Optimal Real-Time Operation of Urban Water Distribution Systems Using Reduced Models

Uri Shamir, F.ASCE[1]; and Elad Salomons[2]

Abstract: A method for near-optimal real-time on-line operation of urban water distribution system is presented and demonstrated. It uses a reduced model (RM) of the network which reproduces its performance over time with high fidelity with optimization by a genetic algorithm (GA). The RM-GA software uses network data, forecasted demands for an operational planning time-horizon (24 h ahead), field data from a SCADA on the current status of the network, time-of-day energy cost data, and operator-imposed constraints on tank water levels and demand junctions pressures. The GA looks for the near-least-cost operation plan for the whole time horizon, using the reduced network model, and activates the first hour of the plan through the SCADA. At the end of the hour, the status of the network is updated from field data, the time horizon is rolled ahead by 1 h, and the process repeated. The software was developed for and demonstrated on the distribution system of Haifa. Experiments were conducted, in which the operation which simulates the operators' set-point operation is compared with that obtained by the RM-GA, and energy cost savings of 8 and 10% were calculated for a summer and winter month, respectively.

CE Database subject headings: Water distribution systems; Operation; Optimization; Algorithms.

Introduction

Optimal real-time operation of urban water systems aims to minimize operational costs, while meeting demands with required pressures. Energy constitutes the major component of the cost that is affected by the operation, since other costs (manpower, maintenance) are practically independent of real-time operational decisions. Energy cost savings result from using the operational storage to shift pumping to times of low energy cost. This requires knowledge of the physical system, the energy cost schedules, a SCADA system to import system data and to export commands to field equipment, and a forecast of the demands for an operational planning horizon, which in most urban system ranges from a minimum of 1 day (24 h) up to a maximum of 1 week (168 h), depending on the size of the storage relative to the demands.

The software system described herein is designed to generate a near-optimal operating plan for a rolling planning horizon: optimize the operation for a period of 24 h ahead with a demand forecast for this planning period, implement the first hour of the

operation, update the actual status of the system from field data at the end of this hour, move the demand forecast 1 h ahead, and optimize again for the next period 24 h. A 24-h time period is normally adequate and will be referred to throughout this paper. A somewhat longer planning period may be required if the storage is large enough to provide the system more "memory" possibly 2 days ahead and up to 1 week. Storage in the Haifa system is relatively small, and a 24-h planning horizon is adequate, but the methodology has also been tested with a time horizon of 32 h, to allow some consideration of the following day.

The software evolved from that developed in a project called potable water distribution management (POWADIMA), led by Professor Derek Jamieson from the University of Newcastle-upon-Tyne, United Kingdom, funded by the European Union, and carried out by a combined team from the University of Newcastle-upon-Tyne, the Technion-Israel Institute of Technology, the Universidad Politecnica de Valencia, and the Università degli Studi di Ferrara. The methodology and its application to two urban systems (Valencia and Haifa) are presented in a series of six papers (Jamieson et al. 2007). The POWADIMA software system combines three components: replacement of the network solver by an artificial neural network (ANN) to reduce computation time in the optimization, a genetic algorithm (GA) to optimize the operation, and demand forecasting. optiGA (2001), a general purpose GA engine, was used for the optimization.

The POWADIMA software was applied to part of the Haifa system, labeled Haifa-A, which has 126 pipes, 112 nodes, nine storage tanks, one operated pressure reducing valve, and 17 pumps in five pumping stations. A calculated savings of ~20% in annual energy cost, as compared to (simulated) manual operation, for the demand data of the year 2000 (Salomons et al. 2007) was achieved. A similar percentage saving was found for the Valencia system (Martinez et al. 2007), which is much larger than the Haifa system, but covers a much flatter terrain and has only two

[1]Professor Emeritus, Faculty of Civil and Environmental Engineering, and Stephen and Nancy Grand Water Research Institute, Technion-Israel Institute of Technology, Haifa 32000, Israel (corresponding author). E-mail: shamir@tx.technion.ac.il

[2]OptiWater, and Research Engineer, Stephen and Nancy Grand Water Research Institute, Technion-Israel Institute of Technology, Haifa 32000, Israel.

Fig. 1. Haifa-B full model (867 nodes, 987 pipes)

Fig. 2. Haifa-B reduced model (77 nodes, 92 pipes)

supply plants, with storage, from which it is fed by gravity with many valves to control the flow.

Haifa-B Distribution Network

The new software system has been developed for the City of Haifa. The model, shown in Fig. 1, covers the main supplies and storages and about 20% of the distribution network. It is more detailed than the network that was analyzed in the POWADIMA project, and is therefore called Haifa-B. The software was designed for implementation in a new SCADA system, but since the SCADA is far from completion, the software could not be implemented in the field, and is still waiting completion of the SCADA. This paper reports the new software system and comparisons of the optimal cost it computes, for one summer month and one winter month, with the cost calculated by simulating the current operation. Due to the delay in installing Haifa's SCADA system, we could not test the software in the field. The results reported herein are therefore those of simulation: results of the optimization compared with simulation of the system under decision rules represented by set points installed by the operators.

The current application replaces the ANN by a reduced (skeleton) model of the network that better meets the requirements for computational efficiency and has further advantages, as will be explained below. The full network model is shown in Fig. 1. The Haifa-B system serves a population of some 60,000 and ranges in elevation over 450 m.

The network model was constructed with GISRed (Martinez and Bartolin 2005) in the ArcView 3.2 environment, which takes AutoCAD files and creates an EPANet (USEPA 2001) network model. The following data were used:
1. Pipes: AutoCAD files (with mostly estimated roughness values, as few field data were available), superimposed on a DTM model of the city's topography;
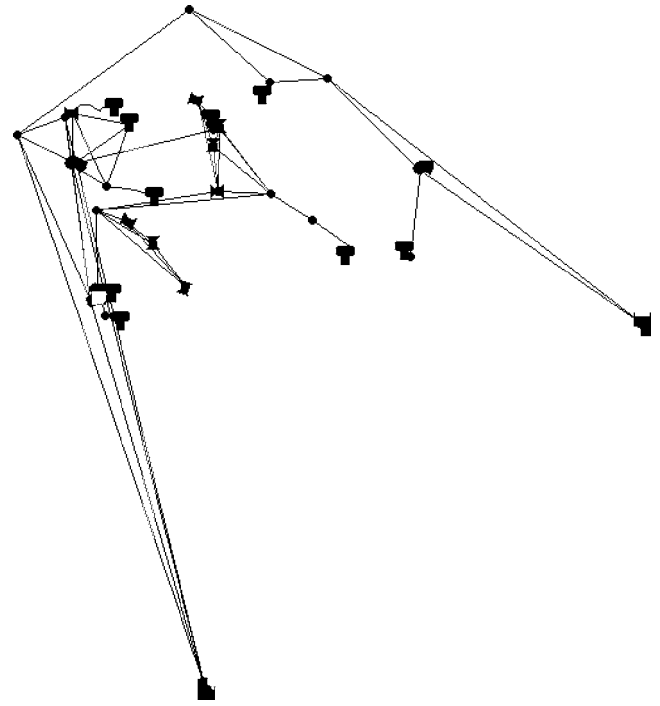2. Pumps: taken from system files and pump tests;
3. Regulating and pressure reducing valves: from data files;
4. Tanks: physical data from files, and constraints on levels at prescribed times (high level at the end of the low tariff period) from the operators;
5. Demands: a file of hourly demands at all nodes for an entire year was prepared off-line (see section below) and used as if it were computed at each hour for the next 24 h; and
6. Electric tariff: the time-of-day electric tariff includes three time periods, representing high, medium, and low energy costs. The tariff is different for the weekend and for holidays and for the different seasons of the year.

Network Skeletonization

The algorithm developed by Ulanicki et al. (1996) was used to create the reduced (skeleton) model. The algorithm proceeds in a step-by-step elimination of pipes and nodes, allocating the demand at the node being eliminated to its neighboring nodes. Obviously, all pumps, valves, and tanks have to remain in the reduced network: the pumps and valves are the decision variables in the optimization algorithm, and tank levels are the resulting state variables. The validity of the reduction is measured by the similarity of the trajectory of tank levels over time in the reduced model with that calculated by the full model (as will be shown in a later section). Once the control routine is found, it is used in the full network model, and node pressures should be close to those calculated with the full model.

The full Haifa-B model shown in Fig. 1 has 867 nodes, 987 pipes, nine tanks (operational reservoirs), 17 pumps in five pumping stations, and eight pressure reducing valves. There are six demand management areas (DMAs), which lie between a pumping station and a tank, as seen in the system schematic on the user interface panel (Fig. 2) which is the user interface of the RM-GA software. The upper part of Fig. 2 is a schematic of the system:
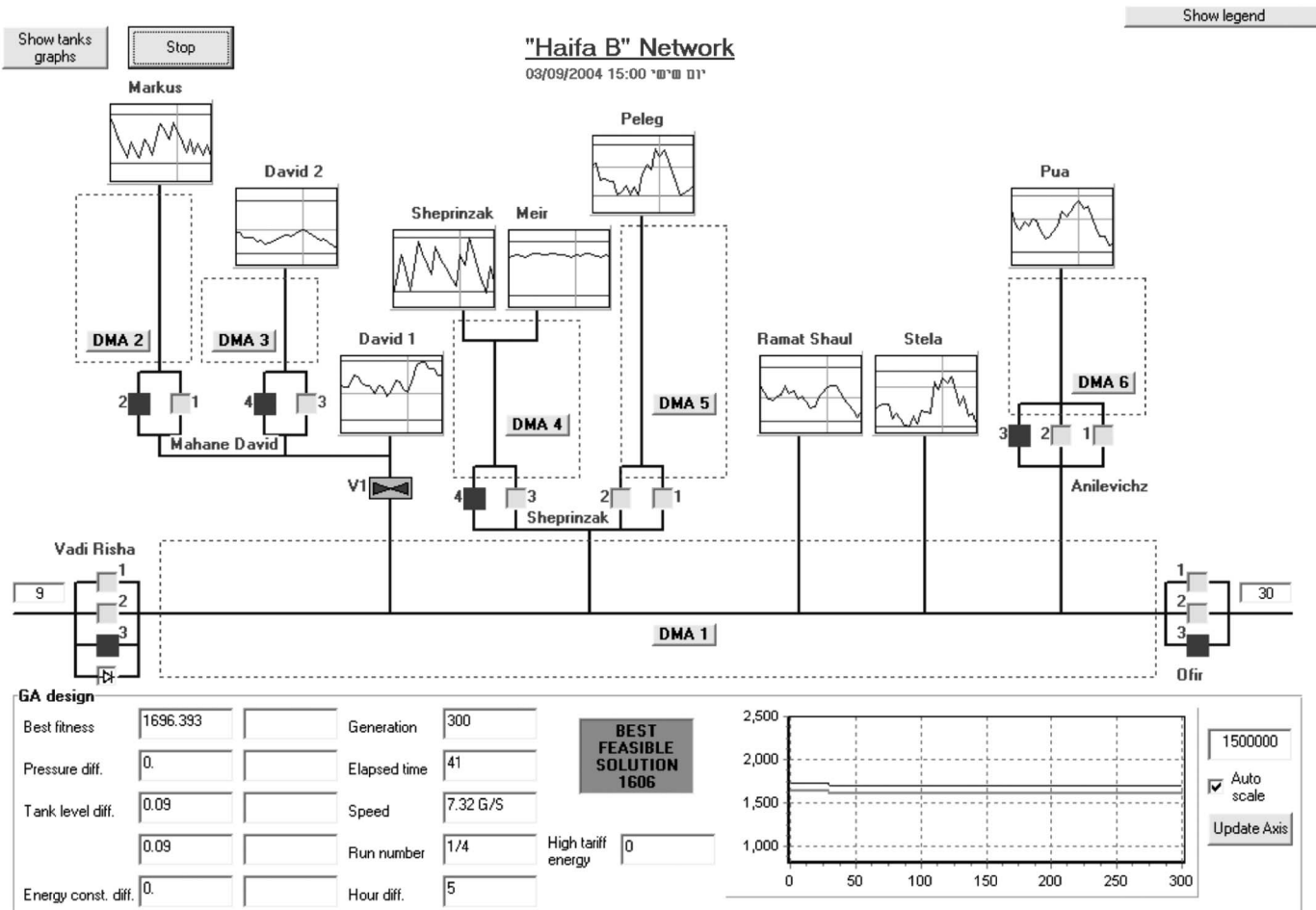
Fig. 3. User interface—Haifa-B RM-GA model

the horizontal line at the bottom is the main pipeline, which is fed from both directions through pumping stations. The nine tanks are fed directly from this line or through pumping stations, and control the pressures in the six DMAs. The trajectory of their levels at the current iteration is shown within each of their "boxes," which also show the admissible level ranges and the minimum level that has to be reached at the end of the low tariff period. There is a control (pressure reducing) valve on one of the lines. The bottom part of Fig. 2 contains GA information and indicators of the progress of the solution (including a graph of the value of the objective function as it changes over the iterations). Program control buttons are in the upper left hand of the schematic.

The reduced model (Fig. 3) contains 77 nodes and 92 pipes, a reduction factor of 10-11, and computation time for a 24-h network simulation is thereby reduced by a factor of ~15. The pumps and tanks are all retained in the reduced system. The reduced model is used by the GA optimization module [instead of using the ANN as was done in the POWADIMA project (Salomons et al. 2007)] to create the reduced model-genetic algorithm (RM-GA) software.

The results of the network reduction algorithm depend on the demands, since the properties of the equivalent pipes which are created when a node is removed depend on the demand at that node (Ulanicki et al. 1996). It would thus seem that it is necessary to produce a reduced network for every hour of the day, since the demands change. However, it is found that within the range of variation of the demands over time, say a factor of 2 between high

and low demands, the resulting reduced network reproduces the results of the full model with very high fidelity.

Calculation of the Haifa-B reduced model takes about 3 s of computer time. Thus, if there is a change in the network, such as when a pipe or a tank are out of service, the recalculation of the reduced model can be carried out in real time, and the modified reduced model can immediately be introduced into the optimization algorithm.

To gain experience and demonstrate the power of the network reduction method, a network of 12,523 junctions and 14,822 pipes, with four pumps, two tanks, and two reservoirs, was reduced to one with 27 junctions and 61 pipes, a reduction by a factor of about 300. The reduced model was calculated in 8 s of computer time.

Demands

Recorded daily quantities produced by each of the pumping stations in 2004 were used to produce an hourly demand pattern; they were distributed over the day according to an hourly pattern found in another, similar, urban system, and divided equally among all nodes within each demand zone. A more complex forecasting method was used in POWADIMA (Alvisi et al. 2007), but experimentation with various forecasting algorithms proved that the saving attributed to the RM-GA does not change when a
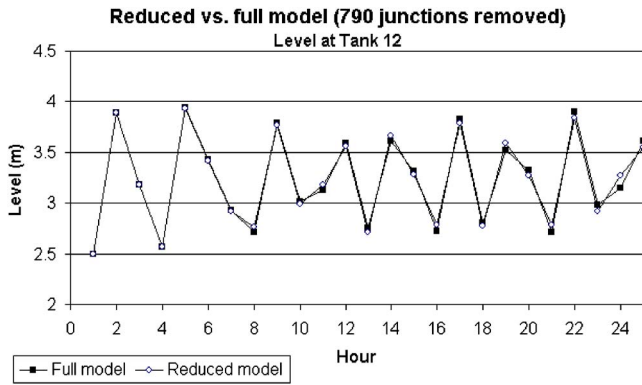
Fig. 4. Comparison of tank level trajectories: reduced network versus full model—points practically coincide

Fig. 5. Comparison of node pressure trajectories: reduced network versus full model—points practically coincide

simple forecast is used. In a real application the accuracy of the demand forecast will have a more important influence, since the GA solution would have to correct more frequently for errors made in the previous hour due to a poor forecast. Even so, the operators would be working with the very same forecast, so the difference between them and the RM-GA would probably remain the same as found in our experimentation.

Results

As a test, we ran the first 15 days of January 2004 with the full network model connected to the GA, and compared the total operating cost to that which would have resulted from the existing set-point operation that the operators use. The saving in cost for this 15-day period was 12%, which amounted to New Israeli Shekels (NIS) ($\sim$ $793) This experiment required extensive computation time, and demonstrated conclusively that use of the full network model cannot be tolerated in real-time operation.

We then ran the RM-GA algorithm for two months of the year 2004: January (low demands) and July (high demands). The corresponding savings are: 11.8% (NIS 7,020=$1,560) for January, and 8.01% (NIS 7,701=$1,711) in August. A higher percentage saving in the low demand month is due to the greater flexibility in shifting the pumping, but it corresponds to a lower absolute saving because the overall cost is lower. From these results we can estimate that the annual savings would amount to some 10% and NIS 19,200 ($4,260). A full-month run, which requires 31 times 24-h optimizations, took about 8 h on a Pentium 4, 2 GHz IBM ThinkPad with 1.5 GB RAM.

The accuracy of network reduction can be seen in Fig. 4, where tank level trajectories over a typical day of the full model and the RM are compared. In fact, it is difficult to see the difference, as the two trajectories practically coincide. Comparison of the trajectories for the two months shows a similar accuracy of 1–2% in tank levels. Similarly, node pressures calculated at pipe nodes that remain in the reduced network with those computed by the full model show similar accuracy (Fig. 5).

Discussion

The Haifa-B network's full model contains 867 nodes and 987 links, while the RM contains only 77 nodes and 92 links (and maintains all pumps and tanks), and still it reproduces the changes
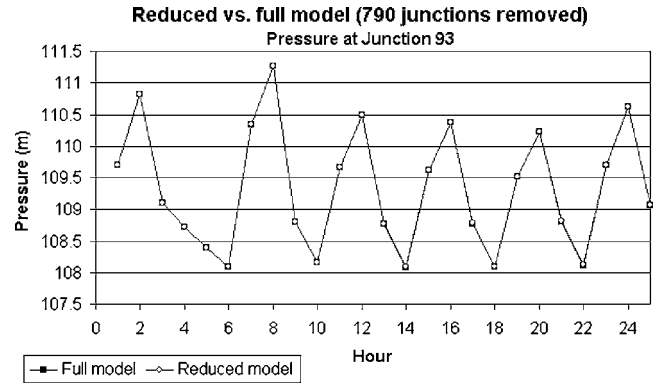
in tank levels and node pressures with high fidelity throughout extended simulations with widely variable loads. Since the energy cost depends on the operating schedule of the pumps (with time-of-day tariff) and on water levels in the tanks, this guarantees that the energy costs calculated with the RM are identical to the value that would be obtained with the full model. The computation time of a 24-h simulation is reduced by a factor of 12; it took typically 40 s (on a Pentium 4, 2 GHz IBM ThinkPad with 1.5 GB RAM) to reach an optimal solution for a 24-h horizon of Haifa-B.

Due to the delay in installation of the SCADA system, the results reported herein compare computational results of the optimization with simulation of the system under control rules installed by the operators as set points. The set points are fixed, and represent no flexibility in adjusting to demand forecasts and their variability over time. The dynamic rolling-horizon optimization has therefore substantial advantages over the operators, which yield the savings reported herein.

The Haifa-B system contains fixed-speed pumps, one operational pressure reducing valve, and several pressure regulating valves. The optimization could readily be expanded to consider other hydraulic components, such as variable speed pumps. Like the pressure reducing valve, a variable-speed pump has a continuous operational value within limits. This is dealt with by the built-in options of optiGA (2001) which can optimize binary, real, and integer variables.

Conclusions

A reduced model-genetic algorithm (RM-GA) has been developed and applied to the water distribution system of Haifa, Israel. The reduction in model size by a factor of about ten resulted in a reduction of simulation time by a factor of about 15, while maintaining very high accuracy in replicating the results of the full network simulation. The efficient computing time allows integration of the reduced model with the GA into a software package that can be run effectively in real time for a large distribution system. Since the network reduction algorithm takes only a few seconds, it is feasible to run it in real time whenever this is required due to a change in network data or network configuration due to failure of components.

Comparison of the operating cost of simulated operation by the operators by a set-point method with the optimized cost shows a savings on the order of 10% for the City of Haifa.

Acknowledgments

References

Alvisi, S., Franchini, M., and Marinelli, A. (2007). "A short-term pattern-based model for water-demand forecasting." *J. Hydroinform.*, 9(1), 39–50.

Jamieson, D. G., Shamir, U., Martinez, F., and Franchini, M. (2007). "Conceptual design of a generic, real-time, near-optimal control system for water-distribution networks." *J. Hydroinform.*, 9(1), 3–14.

Martinez, F., and Bartolin, H. (2005). "GISRed 1.0, A GIS-based tool for water distribution models for master plans." *Effective modeling of urban water systems*, Monograph 13, W. James et al., ed., CHI, Guelph, Ont., Canada, ⟨http://www.redhisp.upv.es/software/gisred⟩.

Martinez, F., Hernandez, V., Alonso, J. M., Rao, Z., and Alvisi, S. (2007). "Optimizing the operation of the Valencia water-distribution network." *J. Hydroinform.*, 9(1), 65–78.

optiGA. (2001). *An ActiveX control (OCX) for Genetic Algorithms (GA)*, ⟨http://www.optiwater.com/optiga.html⟩.

POWADIMA. (2004). ⟨http://www.ncl.ac.uk/powadima/⟩.

Salomons, E., Goryashko, A., Shamir, U., Rao, Z., and Alvisi, S. (2007). "Optimizing the operation of the Haifa-A network." *J. Hydroinform.*, 9(1), 51–64.

Ulanicki, B., Zhenpfund, A., and Martinez, F. (1996). "Simplification of water distribution models." *Proc., Hydroinformatics 96*, A. Muller, ed., Balkema, Rotterdam, The Netherlands, 493–500.

USEPA. (2001). "EPANET 2.00.10." ⟨http://www.epa.gov/ORD/NRMRL/wswrd/epanet.htm⟩.