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Increasing convergence rate in two-objective optimization of water distribution network with engineering judgment

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Abstract

Background: Water distribution networks (WDNs) are facilities that require massive investment and their optimization is very important. This study aimed to optimization and development of models for promoting WDNs with using engineering judgment. In this method, instead of controlling all system states, it is possible to search the optimal set of options based on engineering judgment and hydraulic and physical status of the system. Thus, the time to solve the optimization problem is greatly reduced, which is very important in widespread networks with many components. The case study was a WDN in western Tehran.

Methods: To reduce the calculation size and increase the convergence rate using engineering judgment, the parts of the network where there was no possibility of parallel piping was ignored. For other parts with a low pressure problem, parallel piping was defined. A FMGA and WaterGEMS hydraulic software were used to optimize the WDN. Cost minimization and pressure benefit maximization were the objective functions and the diameters of the pipes were considered to be the decision variables.

Results: The results of optimization the network showed that, the cost decreased 89.84% and the pressure in all nodes, except one node, reached within the standard range (26-60 mH_20). It included 2387 m of pipe with diameters of 100, 150, 200, 250, 350, 400 and 500 mm.

Conclusion: The results of optimization and modification of the network using engineering judgment confirm that the cost decreased significantly and the pressure level in all the nodes increased to above the allowable minimum pressure.

Keywords: Water, Judgment, Software, Pressure, Engineering

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Introduction

A water distribution network (WDN) is an important component of citizen welfare (1). It handles the transfer of water from a reservoir to the consumer and consists of a water supply, consumers, distribution pipes, valves and pumps. This infrastructure provides the basic needs of a society (2,3). Researches are interested in the optimization of WDNs (4). and have used the evolutionary algorithms such as the genetic algorithm (GA) (5,6), ant colony optimization (ACO) (7,8), shuffled frog leaping algorithm (SFLA) (9,10), simulated annealing (SA) (11), honey-bee mating optimization (HBMO) (12), harmony search algorithm (HS) (13,14) and particle swarm optimization (PSO) (15,16). These algorithms do not require calculation of the derivative of the objective function, but the probability of finding a global optimum solution is more than the classic algorithms (17). The problems raised in WDNs are highly complex, so traditional optimization methods used to solve them are time-consuming and require a large amount of computation memory. This has decreased the efficiency of traditional optimization methods. Because WDNs are large-scale and have a large number of variables, evolutionary algorithms are preferred because they take less time to solve the problem (4). Even Fuzzy logic has been used for assessment of water quality in WDNs (18). Many real-world engineering problems are multi-purpose and usually conflict. To find an optimal response in such cases is not possible. In these cases, a set of solutions must be found that can establish the relative balance between different objectives. This set of solutions, known as the Pareto front, allows the designer engineer to choose one solution according to the specific conditions.

When faced with multi-objective optimization, classic optimization methods are inefficient for three major reasons. First, most cannot find several solutions in a single run. In addition, multiple applications of these methods do not guarantee the generation of widely different Pareto optimal solutions. Finally, most of them are not efficient in multi-objective optimizations that deal with discrete variables (19).

Seyoum et al used a penalty-free multi-objective evolutionary optimization to solve a real life network (20). Wang et al evaluated low and high level hybrid algorithm on optimization of WDNs. They compared the number of runs, convergence and diversity to detect the final solution (21). Tang et al used multi-objective analysis to reveal the benefits of water transfer between two reservoirs (22). In many of these methods, single-objective optimization is used to minimize the cost of pipes as the target. Some studies also have focused on the reliability and stochastic modeling of the demand (23,24).

Walski stressed the need to develop new models based on minimization of network costs and maximization of net profits (25). Halhal et al were the first ones who optimized WDN using a multi-objective GA. They minimized cost and maximized profit using a structured messy genetic algorithm (SMGA) to solve the optimization problems (26).

Walters et al used the SMGA to optimize the “anytown” distribution network (27). Prasad and Park optimized a two-loop reference network using a multi-objective GA. Their objective functions involved decreased the cost and increased the reliability of the network (19).

Although optimization techniques are more common, engineering judgment and experience are necessary along with them. Optimization techniques usually can be used as a backing instrument for decisions and provide a better result when combined (28). Iglesias-Ray et al combined engineering judgment and a model optimizer (pseudo-GA) to increase the energy efficiency and manage leakage in the WDNs. Their optimization problem had more than 70 000 decision variables and was divided into three parts. The first part was preliminary analysis to define the criteria for replacing pipes and pumps. The second was the use of an optimizer model and the third part was the correct adjustment of the control valves, pressure relief valves and pumps replacement. Here, a proper combination of optimization techniques and manual adjustments based on engineering judgment has been used to solve the general problems of water supply networks (29). Khedr and Tolson obtained a Pareto front with optimal quality by relying on engineering judgment without the need for complex calculations (28).

In the current study, a two-objective FMGA was used to obtain the best solution with the lowest cost and the most pressure benefit with the help of engineering judgment in a Pareto front from the set of non-dominant solutions to optimize a WDN. The FMGA performance was evaluated using Bentley WaterGEMS V8i hydraulic software for the design and modification of WDNs with the engineering judgment on a real WDN in western Tehran.

In this study, a new method for reducing the rate of convergence, optimization and development of models for promoting WDN has been presented. Based on the proposed method, instead of controlling all system states in the optimization model, it is possible to identify and search for the optimal set of options based on engineering judgment and hydraulic and physical status of the system. Thus, the time to solve the optimization problem is greatly reduced, which is very important in widespread networks with many components.

firstly, the nodes with pressure deficiency was determined. Then the parts of the network for which there was no possibility of parallel piping (physical limitations in urban areas for new piping such as narrow roads and intersections with underground facilities) was ignored and for the other parts with the low pressure problem and the upstream pipes with the lowest diameter were doubled. This is done because the maximum head loss is due to the smallest pipe diameter. Finally, the node pressure with the performed changes was checked to ensure the sufficiency of the pipe parallelizing. If there is still pressure deficiency in that point, the next upstream pipe is considered for parallelizing. It makes the decision space smaller and makes it easier to find a solution in a reasonable time. Based on the proposed method, instead of controlling all system states in the optimization model, it is possible to identify and search for the optimal set of options based on engineering judgment and hydraulic and physical status of the system. From the analysis of the results, it was observed that use of engineering judgment gave better results.

This study shows that relying on engineering judgment can produce reasonable of the Pareto front of multi objective WDN design problems. The engineering judgment solution generated a high-quality result and was able to identify a more realistic number of changes in the WDN with a very small computational budget and properly pressure in nodes.

Methods

Engineering judgment approach

In the engineering judgment approach, the operation is broken into two phases to obtain an appropriate practical Pareto front, minimize the cost and maximize the pressure profit. First, engineers must identify all practical and possible solutions. The most important part of this step, after determination of the objective functions, is to identify the decision variables. Hydraulic network analysis was utilized to detect nodes with low pressure for which parallel pipes can be used. The use of an optimizer algorithm is the second step in which the Pareto front is obtained by engineering judgment that provides cost-effective and efficient solutions. If there is more than one objective function, there will be a set of solutions so-called Pareto-optimal solution or non-dominated solution (30). These solutions are superior to others in the search space; however, one must recognize that optimization is an auxiliary tool for design engineers and the designer must select the proper solution using engineering judgment and expertise (31).

Optimization of water distribution network

In this study, WDN optimization is solved with objective functions of the cost minimization and the pressure benefit maximization. This is classified as multi-objective problems. The Eqs. 1 and 2 are objective functions used by Bentley WaterGEMS V8i software to optimization (32). Diameters of pipes and velocity in the pipes are considered as the decision variables and optimization constraint, respectively. Energy conservation and continuity laws are the main constraints which are always respected by the software Bentley WaterGEMS V8i.

$$Minimize\ F1 = \sum_{k=1}^{DP} (C_k(d_k)L_k) \tag{1}$$

$$Maximize\ F2 = \sum_{k=1}^{ND} [a \sum_{i=1}^{NJ} (\frac{JQ_{i,k}}{JQTotal_k})(\frac{P_{i,k}-P_{i,k}^{REF}}{P_{i,k}^{REF}})^b] \tag{2}$$

In the Eq. (1), *DP* represents the total number of design pipes in the network and $C_k(d_k)L_k$ is the cost of the pipe *k* with the length *L* and diameter *d*.

And in the Eq. 2,

ND: The number of design states

NJ: The number of nodes

$JQ_{i,k}$: The demand at the node i in alternative k

$JQTotal_k$: The total of demand in alternative k

$P_{i,k}$: The calculation pressure at the node i in alternative k

$P_{i,k}^{REF}$: The required minimum pressure determined by the designer

a, b: a is the linear parameter and *b* is the parameter which is less than 1 (about 0.5) (32).

Optimization algorithm

GA is an evolutionary algorithms based on natural selection. It was initially completed by Holland and then by Goldberg. First in the GA, multiple answers are randomly generated to the problem (an initial population) for which each answer is called a chromosome. Next, following the selection of the better chromosomes, the GA operators are composed and mutated. Finally, the current population composes with the new population resulted from the chromosomes composition and mutation. In fact, to create a new generation, the competence level is calculated according to the purpose. Those with more competence are more likely to produce the next generation. This algorithm continues until the desired limitation is satisfied.

GA as one of the most important evolutionary algorithms plays an important role in optimization of the WDNs. This algorithm has always faced a lot of changes and reforms. Fast messy GA is one of the GAs and in here is utilized as the optimizer model. It can evaluate chromosomes that are not equal in terms of gene strings and can increase the convergence rate by decreasing the chromosomes length and eliminating undesirable genes. FMGA acts as a filter to remove undesirable genes so that the population only contains short chromosomes with desirable genes. The filtering process continues until the length of all chromosomes decreases to a desirable length. This algorithm resists falling into a local minimum, which improves its ability to solve problems in a short time. FMGA is safer than standard GAs to be deceived and converges better to an optimal solution (33).

Optimal solutions in GA depend on factors such as population size, cut probability, splice probability, mutation probability and, most importantly, computational search space. Bentley WaterGEMS V8i software which works based on the fast messy GA was used to optimize the WDN in this study.

Assessment of the proposed Model

Case study

The case study was a WDN in Tehran, the capital of Iran. Given that the number of pipes and nodes of the network was huge, the network was simplified by deleting pipes with small diameters located as branches in the network. The simplified structure of the network consisted of 181 pipes, 138 nodes, a reservoir with a maximum water level of 1324.21 m and 10 pressure relief valves (PRV) (Figure 1) (34).

Table 1 lists the characteristics of the network pipes. It consisted of 45 019 m of steel and ductile iron pipes. The population and area covered by the reservoir contained 113378 peoples and 659.18 hectares, respectively. The maximum hourly demand (at 1 PM) was 682 L/s and the minimum hourly demand (at 4 AM) was 361 L/s.

The network available for the future (horizon plan) was examined. For the horizon plan, the maximum and minimum hourly demands were 1023.07 and 536.69 L/s, respectively. This network needed to be optimized to satisfy the minimum and maximum pressure in the nodes. Ductile iron pipes were used to improve the network.

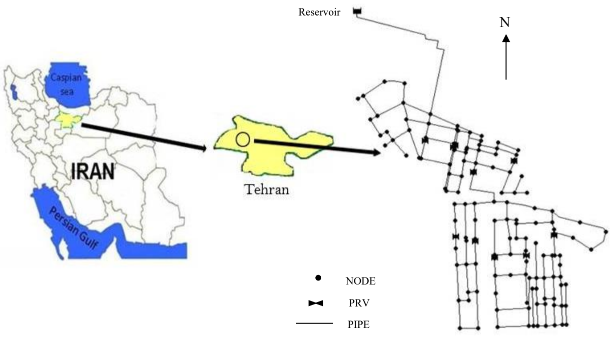

Figure 1. Layout of the WDS model (34).

Table 1. Characteristics of network pipes (34)

Material	Total length in the considered WDN (m)	Diameter (mm)
Ductile iron	835	60
	1170	80
	8052	100
	9681	150
	8718	200
	3263	250
	1836	300
	1438	350
	2290	400
	1130	500
	1714	700
Steel	7354	1200
	4513	900
Total	45019	

Nine commercial diameters were introduced to optimize the network (100, 150, 200, 250, 300, 350, 400, 500 and 600 mm at a cost of USD 30.53, 44.61, 60.79, 73.42, 92.76, 121.32, 145, 197.37 and 257.63 per unit length, respectively).

The network was examined under two conditions. In condition 1, parallel pipes were considered for all pipes except in the areas in which it was not possible and physical limitations. In condition 2, as is shown in Figure 2, parallel pipes were considered for pipes with low pressure problem and those that acted as pressure amplifiers in the mentioned pipes.

Results

After optimizing the maximum hourly demand at 1023.07 L/s, 20 solutions were obtained for each condition to optimize the network. These included new diameters for the parallel network pipes. In solution 16, 133 parallel pipes out of 167 predefined parallel pipes were selected. In solution 19, 13 out of 18 predefined parallel pipes were parallelized. In the creation of the scenario and its transfer to Bentley WaterGEMS, the effects of these diameters were imposed on the network.

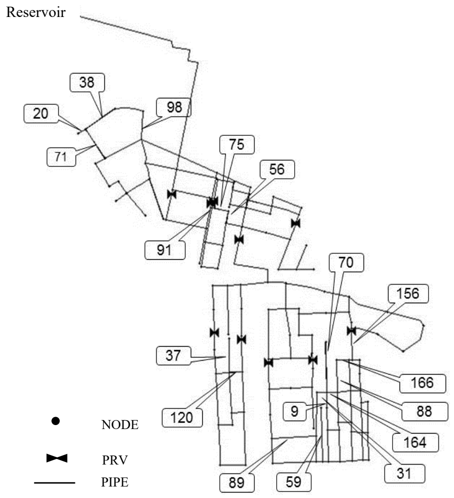

Figure 2. Layout of the WDS model in condition 2.

Figures 3a and 3b show the Pareto front obtained for the cost versus pressure benefit for both conditions. Table 2 shows 20 solutions for minimizing the cost and maximizing the pressure benefit for both conditions using 167 parallel pipes (condition 1) and 18 parallel pipes (condition 2). As seen, almost at the same total benefit (total benefit = 168.843 for condition 1and 168.915 for condition 2). Solution 16 (condition 1) and solution 19 (condition 2) have the permitted pressure and the lowest cost (total cost of condition 1 = US$2 325 798 and of condition 2 = US$236 188). As observed, condition 2 is economically more cost-effective than condition 1, as the cost of condition 2 decreased 89.84% compared to condition 1.

After the network and economic analysis and the control of diameters to meet the minimum hourly demand (536.69 L/s), it was seen that condition 2, using parallel pipes in areas of low pressure, improved the pressure rate. Table 3 shows the pressure before and after optimization and reveals that the existing pipes could not meet future

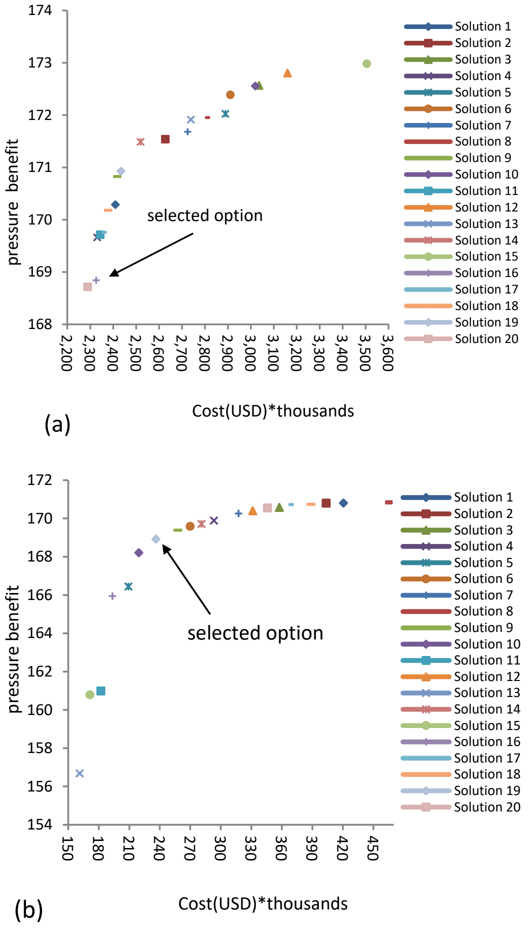

Figure 3. (a) Pareto front in condition 1 (b): Pareto front in condition 2

Table 2. Comparison of solutions in two conditions

Condition 1					Condition 2				
Solution	**Total cost (USD)**	**Pressure benefit**	**Maximum pressure (mH$_2$0)**	**Minimum pressure (mH$_2$0)**	**Solution**	**Total cost (USD)**	**Pressure benefit**	**Maximum pressure (mH$_2$0)**	**Minimum pressure (mH$_2$0)**
1	2409665	170.289	66.84	26.01	1	420504	170.801	66.72	26.05
2	2627280	171.54	66.82	26	2	403592	170.795	66.72	26.05
3	3035477	172.568	66.88	25.96	3	357456	170.577	66.72	26.04
4	2330004	169.662	67.07	25.91	4	293158	169.885	66.72	25.99
5	2889061	172.026	66.86	26.06	5	209102	166.435	66.72	25.82
6	2910663	172.389	66.77	26	6	269917	169.587	66.72	26.02
7	2724399	171.682	66.85	25.99	7	317362	170.258	66.72	25.99
8	2804143	171.952	66.75	25.96	8	462332	170.84	66.72	26.05
9	2417678	170.825	66.84	25.98	9	257790	169.376	66.72	25.85
10	3019325	172.558	66.89	25.98	10	219411	168.21	66.72	25.86
11	2343518	169.712	66.72	25.96	11	182057	160.983	66.72	24.93
12	3159449	172.806	66.89	25.9	12	331278	170.396	66.72	26.02
13	2738521	171.916	67.19	25.96	13	161244	156.679	66.72	24.17
14	2518845	171.489	66.84	25.96	14	280920	169.715	66.72	26.05
15	3505036	172.984	66.85	26.04	15	171257	160.788	66.72	24.96
16 (Selected option)	**2325798**	**168.843**	**66.85**	**26.06**	16	193443	165.939	66.72	25.43
17	2354281	169.759	66.79	25.84	17	367501	170.718	66.72	25.99
18	2377897	170.18	66.71	26.09	18	388651	170.732	66.72	26.05
19	2433348	170.928	66.84	25.95	**19 (Selected option)**	**236188**	**168.915**	**66.72**	**26.05**
20	2289175	168.717	66.85	26.05	20	345902	170.542	66.72	25.99
Control for minimum hourly demand			69.02	26.28	Control for minimum hourly demand			68.84	26.33

demand. This problem could be resolved using parallel pipes. According to the local standards (35), the network must be designed in such a way that the minimum and maximum pressure in the nodes to be satisfied. The allowable limit of pressure changes in the nodes is 26 to 60 mH_2O (in certain circumstances). As observed, at 4 nodes (123, 124, 125 and 126) the pressure is higher than the standard level. In condition 1, the pressure at the node 124 is 66.72 mH2O. Of course, the node of 124 was located in pressure zone 1 with a static pressure of 69.91 mH_2O. Such pressure is not unexpected because the nominal pressure of the pipes applied to the network was 10 atm, which makes the reported pressures acceptable.

Table 4 shows that the cost of condition 2 decreased 89.84% compared to condition 1.

Table 5 shows the nodes pressure percentage before and after optimization. As observed, the pressure percentage of less than 26 mH_2O has reached zero after optimization. But in some nodes, it is 2.9% and 0.72% in conditions 1 and 2, respectively.

Figure 4 shows that the pressure in the nodes is higher than the standard level in the two conditions (nodes 123, 124, 125 and 126 in condition 1 and 124 in condition 2). Figure 5 shows the diameter and amount of pipe to be used in the network for both conditions. Solution 16 in condition 1 includes 31304 m of pipe with diameters of 100, 150, 200, 250, 300, 350, 400, 500 and 600 mm and solution 19 in condition 2 includes 2387 m of pipe with diameters of 100, 150, 200, 250, 350, 400 and 500 mm. Comparison of conditions 1 and 2 confirms that the implementation of solution 19 is more affordable.

Discussion

In this study, the FMGA and WaterGEMS hydraulic software were used to optimize a WDN in western Tehran with the help of engineering judgment. It was optimized using the objective functions of cost minimization and pressure benefit maximization under two conditions.

Table 4 shows that the costs decreased 89.84% with the use of engineering judgment. Using this approach, for reducing calculation volume the parts of the network with no possibility of parallel piping (physical limitations such as narrow roads and intersections with underground facilities) was ignored. In parts experiencing low-pressure, parallel pipes were defined.

One-way analysis of variance (ANOVA) was used to compare the mean of the numbers obtained for the pressure variable in three options, including the existing pipes, condition1 and condition 2.

The mean of the pressure in the existing pipes has been 34.45 with the standard deviation of 16.88, in condition 1, 44.36 with the standard deviation of 9.60 and in condition 2, 41.55 with a standard deviation of 8.91. The results of analysis indicate that there is a significant difference between the three groups in the amount of pressure ($P<0.001$). Scheffe test analysis was used to find out what differences were observed among the groups.

It was observed that the mean pressure in the existing

Table 3. Comparison of nodes pressure before and after optimization in both conditions

Label	Existing pipe	Condition 1	Condition 2	Label	Existing pipe	Condition 1	Condition 2	Label	Existing pipe	Condition 1	Condition 2
		Solution 16	Solution 19			Solution 16	Solution 19			Solution 16	Solution 19
	Pressure (mH_2O)	Pressure (mH_2O)	Pressure (mH_2O)		Pressure (mH_2O)	Pressure (mH_2O)	Pressure (mH_2O)		Pressure (mH_2O)	Pressure (mH_2O)	Pressure (mH_2O)
1	27.7	27.7	27.7	47	29.9	37.33	39.32	93	47.99	48.01	48
2	-3.4	34.73	35.96	48	20.76	40.8	42.98	94	48.46	48.47	48.46
3	25.43	27.44	26.21	49	-9.58	38.07	36.3	95	56.13	56.35	56.12
4	26.01	26.06	26.05	50	37.77	38.25	38.18	96	47.47	48.85	47.49
5	25.85	26.07	26.08	51	37.48	38.23	38.12	97	40.9	50.78	41.34
6	26.15	26.12	26.13	52	35.86	40.56	35.97	98	50	50.27	49.99
7	28.32	27.24	28.49	53	13.34	44.23	41.77	99	50.09	50.42	50.08
8	31.58	31.69	31.58	54	25.99	40.41	40.75	100	57.16	57.45	57.18
9	24.45	27.08	26.71	55	44.32	44.74	44.2	101	38.86	52.38	38.88
10	24.93	27.15	26.77	56	35.04	37.43	40.95	102	58.2	58.51	58.24
11	27.64	27.64	27.64	57	34.86	37.45	40.54	103	58.87	58.95	58.94
12	30.1	31.35	30.85	58	13.09	45.19	41.97	104	44.29	52.91	44.58
13	-3.35	34.21	36.66	59	45.53	45.54	45.58	105	39.29	52.84	39.3
14	26.43	31.3	26.55	60	21.74	42.45	42.05	106	51.92	52.23	51.91
15	31.96	33.98	31.97	61	8.54	45.68	37.62	107	52.44	52.46	52.45
16	36.66	36.66	36.66	62	13.18	45.72	39.55	108	52.12	53.37	52.12
17	1.94	38.38	41.3	63	14.51	46.96	40.1	109	43.32	53.84	43.81
18	27.79	31.22	28.81	64	39.3	41.57	39.42	110	59.89	59.93	59.93
19	37.3	37.3	37.3	65	31.13	30.54	31.13	111	59.48	59.77	59.52
20	30.51	30.97	30.62	66	9.6	46.81	38.67	112	41.4	55.2	41.61
21	37.24	37.24	37.24	67	15.94	47.9	40.92	113	37.72	55.44	37.94
22	0.82	38.15	29.9	68	10.62	47.36	39.72	114	45.05	56.05	45.32
23	14.44	35.27	38.39	69	42.76	45.47	43.28	115	49.92	55.86	49.91
24	34.21	34.57	34.12	70	16.87	48.7	41.8	116	37.94	55.99	38.16
25	37.19	37.27	37.14	71	37.68	38.46	37.68	117	53.52	55.96	53.52
26	33.03	33.06	33.06	72	47.25	47.63	47.08	118	50.84	56.5	50.84
27	28.8	29.58	28.8	73	44.58	46.77	44.79	119	56.21	56.54	56.18
28	4.27	40.64	43.43	74	17.8	49.28	46.49	120	56.37	56.71	56.36
29	35.13	36.37	35.9	75	43.5	44.19	44.04	121	57.14	57.51	57.14
30	35.63	38.25	36.2	76	50.71	51.53	50.76	122	57.87	58.18	57.86
31	40.61	40.41	40.7	77	18.43	51.21	44.54	123	52.77	65.39	52.76
32	35.1	38.4	35.61	78	46.84	50.89	46.27	124	66.71	66.85	66.72
33	35.4	38.42	35.9	79	44.38	45.02	44.85	125	56.4	66.7	56.39
34	33.26	41.07	36.88	80	19.51	52.58	45.05	126	55.69	60.53	55.4
35	15.73	39.96	42.59	81	52.1	52.45	52.01	127	46.06	50.46	45.8
36	37.53	39.53	37.71	82	32.23	45.66	32.25	128	40.56	44.02	40.39
37	37.92	40.06	37.93	83	20.29	53.14	45.63	129	46.46	51.5	46
38	-11.45	36.26	34.35	84	52.88	53.03	52.87	130	37.29	37.35	37.26
39	17.15	43.86	39.46	85	45.11	46.53	45.1	131	50.57	50.93	50.47
40	4.88	41.69	34.45	86	28.61	47.03	28.83	132	44.85	45.76	45.24
41	10.69	44.33	40.95	87	45.26	46.73	45.29	133	48.01	48.18	47.96
42	33.5	42.61	37.96	88	53.75	53.84	53.78	134	33.25	38.09	35.34
43	16.34	44	39.26	89	54.09	54.08	54.11	135	32.9	35.79	32.91
44	-11.83	35.22	32.99	90	37.32	48.09	37.7	136	28.54	31.52	29.3
45	34.66	39.36	34.78	91	37.6	47.46	38.04	137	26.49	26.43	26.45
46	-9.68	37.37	35.14	92	47.74	47.74	47.74	138	56.61	56.63	56.64

pipes was significantly lower compared to conditions 1 and 2 ($P<0.001$). Also, the average pressure in condition 1 is 2.80 points more than the condition 2. But the difference between these conditions is not statistically significant ($P = 0.170$).

According to the results of analysis, due to the lack of significant difference in pressure between conditions 1 and 2, for choosing the ideal solution, the lowest cost and the number of nodes outside the normal range can be chosen as selection criteria.

As shown in Table 3, in condition 1, four nodes (nodes 124,123, 125 and 126), and in condition 2 only the node 124 are outside the normal range. Also, economically, condition 2 is more cost- effective than the condition

Table 4. Comparison of costs and total benefit in both optimizations

Parameters	Condition 1	Condition 2
Total cost (USD)	2325798	236188
Total benefit	168.843	168.915

1. In condition 1, there are nine pipe sizes with 331 304 m piping, but in condition 2 there are seven pipe sizes with 2387 m piping. According to Table 4, the cost of condition 2 dropped 89.84% than the condition 1. Thus, the condition 2 is preferable than the condition 1.

The results indicate that engineering knowledge and experience must be combined with optimization techniques to provide the best solution.

Iglesias-Rey et al employed engineering judgment and a model optimizer (pseudo-GA) to improve the energy efficiency and management of leakage in WDNs. The results showed that the total cost reached from €4 942 793 to €1 252 085. In fact it decreased approximately 3.9 times with a proper combination of optimization techniques and manual adjustments relying on using engineering judgment (29).

Khedr and Tolson (28) compared optimization techniques with an engineering judgment approach to design of WDN. They solved a simplified version of the Battle of Background Leakage Assessment for Water Networks (BBLAWN) problem using both the engineering judgment approach and a multi objective optimization algorithm, and compared the corresponding Pareto fronts. Their study shows the engineering judgment solution generated a high-quality result to identify a more realistic number of changes in the WDN (about 10% of WDN) compared with BBLAWN teams based on global optimization algorithm (27).

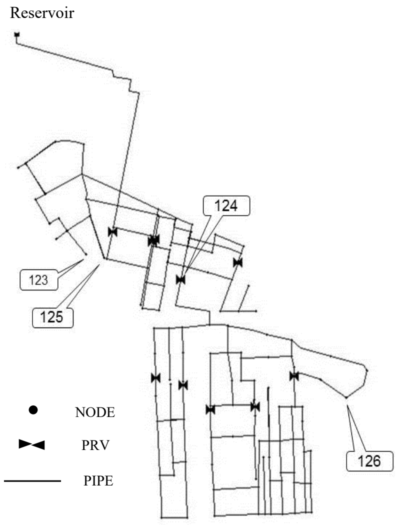

Figure 4. The nodes with the pressure higher than the standard level in two conditions.

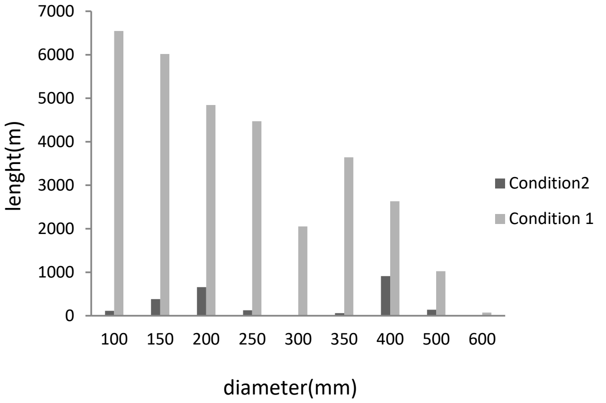

Figure 5. The diameter and amount of the proposed pipes in two conditions.

Algorithm settings for the two conditions are: Population size: 240, cut probability: 1.8, splice probability: 80, mutation probability: 0.9, Max.trials: 30000.

Matthews et al showed the engineering judgment approach could provide a very good Pareto front. Moreover, this approach coupled with a heuristic global optimization algorithm can yield even better results than engineering judgment alone (36).

Conclusion

In engineering judgment approach, the operation was broken into two phases to obtain an appropriate practical Pareto front for minimizing the cost and maximizing the pressure benefit. First, engineers must identify all practical and possible solutions. The most important part of this step after determining the objective functions is to identify decision variables and decrease the search space. The second step includes using an optimizer algorithm by which the Pareto front is obtained with the help of engineering judgment to produce solutions which are cost-effective and efficient.

Table 5. Comparison of the nodes pressure percentage before and after the optimization of the network

Pressure limit (mH_2O)	Pressure (%) with the existing pipe	Pressure (%) The first condition	Pressure (%) The second condition
		Solution 16	Solution 19
<26	25.36	0	0
<40	35.51	36.23	47.83
<50	18.84	31.88	32.61
<60	19.57	28.99	18.84
<70	0.72	2.9	0.72

Many models of WDNs optimization perform designing based on minimizing the cost that leading to a pressure close to the minimum allowable pressure and decrease of the network performance. In this study, the multi-objective fast messy GA and Water GEMS V8i hydraulic software were used to optimize a real WDN in the western Tehran with the help of engineering judgment. This approach decreased the search space to produce the best possible solution with the lowest cost and the most pressure benefit using a Pareto front from a set of non-dominant solutions. To reduce the volume of computation the parts of the network for which there was no possibility of parallel piping was ignored and parallel piping was defined for other parts with low pressure. The results of optimization and modification of the network confirm that, with the help of engineering judgment, the cost decreased 89.84% in the real network and the pressure level in all the nodes increased to above the allowable minimum pressure.

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Ethical issues

It is confirmed that this manuscript is the original work of the authors. It has not been published, nor is it under review in another journal, and it is not being submitted for publication elsewhere.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

All authors contributed equally and were involved in the study design, data collection, analysis, and interpretation of the data. All authors critically reviewed, refined, and approved the manuscript.

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