these benefits can be limited by the design of the WWTPs themselves, because design has not always been made with controllability in mind.

15.4 INSTRUMENTATION AND MONITORING

'To measure is to know'. Measured or observed phenomena form the basis for all feedback. In water systems it is apparent that flow rates and a multitude of concentrations and quality parameters are the foundation for all operations. The instrumentation must be robust, easy to maintain and cost-effective. This is even more important in an unmanned process.

15.4.1 Sensors and instruments

For a long time instrumentation (here we use the common terms *measuring instruments* or *instrumentation* for sensors, analysers and other measuring instruments) was considered the bottleneck for control and automation in water systems. This has been considerably improved during recent decades. An important development of nutrient sensors has taken place from automated laboratory *ex-situ* analysers that had to be protected from the measured system through filtration units to *in-situ* sensors that can be placed directly in the liquid to be monitored. There is also an interesting development towards increasingly 'smart' sensors with multiple heads, which can be placed anywhere in the processes. Below is a list of just some of the key measurements in water systems. Further details on sensor properties are found both at vendor websites (search for 'water and wastewater sensors' and similar keywords) and in Ingildsen and Olsson (2016).

Measurements form the backbone of the operation in water systems:

- *Physical measurements:* flow rates, water levels, and air flow rates and air pressures.
- *Water quality measurements*: dissolved oxygen (DO), total suspended solids (TSS), ammonia, nitrite and nitrate, phosphate, organic content as chemical oxygen demand (COD) or biochemical oxygen demand (BOD), sludge level, and respirometry.

The introduction of a sensor in a plant or system requires not only confidence in the equipment. If the value of the measurement is not understood, then it is too easy to lose interest in the sensor and consequently the performance of the measurement will gradually decrease because of lack of attention or maintenance. Too many high-quality instruments have failed because of this lack of connection with the purpose of the information. Increased confidence in instrumentation is now driven by the fact that clear definitions of performance characteristics and standardized tests for instrumentation have become available (ISO 15839, 2003).

Standardisation of instrumentation specifications makes it possible to specify, compare and select the most adequate instrumentation, not only in technical terms but also in economic terms through calculation of the cost of ownership (Table 15.1). The investment costs for the device itself are often a minor part of the costs during the lifetime of the instrumentation. However, it is emphasized that a simple cost-benefit analysis is often insufficient to evaluate the benefit of instrumentation. The value of a sensor depends on how intelligently it is used. It is required that operators have a certain level of understanding of their process to run the plant with reasonable confidence.

Measurements from the instrumentation should be available 24 hours a day and 7 days a week. Information needs to be properly extracted from the measured data. Thus, instrumentation must always be combined with adequate data screening, measurement processing, and extraction of features from the measurements, as discussed in the next section.

Table 15.1 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

There are many interesting sensor developments taking place in companies and research laboratories around the world. This will of course increase the opportunities to make plant operation smarter in many senses. Some significant developments are (Ingildsen and Olsson, 2016):

- *Adding processor power to sensors:* making the sensors more complex by adding processor power to the primary sensor will enhance the monitoring capability, see below. The Internet of Things (IoT) adds another layer of 'smartness' with increasing communication facilities from the sensors directly to the measurement analysis and control decision.
- *Micropollutants:* detection and measurement of micropollutants in water is an increasing challenge. The first step to be able to remove these contaminants is of course to be able to detect them and to measure their concentration.
- *Spectroscopy* offers the ability to measure the whole spectrum online and can give a much more complete picture of water quality than the measurement of only specific wavelengths.
- *Wireless communication* is part of the IoT development and makes it possible to achieve field measurements more easily from distant locations, thus increasing the probability of successfully utilizing early warning systems.

15.4.2 Monitoring

To track the current process operational state via the instrumentation is called *monitoring*. Monitoring can give transparency into what is happening in the plant. Without it, the processes are like a black box. 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. A consistent monitoring of the product quality will help us to avoid problems growing too large, as illustrated in Figure 15.8.

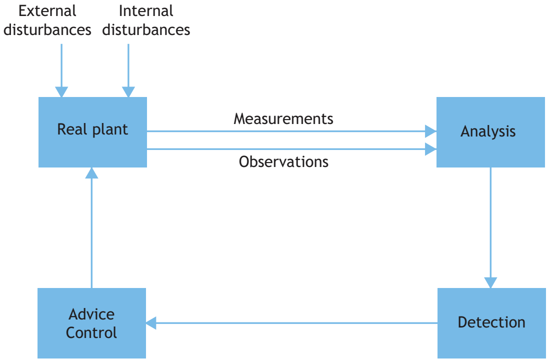

Figure 15.8 A monitoring system is based on analysis of the measurements and observations. A fault or failure can often be detected automatically. Based on the result, some advice or operator support can be given, and a control action can take place.

There is a huge data flow from the processes in a sophisticated treatment plant. More instrumentation and new instrumentation development will further provide more data. However, it should be emphasized that more data is not valuable unless we succeed in translating data into actionable information.

Unlike humans, computers are infinitely attentive and can detect abnormal patterns in plant data. The early detection and isolation of faults in biological processes are very effective because they allow corrective action to be taken well before the situation becomes unfavourable. Slow changes in biological properties are not easily observed by humans and may gradually grow until they become a serious operational problem.

All data analysis may not be in real-time. There is also value in long-term analysis. There is a limit to any human being's ability to take in data. However, supported by computers we may understand more than by just looking at data, but this requires the mastering of relevant analysis tools as well as a deep-seated understanding of what is happening in reality.

Some examples of basic monitoring are described below. Figure 15.9 illustrates daily variations (during some 3 weeks) of influent flow rate. Some significant peaks in the flow rate are obvious. The line indicates the mean value and the ±2σ and ±3σ deviations from the mean. It is obvious that deviations larger than 3σ ought to be observed carefully and suitable operations must be implemented.

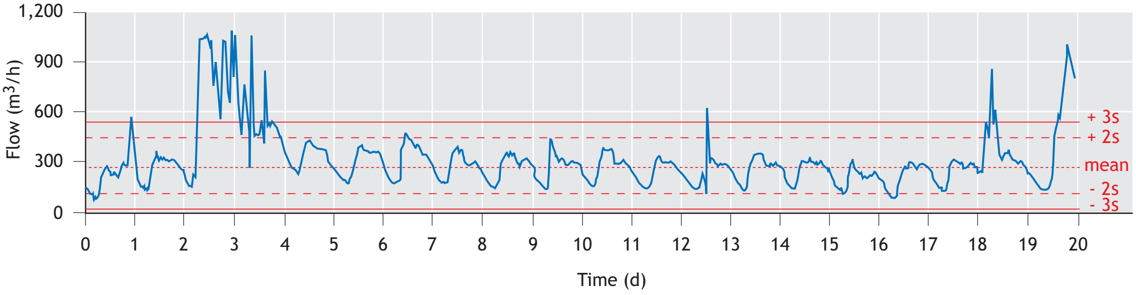

Figure 15.9 Influent flow rate variations during a three-week period. The mean value and the ±2σ and ±3σ limits are indicated.

Figure 15.10 illustrates what happens when there is a sensor failure. The upper figure shows the measurement signal and the observant operator can notice a change in the signal character at approximately time 900. By filtering the signal, however, the changes can be made more obvious. A high pass filter essentially shows the variability (or rate of change) of the signal. The filtered signal is displayed in the lower figure and reveals a significant change in the noise character of the signal, thus exposing a sensor problem. Obviously, it is possible to spot the change with the naked eye, but that requires attention by someone. By transforming the noise into a separate signal, it is possible to set up automatic alarms and hence react to the change in a timely manner, rather than realising this too late.

Any monitoring system must determine whether the acquired data are meaningful and correct, so data screening is essential. As a minimum it should include normal range comparisons (high and low limits), rate of change, and variance. Filtering techniques are essential to remove noise while retaining the essential signal information. High pass filters can detect sudden or fast changes.

By rapidly detecting deviations from 'normal' it is possible to minimize the cost of abnormal behaviour. Monitoring as a basis for early warning systems in wastewater treatment is described in literally hundreds of papers. Overviews are found in Irizar *et al*. (2008), Hamouda *et al.* (2009), and Olsson *et al.* (2014). Yuan *et al.* (2019) have reviewed detection methods for water supply, water distribution, sewer systems and wastewater treatment.

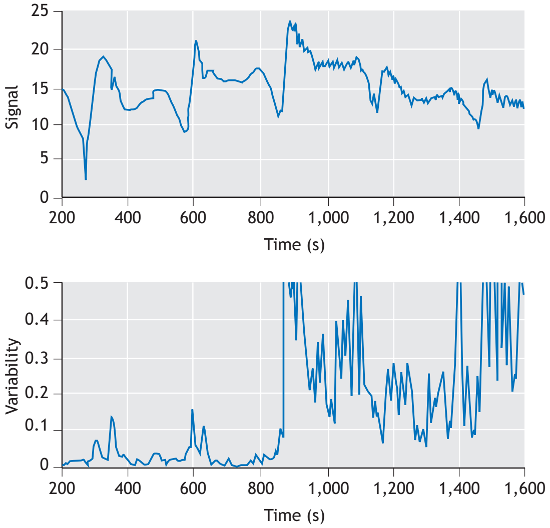

Figure 15.10 Detection of a sensor problem. The upper figure shows the sensor signal. The noise character will change after time 900, indicating a sensor problem. The lower figure shows the variability of the signal. When the variability exceeds a threshold (for example, 0.15) the monitoring system can give an automatic alarm.

Process knowledge is an essential condition for adequate diagnosis. A primary observation may lead to a whole chain of examinations of the problem, as in medical diagnosis. For example, a high turbidity of the effluent may be a primary warning. The reason may be a too high influent flow rate, poor sludge settleability, or a high sludge blanket. By back-chaining and asking questions (automatically or manually), the primary cause of the problem may be tracked down.

By combining information from multiple sensors and mathematical models, other operational parameters that are not directly measurable can be estimated: these are known as soft sensors, and they allow powerful monitoring tools to be built up. An early application of soft sensors to check the performance of instrumentation is described by Lumley (2002). Leonhardt *et al*. (2012) used a soft sensor to estimate stormwater overflow. Racault *et al*. (2011) demonstrated how oxygen transfer rate is estimated from mass balances. By measuring DO concentrations combined with models it is possible to estimate the oxygen uptake rate, and thus the reaction rate. An excellent overview of soft sensors in biological wastewater treatment is presented by Haimi *et al.* (2013).

Multivariate analysis is a method to detect changes in patterns and correlations in large data sets, including more than two variables. By using this analysis, it is possible to detect situations that call for human intervention. It is a viable alternative to manual examination of data; despite many hours of observation, it is still not possible to track all the changes that computer algorithms can. Hence this is a help to understand when to deploy the analysis team.

Multivariate analysis had been used for many years in the chemical process industry and 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 a 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. PCA has been used in sequencing batch reactors for monitoring (Villez *et al*., 2008) and as a basis for control of the phase length (Villez *et al*., 2010). Ruiz *et al*. (2011) used PCA for fault detection.

However, PCA methods are insufficient to deal with highly variable data, such as influent flow rates and compositions (Rosen *et al*., 2003). Wastewater treatment plants have a wide range of time constants, and it is difficult to look at correlations of data in just one timescale. Various methods to extend the PCA to dynamic data in wastewater treatment systems have been developed (Rosen and Lennox, 2001; Lennox and Rosen, 2002). Flores *et al.* (2007) evaluated selected multivariable statistical techniques for various control strategies for plant-wide wastewater treatment plant control.

Corominas *et al.* (2018) reviewed many commonly used computer-based methods that can transform data into useful information. These include methods based on control charts, mass balances, regression models (multi-linear, partial least squares (PLS)), self-organizing maps (SOM), principal component analysis (PCA), independent component analysis (ICA has another meaning here), artificial neural networks (ANNs), clustering, fuzzy methods, support vector machines (SVMs), and techniques for the recognition of qualitative features in data series. Computer-based tools for information (Environmental Decision Support Systems, EDSS) and knowledge management (ontologies) are also discussed. It is easy to get lost on how to select the best method for data analysis and there is no simple shortcut to how to find the best one. A specific review of machine learning techniques applied to the field of water and wastewater is described by Hadjimichael *et al.* (2016).

Several books and articles on elementary data analysis are freely downloadable from the Internet (search for ‘data analysis’, ‘statistical data analysis’, and ‘data mining’). There is a lot of freely available as well as commercial software for data analysis. All the methods described here can be executed on some available software. Software such as Excel can be used successfully for elementary data analysis, while more sophisticated software products such as Matlab[1] or SAS[2] contain a multitude of data analysis methods.

15.5 THE IMPORTANCE OF DYNAMICS

It is crucial to be reasonably familiar with dynamics in order to understand control. Basically, this means that the result of a corrective action will take some time; it will never appear instantaneously. Therefore, the timescale of any process change is extremely important. The dynamics of a wastewater treatment system involve a wide range of timescales, from seconds to months. Human perception is not very good at dealing with dynamics that are very fast or very slow. It also requires a lot of training and deep understanding of systems to comprehend processes that work and interact in different time domains. It is too easy to come to the wrong conclusion. Therefore, intelligent control systems that are tuned with the right time constants and gains are important in handling this problem. Additionally, such systems are attentive all around the clock.

The dynamics of the typical process units can be classified as fast, medium, and slow as described in Table 15.2 and this classification influences the type of model that can be developed and also the design of control strategies.

There is a wide difference between the fast and the slow timescales (Table 15.2). This allows the separation of the various control actions into different time domains. In the fast timescale the variables that change very slowly will be considered constant. For example, the DO concentration can change within a fraction of an hour. In this timescale the biomass concentration can be considered constant. Conversely, in the slow timescale, for example when we aim to control the total sludge inventory, then the DO concentration can be considered to be changing instantaneously.

This separation in time makes the control problem less complex. It allows control actions to be compartmentalized into fast, medium and slow timescales and we can consider them and often analyse them separately.

A continuous flow wastewater treatment system is in a transient state most of the time, because the influent flow rate and its concentration and composition are hardly ever constant. The control system aims to take care of these changes. Online

---

[1] http://se.mathworks.com/
[2] http://www.sas.com

measurements and corrective actions should bring the various process variables to their desired values. By contrast, in a sequential batch reactor the system is purposefully in a transient state. An oxidation phase will continue until the oxidation is completed, and then a reduction phase (such as denitrification) will take over and will finish when the reduction of nitrate has been completed. A sequential batch system is therefore very suitable for dynamic process control.

Table 15.2 Biological nutrient removal process dynamic response times.

Speed	Timescale	Wastewater treatment mechanism
Fast	Minutes-hours	Hydraulics and flow dynamics Oxygen mass transfer Chemical precipitation DO dynamics Solids-liquid separation
Medium	Hours-several hours	Concentration dynamics Nutrient removal
Slow	Days-months	Biomass growth

Sometimes the time needed for measurements must be taken into consideration. To get a DO reading takes a few seconds. However, this delay is small compared to the typical time for a DO change, which is a fraction of an hour. A respirometer reading will take a longer time, typically half an hour. It is obvious that such a measurement can be used only for slower corrective actions, of the order of hours. It is also important to remember that the measurement value is often corrupted by noise. The noise variations may be quite fast, and the controller must not react to the fast and false variations. Therefore, filtering the signal is crucial.

It is important to remember the dynamic when closing the loop. Controlling the total sludge inventory by the waste sludge flow rate is a very slow process. The rate of change depends on the biomass growth rate and the typical timeframe is of the order of several days. Typically, to change the sludge retention time from 10 to 11 days will take 10-20 days. The sludge retention time is an average value and cannot be calculated on a day-to-day basis. Instead the flow rates and sludge concentrations must be averaged over a longer time, typically weeks.

Sometimes the controllers are tuned to be too ‘ambitious’. For example, even if a DO sensor can produce a DO concentration value several times every minute this does not mean that the airflow rate should be changed every minute. Since the typical response time in a full-scale aerator is 15-30 minutes, a change of the airflow every minute will only produce meaningless control actions and wear out the valves. Instead, a control action every 8-12 minutes is adequate and more appropriate. In this timeframe the controller can see some results of the changing air flow.

Modelling for control is not the same as modelling for understanding basic kinetic mechanisms. Consequently, models such as the Activated Sludge Models 1, 2, and 3 (Henze *et al.,* 2000) or the Anaerobic Digestion Model (Batstone *et al.,* 2002) are not meant to be the basis for controller synthesis. Instead, they represent detailed descriptions of the way we understand the mechanisms of the biological processes. The comprehensive models are, however, excellently suited as testbeds for controllers, to understand behaviour in the different time domains. In control implementation, on the other hand, one needs to identify key parameters that are crucial for the operation of the plant. Such parameters can be oxygen uptake rate, respiration rate, and reaction rates for BOD removal, for nitrification or for denitrification. Redox can reflect the progress of the anoxic denitrification process.

The key parameters are calculated from primary measurements. For example, the DO concentration can be used as a basis for the estimation of oxygen uptake rates. Online measurements of ammonia nitrogen or nitrate can be further elaborated to calculate nitrogen removal reaction rates. Consequently, estimation of dynamical parameters is an important part of the modelling that will form the basis for more advanced control (compare Section 15.4.2).

15.6 MANIPULATED VARIABLES AND ACTUATORS

Several variables can be used to manipulate biological wastewater processes. Nevertheless, the possibilities to control the plant in a flexible manner are quite limited. A major problem in many plants is the lack of controllability of pumps or compressors. Hence, designing new plants for flexibility and controllability is an important challenge. This not only requires the use of variable actuators, but also that these are variable in the adequate operational range (Section 15.1.2).

Flexibility and controllability are a key to effective and efficient operation. However, be aware that it is also true that if the controllability is not used wisely, based on sensor inputs and intelligent use of controls, it is of no, little or even negative use.

Section 15.2 gave an example of how on/off pumping can create problems later on in the process. Variable speed control is a proven technology and is one important prerequisite for good control, both for pumping of water and sludge flows and for controlling air flow for DO control.

The manipulated variables can be categorized into the following groups:

- Hydraulic, including sludge inventory variables and recirculation flows,
- Additions of chemicals or carbon sources,
- Air or oxygen supply,
- Pre-treatment of influent wastewater.

There are several other manipulated variables in a plant that are related to the equipment and to basic control loops in the process, such as flow controllers, level controllers etc. They are not included in this discussion.

15.6.1 Hydraulic variables

Most of the manipulated variables change the hydraulic flow patterns through the plant. The different flow rates will influence the retention times in the various units. Moreover, the rate of change is crucial in many parts of the treatment plant, since it influences the clarification and thickening processes. The hydraulic flows also determine the interaction between different unit processes. Thus, the hydraulic manipulated variables can be divided into the four groups:

- Variables controlling the influent flow rate,
- Variables controlling the sludge inventory and its distribution,
- Internal recirculation within the biological process,
- External recycle streams, influencing the interactions between different unit processes.

In this category we will also include the control of the phase length in sequential batch reactors, which is equivalent to controlling the retention time of a continuous unit.

The influent flow rate to the activated sludge system can be manipulated in various ways. From a plant point of view the influent flow rate may be considered an external disturbance that has to be handled by the various control systems. Then we emphasize that the pumping of the influent flow must be smooth and variable speed pumping is recommended (compare Figure 15.3). On the other hand, if there is an equalization basin available or if the sewer network can be used as a buffer volume, then the influent flow rate becomes a control variable. The additional volumes before the plant will allow us to control the influent flow rate to minimize the detrimental consequences of the influent variations.

Many plants are designed with two or more parallel aeration basins. The flow splitting process is crucial if the load is to be evenly distributed. This is often not the case, which results in apparent overloading in some parts of the system. In many plants the flow splitting is carried out by a fixed arrangement of channels, which may not guarantee at all that the real flow is split correctly. If flow splitting has to be guaranteed, then the flow rates must be measured, and the individual flow rates controlled.

Bypassing should be a manipulated variable in the sense that it should never occur, unless it is ordered. It must be compared with the alternative of not performing bypassing and has to be based on some quantitative calculation with a suitable time horizon (compare Section 15.1.1).

All the different modes of influent flow control are simply different ways to increase the control authority. In other words, sewer or equalization or bypass control all contribute to making it easier to obtain a smooth flow rate into the plant. Their goal is disturbance rejection. A smooth variation of the flow rate is crucial for the secondary clarifier operation. It requires not only variable speed pumping at the operating level to avoid disturbances, but an adequate storage capacity in wet wells or upstream tanks to damp disturbances which cannot be avoided. Poor pumping control can deteriorate the plant performance considerably.

The sludge inventory can be controlled primarily by three manipulated variables:

- The waste sludge flow rate,
- The return sludge flow rate,
- Step feed flow rates.

Manipulation of the waste sludge flow rate is used to control the total inventory of sludge in the process. Since the total inventory is a function of the total growth rate of organisms, it is used to control the sludge retention time, or the sludge age. This manipulated variable will influence the system in a timescale of several days or weeks.

Manipulation of the return sludge flow rate is used to distribute the sludge between the aeration basins and the settler units or between the acidogenic and methanogenic reactors in two-stage anaerobic systems. Recycle from the settling stage is an important variable for obtaining the right operating point in the reactors, but seldom useful for the control on an hour-to-hour basis. Some systems are supplied with several feeding points for the return sludge. This has a potential for sludge redistribution for certain loads, such as toxic loading. A combination of different recycle streams may be important. In systems with chemical precipitation, sludge from the secondary settler may be combined with chemical sludge from a post-precipitation settler unit. In this way the floc properties may be influenced, and the chemicals better utilized for phosphorus removal.

By controlling the step feed in an activated sludge plant, the sludge within the aeration basin can be redistributed, given the proper amount of time. Uniquely for step-feed control, one will obtain a contact stabilization structure. Also, the return sludge may be fed back not only to the inlet part of the aeration basin, but into different feeding points along the basin, which is known as step return sludge control. This may prove to be an efficient way of preventing bulking sludge.

Internal or external recirculation flows provide couplings between the different units of the plant. The recycle streams can be considered as controllable disturbances to the reactor-settler system. They must be manipulated so that their detrimental impact is minimized. Some of the recirculation flows have very large flow rates, such as the recirculation of nitrate in a pre-denitrification plant. Having a system with pre-denitrification, it is necessary to recirculate nitrate-rich water from the outlet of the nitrifying aerator. In particular, the oxygen contained in the recirculated water may limit the denitrification rate in the anoxic zone.

Section 15.2 demonstrated that the backwashing flow from a deep-bed filter can create major disturbances and must be manipulated properly. Other streams may have extremely large concentrations, such as supernatants from the sludge treatment, as indicated in Section 15.2. Most of them can be manipulated purposefully to achieve a better plant performance. In a bio-P system there are three types of reactors: anaerobic, anoxic and aerobic. Depending on the design, there are many recirculation patterns in such a plant. In a two-stage anaerobic system the recirculation helps to keep the methanogens washed out of the acidification stage and restores pH buffering capacity to reduce caustic usage.

15.6.2 Chemical addition

Chemicals are added for two different reasons, to achieve chemical precipitation for phosphorus removal, or to form a better settleability of the sludge. For phosphorus removal, ferrous, ferric or aluminium salts are added to obtain chemical precipitation by forming insoluble phosphates. A change in chemical dosage can have quite a fast influence on the floc formation and the settling. In Section 15.8 the control of chemical precipitation is discussed.

In addition to the normal use of chemicals for P removal, chemicals can be added to improve sludge settling properties in the secondary settler. Sometimes chemicals are added to the primary settler to reduce the load to the aerator, although this may lead to insufficient carbon for the nutrient removal.

Polymer addition may be used in emergency situations to avoid major settler failures. On a routine basis it is used for sludge conditioning to improve dewatering properties. In addition, polymers can be used to further enhance the efficiency of the pre-precipitation process.

Caustic addition is applied in two-stage anaerobic processes to control the pH, which can inhibit the methanogenic microorganisms.

15.6.3 Carbon addition

Carbon source addition is sometimes needed in denitrification to obtain an adequate carbon/nitrogen ratio in the system. Too little carbon results in incomplete denitrification, while too much carbon adds a cost for the chemical and its subsequent removal. The timescale of such an operation is related to the retention time of the denitrification. For a pre-denitrification system, carbon is usually supplied via the influent wastewater. However, this may be insufficient during low load periods, so some carbon source needs to be added. In a post-denitrification system a carbon source (such as methanol or ethanol) always has to be added. Then the problem appears of how to adjust the dosage to the carbon need, without extensive measurements.

15.6.4 Air or oxygen supply

Dissolved oxygen (DO) is a key variable in activated sludge operation. From a biological point of view, the choice of a proper DO setpoint is crucial. The dynamics of the DO is such that the DO can be influenced within fractions of an hour. Key factors related to the DO supply are the total air supply, the DO setpoints, and the DO spatial distribution. To obtain the required DO profile one needs individual airflow measurements and feedback control over the valves to each zone of the aerator. DO control will be further discussed in Section 15.8.

The airflow rate is recognized to be of major importance for the whole operation. It is reasonable to assume that a well-functioning DO control system should be available. However, since the energy cost is significant, it is of interest to minimize the air supply. It is well known that insufficient air supply will influence the organism growth, the floc formation and the sludge settling properties. However, once undesirable organisms are formed, it is not always obvious how to get rid of them by only DO control.

15.7 BASIC CONTROL CONCEPTS

The fundamental principle of control is feedback, illustrated by Figure 15.1. The process (for example, an aerator, a chemical dosage system, or an anaerobic reactor) is all the time subject to external disturbances. These are mainly caused by the variations in the influent load, but can also be caused by internal changes, such as recycles, pumping, etc. The current state of the process measured by a sensor forms the basis for a decision. In order to make this decision the goal or purpose must be stated. Having made the decision it then has to be implemented via an actuator, which is typically a motor, a pump, a valve or a compressor.

Control engineering today can offer almost anything in terms of methods and algorithms that the water operation might need. Automatic control is sometimes called the hidden technology. It appears everywhere around us and we do not even think about it. We only notice it when it does *not* work. We are subject to feedback in our daily life. In the human body the nerve cells sense the temperature and the brain controls the muscles to restrict the skin capillaries. Balancing the body requires that we sense the direction via our balancing system. The brain controls the muscles in the feet and legs to keep us upright. While driving a car the driver all the time applies feedback. The eyes watch the speedometer and the road etc. and the brain will compile all that information and decide what to do in the next moment. This is translated to the muscles to turn the steering wheel, to brake or to accelerate. The reason for the constant feedback is that the scene is changing continuously. In other words, the process is subject to disturbances that force us to use feedback.

Even if control is applied in completely different areas, there is a common theory that is independent of the applications. There are literally hundreds of textbooks on control. The textbook by Åström and Murray (2014), available on open access, is recommended, since the authors are world leaders in the development of control theory and engineering.

In other words: control is about how to operate the plant or process towards a defined goal, despite disturbances. With the manipulated and controlled variables identified in the previous step, a proper control configuration has to be defined using an adequate control algorithm. The block diagram in Figure 15.11 is a control engineering representation of the simple feedback controller shown in Figure 15.1. It describes the signals (the information flow) of the control system. Note that the terms 'closed loop control', 'feedback control' or just 'control' are often used as synonyms. This kind of control loop appears in all the local control of levels, pressures, temperatures and flow rates. The controller has two inputs, the measurement (actual) value y and the reference (setpoint) value u_c and one output, the control signal u. In this simple case, however, the controller uses only the difference between the two inputs.

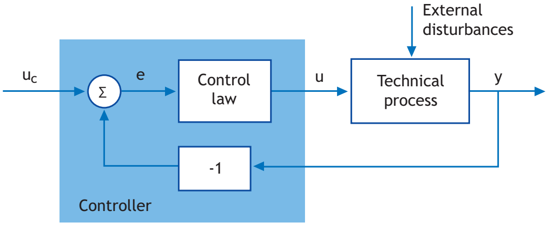

Figure 15.11 The simplest feedback control structure.

The properties of the controller (the controller parameters) can be changed (we usually call this procedure tuning) so that the output of the system gets as close as possible to the setpoint. The controller tries to make the error $e = u_c - y$ as small as possible. It is reasonable to think that the more parameters a complex controller contains, the more degrees of freedom it has. With the help of these parameters this can be changed at will, and the behaviour of the closed loop system can also be changed more arbitrarily.

Note the difference between *open loop* and *closed loop* control. In an open loop controller, the control action is not based on any feedback or measurement, but rather based on time. For example, a compressor providing air to an aerator can be turned on and off at certain times. No measurement of the DO is made and there is no guarantee that the DO concentration will be correct. Such an open loop control is completely different from closed loop control, where the change of aeration is based on true DO measurements.

The design of feedback controllers has attracted considerable attention in the control literature. Many advanced control algorithms based on, for example, dynamic models, neural networks and fuzzy logic have been proposed. Control systems based on simple rules (rule-based control) have also found successful applications. However, little convincing evidence has been presented suggesting that these advanced algorithms produce better unit process control performance in wastewater treatment systems than the conventional PID (proportional-integral-derivative) algorithms, which have been used in most practical process control applications (more than 95% of the controllers in a typical paper and pulp industry are PID controllers). Of course, this assumes that the PID controllers are correctly tuned, which requires technical understanding and experience with PID controllers and dynamic systems.

15.8 EXAMPLES OF FEEDBACK IN WASTEWATER TREATMENT SYSTEMS

The traditional WWTP control is still largely unit-process-oriented. Some examples of state-of-the-art unit process control include:

- DO control with a constant or a variable setpoint as part of the aerator unit process operation. In a nitrifying plant the DO setpoint no longer needs to be constant. It is calculated online based on information of nitrogen-removal performance, monitored with ammonia sensors.
- Aeration phase-length control in alternating plants based on nutrient sensors.
- Nitrate recirculation control in a pre-denitrification plant based on nitrate and DO measurements in the aerator and in the anoxic zone.
- Sludge retention time control based on measurements of effluent ammonia concentration and of estimates of nitrification capacity.
- Return sludge control based on sludge blanket measurements in the settler.
- Aeration tank settling (ATS) as a way of temporarily increasing the plant capacity in storm conditions (Nielsen *et al.,* 1996; Gernaey *et al.,* 2004).
- The control of anaerobic processes aims to stabilize the process and to maximize the biogas production. In most cases the control is based on biogas flow measurements only. Information from the reactor itself, such as pH, is needed for better control. More advanced measurements are under development.
- Dosing control in chemical precipitation control based on local measurements of pH, alkalinity or phosphate concentration.

Comprehensive reviews of these control systems can be found in Olsson *et al*. (2005, 2014), Åmand *et al.* (2013, 2014), Olsson (2012) and in Ingildsen and Olsson (2016).

A further challenge that future ICA systems ought to address is the mitigation of greenhouse gas emissions, such as N_2O, from biological nitrogen removal plants (Mannina *et al.,* 2016). The control of these parameters at levels that minimize N_2O emissions and still allow satisfactory nitrogen removal must be developed and demonstrated.

Example: Dissolved oxygen control

Dissolved oxygen control is of primary importance in the activated sludge process, both in recirculating plants and in alternating or intermittent systems. The control of aeration has been the subject of considerable research since the 1970s, when DO sensors reached a level of robustness and precision suitable for feedback control. Today, the control of DO to a setpoint is a mature technology from a methodological point of view, though in reality it is still suffering from underperformance and even encounters occasional failures due to physical limitations (*e.g.* inadequate capacity of the blowers) and/or hardware malfunctions (*e.g.* breakdown of a DO sensor). We will consider here the control of the DO concentration to a pre-specified setpoint through manipulating the airflow rate, as illustrated by Figure 15.12.

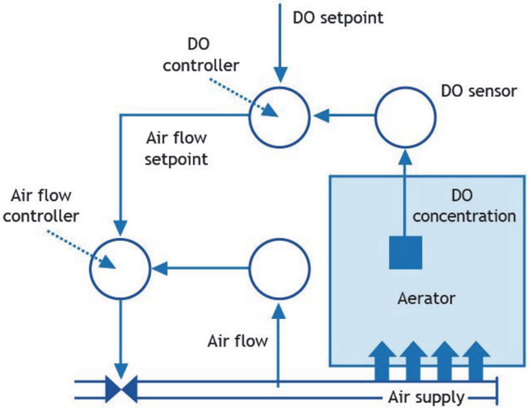

Figure 15.12 Structure of a standard dissolved oxygen control loop.

The DO is measured at one point in the aerator. The concentration is compared with the DO setpoint and the DO controller (the 'master') will calculate the necessary airflow change required to modify the DO concentration towards the desired value. However, the DO controller does not directly manipulate the air valve. Instead the desired airflow is given as a setpoint to a second controller, the airflow controller (the 'slave'). This controller receives the airflow rate measurement and compares it with the desired airflow. This difference will then make the actuator (a compressor or a valve) change the airflow to the required value. The control structure is called a cascaded control loop and is the standard configuration in this kind of system.

There are two important reasons why the DO controller is not directly coupled to the valve. The first reason has to do with the valve characteristics. Usually valves are nonlinear, as in a butterfly valve. A 10% change in the valve signal will produce significantly different responses if the valve is almost closed, in the mid-range or almost fully open. This means that a desired airflow change will require very different valve movements if the valve is almost closed or if it is almost fully opened. If the airflow rate is measured, then the flow controller can produce the required flow rate independent of the valve nonlinearity. Having the closed-loop slave controller in place means that the master controller will see a linear behaviour of the airflow system. The second reason has to do with the commissioning of the control system. The slave controller is tuned while the master controller is set to manual. In this way one can ensure that the response of the airflow system is adequate. Having completed this, the master controller can be put into automatic mode and subsequently tuned.

Example: DO setpoint control based on ammonium measurements

With the development of nutrient sensors, it has been possible to extend the DO control to allow for an online adjustment of the level of oxygen supply. For a recirculating system this means that the appropriate DO setpoint can be determined by online measurements.

An online ammonia analyser is placed near the outlet of the aeration basin. Under ideal conditions the ammonia concentration will decrease along the aerator and reach a low value just before the outlet. If the ammonia concentration is too low, then we may have been too ambitious. If so the effluent quality can be achieved with less air. Consequently, the DO setpoint can be decreased for the last zones of the aerator. Conversely, if the ammonia concentration is too high at the outlet, then we will try to improve the nitrification rate by increasing the DO setpoint so that we can reach the required low ammonia concentration. However, it may not be enough to increase the airflow. The load may simply be too high and the nitrification capacity insufficient for this load. Therefore, the upper value of the DO setpoint should be limited.

Figure 15.13 shows the result of DO control with a variable DO setpoint at the Källby WWTP in Lund, Sweden. It is a 100,000 PE plant of the pre-denitrification type. In one of two parallel identical lines a DO setpoint controller was tested based on ammonium concentrations at the end of the aerated part of the plant. A simple PI controller was used to change the DO setpoint value, based on the ammonia sensor signal at the outlet of the aerator. The DO setpoint value was sent to the DO controller system, as the one shown in Figure 15.12. The resulting controller is expanded to a structure of three controllers working in cascade using the master-slave principle. The controller performance is shown in Figure 15.13. At times with high ammonia concentration in the influent the DO setpoint is raised to its maximum (set to 3 mg/l). At periods with low ammonia load the DO setpoint can be decreased to much smaller values. Here it is limited to stay above 0.5 mg/l. By allowing a variable DO setpoint we will save energy for aeration. During the testing period in this plant, aeration energy savings of 28% were obtained compared to the parallel line where a constant DO setpoint was applied. This corresponds to a significant part of the operating costs and compensates readily for the extra cost of an ammonia analyser.

There are many publications on DO control. Åmand *et al.* (2013, 2014) and the two book chapters Olsson *et al.* (2019a, 2019b) present comprehensive reviews of aeration control.

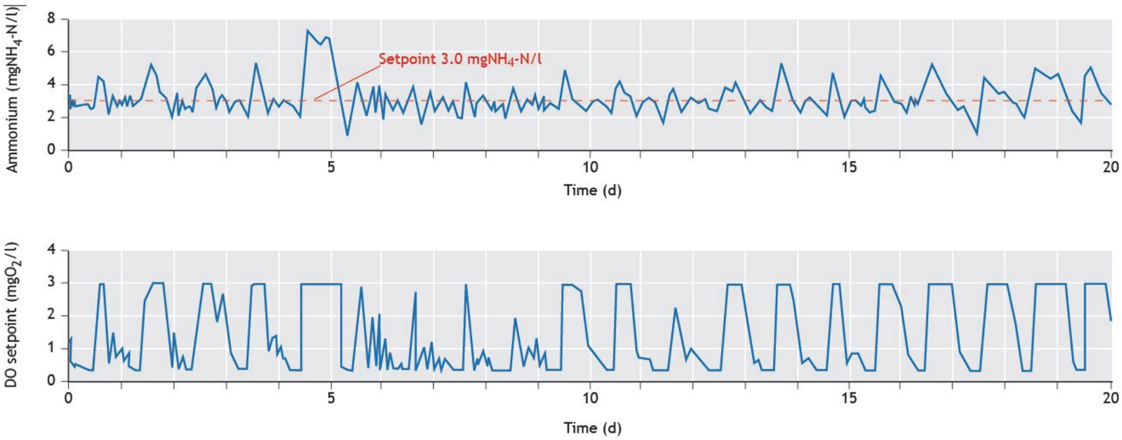

Figure 15.13 DO control with a variable DO setpoint. The upper plot shows the ammonium concentration at the end of the aerated part of the plant. The ammonium setpoint is 3 mg/l of NH4-N. The lower plot shows the DO setpoint in the last aerator zone during the same period of time. The DO setpoint is limited between 0.5 and 3 mg/l (from Ingildsen, 2002).

Example: Chemical precipitation control

In many plants and places phosphorous removal is obtained using chemical precipitation. Chemical precipitation processes are a lot faster than biological reactions. Compared to the timescale of the variations in wastewater flow rate and composition, chemical precipitation can be assumed to occur instantaneously. This represents a useful feature from a control point of view and implies that the disturbance can be quickly dealt with through feedback control. However, the challenging issue is the timely and reliable measurement of the key process variables so that a feedback control system can be established.

Chemical precipitation can be applied either prior to or after the biological treatment step, called *pre-precipitation* and *post-precipitation,* respectively. Chemicals can also be added directly into the aerator, which is known as simultaneous precipitation. Many plants apply a combination of these different types of precipitation. Here we will show that with a phosphate sensor in place, excellent control performance can be achieved using a simple feedback controller, demonstrated here for a post-precipitation process.

Phosphorous is precipitated by post-precipitation at the Källby treatment plant, Lund, Sweden. The line consists of a dosage system, where the precipitation chemicals are introduced into the water stream that runs into a flocculation chamber where soft mixing ensures the build-up of chemical flocs, followed by a settler for sludge removal. The average retention time in the flocculation chamber is 1 hour and the average retention time in the settler is 4.3 hours. The preceding biological lines achieve partial biological phosphorous removal, and chemical precipitation is applied to remove the remaining amount of phosphate which is typically around 2 mgP/l.

Here we will compare two control strategies first implemented by Ingildsen (2002):

1) *Flow proportional dosage:* This is a common strategy but relies on the assumption that the P concentration is constant. This is ho*wever mostly not the case; the assumption of the constant relationship between influent phosp*hate load and dosage may not be entirely correct, as factors such as pH may influence the process.
2) *Feedback control*: A feedback loop is applied that controls the dosage toward a certain phosphate setpoint in the effluent. The feedback signal comes from an online phosphate analyser located at the end of the flocculation chamber.

A flow proportional controller was tested for 35 days. The performance in terms of effluent phosphate can be seen in Figure 15.14. Four periods of malfunction are noticed in the effluent phosphate concentration (days 9, 10, 11 and 15). Especially the last incident (day 15) is easily detectable, where the effluent phosphate concentration increases drastically. The effluent criterion is 0.5 mg/l and it is obvious that the concentration is often lower than 0.5 mg/l. At other periods it is far higher, so the variability of the phosphate in the effluent is high. Obviously, the dosage is too ambitious at times, and this will be directly reflected in the operating costs.

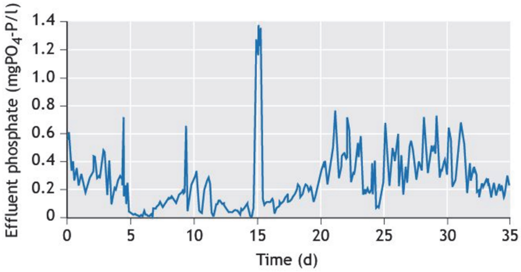

Figure 15.14 The effluent phosphate concentration with control of chemical dosage based on the hydraulic flow rate (from Ingildsen, 2002).

The retention time in the flocculation chamber is short, on average around 1 hour. This is considerably shorter than the time constant of the variation in the influent load of phosphate to the chemical step. Hence, it should be possible to control the phosphate precipitation by means of feedback control based on an *in-situ* phosphate sensor located in the effluent of the flocculation chamber. The influent phosphate concentration to the chemical step varied from about 1 to 3 mg/l, while the target value was 0.5 mg/l.

The performance in terms of effluent phosphate concentration is displayed in Figure 15.15. The setpoint was purposefully changed from 0.5 to 0.4 mg/l PO_4-P on day 23 and back to 0.5 mg/l on day 33. The peak concentration on day 31 is due to a malfunction of the dosage pump. The proposed controller is based on the effluent phosphate concentration while most effluent permits are defined in terms of effluent total phosphorous concentration. At the Källby plant it was verified that the total phosphorous and the orthophosphate concentrations are linearly correlated, with a regression value of 0.96. This means that it is possible to control the process towards a certain phosphate setpoint and be reasonably certain that the total phosphorous concentration will also be in compliance.

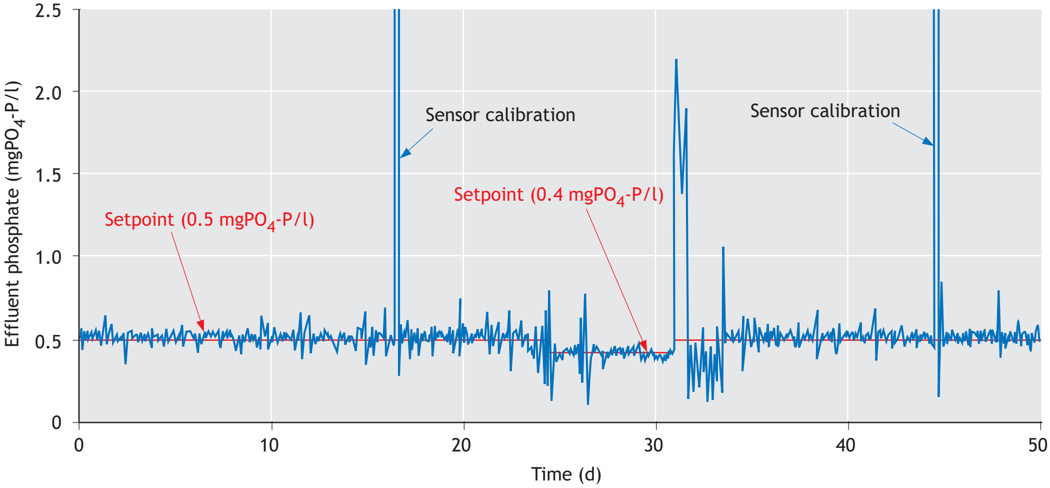

Figure 15.15 The effluent phosphate concentration with control of chemical dosage based on in-situ phosphate measurements (from Ingildsen, 2002).

The feedback controller works well in terms of precision. This can be used to quantify the savings when comparing various strategies. The *in-situ* feedback control with 0.5 mg/l as a setpoint is used as a basis for comparison. We can now compare the chemical dosage for the different strategies based on 90% compliance. If compliance in 90% of the time is accepted, this means that 10 % of the time the dosage may be less than in the feedback controller. This 90% compliance quantification is included to avoid extreme situations. In this case one line of the plant was operated with flow-proportional dosage while the parallel line was operated based on the phosphate measurements. The amount of dosage chemicals using the feedback control was decreased by more than 35% compared with the flow-proportional dosage control. The payback time for a phosphate analyser is consequently short, just a few months.

Example: Anaerobic reactor control

A main difficulty of anaerobic digestion (AD) is that it is often perceived as being unstable during both start-up and steady-state operations. Imbalances in the microbial ecosystem may lead to organic overload, causing severe reduction in degradation capability and washout of the microorganisms, resulting in poor reactor performance, reduced biogas production and even shut-down. The traditional way of avoiding this kind of instability is to operate the process far below its theoretical reactor capacity. In addition, the nature of the influent characteristics involves dynamic variation in both flow rate and composition, which are significant disturbances to the processes. Handling of these disturbances by attenuation or rejection is thus important for stable operation. A more economically viable approach to overcoming the problem is by applying close monitoring and automatic control of the process in order to enhance the operational stability, to attenuate and reject disturbances and to allow the treatment of waste and biogas production at a higher specific rate (Liu, 2003).

It is crucial to characterize the feed to a digester in order to obtain a reliable AD operation. Jinguara and Kamusoko (2017) present a review of feed characterization methods. Today there are analytical tools available to automatically test the biochemical methane (biogas) potential, the anaerobic biodegradability, as well as the specific methanogenic activity. Liu *et al*. (2019) describe the automation potential of feed testing for the non-specialist.

Many anaerobic bioreactors are still operated without close monitoring or control. This is not only because AD involves complicated degradation steps, but also due to lack of proper analytical devices. In fact, sensor technology is the weakest part of the process chain (Liu, 2003; Boe, 2006; Olsson *et al.,* 2005). Close monitoring and control of the AD process firstly requires identification of suitable process parameters, which can give indications of imbalances in the microbial ecosystem and warnings of external disturbances. The activity of the different microbial groups involved in the AD process can be measured indirectly by monitoring the metabolites. In general, it is now possible to analyse pH, alkalinity, biogas flow and composition, VFAs, biodegradable organic matter, dissolved hydrogen, and toxicity online by less expensive sensors and instruments (Liu, 2003).

The timing of measurements is important. Controlling the AD process by regulating the feed based only on the biogas flow rate is not an efficient control, simply because the gas flow rate is very late information for the controller. Any feed rate change will be noticed after a significant time delay. If any variable can be measured in the bioreactor itself, it will provide earlier and more useful information. Measuring the pH also adds important information, as demonstrated by Steyer *et al.* (1999). The alkalinity and hydrogen content in the gas phase have also been used. The feed rate is the typical control variable, since the organic loading rate should be adapted to the treatment capacity of the system in order to obtain an efficient process operation. Jimenez *et al.* (2015) present an overview of instrumentation and control problems in AD.

The start-up of anaerobic reactors is relatively slow due to low net growth of anaerobic biomass and required adaptation to specific wastewater components. Therefore, the start-up is a critical process that relies heavily on the operator skills. Also, after the start-up period the process is vulnerable to disturbances such as temporary overloading, biomass washout and toxicity. With a good control system the anaerobic reactor can – even during the transient start-up mode and at large loading – be operated close to its capacity and still maintain stable operation (Liu *et al*., 2004).

More advanced control

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 the model parameters to be uniquely updated from available online measurements and with different predictive time horizons will prove useful. Naturally, the timescale of the models must also be related to the timescale 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 a fall-back control is essential. When severe problems occur, for example actuator or sensor failures, the control system should react to 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 redesign in the future. In many situations this is a major bottleneck for successful implementation of control in water and wastewater systems.

15.9 OPERATING COST SAVINGS DUE TO CONTROL

Electrical energy consumption is closely related to advanced wastewater treatment systems. Treatment and transmission of water and wastewater consume large amounts of energy. Estimates indicate that on average wastewater treatment alone requires around 1-3 % of the total electricity energy output of a country, representing a significant fraction of municipal energy bills. The energy utilisation of treatment plants is in the range of between 20 and 45 kWh per head of population per year. Older plants may have even higher demands. This figure does not include the primary pumping of the influent water. In this section we will emphasize how control and automation can reduce the electrical energy requirement. More detailed discussions on energy requirement in wastewater treatment are presented in Olsson (2015, chapters 15-19) and in Capodaglio and Olsson (2020).

DO control has been discussed and it is now obvious that even simple DO control, based on only one DO sensor, will save a lot of electrical energy compared to no control at all. Furthermore, having a time-variable setpoint of the DO concentration will further reduce the energy consumption, as discussed in Section 15.8. There are further possibilities to save energy in the DO control. For example, the air pressure can be minimized. Assume that the plant has two or more parallel aerators. The air system must supply sufficient air to the plant. However, sometimes the pressure can be lowered. This is noticed if the airflow valves are not fully open, which causes a pressure drop across the valves. The idea is to gradually decrease the airflow pressure so that the most open air flow valve becomes almost fully open. This will minimize the pressure drop and further energy savings are possible. Such control methods have been implemented; see *e.g.* Olsson and Newell (1999).

Large pumps, primarily for influent water, are often the most energy-demanding equipment in a plant. In many cases the pumping equipment has not been designed for adequate flow rates. If the pump is over-designed, then it may be operated with a low level of efficiency for small flow rates. In some cases it is profitable to install a special pump for small flow rates. The pump should be designed to work at the most efficient operation point for the most common flow rates (Olsson, 2015, Chapter 16).

Aeration by compressors ought to be continuously variable. However, to control airflow by closing airflow valves will cause considerable energy loss. Variable speed compressors will save energy significantly. Typically, the power requirement for the airflow is proportional to n^3, where n is the rotational speed. This means that only 1/8 of the power is needed to produce half the flow rate. Consequently, the potential for energy savings is considerable.

The cost for chemical precipitation is significant. In Section 15.8 we demonstrated that feedback control can contribute to much lower operating costs.

A wastewater treatment plant in fact should be considered a recovery plant for both nutrients and energy. Considering the energy potential in anaerobic digestion, there is a huge unused potential in most plants. Just one plant (in Sweden) can illustrate this: the plant uses 41 kWh/person.year of electrical energy. At the same time the plant produces biogas corresponding to 72 kWh/person.year. Furthermore, the heat content of the effluent water is taken care of in heat pumps that produce 336 kWh/person/year. The plant is in fact an important energy producer.

As discussed in Section 15.8, AD is a crucial process to obtain a zero-energy plant. In too many plants the AD uses only a fraction of the energy content of the sewage. Major savings happen when adequate instrumentation and control allows the plant to operate at a higher capacity. An implementation of control that avoids a plant extension has a very favourable cost-benefit ratio. By-products from sewage treatment can also provide a valuable source of energy if managed and utilized effectively. In addition, costs of sludge transportation and disposal, which currently place a major burden on the industry, can be reduced.

15.10 INTEGRATION AND PLANT-WIDE CONTROL

Integration aims at minimizing the impact on the receiving water, while ensuring a better resource utilisation. The system resilience is an important factor. This includes its ability to attenuate disturbances but should also reflect its sensitivity to major disturbances or even purposeful and harmful attacks. In the integrated approach the goal is to formulate criteria for the receiving water and its ecological quality while satisfying various economic and technical constraints. It is a major challenge to relate this performance to the plant effluent and possible sewer overflow. We need performance measures of the plant operation that relate effluent quality to the resources that are needed to obtain it, such as energy, chemicals, and other material and operating costs. Models are being developed to find strategies to dynamically find maximum WWTP loading according to continuous monitoring and prediction of the operational state. One example is maximizing the nitrification capacity in the activated sludge process, depending on the load to the system. Some full-scale results are reported by Rosen *et al.* (2004, 2006). Another aspect is storage management (in the sewer system and in retention tanks), not only during storms but also during normal operations. By mixing different types of wastewater to compensate *e.g.* for nutrient deficit or overload, the capacity of the plant can be maximized.

All integration means some compromise. If there were no interactions, then the individual optimization of each sub-process would be the best strategy. An integrated view of the operation will give a better result than if each one of the processes were controlled separately. This is the essence of a multi-criteria index: various performances are weighted and compared with each other. This can be illustrated with some examples:

- The interaction between the aerator and the settler is a classical integration problem, reflected in the compromise that must be made in the control of return sludge flow rate.
- The anoxic zone in a pre-denitrifying plant interacts closely with the nitrifying aerator. Oxygen-rich water is recirculated from the aerobic zone to the anoxic zone. The DO level towards the outlet of the nitrification zone must be a compromise between sufficient nitrification and the denitrification following the nitrification.
- There is interplay between serially linked processes. For example, chemical pre-precipitation in a primary settler will remove not only phosphates but also particulate organic material, saving aeration energy. On the other hand, a pre-denitrification may then obtain too little carbon. Similarly, if the precipitation is combined with a bio-P process the latter may be carbon-limited.

- Recycle streams interconnect various parts of a treatment plant. Supernatants from sludge treatment are most often highly concentrated in nutrients and should be synchronized in time with the plant influent load.
- Backwash water from deep-bed filters is recirculated to the input of the plant. Since the flow rates are often significant a synchronized control of the flow rate to the plant load is necessary.
- The target for the sludge production is not the same in different plants. Sometimes the target is to maximize the methane production, while at other plants the sludge production needs to be minimized.

In the combined sewer and WWTP operation the individual system operations are sometimes in conflict, so the overall goal of minimizing the load to the receiving water must overrule the individual goals (Rauch and Harremoës, 1996a; Schütze *et al*. 1999; Vanrolleghem *et al*., 1996b). An early approach to integrated control was published by Rauch and Harremoës (1996b).

A plant-wide control system will assume that all the different unit processes are controlled locally. In addition it will consider the interaction between different parts of the plant, for example by computing suitable setpoints for the local controllers. The sewer control system will control the flow rate in the various parts of the sewer system using the information from water level and flow rate sensors, pumping equipment, as well as rain gauges. The coupling between the sewer system and treatment plant control is achieved when the plant influent flow rate can be predicted and manipulated. Typical measurements and control handles for the interacting sewer system and WWTP are listed in Table 15.3.

Table 15.3 The objectives, measurements and control handles for a combined sewer-wastewater treatment system operation.

	Partial aim	Measurements	Control handles
Sewer system	Minimize upstream overflow Utilize basins for most polluted water	Rain levels Flow rates	Pumping stations Adjustable weirs Basins
Wastewater treatment plant	To treat as much wastewater as possible during and after rainfall Reduce hydraulic load and sludge load in secondary sedimentation tanks	Flow rates (inlet, outlet, return sludge, recycles) Suspended solids (aeration tanks and return sludge) Sludge blanket	Return sludge pumping (control of sludge blanket in sec. sedimentation tanks) ATS control (sedimentation in aeration tanks) Primary pumping (bypass before biological section or the total plant)

Following the development of models, researchers together with operators have developed necessary technologies and experience for reliable online monitoring of sewer systems which complements the more established monitoring of treatment plants. Integrated control has now been realized in real life, for example in The Netherlands (Weijers *et al.,* 2012), in Denmark (Grum *et al.,* 2011), and in Germany (Seggelke *et al.,* 2013). Benedetti *et al*. (2013) present a comprehensive review of the integration challenges and solutions.

15.11 CONCLUDING REMARKS

Automation is the method of making a process or a system operate and adapt automatically. Uncertainty in the process or in the environment around the process makes automation both an opportunity and a great challenge. Disturbances are everywhere and are the main reason for control. Another reason is to be able to operate at optimum, and control would be relevant even if there were no disturbances.

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, are today gathered online in the SCADA systems of treatment plants, and data analyses with varying degrees of sophistication 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. It should be noted that plant operation becomes sub-optimized with only local controllers. The potential of plant-wide automation is to coordinate the various unit processes so that the overall performance requirements are better fulfilled. Succeeding with this means that automation gets a third purpose beyond information acquisition and process control. This can be called overall optimisation and is realized in the integrated operation of the urban water cycle. Encouraging developments have been reported during the last few years. It is quite apparent that effective operation must rely on functioning equipment. All the links in the chain must 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. Note that if all the components are not functioning at all times, fall-back strategies must be in place.

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. Although there is a limit to how much expertise a treatment plant can afford, given that plant data can be made available anywhere it is possible to utilize specialist competencies wherever they are located. Nevertheless, there are several human and managerial aspects of how to distribute the responsibility and decision-making in various sectors. There is also already commercial software available for decentralized process monitoring and control. Naturally there has to be caution against publicizing sensitive data or against misuse of information and there is also a need to guarantee that data from each individual plant is correctly interpreted.

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 also motivated by economic and environmental obligations and it 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 investment.

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 online process control is still an emerging concept (Yuan and 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 systematically. Modern molecular techniques allowing 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 only notice it when it does *not* work. The complexity of modern WWTPs is often reflected in ICA systems. Several specialties must cooperate to achieve 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. Process specialists and designers should be able to appreciate the implications of ICA and computer and control engineers must understand the process controllability and its constraints. This further emphasizes the multi-disciplinary character of water operations.

The primary aim of developing our utilities into a higher level of smart operation is to ensure not only that the water system is operated more efficiently but also adapting to the environment and the human society in a sustainable fashion. We ought to try to understand our human infrastructure systems as an integral part of the nature we inhabit. We need to sense our environment, our systems and our usage to make sure that the three systems are working in synchronicity. Indeed, we must think in terms of 'partnership with nature' – sustaining, preserving, restoring and learning from nature in all our operations with water. This is not in conflict with the original aim of applying instrumentation, control and automation (ICA) to make operations less expensive. It is a much loftier goal to reach true sustainability and the task is much more complex, requiring a deeper understanding of our infrastructure systems, the natural physical and biological systems they interact with, and our usage.

We should think in terms of feedback at all levels, from the equipment to high-level management and strategic decisions. Also, note that feedback should be used to ensure our continuous learning. When we troubleshoot and implement the wrong solutions occasionally, we should use 'feedback thinking' to find a way to learn from our experiences. The framework is always the same, whereas the measurements, the analysis and the decisions are different. This involves:

- Making use of huge amounts of data,
- Analysing the data to become reliable and useful information,
- Exhausting the possibilities with digital communication,
- Using the potential of control and decision methods at all levels of the operation.

It is also still true many years into the future: water is life and we must treat it wisely. As we said more than two decades ago and it should still be kept in mind (Olsson and Newell, 1998), 'Our societies will need clean water and clean air. Sustainability will not only be a matter of cost. In fact, it is already a matter of survival in some countries. What role will ICA play in this development and how can we meet that challenge?' This is our challenge for years to come.

REFERENCES

Ahm M., Thorndahl S., Nielsen J.E. and Rasmussen M.R. (2016). Estimation of combined sewer overflow discharge: a software sensor approach based on local water level measurements. *Water Science and Technology,* 74(11), 2683-2696.

Åmand L., Olsson G. and Carlsson B. (2013). Aeration control - a review. *Water Science and Technology,* 67(11), 2374-2398.

Åmand L., Laurell C., Stark-Fujii K., Thunberg A. and Carlsson B. (2014). Lessons learnt from evaluating full-scale ammonium feedback control in three large wastewater treatment plants. *Water Science and Technology,* 69(7), 1573-1580.

Åström K.J. and Murray R.M. (2014). Feedback Systems: An Introduction for Scientists and Engineers. The complete book is available free of charge on the web, called FBSwiki http://www.cds.caltech.edu/~murray/amwiki/index.php/Main_Page (accessed 21 January 2020).

Batstone D.J., Keller J., Angelidaki R.I., Kalyuzhnyi S.V., Pavlostathis S.G., Rozzi A., Sanders W.T.M., Siegrist H. and Vavilin V.A. (2002). *Anaerobic Digestion Model No.1*. Scientific and Technical Report No.13, IWA Publishing, London.

Beck M.B (2005). Vulnerability of water quality in intensively developing urban watersheds. *Environmental Modelling & Software*, 20, 381-400.

Benedetti L., Langeveld J., Comeau A., Corominas L., Daigger G., Martin C., Mikkelsen P.S., Vezzaro L., Weijers S. and Vanrolleghem P.A. (2013). Modelling and monitoring of integrated urban wastewater systems: review on status and perspectives. *Water Science and Technology,* 68(6), 1203-1215.

Boe K. (2006). Online monitoring and control of the biogas process. PhD thesis, Danish Technical University (DTU). Available at https://backend.orbit.dtu.dk/ws/portalfiles/portal/127333186/-MR2006_055.pdf (accessed 20 January 2020).

Capodaglio A.G. and Olsson G. (2020). Energy issues in sustainable urban wastewater management: use, demand reduction and recovery in the Urban Water Cycle. *Sustainability 2020*, 12, 266; doi:10.3390/su12010266.

Corominas L., Garrido-Baserba M., Villez K., Olsson G., Cortés U. and Poch M. (2018). Transforming data into knowledge for improved wastewater treatment operation: A critical review of techniques. *Environmental Modelling and Software,* 106, 89-103.

Flores X., Comas J., Roda I.R., Jiménez L. and Gernaey K.V. (2007). Application of multivariable statistical techniques in plant-wide WWTP control strategies analysis. *Water Science and Technology,* 56(6), 75-83; DOI: 10.2166/wst.2007.586.

Gernaey K.V., Nielsen M.K., Thornberg D., Höök B., Munk-Nielsen T., Ingildsen P. and Jørgensen S.B. (2004). First principle suspended solids distribution modelling to support ATS introduction on a recirculating WWTP. *2nd Int. IWA Conference on Automation in Water Quality Monitoring*, Vienna.

Grum M., Thornberg D., Christensen M.L., Shididi S.A. and Thirsing C. (2011). Full-scale real time control demonstration project in Copenhagen's largest urban drainage catchments. In Proceedings of the 12th International Conference on Urban Drainage, Porto Alegre, Portugal.

Hadjimichael A., Comas J. and Corominas L. (2016). Do machine learning methods used in data mining enhance the potential of decision support systems? A review for the urban water sector. *AI Commun*. 29, 747–756. doi:10.3233/AIC-160714.

Haimi H., Mulas M., Corona F. and Vahala R. (2013). Data-derived soft-sensors for biological wastewater treatment plants: an overview. *Environmental Software & Modelling*, 47, 88-107.

Hamouda M.A., Anderson W.B. and Huck P.M. (2009). Decision support systems in water and wastewater treatment process selection and design: a review. *Water Science and Technology,* 60(7), 1757-1770; DOI: 10.2166/wst.2009.538.

Henze M., Gujer W., Mino T. and van Loosdrecht M.C.M. (2000). *Activated Sludge Models: ASM1, ASM2, ASM2d and ASM3*. Scientific and Technical Report No. 9, IWA Publishing, London.

Ingildsen P. (2002). Realising full-scale control in wastewater treatment systems using in situ nutrient sensors. PhD thesis, Dept. of Ind. Electrical Engineering and Automation (IEA), Lund University, Lund. Available at https://www.iea.lth.se/publications/Theses/LTH-IEA-1030.pdf (accessed 20 January 2020).

Ingildsen P. and Olsson G. (2016). *Smart water utilities*. IWA Publications, London.

Irizar I., Alferes J., Larrea L. and Ayesa E. (2008). Standard signal processing using enriched sensor information for WWTP monitoring and control. *Water Science and Technology,* 57(7), 1053-1060; DOI: 10.2166/wst.2008.139.

ISO (2003). *ISO15839:2003 Water Quality – On-line sensors/analysing equipment for water – Specifications and performance tests*. First edition. International Standard Organization.

Jimenez J., Latrille E., Harmand J., Robles Martínez Á., Ferrer Pol J., Gaida D. and Wolf C. (2015). Instrumentation and control of anaerobic digestion processes: a review and some research challenges. *Reviews in Environmental Science and Biotechnology*, 14(4), 615-648. doi:10.1007/s11157-015-9382-6.

Jinguara R.M. and Kamusoko R. (2017). Methods for determination of biomethane potential of feedstock: a review. *Biofuel Research Journal,* 14, 573-586.

Lennox J. and Rosen C. (2002). Adaptive multiscale principal components analysis for online monitoring of wastewater treatment. *Water Science and Technology*, 45(4-5), 227–235.

Leonhardt G., Fach S., Engelhard C., Kinzel H. and Rauch W. (2012). A software-based sensor for combined sewer overflows. *Water Science and Technology,* 66(7), 1475–1482.

Liu J. (2003) Instrumentation, Control and Automation in Anaerobic Digestion. PhD thesis, Dept Biotech., Lund University, Lund. https://lup.lub.lu.se/search/publication/466476 (accessed 20 January 2020).

Liu J., Olsson G. and Mattiasson B. (2004) Control of an Anaerobic Reactor towards Maximum Biogas Production, *Water Science and Technology*, 50(11), 189-198.

Liu J., Strömberg S. and Nistor M. (2019). How standardization and automation of lab equipment could help biogas research. Available at https://www.bioprocesscontrol.com/media/2132/how-standardization-and-automation-of-lab-equipment-could-help-biogas-research.pdf (accessed 20 January 2020).

Lumley D. (2002). On-line instrument confirmation: how can we check that our instruments are working? *Water Science and Technology*, 45(4-5), 469–476.

Mannina G., Ekama G., Caniani D., Cosenza A., Esposito G., Gori R., Garrido-Baserba M., Rosso D. and Olsson G. (2016). Greenhouse gases from wastewater treatment – a review of modelling tools. *Journal Science of the Total Environment*, 551-552, 254-270.

Nielsen M.K., Carstensen J. and Harremöes P. (1996). Combined control of sewer and treatment plant during rainstorm. *Water Science and Tech*nology, 34(3-4), 181-187.

Nowak O., Keil S. and Fimml C. (2011). Examples of energy self-sufficient municipal nutrient removal plants. *Water Science and Technology,* 64(1), 1-6.

Olsson G. (2012). ICA and me – a subjective review. *Water Research,* 46(6), 1585-1624.

Olsson G. (2015). *Water and energy – threats and opportunities*, 2nd edition. IWA Publications, London.

Olsson G., Eklund K., Dahlqvist K.I. and Ulmgren L. (1973). Control Problems in Wastewater Treatment Plants. (Research Report TFRT-3064). Department of Automatic Control, Lund Institute of Technology, Sweden. Available at http://portal.research.lu.se/portal/files/4620667/8726145.pdf (accessed 20 January 2020).

Olsson G. and Newell R.B. (1998). Talking of RAS - Reviewing, Assessing and Speculating), Final address at the 7th IAWQ Symposium on ICA, Brighton, UK, July 1997, *Water Science and Technology,* 37(12), 397-401.

Olsson G. and Newell B. (1999). *Wastewater Treatment Systems. Modelling, Diagnosis and Control*. IWA Publishing, London.

Olsson G., Nielsen M.K., Yuan Z., Lynggaard-Jensen A. and Steyer J.P. (2005). *Instrumentation, Control and Automation in Wastewater Treatment Systems*. Scientific and Technical Report No.15, IWA Publishing, London.

Olsson G., Carlsson B., Comas J., Copp J., Gernaey K.V., Ingildsen P., Jeppsson U., Kim C., Rieger L., Rodríguez-Roda I., Steyer J.-P., Takács I., Vanrolleghem P.A., Vargas Casillas A., Yuan Z. and Åmand L. (2014). Instrumentation, Control and Automation in wastewater – from London 1973 to Narbonne 2013. *Water Science and Technology,* 69(7), 1373-1385. doi: 10.2166/wst.2014.057.

Olsson G., Åmand L., Rieger L. and Carlsson B. (2019a). Aeration control – fundamentals. Chapter 4 in *Aeration, mixing and energy. Bubbles and sparks.* (D. Rosso, editor), IWA Publishing, London.

Olsson G., Åmand L., Rieger L. and Carlsson B. (2019b). Aeration control – implementation. Chapter 5 in *Aeration, mixing and energy. Bubbles and sparks.* (D. Rosso, editor), IWA Publishing, London.

Rauch W. and Harremoës P. (1996a). The importance of the treatment plant performance during rain to acute water pollution. *Water Science and Technology*, 34(3-4), 1-8.

Rauch W. and Harremoës P. (1996b). Minimizing acute river pollution from urban drainage systems by means of integrated real time control. *Proc. 1st Int. Conf. On New/Emerging Concepts for Rivers (RIVERTECH '96)*, 22-26 September, Chicago US.

Racault Y., Stricker A.-E., Husson A. and Gillot S. (2011). Monitoring the variations of the oxygen transfer rate in a full-scale membrane bioreactor using daily mass balances. *Water Science and Technology,* 63(11), 2651–2657.

Rodriguez-Roda I., Sànchez-Marrè M., Comas J., Baeza J., Colprim J., Lafuente J., Cortés U. and Poch M. (2002). A hybrid supervisory system to support WWTP operation: implementation and validation. *Water Science and Technology,* 45(4-5), 289-297.

Rosen C. and Olsson G. (1998). Disturbance detection in wastewater treatment systems. *Water Science and Technology*, 37(12), 197–205.

Rosen C. and Lennox J.A. (2001). Adaptive and multiscale monitoring of wastewater treatment operation. *Water Research*, 35(14), 3402–3410.

Rosen C., Röttorp J. and Jeppsson U. (2003). Multivariate on-line monitoring: challenges and solutions for modern wastewater treatment operation. *Water Science and Technology,* 47(2), 171–179.

Rosen C., Ingildsen P., Guildal T., Nielsen M.K., Jacobsen B.N. and Ønnerth T. (2004). On-line estimation of nitrification and denitrification capacity at Avedøre wastewater treatment plant. *Proc. Int. Conf. Upgrading of Wastewater Treatment Plants (AquaTech2004)*, 30 September-1 October, Amsterdam.

Rosen C., Ingildsen P., Guildal T., Nielsen M.K., Munk-Nielsen T., Jacobsen B.N. and Thomsen H. (2006). Introducing biological phosphorous removal in an alternating plant by means of control – a full scale study. *Water Science and Technology*, 53(4-5), 133-141.

Ruiz M., Sin G., Berjaga X., Colprim J., Puig S. and Colomer J. (2011). Multivariate Principal Component Analysis and Case-Based Reasoning for monitoring, fault detection and diagnosis in a WWTP. *Water Science and Technology*, 64(8), 1661–1667.

Schütze M., Butler D. and Beck M.B. (1999). Optimisation of control strategies for the urban wastewater system – an integrated approach. *Water Science and Technology*, 39(9), 209-216.

Seggelke K., Löwe R., Beeneken T. and Fuchs L. (2013). Implementation of an integrated real-time control system of sewer system and waste water treatment plant in the city of Wilhelmshaven. *Urban Water Journal*, 10(5), 330-341.

Steyer J.P., Buffiére P., Rolland D. and Moletta R. (1999). Advanced control of anaerobic digestion processes through disturbances monitoring. *Water Research,* 33(9), 2059-2068.

Vanrolleghem P., Fronteau C. and Bauwens W. (1996a). Evaluation of design and operation of the sewage transport and treatment system by an EQO/EQS based analysis of the receiving water immission characteristics. *Proc. WEF Conf. Urban Wet Weather Pollution*, 16-19 June, Québec, 14.35-14.46.

Vanrolleghem P.A., Jeppsson U., Carstensen J., Carlsson B. and Olsson G. (1996b). Integration of wastewater treatment plant design and operation - a systematic approach using cost functions. *Water Science and Technology,* 34(3-4), 159–171.

Villez K., Ruiz M., Sin G., Colomer J., Rosen C. and Vanrolleghem P.A. (2008). Combining Multiway Principal Component Analysis (MPCA) and clustering for efficient data mining of historical data sets of SBR processes. *Water Science and Technology*, 57(10), 1659–1666.

Villez K., Rosen C., D'hooge E. and Vanrolleghem P.A. (2010). Online phase length optimization for a sequencing batch reactor by means of the Hotelling's T2 statistic. *Industrial & Engineering Chemistry Research,* 49, 180–188.

Weijers S.R., De Jonge J., Van Zanten O., Benedetti L., Langeveld J., Menkveld H.W. and Van Nieuwenhuijzen A.F. (2012). KALLISTO: cost effective and integrated optimization of the urban wastewater system Eindhoven. *Water Practice and Technology*, 7(2), 1-9.

Yuan Z. and Blackall L. (2002). Sludge Population Optimisation, A New Dimension for the Control of Biological Wastewater Treatment Systems. *Water Research,* 36 (2), 482-490.

Yuan Z., Olsson G., Cardell-Oliver R., Van Schagen K., Marchi A., Deletic A., Urich C., Rauch W., Liu Yanchen and Jiang Guangming (2019). Sweating the assets – the role of instrumentation, control and automation in urban water systems. *Water Research*, 155, 381-402.

NOMENCLATURE

Abbreviation	Description
AD	Anaerobic digestion
ATS	Aeration tank settling
BOD	Biological oxygen demand
DO	Dissolved oxygen
ICA	Instrumentation, control and automation
IWA	International water association
PI	Proportional-integral
PID	Proportional-integral-derivative
SCADA	Supervisory control and data acquisition
SRT	Sludge retention time
VFA	Volatile fatty acid

Figure 15.16 Detail of measuring and control system of activated sludge aeration tank (photo: D. Brdjanovic).