Plant-wide control: dream, necessity or reality?

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Abstract Instrumentation, control and automation (ICA) are key technologies in modern water and wastewater systems. Despite the variability of the influents the system outputs have to be satisfactory. Economic realities and new water directives encourage the application of ICA to make a maximum use of plant and other storage capacities. The final goal of protecting the environmental resources necessitates an integrated view of several interdependent systems, including the collection, transport and treatment processes. In this integrating development ICA will be a decisive technology.

Keywords Control; integration; modelling; plant-wide; sewer; computer control

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Introduction

There are several driving forces that motivate the challenge to integrate all wastewater operations in a drainage area. From a European perspective the need for integrated modelling and control has increased dramatically by the EU-Water Framework Directive (WFD, 2000), which forms a basis for water policy for the EU and associated countries. The system boundaries are extended to include river management at a basin scale as well as point source and diffuse source pollutions. The WFD also promotes the reorganisation of existing water authorities into more all-embracing entities.

Instrumentation, control and automation (ICA) play an important role for the integration and concepts such as *integrated* control, *system-wide* control and *plant-wide* control are often mentioned. Both the sewer system (as combined sewer flows, CSOs) and the WWTP have an impact on the receiving water, the former as discontinuous events and the latter on a continuous basis. Here, we define the concept of plant-wide control as the combined sewer and WWTP control and operation.

For the sewer the goal is to minimise the amount of CSO (Schilling, 1989). The aim of the control of the WWTP is to satisfy the effluent requirements while minimizing the operational costs (Olsson and Newell, 1999). During storm conditions these goals may be difficult to reach. It is obvious that the control of the sewer system – isolated from the WWTP operation – will lead to suboptimal solutions. If the goal of the sewer operation is to minimise the CSO the WWTP may soon be overloaded. The result of such an overload is firstly a short-term impact due to the increased effluent pollution. Then, a possible washout of organisms may cause long-term impact by making the WWTP operation less efficient during an extended period of time.

In order to implement plant-wide control the interactions between the system parts and their dynamic characteristics have to be understood. This includes choosing the best locations of sensors and actuators, which is the basis for the control structure. In the rest of the paper we will discuss the impact of ICA and some of the compromises that appear when integration of different unit operations is realised. Modern plant computer systems allow a wide distribution of control, but this is not always met by corresponding control structures. It is shown that integrated modelling reflects an increasingly high understanding

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of the complexity of the large systems, and some integrated control experiences are described.

ICA in wastewater treatment

ICA plays a major role to reach the operational goals of wastewater treatment, which has been recognised within the International Water Association (IWA) for more than 30 years. As described in a IWA state-of-the-art book (Olsson *et al.*, 2005) several aspects of ICA are identified: modelling, instrumentation, data collection, observation and monitoring, and control.

The timescales of wastewater treatment operations span a huge interval, from seconds and minutes to weeks and months. Generally speaking, the machines will dominate the fast timescales and human interaction will dominate the slower timescales. The human effectiveness in making assessments and decisions in the presence of incomplete and uncertain information needs to be considered. The traditional approach of plant control and automation is by "divide and conquer". Each unit process is considered to operate relatively independently from the others. The different timescales offer another way of decoupling. Working in the fast timescales we assume the slow processes are constant. Conversely, working in the slow timescales the fast phenomena can be approximated as infinitely fast.

Plant-wide computer systems

The concept of *plant-wide* has many interpretations. In some sense the information between the various unit operations of the plant or an infrastructure are interconnected. A plant real-time computer will play a key role to make plant-wide control possible. Many manufacturers and plant operation people refer to *plant-wide* as the ability to communicate between the plant parts, and here we refer to some key elements of plant-wide supervisory control.

Data collection, reporting and information sharing

A plant-wide solution can connect to hundreds or thousands of devices and collect critical data through a variety of high performance drivers as well as standard communication interfaces. Data distribution and communication architecture ensures that these data are provided to the user community, to other plant systems and to various databases.

Real-time visualization

The operator needs data transformed into useful information. The system should be able to make data available not only to control room screens but also to handheld portable devices. Alarm information can be sent to standard alphanumeric pagers or as SMS messages to mobiles telephones. No matter where operators, process engineers or managers are, in the plant or away from the plant, they wish to get relevant information.

Alarm management

A good supervisory control system should provide alarm functions that offer automatic responses ranging from alerting staff with messages on a screen, informing other process parts of relevant events, and paging the appropriate operator or engineer. An ideal alarm system should identify and solve potential problems before they occur.

Mobile and remote access

It is common that an operator can use a modem or a plant intranet to connect remotely for alarm reporting and checking plant status. Using the same connection, operators and managers can remotely check the operational status and/or make system modifications. Recent innovations have increased the reach of remote capabilities. Handheld computers with a wireless local area network (LAN) connection and human–machine interface (HMI) software allow operators and maintenance personnel access to alarms and control points from anywhere within the plant to improve reaction time and operator flexibility. Casual users may access security-cleared areas of the control system through the internet using industry standard browsers. This means that the virtual control room is here. Consequently, operational control and command centres, where a group of experts are available around the clock to assist in the operation of wastewater systems within an entire region in case of emergencies, may be the next logical step.

Open architecture

For decades, supervisory systems were proprietary, meaning that manufacturers produced components that only worked within a single family. Today, many devices are designed with an open architecture. The controllers, I/O and buses are built to accommodate third-party modules and to integrate easily for fast setup. This feature gives facilities the freedom to choose the best and latest technologies from manufacturers without having to stay within product lines or fear product obsolescence.

Integrated automation systems

An integrated automation system should closely link together the process control with other automation applications, essential to the system performance. This includes engineering, documentation, quality control (of all components and operations), safety, instrumentation, asset and maintenance management. All these aspects of information ought to be accessed and modified from a single location. Also, an integrated framework means that all controllers are programmed and configured in the same way. The data models in the system are the same and the system provides a natural link between the plant operation and the management system.

Control structures

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 ultimate goal is to formulate some criterion for the receiving water and its ecological quality while satisfying various economic and technical constraints. There is a great 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. This is not yet solved satisfactorily, but promising research is in progress, such as the EU research project CD4WC (2005). Models are being developed to find strategies dynamically to find maximum WWTP loading according to continuous monitoring and prediction of the operational state. One example is maximising 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 maximised.

All integration means some kind of compromise. If there were no interactions, then the individual optimisation of each subprocess would be the best strategy. Having couplings in reality we aim at a better result, than if each one of the processes were controlled separately. This is the essence of a multicriterion index: various performances are weighted and compared with each other. Let us illustrate the idea with some examples:

- The interaction between the aerator and the settler is a classical integration problem, reflected in the compromise that has to be done in return sludge flow rate control.
- The anoxic zone in a pre-denitrifying plant interacts closely with the nitrifying aerator. Oxygen-rich water is recirculated from the aerator to the anoxic zone. The DO level has to be a compromise between sufficiently good nitrification and denitrification.
- There is interplay between serially linked processes. For example, a chemical pre-precipitation in a primary settler will remove not only phosphates but also particulate organic material. This will save 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 the sludge treatment are most often highly concentrated in nutrients and have to be synchronised 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 synchronised 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 maximise the methane production, while at other plants the sludge production needs to be minimised.
- In the combined sewer and WWTP operation the individual system operations are sometimes in conflict, so the overall goal of minimising the load to the receiving water has to overrule the individual goals (Vanrolleghem *et al.*, 1996; Rauch and Harremoës, 1996a; Schütze *et al.*, 1999). An early approach to integrated control was published by Rauch and Harremoës (1996b).

Operational objectives

Plant-wide control means that boundary conditions are defined, both what is possible to manipulate and how the performance criterion is formulated. If a WWTP is controlled independently of the sewer system, then the plant influent flow rate is an external disturbance. If, however, the sewer and plant are controlled together, then the influent flow rate becomes a manipulated variable and the external disturbances are now located further upstream.

It should be noted that a “plant-wide” computer system does not imply what we mean with plant-wide control. The integrated computer system, however, gives the *necessary information infrastructure* for such control. The traditional WWTP control is still unit-process oriented to a great extent. Some examples of state-of-the-art control (see further Olsson *et al.*, 2005) can be mentioned:

- DO control with a constant or a variable setpoint is part of the aerator unit process operation.
- Aeration phase-length control in alternating plants is based on nutrient sensors, but still locally.
- Nitrate recirculation control in a pre-denitrification plant can be based on nitrate and DO measurements in the aerator and in the anoxic zone.
- Advanced sludge retention time control is based on local measurements of effluent ammonia concentration and of estimates of nitrification capacity.
- Return sludge control is based on measurements in the settler.

- Aeration tank settling (ATS) is one way of temporarily increasing the plant capacity at storm conditions (Nielsen *et al.*, 1996; Gernaey *et al.*, 2004).
- The control of anaerobic processes aims at regulating the biogas flow, at stabilising the process and at maximising its productivity. Still current state-of-the-art focuses on unit process operation.
- Successful chemical precipitation control can be based on local measurements of phosphate concentration.

The examples illustrate that a plant-wide computer system does not necessarily indicate controllers that are based on measurements in one part of the plant system to manipulate actuators in another part of the system. The information and communication are plant-wide, thus allowing the virtual control room, but mostly the controllers relate to one unit process.

A plant-wide control system will assume that all the different unit processes are controlled locally. On top of that 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 1.

Integrated modelling

An urban drainage system includes three major components: the sewer system, the wastewater treatment plant and the receiving water. Integrated modelling can be defined as modelling of the interactions between two or all of these. During the last 25 years, mathematical models describing the behaviour of each individual system have evolved considerably (see e.g. Ashley *et al.*, 1999; Henze *et al.*, 2000; Reichert *et al.*, 2001; Batstone *et al.*, 2002). However, they generally describe the performance of each process according to its own needs and objectives. The issue of integrating the models on a larger scale is more recent (e.g. Schütze *et al.*, 1996, 1999; Fronteau *et al.*, 1997; Mark *et al.*, 1998; Rauch *et al.*, 2002). The obvious purpose of such an approach is to allow for assessment,

Table 1 The objectives, measurements and control handles for a combined sewer–wastewater treatment system operation

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

prediction, evaluation and possibly control of the entire system and thereby optimise (or at least avoid to suboptimise) the quality of the receiving water while minimising the overall treatment cost.

Calibration of integrated models is a complex task. The individual submodels should first be calibrated and validated individually and thereafter the complete model should be tested and validated for the specific situation. Measuring campaigns to support such individual and holistic identification are expensive and time-consuming as there are both temporal and spatial dimensions to consider (Mark *et al.*, 1998; Vanrolleghem *et al.*, 1999; CD4WC, 2005). However, in many cases the primary need is to identify relative differences between different operational scenarios. Then a much higher degree of uncertainty with regard to the detailed absolute predictions is acceptable and "default" model parameter values can often be assumed. Moreover, it is often not necessary to model all types of behaviour and impacts but rather focus on the dominating ones for the specific purpose of the investigation. The most complex model is not the best one; instead, the least complex model describing accurately the most important effects represents the best.

Although the main water quality processes for all aquatic systems are similar – water motion, transport and conversion of matter – model integration is not an easy task. Incompatibility problems related to state variables and model parameters and how these are interpreted (internal composition, etc.) in the different models complicate the reconciliation process. Conversion factors, transformers and model interfaces are almost always required and too often the mass balances are not maintained during these transformations. The recent River Water Quality Model no. 1 (RWQM1, Reichert *et al.*, 2001) was developed with the intended aim of compatibility with the family of activated sludge models (Henze *et al.*, 2000) to allow for integrated analysis. According to the RWQM1 authors, integration can be done but requires "some major assumptions" and "the work needed in order to do this is significant". It should be simpler to at least integrate the wastewater and sludge treatment within a WWTP? For the new Anaerobic Digestion Model no. 1 (ADM1, Batstone *et al.*, 2002), a rudimentary model interface only to ASM1 is outlined. Consequently, two alternative approaches have already been published (Copp *et al.*, 2003; Vanrolleghem *et al.*, 2005), where the first one represents a non-complex way of interfacing the specific models and the second (further extended in Zaher *et al.*, 2005) is a general protocol of how to interface models defined by Petersen matrices. The methodology defined in the latter will allow for model developers to define detailed model interfaces already when the model is created and could hopefully alleviate the reconciliation problem in the future.

The traditional deterministic modelling approach is still dominating. However, in many cases the underlying processes are truly stochastic or too complex for a stringent deterministic description. Alternative approaches, such as grey-box and stochastic models (Harremoës and Madsen, 1999) and models based on Bayesian techniques (Reichert, 1997) may certainly prove useful for integrated modelling. In principle, any model simulation results should always be accompanied by sensitivity and uncertainty analyses. Also, different types of risks and qualitative effects (e.g. foaming, rising sludge) can be included by means of logical and fuzzy modelling to extend the predictive capability of mechanistic models (Comas *et al.*, 2006).

Currently, a few software tools, e.g. SIMBA® (ifak system GmbH, Germany), WEST® (Hemmis N.V., Belgium), MIKE URBAN (DHI Water & Environment, Denmark), are available which allow the urban wastewater system to be considered as one single system to carry out parallel simulations.

Examples of plant-wide control

In plant-wide control the wastewater treatment plant influent is no longer an external disturbance but an internal variable of the integrated system. There is a major challenge to predict the influent flow rate, and a generally available tool is still to be found. The deterministic modelling of settling and resuspensions of pollutants is still unreliable and not sufficiently accurate. However, by using the well-determined daily variations of flow rate and concentrations from the plant and the sewer system, it is possible to develop grey-box models with much better predictive capabilities than traditional models (Carstensen *et al.*, 1997; Bechmann *et al.*, 1999). The predicted flow rates can be calculated from pumping station data, i.e. electric current measurements and signals from a single pumping station are converted into flow rates. When using data from pumping station(s) placed in the catchment area of the plant instead of using rain gauges a major uncertainty in the calculations is avoided. Rain measurements normally only sample rain from a few hundred square centimetres, but a pumping station samples from an area of the order of a few hundred square metres. This means that the uncertainty from the rain distribution is much less using pumping station data compared with using rain measurements and makes the pumping station-based model more reliable for control during rain situations (Nielsen *et al.*, 2005). Some further examples of plant-wide control are described in Olsson *et al.* (2005, Chapter 11).

Integrated control

Reliable integrated models are essential for developing control strategies for the overall system. Real-time control should be used to minimise the impact of the urban water system on the receiving water. Controlling the sewer and the WWTP separately will enhance the performance of the system compared with the non-controlled case. An integrated approach could do even more. Rauch and Harremoës (1999) showed that minimising the total volume or pollution load, hence only looking at the emissions, does not guarantee the best resulting water quality. Besides the pollution load entering the river, also the timing and the location of the pollution entering the river may have a significant impact. The interactions between the WWTP, the sewer system and the receiving water as well as interactions between the wastewater and sludge treatment within a WWTP are important to consider from a control perspective.

Full-scale validation of integrated control is seldom accomplished. Normally a number of scenarios and strategies are tested by simulation. To allow for objective evaluation of proposed control strategies the existing COST/IWA Benchmark Simulation Model is currently being extended to include a complete WWTP (i.e. wastewater, sludge treatment and interactions between them, see Jeppsson *et al.*, 2006). Moreover, a simplified phenomenological model of a sewer system is also being added (Gernaey *et al.*, 2005), which will allow for more relevant integrated control evaluation.

Conclusions

We believe that the dream is becoming a reality. The goal is not to build up increasingly complex ICA systems. Quite the opposite: an ICA system has to be constructed in a systematic way so as to deal with the intricate couplings of a very complex process. These couplings appear between competing biological processes, between unit processes, between fast and slow reactions, between sewer systems and treatment plants and between the treatment plants and the receiving water. Integrated control is still in its infancy. The necessary condition of having a plant-wide computer information system is often satisfied. Now, the operation and control have to take advantage of the system-wide information and integrate the operation of one unit with other interacting system units. It will probably be a dominating development for the next decade. Then it may be considered also a necessity!

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