G Model
SUSCOM-119; No. of Pages 7
ARTICLE IN PRESS
Sustainable Computing: Informatics and Systems xxx (2015) xxx–xxx
Contents lists available at ScienceDirect
Sustainable Computing: Informatics and Systems
journal homepage: www.elsevier.com/locate/suscom

Comparative evaluation of three distinct energy optimization tools applied to real water network (Monroe)

Fatemeh Alighalehbabakhani [a], Carol J. Miller [a,*], Seyed Mohsen Sadatiyan Abkenar [a], Paulo Thiago Fracasso [c], Steven X. Jin [b], Shawn P. McElmurry [a]

[a] Department of CEE, Wayne State University, Detroit, USA
[b] Tucker, Young, Jackson, Tull, Inc., Detroit, USA
[c] Universidade de Sao Paulo, Sao Paulo, SP, Brazil

ARTICLE INFO

Article history:
Received 6 December 2013
Received in revised form 8 October 2014
Accepted 5 November 2014

Keywords:
Pump
Energy optimization
PEPSO
Darwin scheduler
Markov decision processes

ABSTRACT

Pump station is the biggest energy consumer in a water distribution system (WDS). A large amount of money is expended to provide energy for pumps. The environmental footprint associated with these excess energy demands is a source of concern. By implementing an optimum pump schedule that needs a minimum amount of energy to provide enough pressure and flow for water system, operational cost will be reduced and water system will be more environmentally friendly.

Researchers are trying to find practical tools and methods to optimize pump operation. In this research, Pollutant Emission Pump Station Optimization (PEPSO), Darwin Scheduler (DS) and another approach that uses Markov Decision Processes (MDP) have been used as three different tools for optimizing pump operation of WDS of Monroe, MI, USA. In all three methods pumping optimizations have been done based on reducing energy usage, at the end results of running these three tools have been compared. The comparison results show that pump operation that has been taken from MDP algorithm has the best result in terms of energy usage and the number of pump switches, while pump operation taken from DS can be more effective at volume stored in tanks. The simulations showed PEPSO to be considerably faster than the other two evaluated methods in arriving at the optimum solution.

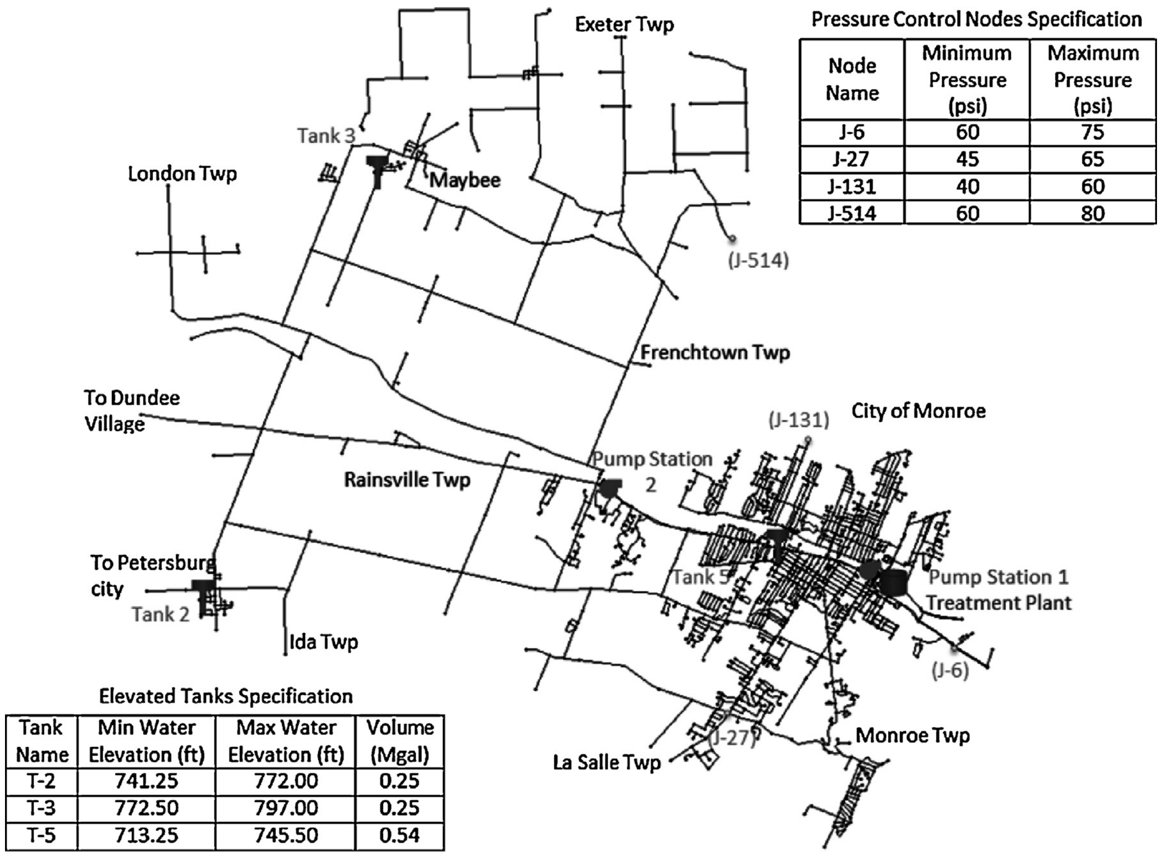
1. Introduction

Water and energy are essential resources that our lives are depending on them, also these two resources are intricately intertwined. For instance, electricity generators, extract energy from water, and water is treated and transferred to consumers by electrical energy. Treating and transferring water to consumers need significant portion of energy. For example, approximately 35% of municipal energy usage is consumed in the water and wastewater facilities [1]; in addition, the most extensive part of the energy is used at pump stations [2]. In the United States 3% of all energy consumption is related to transferring portable water [3]. So optimizing pump operation can result in noticeable energy saving. Beside of energy usage in pump stations, the cost of energy is considerable issue. Over the lifetime of a typical pump, 3% of the total cost is for purchase and 74% is for providing energy [4]. Due to the significant financial implications, engineers, operators and policy makers are trying to find ways to improve the energy efficiency of pumping water in large water transmission systems [2]. Another hazard of over consuming energy is air pollution emission associated with generating and using energy. To consider a WDS as a sustainable system, assessing the amount of pollutant emissions associated with energy consumption is required [5]. Therefore, energy usage, energy cost and pollutant emission, are important factors that should be considered for optimizing a pump operation plan.

Traditionally engineers and experts define some scenarios that include required pressure and flow of WDS and based on available pumping capability and physical characteristics of the network, try to find an operational plan which can answer required pressure and flow of WDS and consume lowest possible amount of energy. But as the number of possible operational plans for a WDS is so large, it is not possible to investigate all possible pump schedules and find the optimum solution. So about four decades ago, researchers started to use some optimization techniques to find the optimum

* Corresponding author.
E-mail addresses: fatemeh@wayne.edu (F. Alighalehbabakhani), cmiller@eng.wayne.edu (C.J. Miller), mohsen@wayne.edu (S.M.S. Abkenar), paulo.fracasso@usp.br (P.T. Fracasso), sjin@tyjt.com (S.X. Jin), s.mcelmurry@wayne.edu (S.P. McElmurry).

http://dx.doi.org/10.1016/j.suscom.2014.11.001
2210-5379/



Pressure Control Nodes Specification

Node Name	Minimum Pressure (psi)	Maximum Pressure (psi)
J-6	60	75
J-27	45	65
J-131	40	60
J-514	60	80

Elevated Tanks Specification

Tank Name	Min Water Elevation (ft)	Max Water Elevation (ft)	Volume (Mgal)
T-2	741.25	772.00	0.25
T-3	772.50	797.00	0.25
T-5	713.25	745.50	0.54

Fig. 1. Monroe water distribution system.

or near optimum solutions [6,7]. It starts with using some deterministic methods but as this type of problem are nonlinear and non-convex, those methods were not so efficient. So about two decades ago, implementing the meta-heuristic and evolutionary methods for operational optimization of WDS gets popular. One of the most famous methods among evolutionary algorithms is the Genetic Algorithm (GA). In mid-nineties, Murphy, Dandy et al. suggested to use the GA in this field and even now it is a popular and effective method for solving these types of problems [8]. GA is one of the most accepted methods to optimize pump operation of WDS [9]. At this time, even most of the commercial WDS optimizers are using this method [10,11]. Although the evolutionary algorithms and specifically GA provided acceptable result but we can find some other research efforts that are focusing on other alternative methods that some aspect of their solution can be better than the near optimum result of other methods like GA. For instance MDP is one of them that Fracasso, Barnes et al. used that for optimizing pump operation of WDS [12].

In this research, three different tools and methods that can optimize pump operation based on reducing energy consumption have been compared. These optimizing approaches include Darwin Scheduler (DS), Pollutant Emission Pump Station Optimization (PEPSO), and Markov Decision Process (MDP). The DS is an optimization tool of a comprehensive commercial water distribution modeling software package (WaterGEMS) that has been developed and distributed in the market by the Haestad Methods. PEPSO is an optimization software that has been developed by a team of engineers and researchers at Wayne State University. These two methods, can optimize pump operation with using genetic algorithm (GA), while in the third method, the MDP was used to optimize pump schedule.

Pump stations of Monroe WDS in Michigan State have been chosen as a case study and used for comparing three optimizing approaches. In addition, for hydraulic simulating of the water system, WaterGEMS software was used in all three methods. This paper is organized in 5 sections, in the second section water system and in the third section three methods have been explained. The fourth section describes the experiment and reports the results, and finally the last section summarizes our conclusion.

2. Water system characteristics

The city of Monroe is located 25 miles south of Detroit in southeastern part of Michigan State, along west coast of Lake Erie. The system serves a population of about 40,000 people with total demand of approximately 9.63 million gallons per day (MGD). Its service area covers 117 square miles, including the City of Monroe, City of Petersburg, all of Monroe Charter Township, Raisinville Township and Village of Dundee and Maybee. Also portions of LaSalle, Exeter, London, and Ida Townships are served by Monroe WDS. Total water demand for this system was calculated based on the daily discharge flows from the high lift pumps and water storage tanks. Diurnal patterns of water use were developed from operating logs provided by the utility. General characteristics of Hydraulic model are presented in Table 1.

A model schematic of the Monroe system is illustrated in Fig. 1. For running the water network in allowable pressure range, pressure of several critical nodes has been constrained. The minimum and maximum pressures for these junctions are shown in the upper right corner of Fig. 1. In addition, the minimum and maximum water levels and storage capacities for all three tanks within the system are presented in lower left corner of Fig. 1.

Please cite this article in press as: F. Alighalehbabakhani, et al., Comparative evaluation of three distinct energy optimization tools applied to real water network (Monroe), Sustain. Comput.: Inform. Syst. (2015), http://dx.doi.org/10.1016/j.suscom.2014.11.001

Table 1
Main characteristics of Monroe hydraulic model.

Component	Quantity	Description
Fixed speed pumps	11	7 types of pumps – Located at main station
Variable speed pumps	2	One type of pump – Minimum relative speed 65% – Located at booster station
Reservoir	1	Only source of water
Elevated tanks	3	Total volume of 1.04 Mgal
Pipes	1940	280 miles from 2 to 99 inch
Junctions	1550	From elevation 573–662 feet

3. Methods & software

In this section, DS, PEPSO and MDP methods and its application explained briefly.

WaterGEMS accompanies all three optimizing tools, at hydraulic simulation of water network and check system requirement (e.g. flow and head), after optimizing pump operation.

3.1. Darwin Scheduler (DS)

WaterGEMS is a well- known water distribution modeling software package distributed by the Bentley Company. Not only this software performs hydraulic, energy and financial analyses but also it provides advanced optimization of designing water networks and operating pumping stations [6]. DS is one of WaterGEMS tools that optimize pump operation plan. DS can optimize pump operation based on energy used and energy cost. But in this work, we just compare three mentioned approaches based on minimizing energy usage.

The DS has the potential of defining maximum and minimum pressure range in nods, maximum velocity of water in pipes, maximum number of pump starts allowed and finally tank level, it can optimize pump operation considering defined constraints. However, in this work, just maximum and minimum pressure of some critical nods has been defined and used.

The DS uses GA for optimizing pump operation, and based on amount of fitness, the best solution (pump operation) can be chosen. In this work, fitness is calculated according to the following equation:

$$\text{Fitness} = \text{Total Energy usage} + \text{Pressure Penalty} + \text{Marginal Value} \quad (1)$$

$$\text{Pressure Penalty} = \sum_{i=1}^{n} (\text{Avg.Absolout Pressure Violation})_i \times (\text{Pressure Penalty Facter}) \times 10,0000 \quad (2)$$

$$\text{Marginal value} = (\text{No. of Pump Starts})^{1.5} \times 0.005 \times \text{Total Energy usage} \quad (3)$$

The absolute pressure violation is the absolute amount of pressure difference of each point from its allowed pressure range. Pressure penalty factor is a parameter that shows the importance of pressure violation during the optimization process and can select from a range of 0.5–2.0. By increasing the weighting factor of pressure penalty, the effect of pressure violation on the final amount of fitness value will increase. So it forces optimizer to find a solution with the lower pressure violation. Although this effect is desirable, but it might act as a strict constraint and prevent search process to explore freely the whole domain of the solution space for finding the near optimum solution. So there is a tradeoff between increasing and decreasing this weighting factor and it should be decided based on the performance of DS in finding near the optimum result of each specific problem.

In this study, we selected the recommended and default value of one for this parameter. As it can be seen later in the result section, the selected value was reasonable for this test case and resulted acceptable solutions without pressure violation. Table 2 shows the GA parameter that has been input in DS for optimizing pump schedule.

Table 2
GA parameters of WaterGEMS.

Parameter	Amount	
Maximum generations	1000	Stopping criteria
Maximum non improvement generations	200	
Maximum eras	10	
Maximum trials	100,000	
Population Size	100	GA parameters
Elit population Size	10	
Number of crossover points	4	
Probability of crossover	95%	
Probability of mutation	1.5%	
Probability of creeping mutation	0.1%	
Probability of creeping down	65%	
Probability of cut	1%	
Probability of splice	90%	
Probability of elite mate	0.5%	
Probably of tournament winner	95%	

3.2. Pollutant Emission Pump Station Optimization (PEPSO)

PEPSO is a computer program that is developed during a research project at Wayne State University. This software designed to optimize pumping schedule of WDSs based on energy usage and pollution emission which is caused by electricity generation. This software uses GA with a binary coding method to find a near optimum pumping schedule. Abkenar et al. [13] explained details of coding method that is used by PEPSO in their article. Although reduction of energy usage was the main objective of optimization, but to get a practical result, pressure of strategic nodes of water network have been constraint too. Through GA process, 100 random pumping schedules formed the first generation of the solution and by conducting elitist, crossover and mutation steps next generation of better solution produced. Best pump schedule of the last generation is reported as the near optimum pumping schedule. Table 3 shows GA parameters that have been used by PEPSO. With a population size of 100, after 1000 generations, about 100,000 pump schedules are evaluated by PEPSO to find the near optimum pump control set. PEPSO uses EPANET 2.0 hydraulic toolkit to analyze hydraulic effect of each pump schedule on WDS.

Table 3
GA parameters of PEPSO.

Parameter	Amount	
Maximum generations	1000	Stopping criteria
Maximum non improvement generations	200	
Population size	100	GA parameters
Elite population size	10	
Number of crossover points	2	
Probability of organism mutation	Random	
Probability of chromosome mutation	Random	
Probability of gene mutation	Random	

Please cite this article in press as: F. Alighalehbabakhani, et al., Comparative evaluation of three distinct energy optimization tools applied to real water network (Monroe), Sustain. Comput.: Inform. Syst. (2015), http://dx.doi.org/10.1016/j.suscom.2014.11.001

EPANET developed by Water Supply and Water Resources Division of united state environmental protection agency and is a public-domain software that can simulate and analyze WDS. By analyzing water network, pressure of each demand node and total energy usage of pumps can be calculated. An optimization run of PEPSO on Monroe water network, with a computer system that has 8GB of RAM and 2.3 GHz CPU, in average takes about 2–3 h. It should be noted that this time is considerably depended to computer hardware that has been used for running PEPSO.

For measuring goodness of solutions, amount of power consumption and pressure penalty have been calculated for each solution. Pressure penalty is a polynomial function of pressure violation. Similar to the DS, the pressure violation is the amount of pressure of control nodes which has gone beyond the allowable pressure limits. Fitness of each solution has been calculated by adding the amount of energy consumption to pressure penalty that have been multiplied by a weighting factor of five. Amount of pressure penalty has been multiplied by five to increase its effect on fitness. By using this weighting factor, the probability of selecting pump schedules with lower pressure penalty during the elitist step of the GA is increased. So the probability of generating a near optimum solution that can satisfy practical pressure range of water network has increased. Each solution that has a smaller fitness is a better solution. As it is shown in Table 3, 10% of solution population of each generation that had lower fitness were selected as elite population and used in crossover and mutation step to create the next generation. After 1000 generations or when the fitness of best pump schedule does not improve for 200 generations, GA stops and reports the near optimum pump schedule with the least amount of fitness as the final solution. Output of the optimization process of PEPSO is a text file & some graphs that contain information about amount of energy usage, pressure violation, and pressure of control nodes during 24 h period of simulation and optimum pumping schedule. Also PEPSO can export optimized pumping schedule in the format of EPANET input file. This file can be loaded into EPANET to investigate the detailed hydraulic effect of near optimum pump schedule on component of water network (e.g. tank level, flow velocity).

3.3. Markov Decision Processes (MDP)

MDP is a powerful framework that can be applied to solve a huge variety of optimization problems in different fields [14]. It works in a sequential process of decision epochs by performing actions that change the state at the next decision epoch through a transition probability function and that provides rewards/punishment to an agent, who executes the actions [12]. Since the system is ongoing, the state of the system prior to next decision depends on the present decision. Therefore, the agent's goal is to identify, for each state, the action that produces the highest expected reward in a long time horizon and that will result in the system performing optimally with respect to some predetermined performance criterion. For accessing to the further details about this method, refer to [12]. One of the biggest issues to use MDP in problems with many variables (states or actions) is the combinatorial explosion of them. In this experiment, the number of possible actions is: $2^{Nu} = 2^{13} = 8192$ combinations. This number is oversized, especially due to existence of equal pumps connected in parallel. The pumps W-8, W-9 and W-10, besides pumps E-3, E-4 and E-5 are the same type. Removing these permutations from the initial set of combinations, it is possible to reduce to 1024 combination Moreover, the physical limitations of the pumps, either by flow or head, make possible to reduce even more this set.

The considerable difference between three optimizing methods is a user interface at selecting a potential pump for operating. In MDP method, user selects pumps for operating, although in DS and PEPSO user has no role in choosing a pump.

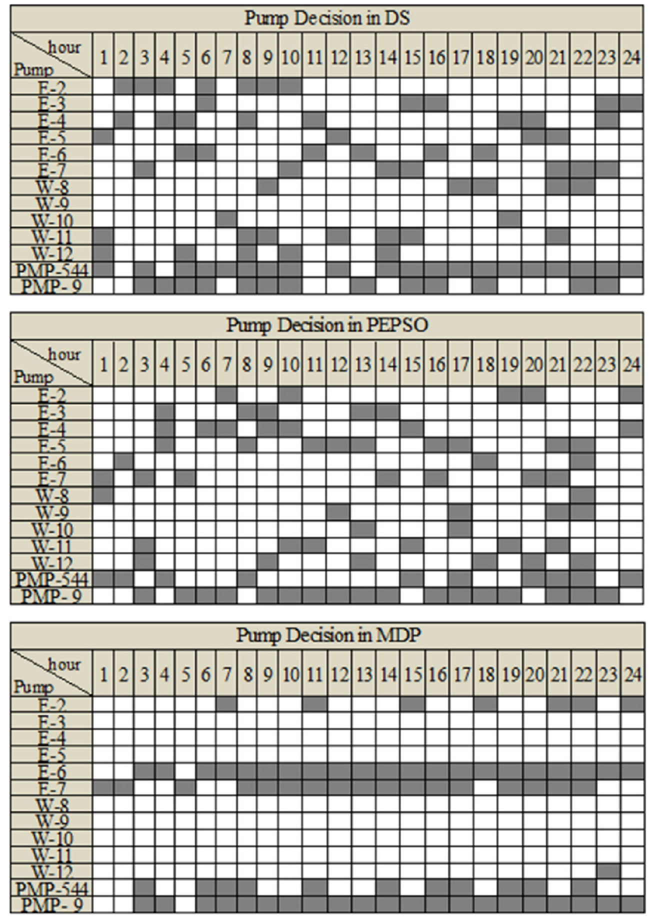


Fig. 2. Pump operation in three methods.

4. Results & discussion

As it was explained three above mentioned methods were used to optimize the Monroe WDS. In this section result of the optimization processes presented and compared. Fig. 2 presents pump operation of all three runs. As can be seen in MDP result, the number of pump duty cycle is less than the two other methods. By using this method, just 6 pumps work in a day, while based on PEPSO & DS results almost all 13 pumps are supposed to work in a day. This difference can be explained by the user different level of control of user on optimization process of these three methods.

As it was mentioned in the previous section, user of MDP method can do a pre-process on water network and reduce the number of pumping permutation by recognizing similar pumps and considering physical limitations of pumps in delivering head and flow. So in this method, solution space has been limited. As this process is not part of PEPSO or DS approaches, in their results, pump usage pattern looks more random and one can see more pump duty cycle with shorter duration. Although the user interfere in MDP process make it less automatic, but it can help the process to result more practical pump schedules with lower number of pump cycles. As higher number of pump switches can increase the risk of the pump operation problem and increase the maintenance cost of pumps [15], MDP results potentially can reduce the maintenance cost. In the other hand, manually selection of some pumps for operating may cause over usage of those pumps and while the other available pump has been put aside. This can reduce the life expectancy

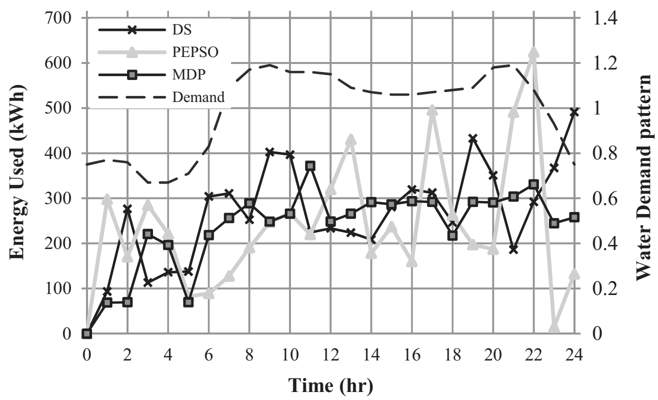


Fig. 3. Energy used in all approaches.

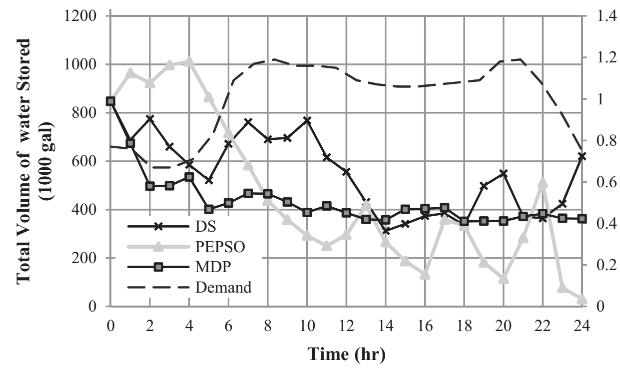


Fig. 5. Total volume stored in tanks in all approaches.

of selected pumps. So the final result of MDP may need an additional final polish to distribute required pumping period between similar pumps and use all pumps capability.

Fig. 3 shows the energy consumption of all three methods, during 24 h. To relate the energy usage results with water demand, water demand pattern has been added to this figure. As it was expected and can be seen, in all methods energy usage increases with rising water demand, so the trend of increasing energy consumption is approximately similar to rising demand. There is fluctuation in energy consumption of all methods, but the amount of fluctuation in PEPSO result is higher. For example, at 11 PM PEPSO has the highest energy consumption and at 10 PM has the least energy consumption, the high amount of fluctuation shows part of energy in PEPSO method has been wasted. Total energy usage in all approaches has been illustrated in Fig. 4 (left vertical axes). Energy usage in MDP and PEPSO methods are almost similar and energy consumption in PEPSO has been just 0.60% higher than MDP, while energy consumption in DS is about 10% more than PEPSO.

Another remarkable item, beside total energy consumption, that should be noticed is total energy used per volume pumped that has been shown in Fig. 4 (right vertical axes).

Energy consumption per volume pumped of DS and PEPSO results are relatively close and have just 1.14% difference. But in comparison with MDP approaches, PEPSO and DS results are 8% and 9% higher respectively. Although the amount of energy consumption in PEPSO result is low, but energy consumption per volume pumped shows that the total energy consumption was not more effective than the two other methods. To discuss it more, volume of water that has been stored in or drained from the tanks should be considered. Solid lines in Fig. 5 shows the total volume of water stored in all three tanks based on the results of the three methods. In the Monroe water network, total available storage of all tanks is about 1.05 MG. As the initial condition of tanks for all three methods

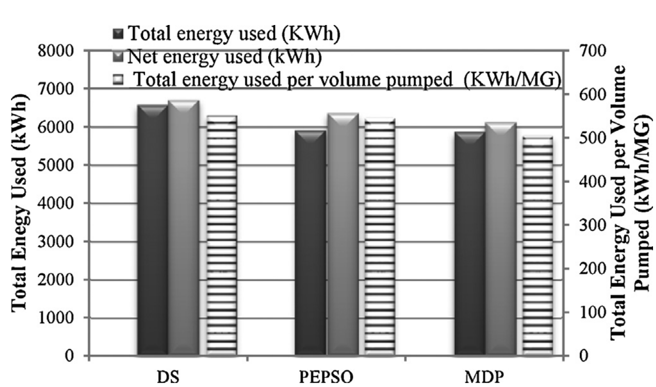


Fig. 4. Total energy used in all approaches.

were the same, and the volume stored in all three approaches is about 0.85 MG. Therefore at the time zero about 80% of tanks was full, it is predictable that optimum pumping policies tend to use some amount of stored water instead of consuming energy to pump water to demand nodes. Dashed line in this figure shows water demand during 24 h. The graph presents that in all three methods with increasing water demand (for example from 7 AM to 9 PM), total volume of water stored decreased. Based on different pumping policy of three optimization methods, final amount of stored water after 24 h simulation were not similar. Fig. 5 shows that based on pumping policy of PEPSO, 0.82 MG (96%) of stored water has been used. But MDP and DS results used 0.49 MG (57%) and 0.23 MG (27%) of stored water.

Although PEPSO result shows that this software found a pumping schedule that needs a minimum amount of energy; but this pumping schedule almost completely drained the tanks, and it cannot be considered as a good and practical result. This policy shifts the energy usage to the next day to fill tanks again. So it seems that PEPSO needs a constraint that prevents to select those sorts of pumping schedule that use minimum energy but mostly relay on stored water in tanks. DS tool has an option to control tank level and force program to find some solutions that do not drain tanks. Although this option has not been used in this study, but even without using this option, it can be seen that DS provides a result that did not consume a lot of stored water. So it is possible that some parts of internal code of GA in DS, lead program to find these types of pumping schedules. MDP method controls the level of water in tanks so as it was mentioned above, in this method just about half of stored water in tanks is consumed during 24 h and tanks did not drained completely. From an operational point of view and regarding the water level in tanks, DS provided the best result.

To conclude the effect of stored water on total energy consumption of these three methods, energy used per volume pumped energy was multiplied by the change in stored volume of water in tanks. The result is some amount of energy, which is stored in or drained from the tanks. By adding this energy to the total energy usage for pumps, net energy consumption had been calculated for all three methods and presented in Fig. 4 (left vertical axes). The net energy used bar chart shows that, although total energy usage of PEPSO and MDP did not have significant difference, but after considering the effect of tank drain, the net energy usage of MDP solution is about 4% less than solution of PEPSO. It should be noted that, total and net energy used by the DS method is 10% and 5% higher than PEPSO result.

Fig. 6 compares peak 60 min power demand of pumps in all three methods. The data shows that PEPSO has the highest power demand. It means that in the final solution of PEPSO, we can see at least 1 h of the day that some large pumps were on at the same time and their cumulative power demand increased the peak

G Model
SUSCOM-119; No. of Pages 7
ARTICLE IN PRESS

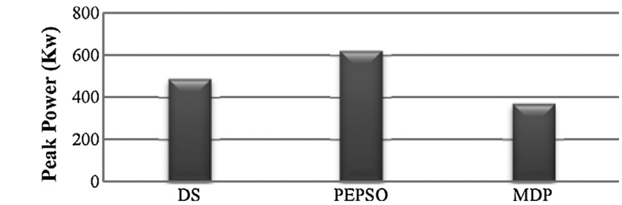


Fig. 6. Peak hourly power demand in all approaches.

60 min power demand of the solution. Based on electricity tariff, considerable part of the energy usage cost (about half of electricity bill) can be related to peak power demand. In this case, the best pump schedule is a pump schedule that has the lowest peak power demand. Electricity tariff of Monroe WDS includes the power demand charge.

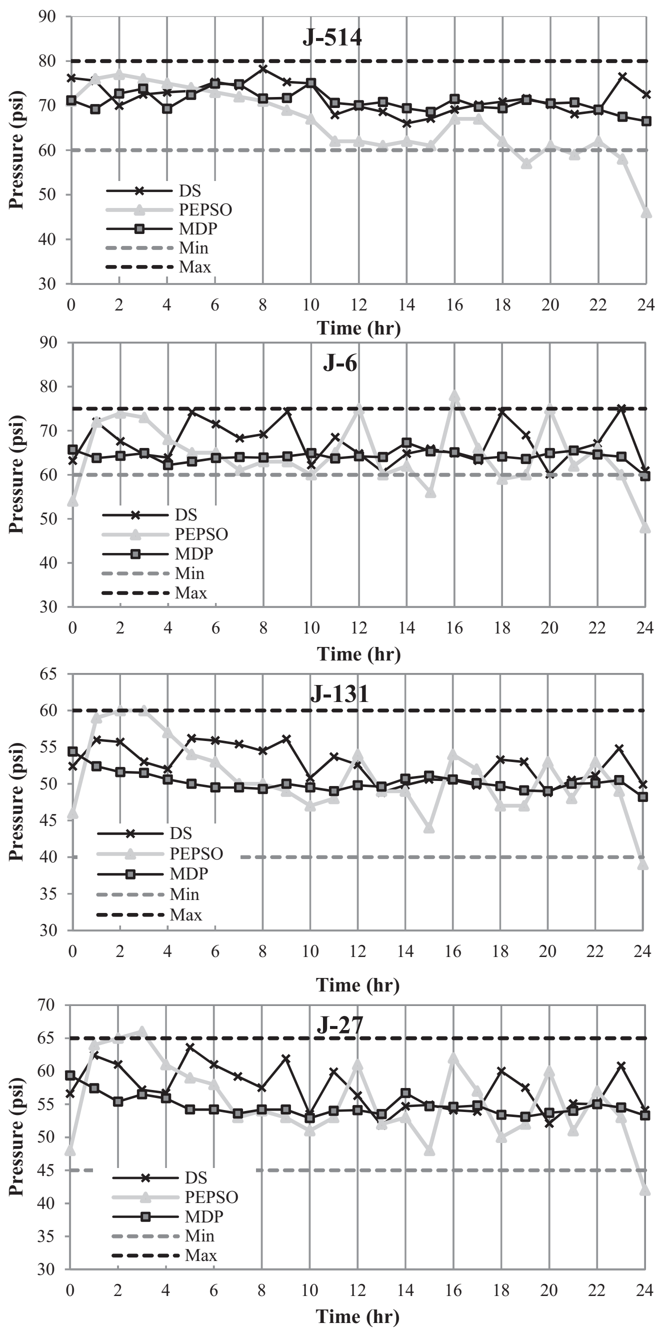


Fig. 7. Pressure of pressure control nodes (J-514, J-6, J-131 & J- 27) of three methods.

Although these optimizations were based on energy usage not the energy cost, but it seems that MDP method can provide the optimum result considering both minimum energy usage and minimum power demand. As it was explained in the previous parts, six strategic points of WDS have been chosen as pressure control nodes. Fig. 7 shows the pressure of these junctions during 24 h. Pressures of control nodes of DS and MDP runs are in the allowable pressure range, so the pressure penalty for the results of both methods are zero.

However, for PEPSO, pressure of some of the control nodes, especially at starting and ending time of day, exceed allowable limitation. Pressures of these nodes in DS result have some fluctuations during the day. But in MDP result, pressures of the control nodes have more smooth changes and are mostly at the middle of the allowable pressure range. Average duration that a computer system with 8 GB RAM and 2.3 GHz CPU needs to run PEPSO for optimizing pump operation of Monroe network was considerably lower than required time for two other methods. PEPSO needs about 2–3 h, but DS needs about 22 h and MDP needs about 30 h. Required time for optimizing is an important factor, especially for optimizing large water networks. To have best result based on real-time demand and condition of WDS, an optimizer need to provide optimum solution as fast as possible and repeat the optimization process based on changed initial condition several times in a day. Another important issue about these methods is that the whole optimization process of PEPSO and DS was automatic and after inputting water network model and the optimization parameters, user does not need to do anything to receive the final optimum solution. But as it was explained MDP needs user to select required pump for optimization. So running MDP needs an expert some knowledge about the water network and characteristics of the pump. And the process can't be done automatically.

5. Conclusion

In this research, result of three optimization approaches for pump operation optimization of Monroe city WDS have been compared. This study shows:

1. The number of pump duty cycle in MDP result is less than two other methods, because of pre-processing on the network and decreasing pumping permutation.
2. In all three approaches, as it was expected, the trend of increasing energy consumption is almost similar to water demand pattern of the network, also there are some fluctuations in the trend of energy usage, that shows pumps are working more than demand. The amount of fluctuation in PEPSO result is higher than two other methods that shows part of energy have wasted.
3. Total energy consumption of DS result is higher than the two other methods. The difference between PEPSO and MDP results is too low; while in the term of energy consumption per volume pumped, DS and PEPSO result are close and both are higher than the result of MDP. MDP shows the best result in net energy usage too. Net energy usage of DS result is 9%, and in PEPSO result, 4% higher than MDP.
4. In all three runs stored volume of water in tanks reduced, but the rate of decreasing volume stored in PEPSO run is much higher than two other methods. It shows that, although PEPSO approach needs minimum energy, at the end of the day considerable portion of stored water in tanks drained. For solving this issue in PEPSO, final tanks level change should be constrained.
5. Result of PEPSO shows the highest 60 min peak power demand among other methods. As electricity tariff of Monroe city includes both energy usage and power demand cost. The high peak power demand increases the total cost of electricity used.

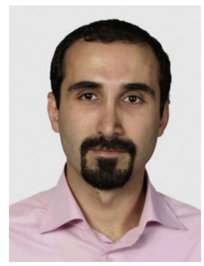
6. In PEPSO results, there are several pressure control junctions that those pressures exceed allowed pressure range. While in other methods, especially in MDP methods, pressures of all control nodes were in the pressure range and have smooth changes.
7. Among three approaches, PEPSO needs lower time to optimize pump operation, while MDP needs much more time, in addition, User of MDP should do some steps manually. But Both PEPSO and DS methods are almost automatic process that receive the hydraulic model of WDS and return near optimum pump schedule. So both PEPSO and DS can be used repetitively and without expert interference during real time optimization of WDSs.

References

[1] Water/Wastewater Systems Fact Sheet, Consortium for Energy Efficiency, 2007.
[2] R. Lightle, Article Published in World Water November/December, 2008.
[3] M. Rogers, Y. Wang, C. Wang, S.P. McElmurry, C.J. Miller, Evaluation of a Rapid LMP-Based Approach for Calculating Marginal Unit Emissions, Int. J. Energy Res. (2013) (in press).
[4] W. Krewitt, T. Heck, A. Trukenmüller, R. Friedrich, Environmental damage costs from fossil electricity generation in Germany and Europe, Energy Policy 27 (3) (1999) 173–183.
[5] A.B. Judith, The Alliance to Save Energy. Energy and Water Efficiency in Municipal Water Supply and Wastewater Treatment, 2007, February.
[6] M.J.H. Sterling, B. Coulbeck, Technical note. A dynamic programming solution to optimization of pumping costs, ICE Proc. 59 (4) (1975) 813–818.
[7] I. Gupta, Linear programming analysis of a water supply system, A I I E Trans. 1 (1) (1969) 56–61.
[8] L.J. Murphy, G.C. Dandy, A.R. Simpson, Optimum Design and Operation of Pumped Water Distribution Systems. Hydraulics in Civil Engineering, Institution of Engineers, Australia, Brisbane, 1994, pp. 1–13.
[9] J. Nicklow, P. Reed, D. Savic, T. Dessalegne, L. Harrell, A. Chan-Hilton, M. Karamouz, B. Minsker, A. Ostfeld, A. Singh, E. Zechman, State of the art for genetic algorithms and beyond in water resources planning and management, J. Water Resour. Plan. Manage. 136 (4) (2010) 412–432.
[10] Heasted Methods Solution Center, WaterGEMS Darwin Scheduler. Computer Software. Darwin Scheduler. Vers. 8i. Bentley System, 2014, Web. 2014.
[11] Innovyze, InfoWater Scheduler Computer software. InfoWater Scheduler. Vers. 1.0, Innovyze, 2013, Web. 2014.
[12] P.T. Fracasso, F.S. Barnes, A.H.R. Costa, Energy cost optimization in water distribution systems using Markov Decision Processes, in: Green Computing Conference (IGCC), Arlington, VA, 2013, pp. 1–6.
[13] S.M.S. Abkenar, S.D. Stanley, C.J. Miller, D.V. Chase, S. McElmurry, Evaluation of genetic algorithms using discrete and continuous methods for pump optimization of water distribution systems, Sustain. Comput. Inform. Syst. (2014), http://dx.doi.org/10.1016/j.suscom.2014.09.003 (Available online 2 October 2014, ISSN 2210-5379).
[14] M.L. Puterman, Markov Decision Processes – Discrete Stochastic Dynamic Programming, 1st ed., John Wiley & Sons, New York, NY, USA, 1994.
[15] J.-Y. Wang, T.-P. Chang, S. Chen Jr., An enhanced genetic algorithm for bi-objective pump scheduling in water supply, Expert Syst. Appl. 36 (7) (2009) 10249–10258.

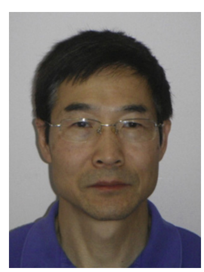
Fatemeh Alighalehbabakhani graduated from PWUT, Tehran, Iran in 2009 with a major in Water and Wastewater Engineering. At that time she was working on the prevention of biofilm formation in water and wastewater installations by application of TiO_2 nano particles coating. Then she moved to the US for continuing her education at PhD degree.

Professor Carol Miller of the Department of Civil and Environmental Engineering, Wayne State University has research interests spanning urban water sustainability, environmental pollutant transport, and the energy/environment interface. Dr. Miller is the previous Chair of the State of Michigan Board of Licensing for Professional Engineers and the current U.S. Chair of the bi-national Great Lakes Science Advisory Board of the International Joint Commission. Her research has been funded by numerous agencies including the Great Lakes Protection Fund (sponsoring the present project), US Army Corps of Engineers, National Science Foundation, US EPA, DTE Energy, the Great Lakes Commission, and others.



Seyed Mohsen Sadatiyan Abkenar is a PhD student of the Department of Civil and Environmental Engineering, Wayne State University, Michigan. He took his MSc degree in Water and Wastewater Engineering from PWUT, Tehran, Iran in 2009. His research efforts at that time was focused on increasing the durability of concrete sewer pipes by using alkaline aggregates. Then he came to USA for continuing his studies and got interested in optimizing the operation of water pumping systems by using evolutionary algorithms and machine learning techniques.

Paulo Thiago Fracasso received the B.S., M.S. and PhD degrees in Department of Electrical Engineering from the University of Sao Paulo – Brazil, in 2004, 2008 and 2014 respectively. His current interests are focused in modeling water distribution systems using Markov Decision Processes to reduce electricity expenses and to increases the reliability of the system. Additionally, recent areas of research interest include flow measurement, energy efficiency, artificial intelligence, smart grid and fluid dynamics.



Steven Jin is a senior environmental engineer in Tucker Young Jackson Tull Inc. He has more than 20 years of engineering experience in hydraulic and water quality modeling, Computational Fluid Dynamics (CFD) simulation, water treatment and pipeline design, water and wastewater field testing, water system planning as well as CSO Analysis. He has been responsible for constructing and calibrating computer models using WaterGEMS, KYPIPE, EPANET and SWMM computer software, conducting water main design, performing reservoir water quality analysis, ozone pilot treatment, water transmission system field sampling and pump test. Mr. Jin also has significant experiences in using ESRI's ArcGIS software and developing GIS applications for water and wastewater projects.

Dr. Shawn McElmurry, Associate Professor of Civil and Environmental Engineering, is one of the original developers of the LEEM technology. Shawn has a broad range of skills related to contaminant transport, air quality, and computational modeling that support product development. Dr. McElmurry's research has been supported by a wide range of agencies including the US EPA, the International Joint Commission, and others. He is a well-known expert in the fate and transport of heavy metals.

Please cite this article in press as: F. Alighalehbabakhani, et al., Comparative evaluation of three distinct energy optimization tools applied to real water network (Monroe), Sustain. Comput.: Inform. Syst. (2015), http://dx.doi.org/10.1016/j.suscom.2014.11.001