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Optimization of Water Supply Networks With Multiple Inputs Using Genetic Algorithms

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ABSTRACT

Optimization of water distribution networks with multi-reservoirs using genetic algorithm is studied .Decision variables are pipe diameters and inlets discharges which are provided by the reservoirs. The constraints consist of upper and lower bounds of pipe sizes, flow velocities, and inlet discharges. The objective function which should be minimized is the total costs of pipes, pumping stations and energy.

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INTRODUCTION

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.

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.

Alprovitez and Shamir [1] 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 Alprovitez and Shamir [1] 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 [5] 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 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

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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 [6], Gupta and Hassan [7], Quindry [9], Bhave and Sonak [2]. Other researchers such as Chiplunkar [3], Walski [15], Ormsbee [8], Samani and Naeeni [12] used nonlinear optimization method. Samani and Mottaghi [11] used integer linear programming method. Samani and Zangeneh [10] invented a mixed linear optimization method of real and integer numbers which was of a good speed and accuracy. Savic and Walters [14] 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 linearize relationships or to calculate partial derivatives Cunha and Sousa [4] used cooling the metal optimization method. Samani and Haghighi [10] 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. In this paper, networks with multiple inputs are considered. The amount of discharge in these inputs can have a great effect on costs, therefore in this paper besides the diameter of network pipes, input discharges are also considered as decision variables.

MATERIAL AND METHODS

Total cost of water supply networks:
The costs of a water supply network include:

1. The cost of pipes including: purchasing, transporting, and installing the pipes.
2. The cost of power supply equipment (reservoirs, side buildings, and pumps)
3. The costs of pumping energy during operating the design. It should be noted that some of these costs such as side buildings and reservoirs are constant.

Thus the total cost formula is stated as equation (1) and its mathematical form is shown in equation (2).

Objective function (annual total cost) = pipes cost + pumps cost + consumed energy cost (1)

$$(TC)_{anwal} = R\left(\sum_{i=1}^{np} D_j L_i C_{pj} + \sum_{i=1}^{np} K_p P^{mp} + \sum_{i=1}^{np} t\,\gamma\,Q_L\,H_{PL}\,C_k\right) \tag{2}$$

In which:

$(TC)_{anwal}$: Design total annual cost

R : Interest rate

L_i : Pipe Length

C_{pj} : The Cost of pipe unit length with diameter of D_j

K_p And mp are the factors which are archived through processing of cost function against the power of pump

P : The power of pumping station

np : Number of pumps

t : Operating time of pumps in a year based on hour

Q_L : Discharge of the pumping station

H_{PL} : Head of pumping station L

C_k : Cost of energy unit based on currency per KW/h

γ : Specific weight of water based on KN/M^3

Regarding the fact that the element of time affects on pumping cost, thus all the expenses in equation (2) should be selected for a certain period of time. In this study the time mentioned is based on year.

The decision variables that should minimize the abovementioned objective function are: the diameter of network pipes and the discharges of pumping station (All Q_L).

Constraints:

The constraints of the problem consist of pressure, speed, and discharge in inputs.

Pressure constraint:

Pressure in nodes should be at a limit of minimum and maximum and is presented in equation (3).

$$\frac{P_i}{\gamma} \le \frac{P_{\max}}{\gamma}$$
$$\frac{P_i}{\gamma} \ge \frac{P_{\min}}{\gamma} \quad (3)$$

Speed constraint:

Speed in pipes should be at a limit of minimum and maximum and is presented in equation (4).

$$V_M \le V_{Max}$$
$$V_n \ge V_{\min} \quad (4)$$

Discharges constraints in inputs:

Discharges constraints in inputs are presented in equation (5).

$$\sum_{j=1}^{N} Q_j = \sum_{i=1}^{N} Q_i \quad (5)$$

In which:

Q_j : Input discharge in node no. j

Q_i : Consumption discharge node no. i

N : *The number of nodes in the network :*

In genetics algorithm the constraints should be included in the objective function as penalty functions. Thus the objective function is as in equation (6).

$$\begin{aligned}(TC)_{anwal} = R &\left(\sum_{i=1}^{np} D_j L_i C_{pj} + \sum_{i=1}^{np} K_p P^{mp} + \sum_{i=1}^{np} t\,\gamma Q_L H_{PL} C_k\right) \\ &+ Pen_1\left[\max\left(0, H_{\min} - {P_k}/{\gamma}\right)\right] + Pen_2\left[\max\left(0, {P_k}/{\gamma} - H_{\max}\right)\right] \\ &+ Pen_3\left[\max\left(0, V_{\min} - V_i\right)\right] + Pen_4\left[\max\left(0, V_i - V_{\max}\right)\right]\end{aligned} \quad (6)$$

In which:

Pen *: are the penalty functions and large numbers are chosen:*

In equation (6) if the pressure or speed be in allowed limit the penalty function will be zero. If not, the penalty number will be so big and will remarkably increase the total cost so that option cannot become optimum.

Simultaneous analysis of hydraulic and optimization:

For hydraulic analysis of the network EPANET software is used and for optimization analysis, a program based on genetics algorithm is written which is combined by EPANET software and the calculations are done in a reciprocating way between these two soft ware's.

Optimization algorithm of water supply networks with multiple pumping stations:

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. Calculation of annual cost of the pipes, pumps and the energy of primary population series is done, i.e. objective function of equation (6) regarding input data relating to the costs is calculated for all pipe series.
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).

In the following, an example is presented to demonstrate the efficiency of the method.

Example

Water supply network as shown in figure (1) is so similar to the network of the city Hanoi but have two power supplies in nodes no. 1 and 11. Optimization variables in this network besides the diameter of pipes can also be inputs (pumping stations) in the mentioned nodes. The information related to the nodes, pipes, constraints, and the diameter of the pipes available in the market and the information related to the power of pumps and their coefficients, the cost of consumed electricity etc. are presented in tables (1) to (5). Also Hazen-Williams coefficient is considered equal to 130 for all the pipes. The values of height of all the nodes except the nodes of reservoir are zero. This example is solved for the following different states of optimization.

A) Optimization is only done in determining the diameter of network pipes and inputs are not included in the optimization process.
B) Besides the diameter of the network pipes, one of the inputs i.e. node (1) is also participated in optimization process.
C) Besides the diameter of the network pipes, both inputs are participated in optimization process.
D) Optimization is only done on the diameter of network pipes, but discharge is dictated to the network in inputs.

Table 1: Specification of network nodes examples of 28 branches.

Number of nodes	Discharge used $\left(Lit/Sec\right)$	Number of nodes	Discharge used $\left(Lit/Sec\right)$	Number of nodes	Discharge used $\left(Lit/Sec\right)$
1	0.00	14	170.83	27	102.78
2	247.22	15	77.78	28	80.56
3	236.11	16	86.11	29	100.00
4	36.11	17	240.28	30	100.00
5	201.39	18	373.61	31	29.17
6	279.17	19	16.67	32	223.61
7	375.00	20	354.17		
8	152.78	23	290.28		
9	145.83	24	227.78		
10	145.83	25	47.22		
11	0.00	26	250.00		

Table 2: Profile piping network **,**for example 28 branch.

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

Table 3: Constraints on the network example 28 branch.

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

Table 4: Tube diameter in the market **,**example the network information 28 branch.

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

Table 5: Coefficients of the pumps **,**the cost of energy consumed and the amount of fines for example networks.

Coefficient	K	m	η	T	$E.P$	Pen
Unit	-	-	-	hr	$\$/kw.hr$	$\$$
Amount	156	0.8589	0.8	7000	0.05	100000

In table (5): K and m are the coefficients of pump cost function (cost$=kp^m$) , η efficiency of the pump, T number of pumping hours in a year, E.P the sum of KW/h energy in dollar and pen is the sum of penalty in dollar.

Analysis of the Results:

- The results from solving state (a) of the example are presented in table (6)

Table 6: Results solely diameter pipe network optimization example 28 branch.

Number of pipes	Pipe diameter (mm)	(in)	The discharge tube $(lit/\sec)$	Velocity in the pipe $(m/\sec)$	Number of nodes	Push the node (m)
1	762	30	2527.38	2.54	1	100*
2	1016	40	2280.16	2.41	2	97.26
3	609.6	24	1080.63	2.70	3	89.74
4	609.6	24	1044.52	2.58	4	74.57
5	609.6	24	843.13	2.29	5	56.37
6	508	20	563.96	2.28	6	40. 92
7	406.40	16	188.96	1.46	7	35.39
8	304.80	12	36.18	0.50	8	31.29
9	304.80	12	109.65	1.50	9	30.51
10	1016	40	2062.91	2.54	10	36.23
13	508	20	255.48	1.26	11	100*
14	508	20	426.31	2.10	14	38.50
15	508	20	504.09	2.49	15	42.17
16	304.8	12	98.26	1.35	16	47.66
17	304.8	12	142.02	1.95	17	31.72
18	406.4	16	515.63	2.28	18	51.92
19	406.4	16	532.30	2.67	19	76.63
20	406.4	16	431.12	2.32	20	40.94
23	304.8	12	76.95	1.05	23	31.09
24	304.8	12	174.43	2.39	24	51.86
25	406.4	16	402.21	2.45	25	77.22
26	609.6	24	1041.24	2.76	26	63.84
27	609.6	24	791.24	2.71	27	61.00
28	508	20	688.46	2.40	28	32.67
29	304.8	12	38.89	0.53	29	49.43
30	304.8	12	119.45	1.64	30	90.74
31	304.8	12	219.45	2.67	31	98.49
32	304.8	12	319.45	2.78	32	87.01
33	762	30	1714.28	2.56		
34	762	30	1490.67	2.89		

***** It should be noted that the first optimization calculations show that for providing minimum pressure and applying usual and common diameters for pipes, selecting the pressure of 100 meter is suitable for pumping stations.

- The results from solving state (B) of the example are presented in table (7)

Table 7: Results of pipes and optimization of inputs (Node 1) Network Example (28) branch.

Number of pipes	Pipe diameter		The discharge tube	Velocity in the pipe	Number of nodes	Push the node
	(mm)	(in)	$(lit/\sec)$	$(m/\sec)$		(m)
1	1016	40	3406.81	2.87	1	53.12
2	1016	40	3159.59	2.78	2	51.59
3	1016	40	1211.04	1.49	3	38.19
4	1016	40	1174.93	1.45	4	36.63
5	1016	40	973.54	20.1	5	34.75
6	762	30	694.37	1.52	6	33.08
7	762	30	319.37	0.70	7	31. 95
8	508	20	166.59	0.82	8	31.44
9	406.4	16	20.76	0.36	9	30.35
10	1016	40	1183.48	1.46	10	30.28
13	508	20	125.07	0.62	11	100*
14	609.6	24	295.90	1.01	14	30.89
15	762	30	373.68	0.82	15	31.66
16	1016	40	704.70	0.87	16	32.10
17	1016	40	944.98	1.17	17	33.83
18	1016	40	1318.59	1.63	18	35.74
19	1016	40	1335.26	1.65	19	37.36
20	609.6	24	377.17	1.29	20	32.90
23	304.8	12	23.00	0.32	23	31.85
24	406.4	16	91.32	0.70	24	30.30
25	508	20	136.46	0.67	25	31.46
26	406.4	16	107.87	0.83	26	30.01
27	609.6	24	142.13	0.49	27	30.13
28	508	20	244.91	1.21	28	35.13
29	609.6	24	358.59	1.23	29	81.03
30	406.4	16	439.15	2.56	30	99.14
31	508	20	539.15	2.66	31	99.46
32	762	30	639.15	1.40	32	72.94
33	406.4	16	515.16	2.89		
34	304.8	12	291.55	2.98		

It should be noted that the first optimization calculations show that for providing minimum pressure and applying usual and common diameters for pipes, selecting the pressure of 100 meter is suitable for pumping stations.

- The results from solving state (c) of the example are presented in table (8)

Table 8: Results from both the inlet pipe network optimization example (28) branch.

Number of pipes	Pipe diameter		The discharge tube	Velocity in the pipe	Number of node	Push the node
	(mm)	(in)	$(lit/\sec)$	$(m/\sec)$		(m)
1	1016	40	2501.34	2.89	1	42. 64
2	1016	40	2254.12	2.78	2	41.98
3	1016	40	1057.28	1.30	3	34.61
4	1016	40	1021.17	1.26	4	33.40
5	1016	40	819.78	1.01	5	31.95
6	1016	40	540.61	0.67	6	30.74
7	609.6	24	165.61	0.57	7	30.56
8	304.8	12	12.83	0.32	8	30.11
9	609.6	24	133.00	0.46	9	30.00
10	1016	40	2088.96	2.58	10	30.28
13	762	30	278.83	0.61	11	40.19
14	1016	40	449.66	0.55	14	30. 65
15	762	30	527.44	1.16	15	30.79
16	304.8	12	20.15	0.35	16	31.62
17	609.6	24	220.13	0.75	17	30.77
18	762	30	593.74	1.30	18	32.32
19	762	30	610.41	1.34	19	33.82
20	609.6	24	350.32	1.20	20	30.00
23	304.8	12	3.85	0.33	23	30.04
24	609.6	24	260.05	0.89	24	31.53
25	762	30	487.83	1.07	25	33.22
26	1016	40	986.48	1.22	26	32.22
27	1016	40	736.48	0.91	27	32.01
28	1016	40	633.70	0.78	28	31.27
29	304.8	12	34.07	0.47	29	35.10
30	406.4	16	114.63	0.88	30	38.39
31	508	20	214.63	1.06	31	38.65
32	609.6	24	314.63	1.08	32	35.73
33	1016	40	1745.14	2.15		
34	1016	40	1521.53	1.88		

- The results from solving state (D) of the example are presented in table (9)

Table 9: The results of network optimization by merely diameter dictate the flow of the network nodes Example (28) branch.

Number of pipes	Pipe diameter		The discharge tube $(lit/\sec)$	Velocity in the pipe $(m/\sec)$	Number node	Push the node (m)
	(mm)	(in)				
1	1016	40	4000*	2.98	1	62.68
2	1016	40	3752.78	2.94	2	61.10
3	1016	40	1515.34	1.87	3	42.18
4	1016	40	1479.23	1.82	4	39. 83
5	1016	40	1277.84	1.58	5	36.95
6	1016	40	998.67	1.23	6	34.18
7	1016	40	623.67	0.77	7	33.63
8	762	30	470.89	1.03	8	33.20
9	762	30	325.06	0.71	9	32.16
10	304.8	12	590.29*	2.89	10	31.67
13	609.6	24	179.23	0.61	11	100
14	406.4	16	8.40	0.32	14	31.18
15	304.8	12	69.38	0.95	15	31.18
16	609.6	24	129.50	0.44	16	32.86
17	762	30	369.78	0.81	17	33.77
18	609.6	24	743.39	2.55	18	35.14
19	1016	40	760.06	0.94	19	41.89
20	1016	40	1241.27	1.53	20	38.20
23	1016	40	887.100	1.09	23	35.62
24	1016	40	540.17	0.67	24	35.15
25	1016	40	312.39	0.39	25	34.96
26	609.6	24	378.77	1.30	26	32.90
27	1016	40	128.77	0.34	27	32.89
28	508	20	25.99	0.31	28	32.46
29	304.8	12	56.65	0.78	29	33.32
30	304.8	12	23.90	0.33	30	47.66
31	304.8	12	123.90	1.70	31	47.67
32	1016	40	223.90	0.41	32	35.57
33	406.4	16	337.21	2.60		
34	508	20	113.60	0.56		

*Discharge of 4000 lit/sec in pipe no. (1) And discharge of 590.29 lit/sec in pipe no. (10) Are dictated to the program.

Table 10: The results of the different states of network optimization example (28) branch.

Number of columns	1	2	3	4	5	6	7
Topic	Components participating in the optimization process	Total cost per year	Reliability	Pressure node (1)	Pressure node (11)	discharge tube No (1)	discharge tube No (10)
Unit Line	-	$(\$)$	-	(m)	(m)	$\left(lit/\sec\right)$	$\left(lit/\sec\right)$
1	Only pipes	2152449	0.79	100 *	100 *	2527.38	2062.91
2	Pipes and pumping stations located at node (1)	1608372	0.89	47.43	100	2842.99	1747.30
3	Pipes and pumping stations located at node (11) and (1)	1124694	0.85	42.64	40.19	2434.7	21555.9
4	Just dictate the flow tube and the input station	1691420	0.88	62.68	100	4000	590.29

***** It should be noted that the first optimization calculations show that for providing minimum pressure and applying usual and common diameters for pipes, selecting the pressure of 100 meter is suitable for pumping stations.

- After presenting different states of optimization of networks with multiple inputs using different states of example, for better understanding of this subject, it is necessary to discuss the results summary of the mentioned example, considering table (10).

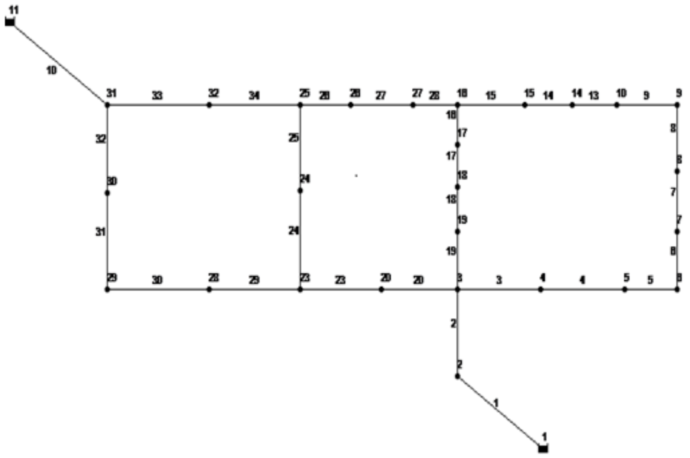

Fig. 1: Network of 28 branches.

Conclusions and discussions:

Conclusion of optimization of water supply networks with multiple inputs:

As it is shown in column no. (2) of table (10), the highest annual total cost among 4 states of optimization network with multiple inputs, is related to the first state, i.e. the state in which only the pipes take part in optimization process. And the least cost is related to state (3), i.e. the state in which the pipes as well as all the pumping stations take part in optimization process.

In this way, if in optimization of the water distribution networks, the software used has the capability of including also inputs in the optimization process, then the costs of the network will be remarkably reduced. Total annual costing the designed network, in the state that both inputs take part in optimization process (state 3), equals 1124694 dollars, and in the state that only the pipes are participated in optimization, equals 2152449. By participating the inputs in optimization process an amount of 1027755 dollars decrease occurs in total annual cost, and this means that if the software used for the design, has the capability of entering network inputs to the optimization process; in competition with other available soft ware's, has the ability of remarkably reducing the project cost, in comparison with the state that the inputs do not participate in the optimization process.

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