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Compared To optimize of Water Distribution Networks with Two Methods Based only on Costs and Reliability Varies

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ABSTRACT

This paper introduces a method for optimal design of water distribution networks with desired reliability. In this paper, using genetic algorithms presents some methods for the optimization of water supply networks to which, in addition to common specifications in water supply networks, network reliability has also been applied in it. Specifications of optimization include minimum and maximum pipe diameters with regard to their availability in the market, minimum and maximum speeds in the pipes, minimum and maximum pressures in the nodes, and one of the scales of reliability based on optimization method. The decision making variable which must be determined in the optimization process is pipe diameter. This degree of reliability is given to the computer software program as an input constraint. Moreover, the program has the capability to design the optimal network by other degree of reliability. The results show that networks designed accordingly has good reliability and cost is acceptable.

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INTRODUCTION

Until several years ago to economically supply network design would minimize its cost. But now, another important goal, other than minimizing their high expenses, which should be taken into account, is the reliability of these networks. These two goals (minimal design expenses and reliability) form a Pareto front against each other. In customary methods, the goal of optimizing water supply networks is in a way in which specifications related to the speed of flow and pressure in the nodes are observed.

The history of designing urban water distribution networks using new optimization methods goes back to thirty years ago. Prior to that most of the designs were based on engineering judgment or trial and error methods. In this way, it is natural that due to the complexity and extent of decision space of issues related to water distribution networks, lack of optimization in these designs be expectable. Therefore, improving design methods and using optimization methods, especially the ones in which reliability is included too, was inevitable. In the following its history is reviewed.

Alprovitezand Shamir (1997) presented a design method for the first time, which was based on linear programming. With this method the fundamentals of mathematics entered water distribution network designs and in this way, it introduced new horizons to the researchers and designers. To reform the traditional design methods using gradient linear programming Alprovitezand Shamir (1977) directly entered flow equations to an LP optimization model. In that study, choosing optimum size for different network components (diameter of pipes, capacity of pumps, diameter of valve, and size of reservoir) in normal and critical demand conditions was considered as the purpose of optimum design. Then, using LP method for designing the network was completed and generalized. Fujiwara and kang (1990) suggested two-phase decomposition method for designing water distribution network. In the first phase of the presented method in their study a local optimum response using gradient nonlinear programming method is determined. Then, this response enters the second phase and improves and this iterative process continues till the ultimate response becomes stable. However, it should be noted that the issue of optimizing water distribution network is essentially nonlinear, so that to solve this, some of the researchers tried to make linear relationships and some others used different types of NLP (nonlinear

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programming) methods; but in these methods decision variables are considered continuous and lead to presenting continuous diameters which should be replaced with the discontinuous diameters available in the market. This diameter conversion not only affects the revised response to be optimum, but also sometimes questions meeting hydraulic limits.

The other researchers who used linear programming method were: Gupta (1969), Gupta and Hassan (1972), Quindry (1981), Bhave and Sonak (1992). Other researchers such as Chiplunkar (1986), Walski (1987), Ormsbee (1989), Samani and Naeeni (1996) used nonlinear optimization method. Samani and Mottaghi (2006) used integer linear programming method. Samani and Zangeneh (2010) invented a mixed linear optimization method of real and integer numbers which was of a good speed and accuracy. Savic and Walters (1997) suggested using evolutionary and analytical methods such as Genetics Algorithm. In general, evolutionary and analytical methods are very efficient for optimizing nonlinear problems and it is not necessary to linearism relationships or to calculate partial derivatives Cunha and Sousa (1999) used cooling the metal optimization method. Samani and Haghighi (2011) used hybrid optimization method in which mixed optimization of linear real and integer numbers are integrated with genetics algorithm. In abovementioned cases decision variables are usually pipes diameters and the discharges in inputs are previously determined.

Material and Model:

Diameters of pipes is the only optimization variable for water supply networks with tanks of a constant and specified height. The objective function is defined in equation (1):
Objective function = cost of pipes

$$TC = \sum_{i=1}^{np} D_j L_i C_{pj} + Constraints \tag{1}$$

In which:

TC :is the objective ،function D_j : The pipe diameter، L_i : The pipe length، C_{pj} :The cost of the unit length of pipe with diameter D_j ، np : The number of pipes، j : is selected from the table of pipes that are to be used.

Variables that must be optimized in decision making so that the above-mentioned objective function can be minimized are the diameters of the pipes under the constraints of pressure and speed. Moreover, where one of the values of reliability, coefficient of Resiliency, or variance of discharge distribution is dictated to the network, the reliability constraint is applied to the equations as needed.

Constraints:

The constraints involved in the problem include the pressure constraint, the speed constraint, andthe constraints of reliability.

Pressure constraint:

Pressure constraint at the nodes must be in a range of minimum and maximum values, and is expressed in the form of equation (2)

$$\frac{P_i}{\gamma} \le \frac{P_{\max}}{\gamma}$$
$$\frac{P_i}{\gamma} \ge \frac{P_{\min}}{\gamma} \tag{2}$$

In which:

P_k :Stands for the pressure in node K in meters، γ : The mass volume density of water in kilograms per cubic meter، $H_{\min}$:The minimum allowable pressure in meters، $H_{\max}$:The maximum allowable pressure in meters.

Speed constraint:

Speed in pipes must be in a range of minimums and maximums, and is expressed in equation (3)

$$V_M \le V_{Max}$$
$$V_n \ge V_{\min} \tag{3}$$

In which:

$V_{\min}$:The minimum allowable speed in the network in meters per second، v_i : Represents the speed in pipe I expressed in meters per second، V_{Max} :The maximum allowable speed in the network in meters per second.

Reliability constraint:

If the network is designed based on a specific degree of reliability, this is introduced to the program as constraint in the form of equation (4)

$$\mathrm{Rel} > (\mathrm{Rel})_{selected} \tag{4}$$

In which:

Rel :Stands for the reliability coefficient of the network, $(\mathrm{Rel})_{selected}$:The minimum reliability coefficient the user has in mind for the network.

The objective function for optimizing water supply networks by using only on cost

The objective function for this optimization is defined in the forms of the following equations:

$$\begin{aligned} TC = \sum_{i=1}^{np} D_j L_i C_{pj} + Pen_1\left[\max\left(0,\, H_{\min} - {P_k}/{\gamma}\right)\right] + Pen_2\left[\max\left(0,\, {P_k}/{\gamma} - H_{\max}\right)\right] \\ + Pen_3\left[\max\left(0, V_{\min} - V_i\right)\right] + Pen_4\left[\max\left(0, V_i - V_{\max}\right)\right] \end{aligned} \tag{5}$$

In which:

Pen : Is representing penalty functions.

The objective function for optimizing water supply networks by using the reliability constraint

The objective function for this optimization is defined in the forms of the following equations:

$$\begin{aligned} TC = \sum_{i=1}^{np} D_j L_i C_{pj} + Pen_1\left[\max\left(0,\, H_{\min} - {P_k}/{\gamma}\right)\right] + Pen_2\left[\max\left(0,\, {P_k}/{\gamma} - H_{\max}\right)\right] \\ + Pen_3\left[\max\left(0, V_{\min} - V_i\right)\right] + Pen_4\left[\max\left(0, V_i - V_{\max}\right)\right] + Pen_5\left[\max\left[0, (\mathrm{Rel})_{selected} - \mathrm{Rel}\right]\right] \end{aligned} \tag{6}$$

In which:

$$\mathrm{Re}l = R_v \times F_t \times F_n \tag{7}$$

In which:

$\mathrm{Re}l$:Stands for the reliability coefficient of the network, R_v : The coefficient of the volumetric reliability of the network، F_t :The time factor، F_n :The node factor.

$$R_v = \frac{\sum_s \sum_j V_{js}^{avl}}{\sum_s \sum_j V_{js}^{req}} = \frac{\sum_s \sum_j Q_{js}^{avl} t_s}{\sum_s \sum_j Q_{js}^{req} t_s} \tag{8}$$

In which:

V^{avl} :represents the available volume، V^{req} :The required volume، Q^{avl} :The available discharge، Q^{req} :The required (demanded) discharge، t_s : The cycle time، j : The index number of the node.

$$F_t = \frac{\sum_s \sum_j a_{js}\, t_{js}}{JT} \tag{9}$$

In which:

J :Stands for the total number of the nodes in the network، T :The total cycle time of network analysis (T = $\sum t_s$)، a_{js} :The coefficient that is dependent on the ratio of discharge $\left(\frac{Q_j^{avl}}{Q_j^{req}}\right)$

If the ratio $\left(\frac{Q_j^{avl}}{Q_j^{req}}\right)$ is bigger than or equal to 0.5, the value of a_{js} is 1; otherwise, the value of a_{js} will be 0.

$$F_n = \left[\prod_{j=1}^{J} R_{nj} \right]^{1/J} \tag{10}$$

In which:

R_{nj} :Represents the factor of reliability in each node, which is the ratio of the total available outflow to the required outflow in the node during all periods.

This ratio is calculated using equation (11)

$$R_{nj} = \frac{\sum_s V_{js}^{avl}}{\sum_s V_{js}^{req}} = \frac{\sum_s Q_{js}^{avl} t_s}{\sum_s Q_{js}^{req} t_s} \tag{11}$$

Note: all the parameters in the above equation were introduced in the definition of the volumetric reliability factor (R_v).

Simultaneous hydraulic and optimization analysis:

For all states of optimizations (only on cost and varying degrees of reliability)the EPANET software was used in the hydraulic analysis of the network. For optimization analysis, a software program based on the genetic algorithm was written and combined with the EPANET software, and calculations were made back and forth between these two.

Optimization algorithm of water distribution networks with tanks of constant height based only on cost or a specified degree of reliability

1- Input data such as network properties including consumptions in nodes, the diameter and material of pipes (based on which the factors of Haizen –Williams or Darcy-Weisbach are determined), the values of the reservoirs, pumps properties and the optimization parameters of genetics algorithm including limits and constraints, primary population, the population of each generation, maximum repetitions, mutation rate, and penalty parameters and the costs of unit length of the pipes with different diameters, the cost of consumed electricity based on KW/h, the coefficients of equation, the cost of pump based on power and interest rate, are given to the software.

2- Genetics algorithm program runs and accidentally based on the number of population, the original program is chosen, and the series of diameters and discharges of pumping stations of network feeders for the pipes generates and are given to the program.

3- EPANET software for all the selected diameters by genetics algorithm in step (2) runs and using this software pressure in nodes, discharge in pipes, flow velocity in pipes, and pipe's energy loss are calculated.

4- Calculate minimum cost or reliability and the cost (i.e., the objective function includes the case of) Series executed in EPANET initial population according to input data relating to the cost of calculated for all series of pipe If the reliability of the distribution is less than a specified amount of fines to be imposed.

5- Equal to the first generation of the series with the least cost arrange in order and consecutively (in an ascending way).

6- Genetics algorithm program accidentally divides the series of each generation in two.

7- The generations (decision parameters such as diameters) from coupling are sent to EPANET software (step (3)) for hydraulic analysis and steps (3) and (4) are repeated once again. Then using genetics algorithm program the results are once again arranged in an ascending way.

8- Mutation regarding the mutation rate given to the program is applied. In this way the mutated genes are developed and new series are generated and steps (3) and (4) of the program run once again and the results are arranged in an ascending way one more time and again return to step (6). The abovementioned operation repeats equal to the number of defined cycles in inputs (maximum of repetitions).

Example of a water supply network:

The distribution network studied in this example, which is one of the most famous problems that are solved in the area of optimizing distribution networks, is related to the Alprovitez network. The only optimization variables considered in this network are the diameters of the pipes and the height of the constant tank. Figure (1) presents the statement of the problem and the lay- out of network elements, and Tables (1) to (3) the related characteristics of the pipes, the nodes, the diameters, and of the constraints. The Hazen-Williams coefficient of 130 is considered for all of the pipes. Moreover, all of the nodes are in the same elevation contour.

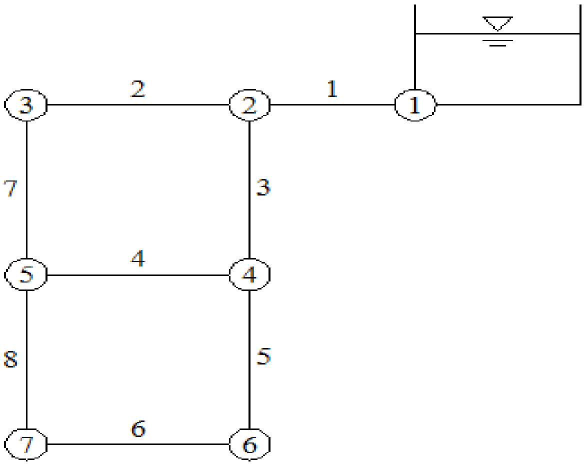

Fig. 1: The Alprovitez water supply network with 8 pipes.

Table 1: Characteristics of the nodes in the example.

Number of nodes	Elevation (m)	Discharge used $\left({}^{Lit}/_{Sec}\right)$
1	210.0	0.0
2	150.0	27.8
3	160.0	27.8
4	155.0	33.3
5	150.0	75.0
6	165.0	91.7
7	160.0	55.6

Table 2: Characteristics of the pipes in the example network.

D (in)	Cost ($/m)	D (in)	Cost ($/m)
1	2	12	50
2	5	14	60
3	8	16	90
4	11	18	130
6	16	20	170
8	23	22	300
10	32	24	550

Table 3: Constraints of the example network.

Type of Restriction	Allowable pressure (m of water)
minimum	30
Maximum	100

Solution:

Information regarding the example is introduced to the designed software input and the program is run on this information.

1. *Optimizing the network based only on costs:*

First application-specific research networks based only on cost optimization and the results are compared with results from other researchers that the results in Tables (4) to (6).

2. *Optimizing the network based on specified and defined degrees of reliability:*

Here, the network is first optimized using the objective function of minimizing costs and the constraint of a specified degree of reliability intended by the user for the network. These operations are repeated for the different degrees of reliability the user has in mind, and, finally, the diagram of the corresponding costs against the related degrees of reliability (the solution set) is drawn. Results of the optimization performed against different degrees of reliability are presented in Table (5), and the Pareto cost curve against the degree of reliability in Figure (2).

Table 4: Cost-based optimization of the network as an example.

Columns Number	1	2	3	4	5	6	7	8
Method name	Savic & Walters (1997)	Abebe & Solomanite (1998)				Cunha & Sousa (1999)	Samani & Naeeni (2010)	Kazemi nejad (2013)
Number of pipes	GA1	GA	ACCOL	CRS4	CRS2			
1	18	18	22	18	18	18	18	18
2	10	14	18	16	10	10	10	10
3	16	14	20	14	16	16	16	16
4	4	1	3	2	4	4	4	4
5	16	14	16	14	16	16	16	16
6	10	1	4	1	10	10	10	10
7	10	14	18	14	10	10	10	10
8	1	12	16	10	2	1	1	1
Cost(1000*$)	419.0	424.0	447.0	439.0	422.0	419.0	419.0	419.0

Table 5: Node pressure values(m) in the Optimal network example.

Columns Number	1		2	3	4	5	6	7	8
Method name	Savic & Walters (1997)		Abebe & Solomanite (1998)				Cunha & Sousa (1999)	Naeeni & Samani (2010)	Kazemi Nejad (2013)
Nodes Number	GA1		GA	ACCOL	CRS4	CRS2			
2		53.29	53.21	57.45	53.21	53.21	53.29	53.24	53.16
3		30.48	36.62	45.59	39.79	30.50	30.48	30.45	30.40
4		43.48	43.92	51.65	43.89	43.36	43.48	43.44	43.26
5		33.84	42.01	54.31	45.22	33.92	33.84	33.79	33.8
6		30.47	31.51	40.32	31.47	30.30	30.46	30.43	30.18
7		30.56	30.01	42.86	30.34	30.25	30.56	30.53	30.05

Table 6: Design speed (m /sec) in the pipe of the optimal network example.

Columns Number	1	2	3	4	5	6	7	8
Method name	Savic & Walters (1997)	Abebe & Solomanite (1998)				Cunha & Sousa (1999)	Naeeni & Z.Samani (2010)	kazemi nejad (2013)
Number of pipes	GA1	GA	ACCOL	CRS4	CRS2			
1	1.90	1.90	1.27	1.90	1.90	1.90	1.90	1.90
2	1.85	1.59	0.94	1.22	1.84	1.85	1.85	1.83
3	1.46	1.26	0.64	1.27	1.47	1.46	1.46	1.47
4	1.12	0.31	0.34	0.34	1.10	1.12	1.12	1.10
5	1.14	0.93	0.73	0.93	1.14	1.14	1.14	1.14
6	1.10	0.30	0.32	0.29	1.12	1.10	1.10	1.12
7	1.30	1.31	0.77	1.31	1.29	1.30	1.30	1.28
8	0.31	0.76	0.41	1.09	0.46	0.31	0.31	2.19

Table 7: Reliability against optimal costs of the example network.

Row	Reliability ($\mathrm{Re}l$)	Dollar-cost pipe networkoptimization ($Cost$)
1	0.51	419000
2	0.59	446000
3	0.63	457000
4	0.67	462000
5	0.76	464000
6	0.78	473000
7	0.83	479000
8	0.88	487000
9	0.92	496000
10	0.96	602000

Conclusions:

By comparing the results of the computer program with results from other researchers of this study found that the application of this research is too accurately and quickly. Also constraint to the objective function of reliability, with some additional cost of the network can be designed for consumers with good satisfaction. Because Excessive concentration of design models on minimizing construction costs without considering the efficiency, or reliability, factors of the network has been the main reason for the inefficiency of these models in recent years. This one-dimensional approach of reducing costs may result in having networks that are inefficient, do not provide the required pressure, and fail to satisfy the needs of each node when one of the pipes fails and is taken out of the operational orbit. Therefore, in designing networks, besides considering the minimization of costs as a main goal, the reliability of the network should be defined as one of the other main goals. Based on this, in the objective function and, consequently, in the designed software introduced in this article, the index of reliability, were considered in the design of a reliable and optimal network. The obtained (Pareto) curve of the solution set starts at the point of minimum costs and minimum reliability, which is the optimization point of the network based only on costs.

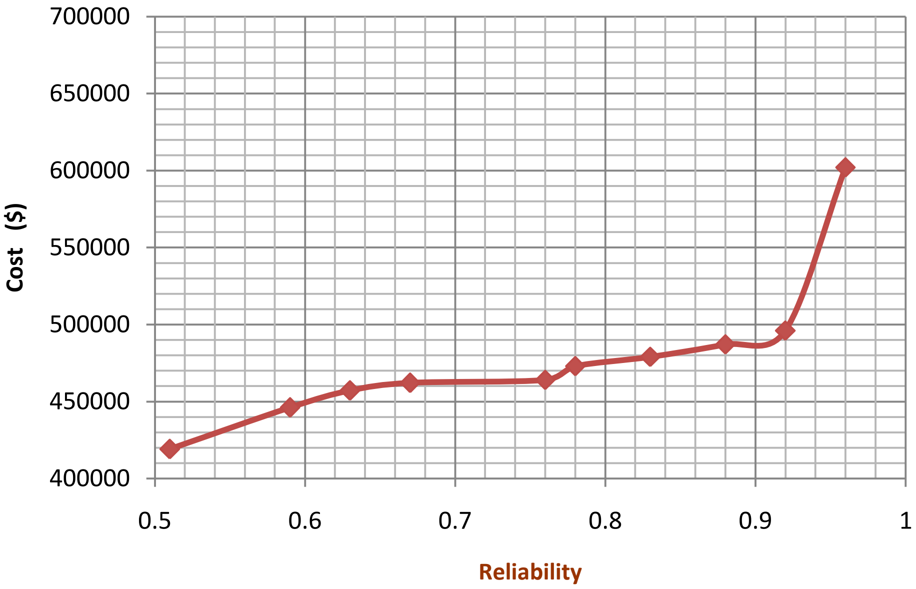

Fig. 2: The reliability curve against optimal costs of the example network.

In fact, this point is related to the design of a network with minimum costs irrespective of its reliability, a design that was used in the past several decades. From this point onward, the degree of reliability of the network rises and, hence, network costs increase until the end of the curve, where the optimal network will have the maximum reliability and the highest design costs. Obviously, the first point in the curve is very desirable with respect to costs because an optimal network designed at this point will have the minimum costs, but its reliability and efficiency will be less than those optimal networks designed at other points of the curve. On the other hand, the last point cannot be the desired one because the costs of an optimal network designed at this point are more as compared to other points, although this point is the best option with respect to the reliability and the efficiency of the designed optimal network. Therefore, the user should decide, based on his/her economic situation and on other considerations, what degree of reliability to consider for the network. The user, based on his/her past experiences, economic power and other conditions he/she has in mind, should select a point on the curve of the solution set that yields an optimal network with acceptable reliability and minimum corresponding costs.

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