A drinking water treatment plant simulator using real-time plant data for enhanced operator training and model evaluation
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ABSTRACT
Waterspot is a plant-wide drinking water treatment simulator that has been developed in a 3 year research project. The incorporation of real-time and historical data of on-line water quality measurements, flow measurements, process data and water quality laboratory measurements in the simulator improves the acceptance of model output by technologists, ensures a more realistic training of operators and shows the potential of detecting deviations from the expected water quality and control of the plant. The optimal position of the simulator in the automation architecture was found to be on the process information management system (PIMS) network.

Key words | drinking water treatment, historical data, modelling, pellet softening, real-time data, simulator

INTRODUCTION
‘Waterspot’, a plant-wide simulator, was recently developed for the Weesperkarspel drinking water treatment plant of Waternet, the water cycle company for Amsterdam and surrounding areas. In the Weesperkarspel simulator, three process models run simultaneously: a water quality model, a hydraulic model and a process control model (Worm et al. 2009a). The simulator has a graphical user interface similar to a supervisory control and data acquisition (SCADA) system. For example, Figure 1 shows a Waterspot simulation run for ozonation reactor 1, during which the ozone dosage in reactor 1 and the flow through reactor 1 were varied. In the graph in Figure 1 the changes on the effluent water quality are shown. The change in flow at 21:35 does not lead to changes in the effluent water quality because the ozone dosage is proportional to the flow. The changes in the ozone dosage at 19:30 (lowering of ozone dosage from 2.4 to 2.0 mg-O3/l) and at 23:45 (lowering of ozone dosage from 2.4 to 2.0 mg-O3/l) directly influence the effluent water quality parameters, for instance CT (ozone in water concentration ‘C’ times contact time ‘T’), which is a measure for ozone exposure and which decreases twice, and bromate formation, which also decreases twice.

An example of the use of plant-wide simulators for water treatment is the Badiolegi wastewater treatment plant simulator (Ayesa et al. 2001). The simulator is based on a complete connection between real data and a mathematical model of the plant that facilitates model calibration and the exploration of different operational strategies. The study showed the possibility of implementing the simulator as a useful tool for plant management and operation. Krause (2007) developed a simulator for Liquid Natural Gas (LNG) plant under construction consisting of: an emulator of the digital control system (DCS), which is a copy of
programmable logic controllers onto a PC workstation; a dynamic process model; and the original SCADA system. This situation resulted in a virtual LNG plant running on PC workstations with exactly the same user interface as the future real plant. The virtual plant was used by Krause for virtual commissioning of the plant and for operator training. This situation resulted in a huge number of plant operation and automation issues that were resolved before problems occurred on the real system.

The Waterspot simulator of the Weesperkarspel drinking water treatment plant is used by drinking water technologists for plant-wide optimisation and can be used by operators for training. The expectation is that incorporating real-time and historical data of actual measured flows and water quality parameter values, as simulator input and for evaluation of simulator output, will lead to improved operator training and model evaluation. In this research, the possibility of incorporating real-time and historical data in the simulator was investigated, the best position of the simulator in the automation was determined, and the added value of incorporating real-time and historical data was evaluated for the simulator use by technologists and operators.

**MATERIALS AND METHODS**

**Drinking water treatment plant Weesperkarspel**

The Weesperkarspel treatment plant receives pre-treated seepage water from the Bethune polder, sometimes mixed with Amsterdam-Rhine Canal water, for the production of drinking water. The first process at the Weesperkarspel treatment plant see Figure 2, is ozonation for disinfection and oxidation of organic matter, which results in an increase in the biodegradability of the natural organic matter (NOM). Thereafter, pellet reactors are used to reduce hardness (softening) and biological activated...
carbon (BAC) filtration is applied to remove NOM and organic micro-pollutants. The last step in the treatment is slow sand filtration for nutrient removal and reduction of suspended solids. This process is also the second important barrier against pathogens and is especially important for removing persistent pathogens with low susceptibility to ozone (e.g., Cryptosporidium). The drinking water is transported and distributed without residual chlorine.

Weesperkarspel Waterspot simulator

For the simulation of the water quality parameters, the Waterspot simulator contains dynamic water quality models of the ozonation, pellet softening and activated carbon filtration processes. The water quality models are described by van der Helm (2007), Rietveld et al. (2008, 2009), van Schagen et al. (2008) and van der Helm et al. (2009). The water quality models were built in Stimela (van der Helm & Rietveld 2002), a modelling environment for drinking water treatment processes. The Stimela models were developed in Matlab/Simulink®. Partial differential equations were numerically integrated so variations in time and space can be followed. The various drinking water treatment processes can be simulated simultaneously. Other possibilities for drinking water treatment modelling environments such as Stimela are described by Dudley et al. (2008). In order to have an understanding of the complexity of the water quality models used in the simulator, the partial differential equations for the ozone concentration in water and in gas in the ozonation model are given below (van der Helm 2007):

\[
\frac{\partial c_{O_3}}{\partial t} = -u \frac{\partial c_{O_3}}{\partial x} + k_L \frac{Q}{v_g} \frac{6}{d_b} (a k_D c_{O_3g} - c_{O_3}) - k_{UVA} (UVA - UVA_0) Y - k_{O_3} c_{O_3}
\]

where \( u \) is the water velocity (m/s), \( x \) is the length of the reactor (m), \( k_L \) is the gas transfer coefficient (m/s), \( Q \) is the gas to water flow ratio \( (Q_g/Q) \) (Nm\(^3\)/m\(^3\)), \( Q \) and \( Q_g \) are the water flow (m\(^3\)/h) and gas flow (Nm\(^3\)/h), respectively, \( u_g \) is the gas velocity (m/s), \( d_b \) is the bubble diameter (m), \( \alpha \) is the temperature and pressure correction factor \( \alpha = (P_o/P_g)(T_o/T_g) \), \( P_o \) and \( P_g \) are the standard pressure (101,325 Pa) and the gas pressure in the reactor (Pa), respectively, \( T_o \) and \( T_g \) are the standard temperature (273.15 K) and the gas temperature in the reactor (K), \( k_D \) is the distribution coefficient, \( c_{O_3g} \) is the ozone in gas concentration (g-O3/Nm\(^3\)), \( k_{UVA} \) is UV absorbance at 254 nm (UVA\(_{254}\)) decay rate (1/s), \( UVA \) is UVA\(_{254}\) in water (1/m), \( UVA_0 \) is the stable UVA\(_{254}\) after completion of the ozonation process (1/m), \( Y \) is the yield for ozone consumed per UVA\(_{254}\) decrease ((mg-O3/l)/(1/m)) and \( k_{O_3} \) is the slow ozone decay rate (1/s).

The partial differential equations used for UVA\(_{254}\) decrease, bromate formation, CT and assimilable organic carbon (AOC) formation during ozonation are described in van der Helm (2007). The models used in the plant-wide simulator are calibrated and validated in pilot plant research and in the full-scale Weesperkarspel drinking water treatment plant.

For the simulation of flows, flow divisions and pressures in the treatment plant, a hydraulic EPANET model (Rossman 2000) was integrated into the simulator. In EPANET, distribution networks are defined by elements such as junctions, pipelines, pumps, valves, tanks and reservoirs. In order to model the resistance and free water surfaces in the treatment plant e.g. filter beds and supernatant water levels, a combination of different valves was
set up (Worm et al. 2009b). As an example, the valve setup in the EPANET model of a BAC filter with fixed supernatant water level using a control valve in the effluent pipe is described here. The water inlet is modelled with a general purpose valve (GPV) followed by a pressure sustaining valve (PSV) to simulate a weir. The two valves are followed by a tank that represents the supernatant water. After the tank, a pressure breaker valve (PBV) represents the pressure drop over the filter bed. The value of the pressure drop is calculated in the Stimela water quality model. The resistance of the filter bottom nozzles is modelled using a throttle control valve (TCV) and the control valve in the effluent pipe, maintaining the level of supernatant water, is modelled as a second TCV (Worm et al. 2009b).

For simulation of the control algorithms that are used in the treatment plant, a control model was incorporated that also has a proportional-integral-derivative (PID) controller function. The last model is the object model, which is the virtual representation of all field elements, e.g. sensors, reactors and pipes. The object model forms the structure of Waterspot. The Waterspot engine facilitates communication between the Stimela model, EPANET model and control model, see Figure 3.

By using open standards for communication, the possibility exists of integrating other model platforms in the future. For communication with Stimela, a dedicated OPC-DA server (Object linking and embedding for Process Control – Data Acquisition) is used. For EPANET, an interface is used which reads from and writes to the EPANET dynamic link library (dll) files through an API (Application Programming Interface) and to connect with a production database, a JDBC (Java Database Connectivity) interface is used.

**Position of Waterspot in the automation architecture**

Incorporating real-time and historical plant data in the simulator affects the position of the simulator in the Waternet automation, which consists of office automation (OA) and process automation (PA). These systems are connected via a demilitarised zone (DMZ). Figure 4 shows that there is no direct communication between OA and PA, the reason for this situation being security demands. The OA is most vulnerable to possible viruses (OA zone), the DMZ is better secured (DMZ zone) and the PA is the most secure network (PA zone).

The process information management system (PIMS) contains laboratory measurements of water quality, online water quality measurements, flow measurements and process data used in the SCADA system. The data are available in real-time. The PIMS can be addressed from an OA application and is fed from the PA. Different configurations
of the Waterspot simulator in the automation architecture were assessed for an optimal connection to real-time and historical data in PIMS for maximum safety and performance.

**Use of real-time and historical plant data in Waterspot**

Incorporating real-time and historical data in the Waterspot simulator gives four options for different usage of the data in the simulator:

- Measured water quality data for model input instead of fixed water quality influent values;
- measured process data for model input instead of using the control model in the simulator. This approach makes it possible, for instance, to use a measured flow in the simulator as input;
- plotting measured data in output graphs together with the model results. This approach makes it possible to compare model results with measured data in the plant;
- writing data to PIMS for representation in reports or SCADA.

A model run was performed for the case of pellet softening at the Weesperkarspel treatment plant where real-time and historical data from PIMS was used in the simulator. There was no pre-processing executed on the PIMS data, meaning that there was no fault detection and no data reconciliation algorithms used on input data series. This choice was made in order to have the simulator act on exactly the same data as the control of the full-scale plant. If an online measurement is not correct, and the control action based on this erroneous measurement is the same in the simulator as in the full-scale plant, a difference in the effluent water quality will occur that is measured and calculated. In this way, an erroneous online measurement can be detected. The real-time and historical data used in the simulator are not meant to validate the model but to validate the processes. The calibration and validation of the models was done based on pilot plant research and on pre-processed historical data from the full-scale plant. The added value of using real-time and historical data in the simulator was evaluated by interviewing end-users.

**RESULTS AND DISCUSSION**

**Position of Waterspot in automation architecture**

The different possible positions of Waterspot in the automation architecture are:

- On the DMZ in the PA;
- on the PIMS network in the OA;
- on the central office Ethernet in the OA.

Given the end-users, the simulator can be placed in the OA for easy access by technologists or in the PA for easy access by operators. The advantage of the simulator in the PA is the direct access to process control data; however the laboratory data cannot be easily accessed in the PA and use by technologists from the OA is difficult because of security issues that do not allow direct access to the PA from the OA. This factor disqualified the positioning of the simulator in the PA. Other applications such as advanced process controllers, such as model predictive control of pellet softening as described by van Schagen (2009), are positioned in the PA of Waternet. The main reason is that the advanced process controllers are regarded as the regular control. Other reasons are the reliable and fast access to process control data and easy access for operators to the advanced process controllers, in order for them to have good insight in the decisions taken by the advanced process controllers.

The remaining options for the position of the Waterspot simulator within the OA were on the PIMS network or the central office Ethernet. Databases with real-time and historical data for on-line water quality, flow measurements, process data and laboratory measurements are on the PIMS network. Optimisers will also be positioned on the PIMS network. The difference between optimisers and advanced process controllers is the loop time for the application and the abstraction level, ranging from a single process in a plant to multiple plants. For advanced process controllers, the loop time is short (from seconds to minutes) and the abstraction level is usually a single process. For optimisers, the loop time is in the order of hours to days and the abstraction level is plant-wide optimisation to optimisation over multiple plants. The advantages of positioning the Waterspot simulator on the PIMS network was that the application is on the same network as the databases, so there is no need for data traffic over the
central office Ethernet, as would be the case if Waterspot was on the central office Ethernet. For the end-user there was no difference in use of the simulator whether positioned on the PIMS or the central office Ethernet. Therefore it was decided to position the Waterspot simulator on the PIMS network.

**Use of real-time and historical plant data in Waterspot**

In the Waterspot simulator the different usages of data were incorporated through a JDBC connection. The simulator engine retrieves real-time and historical data over the JDBC connection. The data are retrieved within the time steps (granularity) of the running simulation. When no historic data are available in a time step, the most current value is kept until a new value is found.

In Figure 5 the overview screen of the Weesperkarspel drinking water treatment plant simulator is shown. The processes in the overview are ozonation, pellet softening with bypass, and two lanes of BAC filtration and slow sand filtration. The popup window in the screen is for defining the water quality input parameters. Next to the possibility of entering a fixed value, for instance for temperature and pH, there is an extra option developed for using real-time data or historical data. Real-time data are used when the start time chosen for the simulator is equal to the actual time, and historical data are used when the start time chosen for the simulator is in the past. The option for use of real-time or historical measured influent water quality parameters for model input can be activated by means of the tick marks next to value input fields. In this case only real-time data of an on-line influent pH measurement was used instead of a constant value.

In Figure 6 the subscreen of the pellet softening process for removal of calcium is shown. The pellet softening process consists of eight reactors and a bypass. After mixing of the softened water with the non-softened water over the bypass, hydrochloric acid is added to prevent supersaturated calcium from precipitating. The popup window in Figure 6 is the faceplate from the influent control valve of reactor 1. In the faceplate the control valve can be opened or closed, a set point can be entered manually or set by the control function (in this case dependent on the water temperature), or the tick mark for using real-time and historical data can be...
activated and the set point is set from the measured flow through the valve. In Figure 6 the real-time measured flow through the valve and thus through the pellet softening reactor 1 was used as input for the simulator.

In Figure 7 the detail screen for softening reactor 1 is shown. It gives information of the influent and effluent water quality of the reactor, the caustic soda dosage, the garnet sand addition (calcium precipitates on the garnet sand) and the pellet discharge (garnet sand coated with calcium). The control for the caustic soda dosage, garnet sand addition and pellet discharge are described in van Schagen (2009). Four lines are plotted in the graph in Figure 7:

- The real-time measured effluent Total Hardness;
- the simulated effluent Total Hardness;
- the simulated effluent pH;
- the real-time measured flow through reactor 1 used in the simulation.

The graph is an example of plotting measured data in output graphs together with simulator results by plotting the on-line measured Total Hardness next to the simulated Total Hardness.

Interviews with technologists and operators showed that use of the simulator increased with the incorporation of real-time and historical data. Technologists stated that they had more confidence in the simulator output when real-time and historical data were incorporated. They could evaluate whether the actual plant was running according to control by changing from the control model to real-time data for model input. Operators stated that training with real-time and historical data made the training more realistic. They also stated that using the actual SCADA interface instead of the simulator interface would further increase the reality of training. Waternet decided not to use the current simulator for training of operators but to start additional research on the possibilities of a simulator with an emulation of the PA coupled with the plant-wide water quality and water quantity models. By doing so, operators will experience no difference in operating the real plant or the simulator, because the graphical user interface and the control model in the simulator are one-to-one.
copies. This approach will make it possible to have a realistic and therefore more effective training of operator skills. An important issue within this additional research is the evaluation of the possibilities of using the simulator not only for operator training, but also for PA software development and management and use by technologists. Current simulator use by technologists is limited, on average half a day a month. The reason is mainly that it is seen as an additional option to evaluate the processes, and not yet an integral part of their work. The main use until now has been evaluating decisions made in the past under critical circumstances, e.g. process performance during very low water temperatures under 5 °C.

CONCLUSIONS

A simulator was built for the Weesperkarspel treatment plant. The optimal position of the simulator in the automation architecture was on the PIMS network. The simulator was evaluated for the possibility of incorporating real-time and historical data from PIMS and for the added value of incorporating these data for use by technologists and operators. The incorporation of real-time and historical data of on-line water quality measurements, flow measurements, process data and water quality laboratory measurements in the Waterspot simulator has been found to improve the acceptance of model output by technologists, ensures a more realistic training of operators and it has the potential of detecting deviations from the expected water quality and the control of the plant. However, the use of the simulator by technologists is still limited due to the fact that it is seen as an additional option to evaluate treatment processes and the simulator is not yet an integral part of their work. The challenge now lies in integrating the use of the simulator in their work so that the simulator is used when the need for decisions arises, instead of evaluating decisions in hindsight. The decision was made not to train operators on the current simulator because it is believed that an effective training of operator skills is only possible with an emulation of the PA coupled with the plant-wide water quality and water quantity models. In that case, operators will not experience differences in

Figure 7 | Real-time total hardness measurement next to modelling results of the simulator.
operating the real plant or the simulator because the graphical user interface and the control model in the simulator are one-to-one copies. Therefore, additional research in to the possibilities of a simulator with an emulation of the PA has recently been started.

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REFERENCES


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