Integration of drinking water treatment plant process models and emulated process automation software

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Proefschrift

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Introduction

1.1 Introduction

Drinking water treatment in the Netherlands

The most striking changes since the introduction of a centralized drinking water system in the Netherlands in 1853 are the improvement of the water quality, the improvement of reliability of delivery, and the increase of efficiency (Groen, 1970). Unchanged is the setup of a centralized drinking water treatment system and the management's desire to limit the risks of contamination of the water and interruption of the delivery. Both aspects have yielded redundancy of installations, pipes, supporting systems and personnel.

The quality of Dutch drinking water has increased up to the level that zero Escherichia coli and Enterococcus bacteria are found in 100 ml of drinking water. For the majority of drinking water treatment plants in the Netherlands, the risk of getting infected by drinking unboiled water is less than one per 10,000 persons per year (Schijven and de Roda Husman, 2009). Source protection, double barriers in the treatment plants for disinfection, focus on producing biologically stable water and the high quality of the distribution networks allow Dutch water supply companies to limit or avoid chlorine dosage before distributing the water (Smeets *et al.*, 2008). The companies which use surface water as a source, remove organic micro pollutants with advanced oxidation, or consider to do so. The reliability of delivery is up to the level that an average Dutch household experiences the tap pressure being less than the common 200 kPa entering the house in less than 17 minutes per year of which more than 9 minutes as a consequence of planned maintenance (Geudens and van Beek, 2010).

The number of water supply companies in the Netherlands has decreased from 229 in 1937 to ten today (Geudens, 2012). As a consequence of the merging of companies and stimulated by a national financial benchmark of water supply companies which was introduced in 1997, the number of employees in the water supply sector has decreased, from 8449 full time equivalent in 1991 to 4893 in 2007 (Geudens, 2012). Figure 1.1 indicates that the Dutch drinking water sector has increased its efficiency as from 2000 to today; with less people, more mains and connections were managed. In the meantime, the level of annual investments by water supply companies in new and existing assets decreased from 419 M€ in 2000 to 323 M€ in 2008. But, the estimated level of investments needed to maintain the functions of assets is estimated to be 650 M€/year (van Eekeren, 2012). Has this increased efficiency and decreased level of investments in replacement of assets threatened the reliability of delivery or the water quality in the Netherlands? If so, the common redundancy in mains and installations, the multi barriers treatment and the common overcapacity to anticipate on unexpected growth of demand or calamities, have concealed the increased risk of worse performance. The increase of the number of employees since 2007, the increase of investments in the drinking water supply sector since 2008 up to 458 M€ in 2010 (Geudens, 2012) and the growing interest in asset management of installations and mains show that the sector aims to prevent the dark side of the efficiency coin. An increase of the drinking water price in the near future seems a logical and necessary consequence of this development.

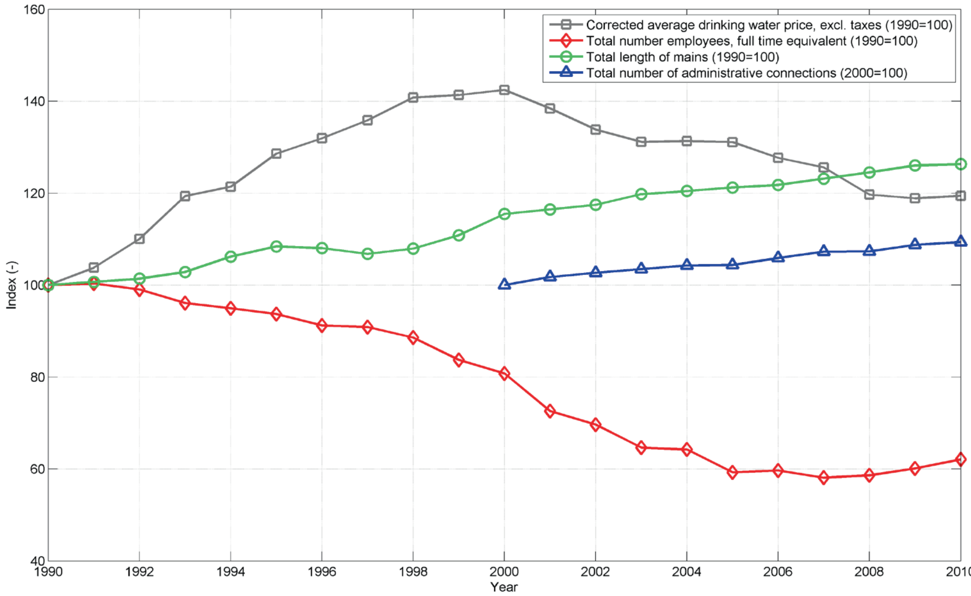

Figure 1.1. Developments in the Dutch drinking water supply sector. The indexed drinking water price (average of households and companies, corrected for inflation, all taxes excluded), the indexed total number of employees of water supply companies in full time equivalent, the indexed total length of drinking water transport mains, and the indexed number of administrative connections. Data derived from (Geudens, 2012).

Process automation

Striving of water supply companies for more efficiency has boosted the change from direct human control to remote multi-task supervisory control operation. Today, for some of the Dutch water supply companies the operation of the treatment plants is fully automated based on an office hours' watch. Apart from more efficiency, the drivers for the increasing presence of process automation (PA) are higher and more stable drinking water quality, higher endurance (automation systems can make 'endless' shifts), prevention of personal preferences, higher reliability and lower costs. As is common in other industrial plants, in drinking water treatment plants the PA-system consists of programmable logic controllers (PLCs). The first PLCs had the capability to control a local process whereas today PLCs are often interrelated and form DCSs (distributed control systems) with SCADA (supervisory control and data acquisition). To increase the robustness of the treatment plant these systems are set up hierarchically. When a single PLC or the communication between the PLCs fails the remaining PLCs will continue to control 'their' processes within the operational windows based on the last received setpoint(s) and/or measurement(s). Nowadays, advanced software is connected to PA-systems to calculate setpoints or to optimize processes, called MES (manufacturing execution systems) applications. Each automation system has a graphical user interface or human-machine interface (HMI) to read from the system. Control data and measurements are stored in a database, called a historian. Figure 1.2 shows a typical setup

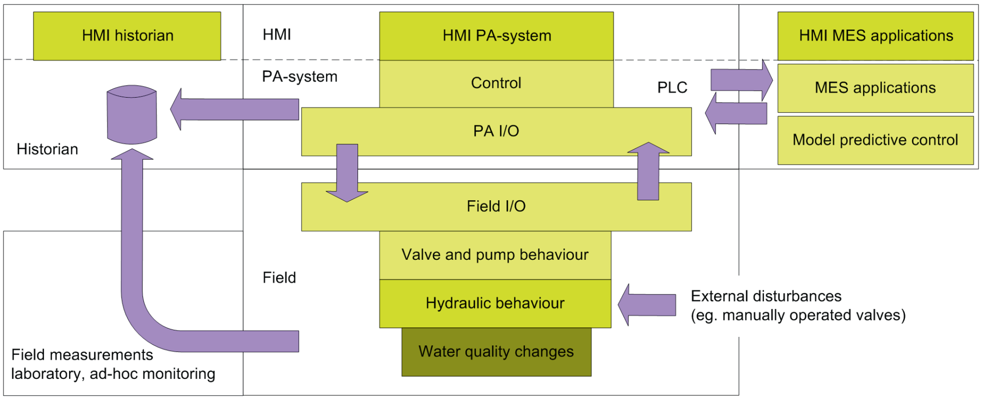

Figure 1.2. Typical setup of a PA-system, the field, the human-machine interface (HMI), the manufacturing execution systems (MES applications) and the historian containing data. I/O stands for input/output.

of a PA-system, the relation to the field, the HMI, the MES applications and the historian. In the Netherlands the ten water supply companies differ in their PA-strategy. Some companies select a PA-vendor each time a piece of automation is needed, other companies like PWN, Waternet and Dunea have long term commitments with a single PA-vendor. Some companies, like Waternet, use the software library of the PA-vendor. Other companies, like Dunea and PWN have developed their own.

Emulation of PA-software

Emulation of PA-software is the imitation of a PLC on a personal computer (PC), see Figure 1.3, in a way that the PA-software is not able to distinguish between the two environments. The virtual PLC is called a soft-controller. The drivers for this development are i) the increased complexity of the PA-software and the increased interaction between PLCs and ii) minimization of hardware costs. Especially in advanced treatment processes like membrane filtration, multiple interacting PLCs are active requiring mutual communication. Where the first emulation platforms, like Siemens' PLCSIM were able to emulate a single PLC on a PC, now multiple PLCs and their mutual communication can be emulated on a PC. The hardware alternative, multiple test PLCs connected via a network, requires more efforts to set up and manage and have higher investment costs. A relevant characteristic of the modern emulation platforms is the possibility to copy the PA-software from the field PLC to the soft-controller without changing the software at all, and vice versa. This saves time and limits the risk of errors as a consequence of changing the software during the transfer.

Process models

When studying the water quality and reliability of delivery, process models are valuable tools. Although drinking water treatment has a long history, the mathematical analysis for operational improvements of treatment processes and water distribution is still young. Process model Stimela was introduced in literature in 2002 (van der Helm and Rietveld, 2002),

Figure 1.3. Emulation of PA-software. A PC imitates a PLC, indistinctive for the PA-software.

the manual of EPANET was published in 2000 (Rossman, 2000). Using mathematical models to represent each treatment unit and connecting processes to represent entire water works, factors such as quality (good, constant and reliable), quantity, costs, environmental impact (low energy consumption and low green house gases emissions), design redundancy and flexibility can be evaluated and operational conditions can be optimized, using the existing infrastructure as efficiently as possible (Bosklopper *et al.*, 2004).

As described by Argent (2004), four level of process models' development and application can be distinguished. In Level I, a researcher develops a model for a specific purpose, often based on a particular problem at a particular scale or site. At the second level, these research-focussed models have shown to be more generally applicable to a range of problems at various sites or scales. As an example, the Stimela model for pellet softening, developed for application in the Weesperkarspel plant was validated with data from the Katwijk plant (van Schagen *et al.*, 2008). In the next level of development and application, Level III, it is responsible to apply the model to a wider range of situations because sufficient case studies are available. The model usefully describes some natural phenomenon at a level of detail with manageable data requirements. In drinking water treatment plants, Level III process models are used by technologists for process optimization (Rietveld *et al.*, 2008) and economic optimization (Douveneau *et al.*, 1997). Finally, in the fourth level, the model is removed from the original development, and becomes part of a bigger system, thus prolonging the lifetime of the models (Hass *et al.*, 2005). Examples are human-in-the-loop simulators or a soft sensor as PWN is implementing for the pellet size distribution in the pellet softening reactors at treatment plant Wim Mensink in Wijk aan Zee, owned and operated by PWN (van Schagen *et al.*, 2008).

In Level IV, advanced process and control models will interface with the PA-software, the treatment process will be monitored using on-line qualitative and quantitative indicators and innovative analysis techniques and (soft-) sensors will supply comprehensive information necessary to make control decisions. Real-time performance indicators will constantly evaluate the effectiveness of each process (Rosen, 2000; Trussell, 2000).

Human roles in fully automated operation

In fully automated operation of drinking water treatment plants, three types of employees are involved in working with PA-systems and process models, i) technologists, ii) operation supervisors, and iii) control or application engineers. Before explaining the possible interest of these employees in the integration of process models and PA-emulation, these three roles are further elaborated.

Technologist. Technologists can be either 'traditional' academic civil, chemical or process technology engineers who design drinking water treatment plants, deal with long term and often multidisciplinary problems in the treatment, or process engineers who deal with daily problem solving and optimization of the treatment processes. Both determine the design and operational windows of the treatment units and are the first line help for operation supervisors to deal with or prevent upsets in the treatment plant. Apart from being end-user of integrated process models and PA-emulation, the academic technologist contributes in setting up, calibrating and validating the process models.

Operation supervisor. With a more advanced control, the number of sensors, actuators and hardware and software for control and communication, has increased. More advanced control opened the gate to the centralization of the control of multiple treatment plants and to an increase of the plants' capacities, thus increasing the span of control of the operators. In fact, at modern drinking water supply companies, the operator has evolved into an operation supervisor. He is involved in several tasks related to the drinking water treatment and distribution process; inspecting the treatment plant and PA-system, shutting down and starting up parts of the plants for reasons of maintenance or upsets, and advise during renovation of existing installations or building of new ones. During his regular work an operation supervisor will rarely experience extreme situations with a possible major impact on the drinking water supply to customers. The impact of a human, mechanical or digital failure today is bigger compared to the historical situation with smaller or less pumping stations involved, because the numbers of affected customers is higher. As a consequence, the responsibility of the human operation supervisor has increased. At the same time, the most irregular or least frequent occurring tasks, e.g. operate when two or more pieces of equipment have failed simultaneously, have not been automated for economic and maintenance reasons. These tasks need to be executed by the operation supervisor who, as a consequence of automation, lacks regular hands-on training. In the mean time, fully automated operation does not change the fact that the operation supervisor is responsible for the drinking water delivery (Wu *et al.*, 2009) from source to tap, in terms of quantity, quality and pressure.

Today, in the Netherlands, operation supervisors of drinking water treatment plants are in their forties or fifties. At PWN in 2011 the youngest operation supervisors were 42 years old, 23% of the 17 supervisors were between 41 and 45 years old, 35% between 46 and 50 and the rest older than 51 years old. While the operators of today have grown into fully automated operation gradually, the next generation of operation supervisors will lack background knowledge of the behavior of the treatment and distribution processes. At this moment at PWN, it takes two years of education and training (on the job) to become an independent operation supervisor.

Control engineer. The control or application engineer designs robust and optimal control of (the interaction between) treatment units. Optimal can be related to water quality, energy use, chemical use and/or any other objective. Often control engineers are active in multiple application areas and as a consequence, unlike technologists, they are less interested in the objective of the treatment process itself, but rather in the parameters that influence or disturb this objective.

Integration of process models and PA emulation

To add the plant's 'behavior' to an emulated PA-system, a limited number of input/output (I/O) signals of the emulated PA-system are connected to process models, see Figure 1.4. When Figure 1.5 is compared with Figure 1.2 it can be seen that an emulated PA-system with integrated process models has a similar set up as a PA-system and the plant. In fact, this setup is a high fidelity representation of the drinking water treatment plant and its PA-system. The value of the integration of process simulation and PA emulation is expected in three areas, i) optimization of process control by technologists, ii) training of operation supervisors, and iii) virtual commissioning of PA-software by control engineers.

Figure 1.4. Process models connected to the emulated PA-software. The 'behavior' of the plant is added

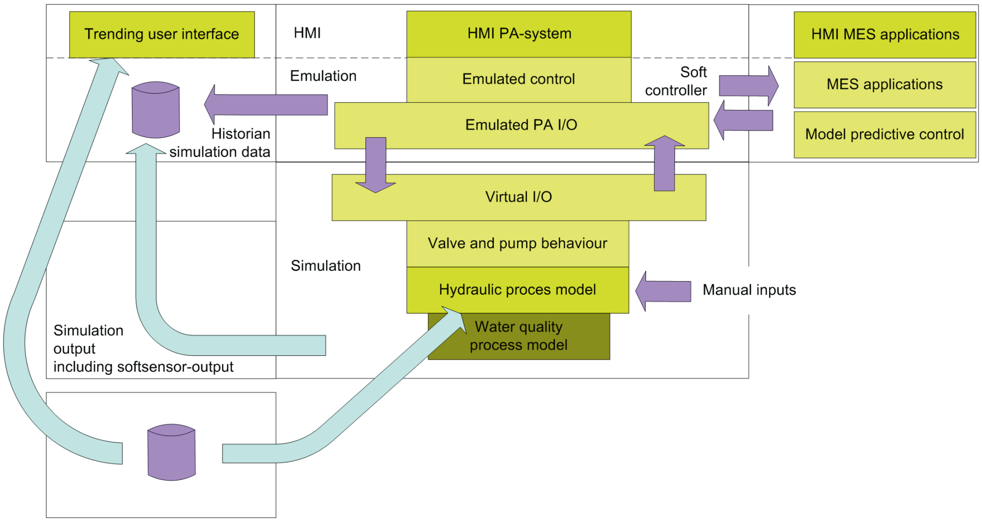

Figure 1.5. The virtual representation of the PA-system and field. HMI is human machine interface, MES is the manufacturing execution system, I/O stands for input/output.

Optimization of process control by technologists. The most basic form of process control optimization is changing parameters in the field installation, which comes with the risk of disturbing the process instead of improving it. To prevent this risk, optimization of the process control can be done in a separate installation, an expensive solution. Costs can be saved by limiting the scale of the pilot installation, but then the risk of unexpected effects is introduced when transferring the optimized control to the full-scale installation. Today, process models can be used to evaluate and optimize process control systems (Stare *et al.*, 2007; Vrecko *et al.*, 2006) leaving the need for a physical (pilot) installation behind. The optimization can be done in a stand-alone system by embedding a control file to the process model (van der Helm *et al.*, 2009) or by comparing control strategies in an advanced virtual commissioning (AVC) system. An advantage of the latter would be that the optimized control strategy can be uploaded to the field PLC 'with a single click'.

Training of operation supervisors. Most often the process automation is working well, which may make operators inattentive (Bruzzone *et al.*, 2007; Olsen and Rasmussen, 1989). But when a calamity occurs, the operator needs to process a large amount of information. In this case, the operator first may have to reclaim control and stabilize the process and then diagnose and solve the fault. For the former he will need most manual skills, for the latter cognitive skills. To be able to generate alternative strategies for the unusual situation and to be able to check proper functioning of protective rules in the automation system, the operator needs to have in-depth knowledge of the process. Efficient retrieval of this knowledge depends on the frequency of use of this knowledge (Bainbridge, 1983).

The emulated PA-system integrated with process models can be used as a high fidelity, PC-based, human-in-the-loop training simulator. Human-in-the-loop simulators are widely used for decision support, training and assessment (Sheridan, 2002), as well as for knowledge elicitation (Edwards *et al.*, 2004) in applications such as aviation (Salas *et al.*, 1998), medical education (Scalese *et al.*, 2007), car driving (de Winter *et al.*, 2009), and defence (Hone and Morrison, 1997). A high fidelity (i.e. close to reality) human-in-the-loop simulator can help to i) get acquainted with manual controlling from a distance, ii) experience the response of the PA-system to extreme conditions and iii) increase the understanding of the processes and PA-system in general. All these aspects will contribute to fewer mistakes (Beltz, 2012) in the rare critical situations, thus limiting the risks as desired by the management.

The need for a human-in-the-loop training simulator in drinking water treatment has not yet been felt, because the treatment processes are relatively slow and short term risks are limited. This will change because the public becomes less tolerant for interruption of the delivery of gas, drinking water and electricity and because the impact of failures has increased with the increased span of control of the operation supervisors. Furthermore, the increased use of automation has led to alienation of the human operator from the process (Sheridan, 2002) and to a change in the necessary skills and knowledge of operators (Bainbridge, 1993). Finally, the increased availability of user friendly and powerful emulation software and process models have made it economically feasible to increase the efficiency of operation supervisors' education, training and assessment.

Virtual commissioning of PA-software by control engineers. Traditional PA-software testing consists of a factory acceptance test (FAT) followed by a site acceptance test (SAT) in the plant. To start the FAT, the new software is uploaded to a physical PLC in an offline environment. The I/O signals are simulated with physical switches, with a tailor made tool, for example programmed in Visual Basic or within the tested PA-software itself. Possibly tags need to be renamed for testing. The possibilities to connect test-PLCs mutually are limited, making it hard to test the communication between PLCs and functions with interactions between multiple PLCs as is often the case in practice. A single HMI client is available for navigation. Sometimes new PA-software is extended with code exclusively for the reasons of simulation during testing. These code lines are removed or disabled, before the upload to the PLC in the plant. During the SAT the plant or treatment step is out of operation or operated manually. The FAT aims to minimize the SAT time, by limiting the risks of unexpected or undesired situations. Moreover, the FAT gives opportunity to expose the new software to extreme situations like power breakdowns or hardware failures which, most probably and preferably, will not occur during the SAT.

A recent development in the process automation software engineering is virtual commissioning (VC) instead of the traditional FAT (Reinhart and Wünsch, 2007). VC is the testing of software in a near-reality situation, using multiple virtual PLCs (often called soft-controllers), multiple HMI-clients possibly covering different hierarchical automation levels, emulated PA-software and dynamic virtual I/O. The virtual I/O is standardized and might be dynamic since the virtual signals can be ramped or delayed. A relevant recent development is that vendors of PA-systems like Siemens and ABB offer emulation platforms like (respectively) Simit and 800xA Simulator which can test PA-software in an emulation without needing to change the software when transferring from PLC to the emulation platform, and vice versa.

Still, VC can not replace the SAT. The crucial difference is the lack or limited presence of the behavior of the process in the VC setup. To compensate for this deficiency, process models can supply dynamic and realistic values to online measurements. AVC is VC with the addition of process models. It can be realized in three steps. The first step is the addition of basic parameter relations to the VC platform, e.g. to write a value on a virtual input signal of flow when the virtual output signal of a pump-speed changes from zero to any positive value. Since flow through a unit is an important parameter in terms of the unit's effectiveness (van Schagen *et al.*, 2006), the second step can be connection of a hydraulic model. To complete the process simulation of a drinking water treatment plant, the final step can be the connection of a water quality model. A robust interaction of the process models with the emulation of the PA-software requires a decent software design and traffic rules.

Objective

The objective of this research is to limit the risks of fully automated operation of drinking water treatment plants and to improve their operation by using an integrated system of process models and emulated PA-software. This thesis contains the design of such an integrated system. The use of the system is investigated in the three identified applications, i) optimization of process control, ii) training of operation supervisors and iii) virtual commissioning of PA-software. A supplementary objective is to increase the life time of the Stimela water quality models by transferring them to the fourth and final level of development (Argent, 2004).

1.2 This thesis

Chapters 2, 3 and 4 deal with the design of the integrated system of emulated PA-software and process models. Chapter 2 describes the software architecture of the system, Chapter 3 the set up and validation of the EPANET hydraulic model, and Chapter 4 the set up and validation of the Stimela water quality model. Chapter 4 also describes that with Stimela standalone, process control strategies can be evaluated and optimized, thus limiting the need to investigate the use of the integrated system for the same purpose. Chapter 5 describes the use of a basic version of the integrated system to train operation supervisors. Chapter 6 describes the use of the fully integrated system in virtual commissioning of PA-software. The following paragraphs describe the knowledge gaps which are dealt with in this thesis.

Software architecture. At the start of this research PWN was launching fully automated operation in the Netherlands and Dunea started to implement full automation, thus introducing the possible risk of insufficiently trained operation supervisors, the increased importance of efficient and robust control rules and the need for thorough PA-software testing. The knowledge gap identified in Chapter 2 is the design of a virtual representation of a drinking water treatment plant's PA-system, including simulation of its process' behavior. As far as the author is aware such a system did not exist yet, or was not reported yet in literature. The software architecture and the traffic rules between the different modules of the system are described.

Hydraulic model. Flow is a relevant parameter in the efficiency of treatment processes in drinking water treatment plants, but is often neglected in water quality modeling. Therefore, two process models simulate the process' behavior of the treatment plant, i) a hydraulic model and ii) a water quality model. In Chapter 3 the setup and validation of the hydraulic model is described, thus identifying the knowledge gap of the use of EPANET to model the (division of) flows in a drinking water treatment plant. EPANET is worldwide applied freeware to model water distribution networks, but lacks a library of representations of treatment units.

Water quality model and optimization of process control. Chapter 4 describes the set up and validation of the water quality model. Using this model the knowledge gap is filled how to select the optimal control strategy for a treatment unit when multiple control strategies meet the requirements and boundary conditions. Can Stimela process models be used to evaluate control strategies of drinking water treatment steps, which have been set up using the control-design methodology for drinking water treatment plants (van Schagen et al., 2010)? This stand-alone use of Stimela is a typical example of a Level III application (Argent, 2004).

Training. Chapter 5 describes how a stand-alone version of the system was used as a human-in-the-loop simulator to train operation supervisors. Stand-alone refers to the fact that the system was not integrated yet with the emulated PA-software, and that control rules and the GUI were embedded on the USE® platform. A large number of processes in drinking water treatment can be classified as slow, i.e. have a typical time scale of hours up to months. The residence time of water in a treatment plant (time in the reservoirs excluded) is approximately half an hour, a filter run of a rapid sand filter takes days, and the recovery of a disturbed fluidized bed in a pellet softening reactor can take tens of days. Humans are expected to have more problems controlling a process with a time scale of weeks to months than controlling a process with a typical time scale of minutes. Chapter 5 fills the knowledge gap whether training using accelerated simulation, improves the learning of operation supervisors in a human-in-the-loop simulator compared to training with real time simulation.

Virtual commissioning. In Chapter 6 the use of AVC using the fully integrated system is described for commissioning of new or modified PA-software. For water supply companies the expected decrease of errors in the software which appear during or after the site acceptance test is relevant. Never a single piece of PA-software was tested parallel in a virtual test environment with process models and in a virtual test environment with basic parameter relations. The results of this experiment are described, thus aiming to fill the knowledge gap of the benefits of the integration of process models to virtual commissioning test systems for PA-software.

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2

Integration of models, data management interfaces and training support in a drinking water treatment plant simulator

Based on

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Abstract

Water supply companies are gradually changing to centralized, fully-automated operations. The drivers for this change are the increase in efficiency and a better and more stable water quality. Fully-automated treatment plants will require more sophisticated operator care than manually operated plants, so operation supervisors should periodically train in a drinking water treatment plant simulator. But, a nearly realistic training simulator for drinking water treatment plants does not exist yet. The design and successful first time setup of such a simulator is addressed in this chapter. Two process models, a hydraulic model and a water quality model, simulate the process behavior of the treatment plant. The set up and validation of these models is elaborated in Chapters 3 and 4. Environmental decision-support systems (EDSSs) were used as a blueprint for the simulator because the integration of different models is common in EDSSs. By applying a SCADA-like graphical user interface and several report options, even a group of end-users without specific modeling skills or knowledge can take advantage of the use of integrated hydraulic, water quality and process control models. The 'Waterspot' drinking water treatment plant simulator has been developed and applied to Dutch drinking water treatment plants.

Keywords

Drinking water treatment; model integration; mother duck-duckling; process optimization; simulator; training.

2.1 Introduction

Water supply companies are gradually changing to centralized, fully-automated operations. The drivers for this change are the increase in efficiency and a better and more stable water quality. Fully-automated treatment plants will require more sophisticated operator care than manually operated plants (Trussell, 2000). The distinct difference with locally, manually operated water treatment plants is that the supervisor will be responsible for the entire treatment, often with multiple plants, and for the transport and distribution system from source to tap. During normal working hours, the supervisor will validate production data, analyze deviations of process parameters, and check the health of the automation system. The supervisor remains responsible for dealing with emergencies, alarms and “long distance” problem solving. To excel in these tasks, the supervisor needs to understand the entire treatment process, and transport and distribution systems thoroughly. The supervisor needs to speak the language of automation and data communication fluently and needs to have the knowledge, as well as the skills, to react adequately in the one percent “irregular” situations. At the same time, fully-automated operation opens the gate to online process optimization. Online measured water quality data will feed models that predict the development of process parameters. Proactively, the treatment processes will be adjusted to prevent the violation of operational windows of water quality parameters and to save costs and emissions by reducing the use of chemicals and energy.

During the introduction of a fully-automated operation, the risk of erosion of skills and knowledge of the operation supervisors was identified by several Dutch water supply companies. To deal with this risk, operation supervisors should periodically study and operate parts of the plant manually. Alternatively, a simulator can be used to train operation supervisors. The setup of such a simulator is addressed in this chapter.

A simulator is considered to be a decision-support system (DSS). As in a DSS, it simulates the behavior of the represented system and offers the end-user insight into the consequences of decisions. In the most diverse fields of research and applications, production, operation, marketing, transportation, government, education, etc., DSS use has been reported (Eom and Kim, 2006). A DSS can be classified by the number and types of models that feed the system. The most basic DSS relies on a collection of experiences in a knowledge database with decision-tree navigation. The more developed systems use deterministic models, or neural networks, to find unknown relationships in large amounts of data. The integration of different models, in terms of temporal scale, calculation method, types of input and output, etc. is common in environmental decision-support systems (EDSSs). The development of EDSSs has gone as far as standardizing an interface that enables linking models with different spatial and temporal scales (Gregersen *et al.*, 2007). Because of this level of development, EDSSs were used as a blueprint for a simulator of drinking water treatment plants. An EDSS can be described as various coupled models, databases and assessment tools, which are integrated under a graphical user interface (GUI) often realized by using spatial data management functionalities provided by geographic information systems (GIS). Typical end-users of an EDSS are decision-makers in public or private entities in land and water management. The variety of applications makes the time dimension of decision-support systems vary from close to real time to long term for design (Rivas *et al.*, 2008), strategy or policy making.

The boundary between modeling and decision support is vanishing in environmental sciences. Whereas a decade ago references in the modeling literature to EDSSs were often restricted to the conceptual framework or to 'future work' paragraphs, the integration of models in EDSSs is now taking place. The strong interest in EDSSs shows a change in direction in the scientific community to extend research objectives from pure analysis towards application in a decision-making or a policy context (Matthies *et al.*, 2007). The possibility of combining individual models to bigger systems of models requires that scientists develop models that can be integrated. During the development of models, mostly arising from scientific investigation, often little thought is given to the problems of model integration in the later life of the model. Models pass through some or all of four levels of development (Argent, 2004). As important as the successful technical integration of the different components mentioned above, so is the perception of intended end-users of the usefulness and practicality of a system, as well as their acceptance (van Delden *et al.*, 2007). At the start of this research, several deterministic models were available which were developed to study water quality issues in drinking water treatment and deterministic hydraulic models for design or operation of pipe networks. In this chapter the integration of models, data management, interfaces and training support features is reported. The 'Waterspot' drinking water treatment plant simulator has been developed and applied to Dutch drinking water treatment plants. To demonstrate the successful application of the simulator, a case study is described in this chapter for the drinking water treatment plant at Weesperkarspel, operated by Waternet, the water cycle company for Amsterdam and surrounding areas.

2.2 Materials and methods

Integration of components

Models are referred to as stand-alone models or modeling suites and DSS as tools based on artificial intelligence and scenario techniques. For the drinking water treatment plant simulator, the object model, running on the USE® platform, forms the connecting grid. This commercial platform allows the handling of multiple sources of data from models and uses the data according to predefined rules. The simulator can then be extended with training and process optimization features. Models are an essential part of the simulators since they represent the behavior of the treatment plant's processes. An overview of the simulator's software structure is shown in Figure 2.1.

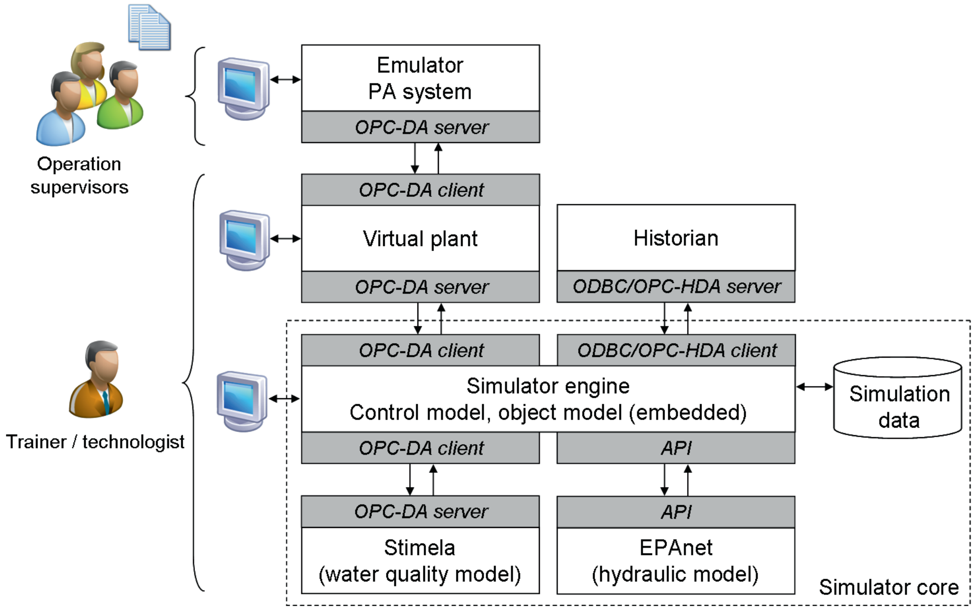

Figure 2.1. Simulator's software structure.

Models

Four models run simultaneously in the simulator, i) a water quality model, ii) a hydraulic model, iii) a process control model and iv) a field object model.

Water quality model. To simulate the changes in water quality in the different water treatment steps, Stimela models were used (van der Helm and Rietveld, 2002; Bosklopper *et al.*, 2004; Rietveld *et al.*, 2008). Stimela is an environment in which different drinking water treatment processes can be dynamically modelled. The Stimela models are developed in Matlab®/Simulink®. Partial differential equations are numerically integrated to enable the assessment of variations in time and space. To determine the level of development of the models, communication about the models before the start of this project was via different case studies and journals, conference proceedings and lecture notes. The model of the test environment at Weesperkarspel, which was used in the case study, is shown in Figure 2.2. The level of validation and calibration of the models is extensive (van der Helm *et al.*, 2007; van Schagen *et al.*, 2008).

Hydraulic model. For the simulation of flows, flow divisions and pressures, an hydraulic model was integrated into the simulator. EPANET is water distribution network modeling software that has been developed and is distributed freely by the US Environmental Protection Agency. In EPANET, distribution networks are defined by elements such as junctions, pipelines, pumps, valves, tanks and reservoirs. Because it was developed to model water

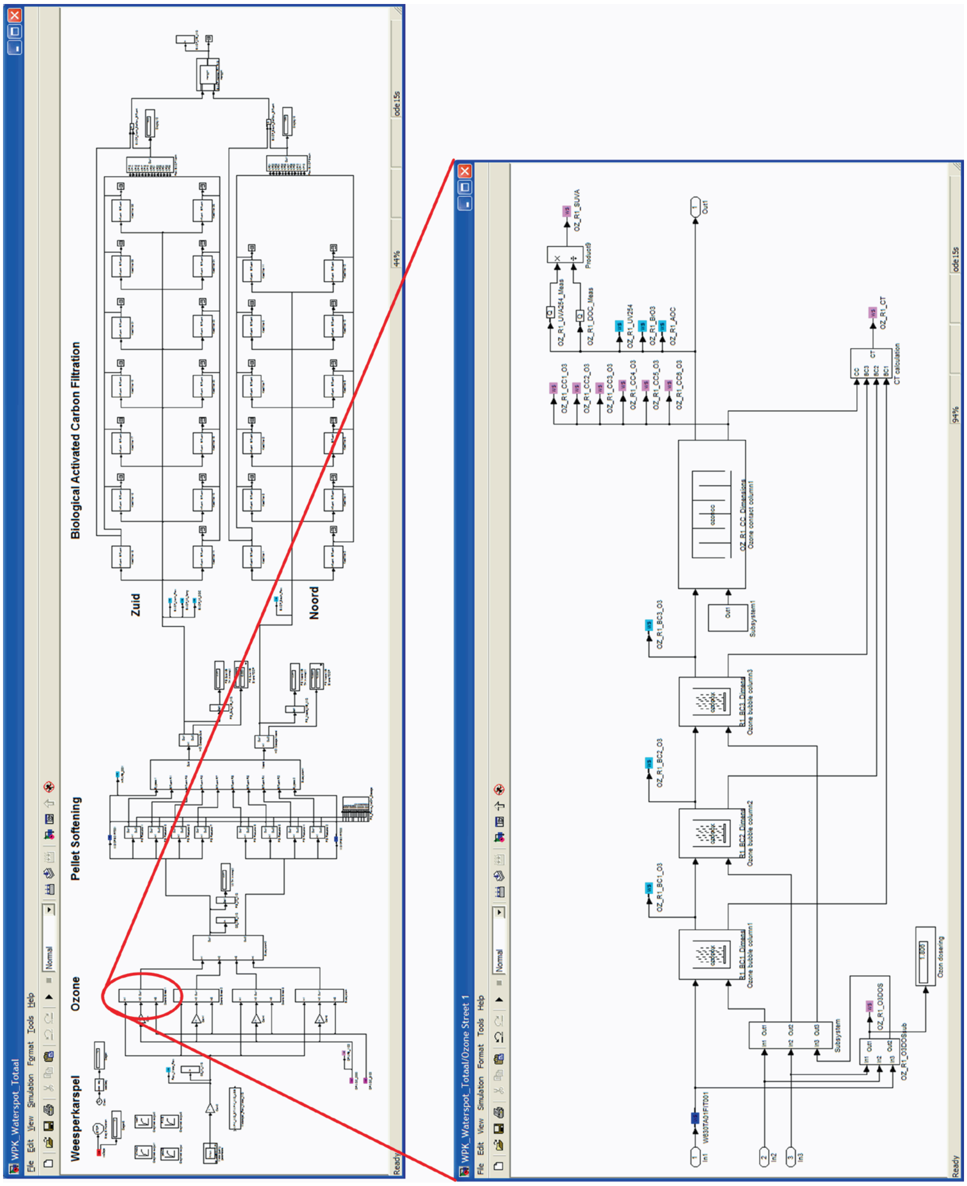

Figure 2.2. Impression of the Stimela model for the drinking water treatment plant at Weesperkarspel.

distribution piping systems, the EPANET library lacks elements needed to model the hydraulic behavior of treatment plant processes, such as weirs in a cascade, filter beds and filter nozzles. These elements are described in Chapter 3 (Worm *et al*, 2009). For control valves, the relationship between the setting of a throttle control in the model and the opening angle of the valve was derived using valve characteristics as specified by manufacturers.

Input for the model includes valve settings, speeds of pumps and pressure drops for filters and reactors, output includes flows in pipes, reactors, canals and filters. See Figure 2.3 for the EPANET model at the Weesperkarspel treatment plant.

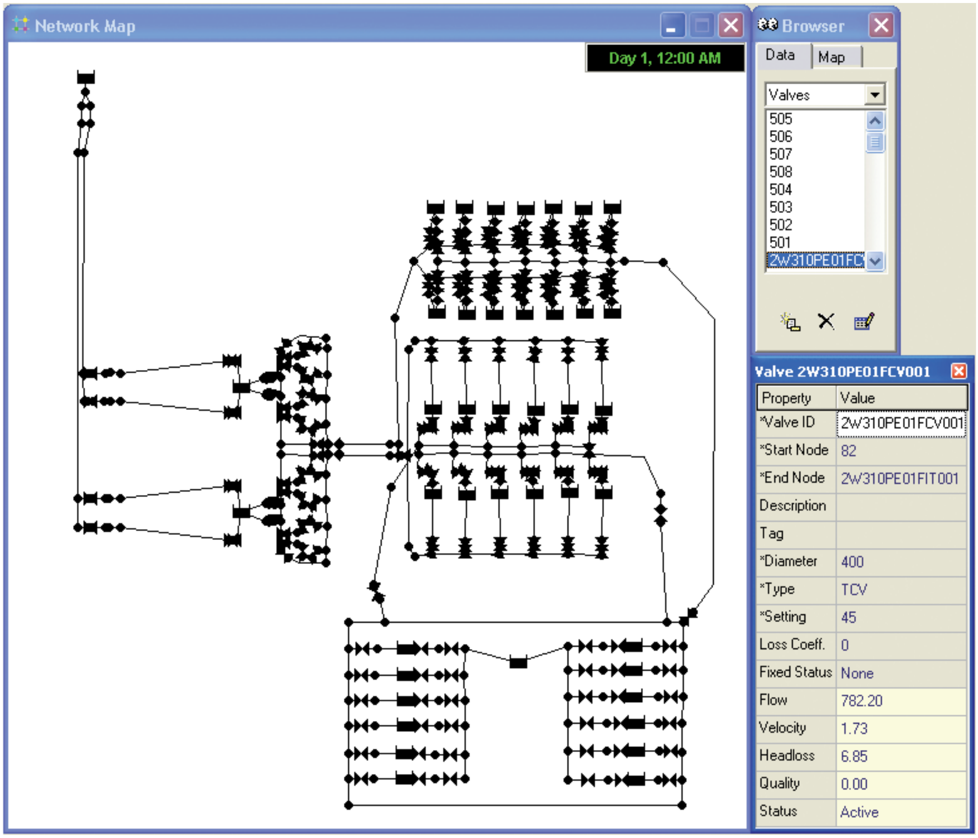

Figure 2.3. EPANET model for the drinking water treatment plant at Weesperkarspel.

Control model. The control model represents the control algorithms that operate in the treatment plant, e.g., a function to determine the valve resistance up to the level where a preset flow is passing through the valve or a proportional-integral-derivative (PID) controller function to calculate the dose of caustic soda in a softening reactor to reach a preset total hardness of the effluent. As described in Chapter 6, emulators will be connected to the simulator which will take over the control of the simulator. Bypassing the simulator's control functions is easier when they are concentrated in one place, and centralizing the control functions yields maximum transparency. The simulator's control model consists of a manual/auto mode switch and the following controls: on/off, single point process, proportional and derivative (PD), proportional and integral (PI), proportional, integral and derivative (PID) and cascaded.

Object model. The object model is the virtual representation of all field elements, i.e., sensors, actuators, reactors, vessels, pipes, etc. The model forms the structure of each test environment and facilitates transparent communication between the other three models. The framework for the object model is a hierarchical six-layer setup of generic classes and subclasses. These classes and subclasses were defined according the ANSI/ISA-88 standard (S88) for batch process control. Each generic subclass has attributes and specific behaviors. To make a company-specific object model, objects were defined as instances of the classes or subclasses. Existing process decompositions can be used as a blueprint for the object model. The use of company standards such as process decomposition and tags for field objects will be useful during connection to historians, emulators or process automation systems in future.

Graphical user interface

When a model has developed up to the level where it is integrated in a decision-support system, the distance between an end-user and the model has increased. The acceptance and appreciation of the simulator by end-users is increasingly determined by the 'look & feel' of the system. From this, the increasing importance of the graphical user interface (GUI) has been recognized. Graphic designers have been involved in the development of the simulator for the design of screens and buttons. The GUI follows the standards for SCADA system design, i.e. limited use of distinctive colors, hierarchical setup of screens to limit the amount of information on a screen, and standard logos for the treatment units. If applicable, every screen has a box showing the relevant quality and quantity parameters for the influent on the left side and on the right side for the effluent. In the future, a connected emulator will provide the company a specific human-machine interface (HMI).

End-users

The simulator has three types of end-users, i) the operation supervisor, ii) the trainer and iii) the control engineer. During pilot research and through interactive sessions using a storyboard, the required functionalities were identified, among which were a start-up wizard including simulation templates, a snapshot function, definitions and the (unexpected) loading of malfunctions, a play-pause-resume function, an acceleration and deceleration function, a real-time presentation of selected process parameters during simulation, training case definitions, and the loading and comparison of operation scenarios. The storyboard was presented using a PowerPoint presentation with hyperlinks to simulate the future simulator's GUI.

Data and command management

A distinction is made between commands and data in the simulator. Commands are volatile signals, data can be stored in a database. When a command is stored by the simulator in an action log, the entry in the log becomes data.

Commands and traffic rules. In the simulator two types of commands occur: commands for simulator control and commands for process control. For the simulator control, basic traffic rules were defined in the simulator engine. A parameter value is owned by one model at a time, exclusively. No iteration takes place yielding models, depending on the granularity of the simulation or training data that might need to use data from a previous time step. Models run independently and try to follow the simulated time as closely as possible. To make sure the presented results are credible, communication between the models and the USE® platform follows the 'mother duck – duckling' principle. The value of this principle is best shown for the most complex of the models used, the water quality model. Stimela increases the number of calculations when changes in water quality occur, as a consequence of which the difference between the simulation time and the Stimela time increases. If the delay exceeds a certain amount or ratio the simulation time decelerates until the Stimela calculations have caught up. This is like a duckling that follows its mother. It starts to swim when the mother starts to swim, but the mother will decelerate as the distance between her and the duckling has reached a maximum. The 'mother duck – duckling' principle allows adding and removing new independent layers (or modules) of functionality to the simulator. For the hydraulic model, the iteration within the model was minimized. The model calculates the static hydraulic situation (division of flows) in the water treatment plant for the actual settings of valves and pumps. The values of time-dependent parameters like filter water levels are calculated within the Stimela model. Process control commands are generated by the control model and adjust simulated process actuators, e.g. valves, pumps.

Data. Three data sources were identified in the simulator: EPANET, Stimela and the simulator engine. To describe the dependency and hierarchy, data are classified as primary, secondary and tertiary data. The primary data consist of process and simulation start-up data, of which only the actual process data are dynamic. Historical process data and start-up data are static. Start-up data include user information, initial states of a simulation and definitions of malfunctions and scenarios. Secondary data consist of action and alarm logs; tertiary data are the trace logs for the system developer. Trace data consist of a complete set of commands and system statuses. In future developments, any other kind of data can be added to the simulator as long as internal data handling rules are extended accordingly. All data have been enriched with type-specific metadata, like a timestamp or unit.

Interfaces. The control model and the object model are embedded in the simulator engine. For integration of the Stimela water quality models in the simulator, a dedicated OPC-DA server (Object linking and embedding for Process Control - Data Acquisition) was developed and set up. For EPANET, an interface was developed which reads from and writes to the EPANET's dynamic link library (dll) files. Not embedding the EPANET source code in the simulator's engine leaves the possibility of integrating other hydraulic modeling environments in the future. To connect with a production database, ODBC and OPC-HDA interfaces have been used. OPC and ODBC are non-proprietary industry standards, so they are easily accessible and well-documented. All inputs in the simulator engine are translated into a generic format which enables the use of data from non-interchangeable sources. These transformed data are used for simulator control, display and reporting purposes. All data can be transformed again into any of the data source formats.

Performance requirements

To prove a stable and quick response of the simulator by adequate cooperation between the water quality model, the hydraulic model and the process control model, a case study was carried out. In the ‘free training’ mode, interventions of an end-user should have a dynamic response to the affected process parameters. End-users should be able to compare the effects of historical or new operation strategy cases. The effect of changing the raw water quality on the drinking water’s quality should be simulated. The simulation should have the possibility of being accelerated and decelerated, to launch changes (malfunctions or changing raw water quality) during simulations, and to be paused and resumed. Apart from dynamic graphs during simulation, the possibility of creating standard reports of relevant input and output parameters should exist. Requirements for performance indicators have been listed in Table 2.1.

Table 2.1. Performance requirements.

Indicator	Requirement
One calculation cycle EPANET including data transfer via API[1]	Max 500 ms
One OPC cycle	Max 500 ms
Delay within ‘mother duck–duckling interface’	Max 10x acceleration[2]
Simulation acceleration	1x - 600x

[1] Application Programming Interface

[2] E.g. when acceleration is 600x, maximum accepted delay model is 6000 s.

Case study of the ‘new softening control at Weesperkarspel’

This simulator is used for training operation supervisors and for process optimization. For the latter, the effects of different settings or control strategies can be evaluated. This case study deals with the evaluation of a new control strategy for the pellet softening reactors. In the softening process the total hardness of the water is decreased by precipitating calcium ions in a fluidized bed reactor (van Schagen *et al.*, 2008). The initial state of the case is a water temperature of 7.3 °C, a bed height of 4.3 m and a maximum pellet diameter of 0.85 mm. The flow at the drinking water treatment plant starts at 3.224 m^3/h, with all four ozone streets in operation, and seven out of the eight pellet softening reactors treating 327 m^3/h each. The sand dosing is 20.8 kg/day, pellet discharge is 522.3 kg/day and caustic soda dosing is 47 l/h. All 26 biological activated carbon filters are in operation. The conditions change. On day 1 the temperature decreases to 5.6 °C, on day 7 to 3.9 °C and continues to be 3.5 °C from days 8 to 15. Formerly, operators would discharge pellets during rapidly decreasing water temperature to lower the bed height. In the new control (van Schagen *et al.*, 2008), the flow through a reactor varies with the water temperature, from 300 m^3/h for water of 0 °C to 400 m^3/h at 30 °C. The flow of the total caustic soda dosage is a fixed ratio of the total flow through the reactors and the bypass. The dosing of grains is a function of the bed height. When the bed height is 4.5 m or more, no dosing takes place. At a bed height of

4 m or lower, the dosing of grains is 57.9 kg/day. For bed heights between 4 and 4.5 m, the dosage is calculated using linear interpolation. Pellet discharge is a function of the pressure drop over the first meter of the reactor. For a pressure drop of 8 kPa and lower, no discharge takes place. For a pressure drop of 8.4 kPa and higher, pellet discharge is calculated as a function of the pellet diameter. For pressure drops between 8 kPa and 8.4 kPa, the discharge is linearly interpolated.

Software availability

The simulator runs on a Dell Precision M65 laptop, Intel Core2Duo T7400 2 processor, 16 Ghz, 2 GB internal memory. The software used is listed in Table 2.2.

Table 2.2. Used software.

Software	Version	License
EPANET	2.00.12	None, public domain
Jasper reports	3.1.0	GPL[1] or LGPL[2]
MySQL Community Version	5.1.3	GPL[1]
Stimela	6.5.59	Project based
Stimela OPC Server	1.0	Project based
Matlab®	6.5 release 13	Individual commercial license
Simulink®	5.0 release 13	Individual commercial license
Waterspot	1.0	
USE®	2.4_2	UReason EULA for USE.
Windows	XP Pro SP 2/3	Microsoft EULA for Windows XP SP2/3

[1] General Public License

[2] Lesser General Public License

2.3 Results and discussion

Figure 2.4 shows the traditional SCADA 'look & feel' page of the pellet softening and the dynamic trend of the total hardness of the mixed effluent of the reactors and bypass during a simulator run. The total hardness drops as a consequence of an increase in the caustic soda dosage. The figure shows the actual acceleration, 60 times, and buttons that give access to the action log, the alarm log and a report. From the pellet softening page, sublevels of the plant can be selected, each providing dynamic information on relevant process parameters.
In Figure 2.5 a selection of the results of the case study is shown. As expected, the former control strategy yields an increasing bed height during a decrease in the water temperature. The effect of the manual pellet discharge is clearly visible. The correction of the bed height appears to be temporary. In the new control of the softening reactors, the bed height changes within a much smaller bandwidth and no sudden decrease occurs.

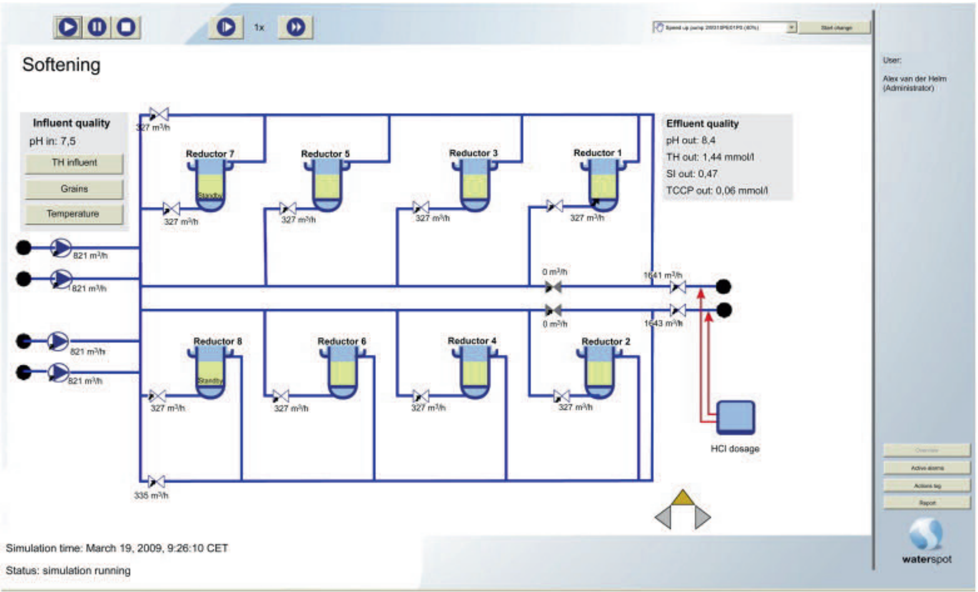

Figure 2.4. GUI of the pellet softening process and an example of dynamic process data. For the purpose of this thesis, the original Dutch texts have been replaced by English.

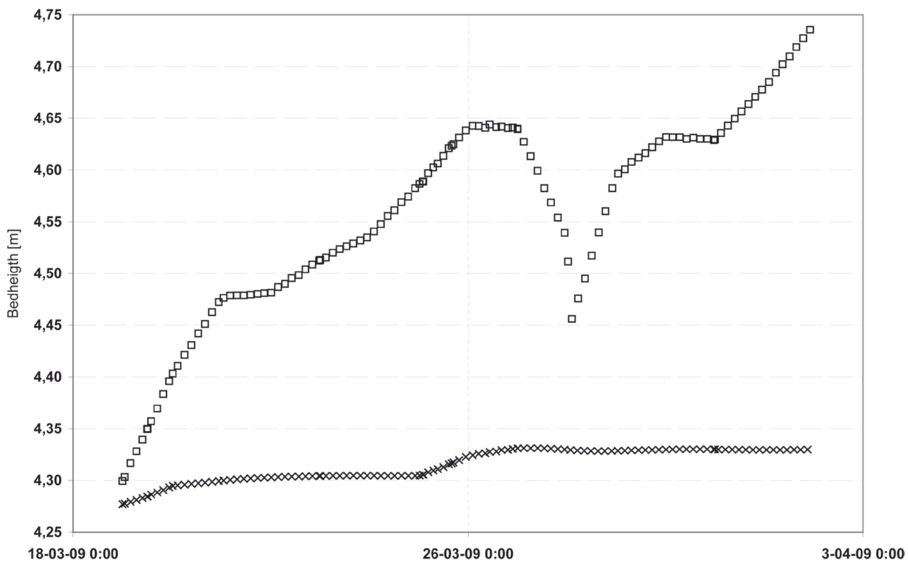

Figure 2.5. Selection of results from the case study as generated by the simulator: bed height with the former control (□) and the new control (×) during decreasing water temperature.

For the case study 'new softening control Weesperkarspel', all performance requirements have been matched, as shown in Table 2.3. Due to restrictions in calculation capacities of the work station and complexity of the water quality model, the number of water quality sub models was limited to one pellet softening reactor. Apart from this issue, it was concluded that more effort must be put into the development of the process control model.

Table 2.3. Simulator's performance.

Indicator	Performance
One calculation cycle EPANET including 2 data transfer via API[1]	150 ms
One OPC cycle	Average 500 ms
Delay within 'mother duck–duckling interface'	Max 10 x acceleration average 4 x simulation speed
Simulation acceleration	0.5x, 1x, 2x, 6x, 60x, 600x, 3600x

[1] Application Programming Interface

During this research the Stimela models transferred from the development level of multiple case-based applications and re-use in academic education to the level of general acceptance of its results and use of the models in daily operation and design decisions.

2.4 Conclusions

The integration of models, command and data management, training and decision-support features, and a GUI in a simulator of drinking water treatment plants was never reported before and is reported in this chapter. The 'Waterspot' simulator gives a wider group of end-users the opportunity to take advantage of the use of integrated hydraulic, water quality and process control models in their daily work. Operation supervisors are able to train themselves, technologists are able to optimize the treatment process, and process software engineers will be able to test their software updates more effectively. The simulator core consists of the simulator engine on the USE® platform, an embedded object model, an embedded control model, a Stimela water quality model and an EPANET hydraulic model. The interfaces between the simulator engine, models and future modules are all industry standards. The interface between the simulator engine and the water quality model follows the 'mother duck – duckling' principle. By using industry standards, by applying the simulator to four test environments at Dutch drinking water treatment plants and by running a case study, it has been demonstrated that a generic simulator has been developed for drinking water treatment plants. As a consequence of the generic setup and standard interfaces, the application of the simulator at a future drinking water treatment plant will only require models to be set up and validated. More effort must be put into the development of the process control model.

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3

Hydraulic modeling of drinking water treatment plant operations

Based on

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Abstract
The flow through a unit of a drinking water treatment plant is one of the most important parameters in terms of a unit's effectiveness, but is often neglected in water quality modeling. EPANET is worldwide used freeware to model water distribution networks. Definitions for the representation of treatment units in EPANET lack, which are needed to be able to use EPANET as the platform for hydraulic modelling in the simulator. In this chapter, a library is presented with these definitions for the drinking water treatment processes 'well abstraction', 'rapid sand filtration', 'cascade aeration', 'tower aeration', and 'pellet softening'. Using this library, two EPANET hydraulic models were set up and validated for the drinking water treatment plants Harderbroek and Wim Mensink. With the actual valve position and pump speeds, the flows were calculated through the several treatment steps.

3.1 Introduction

In plants treating a continuous flow, like in the petrochemical industry, the plant owner determines the flow he wants to treat. In drinking water treatment plants, typically, not the plant owner but the customer determines the flow (van Schagen *et al.*, 2010). Reservoirs are present to balance the flow differences over a day, but to prevent too long residence times and high costs, the reservoirs do not have the volume to balance over days or even longer periods. So, operation supervisors and process technologists of drinking water treatment plants are used to a daily changing flow, thus possibly underestimating the importance of flow on the effectiveness of a treatment unit. Examples are reported of situations where flow plays an important role in a treatment step's performance. The effluent quality of horizontal-flow roughing filters drops drastically at a filtration rate higher than 1 m/h (Ahn *et al.*, 2007). For 'depth' ultrafiltration and microfiltration with reversible adsorption a lower initial permeate flow rate allows to achieve longer operation times (Polyakov & Kazenin, 2005) and the flow rate affects the effluent turbidity of a rapid sand filter (Onat & Dogruel, 2003). For optimal pellet softening the flow through a single reactor should be fixed and the bypass should be maximum while meeting the treatment objectives (van Schagen *et al.*, 2006).

Interventions in the operation of drinking water treatment plants, such as the adjustment of valve positions or pump speeds, will lead to a change in the division of flows through the plant and, thus, in the flow through the individual treatment units. Hydraulic model studies are commonly part of the design of a drinking water treatment plant (Hranisavljevic *et al.*, 1999) or part of a performance study of a single treatment step (Gallard *et al.*, 2003; van Schagen, 2006), but have not been used yet to evaluate or optimize the operations of a complete drinking water treatment plant. In this study a hydraulic model is used to give operation supervisors insight in the effect of interventions in the total flow and the division of flow in the plant.

The free available hydraulic model of the United States Environmental Protection Agency EPANET (Rossman, 2000) is used worldwide to design water distribution networks and to optimize its operation, up to a level of full integration with SCADA (supervisory control and data acquisition) systems (Fontenot *et al.*, 2003; Martínez *et al.*, 2007). The current EPANET library, however, lacks elements that describe the hydraulic properties of drinking water treatment plant units such as aerators and rapid sand filters. In this study a library is presented which enables the use of EPANET to build a hydraulic model of a drinking water treatment plant. The relation is described between the setting of a throttle control valve, the flow coefficient $K_v 0$ from manufacturers' data sheets and the opening angle of the valve as used in EPANET.

Hydraulic models have been set up for ground water treatment plant Harderbroek and Wim Mensink, which treats infiltrated dune water. The models provide a possibility for offline and online control of the division of flows over the plant. The models can be used to support an operation supervisor during (manual) adjustments of pump speeds or valve positions, to evaluate the actual operation, to monitor online flow measurement devices' performance or to serve as a soft sensor at locations where no flow measurement device is available.

3.2 Materials and methods

EPANET drinking water treatment plant library

From a hydraulic perspective a drinking water treatment plant consists of elements that give resistance to the passing flow (e.g. filters, pipes, distribution works), pumps that increase the total head of the flow and reservoirs with a limited surface area and a varying water level. The current EPANET library lacks elements that describe the hydraulic properties of drinking water treatment plant units. Still, with the available elements pipes, valves, pumps and reservoirs, which are connected in junctions, a static hydraulic model of a drinking water treatment plant can be set up. Junctions are not true physical elements but mark points where two or more pipes or valves are connected. An elevation can be assigned to each junction. The total head in a junction is the elevation added up to the pressure in the junction according

$$H = \frac{p}{\rho \cdot g} + z \tag{3.1}$$

where H is the total head [mwc], p is the pressure [N/m^2], ρ is the density of the fluid [kg/m^3], g is the acceleration due to gravity [m/s^2] and z is the elevation of the junction on a chosen level [m]. Pipes are characterized by their length, diameter and roughness. Reservoirs are nodes that represent an infinite external source or sink of water. A reservoir's main input property is its hydraulic head. To model resistances in EPANET six types of valves are available (Rossman, 2000) of which four were used in the treatment plant library presented in this chapter. In the design of a drinking water treatment plant often hydraulic disconnections are added to prevent water from flowing in the opposite direction and to distribute water over lanes. For hydraulic disconnections in EPANET the pressure sustaining valve (PSV) is used. A PSV maintains a set pressure at the upstream point. EPANET computes in which of three different states the PSV is in i) partially opened to maintain its pressure setting on its upstream side when the downstream pressure is below this value, ii) fully open if the downstream pressure is above the setting, or iii) closed if the pressure on the downstream side exceeds the pressure on the upstream. A pressure breaker valve (PBV) forces a specified pressure loss to occur across the valve. Flow through the valve can be in either direction. PBVs are not true physical devices but can be used to model situations where a particular pressure drop is known to exist.

A throttle control valve (TCV) simulates a partially closed valve by adjusting the minor head loss coefficient of the valve. The head loss over a TCV is calculated with

$$\Delta H = \xi \frac{v^2}{2 \cdot g} \tag{3.2}$$

where ξ is the minor loss coefficient [-] and v is the velocity through the pipe [m/s]. A general purpose valve (GPV) is used to represent a link where the user supplies a special flow - head loss relationship instead of following one of the standard hydraulic formulas, like the one mentioned above. The relationship can be linear or quadratic, as well as customly defined.
Table 3.1 shows the representations of treatment steps in groundwater treatment plants. It contains representations of well abstraction, cascade aeration, tower aeration, rapid sand filtration and pellet softening.

Wells. The water level of a phreatic aquifer is modelled with a reservoir. Wells can be equipped with a submerged pump or can be part of a vacuum-gravity system to extract the water from the aquifer. For isolated wells with a constant extracted flow the relation between extracted flow and draw down can be assumed to be linear (Thiem, 1906). For pumped wells, a second non linear term must be added, leading to the following empirical relation (Rorabaugh, 1953) between draw down and extracted flow

$$\Delta z = \frac{Q}{2\pi T} \cdot \ln \frac{R}{r_w} + k \cdot Q^n \tag{3.3}$$

where Q is the extracted flow [m^3/s], T is the soil conductivity [m^2/s], R is the influence well radius [m], r_w is the distance to the well [m], k is a constant [-] and n is an exponent ranging between 1 and 2 [-]. This relation between extracted flow and draw-down is modelled with a GPV.

Cascade aerator. In a cascade aerator water drops down in one or more steps to transfer gas from and to water. The points of interest in a cascade aerator, from a hydraulic perspective, are the level of the upper weir and the water level in the last cascade step, or the collection canal or pipe of the cascade effluent. The setting of the PSV is the level of the crest of the upper cascade, see Figure 3.1. The GPV represents the height of the water surface above the upper weir. The GPV flow - head loss relationship of the upper weir is calculated for a sharp-crested weir corrected for contractions on both ends (Daugherty *et al.*, 1985), assuming the value for the discharge coefficient *CD* is 0.62

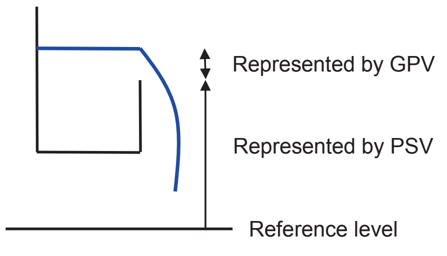
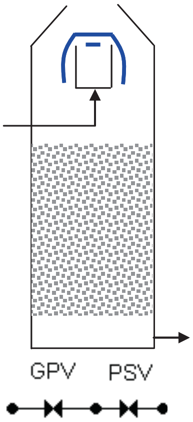
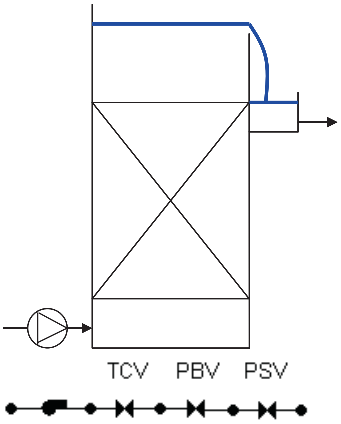
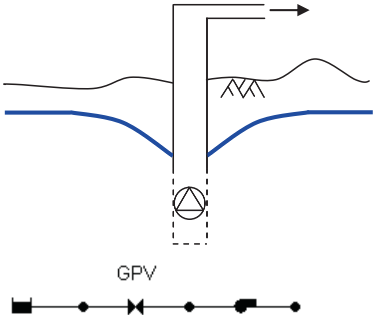
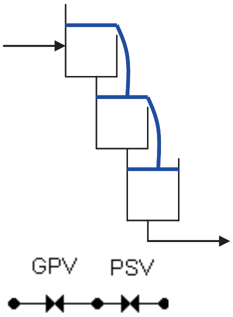
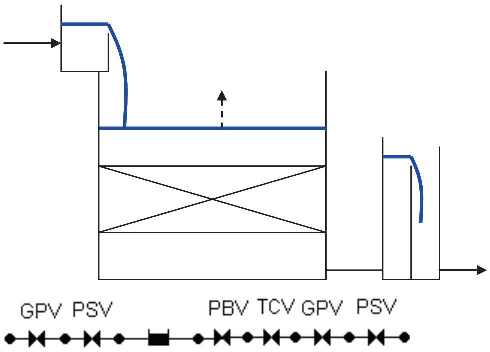
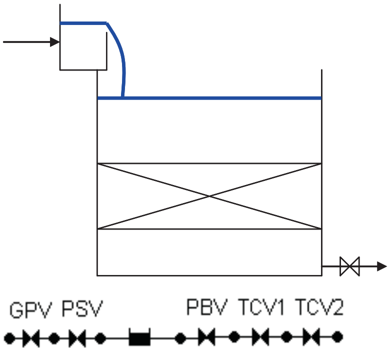


Figure 3.1. Modeling of the upper weir of a cascade aerator.

Table 3.1. EPANET library for drinking water treatment plants (GPV = general purpose valve, PSV = pressure sustaining valve, PBV = pressure breaking valve, TCV = throttle control valve).

 Tower aerator	 Pellet softening reactor
 Well	 Cascade aerator
 Rapid sand filter (rising water level)	 Rapid sand filter (declining velocity)

$$Q = 1.84 \cdot (L - 0.1 \cdot n \cdot H) \cdot H^{3/2} \tag{3.4}$$

where L is the width of the weir [m], n is the number of end contractions [-] and H is the difference in level between the crest and the water in an undisturbed zone in front of the weir [m].

Tower aerator. In a tower aerator, water is distributed over a column with packing, through which air is blown. From a hydraulic perspective, the tower aerator is modelled in the same way as the cascade aerator. The height of the weir, plus the flow on top of the crest of the weir, is modelled using a PSV and a GPV.

Rapid sand filtration. The library contains representations of a rapid sand filter with a fixed supernatant water level during the runtime and a filter with a rising water level. The filter with a constant water level uses a pump or control valve in the effluent pipe that compensates for the increasing filter bed resistance. The total resistance over the filter is mainly caused by the water inlet, the filter bed, the filter bottom nozzles, the effluent pipe inlet and the pump or control valve. The water inlet can be modelled either with a pipe in the case of a siphon, with a TCV in the case of a valve, or with a GPV and a PSV in the case of a weir. The pressure drop over the filter bed increases in time as a consequence of clogging or instantly as a consequence of increasing flow. For a static calculation, the pressure drop as a consequence of clogging is considered to be fixed, and therefore is modelled using a PBV. The resistance of the filter bottom nozzles can often be derived from the specifications of the manufacturer and the number of nozzles. Because of the increasing resistance with increasing flow, the nozzles can be modelled using a TCV, TCV1 in Table 3.1. In practice however, the pressure drop over the nozzles during filtration will be negligible. TCV2 simulates the behavior of the control valve. For the filter with a rising water level, TCV2 is replaced by a GPV and PSV valve, similar with a cascade aerator and TCV1 is renamed in TCV.

Pellet softening. A pellet softening reactor is an up flow fluidized bed reactor often equipped with a dedicated pump to compensate for the head loss over the reactor. To control the flow through the reactor the speed of the pump is adjusted or a valve down stream of a fixed speed pump throttles. An energy loss occurs when the water enters the space under the reactor bottom. The resistance in the nozzles in the bottom of the reactor provides an equal distribution of water over the reactor surface. The pressure drop over the reactor equals the weight of the submerged fluidized pellets. The density of the pellets is a function of the accumulated mass of the crystallized material and the mass of the grains (van Schagen *et al.*, 2008). In the top of the reactor, the effluent is discharged via a weir.

Control valves. In the connection between the treatment steps, lanes or within treatment steps like a rapid sand filter, butterfly valves can be present, which are represented in the model by TCVs. The head loss over a TCV is calculated with Equation 3.2. Since a TCV simulates a partially closed valve by adjusting the minor head loss coefficient of the valve, the relation between the opening angle of the valve and this loss coefficient must be known. The flow coefficient K_v is defined as the water flow in m^3 per hour through a valve creating a pressure drop of 1 bar [$m^3/h \cdot bar^{1/2}$], according

$$K_V = \frac{Q}{\sqrt{\Delta p}} \tag{3.5}$$

The opening angle α is 0° for a closed valve and 90° for an open valve. K_v0 is the K_v of a fully opened valve, the flow coefficient for a valve with opening angle α is

$$K_V(\alpha) = K(\alpha) \cdot K_V 0 \tag{3.6}$$

$K_v(\alpha)$ or $K(\alpha)$ values are often listed in valve manufacturers' specification sheets. If only K_v0 is available an estimation of $K_v(\alpha)$ can be made using

$$K(\alpha) = 1 - \cos\left(\pi \frac{\alpha}{180}\right) \tag{3.7}$$

For a TCV ξ will vary with the extent of opening of the valve and can be calculated from Equations 3.2, 3.5 and 3.6, according

$$\xi = \frac{2 \cdot g \cdot A^2 \cdot 3600^2 \cdot 10.2}{K_V(\alpha)^2} \tag{3.8}$$

Modeling approach

Using the library shown in Table 3.1 models of two drinking water treatment plants were set up, calibrated and validated. To enable the hydraulic model to be integrated in the simulator, no control actions are present in the hydraulic model. The model calculates the hydraulic situation in the water treatment plant at a single moment. To calculate the resistance in the pipes, the Darcy-Weisbach equation is used where roughness coefficient k is assumed to be 0.1 mm.

Drinking water treatment plant Harderbroek

Layout. The groundwater treatment plant Harderbroek, owned and operated by Vitens, consists of 16 deep wells, four cascades, eight rapid sand filters and three tower aerators. The maximum production is 1000 m^3/h. The treatment scheme is shown in Figure 3.2. The

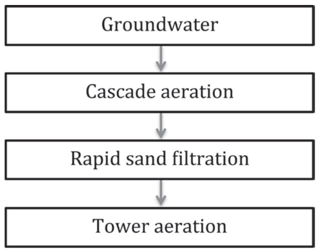


Figure 3.2. Treatment scheme of drinking water treatment plant Harderbroek

model was set up using the hydraulic line scheme of the plant, piping and instrumentation diagrams and drawings and contains 344 pipes, 528 junctions and 207 valves, see Figure 3.3.

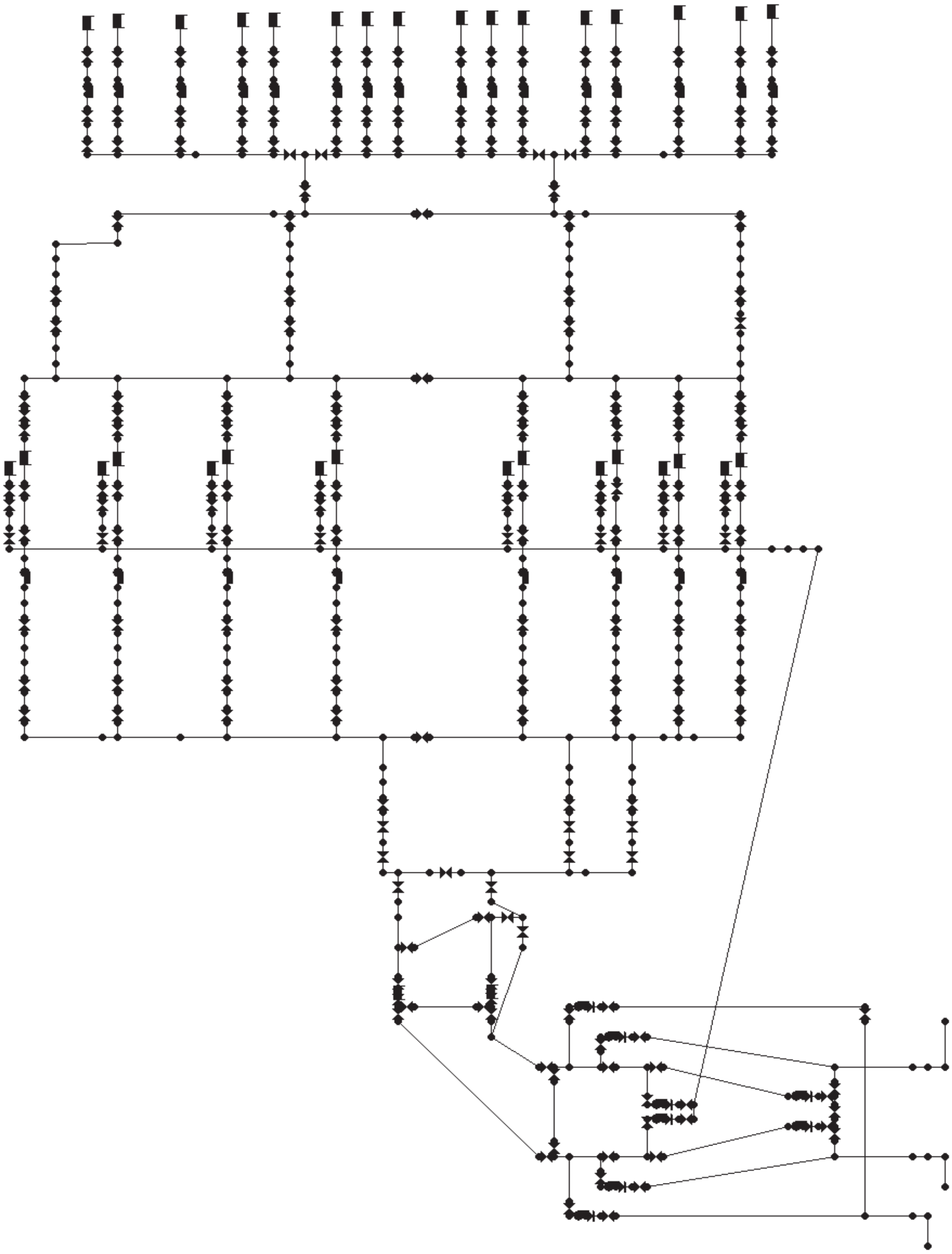


Figure 3.3. EPANET model of Harderbroek

The wells are grouped in two series of seven. Each well is equipped with a submerged pump, which has been added to the model. In each series, one well is equipped with a speed-controlled pump, the other six are equipped with fixed-speed pumps. The water level inside and outside each well is measured and logged, as is the flow per well. While water level measurements inside each well were available, the groundwater level minus actual draw down was used in the model. In this case the hydraulic head of the reservoir model block represents the water level in the well. The value of the water level measurement is the distance between the water level and the sensor at -13.3 m+NAP (Dutch standard level). Based on the pump's characteristic, the water level in the well, pipe resistances and the level of the weir of the upper cascade, the flow per well can be calculated.

The top of the weir of each of the four cascades has a level of 4.71 m+NAP. The relationship between flow and water level is calculated with Equation 3.4. In a normal operation, three cascades are in operation. After aeration the water from the cascades is collected in the rapid sand filter influent canal.

Each rapid sand filter is fed using an open/close valve and a weir. Each filter has a speed-controlled pump in the effluent pipe that controls the water level in the filter at a fixed level. This pump replaces the control valve in the library's model. The water level is measured, and so are the pressure drop over the filter and the pressure under the bottom of the filter. The value of the water level measurement equals the distance from the sensor at 3.80 m+NAP to the water level. The speed of the pump (expressed as a ratio of the nominal speed) is controlled with a current frequency converter. A pump speed ratio of 0 equals a current frequency of 15 Hz and a ratio of 1 equals an current frequency of 58 Hz.

The counter current tower aerators have their weir at 6.08 m+NAP. This is the head that the rapid sand filter pumps face upstream. During normal operation, two aerators are in use, and change according to a fixed scheme. Downstream of the aerators, the head in the pipes is determined by the level of the clear water reservoirs.

Calibration and validation. The pump speeds were derived from the logged current frequencies supplied to the pumps' engines. The relation between the pump speed ratio and the current frequency was calibrated. Pipe roughness coefficient k was kept constant during calibration and possible inaccuracies of measuring equipment were not taken into account.

For validation, eight data sets from the full-scale plant were used within the period June 30th to July 23rd 2008. From the data sets, the following inputs for the model were selected: well water level, the operation of the well pumps ('on' if flow exceeds zero), the operation of the cascades ('on' if flow exceeds zero), the operation of the rapid sand filters ('on' if flow exceeds zero), the water level in the rapid sand filters, the speed of the rapid sand filters' effluent pumps, the operation of the tower aerators and the estimated levels in the clear water reservoirs. Since the speeds of the two speed controlled well pumps lacked in the data set, the speeds of these pumps were set manually so that the yield of the well in the model equalled the yield in the historical data. The model results of the following parameters were compared with the historical data, i) flow per well (excluding the wells containing the two speed-controlled pumps), ii) flow per cascade, iii) influent per filter and iv) effluent per filter. For each validation two moments were selected with a minimum flow, July 7th at 23.30h and July 21st at 19.30h, two with an average flow, July 8th, 10.30h and July 17th, 10.30h, two with a maximum flow, June 30th, 15.30h and July 1st, 15.30h, and two during the backwash of a rapid sand filter, July 4th, 17.30h and July 23rd, 11.30h.

Drinking water treatment plant Wim Mensink

Layout. Drinking water treatment plant Wim Mensink, owned and operated by PWN treats artificially recharged dune water and consists of cascade aeration, pellet softening and rapid sand filtration, see Figure 3.4. The effluent of the rapid sand filters, after chemical dosing, is mixed with water from the reverse osmosis treatment plant Heemskerk. Lane 1 is preceded by pellet softening in fluidized bed reactors. The scope of the model is from dune water intake up to the cascades and contains 48 pipes, 81 junctions and 34 valves, see Figure 3.5. In the dune area pumps bring the collected water from the wells to Wim Mensink. The flow is divided over Lane 1 and 2 using two Ø 1000 mm butterfly valves of which the one passing the largest flow is fully open and the second is controlling. The K_v0 is 73510 $m^3/h \cdot bar^{1/2}$, the cross sectional area is 0.79 m^2, the $K(\alpha)$ as specified by the manufacturer is shown in Table 3.2.

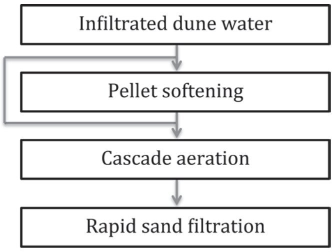


Figure 3.4. Treatment scheme of drinking water treatment plant Wim Mensink

Each of the six fluidized bed reactors of Lane 1 is 6.7 m high, has a 2.66 m diameter and treats 500 m^3/h, being 90 m/h. The reactor bottom is situated 6.0 m below the top of the reactor and contains 144 'PWN design' nozzles. The nozzles are modeled with TCVs with a fixed setting making the pressure drop over the nozzles increases with increasing flow.

The pressure drop over the fluidized bed is modeled with a PBV, because the pressure drop is considered to be constant during the single moment calculation. In the top of the reactor, the effluent is discharged via a weir, modeled with a PSV. The height of the water on top of the weir is small compared to the losses in the reactor and therefore neglected. The discharge of the effluent in the top of the reactor is situated 0.89 m below the top of the reactor.

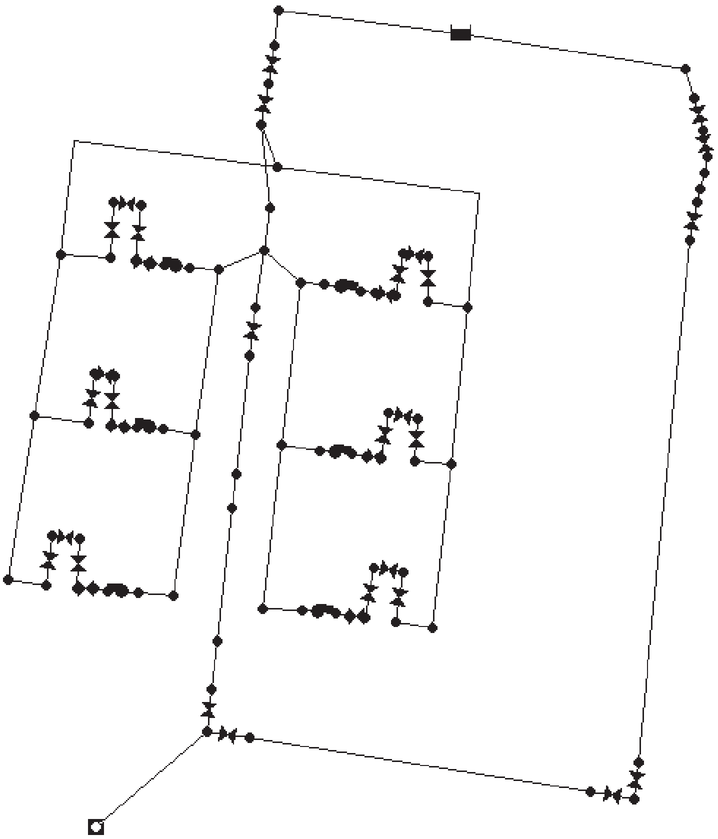


Figure 3.5. EPANET model of the softening plant and raw water supply of Wim Mensink.

Table 3.2. Manufacturer's specifications of the Wim Mensink inlet valves.

α [°]	K(α) [-]	
0	0	Closed
10	0	
20	0.02	
30	0.05	
40	0.1	
50	0.2	
60	0.3	
70	0.5	
80	0.9	
90	1	Open

Table 3.3. Calculation of head losses for the nozzles of the pellet softeners at Wim Mensink with $\xi = 7.4$.

$Q_{reactor}$ [m^3/h]	Q_{nozzle} [m^3/h]	v [m/s]	ΔH [m]
0	0	0.00	0
100	0.69	0.43	0.07
200	1.39	0.85	0.27
300	2.08	1.28	0.62
400	2.78	1.71	1.10
500	3.47	2.13	1.71
600	4.17	2.56	2.47

When the flow over Lane 1 is increasing, reactors are switched on according a fixed table. When the flow over Lane 1 is decreasing, reactors are switched off according a different fixed table. As a consequence in some cases more water is treated by the reactors than supplied. In that case, softened water recycles from the cascades back to the softening reactors. In the cascades the softened water is collected and mixed with the untreated flow.

Calibration and validation. From asset inspection reports, the manually logged pressure drop over the filter bottom was used to determine the average value of ξ over the nozzles was 7.4. With this ξ the relation between flow and pressure drop over the nozzles was calculated, see Table 3.3. Since the flow of the internal by-pass in Lane 1 is not measured and since the flow through the reactors is constant, the validation in the Wim Mensink model was the division of flows over Lane 1 and 2. Field data were collected in the period July 24th 2008 until January 12th 2009. Every time the setting of one of the two inlet valves changed a data point was taken. This occurred 21 times in the mentioned period.

Used hardware and software

The model was run on a HP/Compaq laptop, type 8510w (Intel core2 Duo CPU, 2.4 GHz) with operating system Windows XP 2002, servicepack 3. EPANET version 2.00.12 was used.

3.3 Results and discussion

Harderbroek model

Calibration. The calculated effluent flow of the rapid sand filters appeared to be consistently greater than the measured flow. The factors in the current frequency converter calculation were adjusted: a pump speed of 0 equals a current frequency of 13 Hz instead of 15 Hz and a pump speed ratio of 1 equals a current frequency of 56 Hz instead of 58 Hz. When the pressure drop measurements over the filter beds of filters 5, 6 and 8 appeared to be unrealistically small, the pressure drop was estimated by subtracting the pressure measured in the effluent pipe from 26 kPa, being the average pressure in a non-operating filter. During the validation of the effluent of rapid sand filters in four cases, most probably as a consequence of acceleration during start-up, pump speeds were more than 20% below the low value of the normal range. In these cases, the pump speeds were replaced by the average speed of the pump and the results were excluded for the validation.

Validation. For the wells 55 data points were collected of which 41 (75%) lay within the 5% band around the equivalent line, see Figure 3.6. The average of the absolute errors was 3.6%. In the same way as shown in Figure 3.6, the cascade aerators, the influent flow of the rapid sand filters and the effluent flow of the rapid sand filters were analyzed, see Table 3.4.

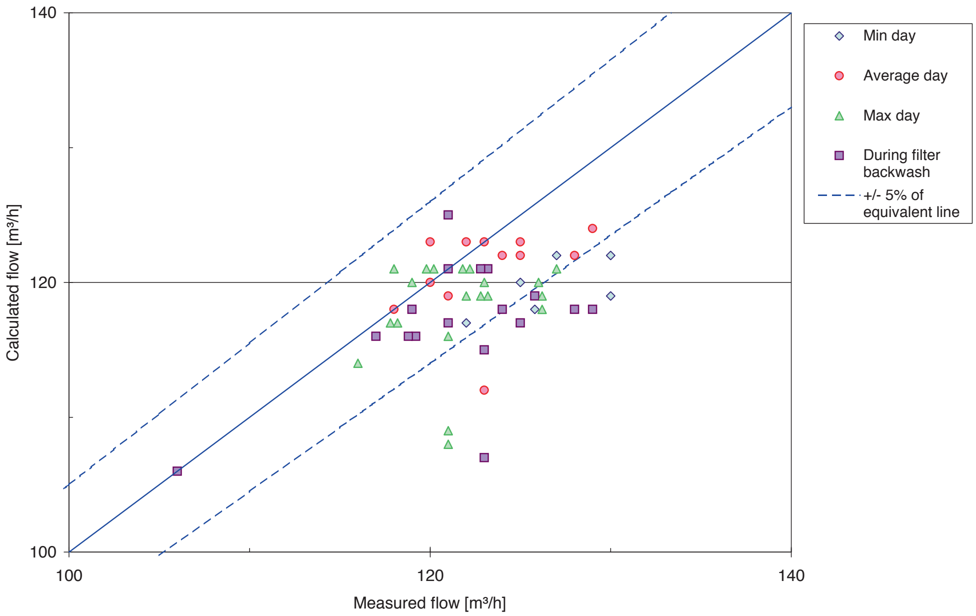


Figure 3.6. Validation results of flows from wells at Harderbroek.

Table 3.4. Results for the validation of the Harderbroek model.

	Number of datapoints [-]	**Mean absolute error [%]**	**Ratio of points within 5% bandwith of equivalent line [%]**
Wells	55	3.6	75
Cascade aerators	22	2.4	95
Influent flow rapid sand filters	34	4.5	68
Effluent flow rapid sand filters	30	2.8	93

Wim Mensink model

Validation. Table 3.5 shows the TCV settings (ξ) for the inlet valves of Wim Mensink as a function of the opening angle α, as calculated with Equation (3.8). The settings were needed to model the division of flows over Lane 1 and Lane 2. Figure 3.7 shows the comparison of the measured flow and the flow as calculated by the model for the 21 selected moments of which 86% lay within the 5% bandwidth around the equivalent line. The Pearson correlation coefficient R of Lane 1 is 0.998 and 0.995 for Lane 2, indicating the model results and historical data were closely related.

Table 3.5. Settings in EPANET for the inlet throttle control valves (TCV) of Wim Mensink for opening angles α.

α [°]	TCV setting [-]	
0	inf	Closed
10	inf	
20	1315	
30	146	
40	30	
50	9.1	
60	3.3	
70	1.2	
80	0.37	
90	0.30	Open

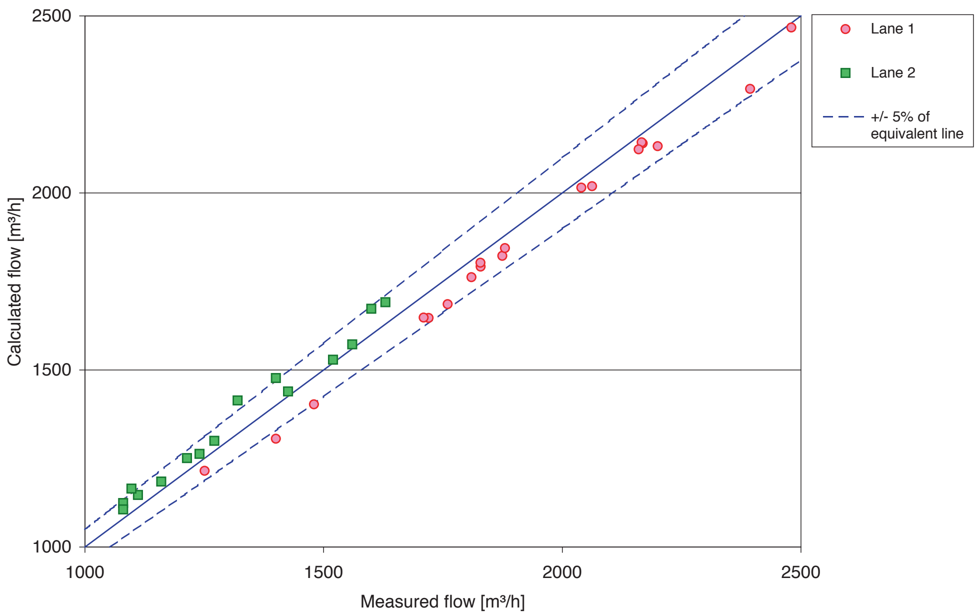


Figure 3.7. Validation of division of flows over Lane 1 and Lane 2 at Wim Mensink.

3.4 Conclusions

Modeling software EPANET can be used to model the hydraulic behavior of drinking water treatment plants by using the library described in this chapter. With the model the effects of interventions in operation on the division of flows over the plant's lanes or units can be calculated. The library contains models for a well, a cascade aerator, a rapid sand filter and a tower aerator, formed by a series of the basic EPANET elements valves, reservoirs, junctions and pipes. Two models were set up, for water treatment plants Harderbroek and Wim Mensink and validated with historical full-scale plant data. The models can be used as a part of an online or offline integrated system for control simulation.

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4

Evaluation of control strategies for drinking water treatment plants using a process model

Based on

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Journal of Water Supply: Research and Technology - AQUA (under review)

Abstract
In this chapter the set up and validation of a Stimela water quality model is described, being one of the two process models feeding the smulator with the plant's process' behavior. The model is used to add a method to evaluate control strategies to the design methodology for drinking water treatment plants. Using the process model, the existing control strategy of a pellet softening treatment step was compared with a new control strategy and the effects of two different sets of input data were studied. It was demonstrated that the efficiency of the pellet softening process and the plant's capacity would increase, and that chemicals and energy usage would be reduced. At the same time, the deviation of the total hardness of the produced water to the desired value would decrease. The research indicates that the stand-alone use of Stimela satisfies for the evaluation and optimization of process control.

Keywords
Control; control-design methodology; process model; drinking water treatment; control strategy evaluation.

4.1 Introduction

In the Netherlands, the operation of drinking water treatment plants has changed over the last seven years. Permanent 24/7 watches have been abandoned and were replaced by a centralized and fully automated operation. The level of automation in water supply companies has increased from human control up to the level of remote multi-task supervisory control (Sheridan, 2002). Although the operation supervisor is still responsible for the drinking water treatment and distribution, process automation software plays an increasing important role. As a consequence more attention should be (and is) paid to the design and testing of new process automation software.

For control-design of a single step of a drinking water treatment plant a methodology has been set up (van Schagen *et al.*, 2010). The methodology takes the specific properties of a drinking water treatment plant into account compared to a classical chemical plant, like the direct dependency of the customers' consumption and the production setpoint, the impossibility to discharge off-spec material and laboratory measurements of water quality which have a delay of several days to weeks. Often, multiple control strategies will be able to meet the objectives within the operational constraints. The methodology by van Schagen however, lacks a way to determine the optimal control strategy. The definition of optimal depends on the company's, plant's and treatment steps' objectives and constraints. The hypothesis in this study is that a process model is a valuable tool to evaluate alternative control strategy designs with predetermined criteria and to determine their ability to meet operational objectives and constraints dynamically in the same way as has been reported for waste water treatment plants (Stare *et al.*, 2007; Vrecko *et al.*, 2006)

This approach has been applied full-scale to drinking water treatment plant Wim Mensink of PWN. To reduce the discharge of reverse osmosis (RO) water to the dune area, a new, more flexible, control strategy for the pellet softening was designed with the control-design methodology for drinking water treatment processes. In this research the evaluation of the current and a new control strategy is described, using the process model Stimela (van der Helm and Rietveld, 2002). An objective and realistic evaluation of a control-design and its expected effects on the produced drinking water is of interest for operation supervisors, control engineers, process engineers and managers.

4.2 Materials and methods

Wim Mensink

The Wim Mensink plant (production capacity 7200 m^3/h) forms an integrated system with the conventional drinking water treatment plant Bergen and the ultrafiltration/RO plant Heemskerk, see Figure 4.1. For reasons of process stability, the RO plant produces a fixed flow of 2100 m^3/h. At Bergen (production capacity 4200 m^3/h) conventionally treated wa-

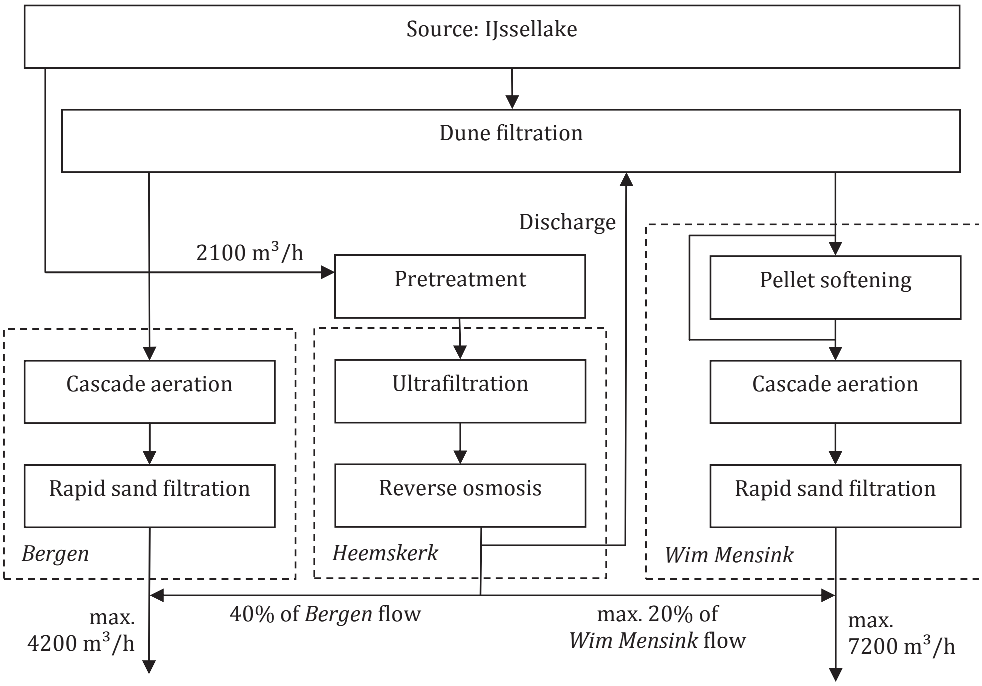

Figure 4.1. The Bergen, Wim Mensink, Heemskerk drinking water treatment system.

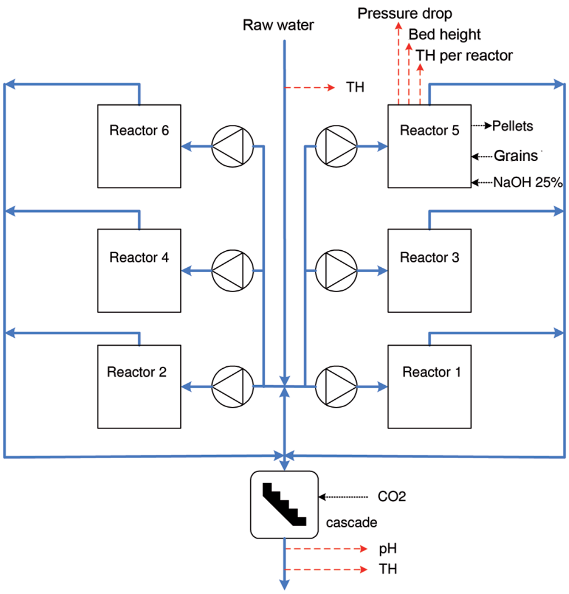

Figure 4.2. Detail of the layout of the pellet softening treatment step. Blue lines are water flows, red dotted arrows are online measurements, small black arrows are control actions. TH is total hardness.

ter is softened by mixing with RO water in a fixed ratio. The water treated at Wim Mensink is softened by mixing with RO water and by applying pellet softening. Because of the fixed production of RO water at Heemskerk and varying flow needed in Bergen, a varying flow of RO water is available for Wim Mensink. Since RO water was supplied to Wim Mensink in a fixed ratio of the produced water as well, sometimes not all RO water can be supplied to Bergen and Wim Mensink. Approximately 10 percent of the produced RO water (1.7 Mm^3/year in 2007 and 2008) was discharged into the dune area.

The Wim Mensink drinking water treatment plant has two lanes. Since the pellet softening is exclusively part of Lane 1, Lane 2 is a by-pass for the pellet softening treatment step. In the current control strategy Lane 1 treats a fixed ratio of 2/3 of the raw water and Lane 2 treats 1/3. Within Lane 1 a second by-pass is available, see Figure 4.2. If the raw water supply to Lane 1 exceeds the water extracted by the softening reactors, the remaining untreated water flows through this by-pass to the cascades directly. If less water is supplied to Lane 1 than extracted by the reactors, water flows from the cascades to the reactors, so in the reverse direction, causing recirculation.

Control strategies

The control-design methodology for drinking water treatment processes consists of five steps; i) determine plant-wide control objectives, ii) determine operational constraints, iii) identify important disturbances, iv) determine controlled variables and v) determine the control configuration.

Table 4.1 shows the control objectives (step 1) using the six controlled variables (step 4) of the Wim Mensink case. The most relevant operational constraints (step 2) are listed in Table 4.2. The most relevant disturbances (step 3) have been derived from historical data in 2007 and 2008 and are listed in Table 4.3. In the control configuration (step 5), not more than three control actions are available which can be used to realize the objectives; i) the RO flow, ii) the number of active reactors and iii) the positions of the valves at the lanes' inlets, see Figure 4.3.

Table 4.1. Controlled variables and control objectives for the Wim Mensink case. TH is total hardness, SI is saturation index.

Controlled variable	Objective	Level
Discharge of RO water	Minimal	Company
$TH_{clear\ water\ reservoir}$	Average 1.5 mmol/l, 1.4 to 1.6 mmol/l in 95% of time	Plant
$SI_{clear\ water\ reservoir}$	Between -0.1 and 0.3	Plant
CO_2 dosage	Minimal	Treatment step
NaOH dosage	Minimal	Treatment step
Number of switching of reactors	Minimal	Treatment step

Table 4.2. Operational constraints for the Wim Mensink case. SI is saturation index.

Parameter	Constraint	Level
Available RO water flow for Wim Mensink	Between 0 and 1300 m^3/h	Company
Production flow	As calculated by daily-demand-prediction software Plenty Control	Plant
Flow per lane	Maximum 3600 m^3/h	Plant
$SI_{effluent\ cascade\ Lane\ 1}$	Between -0.1 and 0.3, to prevent crystallization in the sand filters	Plant
Flow through pellet softening reactors	$n \cdot 500$ m^3/h, with n = number of active reactors	Treatment step
Recirculation within Lane 1	Prevented	Treatment step
Minimal NaOH dosage	50 l/h to prevent dripping nozzles	Reactor

Table 4.3. Most relevant disturbances for the Wim Mensink case. TH is total hardness.

Disturbance	Range	Level
Daily decrease or increase of RO water flow	0 - 300 m^3/h	Company
Daily decrease or increase of production flow	0 - 900 m^3/h	Plant
Variation in $pH_{raw\ water}$	7.5 - 8.1	Plant
Variation in $TH_{raw\ water}$	2.2 - 2.7 mmol/l	Plant

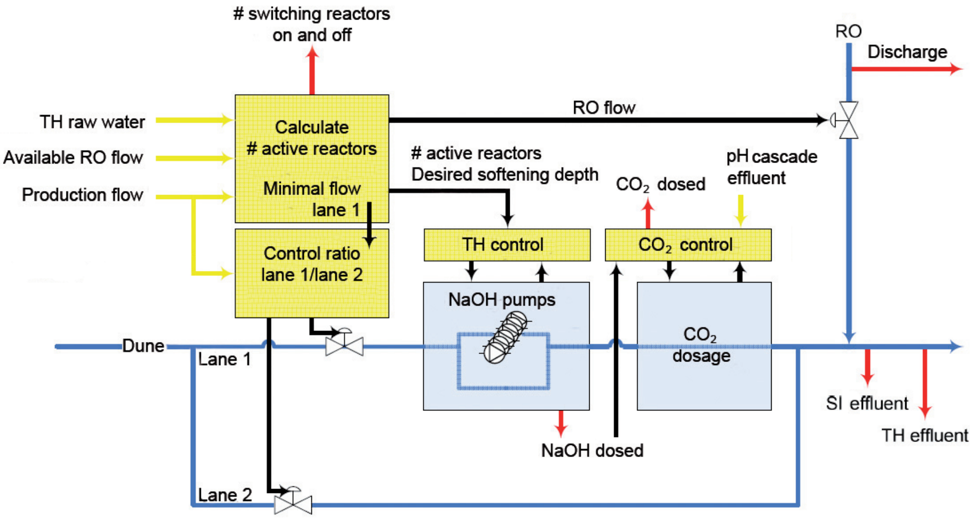

Figure 4.3. Control configuration for the Wim Mensink case. Blue lines are the water flows, yellow arrows are the online measured parameters. Red arrows are the controlled variables, black arrows are the control actions.

Current control strategy. In the current control strategy (CS0) the number of active reactors depends on the flow over Lane 1, see Table 4.4. The NaOH 25% (caustic soda) dosage is calculated with

$$Q_{NaOH25\%} = Q_{Lane1} \cdot \left(\left(TH_{raw} - TH_{Lane1} \right) + \left(TH_{casc} - TH_{Lane1} \right) \right) \cdot \alpha \tag{4.1}$$

where $Q_{NaOH25\%}$ is the total caustic soda 25% flow [m^3/h], Q_{Lane1} is the flow over Lane 1 [m^3/h], TH_{raw} is the total hardness (TH) of the raw water [mol/m^3], TH_{Lane1} is the setpoint for TH in the cascades of Lane 1 [mol/m^3], and TH_{casc} is the TH in the cascades of Lane 1 [mol/m^3]. Constant α [m^3/mol] is calculated with

$$\alpha = \frac{MW_{NaOH} \cdot \beta_{dilution}}{\rho_{NaOH\,diluted}} \tag{4.2}$$

where MW_{NaOH} is the molecular weight of caustic soda [kg/mol], $\beta_{dilution}$ is the dilution factor [-] and ρ_{NaOH} diluted is the density of the diluted caustic soda [kg/m^3]. In this case α is 0,000125 m^3/mol. It represents the volume caustic soda 25% in m^3 needed to lower the TH of 1 m^3 of water with 1 mmol/l. The pellet discharge is based on the pressure difference over the fluidized bed: when the pressure difference is exceeded the three discharge valves in the bottom of the reactor open one by one during a fixed period. A fixed amount of grains is dosed, when a predetermined weight of calcium, representing a number of pellets, has been removed. A fixed weight of grains is dosed, representing the same number as pellets discharged. CO_2 is dosed in the upper cascade in a fixed ratio with the NaOH flow (master control) and fine-tuned on the online measured pH in the cascade effluent (slave control) using a Siemens DR24 and two Siemens DR21 hardware PI-controllers. The flow ratio over Lane 1 and Lane 2 is 2:1 to maximize the by-pass and minimize recirculation. But, this ratio leads to unequal loads of the cascades and rapid sand filters. The value of the ratio is stored as a constant in the MES-application Plenty Control. Control strategy CS0+ differs from CS0 in the control of the bed height (higher) and discharge of pellets (smaller) to increase the available crystallization surface in the reactor.

Table 4.4. Switching on and off reactors depends on the flow over Lane 1.

Reactor	Setpoint switching on reactor [m^3/h]	Setpoint switching off reactor [m^3/h]
1st	450	400
2nd	666	500
3rd	1700	1100
4th	2000	1750
5th	2666	2300
6th	3100	2500

New control strategy. Based on the objectives, operational constraints, possible disturbances and the controlled variables, a new control strategy (CS1) was set up, which calculates the lowest possible number of active reactors based on the maximum removal of TH per reactor. A minimal number of active reactors yields a maximum by-pass and maximum softening depth per reactor which leads to maximum efficiency in the crystallization kinetics and thus maximum saving of NaOH (van Schagen *et al.*, 2006). The total NaOH dosage is calculated from the desired removal of TH (master, P-controller) and fine tuned on the measured TH of the mixed water of Lane 1, Lane 2 and RO water (slave, PI- controller) using a Siemens S7 PLC. The total NaOH dosage is independent of the number of active reactors. The pellet discharge aims to discharge pellets of a constant size. To be able to do so, pellets are discharged when the pressure difference over the lowest half meter of the reactor exceeds a threshold. Grains are dosed based on the online measured bed height. The control of the CO_2 dosage is equal with the CO_2 dosage of CS0 and CS0+. As described in the previous chapter, flow through a treatment step is one of the most important parameters in terms of its effectiveness (Worm *et al.*, 2009). To maximize the filters' effluent quality, equal flows over the cascades and rapid sand filters are preferred over the unequal division of flows in the current control strategy. Therefore, for CS1, the flow ratio over Lane 1 and Lane 2 will be equal as long as enough water is supplied to Lane 1 to prevent recirculation within Lane 1.

Stimela process model

Applying the ten steps of good modeling practice (Rietveld *et al.*, 2010) a Stimela process model was set up. The model calculates the water quality through a drinking water treatment plant dynamically and is used to calculate to what extent the control objectives are met. In this research for each control strategy the control rules were grouped in a separate file. Linking points were added for setpoints (input) and measurements (output) (van der Helm *et al.*, 2009). The calibrated pels25_s_c module describes the fluidized bed behavior and the crystallization of a pellet softening reactor (van Schagen *et al.*, 2008a; van Schagen *et al.*, 2008b). To limit calculation time, a single pellet reactor was modelled. The effluent quality of this reactor was assumed to represent the quality of the other five reactors as well. Like pellet softening, aeration and mixing of different water qualities affect the calcium-carbondioxe equilibrium. To model the water quality the aeration module cascad_s_c was used in the model.

Table 4.5 shows the specifications of the model runs. Model run 1 was done to validate the model. In run 1, run 2 and run 3 the input data were equal, but the control strategy differed. To determine the adaptation of the model and the new control strategy CS1 to perturbations, in run 4 all available RO water was supplied to Wim Mensink and, to compensate, less raw water was taken in. The input parameters for the model are specified in Table 4.6.

Model calibration and validation

The validation of the model, run 1, was done with field data from the full-scale plant. For validation, bed height measurements were taken weekly by lowering a disk in the reactor until it reaches the fluidized bed (accuracy +/- 0.05m), covering a period of 50 days. In the same

Table 4.5. Summary model runs.

Run	Control strategy	Input data	Initial state
1 (validation)	CS0 (current control)	Historic	Bed height 3.2m
2	CS0+ (current control, higher bed)	Historic	Bed height 4m
3	CS1 (new control)	Historic	Bed height 4m
4	CS1 (new control)	Historic, but more RO water and less raw water	Bed height 4m

Table 4.6. Model input data Stimela model Wim Mensink.

Parameter	Unit	Location	Measurement	Frequency
Flow	m^3/h	Raw water Lane 1	Online	1/2 hours
		Raw water Lane 2	Online	1/2 hours
		Supplied RO water	Online	1/2 hours
Temperature	˚C	Influent RO water	Laboratory	1/week
		Influent raw water	Laboratory	1/week
Conductivity	mS/m	Influent RO water	Laboratory	1/week
		Influent raw water	Laboratory	1/week
$[Ca^{2+}]$	mg/l	Influent RO water	Online	1/2 hours
		Influent raw water	Laboratory	1/week
$[Mg^{2+}]$	mg/l	Influent RO water	Laboratory	1/week
		Influent raw water	Laboratory	1/week
$[HCO_3^-]$	mg/l	Influent RO water	Laboratory	1/week
		Influent raw water	Laboratory	1/week
pH	-	Influent RO water	Laboratory	1/week
		Influent raw water	Laboratory	1/week

period, pellet size distributions were determined weekly by sieving samples that were taken each half meter over the height of the bed. The data was acquired in the period January 20th 2009 until March 10th 2009. A stable initial state was made by running the model for 90 days prior to January 20th 2009 with historical input data. First the control of the fluidized bed of a single reactor was validated for the parameters listed in Table 4.7. Then the controls of the water quality of Lane 1 and the complete treatment plant were validated for the parameters listed in Table 4.8.

For the calibration and validation results based on online measurements, the root mean square (RMS) error is calculated, with

$$\varepsilon(t) = y(t) - y_m(t) \tag{4.3}$$

Table 4.7. Validation parameters single reactor.

Parameter	Unit	Location	Type of measurement	Frequency
Bed height	m	Reactor 4	Manual by lowering disc	1/week
Pellet diameter	mm	In each of seven layers in reactor 4	Manual by sieving samples	1/week
TH	mmol/l	Reactor 4	Online	1/hour
NaOH dosage	l/h	Reactor 4	Online	1/2 hour

Table 4.8. Validation parameters Lane 1 and clear water reservoir.

Parameter	Unit	Location	Type of measurement	Frequency
SI	-	Effluent cascade aerator	Calculated by laboratory	1/week
		Clear water reservoir	Calculated by laboratory	1/week
TH	mmol/l	Effluent cascade aerator	Online	1/15 min
		Clear water reservoir	Online and	1/15 min
			calculated by laboratory	1/week

where *y(t)* is the measured value at time *t* and $y_m(t)$ is the model output at time *t*, and

$$RMS = \sqrt{\frac{1}{n}\sum_{t=1}^{n}\varepsilon^2(t)} \qquad (4.4)$$

To calculate the normalized RMS error, the RMS error is divided by the historical data mean.

Evaluation criteria

The controlled variables and objectives (step 1 and 4, shown in Table 4.1) and operational constraints (step 2, shown in Table 4.2) define an optimization problem with the optimal control strategy as a result. Three out of the six controlled variables have been selected as evaluation criteria, i) the average TH in the clear water reservoir, ii) the RO discharge, and iii) the average total NaOH dosage. The desired TH in the clear water reservoir is 1.5 mmol/l. The discharge of RO water into the dune area [m^3/h] should be minimal to save costs, chemicals and energy. The discharge was calculated by extracting the RO flows transported to Bergen and Wim Mensink from the production flow of Heemskerk. A minimal NaOH dosage [l/h] leads to reduction of costs and reduction of emission of greenhouse gases during production (being aware that NaOH is a by-product of the chlorine production) and transport. A fourth criterion is the NaOH efficiency [mmol · h/l^2] which is calculated by dividing the average amount of removed calcium through the average NaOH dosage.

Software availability

Stimela version 10.6 was used, running on the Matlab® (version 7.9.0.529, R2009b) and Simulink® (version 7.2, R2009b) platform. Stimela is owned by DHV water and Delft University of Technology. The latest version can be downloaded from www.stimela.com when logged in. The used data comes from the production Aspentech IP21 database owned by PWN. The model was run on a HP/Compaq laptop, type 8510w (Intel core2 Duo CPU, 2.4 GHz) with operating system Windows XP 2002, servicepack 3.

4.3 Results and discussion

Model calibration and validation

The original value of the diffusion coefficient in the pellet softening model, $2.67 \cdot 10^{-11}$ m^2/s, was derived from data from the Weesperkarspel pilot plant (van Schagen, 2008a). To calibrate the TH of the effluent of reactor 4, the diffusion coefficient of the pellet softening model was increased to $9 \cdot 10^{-10}$ m^2/s. As a consequence, the normalized RMS error of the TH in

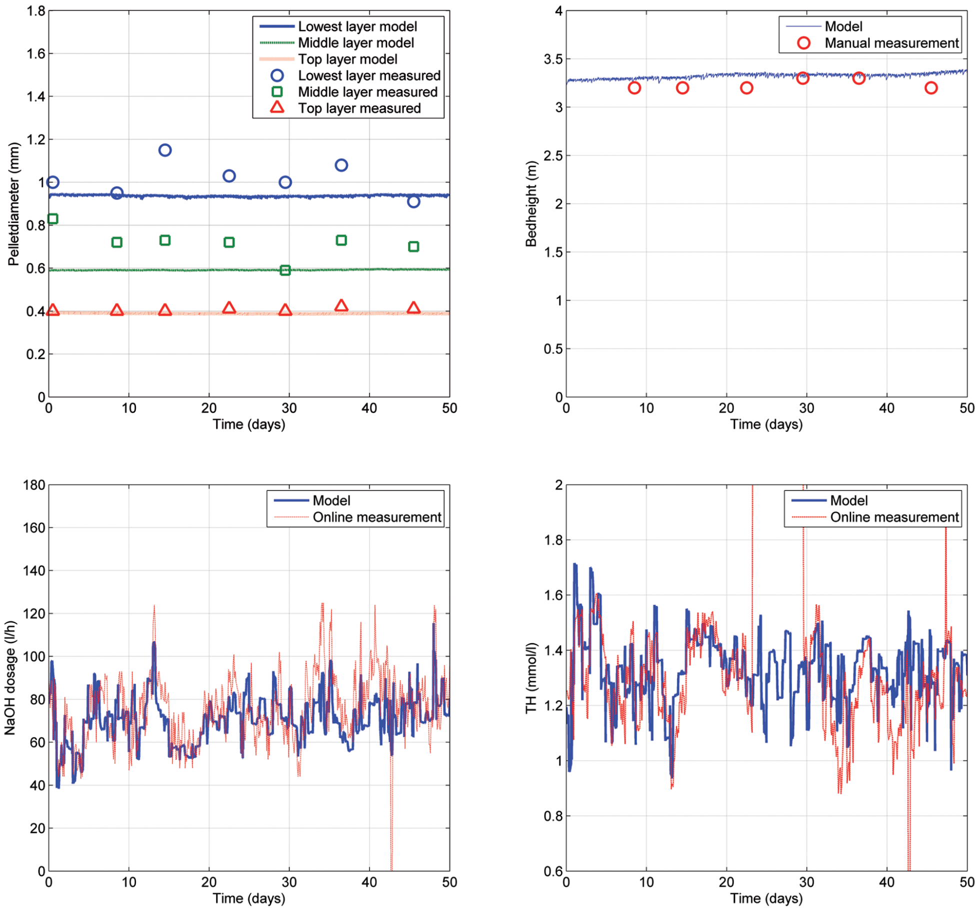

Figure 4.4. Validation results for reactor 4. Pellet size distribution (top left), bed height (top right), NaOH dosage (bottom left) and TH (bottom right).

reactor 4 decreased from 15.5% to 10.6%. Figure 4.4 shows the results of the validation of the modeled control of the fluidized bed, of the NaOH dosage, and of the validation of the removal of calcium in reactor 4. The difference between the measured specific diameters of the pellets and the modeled pellet diameters is caused by the fact that the samples are taken at the lowest part of each layer, while the model calculates a single value for each layer. The extreme peak in online measured data of the TH of reactor 4 between day 23 and 29 and on day 43 is explained by a failing measuring device (the data of the other active reactors showed the same extremes). The average number of pellet discharges in the full-scale plant is five times per day, which approximates the average of six times per day of pellet discharges in the model. Figure 4.5 shows the results of the validation of the modeled water quality in the effluent of the cascade of Lane 1. The saturation index (SI) was calculated by the laboratory from samples. The dissolving of CO_2 in the upper cascade is incomplete as a consequence of

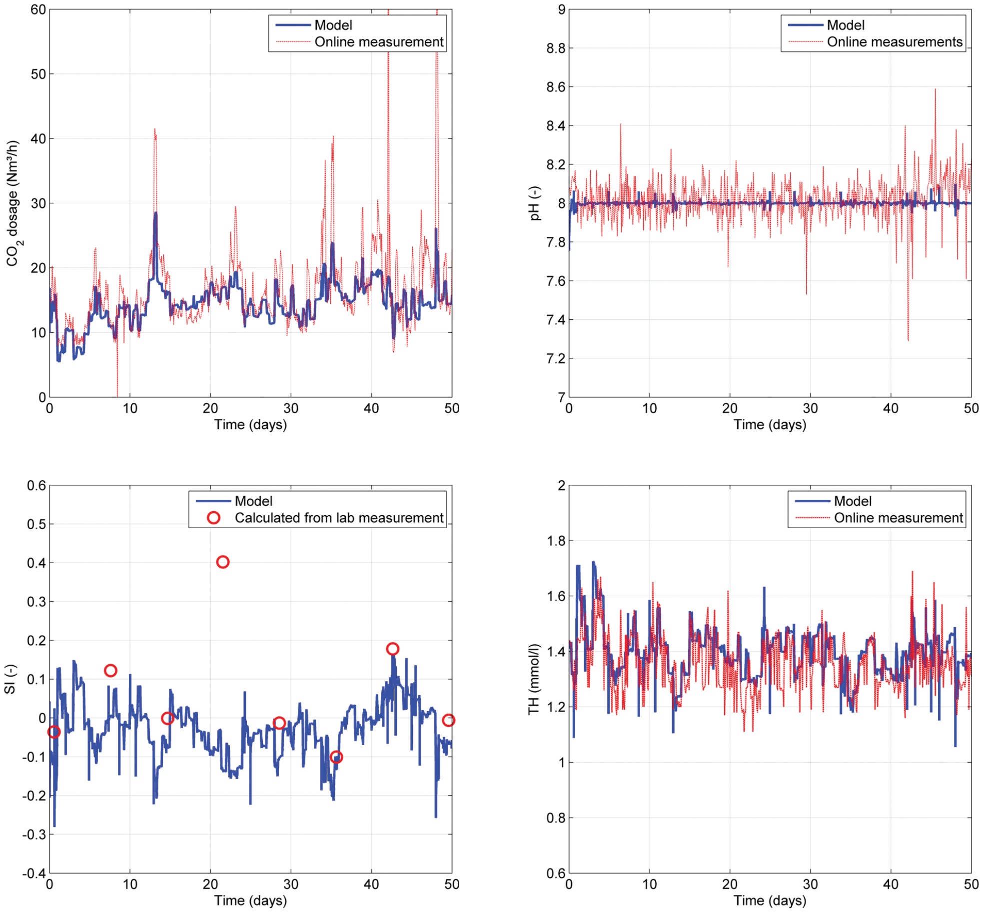

Figure 4.5. Results validation Lane 1. CO_2 dosage (top left), pH (top right), SI (bottom left) and TH (bottom right).

degassing and turbulence in the cascade. To compensate for this ineffectiveness, a factor for CO_2 dissolving efficiency of 0.35 was introduced.

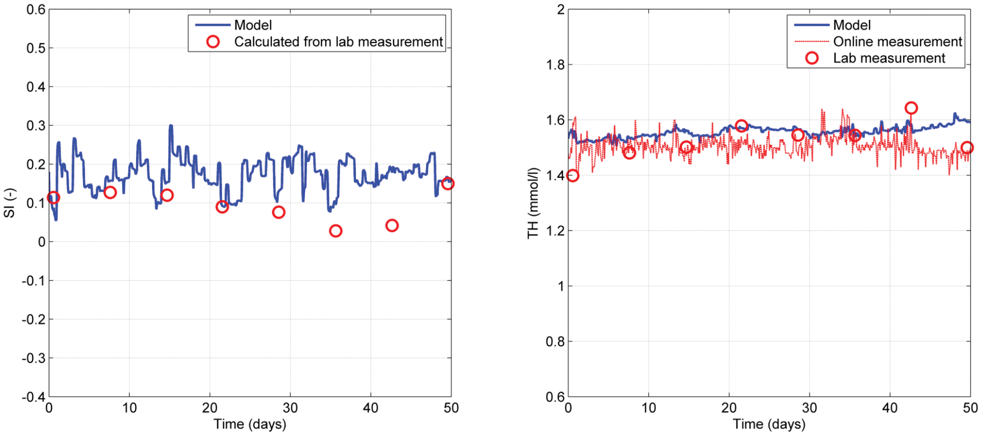

Figure 4.6. Results validation clear water reservoir. SI (left) and TH (right).

Table 4.9. Root mean square error (RMS) for a selection of validation parameters.

Location	Parameter	RMS error	Normalized RMS error [%]	Excl. extreme days
Reactor 4	NaOH dosage	13 l/h	17	Day 42
Reactor 4	TH	0.14 mmol/l	11	Days 23-29 and 42
Lane 1	CO_2 dosage	4.0 Nm^3/h	24	Days 8, 42 and 48
Lane 1	pH	0.11	1.4	
Lane 1	TH	0.09 mmol/l	6.8	
Clear water reservoir	TH	0.07 mmol/l	4.5	

Table 4.10. Summary results case Wim Mensink.

Run (control strategy)	Average number of active reactors [-]	Average total NaOH dosage [l/h]	Average TH clear water reservoir [mmol/l]	Efficiency [$mmol \cdot h/l^2$]	RO discharge [10^3 m^3/h]
1 (CS0)	4.38	310	1.56	0.0144	33
2 (CS0+)	4.38	308	1.55	0.0146	33
3 (CS1)	3.94	332	1.50	0.0146	33
4 (CS1)	3.81	322	1.50	0.0145	0

Figure 4.6 shows the results of the validation of the modeled TH and SI after mixing in the clear water reservoir. Table 4.9 shows the RMS error according Equation 4.4 and normalized RMS error for the online measured parameters shown in Figures 4.4, 4.5 and 4.6. As shown in Table 4.10, the average total NaOH dosage in run 1 is 310 l/h. At Wim Mensink in the period January 20th 2009 until March 10th 2009, according the waybills, 268 ton NaOH 50% was delivered (nine truckloads), equaling an average flow of 357 l/h. Operators mention a small chance that a load was unloaded at a different site than mentioned on the waybill, which might explain the difference. Concluding, the results in Figures 4.4, 4.5, and 4.6 and Table 4.9 show the model can be used for the purpose of this research, evaluating control strategies, especially when considering that field data was used to calibrate and validate.

Evaluation of the new control strategy

The comparison of runs 1 and 2 demonstrate that the increase of crystallization surface in the reactor will lead to a decrease of the NaOH dosage, and to an increase of the efficiency, see Table 4.10. As a consequence of the latter the TH in the clear water reservoir will decrease and will approach the desired TH of 1.5 mmol/l more closely, see Figure 4.7. The main yield of the new control (run 3 and run 4) will be a more constant TH, approaching the desired value of 1.5 mmol/l closely. Since the efficiency of run 3 is equal with run 2, the higher NaOH dosage in run 3 is caused exclusively by deeper softening leading to the desired TH of 1.5 mmol/l in the clear water reservoir. When compared with runs 1, 2 and 3, in run 4, a RO water discharge of $33 \cdot 10^3$ m^3 could be prevented and the average number of active reactors could be reduced from 4.38 to 3.81, thus increasing the softening capacity. The capacity of

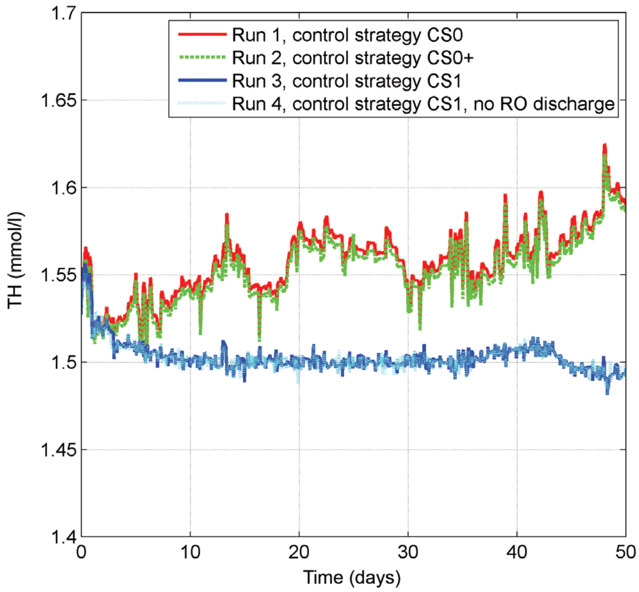

Figure 4.7. TH in the clear water reservoir for run 1 and 2 (upper lines) and for runs 3 and 4 (lower lines).

the plant as a whole could be increased by dividing the flow over Lane 1 and Lane 2 equally. In the present situation, the plant's capacity is limited by the flow over Lane 1, being 2/3 of the total flow. Run 4 shows a decrease of the NaOH dosage as a consequence of the extra RO water supplied and a lower efficiency of the pellet softening compared to run 3, because less water would be softened with the pellet softeners.

So, using the process model it was demonstrated that compared with the present control strategy, the new control strategy would lead to a better water quality in the clear water reservoir, would prevent RO water discharge, would limit the NaOH dosage and would limit the number of active reactors. The reduction of RO water discharge with $33 \cdot 10^3$ m^3 over the 50 days studied would save at least 3 k€ (circa 20 k€/year) on energy and chemicals. The field data was taken in a period when the production of RO water was limited with circa 20% due to maintenance. If the plant would have operated on design capacity, more RO-discharge would have been prevented and, as a consequence, more NaOH would have been saved.

4.4 Conclusions

This research focused on the evaluation of control strategies, set up in the last step of control-design methodology for drinking water treatment plants. The objective was to show that a dynamic process model is a valuable tool to evaluate alternative control strategies for drinking water treatment plants and to determine their expected effectiveness in a short time. The process model Stimela was extended with a separate file with the control rules and points to link to in the model. It was applied to the pellet softening of the Wim Mensink drinking water treatment plant. With the new control strategy the softening and treatment capacity of Wim Mensink could be increased, the TH of the water in the clear water reservoir could be controlled exactly on the desired value of 1.5 mmol/l and the efficiency of the NaOH dosage could be improved. The discharge of RO water could be reduced with $33 \cdot 10^3$ m^3 over the 50 days studied, saving at least 3 k€ (circa 20 k€/year) on energy and chemicals.

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5

Training and assessment with a faster than real-time simulation of a drinking water treatment plant

Based on

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Abstract
The usefulness of a human-in-the-loop drinking water treatment plant simulator was investigated for training and assessment. An in-simulator transfer of training experiment was conducted with three groups training with accelerated simulation, experienced operators (EO), inexperienced operators (IO), and laymen (L60x) and a group of laymen training at real-time speed (L1x). Participants learnt how to improve water quality during training. Upon transfer, when confronted with a different process disturbance than during training, L60x performed significantly poorer than EO and IO combined. No difference was found between EO and IO, and during transfer, L60x outperformed L1x. These results indicate that learning to control slow and complex processes may improve by training with a realistic simulation running at accelerated speed.

Keywords
Training; simulator; acceleration; drinking water.

5.1 Introduction

In applications such as aviation (Salas *et al.*, 1998), medical education (Scalese *et al.*, 2007), car driving (de Winter *et al.*, 2009), and defense (Hone and Morrison, 1997) human-in-the-loop simulators are widely used for decision support, training and assessment (Sheridan, 2002), as well as for knowledge elicitation (Edwards *et al.*, 2004). In drinking water treatment plants, process simulation is used for model-based process optimization (Rietveld *et al.*, 2008) and economic optimization (Douveneau *et al.*, 1997). The need for a human-in-the-loop training simulator in drinking water treatment has not yet been felt, because the treatment processes are relatively slow and short term risks are limited. This will change because emulation software and process models become economically available and because the public becomes less tolerant for interruption of the delivery of gas, electricity and drinking water. Furthermore, as in other industries, the level of automation in water supply companies has increased during the past decades from direct human control up to remote multi-task supervisory control. The development of automation was encouraged by the advantages over human control, like the duration of effort, accuracy, reliability and costs. However, the increased use of automation has led to alienation of the human operator from the process (Sheridan, 2002) and has lead to a change in the necessary skills and knowledge of operators (Bainbridge, 1993).

Remote multi-task supervisory control is more complex than a manually controlled system, because multiple processes, sensors, actuators, and control- and communication software are involved. The more advanced a control system is, the more crucial is the contribution of the human operator. The most complex and/or least frequent occurring tasks have not been automated for economic and maintenance reasons, leaving these tasks for operators who, as a consequence of automation, lack natural frequent hands-on training. Fully automated operation does not change the fact that the operator is responsible for the drinking water delivery (Wu *et al.*, 2009); his responsibility has even increased, since the span of control has increased (Worm *et al.*, 2007).

Indeed, the task of water treatment plant operators has become a supervisory task, in which he or she is continuously checking and monitoring the automation settings and protective rules. Most often the process automation is working well, which may make operators inattentive (Bruzzone *et al.*, 2007; Olsen and Rasmussen, 1989). But when a plant upset occurs, the operator needs to process a large amount of information. In this case, the operator first may have to reclaim control and stabilize the process and then diagnose and solve the fault. For the former he will need most manual skills, for the latter cognitive skills. To be able to generate alternative strategies for the unusual situation and to be able to check proper functioning of protective rules in the automation system, the operator needs to have in-depth knowledge of the process. Efficient retrieval of this knowledge depends on the frequency of use of this knowledge (Bainbridge, 1983). And the knowledge is not static, since the process and process' conditions change over time.

At modern drinking water supply companies, operators are involved in several tasks related to the drinking water treatment process. During this normal task performance (inspecting the treatment plant, shutting down and starting up parts of the plants for reasons of maintenance or upsets, advise during renovation of existing installations or building of new ones) skill- and rule based levels of performance (Rasmussen, 1983) will increase. During this normal performance operators will rarely experience extreme situations with a possible major impact on the drinking water delivery to customers. A human-in-the-loop simulator addresses the concern that the present generation of automated systems is monitored by former manual operators, relying on skills that the new generation of operators does not have.

This chapter focuses on the possibility to train interventions in slow processes. Most processes in drinking water treatment can be classified as slow. The residence time of water in a treatment plant (time in the reservoirs excluded) is approximately half an hour, a filter run of a rapid sand filter takes days, and the recovery of a disturbed fluidized bed in a pellet softening reactor can take tens of days. Humans are expected to have more problems controlling a process with a time scale of weeks to months than controlling a process with a typical time scale of minutes.

The concept of faster than real-time training (or above real-time training) has been applied in training of military pilots. It has been shown that accelerated simulator training yields to faster and equally accurate tracking of a target (Guckenberger and Stanney, 1995; Hone and Morrison, 1997) compared to real-time speed training. Accelerated simulation training has demonstrated to increase performance, increase retention during transfer runs (Donderi *et al.*, 2010), and reduces stress (Miller *et al.*, 1997) compared to real-time simulation training. The training time is reduced leading to a higher attention level during the training. A possible disadvantage is that acceleration results in too aggressive control when transferring to the slow, real process.

This study uses a drinking water treatment plant simulator called Waterspot, in which participants can manually or, if desired, partially automatically control a virtual drinking water treatment plant. During a simulation, every change of a (virtual) pump's speed, a valve's position or a chemical dosage, has an effect on the division of flows in the treatment plant and/or on the chemical properties of the water. Models are an essential part of the simulator since they represent the behavior of the treatment plant's processes. The models have been calibrated and validated for the specific plant. The fidelity of the simulator is medium; the user interface has a realistic SCADA setup, but it is simpler than the user interface of a real plant's automation system. Various scenarios, like switching on and off reactors, failing of pumps or changing chemical dosages can be trained yielding more adequate knowledge-based behavior (Rasmussen, 1983) during upsets and better understanding of the normal operation.

An in-simulator transfer of training (ToT) experiment was conducted with experienced operators, inexperienced operators, and laymen. In-simulator means that transfer of training is measured with the same simulator acting as a stand in of a real plant. An in-simulator transfer paradigm offers various advantages compared to a true transfer design, such as ease of performance assessment, greater experimental control, and the possibility of simulating plant upsets which would be inappropriate to apply in the operational environment (Taylor *et al.*, 1993).

This research aims to investigate the usefulness of the Waterspot drinking water treatment plant simulator for training and assessment of operators. Focus is on the effect of acceleration of the simulation speed on the ToT. The first hypothesis is that the performance of the participants improves significantly during accelerated training. The second hypothesis is that the simulator is able to differ between experienced and inexperienced operators. The third hypothesis is that training on the simulator at 60 times real-time simulation speed yields more increase of knowledge-based performance than training at real-time simulation speed.

5.2 Materials and Methods

Simulator

The Waterspot simulator combines a graphical user interface (GUI) with four models: a process model for water quality, a process model for hydraulics, a control model and an object model as described in Chapter 2 (Worm *et al*, 2010). An overview of the simulator's software structure is shown in Figure 2.1. The Stimela water quality model consists of model blocks of each treatment step (van der Helm and Rietveld, 2002). In the model, the effluent quality properties of a treatment step are the influent quality properties of the next step. For integration of the Stimela water quality models in the simulator, a dedicated OPC-DA server (Object linking and embedding for Process Control – Data Acquisition) (Alves Santos *et al.*, 2005) was developed and set up. The hydraulic model is made in EPANET the worldwide used and well known open source software for modeling of distribution networks. For EPANET, an interface was developed which reads from and writes to the EPANET's dynamic link library (dll) files. The control model represents the control strategy in the plant's PLCs (van der Helm *et al.*, 2009). In future this control model will be replaced by an emulation of the PLCs. The object model describes the equipment and pipes in the plant. The control model and the object model are embedded on the commercial USE® platform that forms the connecting grid between the models. This commercial platform allows the handling of multiple sources of data from models and uses the data according predefined rules. The simulator contains training, reporting and process optimization features. The Waterspot simulator is the world's first simulator for drinking water treatment plant operators. It is a proprietary package, developed for this research and commercial purposes. The used software is listed in Appendix 5A. The simulator was run on a Dell Vostro V1510 laptop and was controlled by the laptop keyboard and a mouse.

The Waterspot simulator of a pellet softening process was used, being a representation of the Wim Mensink drinking water treatment plant in Wijk aan Zee, owned and operated by PWN. Wim Mensink is a conventional drinking water treatment plant with artificially recharged dune water as a source. This dune water has a total hardness (TH) of 2 to 2.5 mmol/l. The treatment consists of pellet softening, cascade aeration, rapid sand filtration and dosage of sodium hypochlorite. Apart from softening the water with pellet softening reactors, the water is softened by mixing reverse osmosis (RO) water (demineralized water). RO water has a very low TH, around 0.05 mmol/l. So, the desired TH of the produced drinking water, 1.5 mmol/l, can be influenced by changing the settings of the pellet reactors and by changing the ratio between RO water and regular softened water.

Pellet softening is one of the more dynamic and complex drinking water treatment processes to control compared to conventional processes such as aeration, filtration or sedimentation. Pellet softening is applied to prevent scaling in household equipment, reduce the need for detergents, and avoid uptake of copper and lead from the distribution network. By dosing caustic soda, the pH is increased and calcium carbonate is crystallized on sand grains in the reactor forming pellets. When pellets are discharged seeding material is dosed. To prevent scaling downstream of the reactors, acid is dosed neutralizing the oversaturated calcium carbonate. When too much acid is dosed the water becomes aggressive yielding metals to dissolve. At optimal operation part of the water is softened deeper than the required level, and part of the untreated water is bypassed (van Schagen *et al.*, 2006), see Figure 5.1.

In the simulator a water quality model (van der Helm and Rietveld, 2002) calculates amongst other parameters, the pH, the TH, and the Langelier saturation index (SI) of the water at different locations, i.e., influent and effluent of individual reactors, mixed effluent, and mixed effluent after acid dosing. The water quality model for softening was developed and cali-

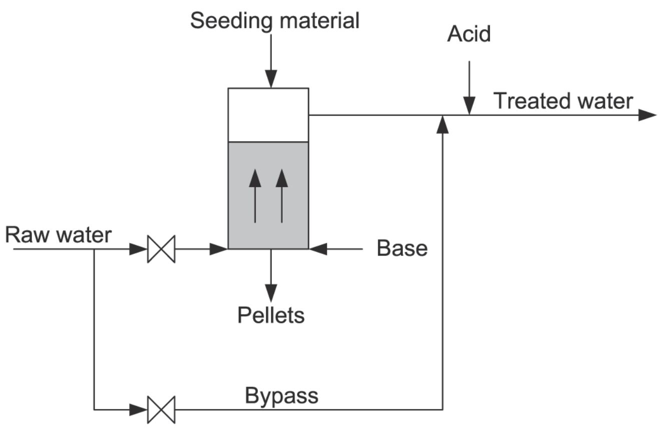

Figure 5.1. Bypass of water in pellet softening (van Schagen *et al.*, 2008).

brated (van Schagen *et al.*, 2006; van Schagen *et al.*, 2008), set up for the Wim Mensink situation, and validated. For validation a 10% deviation of model results compared to historical data was accepted for the bed properties in the reactor and the water quality parameters. A hydraulic model calculates the division of flows over the lanes and reactors in the plant based on valve positions and pump speeds, as described in Chapter 3 (Worm *et al*, 2009). The GUI of the Waterspot simulator follows the design rules of a common SCADA, see Figure 2.4. The GUI consists of a three-level hierarchical set-up to limit the amount of information per screen and consists of standard icons for the various treatment steps. Feedback is given with digital figures as well as with analogue scales showing the actual and desired values for the SI, TH, and pH of the produced drinking water, as shown in Figure 5.2.

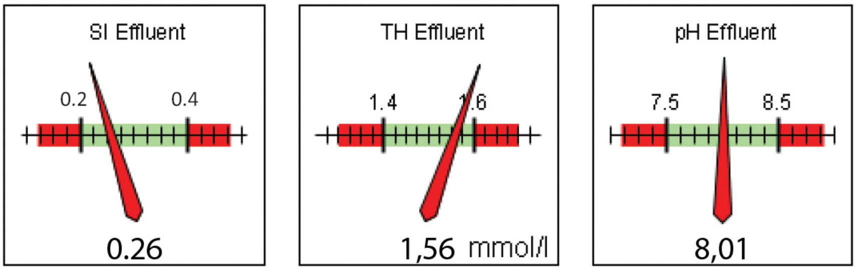

Figure 5.2. Screenshot of the clock faces of the water quality parameters.

Participants

Four groups participated in the experiment. Each group consisted of four participants, all unfamiliar with the Waterspot simulator. The group of experienced operators (EO) consisted of operators of PWN Water Supply Company North-Holland with four to ten years hands-on experience in the softening plant. The group of inexperienced operators (IO) consisted of operators with comparable employment histories and with knowledge of softening using caustic soda, but without specific experience of operation of pellet softening. Eight students from the Delft University of Technology were recruited. These laymen were divided in two groups, laymen who trained with accelerated simulation speed (L60x) and laymen who trained at real-time speed (L1x). The laymen did not have any experience with the drinking water treatment process.

Procedure and task

Participants were given the same, detailed, written instructions prior to the experiment in which the control and navigation within the simulator was explained, as well as the setup of the experiment, the tasks, and the disturbances imposed during the training. EO and IO did the experiment in the offices of PWN Water Supply Company North-Holland in Heemskerk, L60x and L1x did the experiments at Delft University of Technology, all using the same laptop. The participants were instructed to keep the water quality of the produced drinking water within the operational windows. Drinking water should be soft and not aggressive, so the TH should be between 1.4 and 1.6 mmol/l, SI should be between 0.2 and 0.4, and the pH should be between 7.5 and 8.5. To be able to operate within these windows, three variables could be controlled by the participants: i) the number of active reactors (0, 1, 2, 3, 4, 5, or 6), ii) the dosage of caustic soda (0–200 l/h per reactor), and iii) the dosage of carbon dioxide (0–20 Nm^3/h) for pH neutralization.

Affective reactions and utility judgments are predictive of training effectiveness (Alliger *et al.*, 1997). Therefore, the participants were asked to fill out a post-experiment questionnaire containing statements related to affective reactions and utility judgment on a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree), see Appendix 5B.

Experimental setup

The experimental protocol is shown in Table 5.1. The protocol consisted of three training runs of 20 minutes followed by two ToT runs of 20 minutes. For the groups EO, IO, and L60x, the simulation speed during the three training runs was accelerated 60 times, meaning that within the 20 minute run, 20 hours were simulated. The chosen acceleration enabled participants to have a feedback of an action within the training run. During the training runs at 60 times acceleration, the ratio between the mixed water from pellet softening reactors and bypass and the flow of RO water was changed at t = 0, t = 5, t = 10, and t = 15, in which t is the time (minutes) a participant spent behind the simulator. For the real-time simulation speed training run and the first ToT run, the ratio change was done at t = 0 and t = 10, because the process itself would require about ten minutes to return to its operational window after appropriate control actions. The simulation speed for the two ToT runs was real-time for all groups. During the first minute of the second ToT run, the ratio between the flow through the pellet softening treatment process and the bypass was changed. Because this imposed disturbance of the process differed from the one in the training runs, the participants were required to use knowledge of the process, instead of the specific rule they developed during the training runs.

Table 5.1. Experimental set-up. ToT = transfer of training.

	3 training runs	**ToT run 1**	**ToT run 2**
	Change of ratio between dune water and RO water	Change of ratio between dune water and RO water	Change of ratio bypass flow
Experienced operators (EO)	60x speed, 4 changes	1x speed, 2 changes	1x speed, 1 change
Inexperienced operators (IO)	60x speed, 4 changes	1x speed, 2 changes	1x speed, 1 change
Laymen 60x (L60x)	60x speed, 4 changes	1x speed, 2 changes	1x speed, 1 change
Laymen 1x (L1x)	1x speed, 2 changes	1x speed, 2 changes	1x speed, 1 change

Performance indicators

Since the objective of the training is to keep the water quality of the produced drinking water within the operational windows, three performance indicators were defined that are directly related to simulated water quality parameters: i) the integral of the error, ii) the error from first setting and iii) the error from final setting.

Integral of the error. For each of the accelerated training groups (i.e., EO, IO, and L60x), the performance was calculated by taking the integral of the error of each of the quality parameters SI, TH, and pH outside of their operational window (see Figure 5.3, for an example). For each quality parameter, this yielded a vector of 144 integral of the error scores: three groups times four participants per group times three runs times four sections per run (one section per change, four changes in a run). To be able to sum the integral of the error scores for the SI, TH, and pH, these vectors were normalized into standard scores by subtracting the average value and dividing it by the standard deviation. After the standardization the average of the integral of error was zero for each water quality parameter. As a consequence of standardization, the most negative integral of error indicates the best performance. For real-time simulation speed (i.e., L1x) the integral of the error score was not used: as a result of the large delays in the system, the measure would be insensitive to the participant's actions. Furthermore, it would be effective to over-steer the process in order to have it within bounds sooner, neglecting the fact that the process might grow out of bounds as time passes beyond the duration of the run.

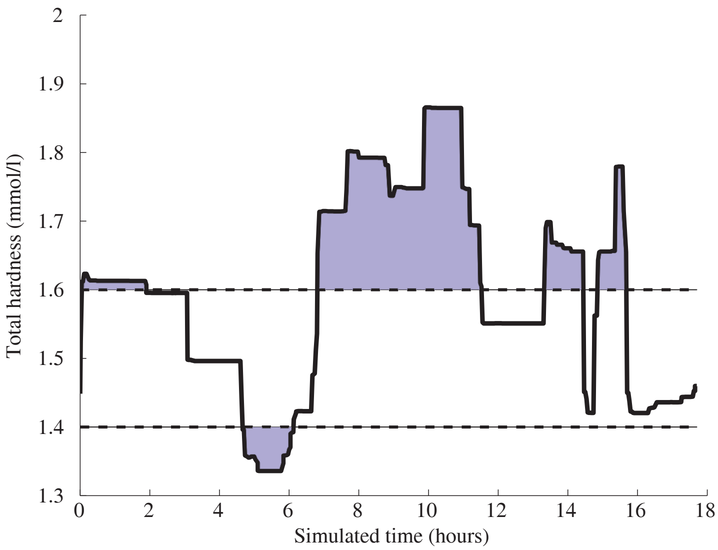

Figure 5.3. Example of calculation of integral of the error for parameter TH.

Error from first and final setting. The error from first setting is defined as the error outside the operational window of the quality parameters when the process is at equilibrium, given the first settings a participant chose in a run. The first setting was defined as the first choice a participant made for all three input settings, within the first 30 seconds after the first imposed disturbance during a run. The error from first setting was calculated after the experiment, by applying the first settings on the simulator at 60 times acceleration and wait for equilibrium. The errors resulting from the three quality parameters were standardized and summed to give a total error score. After standardization the average of the error from first setting was zero for each water quality parameter. As a consequence of standardization, the most negative error from first setting indicates the best performance. The error from final setting was calculated in the same way as the error from first setting, but based on the final settings the participant chose during a run.

Number of control actions. The number of control actions was determined as well, and was regarded as a measure of control activity rather than a measure of performance. The relationship between the number of control actions and performance is complex. Studies in car driving have previously investigated the relationship between the steering wheel reversal rate, being a measure of the number of control actions, and the lane keeping accuracy, being a measure of performance (Macdonald and Hoffmann, 1980; McLean and Hoffmann, 1975). A high steering reversal rate indicates either or both of two situations: the driver is finding it hard to attain an acceptable level of performance or the driver is attempting to steer with excessive accuracy (McLean and Hoffmann, 1975). Operators in general, but especially the experienced operators are expected to know the acceptable level of process variations better than the laymen and they are expected not to strive for maximum accuracy if this would require too many interventions. Obviously the operators know the process behavior better than laymen, reducing the chance of over-steering and as a consequence, the need to do corrective actions. So, the number of control actions is expected to be lower for the experienced operators compared to the laymen. The number of control actions is obtained by counting the changes in control settings during a run.

Statistical analyses

To assess the learning effect in the 60 times accelerated training runs (hypothesis 1) the differences between the integral of the error of the first and the third training run were compared using a dependent t test for paired samples on groups EO, IO, and L60x combined. To evaluate the second hypothesis that a simulator can distinguish between experimental groups, EO was compared with IO, and EO and IO combined where compared with L60x, using an independent t-test. Differences are considered significant if significance $p < 0.05$. The third hypothesis that training on a simulator at 60 times acceleration yields more improvement of knowledge-based performance than training at real-time simulation speed was evaluated by comparing the performance indicators of the ToT runs of L60x and L1x using an independent t test.

5.3 Results and discussion

Training results

Figure 5.4 shows the chosen settings and resulting water quality of a randomly picked training run of a randomly picked participant.

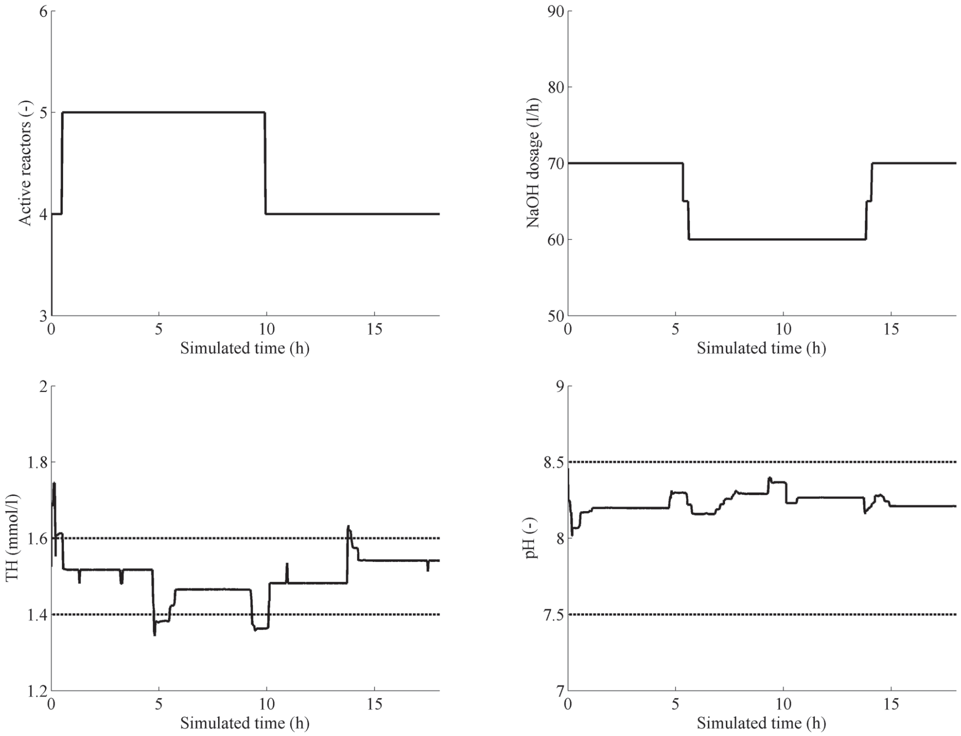

Figure 5.4. Settings chosen by experienced operator 2 during training run 2 (top) and the resulting water quality (below).

Learning effect

Figure 5.5 shows the integral of the error for the 60 times accelerated training runs. The corresponding means and standard deviations are shown in Table 5.2 (the most negative mean values indicate the best performance). A learning effect can be distinguished from the decrease of the integral of the error per run. The t test showed that the integral of the error in run 3 was significantly lower than in run 1 (p = 0.002; one participant was omitted due to his extreme score of 48 in run 1). No significant group differences were found, indicating equal learning capabilities of the participants.

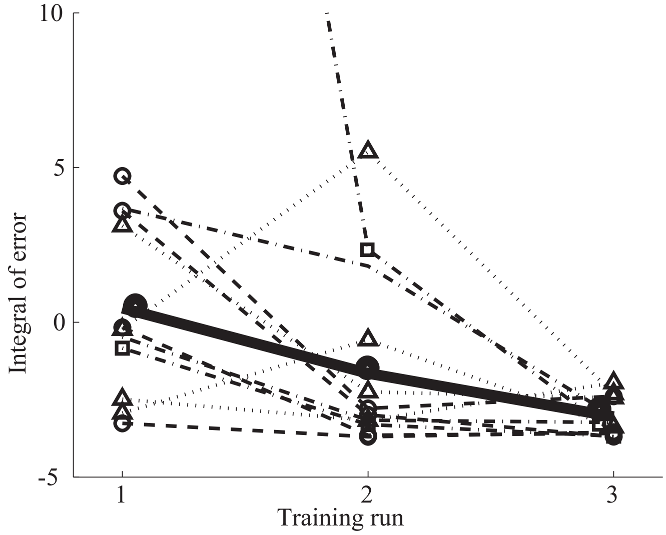

Figure 5.5. Integral of the error scores for the 60x accelerated training runs (○ = experienced operators, Δ= inexperienced operators, □ = laymen 60x). The bold line indicates the mean scores (the extreme data point in run 1 for one of the layman was omitted in the calculation of the mean of run 1).

Table 5.2. Means (M) and standard deviations (SD) of the integral of the error score in the accelerated training runs for experienced operators (EO), inexperienced operators (IO) and laymen 60x (L60x).

	EO		**IO**		**L60x**	
Run	**M**	**SD**	**M**	**SD**	**M**	**SD**
1	1.22	3.65	-0.63	2.77	0.78	2.51
2	-3.28	0.46	-0.12	3.90	-0.57	3.08
3	-3.31	0.62	-2.52	0.61	-3.38	0.30

Table 5.3. Means (M) and standard deviations (SD) of the error from first setting, error from final setting, and number of actions for ToT runs 1 and 2 for experienced operators (EO), inexperienced operators (IO) and laymen 60x (L60x).

		EO		**IO**		**L60x**	
	Run	**M**	**SD**	**M**	**SD**	**M**	**SD**
Error from first setting	1	1.54	3.64	0.52	3.96	-1.39	0.15
	2	-2.06	0.46	-1.79	0.55	1.39	2.79
Error from final setting	1	-1.35	0.97	0.35	2.19	1.84	2.46
	2	0.03	2.96	-1.29	0.81	-1.41	0.87
Number of actions	1	11.5	6.1	9.8	4.8	19.8	5.3
	2	10.8	2.2	6.8	2.6	16.0	6.6

Distinction between EOs, IOs and laymen during transfer runs

Table 5.3 shows the means and standard deviations per group for two performance indicators after ToT runs 1 and 2 (for the error from first setting and error from final setting the most negative mean values indicate the best performance and operators are expected to have a lower number of actions than laymen). Figures 5.6 and 5.7 illustrate the individual data points per group.

During ToT run 1 and 2, no significant differences were observed between the EO and IO groups in terms of errors from first setting, errors from final setting, and number of actions (all six $p > 0.05$). The lack of sensitivity could be caused by the limited number of participants, by the too specific performance indicators not capturing all behaviors of interest, or by the process optimization efforts of the experienced operators. A fourth reason may be that the fidelity of the simulator, despite the SCADA based GUI, was not high enough to be able to assess the participants. However, when comparing the operators (i.e., EO and IO combined) with L60x, significant effects were found for error from first setting run 2 ($p = 0.006$) and a near-significant effect was found for error from final setting run 1 ($p = 0.083$). Furthermore, Table 5.3 shows significant results for the number of actions run 1 ($p = 0.017$), and number of actions run 2 ($p = 0.024$), indicating that the laymen tended to perform poorer than the operators, while at the same time making significantly more actions. Personal observations showed that EO recognized the process after the first run and started to control other variables to optimize the process within the operational windows, even beyond the requirements in the instruction sheet. This explains the higher, instead of the expected lower number of actions of EO compared to IO.

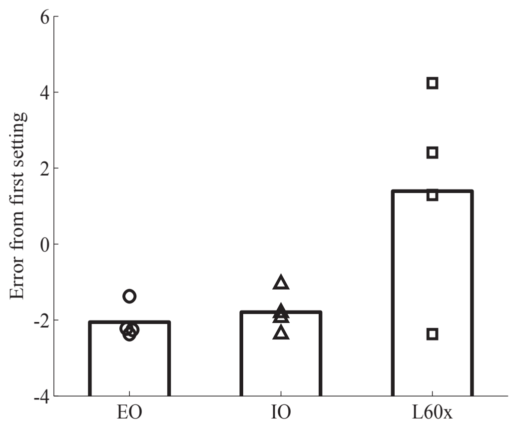

Figure 5.6. Errors from first setting for experienced operators (○), inexperienced operators (Δ) and laymen 60x (□) for ToT run 2. Bars indicate mean scores.

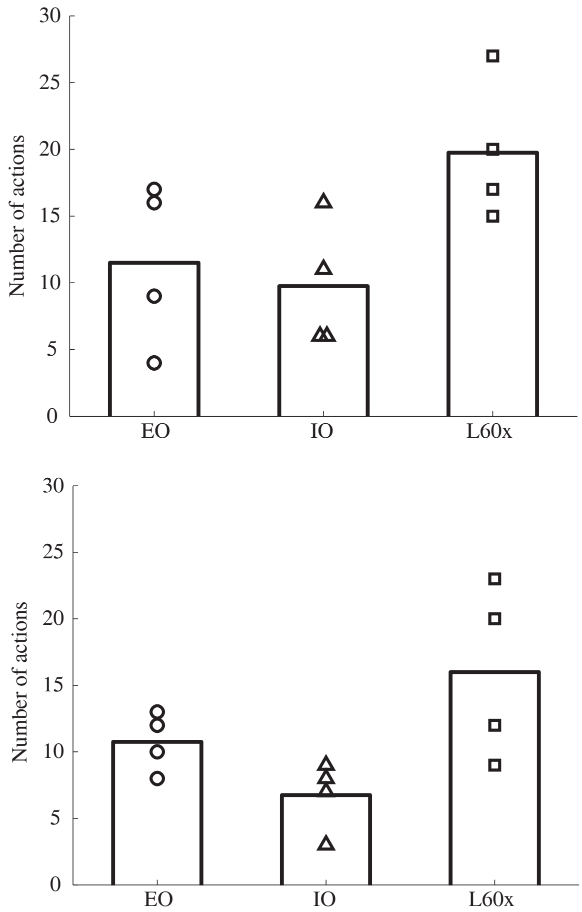

Figure 5.7. Number of control actions for experienced operators (○), inexperienced operators (Δ) and laymen 60x (□) for ToT run 1 (top) and ToT run 2 (below). Bars indicate mean scores.

Table 5.4. Means (M), standard deviations (SD), and significance (*p*) of indicators for laymen 60x (L60x) and laymen 1x (L1x) during ToT run 1 and ToT run 2.

	ToT run	**L60x M**	**SD**	**L1x M**	**SD**	***p***
Error from first setting	1	-1.39	0.15	-0.67	1.59	0.403
	2	1.39	2.79	2.45	3.23	0.637
Error from final setting	1	1.84	2.46	-0.72	2.19	0.171
	2	-1.41	0.87	2.80	2.47	0.018
Number of actions	1	19.8	5.3	30.0	12.4	0.135
	2	16.0	6.6	32.8	8.7	0.022

The effect of acceleration on transfer of training

Table 5.4 shows the means, standard deviations, and significance of two performance indicators for L60x and L1x during ToT run 1 and ToT run 2. For ToT run 1, no significant differences were found between L60x and L1x. In this run, the imposed disturbance was the same as in the training runs. Figure 5.8 shows the results for ToT run 2. For the error from final setting and the number of actions significant differences were found as expected: L60x group performed better than L1x, whereas L1x used significantly more actions.

The results of the questionnaire are shown in Appendix 5B. The questionnaires showed that EO and L60x were concerned that training with increased speed yielded a loss for feeling of the actual process. This concern turned out to be irrelevant for L60x who outperformed the L1x. For all statements, the total mean ratings were between 3.4 and 4.3. The only exception

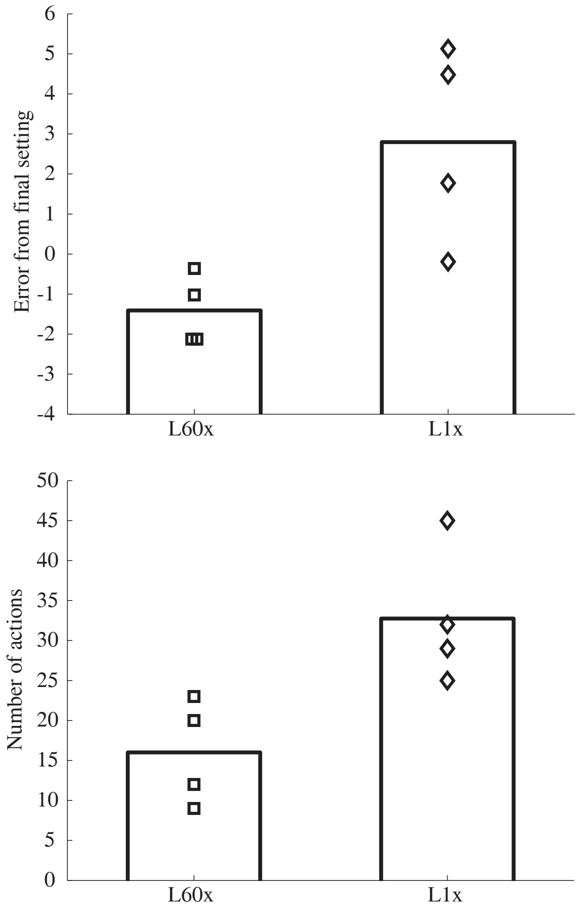

Figure 5.8. Performance indicators for laymen 60x (□) and laymen 1x (◊) for ToT run 2. Bars indicate mean scores.

was the statement "Training on the Waterspot simulator can replace the current training method completely", having a mean rating of 2.6. The highest mean rating, 4.3, was obtained for "Training on the Waterspot simulator challenges to increase my insight in the treatment process". No noticeable differences were found between groups, except for the statement "When the simulation speed of the Waterspot simulator is accelerated I lose my feeling for the process". EO and L60x were most concerned for this, IO the least.

5.4 Conclusions

The human-in-the-loop Waterspot simulator was used for the training of operators of drinking water treatment plants. An experiment was conducted with eight operators and eight laymen to evaluate the added value of accelerated simulation in training interventions in slow processes. The participants completed three training runs and two transfer-of-training runs. To evaluate the participants' performance, three indicators were used, the integral of the error, the error from first setting, and the error from final setting. The number of control actions was determined as well, and was regarded as a measure of control activity. A questionnaire was filled out by the participants after the experiment to collect information on affective reactions and utility judgment.

The experiments clearly showed an increase in the performance of operators over the three trials. During the transfer of training runs, the laymen tended to perform poorer than the operators, while at the same time making significantly more actions. Experienced operators recognized the process after the first run and started to control other variables to optimize the process within the operational windows, even beyond the requirements in the instruction sheet. This explains the higher, instead of the expected lower number of actions of the experienced operators compared to the inexperienced operators. The questionnaire indicated positive utility judgment and affective reactions.

In training of military pilots faster-than-real-time simulation training has demonstrated to yield to increase of performance, higher retention of skills (Donderi *et al.*, 2010) and shorter training durations (Miller *et al.*, 1997). This research seems to confirm these results in the training of drinking water treatment plant operators and laymen. L1x who lacked accelerated simulation used roughly twice as many actions in the second ToT run compared to L60x and were not able to find appropriate settings. The simulator statistically distinguished between laymen and operators, but not between operators – experienced or otherwise. Due to the accelerated simulation speed, it becomes possible to obtain direct feedback on the actions. Therefore acceleration should be a standard feature in slow-continuous-process simulators.

The Waterspot simulator is used at Waternet, the water cycle company of Amsterdam for operator training and process analysis and at Delft University of Technology for education.

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Appendix 5A

Software	Version	Website
EPANET	2.00.12	www.epa.gov/nrmrl/wswrd/dw/epanet.html
Jasper reports	3.1.0	www.sourceforge.net/projects/jasperreports
MySQL Community Version	5.1.3	www.dev.mysql.com/downloads/mysql/5.1.html
Stimela	6.5.59	www.stimela.com
Stimela OPC Server	1.0	
Matlab®	6.5R13	www.mathworks.com
Simulink®	5.0R13	www.mathworks.com
Waterspot	1.0	www.waterspot.nl
USE®	2.4_2	www.ureason.com
Microsoft Windows XP	2002/SP3	www.microsoft.com

Appendix 5B

	EO	**IO**	**L60x**	**L1x**	**Total**
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*	*M*
Training on the Waterspot simulator…					
is fun.	4,5 (0,6)	4,0 (0,0)	4,0 (0,0)	4,0 (0,0)	4,1
is educational.	3,8 (1,3)	4,0 (0,8)	4,0 (0,8)	4,0 (0,0)	3,9
gives an increase of the insight in the water treatment process.	4,3 (0,5)	4,3 (0,5)	4,3 (0,5)	4,0 (0,0)	4,2
can replace the current training method completely.	2,5 (0,6)	2,5 (1,0)	3,0 (0,0)	2,5 (0,6)	2,6
is a good addition to the current training method.	4,0 (0,0)	4,0 (0,0)	3,3 (0,5)	4,0 (0,8)	3,8
challenges to optimize the treatment process.	4,0 (0,8)	4,3 (0,5)	3,8 (0,5)	4,5 (0,6)	4,1
challenges to increase my insight in the treatment process.	3,8 (1,3)	4,3 (0,5)	4,5 (0,6)	4,5 (0,6)	4,3
To increase my knowledge about the water treatment process I'd like to…					
study from books.	3,5 (1,0)	3,5 (0,6)	3,8 (0,5)	3,3 (0,5)	3,5
walk along with more experienced operators.	3,0 (1,4)	4,5 (0,6)	4,0 (0,8)	4,3 (0,5)	3,9
train on the Waterspot Simulator.	3,5 (1,0)	4,3 (0,5)	3,8 (0,5)	4,0 (0,0)	3,9
To increase my knowledge about the water treatment process it is effective to…					
study from books.	3,5 (1,0)	3,5 (0,6)	3,8 (0,5)	3,8 (0,5)	3,6
walk along with more experienced operators.	3,0 (0,8)	4,3 (0,5)	4,3 (0,5)	4,3 (0,5)	3,9
train on the Waterspot Simulator.	3,3 (1,0)	3,8 (0,5)	4,0 (0,0)	4,3 (0,5)	3,8
The Waterspot simulator…					
can be used to discriminate between good and bad operation.	3,3 (0,5)	3,5 (1,0)	3,8 (0,5)	3,5 (0,6)	3,5
is a good approximation of the reality.	3,8 (0,5)	4,0 (0,8)	2,8 (0,5)	3,8 (0,5)	3,6
When the simulation speed of the Waterspot simulator is accelerated…					
different settings can quickly be tested. This gives an increase of my insight in the process.	4,0 (0,8)	4,5 (0,6)	4,3 (0,5)	3,8 (1,0)	4,1
I lose my feeling of the process.	3,5 (0,6)	1,8 (0,5)	3,5 (1,3)	2,5 (0,6)	2,8
Average, excluding the last (negative) question	3,6	3,8	3,7	3,9	3,8

6

The use of process simulation models in virtual commissioning of process automation software in drinking water treatment plants

Based on

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Abstract
This research deals with the contribution of process simulation models to the factory acceptance test (FAT) of process automation (PA) software of drinking water treatment plants. Two test teams tested the same piece of modified PA-software. One team used an advanced virtual commissioning (AVC) system existing of PA-emulation and integrated process simulation models, the other team used the same PA-emulation but basic parameter relations instead of the process simulation models, the VC-system. Each test team found one (different) error of the thirteen errors put into the software prior to the experiment; the majority of the errors was found prior to the functional test. The team using the AVC-system found three errors, the team using the VC-system found four, but the AVC-team judged 1% of the test items 'not possible', the VC-team 17%. It was concluded that the hypothesis that with AVC more errors could be found than with VC could not be accepted. So, for the FAT of PA-software of drinking water treatment plants, the addition of basic parameter relations to PA-emulation satisfied. Not the exact process behavior helped to find errors, but the passing of process thresholds.

Keywords
Virtual commissioning; drinking water treatment; process automation; emulation; process simulation model

6.1 Introduction

As in other industries the level of automation of drinking water treatment plants has increased up to the level of remote multi-task supervisory control (Sheridan, 2002). New process automation (PA) software or software updates are tested extensively to prevent dangerous situations, process disturbances and down-time during or after implementation. At drinking water company PWN, in 2010, 1.7% of the urgent alarms occurred as a consequence of PA-software modifications. Software testing is expensive, since it requires significant efforts of software experts. Still, to correct an error after implementation of the software, costs five to hundred times more (Poon *et al.*, 2011).

The testing of PA-software can be divided in two main phases, i) the factory acceptance test (FAT) by the supplier in the development environment and ii) the site acceptance test (SAT) by the user in the live environment (Lucas, 2003), see Table 6.1. In this research, as is common at PWN, the system test and customer acceptance test (CAT) –both components of the FAT– are combined. This combined test is called the functional test. Notwithstanding the leading role of the supplier in the FAT, the user is involved in the CAT or functional test. Note that often in practice the CAT or functional test are referred to as FAT.

Table 6.1. PA-software testing, based on (Lucas, 2003). FAT is factory acceptance test, SAT is site acceptance test.

Phase	Leading role	Location	Sub phase	
FAT	Supplier	Development environment	Unit test	
			System test	Functional test
			Customer acceptance test	Functional test
SAT	User	Live environment	Installation qualification	
			Operational qualification	
			User acceptance test	

To start a traditional FAT, the new or modified software is uploaded from the engineering station to a physical test-PLC (programmable logic controller) in an offline environment. The input/output (I/O) signals are simulated with physical switches or with a tailor made tool, for example programmed in Visual Basic or within the tested process automation software itself. To test the communication between PLCs and functions with interactions between multiple PLCs, a network must be set up between the PLCs. A single human-machine interface (HMI) client is available for navigation. In the traditional FAT, often new PA-software is extended with code exclusively for reasons of simulation during testing. These code lines are removed or disabled after the FAT, before the tested software is uploaded to the PLC in the plant.

A new development in the process automation software engineering is virtual commissioning (VC) instead of the traditional FAT. VC is the testing of software in a near-reality situation, using multiple virtual PLCs, or soft-controllers, containing emulated PA-software, their mutual communication, multiple HMI-clients possibly covering different hierarchical automation levels, virtual I/O and, possibly, basic parameter relations. The virtual I/O can be seen as equipment simulation and can be standardized by using typicals. The virtual I/O signals can be dynamical since the signals can be ramped or delayed. Examples of basic parameter relations are the relation between a pump's speed and the passing flow, or between the net flow to or from a tank and its level. A relevant characteristic of the modern emulation platforms like Siemens' Simit (Többermann and Fischer, 2007) and ABB's 800xA Simulator (Franke and Doppelhamer, 2007) is the possibility to transfer the PA-software from the field PLC to the soft-controller without changing the software at all, and vice versa. This saves time and limits the risk of errors as a consequence of (not) changing the software before the transfer.

During VC of the control of the Hammerfest LNG plant in Norway more than 500 items were detected and resolved (Krause, 2007). VC has a saving potential of 10-30% in the areas of test and commissioning of PA-software, in addition to the positive effects of VC on reductions of commissioning times and increase of quality of engineering solutions (Drath *et al*., 2008). In the automotive industry time savings in software development are estimated of more than 20% for commissioning using VC (Pellicciari *et al*., 2009; Wildemann, 2005). Within the software development process VC leads to overall economic savings of 20-50% (Reinhart and Wünsch, 2007). A field study has shown the added value of VC to software testing in a simulated production environment. Thirty persons using VC managed to fulfill an average of 85% of the requirements, as where a reference group realized 37%. The VC testers needed 25% of the commissioning time of the 'traditional commissioning'-group (Zäh *et al*., 2006).

Two types of I/O can be distinguished, 'process I/O', signals of online measurements, commands and setpoints for pumps and valves, and 'status I/O', signals like equipment or system statuses. By connecting process simulation models to the 'process I/O' of the VC-system dynamic process behavior is added. Advanced VC (AVC) is defined as VC with added process simulation models. As can be expected, the setup of an AVC-system existing of an emulated PA-system and process simulation, shows great similarities with the setup of a PA-system which is connected to the sensors and actuators in the field (Bradu *et al*., 2009). The differences and similarities between the traditional FAT, VC and AVC are summarized in Table 6.2.

The objective of this research is to limit the process disturbances and downtime of drinking water treatment plants during and after the implementation of new PA-software or software updates. The hypothesis is that with AVC more errors will be found during the FAT than with VC.

Table 6.2. Differences and similarities between the traditional FAT (factory acceptance test), VC (virtual commissioning and (AVC) advanced VC.

	FAT	VC	AVC
Test PLC	Single, physical	Multiple, virtual	Multiple, virtual
Test scope	A single PLC	All PLCs of a plant	All PLCs of a plant
Testing of communication between PLCs	No	Yes	Yes
Virtual I/O	Tailor made, possibly dynamic	Standardized, dynamic	Standardized, dynamic
Software modification when transferred from test-controller to field PLC	Yes	Yes[1]/No	No
Process behavior	Basic parameter relations	Basic parameter relations	Process simulation
Potentially replacing part of the site acceptance test	No	No	Yes

[1] P-, I-, or D-terms of controllers might be suboptimal

6.2 Materials and methods

Test systems

The first application of VC with Simit in drinking water treatment by water supply company PWN in 2011 was the test of the update of the mutual communication of PLCs of the membrane filtration plant Heemskerk I. Errors which were in the existing software for more than ten years were found and solved. The first three projects tested with Simit within PWN yielded SATs without unexpected errors or delays, which was reason to double the number of licenses of the VC-platform. Programmers experienced that the border between software development and testing is vanishing. Particularly, they appreciated the possibilities to transfer software between the emulation platform and the PLC without needing to change the software and to emulate multiple PLCs and their mutual communication. AVC was not applied in drinking water treatment plants prior to this research.

Two test systems were used. The AVC-system existed of an emulation of the PA-software, of I/O virtualization and a process simulator, see Figure 6.1. For emulation and virtualization of I/O, Simit was used. As is common for the PA-system, for visualization of the HMI, WinCC was used. The embedded Object linking and embedding for Process Control (OPC) communication protocol was used to communicate with the process simulator Waterspot running on the USE® platform, as described in Chapter 2 (Worm *et al.*, 2010). The process simulator processed 93 'process I/O' parameters dynamically, in real-time. Waterspot hosts two process simulation models. The hydraulic model was decribed in Chapter 3 (Worm *et al.*, 2009), the water quality model was described in Chapter 4 (Worm *et al.*, under review). Figure 1.2 and 1.5 show the setup of the AVC-system used in this research and the similarities with a drinking water treatment plant.

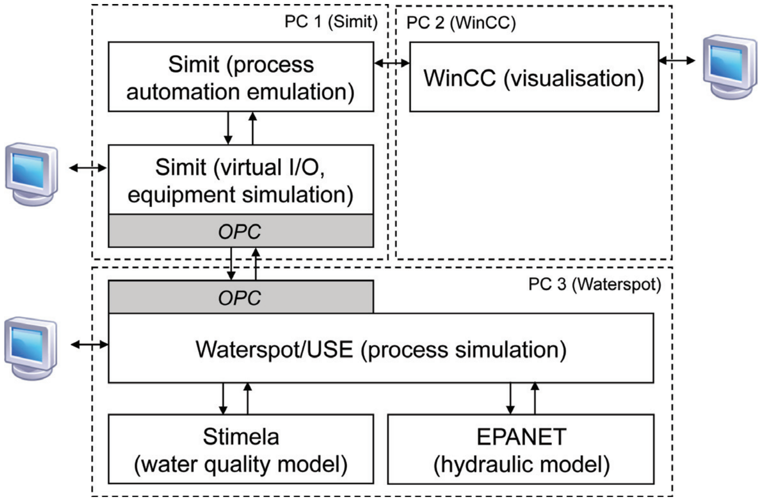

Figure 6.1. Setup of the AVC test system.

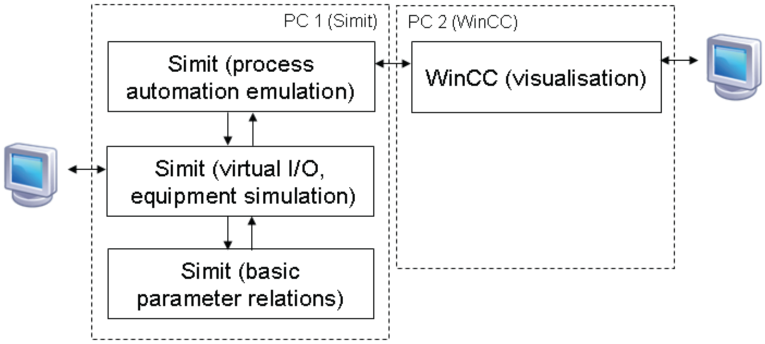

Figure 6.2. Setup of the VC test system.

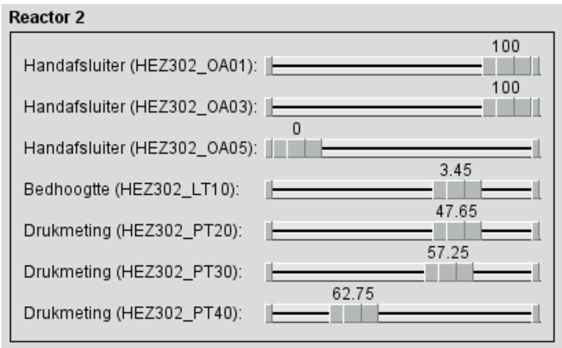

Figure 6.3. Virtual sliders for sensors and actuators of Reactor 2 in the VC-system (labels in Dutch, 'Handafsluiter' is manually operated valve, 'Bedhoogte' is bed height, and 'Drukmeting' is pressure measurement).

As shown in Figure 6.2, the setup of the VC-system equaled the AVC-system, but instead of the process simulation models, a programmer defined twenty basic parameter relations within Simit, e.g. the relation between a pump's speed and the flow. For several parameters, virtual sliders were set up in Simit, as shown in Figure 6.3.

Experimental set-up

For the AVC-system, two hydraulic model environments were available; EPANET, part of the Waterspot simulator and Flownet, a Simit plug-in. EPANET and Flownet were compared using a multi criteria evaluation. Each criterion exists of one or more sub criteria as Table 3 shows. Each sub criterion has the same weight. The sum of the scores of the sub criteria determines the score for the criterion. Each criterion has the same weight.

Table 6.3. Evaluation criteria EPANET versus Flownet

Criterion	Sub criteria
Efforts to set up new model	Setup of a pipe, setup of a weir, setup of a pump, time to set up model, manual
Transparency and maintainability models	Help files, user interface, support, units
Efforts to integrate with Simit	Interface type
Robustness	Accuracy, robustness
Costs/licenses	Price, license restrictions

An optimized control strategy was designed for the existing control of the pellet softening treatment step of drinking water treatment plant Wim Mensink at Wijk aan Zee, as described in Chapter 4 (Worm *et al.*, under review). Prior to the experiment a programmer, who was not involved in the experiment, put 13 errors in the software. Two different test teams did the functional test of the software simultaneously, one team using the AVC-system, the other team using the VC-system. The composition of the Design team, Team AVC and Team VC is shown in Table 6.4. To limit the advantage of foreknowledge of the software, the software designer and the programmer who built the software were not in the same test team. The teams were asked to perform the functional test as they would have done in reality. Suggestions to the test teams during the experiment were minimized and test teams were able to determine their approach. A functional test protocol was available for the test teams during

Table 6.4. Composition of the Design team and the test teams.

Design team	Team AVC	Team VC
Programmer A	Programmer A	Programmer B
Software designer A	Software designer B	Software designer A
	Operation supervisor A	Operation supervisor B

the experiment. The protocol was defined without knowledge of the place or type of errors put into the software. On request, the test protocol was extended for Team AVC to test and optimize the caustic soda dosage controller. The participants knew errors were put in the software, but not the exact number.

During the experiment each test item in the protocol was classified ‘good’, ‘wrong’ or ‘not possible’ by the operation supervisor. ‘Not possible’ could be selected when a test item could not be evaluated. For the experiment two evaluation-parameters were defined, i) the number of deliberately inserted errors found by the test teams and ii) the number of test items classified ‘wrong’ by the test teams. For the latter a Chi square test was executed with two samples and categories ‘good’ and ‘wrong’, yielding one degree of freedom. The null hypothesis was that the test results of the AVC-team equaled the test results of the VC-team and was preferably rejected, to be able to differ between the AVC test method and the VC test method. The test items classified ‘not possible’ were excluded from this evaluation, because they did not contribute to finding errors. Still, fewer ‘not possible’ items indicated a wider scope of the test system. After the experiment, each member of the test teams filled out a questionnaire containing propositions related to the contribution of the process simulation models to the results of the test on a five-point Likert scale (Likert, 1932) ranging from 1 (strongly disagree) to 5 (strongly agree). Three out of the ten propositions were for Team AVC exclusively.

Used software

The used software is listed in Table 6.5.

Table 6.5. Used software. PC numbers match with Figures 6.1 and 6.2.

PC	Software	Version	License
1	Simit	5.4 SP1	Commercial license
	Windows	XP Pro SP 3	Microsoft EULA for Windows XP SP3
2	Simatic WinCC	K6.0.3.0	Commercial license
	Windows	XP Pro SP 3	Microsoft EULA for Windows XP SP3
3	Waterspot		Project based
	USE®	3.0_2	UReason EULA for USE.
	MySQL Community	5.1.3	General public license
	Stimela OPC Server	10.1 Build 2	Project based
	Stimela	10.6	Project based
	Matlab®	6.5 R13	Individual commercial license
	Simulink®	5.0 R13	Individual commercial license
	EPANET	2.00.12	None, public domain
	Windows	XP Pro SP 3	Microsoft EULA for Windows XP SP3

6.3 Results

When comparing EPANET and Flownet, EPANET scored higher on 'efforts to set up new model', 'transparency and maintainability models' and 'costs/licenses', Flownet scored higher on 'efforts to integrate with Simit'. EPANET and Flownet balanced on 'robustness'. EPANET was preferred over Flownet.

Table 6.6 shows the results of the test teams for the thirteen deliberately inserted errors. Four of these errors appeared to be put in unmodified parts of the software. During the functional test, team AVC identified one of these four errors, an unrealistic high maximum value of the total hardness measurement. The other three remained undiscovered. Team VC decided not to test unmodified software. Of the remaining nine errors, the Design team found eight during the unit test. Only team VC identified the ninth, an old tag code in an alarm presentation, during the functional test.

Table 6.6. Test results for the errors put into the software deliberately prior to the experiment.

	Total	**Found by design design team during unit test**	**Found by team AVC during functional test**	**Found by team VC during functional test**
Errors in unmodified parts of the software	4		1	
Errors in modified parts of the software	9	8		1
Total	**13**	**8**	**1**	**1**

Team AVC evaluated 144 test items, Team VC 83 items. This difference was caused by the extended test protocol of Team AVC and by the fact that Team AVC tested unmodified software as well. During the functional test, 78 items were tested by both Team AVC and Team VC. The results of these 78 tests are shown in Table 6.7. The test item on the continuation of the RO-water dosing after switching of a reactor when filling of the tank was interrupted, was tested 'wrong' by both Team AVC and Team VC. The other 'wrong' items were mentioned by a single team. The null hypothesis of the Chi square test could be rejected, meaning the test results of team AVC differ from the test results of team VC, but with significance $p = 0.21$, which is more than the commonly accepted 0.05. The AVC-team judged 1% of the test items 'not possible', the VC-team 17%, indicating a scope limitation of the VC-system, compared to the AVC-system. Most of the 'not possible' test items of Team VC contained process consequences of actions, which were not simulated with the basic parameter relations, e.g. the height of the fluidized bed decreased when the flow through the reactor decreased.

Table 6.7. Judgement of the test items during the functional tests.

Test	Team AVC			Team VC		
	Good	**Wrong**	**Not possible**	**Good**	**Wrong**	**Not possible**
Log in	1			1		
Flushing with RO-water after switching off a reactor	31	3		31	3	
Grain dosing	12			10		2
Pellet discharge	20			9		11
Control of flow through reactors	6			6		
Control of caustic soda dosage	2			1	1	
Water on floor	2		1	3		
Total	**74**	**3**	**1**	**61**	**4**	**13**

In the questionnaire five propositions were judged 'agree' or 'strongly agree' by four or five of the six participants, see Table 6.8. These five propositions dealt with the added value of the Simit emulation platform and the added value of process behavior to the test system. Five out of the six participants were neutral or disagreed with the proposition that in ten years more process simulation models of treatment steps will be set up and connected to Simit. In Team AVC, two participants were 'neutral' and one 'strongly agreed' with the statement that they are positive about their test system, all three participants of Team VC 'agreed'.

6.4 Discussion

Participants mentioned that the addition of basic parameter relations was mainly valuable to accelerate the test and thus increase the efficiency. The setup and validation of process simulation models requires significant efforts. For small and medium size enterprises these efforts might make virtual commissioning unattractive (Hoffmann *et al*., 2010), especially when working with the modeling platform requires substantial skills and knowledge. Process simulation models which describe only a limited part of a treatment plant, which are robust, easy to run, and easy to integrate with (emulated) PA-systems will not only boost the implementation of AVC-systems, but increase the life time of process simulation models (Hass *et al*., 2005) at the same time.

When looking at the errors put into the software, it became clear that the majority of the errors were revealed during the unit test, rather than during the functional test. This either indicates that the programmer who set up the errors lacked specific process knowledge, or that the majority of the errors was related to 'status I/O' or signal connections which did not influence the process directly. When focusing at the 'process I/O', observations during

Table 6.8. Results questionnaire, total score (score Team AVC / score Team VC).

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
I prefer Simit over PLCSIM[1] for software testing	4 (2/2)	1 (1/0)	1 (0/1)		
I prefer Simit over hardware PLCs for software testing	1 (1/0)	4 (1/3)		1 (1/0)	
The addition of process behavior to the test system is valuable[2]	1 (1/0)	5 (2/3)			
The addition of process behavior accelerates software testing		4 (1/3)	1 (1/0)	1 (1/0)	
The addition of process behavior to the test system yields to higher software quality[2]	1 (1/0)	4 (1/3)		1 (1/0)	
In ten years time we will have more process simulation models connected to Simit		1 (1/0)	3 (2/1)	2 (0/2)	
Mainly the hydraulic model contributes to the software test[3]		1	1	1	
Mainly the water quality model contributes to the software test[3]			2	1	
The process simulation did not hinder the software test[3]	1	1		1	
My general opinion on testing with this system is positive	1 (1/0)	3 (0/3)	2 (2/0)		

[1] Predecessor and more basic emulation platform of Siemens.

[2] For the VC-system: the basic parameter relations in Simit, for the AVC-system: Waterspot.

[3] Only for the AVC test team.

the experiment showed that not the exact values were relevant for the functional test, but the response to the passing of process thresholds. This can be understood from the fact that most drinking water treatment processes are relatively slow, meaning that a direct (within minutes) response is not necessary. This is different in drinking water distribution where a direct response to changes in pressure in the network is relevant. In general, the integration of process simulation models for AVC is most feasible when the highest risks can be limited.

The larger amount of ‘not possible’ test items for the Team VC, showed that with the AVC-system more items could be evaluated. In that perspective, the addition of process behavior was valuable. But, the extra items tested by team AVC were mainly related to the performance of the process simulation, rather than the performance of the PA-software. Probably, the ‘wrong’ items, which were identified by the test teams, would have been found if no process behavior would have been present. Observations during and after the experiment showed that the personal preferences in the approach of the operation supervisor during a PA-software test influenced the results of the test noticeably. This assumption is supported by the fact that in the recent test of the software of the Heemskerk I membrane filtration plant, errors that were in the software for ten ygsrs were found by a different test team. The same casus supports the indication that the majority of software errors do not influence the process directly or noticeably.

Recommendation

In future, manufacturers of manufacturing systems will offer simulation models with new equipment (Hoffmann *et al*., 2010). In drinking water treatment this should be requested from suppliers of advanced treatment technologies like membrane filtration and advanced oxidation technologies, processes where a direct response to deviations is relevant, to set up AVC-systems.

6.5 Conclusions

In this chapter the contribution of process simulation models to the FAT of PA-software has been studied, thus introducing advanced virtual commissioning of PA-software in drinking water treatment. The hypothesis was that with AVC more errors would be found during the FAT than with VC. The AVC-system, an integration of the Waterspot process simulator and emulated PA-software on the Simit platform was set up successfully and 93 process parameters were exchanged dynamically. The VC-system was set up being the Simit platform and basic parameter relations. Each test system was used by a different test team to evaluate the same piece of PA-software in a FAT.

During the functional test, each test team found one (different) error of the thirteen errors put into the software deliberately. The majority of these errors was found by the Design Team during the unit test, because the majority of the I/O signals are 'status I/O', and not 'process I/O'. The AVC-team using the system with process simulation found three errors, the VC-team using the system with basic parameter relations found four. The significance p of the difference between the number of 'good' and 'wrong' tested items of both teams is 0.21, more than the commonly used 0.05. It was concluded that the hypothesis that with AVC more errors could be found than with VC could not be accepted. And, that for the FAT of PA-software of drinking water treatment plants, the addition of basic parameter relations to PA-emulation satisfied. Not the exact process behavior helped to find errors, but the passing of process thresholds. Still, the AVC-team judged 1% of the test items 'not possible', the VC-team 17%, indicating a wider test scope of the AVC-system, compared to the VC-system.

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7

Concluding remarks

7.1 Conclusions

To be able to investigate the possible benefits of integrating process models of drinking water treatment plants and emulated PA-software, a pilot system was needed. But the integration of models, command and data management, training and decision-support features, and a graphical user interface (GUI) in a simulator of drinking water treatment plants was never reported before. The first step was to set up a stand-alone training simulator, where an embedded object model, an embedded control model and a GUI replaced the emulated process automation (PA) system. Apart from these models and a GUI, the simulator core consisted of an engine on the USE® platform, a Stimela water quality model and an EPANET hydraulic model. By applying the simulator to four test environments at PWN, Waternet, Dunea and Vitens, it was demonstrated that a generic simulator was developed for drinking water treatment plants. The 'Waterspot' simulator gave a wider group of end-users the opportunity to take advantage of the use of integrated hydraulic, water quality and process control models in their daily work. Water quality model Stimela was removed from its original development and became part of a bigger system, thus entering level IV, i.e. the final level of its development and prolonging its lifetime. The knowledge gap how to set up a virtual representation of a drinking water treatment plant's PA-system including process simulation, was fulfilled.

An EPANET hydraulic model and a Stimela water quality model were set up and validated for the Wim Mensink drinking water treatment plant in Wijk aan Zee. EPANET is worldwide used freeware, but lacked a library to model treatment steps of drinking water treatment plants. Flow is an important parameter in the effectiveness of a treatment step. It was concluded that the division of flows over the lanes of a plant could be calculated for different operational conditions, thus filling a knowledge gap. The lacking library was created in the mean time.

The next knowledge gap was how to select the optimal control strategy for a treatment unit when multiple control strategies meet the requirements and boundary conditions. It was concluded that a Stimela process model could be used to evaluate the control strategies of drinking water treatment steps, which have been set up using the control-design methodology for drinking water treatment plants.

The human-in-the-loop Waterspot simulator was used for the training of operators of drinking water treatment plants. An experiment was conducted with eight operators and eight laymen to evaluate the use of accelerated simulation in training interventions in slow processes. In training of military pilots faster-than-real-time simulation training has demonstrated to yield to increase of performance, higher retention of skills and shorter training durations. This research seemed to confirm these results in the training of operation supervisors of drinking water treatment plants and laymen. The laymen who lacked accelerated simulation used roughly twice as many actions in the second transfer of test run compared to the laymen with accelerated simulation and were not able to find appropriate settings. The simulator statistically distinguished between laymen and operation supervisors, but not between operation supervisors – experienced or otherwise. Due to the accelerated simulation speed, it became possible to obtain direct feedback on the actions.

To fill the final knowledge gap, the contribution of process simulation models to the factory acceptance test (FAT) of PA-software, the stand-alone simulator used in the training experiment, was upgraded. The embedded object model, the embedded control model and the GUI were removed and an interface was set up with an emulation of the new PA-software of the pellet softening treatment step of the Wim Mensink plant. Thus, 'advanced virtual commissioning' (AVC) of PA-software was introduced in drinking water treatment. The hypothesis was that with the AVC-system more errors would be found during the FAT than with a virtual commissioning (VC) system, being an emulated PA-system enriched with basic parameters relations. The AVC-system was set up successfully and 93 process parameters were exchanged dynamically. During a functional test, each of two test teams found one (different) error of the thirteen errors put into the software deliberately. The majority of these errors was found during the unit test, because the majority of the I/O signals are 'status I/O', and not 'process I/O'. The AVC-team found three errors out of the 78 tested items, the VC-team found four. It was concluded that with AVC not more errors could be found than with VC, and that or the FAT of PA-software of drinking water treatment plants the addition of basic parameter relations to PA-emulation satisfied. Not the exact process behavior helped to find errors, but the passing of process thresholds, which triggers actions in the PA-software. Still, the AVC-team judged 1% of the test items 'not possible', the VC-team 17%, indicating a wider test scope of the AVC-system, compared to the VC-system.

7.2 Discussion

Optimization of process control by technologists. Process models can be used to evaluate and optimize the (design of) control of drinking water treatment units. For example in the Wim Mensink case, caustic soda could be saved, the capacity of the plant could be increased and a more stable water quality could be realized. In general, the main advantage of using these models, is that chemicals can be saved, thus saving money and environmental impact, and/or the water quality can be improved without disturbing the process in the plant. Still, the extra benefits of integrating these process models with emulated PA-software to the optimization of the process could not be demonstrated in this research.

Training of operation supervisors. During the seven years of research, the expected increase of the distance between operation supervisors and the treatment process as a consequence of the introduction of fully automated operation was not identified clearly. This seems to be caused by the fact that most of today's operation supervisors rely on their experience and historic knowledge of the process, since they work for the drinking water supply companies for years. Furthermore, the tasks of operation supervisors that replaced 'manual' operations, like contribution to maintenance and projects, process inspections and participation in specialized teams, seem to be effective to keep them fit and ready to act adequately during calamities. Still, operation managers and operation supervisors request for the development of training simulators. But the dialogue between these same managers, researchers and commercial developers on the costs of the development and full-scale implementation of high fidelity training simulators is challenging.

Virtual commissioning of PA-software by control engineers. When setting up an emulation of four programmable logic controllers (PLCs) for the simulator of the Wim Mensink treatment plant, the limitations of an older emulation platform PLCSIM were recognized, like the fact that not more than a single PLC could be emulated per PC and that the setup of the mutual communication between PLCs required significant efforts. This was the reason for supplier Siemens to accelerate the introduction of Simit, their more advanced emulation platform, in the Netherlands. The value of this platform was experienced at PWN during the first usage for the update of the PA-software of the membrane filtration plant Heemskerk I. Users mention the increase of efficiency in software building and testing using the more advanced emulation platform. The addition of process behavior to PA-software emulation can increase the efficiency of a FAT, but the advantage of process simulation models over basic parameter relations, e.g. between a pump's speed and its flow, was not found. When taking into account that process simulation models require significant efforts in setting up and validating, basic parameter relations and virtual sliders on the most often used parameters, will be preferred in virtual commissioning of PA-software.

7.3 Recommendations and future work

Recommendations. Firstly, when looking at slow-continuous-process simulators, acceleration should be a standard feature. Then, to sustain the use of water quality models in virtual commissioning of PA-software, scientists should develop small models, which describe local parameter relations, and which can easily be inserted in a PA-emulation system. End users will accept that these solutions are less accurate or even contradictory when comparing the results with the results of a more complete model like Stimela, which describe the behavior of a complete treatment plant. Finally, for evaluation and optimization of process control strategies, a stand-alone water quality model with an embedded control model should be used.

Future work. The focus of this research is moving from the integration of treatment models to the integration of distribution models and to the integration of data sources. The former aims to minimize the energy use of drinking water pumps and to decrease the number and duration of interruption of delivery as a consequence of inadeqautely responding operation supervisors or failing PA-software. The latter aims to create information for several end-users from the large amount of (often unused) data from internal and external sources.

Summary

Water supply companies are gradually changing to a centralized, fully-automated operation. The drivers for this increasing presence of process automation (PA) are higher and more stable drinking water quality, higher endurance (automation systems can make 'endless' shifts), prevention of personal preferences, higher reliability and lower costs. When making this transition, risks are introduced at the same time. Process distrubances may occur when opeartors are not able (any more) to respond adequately to calamities, and PA-software itself can cause malfunctions, especially during or shortly after the introduction of new software or software updates. Recently emulation platforms of PA-systems have been introduced in the drinking water treatment sector. On these platforms, the software can be transferred from a programmable logic controller in the field to a soft-controller running on a personal computer, and vice versa, without changing anything in the software. In this research process models were connected to an emulation platform for i) optimization of process control by technologists, ii) training of operation supervisors, and iii) virtual commissioning of PA-software by control engineers.

The objectives of this research are to limit the risks of fully automated operation of drinking water treatment plants and to improve their opeartion by integrating process models with emulated PA-software. The sub-objectives are to determine the value of process models in operator training, in virtual commissioning of PA-software and in evaluation and optimization of process control. The aim is to transfer the Stimela water quality model to the fourth level of development.

Centralized fully-automated treatment plants will require more sophisticated operator care than manually operated plants, because of the larger span of control, the larger number of sensors and actuators involved and the complexity of the automation and data communication. Especially since the distance from the operation supervisor to the process has increased. A human-in-the-loop simulator can support operation supervisors in acquiring and maintaining skills and knowledge. The successful first time setup of such a simulator was described. By applying a SCADA-like graphical user interface and several report options, even a group of end-users without specific modeling skills or knowledge could take advantage of the use of integrated hydraulic, water quality and process control models. The 'Waterspot' drinking water treatment plant simulator was developed and applied to Dutch drinking water treatment plants.

The flow through a unit of a drinking water treatment plant is an important parameter in terms of a unit's effectiveness. A new EPANET library was presented with the typical hydraulic elements for drinking water treatment processes. Using this treatment step library, two hydraulic models were set up and validated for the drinking water treatment plants Harderbroek and Wim Mensink. With the actual valve positions and pump speeds, the flows were calculated through the several treatment units.

A method was described to evaluate control strategies to the design methodology for drinking water treatment plants. A process model dealing with parameters related to the calcium carbon dioxide equilibrium was set up and validated. Using the process model, the existing control strategy was compared with a new control strategy and the effects of two different sets of input data were studied. It was demonstrated that the efficiency of the pellet softening process and the plant's capacity were increased, and that chemicals and energy usage were reduced. At the same time, the deviation of the total hardness of the produced water to the desired value was decreased.

The use of a human-in-the-loop drinking water treatment plant simulator for training and assessment was investigated. An in-simulator transfer of training experiment was conducted with three groups training with accelerated simulation, experienced operators (EO), inexperienced operators (IO), and laymen (L60x) and a group of laymen training at real-time speed (L1x). Participants learnt how to improve water quality during training. Upon transfer, when confronted with a different process disturbance than during training, L60x performed significantly poorer than EO and IO combined. No difference was found between EO and IO, and during transfer, L60x outperformed L1x. These results indicated that learning to control slow and complex processes may improve by training with a realistic simulation running at accelerated speed.

Finally, the contribution was investigated of process simulation models to the factory acceptance test (FAT) of PA-software of drinking water treatment plants. Two test teams tested the same piece of modified PA-software. One team used an advanced virtual commissioning (AVC) system existing of PA-emulation and integrated process simulation models, the other team used the same PA-emulation but basic parameter relations instead of the process simulation models, the VC-system. Each test team found one (different) error of the thirteen errors put into the software prior to the experiment; the majority of the errors was found prior to the functional test. The team using the AVC-system found three errors in the 78 tested items, the team using the VC-system found four, but the AVC-team judged 1% of the test items 'not possible', the VC-team 17%. It was concluded that the hypothesis that with AVC more errors could be found than with VC could not be accepted. So, for the FAT of PA-software of drinking water treatment plants the addition of basic parameter relations to PA-emulation satisfied. Not the exact process behavior helped to find errors, but the passing of process thresholds.

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List of abbreviations

API: Application programming interface
AVC: Advanced virtual commissiing
CAT: Customer acceptance test
CS: Control strategy
DCS: Distributed control system
dll: Dynamically linked library
DSS: Decision support system
EDSS: Environmenal decision support system
EO: experienced operators
EPANET: Hydraulic model of the United States' environmental protection agency
EULA: End-user license agreement
FAT: Factory acceptance test
GIS: Geographical information system
GUI: Graphical user interface
HMI: Human machine interface
IO: inexperienced operators
I/O: Input/output signal
L1x: Laymen training with real-time simulation
L60x: Laymen training with accelerated simulation
MES: Manufacturing execution system
NAP: Nieuw Amsterdams peil
ODBC: Open database connectivity
OLE: Object linking and embedding
OPC: OLE for process control
PA: Process automation
PBV: Pressure breaker valve
PC: Personal computer
PID: Proportional integral derivative
PLC: Programmable logic controller
PSV: Pressure sustaining valve
RMS: Root mean square
RO: Reverse osmosis
SAT: Site acceptance test
SCADA: Supervisory control and data acquisition
TCV: Throttle control valve
ToT: Transfer of training
USE®: UReason's solution environment
VC: Virtual commissioning
Waterspot: Drinking water simulator for proactive operation and training
WinCC: Software for visualization of a man machine interface

Samenvatting

Drinkwaterbedrijven gaan over op volautomatische bedrijfsvoering om een hogere en constantere waterkwaliteit te bereiken, minder afhankelijk zijn van menselijke beperkingen (zoals de maximale werkduur en persoonlijke voorkeuren in de bedrijfsvoering), een hogere leveringszekerheid en lagere kosten. Als bedrijfsvoerders door de toegenomen afstand tot het zuiveringsproces niet meer adequaat kunnen handelen tijdens calamiteiten kan dat leiden tot verstoring of onderbreking van de drinkwaterlevering. Bovendien kan de procesautomatisering (PA) zelf falen, met name tijdens of na het in gebruik nemen van nieuwe software of software updates. In de afgelopen jaren zijn emulatie platforms van PA-systemen geïntroduceerd in de drinkwatersector. Op deze platforms kan software worden uitgewisseld tussen een programable logic controller en een soft controller op een PC, en vice versa, zonder iets te wijzigen in de software. In dit onderzoek worden procesmodellen verbonden met een emulatieplatform om, i) om technologen de mogelijkheid te bieden regelingen te ontwerpen en te evalueren, ii) bedrijfsvoerders te trainen in een nagenoeg waarheidsgetrouwe 'human-in-the-loop' simulator, en iii) om PA-software functioneel te testen.

De doelstellingen van dit onderzoek zijn om door procesmodellen te verbinden met geëmuleerde PA-software i) de risico's van volautomatische bedrijfsvoering van drinkwaterzuiveringen te verlagen en ii) de zuiveringsprocessen te verbeteren. Het is de wens de Stimela modellen in dit onderzoek naar hun vierde en laatste fase van ontwikkeling te brengen.

Volautomatische bedrijfsvoering stelt hogere eisen aan bedrijfsvoerders dan handbediening of lokale automatische bediening, vanwege de grotere span of control, het grotere aantal sensoren en actuatoren, de complexiteit van de procesautomatisering zelf en de bijbehorende datacommunicatie en -vaak- vanwege het feit dat de probleemanalyse van afstand moet gebeuren. Een human-in-the-loop simulator kan een bijdrage vormen in het verkrijgen en behouden van kennis en vaardigheden. Het eerste succesvolle voorbeeld van zo'n simulator is beschreven. Milieukundige beslisondersteunsystemen werden gebruikt als blauwdruk voor de simulator omdat het integreren van procesmodellen op zulke systemen gebruikelijk is. Door het toevoegen van een grafische user interface lijkend op de SCADA interfaces uit de praktijk, kunnen ook gebruikers zonder specifieke kennis van modellering gebruik maken van de onderling verbonden hydraulische-, waterkwaliteits- en procesregelmodellen. De 'Waterspot' drinkwatersimulator is ontwikkeld en toegepast bij vier Nederlandse drinkwaterzuiveringen.

Het debiet door een zuiveringsstap is een belangrijke parameters voor de effectiviteit van die stap. Een nieuwe bibliotheek wordt gepresenteerd met onderdelen van een drinkwaterzuivering voor EPANET. Met hulp van deze bibliotheek zijn twee hydraulische modellen opgesteld en gevalideerd, één voor pompstation Harderbroek en één voor pompstation Wim Mensink. De debieten over de straten en onderdelen van de zuiveringen kunnen worden bepaald als functie van klepstanden en toerentallen van pompen.

Een methode is beschreven om regelingen te evalueren die zijn opgesteld met de ontwerp methode voor drinkwaterzuiveringen. Een Stimela waterkwaliteitsmodel van de ontharding van Wim Mensink is opgesteld en gevalideerd. Met dit procesmodel zijn de effecten van de bestaande regeling van de ontharding vergeleken met een nieuwe regeling en werd het effect van een lagere toevoer van RO-water onderzocht. Aangetoond kon worden dat door de nieuwe regeling de capaciteit van de zuivering vergroot kon worden, en dat het gebruik van energie en chemicaliën verminderd kon worden. Tegelijkertijd kon de totale hardheid van het drinkwater dichter bij de gewenste waarde gebracht worden.

Het nut van een human-in-the-loop drinkwatersimulator is onderzocht. De overdracht van kennis zoals is die is opgedaan in een simulator is bepaald in dezelfde simulator met vier testgroepen. Drie daarvan, ervaren bedrijfsvoerders (EB), minder ervaren bedrijfsvoerders (MEB) en leken (L60x) trainden met een versnelde simulatie, de vierde groep, leken (L1x), trainde op normale snelheid. De trainees leerde hoe ze de waterkwaliteit van het effluent van de ontharding reactoren konden regelen. Tijdens het testen van de overdracht van de kennis, wanneer ze geconfronteerd werden met andere procesverstoringen dan tijdens de training, presteerde L60x significant slechter dan de bedrijfsvoerders (EB en MEB). Er werd geen onderscheid gemeten tussen de prestaties van de EB en de MEB en L60x presteerde beter dan L1x. Deze resulaten lijken het idee te bevestigen dat het leren regelen van een langzaam en complex proces kan verbeteren door op een herkenbare manier te trainen met versnelde simulatie.

Tenslotte is de toegevoegde waarde onderzocht van proces simulatie modellen in de 'factory acceptance test' (FAT) van PA software. Twee test teams testten hetzelde stuk aangepaste software. Eén team gebruikte hiervoor een testsysteem dat bestond uit een emulatie van de software geïntegreerd met een proces simulatie model, het AVC systeem. Het andere team gebruikte hetzelfde systeem met in plaats van het process simulatie model, basale parameter relaties, het VC systeem. Elk team speurde één (verschillende) fout op van de dertien fouten die voor het experiment in de software waren gestopt, de meeste fouten waren tijdens de unit test door het ontwerpteam gevonden. Tijdens de functionele test vond het AVC team drie fouten in de 78 geteste items, het VC team vier. Maar het AVC team beoordeelde 1% van de test items 'niet van toepassing', het VC team 17%, een indicatie dat met AVC meer getest kan worden. Met AVC kunnen niet overtuigend meer fouten worden gevonden dan met VC. Niet het proces gedrag is relevant voor de FAT van PA software, maar het over- of onderschrijden van proces grenzen.

Dankwoord

Het zit erop! Ik ben trots op het resultaat, maar vooral dankbaar dat het mij gegund is dit proefschrift af te ronden. Het ligt voor de hand te denken dat dit werk het resultaat is van intrinsieke nieuwsgierigheid, wijsheid en wetenschappelijk talent. Maar dichter bij de waarheid is dat dit het resultaat is van vijf samenwerkingen die, dat mag gezegd, door mij zijn beschreven.

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Curriculum vitae

Gerard Ignatius Maria (Ignaz) Worm was born in Oudewater, the Netherlands, on December 13th 1974. In 1993 he graduated from the Murmellius Gymnasium in Alkmaar and started his studies Civil Engineering at Delft University of Technology, Faculty Civil Engineering and Geosciences, department Sanitary Engineering. Part of his studies was an internship in Saudi Arabia at Saudi de Moel. After an active student life, he finished his MSc-thesis 'Lucht/waterspoeling bij ultrafiltratie' (airflush for ultrafiltration) in February 2000 under supervision of Jasper Verberk and Hans van Dijk. This thesis was awarded with the 'Faculty award for best MSc-thesis' and nominated for the 'Gijs Oskam award'. After his graduation he worked for one year as researcher at Delft University of Technology. Then, after a management traineeship at publisher Wolters Kluwer, Ignaz worked for four years at Dunea (formerly known as Duinwaterbedrijf Zuid-Holland) as consultant processes and technology. Since 2007 he works at PWN as senior advisor water supply and teamleader water technology. In September 2005, besides his work, he started his PhD research at Delft University of Technology. With Jasper Verberk he founded the peer reviewed open access journal Drinking Water Engineering and Science. As from 2009 he contributed to the acquisition, the administration and strategy of Dierenkliniek Vondelpark. In 2012 Ignaz won the 'Best IT-idea in the water sector award' of Koninklijk Nederlands Waternetwerk (KNW) for 'The human sensor'.