A COMPANY SPECIFIC SIMULATOR OF A DRINKING WATER TREATMENT PLANT

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Abstract

Fully automated operation is introduced in drinking water treatment plants. This will open the possibility of model based process control but will cause erosion of skills and knowledge of daily operation supervisors as well. For training of supervisors of fully automated drinking water treatment plants a simulator is developed. In future the same simulator will be used by process engineers for offline and online process optimization.

A pilot simulator has been developed for the softening plant of drinking water treatment plant Monster. A Stimela water quality model for softening using fluidised pellet reactors was defined and validated. When the need for simulating hydraulic behaviour of the plant was identified, an EPAnet hydraulic model was defined and validated basically. Simulator training functionality was identified and partly realised in the pilot project. The economical and technical feasibility of a simulator was studied. The pilot simulator is operational and inspired nine Dutch companies to start the WATERSPOT project.

Keywords: Drinking water treatment, simulator, training, model, operator

Presenting author's biography

Ignaz Worm was born in 1974. In 2000 he graduated as a MSc Civil Engineering from Delft University of Technology with the thesis "Airflush for ultrafiltration membranes". This thesis was rewarded with the Faculty Award for best graduation.

At present Ignaz works for PWN Waterleidingbedrijf Noord-Holland as a consultant in process engineering research.

In November 2006 Ignaz and Luuk Rietveld initiated the WATERSPOT project which has the objective to develop a drinking water simulator for proactive operation and training.

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1 Introduction

In February 2000, the Journal of the American Water Works Association published a "next generation scenario" for water utilities. According to [1] and [2], in 2050 a drinking water treatment plant will be controlled from a central control centre. Advanced process and control models will be incorporated in the process control software. The process will be monitored using on-line qualitative and quantitative indicators. Innovative analysis techniques and (soft-) sensors will supply the program with the comprehensive information necessary to make and implement control decisions. Real-time performance indicators will constantly evaluate the effectiveness of each process. Furthermore, the system will be able to evaluate the effects of control decisions for future decision-making processes, leading to an increase in knowledge about the treatment plant. At present (2007) current water treatment process models will not deliver on this vision, but water supply companies are gradually changing to a fully automated operation. The drivers for this change are increase of efficiency and a higher and more stable water quality.

Fully automated treatment plants will require more sophisticated operator care than manually operated plants. Operators will become more sophisticated, have more specific knowledge and will have to understand what is happening behind the "treatment plant chatter" [2]. The distinct difference is that the supervisor will be responsible for the entire treatment (multiple plants) and the transport- and distribution system from source to tap. During normal working hours he will validate production data, analyze deviations and check the health of the automation system. In shifts, the supervisor remains responsible for dealing with emergencies, alarms and for "long distance" problem solving. To excel in both tasks, the supervisor needs to understand the entire treatment, transport and distribution system thoroughly. He needs to speak the language of automation and data communication fluently and have the knowledge as well as the skills to be able to react adequately in the one percent non regular situations. Education requirements will rise and high-powered computer programs will assist the supervisors.

Although drinking water treatment has a long history, the mathematical analysis for operational improvements of these treatment processes is still young. Using mathematical models to represent each unit process and connecting processes to represent the entire works, factors such as quality (good, constant and reliable), quantity, costs, environmental impact (low residual levels), design redundancy and flexibility can be evaluated and operational conditions can be optimized, using the existing infrastructure as efficiently as possible [3]. With models supervisors can be trained and supported in making decisions during calamities. The use of models will lead to an increased understanding of the processes in general, and to fewer mistakes in the rare critical situations. As a consequence supervisors will be more critical to the performance of the process and the process automation system. The use of models and simulators is common in the process industry, aviation, electricity production, power distribution, car driving and surgery [4].

In this paper a case study is presented where models are used to feed a drinking water treatment simulator for training of operators in fully automated drinking water treatment plants. The case study consists of a pellet softening step at Duinwaterbedrijf Zuid-Holland. A hydraulic model and a model of the pellet softening [5] programmed in Stimela, are validated on data obtained from a full-scale plant. A simulator is fed the different models and tested. Finally, two cases from daily operation are simulated.

Objective of this research is to determine the technical and economical feasibility of a simulator for drinking water treatment plants and to determine the acceptance of the simulator by its future end users. The added value of using a simulator will be determined in comparison to the use of water quality models.

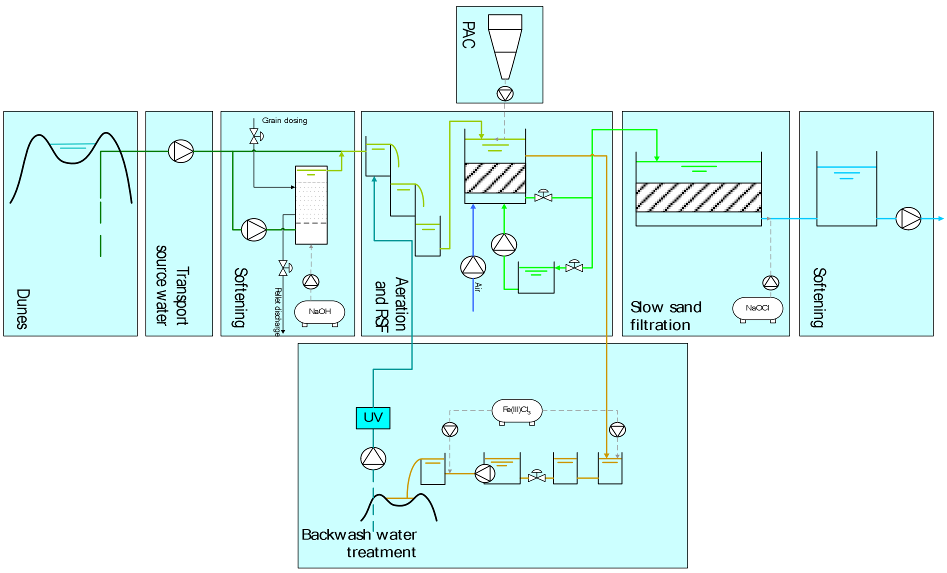

Fig. 1 Process flow drinking water treatment plant Monster

2 Methods and materials

2.1 The Monster plant

For the case in this study the softening plant of drinking water treatment plant Monster was selected. The choice for Monster was made because automation of the plant was finished. The choice for softening was made because a well calibrated dynamic pellet softening model was available [6] and because of the possibility to validate the model with data from the Katwijk plant of which the softening plant is comparable to the one in Monster.

The Monster plant has a capacity of 1000 m^3/h and uses artificially recharged dune water as a source. The dune water is treated with softening, powder activated carbon, aeration, rapid sand filtration and slow sand filtration, see Fig. 1. No chlorine is dosed.

To decrease the hardness of the water and to reduce the copper and lead solvent capacity of the water, two fluidised bed reactors remove calcium ions from the source water. Source water has a typical total hardness (TH, magnesium concentration plus calcium concentration) of 2,0 to 2,5 mmol/l. For an optimal effluent quality the reactors have a constant upward flow of 90 m/h being 285 m^3/h, and a effluent TH down to 0,8 mmol/l. The untreated by pass flow is maximised up to 55%, yielding the mixed effluent TH is as low as 1,5 mmol/l. As in the Katwijk plant in Monster sodium hydroxide (NaOH) is used as the chemical to increase the pH to let the calcium precipitate as calcium carbonate.

2.2 Simulator

A pilot version of the Waterspot simulator was used. The architecture of the pilot simulator is based on a copy of a part of the process automation system of the Monster plant, including the man machine interface (MMI) where the behaviour of field objects is simulated with water quality models and a hydraulic model. The need to run programs and models on different platforms defined the architecture of the simulator. The field controller functionalities, including MMI and a virtual object model were defined as a subsystem running on ABB's Industrial IT platform. The Stimela water quality model runs on a Matlab Simulink platform. The scheduler, containing all training and report functionality, the interfaces between the subsystems and the hydraulic EPAnet model was assigned to a third subsystem containing the USE platform. The USE platform is a commercial platform for object modelling based programming of applications for the process industry. The final architecture of the simulator is shown in Fig. 2. For practical reasons each subsystem was placed on a dedicated PC.

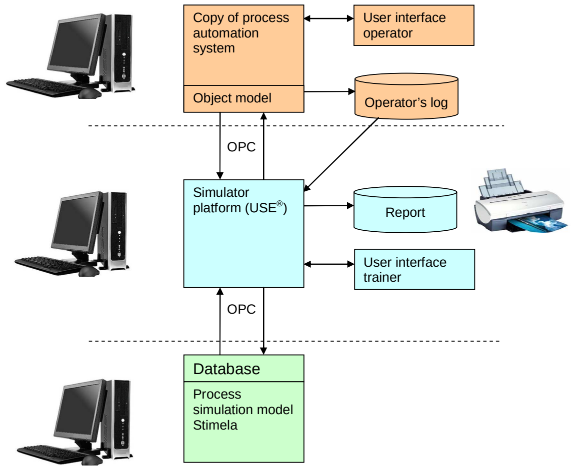

Fig. 2 Architecture of the drinking water treatment simulator

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2.3 Water quality model

The softening process consists of a number of fluidized bed reactors with one single bypass. The chemical reactions in the water take place in the reactor. The mixing process of reactor effluents and bypass water is modeled as instantaneous mixing (taking the calcium carbonic equilibrium into account) without any reaction kinetics.

The Stimela model for softening is a dynamic model of the pellet softening process. The model is based on the calcium carbonic equilibrium, which determines the crystallization in the reactor, the fluidization of the bed, which determines the available crystallization surface in the reactor and the crystallization rate based on the crystallization surface and the calcium carbonic equilibrium [7].

2.4 Hydraulic model

To predict basic hydraulic behaviour of the softening plant, the EPAnet hydraulic model is connected with the simulator [8]. EPAnet performs extended period simulation of hydraulic and water-quality behaviour within pressurized pipe networks. A network can consist of pipes, nodes (pipe junctions), pumps, valves and storage tanks or reservoirs. EPAnet tracks the flow of water in each pipe, the pressure at each node, the height of water in each tank, and the concentration of a chemical species throughout the network during a simulation period comprised of multiple time steps. EPAnet is public domain software that may be freely copied and distributed.

A basic model of the softening plant of Monster was defined and validated.

2.5 Cases

Two cases were studied in the simulator. In the first the effect of changes of the flow trough the reactor was studied on the height of the fluidised bed. Typically, increasing the flow will increase the height of the bed. For different flows the bed height is calculated using the simulator.

In the second case the effect of the dose of NaOH to the reactors on the TH of the mixed water is simulated. For a TH of source water of 2,0 mmol/l, for five different sodium hydroxide dosages, the TH is calculated using the pilot simulator. To produce soft water, optimal TH is believed to be 1,5 mmol/l [9].

With these kinds of cases daily operation of the softening plant can be optimised.

2.6 Users and functionality

From literature, company visits and commercial websites required functionality for the simulator is derived. During development of the pilot alternative end users will be identified.

2.7 Economical feasibility

The economical feasibility depends, upon other things, on the need for a simulator by its end users. The simulator is believed to be an essential tool to prevent erosion of skills and knowledge of operators in fully automated operation. To investigate this, first the responsibilities of nineteen supervisors and managers from a company working and a company going to work with fully automated operation filled out questionnaires. Special attention was paid to the differences in perception of responsibilities between supervisors and managers and between the two companies.

After completion of the pilot simulator, five future supervisors used the simulator and filled out questionnaires again.

Estimation was made of the costs of development of a simulator for a complete drinking water treatment plant.

3 Results and discussion

3.1 Topology softening plant

In Fig. 3 the visualisation of the topology of the pilot is shown. The water flow is represented by the green line, including by-pass flow. The red line represents the caustic soda dosage to the reactors. The yellow line represents the grain material dosing system. The dialogue boxes at the right side of the reactors show the effluent total hardness, the fluidised bed height and the pressure drop over the bed. Most right the total hardness of the effluent of both reactors is shown after mixing with the by-pass flow. The grey square buttons give access to a screen in which predefined changes of process values can be selected and executed, i.e. increasing of flow with ten percent or increase of total hardness of the dune water with ten percent.

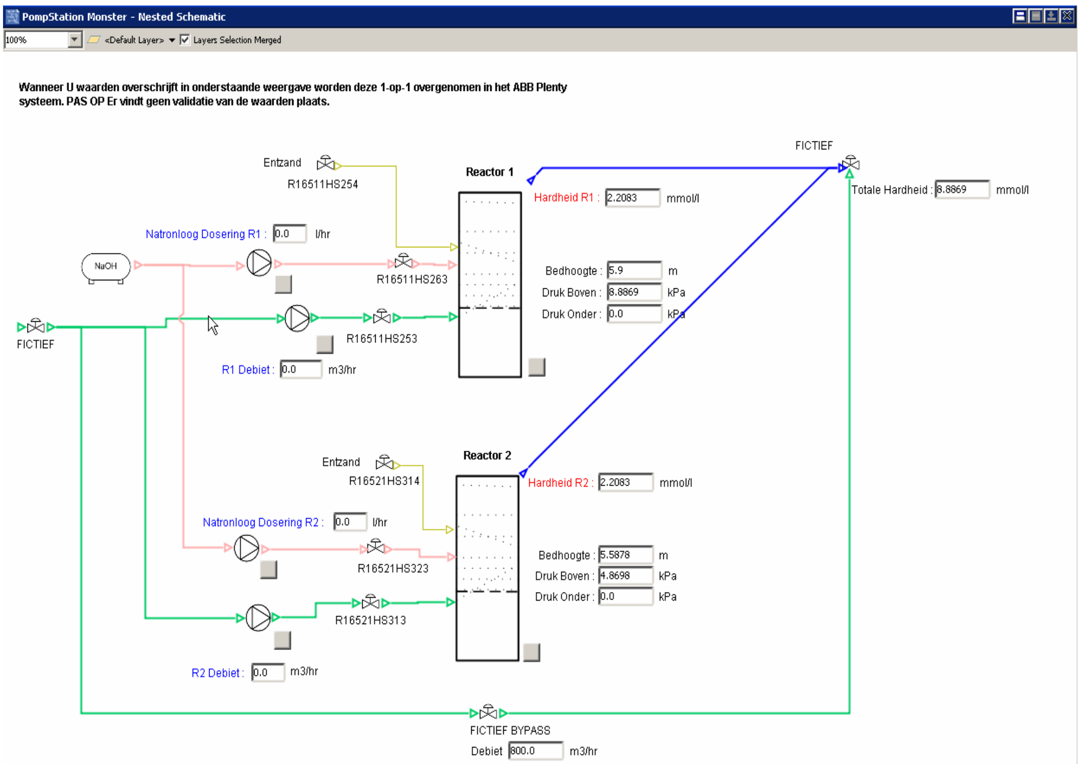

Fig. 3 Screenshot of the trainer's user interface

3.2 Hydraulic model

During development it appeared that the object model did not present the effect of changes of actuators on accompanying sensors. The presentation of these effects is essential for the acceptance of the simulator by its end users. The need for development and insert of a hydraulic model was identified.In a quick scan the hydraulic models Synergee [10], Aleid [11], Wanda [12] and EPAnet were compared and EPAnet was chosen because it is well known, widely applied, reliable, user friendly and free downloadable.

In EPAnet a model was defined as shown in Fig. 4. The fluidised bed was modelled by a valve with rising resistance at increasing flow. Design parameters and model properties were derived from drawings and field measurements.

For validation of the model first the junctions' properties were checked to be logic for an average steady state. Then the model was validated for the actual operation of the softening plant on February 7th 2007 when one reactor was in operation with 284 m^3/h and the by pass flow was 335 m^3/h. The model calculated the pressure under the bottom of the reactor to be 105,9 mwc. The measured value was 107 mwc. The pressure just above the bottom of the reactor was calculated to be 85,9 mwc and was measured to be 91,5 mwc. The bigger difference between measurement and model calculation for the latter is believed to be caused by higher turbulence there. Results are thought to be accurate enough to rely on the EPAnet model in the pilot simulator.

3.3 Continuous versus discrete

The simulator is implemented as a discrete event simulator as this introduces only a number of variable states in time and allows the simulator to advance time, accelerate/decelerate, from event to event. In a discrete event simulator the operation of a system is represented as a chronological sequence of events. Each event occurs at an instant in time and marks a change of state in the system [13]. This as opposed to a continuous simulator, where state variables continuously change with respect to time (e.g. using differential equations).

3.4 Interfaces and traffic rules

With the existing simulators a connection to a copy of field systems cannot be made, making it impossible to train in the company specific look and feel of the automation system. That's why the decision was made to develop a new simulator that easily can be connected to a (copy of) a field automation system.

Communication standard between the subsystems for process data is OLE for Process Control (OPC). OPC is the general accepted interface protocol for software applications in the process industry. Most bigger vendors of process automation systems offer this protocol as a part of their systems or will do so in future.

The Stimela models were extended with an OPC interface. Non process data is written by the simulator to databases using ODBC. An interface to the C libraries of the EPAnet model was developed and its libraries were extended to meet OPC standards.

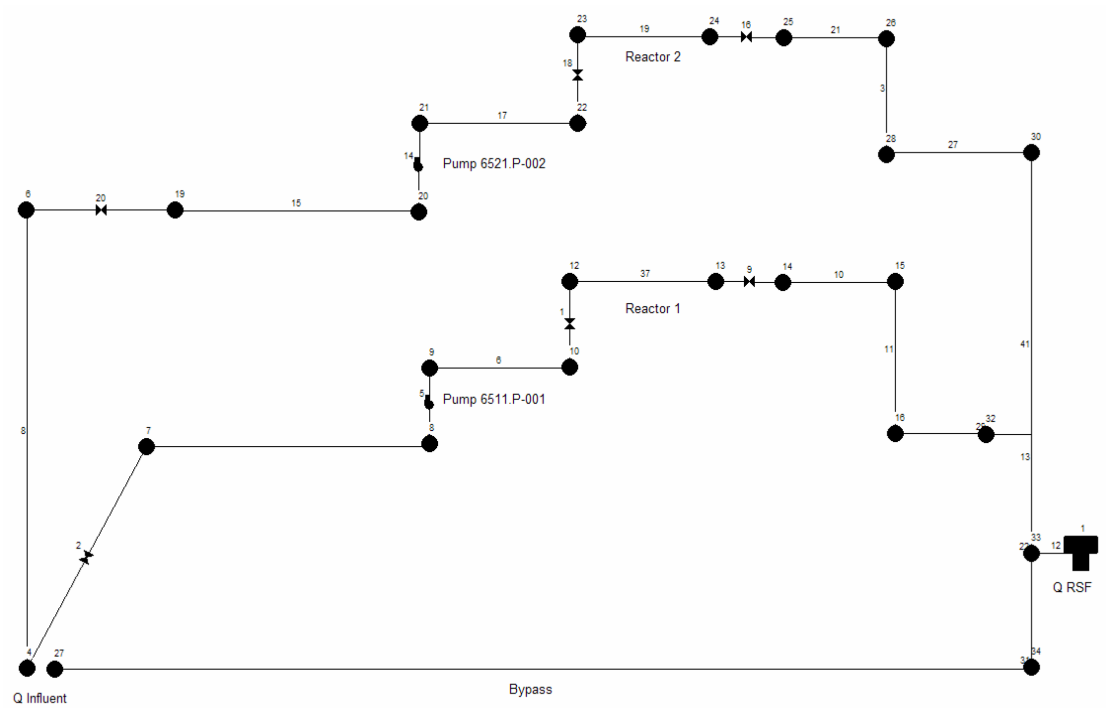

Fig. 4 Hydraulic model of the softening plant of Monster

Using discrete event simulation as the basis for the simulator introduced the complexity of correctly identifying the model precedence for each discrete event in order to determine the new system state.

The difficulty lies in the interaction between the models – a change in the outputs of the Stimela water quality models influences the hydraulic EPAnet model vice versa. Additionally the chosen training type introduces a further complexity with respect to scheduling of the events that influences the system state. In case based training sessions there are two types of events that influence the simulator: scheduled events, e.g. the introduction of an upset and unscheduled events, e.g.. a user changing a setpoint. Precedence is given to scheduled events in such cases (three-phase approach [14]).

3.5 Cases

Increasing the flow through the reactor leads to increase of the height of the fluidized bed, see Tab. 1 and Fig. 5.

Tab. 1: Bedheight at different flows as presented in the pilot simulator

Q [m3/h]	Bed height [m]
140	3.81
175	4.03
210	4.25
245	4.47
280	4.70

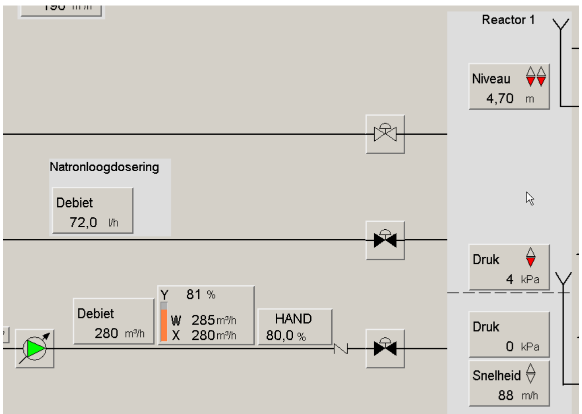

Fig. 5 Screendump bed height at chosen flow

Decreasing the dose of NaOH leads to an increase of the TH per reactor, see Tab. 2 and Fig. 6. As in practice a new equilibrium for the TH is reached after approximately 15 minutes.

Tab. 2: TH per reactor at different NaOH doses as presented in the pilot simulator. Incoming TH 2.00 mmol/l

NaOH dose [l/h]	TH per reactor [mmol/l]
64	0.7
48	1.1
32	1.5
16	1.9

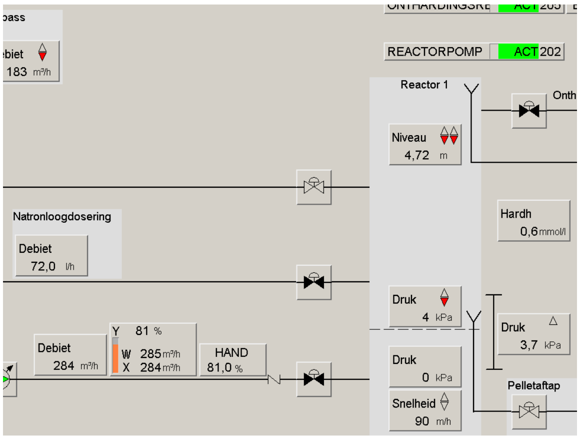

Fig. 6 Screendump TH at chosen NaOH dose

The results of the cases match the expectations and the behaviour of the pilot simulator is close enough to reality to be credible.

3.6 End users and functionality

Most operator training simulators aim on operators of petrochemical plants. Simulators in general consist of a process model, a control model, an I/O model, a trainee interface and a trainer interface. See for example the commercially SIMSCI ESSCOR simulator of Invensys or the INDISS simulator of RSI Simcon. Studied simulators are suitable for multiple operation modes:

- normal operation;
- troubleshooting in daily operation;
- abnormal situations and emergencies;
- start-up and shutdown procedures;
- causes and effect analysis.

From literature, websites and company visits to Shell (Pernis) and the Dutch power distributor Tennet the following functionality was identified as common in simulators:

- Play - pause - resume and run step by step;
- Execute the simulation faster or slower than real-time;
- Record and replay simulation runs or states;
- Make a snapshot and return to last snapshot;
- Define and change initial conditions;

- Activate instrument and equipment faults and malfunctions, if preferred delayed and or ramped;
- Create and execute scenarios, being a group of malfunctions;
- Manage users (accounts, profiles, dedicated exercises);
- Monitor process and control variables;
- Generate reports;
- Concurrent use in training.

At the start of the development, besides a free training mode, one use case for regular operation was defined and one use case for calamity operation. For the definition of the two use cases Unified Modelling Language (UML) sequence diagrams were used. These diagrams describe the actions the trainee is expected to take during a case, as well as the actions of the trainer and the system. The use of UML sequence diagrams based use cases was disappointing because of the effort required to define the expected actions in detail. This is a serious risk in acceptance of the simulator after introduction. Furthermore the use of a strict definition of the expected actions discourages creative solutions of supervisors. Automated reuse of the already defined process protocols and procedures could be investigated.

During the development the end user process engineer, FAT (factory acceptance test) engineer and administrator were identified. With small adjustments the simulator can be put into action for offline process optimization by a process engineer. In future the simulator might be useful to test updates of software more thoroughly.

3.7 User acceptance and business case

The overall response of questionnaires of the nineteen supervisors and their managers showed that the supervisor in fully automated drinking water treatment is responsible for the water delivery from source to transport mains, in terms of pressure, quantity and water quality. It was concluded that the number-one-fear of managers as well as of supervisors is lack of knowledge of the operation.

In general no large differences were identified in the perception of responsibilities between supervisors and managers. One company mentions the importance of team spirit and communication skills, employees of the other company emphasize that manual operation should be prevented.

After completion of the pilot simulator four future end users evaluated the performance of the simulator. They expect to use the simulator once a month, to practice, to understand the process and to replay situations that occurred. They accept the use of the simulator for testing of skills. The use of the copy of the company specific MMI was valued by the supervisors. The general opinion was positive.

The costs of development of a simulator for a complete drinking water treatment plant would exceed 1 M€. The development would include all described functionality, validated water quality models and hydraulic models, but exclude simulation of the source- and distribution system. These costs were considered too high for Duinwaterbedrijf Zuid-Holland to carry alone. A consortium was formed with nine companies, amongst which four water supply companies, to share costs and efforts. The design and expected products were made generally applicable in the world, thus opening an opportunity to Senter Novem (Dutch Ministry of Economic affairs) to award the spin off project with an export grant.

The profits in terms of cost saving are hard to determine. Use of the simulator by operation supervisors will lead to a smaller chance of human mistakes threatening public health and the image of the water supply company. Process engineers are expected to realise cost savings through minimal energy and chemical use and through delay of investments because of optimal use of existing conventional treatment plants.

4 Conclusion

It is concluded that development of a simulator of drinking water treatment plants for proactive operation and training is technically feasible. If the simulator is applicable in every water supply company facing the new possibilities and problems related to fully automated operation, the simulator is economically feasible as well. Future end users are operation supervisors and process engineers.

The pilot simulator contains a Stimela water quality model, an EPAnet hydraulic model, a copy of the company's process automation system and a simulator engine connecting the different parts and offering basic training functionality. The two models mentioned have been validated for the softening plant of the Monster drinking water treatment plant. They proved to be so accurate the simulator behaves credibly.

In comparison to the use of water quality models, a simulator has a friendlier user interface. It is possible to connect efficiently with any (copy of a) process automation system or water quality- or hydraulic model supporting OPC communication.

Results of this pilot and reactions of end users encouraged nine Dutch companies to start the WATERSPOT [15] project in which a generic simulator will be developed, company specific simulators and the possibility of model based process optimization. WATERSPOT is sponsored by Senter Novem, Ministry of Economic Affairs of the Netherlands.

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