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TRADING-OFF CONSTRAINTS IN THE PUMP SCHEDULING OPTIMIZATION OF WATER DISTRIBUTION NETWORKS

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Abstract: Pumps are one of the essential components of water supply systems. Depending of the topography, a water supply system may completely rely on pumping. They may consume non-negligible amount of water authorities' budgets during operation. Besides their energy costs, maintaining the healthiness of pumping systems is another concern for authorities. This study represents a multi-objective optimization method for pump scheduling problem. The optimization objective contains hydraulic and operational constraints. Switching of pumps and usage of electricity tariff are assumed to be key factors for operational reliability and energy consumption and costs of pumping systems. The local optimals for systems operational reliability, energy consumptions and energy costs are investigated resulting from trading-off pump switch and electricity tariff constraints within given set of boundary conditions. In the study, a custom made program is employed that combines genetic algorithm based optimization module with hydraulic network simulation software -EPANET. Developed method is applied on the case study network; N8-3 pressure zone of the Northern Supply of Ankara (Turkey) Water Distribution Network. This work offers an efficient method for water authorities aiming to optimize pumping schedules considering expenditures and operational reliability mutually.

Keywords: Genetic algorithms; water distribution network; energy cost; operational reliability; pump switch; electricity tariff; trade-off constraints

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INTRODUCTION

Water is the most important resource on this planet for the continuation of life. Since ancient times, people have tried to manage fresh water to be able to survive. Today, in modern cities people use water supply systems to access potable water. A water supply system may be defined as a collection of elements such as reservoir(s), pump(s), pipes, different kinds of valves, storage tank(s), having the purpose of providing required amount of potable water at sufficient pressure to the consumers.

Depending on the topography of sources and the targets, almost all water supply systems consume considerable amount of energy that results in high expenditures. As energy prices have tendency to increase, the objective to decrease energy consumption and/or costs becomes a monetary scope for researchers. Also in recent years, energy efficiency and sustainable energy concepts gained much importance and will be continuously significant as the energy need grows. This phenomenon forces the researchers to look for minimization of energy expenditures.

Besides the energy expenditures, operational reliability of pumping systems is also an essential issue for infrastructure authorities. Excessive switching of pumps is a major factor leading mechanical wear of pumps which affects the operational reliability of pumping systems. It may also cause pipe damages in the water supply systems by causing transient actions through the pipeline. Both effects are considerable subjects decreasing operational reliability of pumping systems. Optimizing pumping schedule is considered to be a key operation that will judge both issues and minimize these expenses mutually. Scheduling of pumps can basically be explained as, deciding on which pump shall be in operation through which duration while casting, optimality constraints, hydraulic conformities and electricity tariff.

The problem of pump scheduling is an early optimization objective for many researchers. Being one of the pioneers of the subject, Jowitt & Germanopulos (1992) presented a method based on linear programming to determine a 24 hour pump schedule providing minimum cost. A detailed review of past optimization approaches to pump scheduling problem is made by Ormsbee & Lansey (1994). A dynamic optimization algorithm was developed by Lansey & Awumah (1994) paying special attention to limit the number of pump switches while minimizing the energy consumption cost. Savic *et al.* (1997) used multi-objective genetic algorithms (GA) into the pump scheduling problem presented by Mackle *et al.* (1995). The multi-objective approach considers both the energy cost and pump switching criteria in the same objective; they considered the electricity tariff for two periods; day and night. They also made some improvements in combining GA with two local search strategies based on different definitions. Boulos *et al.* (2001) developed the H2ONET tool, using genetic algorithms for minimal operation costs and pump scheduling. Zyl *et al.* (2004), Yu *et al.* (2005), Farmani *et al.* (2006) and Rao & Salomons (2007) are other researchers who have employed evolutionary algorithms for the solution of the operational optimization problem of Water Distribution Networks (WDN).

More recently, a model for optimizing pump operation and sizing storage, utilizing a framework based on a mixed integer nonlinear programming algorithm and a data-driven neural networks scheme was presented by Pulido-Calvo & Gutiérrez-Estrada (2011). López-Ibáñez *et al.* (2011) focused on the comparison of two most used representations in pump scheduling; binary representation and level-controlled triggers. Furthermore, they defined and analyzed two explicit representations based on time-controlled triggers where the maximum number of pump switches is limited. Fang *et al.* (2011) presented multi-objective evolutionary algorithms combined with a repair mechanism that was used to solve the optimal operation problem within the water distribution network while minimizing both; operation cost and maintenance cost. They utilized statuses of the pumps at a time step of the total operational time period as decision variables. Yuan & Liu (2012, 2013) presented the use of an ant colony optimization model for optimum operation of a pumping unit. Feasible solutions were found by the iterative searching of artificial ants, and then the optimal solution was obtained by applying the rule of state transition and pheromone updating. Kougias & Theodossiou (2013) presented a multi-objective optimization method for pump scheduling problem while considering water supply, pumping cost, electric power peak demand, and pump maintenance cost as optimization objectives. EPANET is implemented in another multi-objective optimization methodology which was presented by Kurek & Ostfeld (2013). They used EPANET for trading off pumping costs, water quality, and tank sizing of water distribution networks. Price & Ostfdeld (2013) used variable speed pumps in order to control pressure/flow to meet the system requirements and save energy. They employed an iterative linear discrete pump scheduling algorithm for the optimization problem. Farina *et al.* (2014) presented a procedure based on the iterative use of a traditional simulation (EPANET) to model water distribution networks. Their approach gave out precise results in the cases of networks featuring large pipe water discharge and user demand values. Odan *et al.* (2015) developed a methodology by integrating three models; (1) real-time demand forecasting, (2) hydraulic simulation of the system, and (3) optimization models. They employed EPANET for hydraulic simulation while minimizing energy usage and maximizing operational reliability of pumping systems. In none of these studies, the relationship between the tariff usage and operational reliability are not underlined. Electricity tariff has generally considered to be a part of cost function and left within this border. This paper reveals another outcome of tariff usage with respect to the operational reliability point of view.

Most of the studies encode the pumping states (on/off) within the defined time period, handling the binary codes for each interval. Code string is determined, depending on the time interval and the number of pumps to be controlled. This study employs EPANET as a hydraulic simulation software and integrate it into a well known evolutionary algorithm. Genetic Algorithms (GAs) are preferred for implementation due to non linear behavior of the problem. Genetic operators such as selection, crossover and mutation are the main parameters used. In this study, excessive switching of pumps is assumed to be a decreasing factor for operational reliability of pumping systems. Throughout the study, by trading-off pump switch constraint with the electricity tariff; the changes between system reliability and energy consumptions are investigated. This paper is started with the definition of problem, continues with the problem formulation, application of the method to the case study network, discussion of outcomes and conclusions.

Problem Formulation

For pump scheduling optimization study, the name of the custom made program is POGA (Pump Optimization using Genetic Algorithms). POGA computes the optimal pump schedule of a given run time duration, casting hydraulic and operational constraints with electricity tariff to minimize the operational consumptions. Pumps are taken as individuals and should be located properly including defined head-discharge curve.

POGA combines built-in hydraulic network simulation software with Genetic Algorithms (GAs), which are search algorithms based on the mechanics of natural selection and survival of the fittest (Goldberg, 1989). GAs basically involves three fundamental operators; selection, crossover and mutation. In this study, fundamental GAs are used with an elitist model that preserves the best two chromosomes in the population for every step, during the process.

Working with a search algorithm, necessitates utilization of the network hydraulically for each circumstance in a reasonable time with a proven preciseness. POGA employs EPANET toolkit (U.S. Environmental Protection Agency, 2007) embedded in the code, which undertakes the hydraulic simulation of the network. Throughout the run of POGA, GAs create, keep and change chromosomes in every cycle; then the operators take place over the chromosomes, EPANET simulates each individual network and helps GAs to give right decisions to find the optimal solution.

Objective Function

The pump scheduling optimality policy results in the lowest operating cost for a given set of boundary and system constraints. This optimality procedure mainly depends on the energy consumption costs that will be the resultant of the duration and rate of pumping. The energy cost minimization objective function and the primary constraints are given below. The primary constraints are the hydraulic necessities of the network such as tank volume limits and node pressure boundaries.

$$\text{Minimize } Z = \sum_{i=1}^{N_p} \sum_{t=0}^{N_t} \left(E_{i,t} \times C_t \right) \tag{1}$$

subject to;

$$P_{t,j} \geq P_{min} \tag{2}$$

$$P_{t,j} \leq P_{max} \tag{3}$$

$$V_t \geq V_{min} \tag{4}$$

$$V_t \leq V_{max} \tag{5}$$

Where:

N_p: Number of pumps
N_t: Number of time steps
$E_{i,t}$: Energy consumption of pump i during time step t (kWh)
C_t: Unit energy cost during time step t (\$/kWh)
V_t: Volume of tank at time t (m^3)
V_{min}, $V_{max:}$ Minimum and maximum volumes of tank (m^3)
$P_{t,j}$: Pressure head of node j at time t (m)
P_{min}, $P_{max:}$ Minimum and maximum pressure head limits (m).

The C_t vector contains the electricity tariff per time steps through the run time duration. For this study, run time duration is taken as 24 hours. For electricity tariff, two types are used; first with constant price for every hour; second, varying prices depending on time of day. The hourly prices are taken from Rebuplic of Turkey Energy Market Regulatory Authority (EMRA) and shown in **Table 1**.

Table 1. Energy prices considered

Constant Tariff	Varying Tariff		
All Day	Day	Peak Time	Night
(1–24 hr)	(Hrs: 06–16)	(Hrs: 17–21)	(Hrs: 22–05)
$/kWh	$/kWh	$/kWh	$/kWh
0.10091	0.10025	0.17936	0.04320

Additional Constraints

For the problem of optimal pump scheduling, besides the mentioned fundamental constraints, additional constraints are included such as reservoir volume deficit, pump switches, operational pressure head and electricity tariff. These constraints are embedded into the main code using penalization methods while addressing multi-objective genetic algorithms problem.

Tank Volume Deficit

While trying to minimize the energy costs of pumping, the trivial solution is to switch off all the pumps. If network can be fed by a tank (reservoir) and if the capacity is big enough to feed the network during run time duration, there is no need for pumps to run. For such case, it is obvious that the reservoir will be emptied, which is not an acceptable situation for water supply security of the network. The periodicity of the reservoir volume shall be maintained. To supply this balance, the volume of the reservoir at the end of scheduling duration shall not be either lower or higher than the initial level. The ideal form is the equality of the final and initial volumes for the scheduling duration; however it may not be completely possible to equalize the volumes. Thus, for resolving this issue a penalty term for reservoir (tank) volume deficit is introduced. The formulization of tank volume deficit penalization is shown as follows;

$$P_{tv} = \sum_{i=1}^{n} \mathrm{abs}\left(WL_{E,i} - WL_{S,i}\right) \times C_{tp} \tag{6}$$

where,
P_{tv}: Tank volume deficit penalty
C_{tp}: Tank volume deficit penalty constant
$WL_{E,i}$: Water level of tank i at the end of run time duration (m)
$WL_{S,i,}$: Water level of tank i at the start of run time duration (m)
n: Number of tanks

Pump Switches

As described above, to conserve mechanical wear and maximize operational reliability supply system, excessive pump switching is introduced into the optimization objective as a constraint. This implementation is applied using a penalty term. The formulization of pump switch penalization is shown as follows:

$$P_{ps} = C_{ps} \times \sum_{i=1}^{n} SC_i \tag{7}$$

where P_{ps}: Pump switch penalti, C_{ps}: Pump switch penalty constant, SC_i: Number of status change for pump i, and n: Number of pumps

In this study, pump switch term is defined as “changing the operational status of pump” including both switching on and off for the pump. Thus, number of pump switches indicates the number of on-off changes of each pump during the run time duration. If a pump starts, runs for a continuous period, then stops during the run time duration, the number of switch (N_s) becomes 2.

For the pump scheduling algorithm considering 24 hours, the pump on-off times are mentioned as chromosomes with 24 bit length for each pump. If there exists two pumps under operation in the case study network, this means that the chromosome length will be 2 (no. of pumps) × 24 (h) = 48 bytes. In the string, “0” means pump is closed while “1” means pump in operation through corresponding 1 h period.

Nodal Pressure Constraint

In this study, the nodal pressures that are out of the boundary limits are also penalized. For this penalization, conditional penalty functions are used. The representation of penalty functions is given below.

$$P_{np} = \sum_{i=1}^{n} \left[\begin{array}{ll} (P_{min} - P_i)^2 \times C_{np} & \text{if } P_i \leq 0 \\ (P_{min} - P_i) \times C_{np} & \text{if } 0 < P_i < P_{min} \\ 0 & \text{if } P_{min} \leq P_i \leq P_{ma} \\ (P_i - P_{max}) \times C_{np} & \text{if } P_{max} < P_i \end{array} \right. \quad (8)$$

where: P_{np} is node pressure penalty, P_i is pressure of node i (m), P_{min} is minimum allowed pressure head (m), P_{max} is maximum allowed pressure head (m), C_{np} is node pressure penalty constant, and n is number of nodes.

In this study, minimum and maximum allowed nodal pressure heads are accepted as 30 m and 80 m respectively.

Table 2. C_t term for constant and varying tariff cases

Hours of Day	1	2	3	4	5	6	7	8	9	10	11	12
Ct for constant tariff	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Ct for varying tariff	0.428	0.428	0.428	0.428	0.428	0.993	0.993	0.993	0.993	0.993	0.993	0.993

Hours of Day	13	14	15	16	17	18	19	20	21	22	23	24
Ct for constant tariff	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Ct for varying tariff	0.993	0.993	0.993	0.993	1.777	1.777	1.777	1.777	1.777	0.428	0.428	0.428

Varying Electricity Tariff

Besides the tank volume deficit, pump switch and nodal pressure penalties, using of varying electricity tariff also acts as a constraint. While electricity consumption and costs are mainly dependent on the run duration of pumps, varying electricity tariff forces the pumps run through the periods of low electricity costs (from 22:00 to 05:00) to minimize the operational costs. That is why electricity tariff is considered as a constraint and included in the objective function with C_t term. The C_t term is defined as a vector of 1×24 dimensions. While applying constant tariff, C_t is taken as a vector of ones, where hourly constants differ for applying varying tariff. In Erro! Fonte de referência não encontrada., C_t term is shown for constant and varying tariff cases.

Modified Form of Objective Function

After introducing the concerning penalty items, the main objective and the penalty items are cast into a single equation while converting the problem into a multi-objective structure. The modified form of the objective function is given below. This multi-objective form is the core of the pump scheduling optimization algorithm.

$$\text{Min.}Z=\sum_{i=1}^{N_p}\sum_{t=0}^{N_t}\left(E_{i,t}\times C_t\right)+P_{np}+P_{tv}+P_{ps} \tag{9}$$

where:

N_p: Number of pumps

N_t: Number of time steps (run duration)

$E_{i,t}$: Energy consumption of pump i during time interval t (kWh)

C_t: Unit energy cost during time interval t (TL/kWh)

P_{np}: Node pressure penalty

P_{tv}: Tank volume deficit penalty

P_{ps}: Pump switch penalti

Application of the Model

The developed pump schedule optimization model is applied to a GIS Based network serving about 40 000 people, N8-3 pressure zone of the Northern Supply of Ankara Water Distribution network. N8-3 network consists of 1 pump station with 2 parallel pumps with different characteristics, 1 storage reservoir with 5000 m^3 capacity, 350 demand nodes and pipes varying from 100 to 500 mm diameter with an approximate total length of 170 km covering an area of 210 hectares. The pump station feeds the network and the reservoir simultaneously depending on the demand hours via transmission line. In other words, the direction of flow on the main line varies depending on the daily demand curve. Thus, the water level of the tank and the water supplied by the pump station is dependent on the whole network hydraulics. On the other hand, the characteristics of pumps are not the same. As the pumps have non-linear head-discharge curves; the rate of pumps are dependent on the hydraulic equilibrium of the system. These are the main reasons, why EPANET is integrated into the optimization problem as the hydraulic simulation software.

The characteristics of topography are different throughout the network. Maximum and minimum serving nodal elevations are 1152 and 1048 m respectively through the network. General layout of N8-3 network, the daily demand curve and the head-discharge curves of used pumps are shown in Erro! Fonte de referência não encontrada.–**3**, respectively.

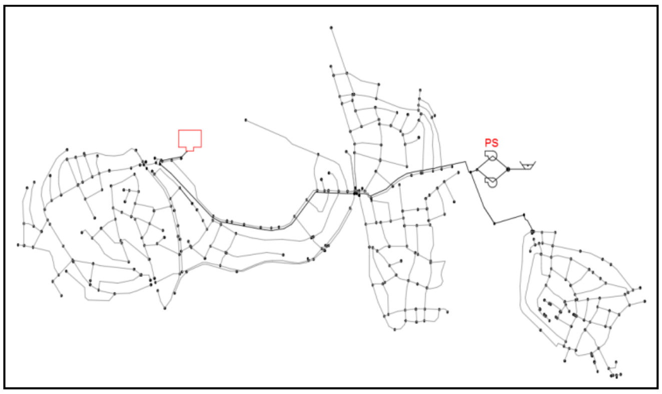


Fig. 1 General layout of N8-3 network.

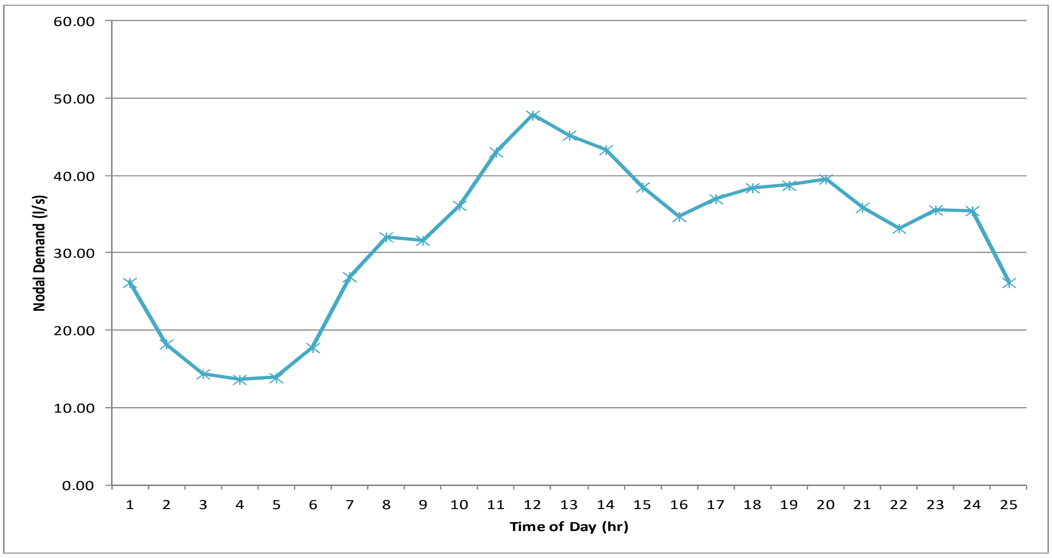
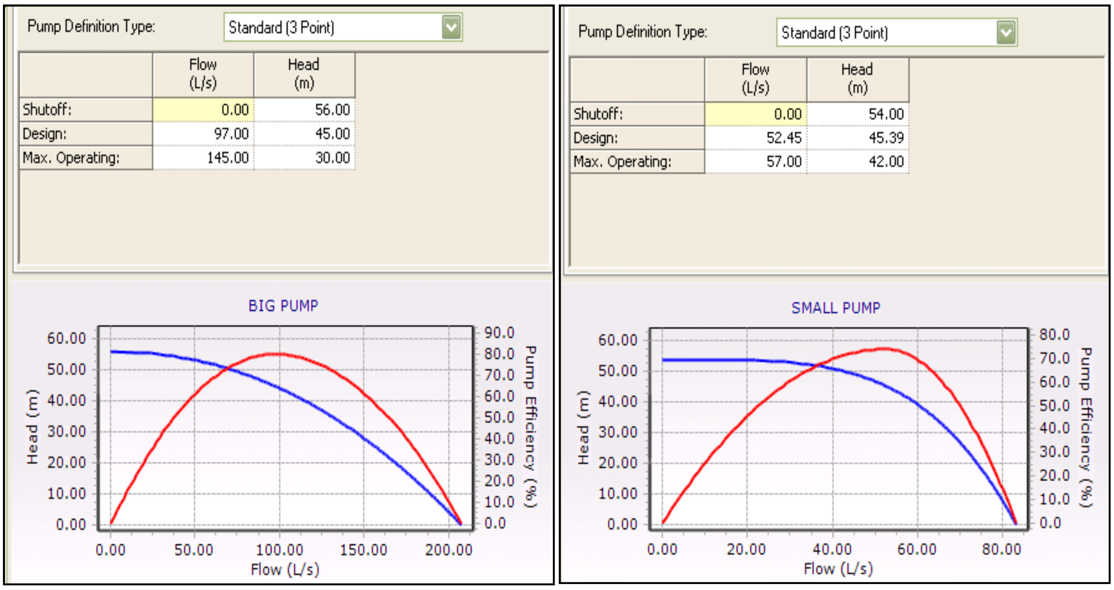


Fig. 2 Daily demand curve of N8-3.

Network



Pump Definition Type: Standard (3 Point)

	Flow (L/s)	Head (m)
Shutoff:	0.00	56.00
Design:	97.00	45.00
Max. Operating:	145.00	30.00

Pump Definition Type: Standard (3 Point)

	Flow (L/s)	Head (m)
Shutoff:	0.00	54.00
Design:	52.45	45.39
Max. Operating:	57.00	42.00

Fig. 3 Head - Discharge curves of used pumps.

Optimization Study

After setting the objective function and the constraints, to look for the effect of pump switch constraint and variation of electricity tariff to the problem of optimal pump scheduling; the trade-offs are made between them and the response of the algorithm is visualized. The tank volume deficit and nodal pressure constraints are considered to be primary and kept active for all cases. The trade-offs are made for following four cases;

(a) Pump Switch Constraint is *Passive* & Electricy Tariff is *Constant*.

(b) Pump Switch Constraint is *Passive* & Electricy Tariff is Varying.

(c) Pump Switch Constraint is Active & Electricy Tariff is *Constant*.

(d) Pump Switch Constraint is Active & Electricy Tariff is Varying.

For above mentioned four cases, the developed program is applied to the network 100 times. In each run, generation number is selected to be 1000. After obtaining the whole outcomes, initially percentage of applicable results with respect to tank volume deficit constraint is handled. While considering the applicability; first, the results which give positive or negative tank volume periodicity violation lower than 1 m^3 (0.02%); then, the results with only positive tolerance are considered as appropriate. After obtaining

Table 3. Summary of analyses

		Percentage of Accepted Pump Schedules		Average Energy Consumption (kWh/day)		Minimum Energy Consumption (kWh/day)		Average Energy Cost ($/day)		Minimum Energy Cost ($/day)		Average Pump Switch Count	
Case No:1	**Pump Switch Constraint (Passive)**	87%	*43%*	486.21	*485.53*	477.09	*477.09*	48.62	*48.55*	47.71	*47.71*	17.29	*17.26*
	Electricity Tariff (Constant)												
Case No:2	**Pump Switch Constraint (Passive)**	95%	*42%*	490.19	*490.98*	480.08	*480.08*	40.87	*40.82*	28.85	*28.85*	16.13	*16.38*
	Electricity Tariff (Varying)												
Case No:3	**Pump Switch Constraint (Active)**	51%	*20%*	488.93	*488.69*	479.12	*480.13*	48.89	*48.87*	47.91	*48.01*	6.82	*6.80*
	Electricity Tariff (Constant)												
Case No:4	**Pump Switch Constraint (Active)**	62%	*34%*	491.35	*494.08*	477.18	*479.89*	42.72	*43.51*	23.32	*29.71*	6.68	*6.47*
	Electricity Tariff (Varying)												

Italic cells indicate the results of Positive Tank Volume Difference Tolerance

the feasibility criteria for pumping schedule alternatives;the outcomes are summarized according to their average and minimum energy consumptions, average and minimum energy costs and average pump switch numbers for both criteria. The summary of analyses is shown in Table 3 in six merged columns. Except first merged column, the left side indicates the applicable results of negative and positive tank volume deficits, while right side shows only the results of positive deficits.

The first merged column of **Table 3** indicates the percentage of accepted solutions (tank volume deficit **Table** 3 show the average and minimum energy consumptions of applicable pump schedules for already mentioned study cases. The average energy consumptions are visualized in **Fig. 5**. As can be seen from **Fig. 5**; introducing of both PSC and TAR to the problem, makes the energy consumptions higher. While both are passive or constant, the program gave out schedule alternatives resulting in lower energy consumptions. However, when these constraints are introduced into the problem step by step, the schedules become more consuming. When the impact of these constraints on energy consumptions is compared, varying TAR is slightly more significant than active PSC.

The fourth and fifth merged columns of show the average and minimum energy costs of accepted pump schedules for study cases. The average energy costs are visualized in **Fig. 6**. Contrary to **Fig. 5**; in **Fig. 6**, the average energy cost values are lower for case 2 and case 4. As varying tariff is introduced to the objective function; it makes the energy costs significantly lower than constant tariff case by running the pumps during hours with low energy price.

<0.02%); and these values are shown in **Fig. 4**. **Fig.** 4, reflects the effects of pump switch constraint (PSC) and electricity tariff (TAR). For first two cases, PCS is passive, and then it becomes active. As can be seen from the figure, by activating PSC in the objective function, the percentage of accepted solutions drops significantly. On the other hand; while the status of PSC remains the same (passive or active), the effect of TAR is controversial but less significant. As the TAR status, change from constant to varying; this made the percentage of accepted results become higher.

The second and third merged columns of

On the other hand, like **Fig. 5**; in **Fig. 6**, activating PSC increases the energy costs. When compared, the effect of TAR is notably higher than PSC on the energy cost objective. When the schedules summarized in **Fig. 6** are considered, although Case 2 give out lower energy costs, Case 4 sound more preferable from the operational reliability point of view.

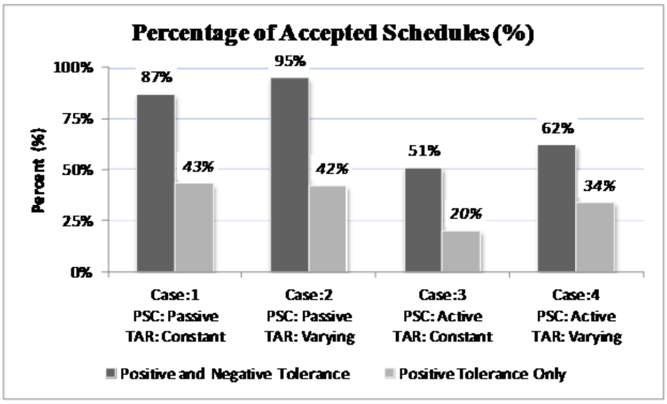


Fig. 4 Percentage of accepted pump schedules with respect to tank volume deficit.

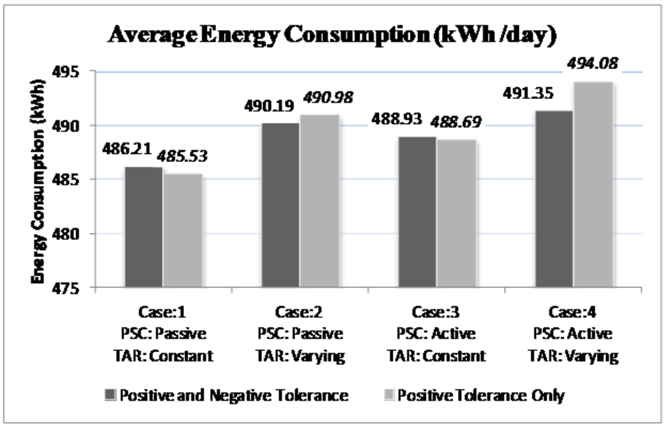


Fig. 5 Average energy consumptions of study cases.

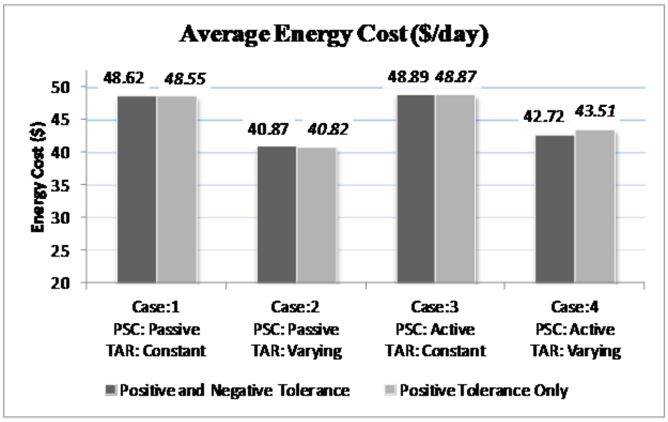


Fig. 6 Average energy costs of study cases.

The last merged column of **Table 3** shows the average number of pump switches for accepted schedules; and these values are drawn in **Fig. 7**. This figure clearly reflects the effect of PCS on the operational reliability of the pumping system. While PCS is passive it is obvious that the resultant pump schedules switches the pumps on and off excessively. When PSC is set to active, the pump runs get into groups that the number of switches drop significantly. For operational reliability point of view, the electricity tariff has also similar effect. As TAR is set to varying from constant, the number of pump switches drop. The effect of TAR is not that much prominent, when compared with PSC, however both constraints push the algorithm to result in more operationally reliable schedules. This phenomenon is the indication of energy price periods on the pump run durations. While varying tariff is included in the objective function, the algorithm tend to run the pumps during hours of cheaper energy price. As the cheap price hours are grouped, the algorithm tend to group the pump runs also. This situation reduces the number of pump switches and increases operational reliability of the system. This phenomenon is a supportive concern for utilization of electricity tariff, for the operational reliability point of view.

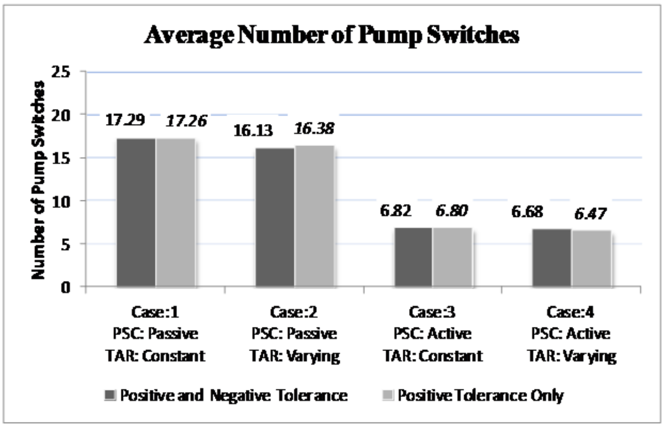


Fig. 7 Average number of pump switches.

Summary and Conclusions

This study represented a discussion of constraints on the optimization technique, for determining optimum pump schedule that will best meet the target hydraulic performance of the water distribution network for a given period of time considering both energy consumptions and operational reliability. A custom made program -integrated with EPANET network simulation software- is developed.

The program searches for the lowest operating consumption of a water distribution network combining Genetic Algorithms (GAs) with network simulation. Besides primary ones; three types of constraints are introduced to the problem; tank volume deficit, number of pump switches and electricity tariff using penalization techniques. With these constraints, the objective function evolved into its multi-objective form by including also operational reliability as another sub-objective. The methodology is applied by trading-off the pump switch constraint and electricity tariff on the case study network; N8-3 pressure zone of the Northern Supply of Ankara Water Distribution System.

The outcomes of the analyses indicate the effects of pump switch and electricity tariff constraints on the optimization objective. Existence of pump switch constraint pushes the algorithm to increase both energy costs and energy consumptions. This constraint makes the pumps run in long period which restrains the systems operational reliability. On the other hand; existence electricity tariff directly affects the energy consumption and energy costs. While using constant tariff, program results in lower consumptions with higher costs. Varying tariff usage reveal out the contradictory between high electricity consumption and low cost. Tariff has also an additive effect on operational reliability. Using of varying tariff makes the pumps run through longer periods and makes the operation of the system more reliable compared to constant tariff case. This effect represents novelty for the subject since no study has not point out this impact yet.

As pump scheduling addresses a multi-objective optimization problem, a perfect balance has to be implemented between the constraints. This study emphasizes the necessity on the utilization of electricity tariff and pump switch constraints for the energy cost minimization and operational reliability maximization objectives. The outcomes, point out the novel relationship between electricity tariff and operational reliability of pumping systems. Since energy efficiency is one of the major issues worldwide, the method presented in the paper needs to be implemented by infrastructure authorities.

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