OPTIMAL PUMP SCHEDULING BY NLP FOR LARGE SCALE WATER TRANSMISSION SYSTEM

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ABSTRACT

In this paper an operational control for the Toronto's Transmission Water System (TWS) is considered. The main objective of the ongoing Transmission Operations Optimizer (TOO) project consists in developing an advanced optimization and control tool for providing such pumping schedules for 153 pumps, that all quantitative requirements (such as pressure, flow, water level and water quality) with respect to the system operation are met, while the energy costs of delivering fresh water are minimized.

We describe here, in general, the concept of TOO system and the large-scale non-linear, so-called Full Model (FM), based on system of hydraulic equations. The FM model is, in fact, a simplified version of EPANET hydraulic simulator with hourly hydraulic time-step, implemented as a complex NLP optimization model and usually solved over 24-hour horizon to deliver the aggregated optimal solution. To solve the resulting large-scale NLP we use the nonlinear interior-point method implemented in general-purpose large-scale IPOPT solver.

Finally, we included the typical numerical example of application of the TOO Optimizer to solve the 24-hour and 7-day FM problems, and compared obtained optimal FM results with results of hydraulic simulation performed under EPANET simulator.

INTRODUCTION: TOO SYSTEM

The City of Toronto water transmission system is a large complex hydraulic network of treatment plants, pumping stations, storage facilities (including underground reservoirs and elevated tanks) and transmission utilities (including hundreds of kilometers of water mains and significant number of control valves). The City of Toronto water supply system capacity is one of the largest in North America. The Water Supply function is responsible for providing services 24 hours per day, seven days per week. The system consists of treated water pumping at four filtration plants, 29 pumping stations, floating storage at 19 reservoirs and 9 elevated tanks, and approximately 520 km of water mains that transport treated water from the lake up through the system. Water is pumped through a hierarchy of pressure districts with elevated storage facilities. At present a large part of the system within the City of Toronto is essentially manually operated, where an operator decides for example when to turn a pump on or off. Even when there are no abnormal situations, manual decision making within the City of Toronto system is a complex process.

With this background, the City of Toronto decided to develop the Optimizer that automatically determines control strategies for the Water Transmission System, based on certain criteria, including meeting service delivery levels (pressures, reservoir levels, water quality). The developed TOO Optimizer works as on-line tool alongside the SCADA control systems. The primary objective of the Optimizer (TOO) is to ensure that required water delivery standards are met, while minimizing electrical cost of water pumping. “The aim of pump scheduling is to minimize the marginal cost of supplying water while keeping within the physical and operational constraints, such as maintaining sufficient water within the system's reservoirs, to meet the required time-varying consumer demands.” – (Methods, 2003). The complexity of the water system and dynamically changing energy rates present potential opportunities for optimizing operations by minimizing water pumping and treatment costs.

The simplified flowchart diagram of the whole TOO system and its main software element, called the Control Strategy Component (CSC) is presented in figure 1. The CSC component consists of:

- the Optimizer using the FM and FMBM optimization models, and also the library of optimization and matrix solvers
- the EPANET hydraulic simulator using the hydraulic and water quality model of TWS system defined in EPANET INP format
- the FM (NLP) and FMBM (LP) optimization models solved by COIN-OR IPOPT and Clp solvers, respectively
- the library of COIN-OR optimization solvers (IPOPT and Clp) together with the library of HSL matrix solvers (MA27, MA57 and HSL_MA97)
- the Simplifier, which produces a simplified hydraulic model
- the Scheduler generating an optimized pump schedules on the base of FMBM and FM optimal aggregated solutions

The FMBM and FM optimization models are automatically obtained from the hydraulic model of network in EPANET INP format and from additional data (provided by the TOO system) describing operational constraints, electricity tariffs and pumping station configurations. In order to reduce the size of the FM optimization problem the full hydraulic model is simplified by the Simplifier, while retaining the nonlinear characteristics of the model. In the simplified model all reservoirs, elevated tanks and all control elements, such as pumps and valves, remain unchanged, but the number of pipes and nodes is

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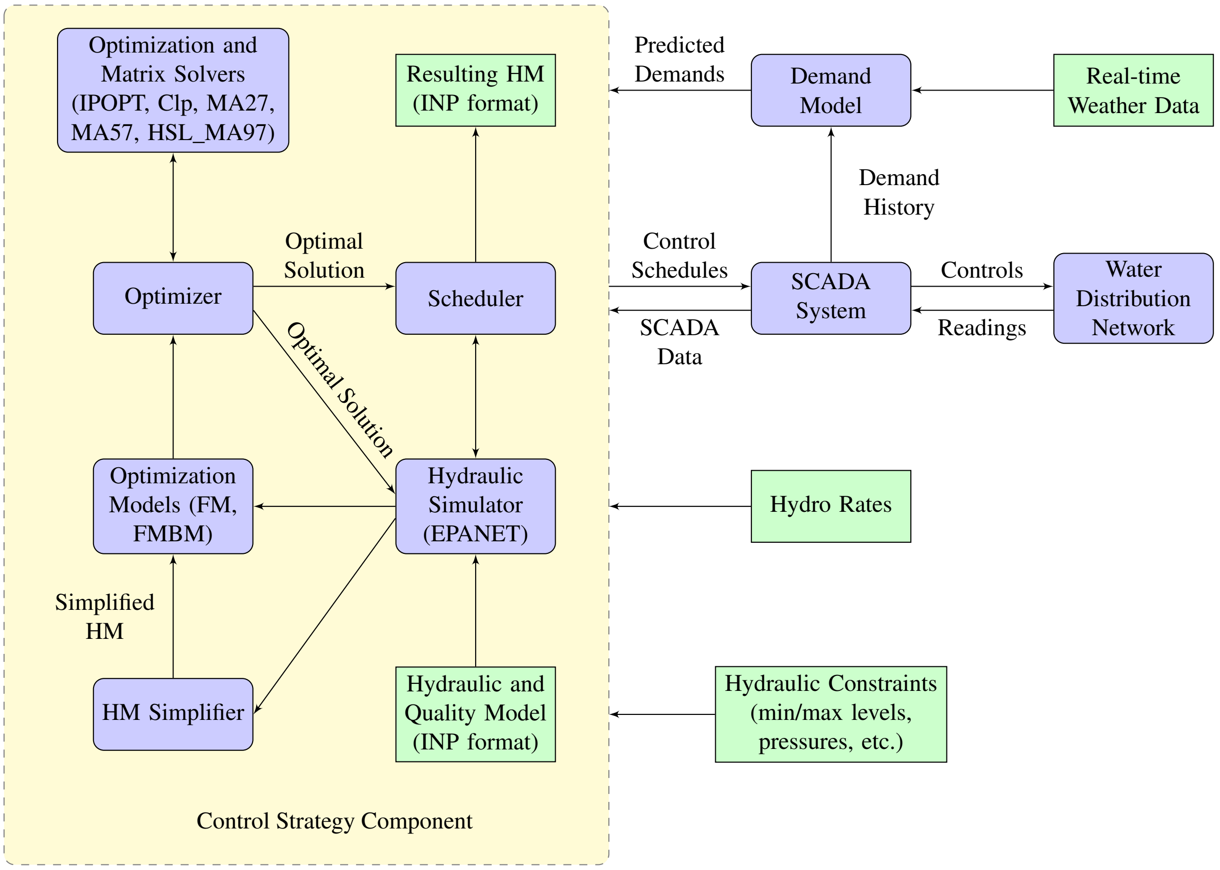

Figure 1: Structure of the TOO system and CSC component

significantly reduced. The final reservoir states for the 24-hour FM problem are taken from the solution of the full mass-balance model (FMBM). The FMBM model is a large-scale linear programming model, solved usually over weekly horizon, and emerges directly from the FM model for which all pressure dependent variables (heads, levels, head losses and head gains) and constraints were omitted or substituted by appropriate parameters. The EPANET hydraulic simulator is used to generate the starting point for IPOPT solver, to validate the optimal aggregated solution provided by FM optimization, and also by the Scheduler to adjust an optimized pump schedule by feedback mechanism from the simulated hydraulic model. The FM optimization model is solved by IPOPT optimizer to produce continuous optimal solution. When the CSC application is employed in real-time TOO environment, the optimal solution form the previous FM optimization can be used as as initial guess for the current FM step. The FM optimal solution is then fed back from IPOPT into the Optimizer for analysis, further processing and exporting of the results outside of the main software module. The CSC module is able to produce resulting EPANET INP file with optimized pump schedules and to send optimized controls (optimal pump schedules and the resulting reservoir level trajectories) to the SCADA system. Moreover, the CSC is also using short term demands predicted by the Demand Model; it works with different demand levels (scaled for different seasons). In general, the CSC runs as follows:

1) Collect external factors (weather, energy rates), system status and data. This includes, but is not limited to, current reservoir and elevated tanks levels, equipment out-of-service, equipment auto/manual modes, production costs.
2) Run demand model to predict demand.
3) Determine final states for reservoirs and elevated tanks by solving the FMBM problem over long-term horizon.
4) Determine optimized pump schedules and tank profiles by solving the FM problem over short-term horizon (with final states taken from the solved FMBM step), and application of the Scheduler.
5) Run hydraulic/quality model to check optimized pump schedules.
6) Analyze results. If results are acceptable (hydraulically feasible), then apply control strategy to SCADA system.

The majority of operational control approaches for water distribution networks (WDN) reported in the literature usually consider small-scale systems as case studies. Moreover, they are typically based on the simulation-optimization methodology using a hydraulic simulator, or they use a simplified mass-balance models as a key element of their optimization process. It is common for practically solved optimal control problems that an objective function is evaluated by solving a complex model (Arabas and Malinowski, 2001; Szynkiewicz and Błaszczyk, 2011), and quite often the only way to effectively deal with complexity of the optimization problem is to use the simulation-optimization approach (Niewiadomska-Szynkiewicz, 2004; Kamola, 2007).

To determine optimal controls the CSC Optimizer uses a full hydraulic model of the water transmission system. The FM optimization model reflects full hydraulic characteristics of the TWS and can be automatically adapted to structural changes in the network, such as isolation of part of the network or changing volume of reservoir by adding/removing a cell, as well as to changes in operational constraints. Furthermore, both optimization models used by the CSC can be generated and solved in an automatic manner for different time horizons and configured by a large set of available options. A more detailed description of the Toronto Water System and the TOO project can be found in (Błaszczyk et al., 2012b,a, 2013).

FM OPTIMIZATION MODEL

The optimization of pump operations is a difficult task due to the significant complexity and non-linearity of WDNs, as well as due to the number of operational constraints and interactions between different network elements. For example, pumps usually do not operate in isolation – a change in the operating duty of one pump may affect the suction or discharge pressure of other pumps in the same hydraulic system.

Optimization methods described in this paper are model based. The hydraulic model is provided as the EPANET INP file and consists of:

1) boundary conditions (water sources, initial reservoir levels and demands),
2) a hydraulic nonlinear network made up of pipes, pumps, valves, and
3) reservoir dynamics.

The NLP algorithm that has been used to compute the continuous schedules, and also the discretized schedule, require the EPANET simulator of the hydraulic network. In the TOO system the EPANET Toolkit has been used to provide the initial feasible solution to the NLP solver by simulating the network, and also the Toolkit has been utilized by the TOO scheduler for discretization of the continuous solution.

The main objective is to minimize the pumping cost subject to the hydraulic network equations and operating constraints over a given time horizon with hourly discretization. The relationships between different components of cost and operating constraints in the whole hydraulic network are of a very complex nature, thus they can only be solved by use of an advanced nonlinear programming solver and optimal scheduler.

The goal of the optimal network scheduling is to calculate the least-cost operational schedules for pumps, valves, and water treatment plants for a given period, typically for 24 hours or one week. The optimization problem is expressed in discrete-time, i.e., in the FM model an hourly time-step is used. The FM optimization problem is given as:

1) minimize objective function consisting of pumping cost and water treatment cost,
2) subject to hydraulic network equations, and
3) operational constraints.

These three parts of the problem are briefly discussed in the following subsections. More detailed description and discussion for the FM model is given in (Błaszczyk et al., 2013).

Objective function

The objective function to be minimized is the sum of two costs associated with the system: pumping cost and water treatment cost. The pumping cost depends on the efficiency of the pumps used and the electricity power tariff over the pumping duration. The tariff is usually a function of time with cheap and more expensive energy periods. The water treatment cost for each water treatment plant (WTP) is proportional to the flow output from a WTP with the unit price.

In general, the pumping cost may be reduced by decreasing the water quantity pumped, decreasing the total system head, increasing the overall efficiency of the pumping station by proper pump selection, or using reservoirs and elevated tanks to maintain highly efficient pump operations. In most instances, efficiency can be improved by using an optimization algorithm to select the most efficient combination of pumps to meet a given demand. Additional cost savings may be achieved by shifting pump operations to off-peek water-demand periods through proper filling and draining of reservoirs and elevated tanks. Off-peek pumping is particularly beneficial for systems operating under a variable-electric-rate schedule.

Decision variables

The decision variables in the resulting aggregated nonlinear optimization problem are the average aggregated flows and average head gains for all logical pumping stations at each hour of the control horizon. Also, the decision variables might be the settings for some throttled valves (minor losses or valve openings) and settings for pressure reducing valves (pressure set-points) in the hydraulic system. The indirect decision variables in the optimization problem are:

- flows and head losses for every pipe and valve
- heads at every junction and demand node
- heads, volumes and water levels for every reservoir and elevated tank

For all those variables there are simple bounds constraints. All variables are related mutually through the hydraulic model.

Hydraulic model

Each network element has a hydraulic equation. For pipes equations, the Hazen-Williams formula is used (Brdys and Ulanicki, 1994). In the optimal scheduling problem it is required that all calculated variables satisfy the hydraulic model equations. The network equations are usually non-linear and are embedded as inequality and equality constraints in the optimization problem. The hydraulic model used by the FM optimization model consists of the following network equations:

- flow continuity at connection nodes
- mass-balance, average head and volume curve for reservoirs and elevated tanks
- head-loss for pipes
- head-loss for TCV valves
- check valves
- PRV valves
- pumping stations

The hydraulic model for TOO system is very complex, nonlinear and large scale. It includes many types of linear and nonlinear constraints modeling behaviour of all network elements.

Operational constraints

The operational constraints have the form of simple inequalities and are applied to keep the system state within its allowed operating range. Thus, we must take into account time varying minimum and maximum reservoir and elevated tank levels and volumes. The reservoir and elevated tank volumes (state variables) should remain within the prescribed simple bounds in order to prevent emptying or overflowing, and to maintain sufficient storage for emergency purposes. The reservoir and elevated tank level constraints are not necessarily equal to the physical limits provided in the EPANET INP file. Similar constraints must be applied to the heads at critical nodes (SYPs) in order to maintain required pressures throughout the water network. The other variables, such as:

- flows for all links (pipes including CVs, TCV and PRV valves, and pumping stations)
- head-losses for pipes and valves, and head-gains for pumping stations
- heads at all nodes (connection junctions, demand nodes, suctions and discharges of pumping stations)
- water levels for reservoirs and elevated tanks

are also constrained by lower and upper limits determined by the features of particular network elements.

Other important constraints are on the final water level (and final water volume) of reservoirs and elevated tanks, such that the final level is not smaller than the initial level. Without such constraints the least-cost optimization would result in emptying all reservoirs. In the case of TOO system such constraint is applied over a long-horizon (up to 7 days) when solving a mass-balance optimization problem.

Final states for reservoirs and elevated tanks

The objective function, representing the total operating cost to be minimized, is usually comprised of energy cost for pumping water and the cost for treating water, although other costs such as penalties for deviation from the final reservoir (and elevated tank) target levels are sometimes included. The final penalty charge is associated with the cost imposed on the state variables for deviation from the specified final reservoir levels.

HYDRAULIC SIMULATION BY EPANET

EPANET is a public domain software developed by the Water Supply and Water Resources Division of the U.S. Environmental Protection Agency's National Risk Management Research Laboratory (Rossman, 2000). EPANET provides an integrated environment for editing network input data, running hydraulic and water quality simulations, and viewing the results in a variety of formats. The hydraulic simulation performed by EPANET delivers information such as flows and head losses in links (pipes, pumps and valves), heads, pressures and demands at junctions, levels and volumes for water storage. This allows computing the pumping energy and cost. EPANET's computational engine is available also as a separate library (called the EPANET Toolkit) for incorporation into other applications. The network hydraulics solver employed by EPANET uses the Gradient Method, first proposed by Todini and Pilati (Todini and Pilati, 1988), which is a variant of Newton-Raphson method.

While EPANET is used as the computational engine for most water distribution system models, most models are developed and maintained in hydraulic modeling packages based on EPANET's computational engine. Some of the major hydraulic modeling packages are:

- InfoWater, developed by Innovyze (formerly MWH Soft, a subsidiary of MWH)
- MIKE URBAN, developed by DHI
- WaterCAD and WaterGEMS, developed by Bentley's Haestad Methods (Hydraulics & Hydrology) group

The EPANET Programmer's Toolkit is a software library of functions that allow developers to customize EPANET's computational engine for their own specific needs. The functions can be incorporated into an applications written in C/C++, Delphi Pascal, Visual Basic, or any other language that can call functions within the EPANET Toolkit library. There are over 50 functions that can be used to open a network description file, read and modify various network design and operating parameters, run multiple extended period simulations accessing results as they are generated or saving them to file, and write selected results to file in a user specified format.

The EPANET Toolkit could be used for developing specialized applications, such as optimization or automated calibration models that require running network analyses as selected input parameters are iteratively modified. It was, therefore, decided that EPANET will be used as the hydraulic model component of the TOO system rather than InfoWater, since the EPANET Toolkit is capable of providing all of the hydraulic modelling functionality that InfoWater provides with the ability to automate the entire process.

InfoWater is used as the primary hydraulic modelling software package for the TWS. The package is capable of producing a text file of the EPANET text file input format (INP). The on-line TOO Optimizer uses EPANET for simulation purposes and the INP file is imported into the tool's structure, which in turn uses the information therein for simulation purposes. Creation and maintenance of this INP file can be handled using InfoWater and exporting the modified model from InfoWater to INP format, and then performing a comparable import at the on-line tool's end.

The modified and extended versions of the EPANET Toolkit and OOTEN library (C++ wrapper for EPANET Toolkit) have been built into the TOO Optimizer and are used to build the FMBM and FM optimization models, to generate the starting point for IPOPT optimizer and to check the aggregated optimal results provided by solving the FM problem. The EPANET Toolkit is also used during iterations of the TOO Scheduler to adjust the optimized pump schedule by feedback from hydraulic simulations of current iteration of the pumping schedule. Furthermore, it also provides the hydraulic and quality simulation results for the final optimized pump schedule, such as reservoir profiles for level volume and water quality, pressure profiles for PS discharges and SYP nodes, energy and power calculations for all pumping stations.

NONLINEAR PROGRAMMING BY IPOPT

The IPOPT solver is based on a primal-dual interior-point method (barrier method) used for nonlinear optimization relying on the solution of sequence barrier problems. The search direction is calculated in full or reduced space. The main advantages of IPOPT are: the possibility of solution of large-scale problems, the availability of different methods for calculation of search direction and for approximation of hessian of Lagrange function, various methods for the solution of reduced system of linear equations, the use in line-search minimization various merit functions and ensuring global convergence of the whole algorithm by using filter algorithm in line-search minimization.

The computationally most expensive part of the optimization algorithm implemented in the IPOPT solver (not including computations of the objective function, constraints and their derivatives) is the solution of the symmetric indefinite system of linear equations, which is most often of high order and has a sparse structure. For its factorization and solution, the IPOPT uses external sparse direct linear (matrix) solvers, such as MA27 (default option), MA57, HSL_MA77, HSL_MA86, HSL_MA97, WSMP, PARDISO and MUMPS.

For the interested reader, more information about IPOPT solver can be found in the doctoral dissertation (Wächter, 2002), in the article discussing in detail the primal-dual interior-point algorithm (Wächter and Biegler, 2006), and also at the web page https://projects.coin-or.org/Ipopt (from which an open source C++ version of IPOPT is available).

In the TOO system, the network scheduling problem is solved by its implementation in C++ programming language and usage of the nonlinear programming solver IPOPT. The IPOPT solver was found to provide very good numerical performance, stability and robustness when solving the real-time NLP problems generated by the TOO system.

The IPOPT solver used in TOO was configured to use the HSL_MA97 matrix solver (Hogg and Scott, 2011, 2013), compiled with OpenMP support to allow for parallel matrix computations. The HSL_MA97 linear solver was found to offer very good performance and robustness for the solved FM problems. It is also bit-compatible, which means that running (in parallel) the same matrix factorization twice will result in the same answers. Such a feature is very important for testing and debugging purposes, i.e., to obtain the same result of optimization regardless of the used number of OpenMP threads.

CONTROL STRATEGY COMPONENT

The Control Strategy Component (CSC) within TOO has been implemented in C++ programming language by the use of a few auxiliary software components, including:

- extended and fixed version of the EPANET Programmers Toolkit 2.0.12
- OOTEN library (C++ wrapper for the EPANET Toolkit)
- COIN-OR IPOPT (Interior Point Optimizer) solver for NLP problems
- COIN-OR CLP solver for LP problems
- CppAD package for automatic differentiation of C++ algorithms
- BOOST C++ library
- GNU Scientific Library (GSL)
- matrix solvers MA57 and HSL_MA97 from Harwell Subroutine Library (HSL)
- Intel Math Kernel Library (MKL)
- Oracle C++ Call Interface (OCCI)

By solving of the FM problem, the CSC ensures that preset minimum and maximum (critical) storage levels are not violated and that optimal pumping strategies are achieved for different seasonal, weekday/weekend and peak-day demands, as well as when abnormal events occur (e.g., pumping station, filtration plant or reservoir cell out-of-service). It also considers the production cost of water which varies from plant to plant in developing the optimal solution. The CSC uses water demand forecasts (for each demand node) and the system hydraulic and water quality model (defined in EPANET INP format). The computed optimal control strategies (pumping schedules and reservoir profiles) enable optimization of water pumping and water quality in the Transmission System. The used FM optimization model is based on the full hydraulic model, thus the optimal FM results are always consistent with results of hydraulic simulation by EPANET. The optimal aggregated FM solution is always validated and analyzed by use of the hydraulic simulation. We have found in very many CSC testing runs (also for CSC working in on-line mode) that FM optimization model provides practically the same results as a hydraulic simulator.

NUMERICAL RESULTS

To solve the FM optimization problem by IPOPT solver both in real-time and in robust way, we had to implement a strategy to generate the starting point for IPOPT solver and also a scaling method of decision variables and NLP problem functions.

Selection of starting point

An important requirement for solving of NLP problems is the selection of a starting point for numerical iterations. Nonlinear programming is a local search method and the starting point should be as close as possible to the final solution. Since both IPOPT solver and EPANET Toolkit are integrated into the CSC software component with a common data structure, the EPANET simulator is used to provide an initial starting point for the network scheduling problem. This facilitates the solution of the initialization problem in a very efficient manner.

At first, the hydraulic simulation is performed using the historical pumping schedules from the initial INP file. The results of this hydraulic simulation (i.e., flows, heads, levels, volumes, head-losses and head-gains) are passed to the NLP solver as a starting point. The next step before starting the right optimization is an initialization of the short-horizon (usually one-day) FM problem by use of the data fetched from the TOO database such as initial reservoir and elevated tank levels, predicted nodal demands, predicted spot energy prices, and the final desired reservoir and elevated tank levels (taken from the optimal solution of the FMBM problem). Finally, all the initial values for decision variables are projected into a simple bound constraints, which are defined internally in the CSC, or are provided by the TOO (for levels, volumes and pressures at SYP points and at discharge nodes of pumping stations).

Scaling of optimization problem

IPOPT solver has some mechanisms to find internal scaling factors; the default one only tries to handle over-scaling, i.e., cases in which the derivatives at the initial point are very large. In general, it is advised to try to scale the optimization problem so that the nonzero elements in the objective and constraint function gradients are roughly on the order of 0.01 to 100 for the points of interest. However, finding a good scaling for an optimization is not an easy task. Obviously, it would be great if the optimization codes could do that on their own, but due to the nonlinear nature of the functions that is in general a tough call. A well-scaled problem makes the solution process easier for any nonlinear optimizer, not just IPOPT. In the case of TOO system we use scaling for flow variables in the constraints modeling CV and PRV valves, and also pumping stations. Furthermore, there is a scaling for volume variables in equations modeling reservoirs and elevated tanks.

Optimization results

The IPOPT solver calculated the optimal aggregated flows and head gains at each logical pumping station over time horizon of 24 hours (with hourly discretization). The FM problem was build from the simplified hydraulic model. Model size reduction, based on an elimination of dead links and short or low resistance pipes, merging of pipe series, parallel pipes and non-critical nodes, allows for much faster IPOPT convergence to a local optimal solution.

The resulting FM model is a large-scale nonlinear optimization problem. The basic, 24-hour period, version of FM model (with additional variables and constrains to deal with an infeasible initial and final states, and also with an infeasible pressure and volume limits) consists of over 100,000 decision variables and nearly 106,000 equality and inequality constraints. The 7-day FM problem has almost 642,000 variables and 680,000 constrains. To better show the obtained optimal FM solution, we present here aggregated results for the control horizon of 7 days. The aggregated original and optimized volume profiles (also simulated by EPANET to check their correctness) for all reservoirs and elevated tanks are presented in figure 2. The figure shows also the total power usage for all pumping stations for manual and optimized aggregated pumping flows and head gains. As can be seen, the aggregated FM optimized volume profile (*Vol Optim*) and that simulated by EPANET (*Vol Optim-EPA*) are consistent. It was found that the FM model adequately replicates the hydraulic behaviour of the original hydraulic model provided in the EPANET INP format. The optimal aggregated volume profile has a direct correspondence with the electricity tariffs. The water storages are emptying during higher tariff periods and vice versa. Also, the optimized energy consumption (*Power Optim*) is higher during lower tariff periods. The obtained energy cost savings, compared to the manual pump controls, were between 5 and 15%.

The IPOPT optimization solver working with HSL_MA97 matrix solver was executed on an Intel i7 X980 CPU with a clock speed of 3.33 GHz. The solution times for the tested 24-hour FM problems were within 2-10 minutes (depending on the used boundary conditions) and required 200-1000 IPOPT iterations. Optimization for 7-day horizon with hourly time-step took around 1-2 hours with more than 1000 IPOPT iterations required. The starting point for IPOPT was generated from EPANET hydraulic simulation of TWS hydraulic model with historical pumping schedules. IPOPT was configured to use OpenMP version of the HSL_MA97 matrix solver and 6 OpenMP threads. The HSL_MA97 solver proved to be the fastest, most stable and reliable matrix solver for IPOPT when solving the FM problem. The IPOPT solver was found to provide very good performance, stability and robustness when solving real-time FM problems generated by the TOO system. It is seen from the Table 1 that optimization time required by IPOPT solver scales well with increasing FM problem size.

Table 1: Optimization results with IPOPT and OpenMP HSL_MA97 for the FM problems of different time horizons; N – number of hourly intervals of time horizon, n – number of decision variables, m – number of constraints, T – solution time (in seconds), I – number of IPOPT iterations, S – aggregated energy cost savings (in %).

N	n	m	T	I	S
1	4093	4164	4.44	223	5.36
2	7910	8213	1.62	51	5.92
3	11727	12262	2.61	63	6.27
6	23178	24409	5.01	62	7.43
12	46080	48703	29.55	166	15.61
18	68982	72997	61.45	209	15.36
24	91884	97291	104.62	225	14.80
36	137688	145879	336.14	430	16.56
48	183492	194467	1249.67	673	15.01
72	275100	291643	1748.46	573	15.65
96	366708	388819	2698.49	584	16.50
120	458316	485995	2675.75	710	15.89
144	549924	582707	2519.70	633	15.52
168	641532	679419	4538.85	1172	15.99

In fact, the authors have found so far only one truly comparable problem, in size and complexity, reported in the literature and concerned with operation of the Berlin Water Works (Berlin Wasserbetriebe), presented in (Burgschweiger et al., 2009b,a). Yet, TWS is about twice as big in size, i.e., in the number of components, than the Berlin system. Also, in the FM model used by TOO system there was a need to include PRV valves, and to use complicated energy tariffs. These components were not present in the schedule optimization for Berlin WDS, while the inclusion of such elements increases considerably both the modeling effort and complexity of the optimization problem.

CONCLUSIONS

We described, in general, the concept of TOO system and a complex, large-scale non-linear FM optimization model, based on the system of hydraulic equations for all elements comprising the water distribution system. The FM optimization model is automatically obtained from a hydraulic model in EPANET format and from additional files describing operational constraints, electricity tariffs and pump station configurations. Then, the FM model is solved over a 24-hour control horizon to obtain an optimal aggregated flows and average pressure gains for all pumping stations. The obtained optimal volume profiles for all reservoirs and elevated tanks confirm a high accuracy of the obtained FM optimal solution when compared with results of hydraulic simulation under EPANET. Thus, the presented FM model can be used as a hydraulic engine embedded in the nonlinear optimization models used for operational control of water distribution systems.

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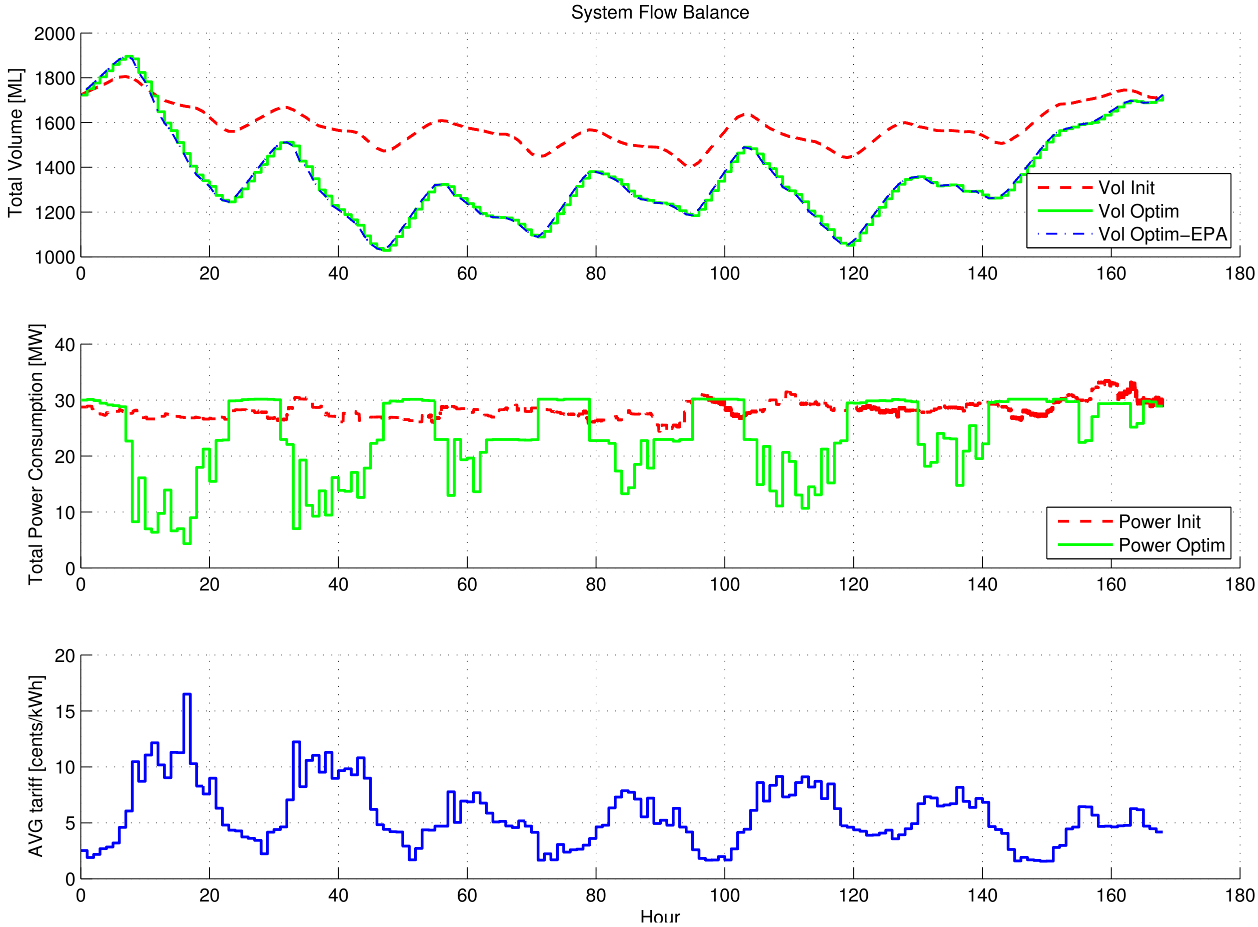

Figure 2: Aggregated volume profiles for all water storages of initial (*Vol Init*) and FM optimized solution – original (*Vol Optim*) and simulated by EPANET (*Vol Optim-EPA*); Total energy usage for all pumping stations of initial (*Power Init*) and optimized (*Power Optim*) pump schedules.

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