Optimal Operational Control of Water Pipeline Systems Using Real-Time Scheduling Framework

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ABSTRACT

Water supply systems (WSS) are lifelines of communities as they enable security, health, and economic prosperity. Pipeline infrastructure in many older regions of the U.S. has deteriorated leading to significant leakages and frequent component failures. These issues currently threaten the supply reliability goals of water utilities and it is important to take cognizance of these vulnerabilities and develop appropriate response strategies. In this paper, a framework for optimized near real-time scheduling for operation and control of WSSs is proposed and demonstrated. The operational statuses of different types of valves and pumps that are inclusive of the system will be controlled based on an evolutionary optimization algorithm that is driven near real-time system monitoring data (e. g. tank level values). Energy efficiency and leakage minimization goals may also be accomplished through better control of system operations using monitoring data. The results of the optimization algorithm will lead to improved system operations and sustainable usage of critical resources such as energy and treated water. The proposed approach is demonstrated using a modified version of Anytown WSS. A genetic algorithm optimization code written in MATLAB is integrated with EPANET programming toolkit to enable the modeling of monitoring-data-driven optimal WSS control. This study and its findings would help water utilities in controlling the operations, maintaining reliability, and planning rehabilitation work of their systems.

INTRODUCTION

Water supply systems are lifelines of communities as they enable security, health and economic prosperity. Across the globe, water utility operators face multiple challenges on a daily basis. Water utility operators strive to maintain and retrofit aging infrastructure in an effort to minimize water quality problems, leaks, and pipe breaks. In addition, they also plan for uncertainties in water supply and demand due to climate change and shifting population centers. As a result, there is pressure on water utilities to ensure a continual water supply for their customers of the required quantity and quality, at a required time, subject to a number of delivery requirements and operational constraints.

About 30–60% of city's energy bill is consumed by water and wastewater utilities, representing one of the main expenditures of these companies (EPA, 2008); with up to 80% of the overall energy consumption is form pumps operation (EPRI, 2002). In order to achieve the operational and economical goals of the WSS, a methodology for optimized pumps and valves scheduling would be helpful to support operators' decision in the control room. A number of such methods have been developed in the past for operation and control of WSS with focus on different optimization methods (Mala-Jetmarova et al, 2017). This paper attempts to develop a real-time scheduling framework using global search methods which became more popular in WSS operation and design, e.g., genetic algorithms (GA). In this paper, an approach for optimized near real-time operation and control of WSSs is proposed and demonstrated. Energy efficiency and leakage minimization goals may also be accomplished through better control of system operations using monitoring data. The results of the optimization algorithm will lead to improved system operations and sustainable usage of critical resources such as energy and treated water.

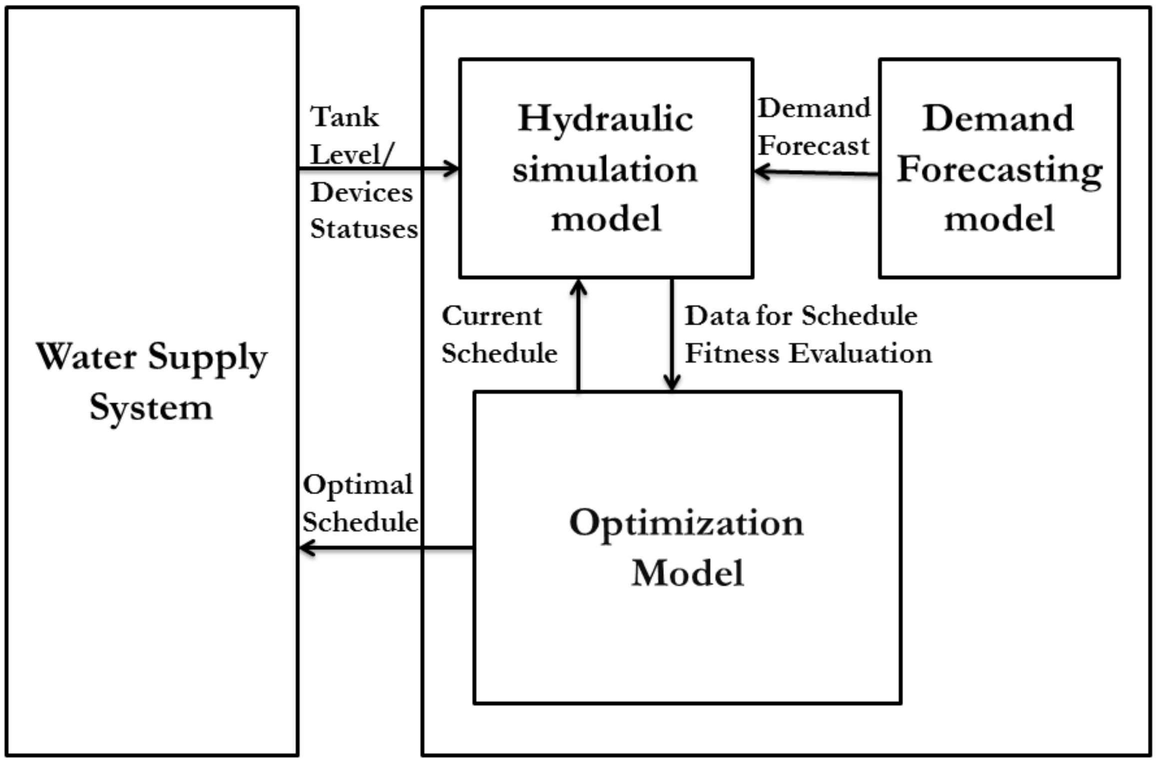

Figure 1. Real time scheduling framework

REAL-TIME SCHEDULING FRAMEWORK

Figure. 1 shows the real-time scheduling framework. The real-time scheduling methodology is based on the integration of two unique models, a specific water demand forecasting model and a specific optimization model, with the conventional hydraulic simulation model into a single framework which is run every time step, as can be seen from this figure. The real-time scheduling procedure follows:

1. Receive latest data from the water supply system. These data comprise tanks levels, pump and valve statuses, and flows in/out of the system that are used to estimate the current water consumption in the system.
2. Forecast water demands for the next time step by using forecasting model based on synthetic past water consumption data generated using a demand function;
3. Update the hydraulic simulation model (or simulator) of the analyzed water distribution system (WDS) by using data obtained in steps 1 and 2;
4. Run the optimization model to identify the optimized system operation, i.e., best pumps and valves schedule for the next time step. During the optimization process use the hydraulic simulator to evaluate alternative pump and valve schedules generated by the

optimizer in terms of optimization objective and to check the feasibility of the generated pumps and valves schedule (with respect to constraints);

5. Implement the optimal schedule identified in the previous step into the water supply system for the next time step. Then test the schedule using the demand function to represent demand uncertainty in the real life system and run the water supply system hydraulic simulation model (Fig. 1); and
6. Repeat steps 1–5 continuously, i.e., until scheduling is completed.

The demand function shown in Eq. 1 is used to generate the hourly nodal demands for a typical week using an hourly demand pattern for the week with some variation (±5% of base demand). The purpose of this function is to provide a substitution data for previous water consumption monitoring data by creating a synthetic data that would serve the same purpose. Moreover, this function is going to be used to test the optimal operation schedule identified in the optimization phase, too.

$$\mathbf{D_{i,t,d} = q_i \times p_{t,d} \times \sigma} \quad (1)$$

Where, $D_{i,t}$: is the generated demand of demand node i, at time step t (i.e., hour) of the day, and day d of the week; q_i: is the base demand of demand node *i*; $p_{i,t,d}$: is the demand pattern value of demand nodes at time step t of the day and day *d* of the week (the demand pattern is adapted from Marchi (2013)); and σ: is the randomness factor for the demand (varying between 0.95 to 1.05)

The demand forecasting model is trained using the synthetic past demand data generated using the demand function presented in Eq. 1. A deep learning algorithm in MATLAB's Neural Network Toolbox is utilized for the training of the demand forecasting model. With the day of the week and the hour of the day as inputs and nodal demands as outputs, the forecasting model was trained based on the synthetic data generated for twelve weeks. The demand forecasting model estimates demands one hour ahead which could be used to optimize the schedule for operation of the WSS for the next time step.

The hydraulic model used here is the well-known EPANET2 simulation model (Rossman, 2000). This model performs extended period simulation of the pressurized water distribution system and is used here to estimate the energy (i.e., the cost of energy used for operations) consumed by the system pumps for given forecasted demands and optimized pumps and valves operations over the 24-hr scheduling horizon.

This paper attempts to develop a real-time scheduling framework using global search methods which became more popular in WSS operation and design, e.g., genetic algorithms (GA). The GA based methods appear to be robust, as they can handle discrete variables efficiently and produce a set of promising results (Prasad & Park, 2004). An EPANET-MATLAB Toolkit (Eliades et al, 2017) associated with a single-objective genetic algorithm in MATLAB programming environment are employed for the operational control purpose to obtain various sets of pumps and valves statuses. With minimizing operations cost as an objective, operational statuses of different types of valves and pumps that are inclusive of the system will be controlled based on the GA optimization algorithm that is driven by near real-time system monitoring data (e. g. tank level values). In regard to optimization parameters considered in the optimization, a population's size of 100 and generation's size of 1000 were used. Furthermore, a total of 6 variables are considered in the optimization with two statuses options for pumps (ON/OFF) and three statuses options for valves (ACTIVE/OPEN/CLOSE) in the WSS operational control. A penalty function has been added to the algorithm to penalize any schedule that produced nodal pressure lower than 40 psi at any WSS demand node. Also, water tank storage levels were monitored closely and any violation would be penalize, too. The operational costs of pumps over the design life time (OC) calculated using equation (2).

$$\mathbf{OC} = \mathbf{C_{PV}} \times \mathbf{N_{OP}} \times \mathbf{C_P} \times \mathbf{P_i} \quad (2)$$

Where C_{PV}: is the present worth of energy costs which is based on an interest rate of 12% and an amortization period of 20 years; N_{OP}: is the number of operating hours in a year (8760); C_P: is the cost of electricity ($0.12/kWh); and P_i is the power expended by pump i (kW).

CASE STUDY

A well-known Anytown WSS benchmark is used as a case application for the real-time scheduling framework. This WSS, which is depicted in Figure 2, was originally presented as the best design in terms of total cost (Minimum capital and operation cost) in (Farmani et al, 2005). This pump-driven looped water distribution network has one reservoir, 19 demand nodes, 3 tanks, 3 identical pumps, and 55 pipes. Three pressure reducing valves (PRV) were added to enhance the system operational control with 80 psi as their setting near node 3, 13, and 9.

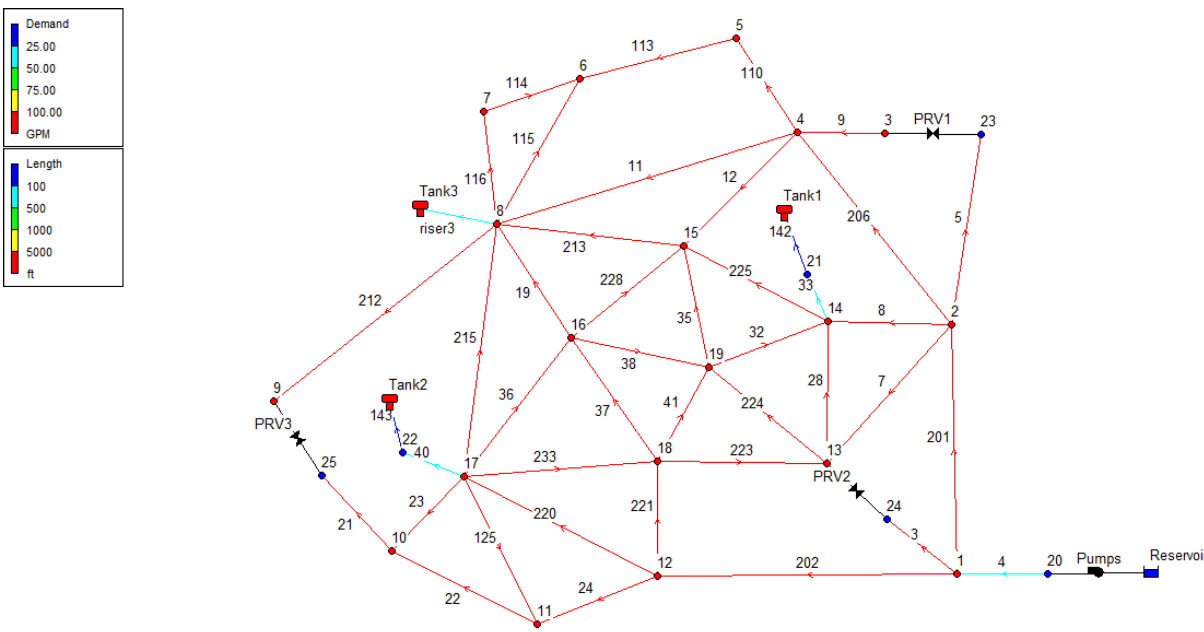

Figure 2. Layout of The Modified Anytown WSS (Originally proposed by Farmani et al., 2005)

RESULTS

In this paper, the proposed real-time scheduling framework is going to determine the control strategies for the next time step (e.g. an hour or less). In this study, the real time schedule was firstly generated for the original operational control setting (every hour) in Anytown WSS. Secondly, to demonstrate the capability of the real time schedule framework developed here, a shorter time step schedule of 15 minutes was produced to better control the operation of Anytown WSS. The cost of operating the system for 24 hours has been investigated using the different time steps duration (1 Hour and 15 Minute) and real time schedules were compared.

Figure 3 illustrates the hourly operational cost for 1-hour and 15-minute control schedules over 24 hours operation period. As can be seen from Figure 3, using 15-minute time step schedule resulted in less energy consumption (low operational cost) during most of time steps. In contrast, 1-hour time step schedule result in higher and continuous high energy consumption during most of time steps. Overall, using 15-minute time step schedule resulted in around 20% saving in operational cost comparing to 1-hour time step schedule. It was observed that the 1-hour time step schedule has a lesser number of pump switches over operation period (24 hours).

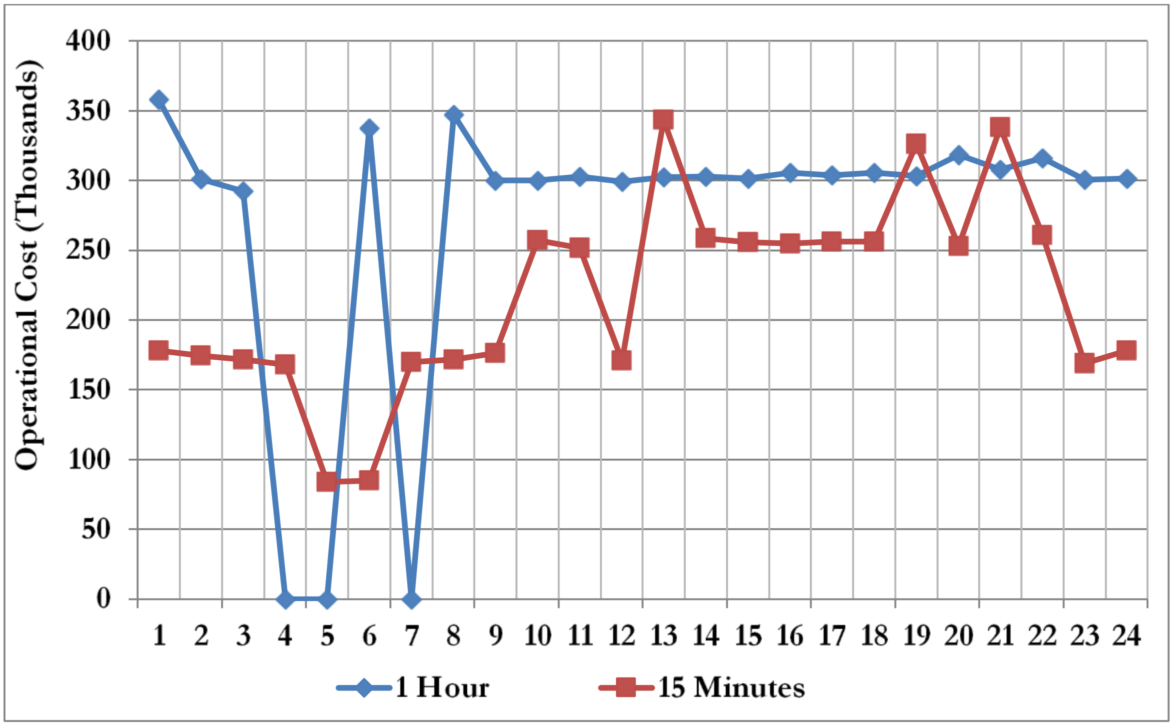

Figure 3. Hourly operational Cost for 1 Hour and 15 Minutes control schedules over 24 hours operation period

CONCLUSIONS AND RECOMMENDATIONS

Pipeline infrastructure in many older regions of the U. S. has deteriorated leading to significant leakages and frequent component failures. These issues currently threaten the supply reliability goals of water utilities and it is important to take cognizance of these vulnerabilities and develop appropriate response strategies. In this paper, a framework for optimized near real-time scheduling for operation and control of WSSs is proposed and demonstrated. The operational of different types of valves and pumps that are inclusive of the system will be controlled based on an evolutionary optimization algorithm that is driven near real-time system monitoring data (e. g. tank level values). The proposed approach is demonstrated using a modified version of Anytown WSS. The real time schedule framework developed in this study was used to generate operational schedule for the original operational control setting (every hour) for Anytown WSS, and compared with a shorter time step schedule of 15 minutes to present the merits of better controlling the operation of Anytown WSS.

This paper attempts to address the energy consumption through better control of system operations schedule using monitoring data. A similar operational control approach maybe applied to minimize leakage in pipeline system. The identification of most competent time step schedule will support optimal operation and control decision making for water distribution systems in a computationally efficient manner. The results of the optimization algorithm will lead to competent and reliable operation and control schedule for WSS and sustainable usage of critical resources such as energy and treated water. This study and its findings would help water utilities in controlling the operations, maintaining reliability, and planning maintenance work of their systems. In this study, the real-time scheduling framework used an optimization model with a single objective of minimizing cost of operation. In future work, a multi-objectives optimization model may be used to improve the scheduling framework results with minimizing number of pumps switches as an additional proposed objective. Lastly, the computationally temporal aspect of the scheduling framework could be another area of development.

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