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Optimization of Water Supply Networks byconsideringvarious indexes

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ABSTRACT

The present study 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 considering various indexes 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. The optimization method used in this paper is Genetic Algorithm method. In this article, a computer software program is introduced that can design water supply networks at minimum costs by taking into consideration all hydraulic constraints for attaining a specific degree of reliability. This degree of reliability is given to the program as an input constraint. Moreover, the program has the capability to design the optimal network by taking into consideration the Resiliency index or the minimum variance of discharge distribution instead of the reliability constraint.

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INTRODUCTION

Being economical, in a way that expenses are kept at a minimum, is the first priority in designing optimal water supply networks. 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. Today, 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 the last three decades, a significant number of researches for the design of water distribution networks have been developed. One approach used in these researches was the optimization of the water supply network without consideration of reliability. Several techniques in this regards have been proposed. The common method of optimization in the context of water distribution network design is linear programming. Dantzig (1963), Gupta (1969), Gupta and Hassan (1972), Alperovits and Shamir (1977), Quindry et al. (1981), and Bhave and Sonak (1992) used linear programming. Kessler and Shamir (1989) have proposed the linear programming gradient method for optimal design of water supply networks. For this purpose, other investigators such as Chiplunkar etal. (1986), Walski (1987), Ormsbee (1989), and Samani and Naeeini (1996) also used nonlinear programming. Walski et al. (1990) developed the WADISO pipe network design program in which the hydraulic analysis was linked to the linear programming for optimization analysis. Also, Morgan and Goulter (1985) linked a Hardy-Cross network hydraulic analysis with linear programming while Zick (1991) employed GIS and AUTO-CAD and linked them with the WADISO computer program. Taher et al. (1996) developed a computer program in which a nonlinear programming algorithm is used for hydraulic analysis of the network coupled with a linear programming algorithm through GIS. Simpson et al. (1994), and Savic and Walters (1997) used genetic algorithms which represents a search method for nonlinear optimization problems. The latter has the merit of reducing the tendency to become entrapped in local minima. Cunha and Sousa (1999)

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employed the simulated annealing approach for optimization of water distribution networks. Mair and Simpson (2003) employed the ant colony optimization method, Eusuff and Lansey (2003) used the shuffled frog leaping algorithm and Liong and Atiquzzman (2004) used the shuffled complex evolution method. In all these methods, only pipe sizes are considered as decision variables in the optimization analysis. Samani and Mottaghi (2006) used the integer linear programming for obtaining the optimum pipe sizes and reservoir elevations in pipe networks. Samani and Zanganeh (2010) modified the integer linear method to a simpler one in which the integer-real-linear programming is used.

Application of optimization algorithm based on minimization of the design cost leads to the openning of the loops, giving rise to pseudolooped networks (Watanatada 1973, Alprovits and Shamir 1977, Rowel and Barnes 1982, Templeman 1982, Goulter and Bouchart 1990, Loganathan et al.. 1995, Khomsi et al.. 1996). This type of loop will not behave properly because the minimum diameter pipe is not of sufficient capacity to convey large flows when any of other loop pipes have to be temporarily drawn out of service. This leads researchers to the subject of reliability based optimization of water distribution networks pointed out by (Goulter 1992, Xu and Goulter 1999). In this method, the optimization algorithm is combined with a method for estimating reliability. Goulter and Bouchart (1990) have solved a reliability constrained least cost optimization problem. Multiobjective optimization formulation is another approach which is able to simultanously consider the cost and reliability of the network. In a multiobjective optimization problem, there exists a set of solutions called Pareto optimal solutions (Hans 1988).The multiobjective optimization method has been employed by (Halhal et al.. 1997, Xu and Walters 1999, Toodini 2000, Tolson 2001, Farmani et al.. 2005, Moneim 2010,). It must be recognized that optimization only assist the designer to decide about the best solution and engineering judgment and experience is still required to provide a practicable solution. The Pareto solutions give the designer more Resiliency in the selection of practicable design. Toodini 2000 introduced the concept of resilience index which is a measure of the capability of the network to cope with failures of pipes and is related indirectly to the network reliability. A third method of optimization of water distribution networks has been proposed by Martinez 2006. In this method, a single objective function in which a new term represents costs of reliability is added to the total cost. This term accounts for the expected annual cost involved in a pipe breakage. This expected cost includes the cost of failure repair and the cost of supplying affected consumers. Every time a pipe breakage occurs, the broken pipe should be removed from the network and the network has to be analyzed in order to determine the total head required to convey water for the affected consumers and consequently the costs of pumping and repairs. This should be done in a number of the pipes that are expected to break and the costs have to be summed. It is obvious that this method requires huge calculations and therefore it is time consuming.

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

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

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, or the Resiliency index, or the variance of discharge distribution is applied to the equations as needed.

Constraints:

The constraints involved in the problem include the pressure constraint, the speed constraint, and one of the constraints of reliability, Resiliency index, or variance of discharge distribution.

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)

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$$\frac{P_i}{\gamma} \le \frac{P_{\max}}{\gamma}$$
$$\frac{P_i}{\gamma} \ge \frac{P_{\min}}{\gamma} \qquad (2)$$

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)

$$V_M \le V_{Max}$$
$$V_n \ge V_{\min} \qquad (3)$$

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 index 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)

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

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.

Resiliency index constraint:

If the network is designed based on a specific index of Resiliency, this is introduced to the program as a constraint in the form of equation (5)

$$\mathrm{Re}s > (\mathrm{Re}s)_{selected} \qquad (5)$$

In which:

$\mathrm{Re}s$:Represents the Resiliency index of the network، $(\mathrm{Re}s)_{selected}$:The minimum allowable Resiliency index the user has in mind for the network.

Variance of discharge distribution in pipe branch pipes index constraint:

If the network is designed based on a specific variance of discharge distribution, this is introduced to the program in the form of equation (6)

$$Var > (Var)_{selected} \qquad (6)$$

In which:

Var : Stands for the variance of discharge distribution in the branch pipes of the network، $(Var)_{selected}$: The variance of discharge distribution in the branch pipes of the network that the user has in mind.

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:

$$TC = \sum_{i=1}^{np} D_j L_i C_{pj} + Pen_1\left[\max\left(0, H_{\min} - P_k/\gamma\right)\right] + Pen_2\left[\max\left(0, P_k/\gamma - H_{\max}\right)\right] \qquad (7)$$
$$+ Pen_3\left[\max\left(0, V_{\min} - V_i\right)\right] + Pen_4\left[\max\left(0, V_i - V_{\max}\right)\right]$$

In which:
Pen: Isrepresenting penalty functions.

$$\mathrm{Re}\,l = R_v \times F_t \times F_n \tag{8}$$

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.

$$R_v = \frac{\sum_s \sum_j V_{js}^{avl}}{\sum_s \sum_j V_{js}^{req}} = \frac{\sum_s \sum_j Q_{js}^{avl} t_s}{\sum_s \sum_j Q_{js}^{req} t_s} \tag{9}$$

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.

$$F_t = \frac{\sum_s \sum_j a_{js}\, t_{js}}{JT} \tag{10}$$

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.

$$F_n = \left[\prod_{j=1}^{J} R_{nj}\right]^{1/J} \tag{11}$$

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 (12)

$$R_{nj} = \frac{\sum_s V_{js}^{avl}}{\sum_s V_{js}^{req}} = \frac{\sum_s Q_{js}^{avl} t_s}{\sum_s Q_{js}^{req} t_s} \tag{12}$$

Note: all the parameters in the above equation were introduced in the definition of the volumetric reliability factor (R_v).
The objective function for water supply networks by using the constraint of Resiliencyindex
This objective function is defined by the following equations:

$$TC = \sum_{i=1}^{np} D_j L_i C_{pj} + Pen_1\left[\max\left(0, H_{\min} - \frac{P_k}{\gamma}\right)\right] + Pen_2\left[\max\left(0, \frac{P_k}{\gamma} - H_{\max}\right)\right] \tag{13}$$
$$+ Pen_3\left[\max\left(0, V_{\min} - V_i\right)\right] + Pen_4\left[\max\left(0, V_i - V_{\max}\right)\right] + Pen_6\left[\max\left[0, (Res)_{selected} - \mathrm{Re}\,s\right]\right]$$

$$\mathrm{Re}\,s = \frac{\sum_{j=1}^{nn} C_j Q_j \left(H_j - H_j^L\right)}{\left[\sum_{K=1}^{nr} Q_k H_k + \sum_{i=1}^{npu} \frac{P_i}{\gamma}\right] - \sum_{j=1}^{nn} Q_j H_j^L} \tag{14}$$

In which:

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H_j : Stands for the available head at node j ، H_j^L : The designed head، H_k : The tank head at node k, nn : The number of nodes، np : The number of the nodes of the tank، npu : The number of pumps in the network.

$$C_j = \frac{\sum_{i=1}^{npj} D_i}{npj * \max\{D_i\}} j \tag{15}$$

In which:
npj : represents the number of pipes connected to node j

D_i :The diameter of pipes that reach node j

If all of the pipes reaching node j have the same diameter, the value of C will be one; otherwise, its value will be less than one.

The objective function for optimizing water supply networks by using the constraint of the variance of discharge distribution in branch pipes
The objective function for this optimization is defined by the following equation:

$$TC = \sum_{i=1}^{np} D_j L_i C_{pj} + Pen_1 \times \left[\max\left(0, H_{\min} - {P_k}/{\gamma}\right) \right] + Pen_2 \times \left[\max\left(0, {P_k}/{\gamma} - H_{\max}\right) \right] \tag{16}$$

$$+ Pen_3 \times \left[\max\left(0, V_{\min} - V_i\right) \right] + Pen_4 \times \left[\max\left(0, V_i - V_{\max}\right) \right] + Pen_7 \times \left[\max\left[0, (\text{var})_{selected} - \text{var}\right] \right]$$

$$Var = \sum_{k=1}^{NP} \frac{\left(Q_k - \overline{Q}\right)^2}{NP} \tag{17}$$

In which:

NP : Represents the number of branch pipes، Q_k :The discharge of each branch pipe، $\overline{Q}$:The numerical mean discharge of the branch pipes.

Simultaneous hydraulic and optimization analysis:

For all optimizations (reliability, Resiliency index, or variance of discharge distribution optimizations), 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 Resiliency networks with tanks of constant height based on a specified degree of reliability, or Resiliency coefficient, or variance of discharge distribution.

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-Weisbachare 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- reliability, or resiliency or variation of flow distribution and the cost (ie, 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 or flexibility to be rate variability or variance 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 city of Hanoi in Vietnam, and can test the capability of the software introduced in this article in solving large- scale problems. 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 (4) 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.

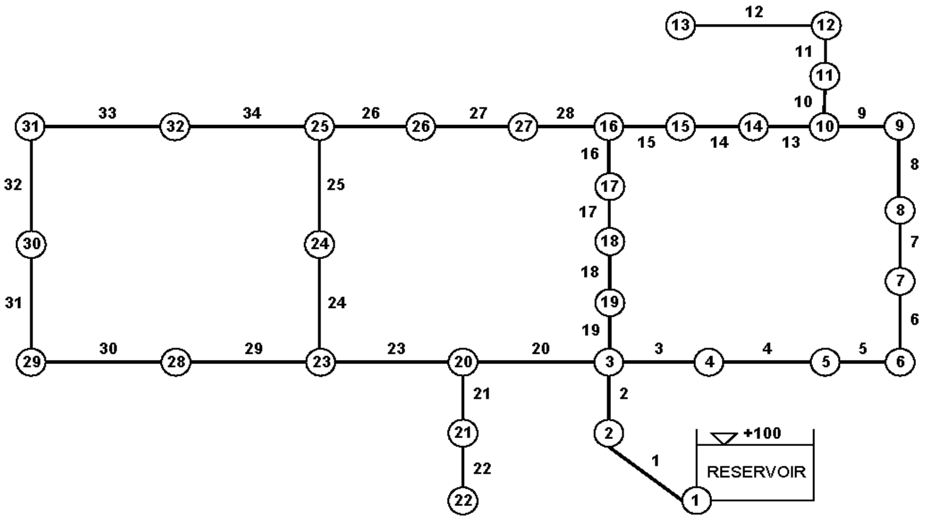

Fig. 1: The water supply network with 34 pipes.

Table 1: Characteristics of the nodes in the example.

Numberof nodes	Dischargeused (Lit/Sec)	Numberof nodes	Dischargeused (Lit/Sec)	Numberof nodes	Dischargeused (Lit/Sec)
1	0.00	12	155.56	23	290.28
2	247.22	13	261.11	24	227.78
3	236.11	14	170.83	25	47.22
4	36.11	15	77.78	26	250.00
5	201.39	16	86.11	27	102.78
6	279.17	17	240.28	28	80.56
7	375.00	18	373.61	29	100.00
8	152.78	19	16.67	30	100.00
9	145.83	20	354.17	31	29.17
10	145.83	21	258.33	32	223.61
11	138.89	22	134.72		

Table 2: Characteristics of the pipes in the example.

Numberof pipes	Length *(m)*	Numberof pipes	Length *(m)*	Numberof pipes	Length *(m)*
1	100	13	800	25	1300
2	1350	14	500	26	850
3	900	15	550	27	300
4	1150	16	2730	28	750
5	1450	17	1750	29	1500
6	450	18	800	30	2000
7	850	19	400	31	1600
8	850	20	2200	32	150
9	800	21	1500	33	860
10	950	22	500	34	950
11	1200	23	2650		
12	3500	24	1230		

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Table 3: Constraints of the example network.

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

Table 4: Information regarding the diameters of the pipes in the example(These pipes are available in the market).

D (in)	12	16	20	24	30	40
Cost ($/m)	45.73	70.40	98.39	129.33	180.74	278.28

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 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 5: Reliability against optimal costs of the example network.

Row	Reliability $(\mathrm{Re}l)$	Dollar-cost pipe networkoptimization $(Cost)$
1	0.776	6309996
3	0.830	7079936
2	0.878	7420375
4	0.904	7513836
5	0.946	7961526
6	0.983	10002289

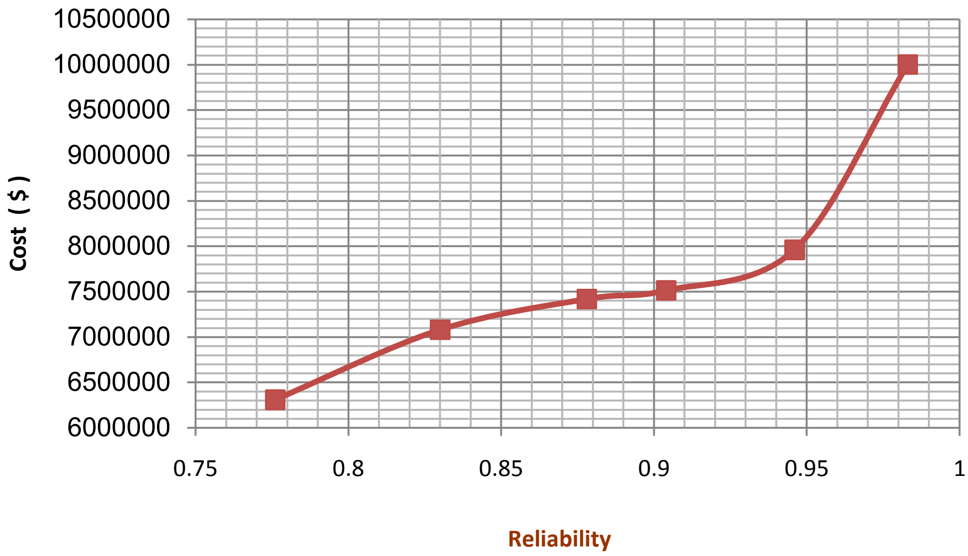

Fig. 2: The reliability curve against optimal costs of the example network.

2. Optimizing the network based on the specified and defined Resiliencyindex for the example network:

Here, the distribution network is first optimized using the objective function, the costs are minimized against a specified and desired Resiliency index for the network, these operations are repeated for different degrees of Resiliency the user has in mind, and , finally, the diagram of corresponding costs against the related Resiliencyindex (the solution set) is drawn. Results of optimization for the various Resiliencyindex are presented in Table (6), and the Pareto cost curve against Resiliencyindex in Figure (3).

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Table 6: Resiliency index against optimal costs of the example network.

Row	Resiliency (Res)	Dollar-cost pipe networkoptimization $(Cost)$
1	0.213	6309996
2	0.402	7879331
3	0.496	9290879
4	0.594	9780847
5	0.699	10664880
6	0.771	12461411
7	0.899	18746175

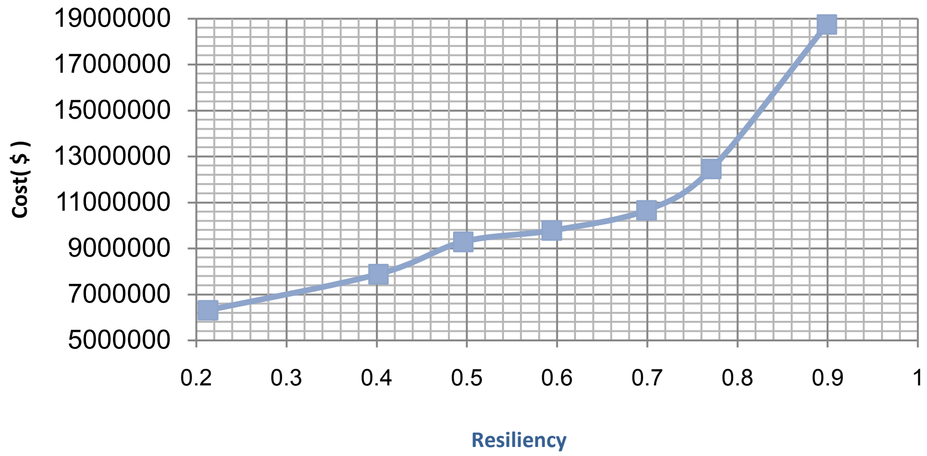

Fig. 3: The curve of Resiliency index against optimal costs of the example network.

3. Optimizing the network based on the specified and defined index of variance of discharge distribution for the example network:

Here, the network is first optimized using the objective function of minimizing costs and the constraint of a specified variance of discharge distribution for the network. These operations are repeated for the various variances of discharge distribution the user has in mind, and, finally, thePareto curve of costs against the variance of discharge distribution of the network (the solution set) is drawn. Results of optimization for various values of variance of discharge distribution are presented in Table (7), and the Pareto curve of costs against the variance of discharge distribution in Figure (4).

Table 7: Variance of discharge distribution in the branch pipes against the optimalCosts of the example network.

Row	Varianceindischargedistributionbranches (Var)	Dollar-cost pipe networkoptimization $(Cost)$
1	1686851.77	7420579
2	1981366.60	8175269
3	2017441.30	8681132
4	2368402.90	6309996
5	2569965.40	8280187

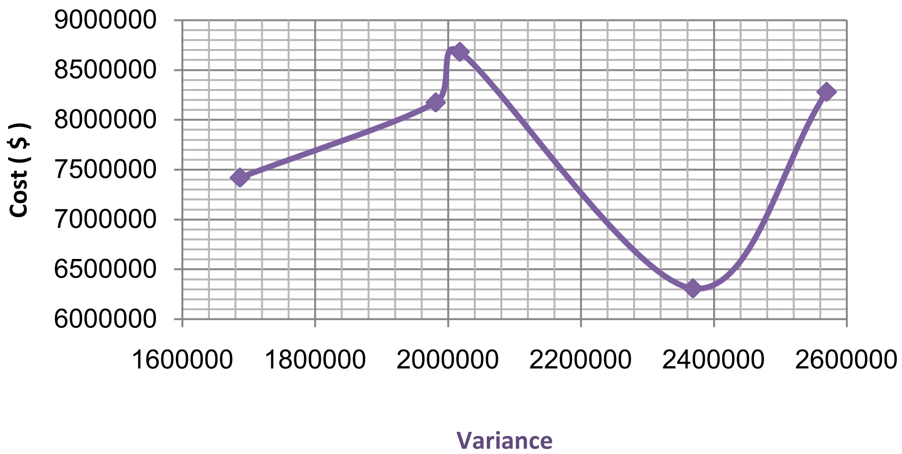

Fig. 4: Curve of variance of discharge distribution in the branch pipes – optimalCosts of the example network.

Conclusions:

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, and other index such as the index of Resiliency and of variance of discharge distribution in the pipe branches, 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 or Resiliency, which is the optimization point of the network based only on costs.

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. Although designing networks based on reliability is more time-consuming and more complicated, figures related to designs made in this way make it clear this method is much more cost effective, compared to those designed based on Resiliency, with respect to total costs. The reason for this difference is that the diameters of pipes in networks having high Resiliency are much larger compared to those of pipes used in designing a similar network based on the index of reliability. However, many researchers still design optimal networks based on the reliability index because the calculations involved are simpler. It was thought that network reliability was directly proportional to the variance of discharge distribution in branch pipes, but the result obtained from drawing the (Pareto) curve of solution set of the variance of discharge-costs shows the opposite: the mentioned curve has no definite trend in that it ascends in some intervals and descends in others. This is contrary to the trend in the (Pareto) curves of solution set of the index of reliability and Resiliency.

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