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OPTIMIZATION OF WATER DISTRIBUTION NETWORKS USING ARTIFICIAL BEE COLONY ALGORITHM

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ABSTRACT

Water distribution networks are such structures, which maintain the distribution of the water necessary for use in the city-life to its users. Among the facilities, which maintain the transmission of the utility water from its resource to the users, water distribution networks are known to have quite high ratio of cost to the overall cost. Certain limitations in the water distribution networks, excessiveness of the parameters being in use in the design, and the high amounts of cost being incurred, have altogether necessitated the cost optimization in the water distribution networks. In this study, cost optimization using the Artificial Bee Colony (ABC) optimization method, which is a novel method, was performed on Alperovits and Shamir network, Hanoi city water distribution network as well as New York city water distribution network as a rehabilitation practice, which were previously used by numerous researchers, and the results were evaluated.

Keywords: Water distribution systems, Artificial bee colony algorithm, Hanoi network, Alperovits and shamir, New York city network

YAPAY ARI KOLONİSİ ALGORİTMASI KULLANILARAK SU DAĞITIM ŞEBEKELERİNİN OPTİMİZASYONU

ÖZET

Su dağıtım şebekeleri, şehir yaşamında kullanmak için gerekli olan suyun kullanıcılarına dağıtımını sağlayan yapılardır. Gerekli olan suyun kaynağından kullanıcılara iletilmesini sağlayan tesisler arasında, su dağıtım şebekelerinin maliyetinin toplam maliyete oranının oldukça yüksek olduğu bilinmektedir. Su dağıtım şebekelerindeki belirli sınırlamalar, tasarımda kullanılan parametrelerin fazlalığı ve ortaya çıkan yüksek miktardaki maliyet değerleri, su dağıtım şebekelerinde maliyet optimizasyonunu zorunlu kılmıştır. Bu çalışmada, yeni bir yöntem olan Yapay Arı Kolonisi optimizasyon yöntemini kullanarak daha önce çok sayıda araştırmacı tarafından kullanılmış olan Alperovits ve Shamir şebekesi, Hanoi şehri su dağıtım şebekesi ve bir yenileme projesi olarak New York şehri su dağıtım şebekesi üzerinde maliyet optimizasyonu yapılmış ve sonuçlar değerlendirilmiştir.

Anahtarkelimeler: Su dağıtım sistemleri, Yapay arı kolonisi algoritması, Hanoi şebekesi, Alperovits ve shamir, New York şehir şebekesi

1. INTRODUCTION

Inview of the ever-increasing population and pollution worldwide, importance of the limited water resources has been on the day by day. Transmission of fresh and quality water to the users depends to the collection of the water right from its resource, followed by its transmission, accumulation, and distribution therefrom. Final stage of transmission of the water to its user is performed by the mediation of the water distribution networks.

Starting with its collection from its resource, and continuing with the steps of accumulation, and transmission to the user, water distribution involves quite costly operations, and the water distribution networks' contribution in the overall cost throughout this process is quite high [1]. High costv alues of the water distribution networks, excess number of the parameters and limitations within the calculation bases, have altogether turned it into an optimization problem to designate a system, which will not only bring minimum cost, but will also meet the conditions being required from the network.

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While analogous methods were initially being used in the design of water distribution networks, the developments in the computer technology have not only led the way to the increase in the number of the works being conducted in this field, and but also brought along the development and utilization of various optimization methods [2].

While deterministic optimization methods, such as linear and non-linear programming, were in use at first, stochastic optimization methods, such as tabu search, genetic algorithms, and simulated annealing, were then put to use in the course of time for determining the optimum system. Among them, stochastic methods were seen to be more successful [3]. In the ensuing years, intuitive algorithms, such as Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), Shuffled Frog Leaping Algorithm (SFLA), and Honey-Bee Mating Optimization Algorithm (HBMO), which model the food-searching behaviors of the creatures living in flocks, were applied in the optimization of water distribution networks.

Out of the conducted studies, it has been found out that, deterministic optimization methods were insufficient in the optimization of the water distribution networks, which consist of non-linear expressions. Stochastic optimization methods, on the other hand, have been found as yielding more successful results. However, finding the optimum system in a long period, and with quite a lot of iterations, was mentioned as a disadvantage of these methods [4].

In view of the literature, it is seen that lots of different optimization methods are in use in the field of network designing. Most frequently used methods may be listed as Genetic Algorithms [5-9], Ant Colony Optimization method [10-13], Particle Swarm Optimization method [14-16], Simulated Annealing method [17-18] and Honey-Bee Mating Optimization Algorithm [19-20]. There are also studies conducted by the methods of Shuffled Frog Leaping [21], Differential Evolution [22-24], Harmony Search [25-27], Tabu Search [28-29], Honey-Bee Mating optimization algorithm [30]. There is no record of previous implementation of ABC method on water distribution networks; however, it was implemented on several different civil engineering problems [31-33]. The main reason for choosing ABC method in this study is the lack of studies on water distribution networks conducted using ABC method in the literature. Accordingly, cost optimization by ABC method was conducted on 3 benchmark networks which were previously used by many researchers.

In part 2 of the study, methodological information about water distribution networks and artificial bee colony method are given and the results obtained from implementation of ABC method on three different networks are presented in part 3 and 4. The results are interpreted in part 4.

2. METHODOLOGY

2.1. Optimum design of the water distribution networks

Hydraulic calculations and energy losses within the system are computed via Williams-Hazen formula (Eq.1) along the hydraulic gradient line (Figure 1). Herein Hk_i shows the energy loss in pipe i.,Q_i shows the flow running through the pipe i., C_{WH} shows the Williams-Hazen roughness coefficient, which varies depending to the type of the pipe, and D_i shows the diameter of the respective pipe.

$$Hk_i = \left[\frac{Q_i}{0{,}2785 x C_{WH} x D_i^{2,63}} \right]^{1,851} x L_i \tag{1}$$

Besides, if the number of the pipes at each division is to be shown by k, vectorial sum of the energy losses within the division towards an agreed (clockwise) direction should be equal to zero (Eq.2).

$$\sum_{t=1}^{k} \overrightarrow{Hk} = 0 \tag{2}$$

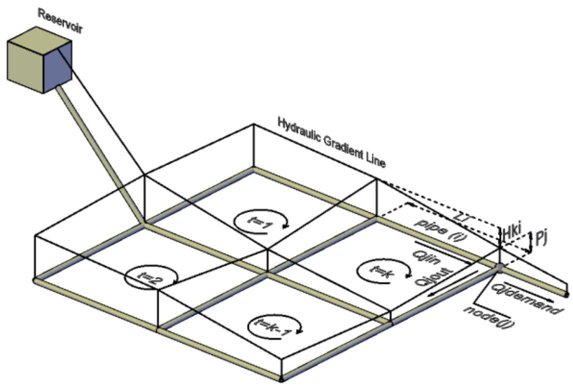

Figure 1. Hydraulic statements of a network

Objective function of the optimum system, pressure and continuity constraints has been shown in Eq.3 respectively.

$$
\begin{aligned}
& Z = \sum_{i=1}^{M} C(D_i)\cdot L_i + P \\
& P_{\min} \le P_j \le P_{\max} \;\; \forall_{\, j} = 1,2,3,........., N \\
& Q_j^{in} - Q_j^{out} - Q_j^{demand} = 0 \;\; \forall_{\, j} = 1,2,3,........., N
\end{aligned}
\tag{3}
$$

Where Z indicates objective function, D_i the diameter of the pipe no i, $C(D_i)$ the unit cost for diameter D_i and L_i the length of pipe no i. The variable designated as P in Eq.(3) is the penalty cost calculated for any solution (Eq.4). As a result, total cost is obtained by adding the cost of piping in the system to the value obtained as a result of penalty function. In this way, the aim is to establish a minimum-cost system.

P_j shows the pressure in node j., and N shows the number of the nodes. Pressure values must be in the [P_{min}:P_{max}] interval. While the flow coming into a node is shown by Q_j^{in}, the flow going out of a node is shown by Q_j^{out} and if any, the flow drained from a node is shown by Q_j^{demand}, the continuity condition given in Eq.(3) should be met.

$$
P = \sum_{i=1}^{N} H\left(P_{\min} - P_i\right)\cdot \varepsilon \cdot \left(P_{\min} - P_i\right) \tag{4}
$$

After starting solving, the penalty function in Eq.(4) was first used to establish solution points that fulfill necessary conditions for the network among all points of solution. Thereby, total cost values of the systems which do not fulfill these conditions are increased, minimum-cost system is stored in the memory during solving process so the potential for obtaining a solution point that fulfills necessary conditions is increased.

H in Eq.(4) represents commonly used Heaviside function. In addition, a constant factor of ε, specified according to the type of the problem is used so that the penalty cost can be significant in comparison to total cost. That the values obtained during the solution are below the minimum limitscause negative values to occur. In such cases, Eq. (4) is used, since negative valuesdo not affect the solution. Heaviside function especially has been selected for this reason in this study.

2.2. Artificial bee colony (ABC) algorithm

ABC algorithm has been developed by Karaboga in 2005 [34] upon being inspired from the food-searching behaviors of the bees. It is not only easy to use, but also easy to be applied to various problems. In terms of ABC algorithm, food places indicate the points of possible solutions, while the amounts of the nectars drained from the food places indicate the solution values corresponding to the objective function. While there are three types of bee behaviors, namely as the employed bee, onlooker bee, and scout bee, being modeled in the algorithm, each and every one of them operates within the algorithm as a separate phase.

Algorithm first of all gets started when scout bees scatter around, and search for food places. Upon finding the food supplies, scout bees then turn into employed bees. As a consequence of the agreement in terms of the algorithm, each source is to have only one bee in charge. Number of the bees in charge is equal to the number of the food supplies [35].

As the starting point of the solution, random points in between the lower and upper limits of the parameters are specified in the search space via Eq.(5). The process represents the random food places being found by the scout bees after scattering around out of their hives. Problem's objective function is used for determining the qualities of the nectars being obtained from the specified food points. While the lowest cost value computed for a minimization problem is entered as GlobalMin, and the food place associated with this solution is entered in the common memory of the colony as GlobalSolution.

$$x_{ij} = x_j^{\min} + rand(0,1)(x_j^{\max} - x_j^{\min}) \text{ i = 1 FN, j = 1..........D} \quad (5)$$

Herein FN is the number food supplies, while D is the number of the parameters to be optimized. While x_j^{min} is the lower limit of parameter j., x_j^{max} is the upper limit of parameter j.

In the employed bee phase, more quality food places are searched by way of making use of the Eq.(6) in the adjacency of the food places having previously been specified by the scout bees. In case when a better food place is found in the adjacency of the former food places, the best of the newly found food places is entered in the place of the former one. Otherwise the related food point's counter for not developing a solution (trial) is increased by one.

$$v_{ij} = x_{ij} + \varphi_{ij}(x_{ij} - x_{kj}) \quad (6)$$

In Eq. (6), j is an integer randomly generated in the range [1, D]. When changing the randomly selected parameter j, the j. parameter of the current source j. After taking the difference of parameter and weighted with φij number which takes random value between [-1,1], j. is added to the parameter [35].

After the worker bee phase is completed, the cost values of the solution points are calculated with the Z objective function and the fitness values of each source are calculated using Eq.(7). Where Zi is the value obtained by the Z cost function of each resource.

$$fitness_i = \begin{Bmatrix} 1/(1+Z_i) & Z_i \geq 0 \\ 1+abs(Z_i) & Z_i < 0 \end{Bmatrix} \quad (7)$$

In the following stage of onlooker bee phase, the probability values belonging to each of supplies are calculated via Eq.(8), and a random number in between the [0,1] interval is generated for each supply. If the p_i value, which is calculated for any one of the supplies, is greater than the said generated number, onlooker bee produces a new solution in this supply area by making use of the Eq.(6). Having the quality of the solution assessed, it is whether entered in the memory if found better than the previous solution, otherwise the previous solution is retained in the memory, and the counter for not developing a solution is increased by one.

$$p_i = \frac{fitness_i}{\sum_{i=1}^{FN} fitness_i} \quad (8)$$

The best (in terms of a minimization problem) among the cost values, which are associated with the last food places formed after the onlooker bee phase, is compared with the GlobalMin value, and if a value lower than the GlobalMin value is obtained, such a value is entered in the common memory of the colony as the new GlobalMin value, while the best food place being formed is also entered in the common memory of the colony as the new GlobalSolution.

Scout bee phase starts when the counter of any one of the supplies for not developing a solution (trial) exceeds a predetermined limit value. Such a circumstance reveals the depletion of food in the respective supply, and the bee in charge of the respective food point turns into a scout bee, and this scout bee starts to search for a new supply by making use of Eq.(5). Limit value in the algorithm is recommended as FN×D. A certain iteration number or a predetermined cost value may be used as the stopping criterion in ABC algorithm [35].

The pseudo code of ABC algorithm for this study is shown below;

****Start***

1. Generation of random flow values to provide Eq.(2) for the network
2. Determination of the starting points for the food places by mediation of Eq.(5), and resetting of the counter for not developing a solution ($trial_i$=0)

3. Operation of the objective function given in Eq.(3) for the attained initial values, and calculation of $fitness_i$ values given in Eq.(7)

#Employed Bee Phase#

*4.**repeat***
*5. **for** i=1 to FN **do***
6. Generate a new supply for the bee in charge of x_i solution by making use of Eq.(6). Calculate the cost value of the new supply by making use of Eq.(3), and the fitness value by making use of Eq.(7)
7. In case the fitness value of the new solution is higher than that of the former solution, enter the new solution point and the cost value thereof in place of the former solution point and the cost value thereof, and reset the counter for not developing a solution, otherwise retain the former solution point and the cost value thereof, and increase the counter for not developing a solution by one.
*8. **end for***
9. Calculate probability value p_i, which is to be utilized by the scout bees at time of selection, by making use of Eq.(8)

#Onlooker Bee Phase#

10. t=0, i=1
*11. **repeat***
*12. **if** random<p_i**then***
13. Generate a new supply for the scout bees by making use of Eq.(6), calculate the cost value of the newly generated supply by making use of Eq.(3), and the fitness value thereof by making use of Eq.(7)
14. Repeat Article 7,
15. t=t+1
*16. **end if***
*17. **until** t=FN*

#Scout Bee Phase#

18. **if** max($trial_i$)>limit **then**
19. Find a new x_i solution point by making use of Eq.(5), and replace the newly found x_i point with the former one
20. Calculate the cost value of the new supply by making use of Eq.(3), and the fitness value by making use of Eq.(7)
21. Repeat Article 7,
22. **end if**
23. Retain the best solution in the memory
24. **until** pause criterion

(adopted from Akay (2009) [35])

3. RESULTS AND DISCUSSION

3.1. Alperovits and shamir water distribution network

The study by Alperovits and Shamir (1977) [36] is one of the first studies published on optimization of water distribution networks in the literature. In that study, a fictitious network composed of two divisions and 8 pipes was addressed and cost optimization was conducted on this network by linear programming gradient method. This network was further used as the test network in numerous studies conducted in the following years ([4]; [18]; [37-40]).

The length of all the pipes being used in the network is 1000 m. Unit pipe cost values as per the commercial diameters being used in the network are given in Table 1. It is desired to have the minimum pressure in the network as being 30 m. C_{WH} coefficient is taken as 130 for all the pipes. Certain details of the network, including the elevations of the nodal points, and flow values being drained from the nodal points are given in Figure 2.

In their study conducted by Linear Programming Gradient method, Alperovits and Shamir (1977) [36] have found the optimum cost as 497,525 units. Having the flows running through the pipes within the system randomly designated at first, it was thereby attempted in the respective study to determine the system yielding the minimum cost by way of optimizing the said flows.

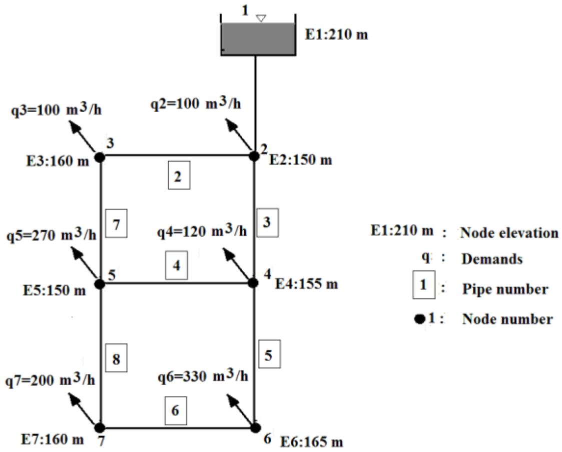

Figure 2. Alperovits& Shamir Network [18]

In this study, which we applied cost optimization to the water distribution networks by means of ABC algorithm, random flow values, which met the continuity condition within the system, were generated at first. ABC algorithm was applied to each of these generated flow values. Solution points are shown in the form of a matrix (Foods Matrix) in the algorithm. Number of lines of the Foods matrix is equal to the number of bees in charge, while the number of columns thereof is equal to the number of dimensions. Having the initial solution points formed randomly, it was then attempted to obtain optimum solution by way of applying the ABC algorithm.

Different values were tried in the algorithm for the number of bees, and for the maximum number of cycles. The most suitable value was consequently attained as 34 bees (17 employed bees + 17 onlooker bees), 1000 iteration, and as the limit value of 272. The algorithm made 84 iterations to reach the optimum solution (Figure 3) and ran the objective function for 17+(17+17)*84=2,873 times. While there were 8 pipes within the system, the problem was solved as 8-dimensioned. Optimum cost was consequently found as 429,000 units. MatlabR2008b program was utilized in the study.

The values, having been obtained by the practiced application, are shown below in comparison with the values from the studies of the researchers, who had applied different methods to the same network. While the diameters, having been obtained from the study are shown in Table 2, similarly attained flows are shown in Table 3, energy losses in the pipes are shown in Table 4, and total cost values are shown in Table 5.

In the study, the initial food places, namely the diameter values, were as constant values between the lowest and highest diameter values, and the results were then discret by way of rounding them up to the nearest commercial diameter. Having the new values, which were attained from each phase, rounded up to the nearest commercial diameter, the final values in Table 2 were thereby attained.

Table 1. Commercial Pipe Data for Alperovits & Shamir Network [18]

Diameter (inch)	Diameter (mm)	Cost per m (units)
1	25.4	2
2	50.8	5
3	76.2	8
4	101.6	11
6	152.4	16
8	203.2	23
10	254.0	32
12	304.8	50
14	355.6	60
16	406.4	90
18	457.2	130
20	508.0	170
22	558.8	300
24	609.6	550

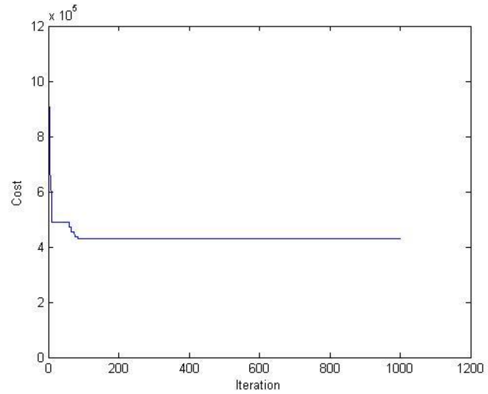

Figure 3. Cost graph of Alperovits&Shamir Network for ABC

Table 2. Pipe Diameters Obtained by Different Approaches for Alperovits&Shamir Network

Pipe Number	[4]	[39]	[18]	Present Work
	HBA	RGBA	SA	ABC
		Diameter mm)		
1	457.2	508.0	457.2	**457.2**
2	406.4	355.6	254.0	**355.6**
3	355.6	406.4	406.4	**355.6**
4	101.6	203.2	101.6	**152.4**
5	355.6	304.8	406.4	**355.6**
6	25.4	76.2	254.0	**101.6**
7	355.6	304.8	254.0	**355.6**
8	254.0	254.0	25.4	**254.0**

In the study, the change in the optimum cost values against the number of iterations for Alperovits and Shamir network is shown in the Figure 3. While the cost value dropped to a certain level throughout the iteration in the algorithm, algorithm was then stuck at the value of 429,000 units, due to not finding a value better than that.

Total cost calculated via ABC algorithm amounts to 429,000 units. In view of the cost values, it may be said that ABC has yielded a worse outcome in comparison to those of RBGA, SA, SFLA, and PSO-DE but a better outcome in comparison to that of HBA. On the other hand, although ABC algorithm cannot obtain the best result in the literature, it is clear that it achieves the current solution with less number of evaluations compared to most other methods.

The cost values, having been attained at the end of the study, are shown in Table 5. It is seen that, Monbaliu et al. (1990) [39], Cunha and Sousa (1999) [18], Eusuff and Lansey (2003)[38], and Sedki and Ouazar (2012) [41] found total cost as 419,000 units for the same network. Mohan and Jinesh Babu (2009) [4] calculated the total cost as 445,000.

3.2. Hanoi water distribution network

Having been made use of firstly by Fujiwara and Khang in 1990 [42], and then become a benchmark network in this field, and made use of there after by numerous researchers ([18]; [37-38]; [43]) as a test network, the Hanoi City water distribution network includes 31 nodal points, and 34 pipes (Figure 4).

Flows drained from the nodal points within the system, and the lengths of the pipes are given in Table 6. Elevation of all points throughout the network is zero meter. Desired minimum pressure within the system is indicated as 30 m. Unit costs are given in Table 7 as per the commercial pipe diameters in use. CWH coefficient is taken as 130 in all pipes. Having Hanoi water distribution network undergone ABC application, random flow values to meet the continuity condition were again generated at all nodal points.

Table 3. Discharge through the Pipes of Alperovits&Shamir Network

Pipe Number	[4]	[39]	[18]	Present Work
	HBA	**RGBA**	**SA**	**ABC**
	Discharge (m^3/h)			
1	1,120.00	1,120.00	1,120.00	**1,120.00**
2	555.39	438.98	336.86	**513.76**
3	464.61	581.02	683.14	**506.23**
4	14.10	122.47	32.56	**39.61**
5	330.50	338.55	530.58	**346.61**
6	0.51	8.55	200.58	**16.61**
7	455.39	338.98	236.86	**413.76**
8	199.50	191.45	-0.58	**183.38**

Optimization algorithm was run for the generated random flow values, and having the best of the attained results recorded, and shown in Table 8 in comparison with the results from the other methods.

Table 4. Head Loss Values Associated with the Pipe Diameters

		H_k (m)		
Pipe Number	**HBA[4]**	**RGBA[39]**	**SA[18]**	**ABC***
1	6.75	4.04	6.75	**6.65**
2	3.27	4.05	12.78	**5.34**
3	4.50	3.55	4.80	**5.19**
4	3.11	5.82	14.64	**2.87**
5	2.40	5.31	3.00	**2.57**
6	5.55	5.00	4.89	**4.14**
7	4.34	5.32	6.66	**3.57**
8	4.84	4.49	6.75	**4.08**

*Results obtained by present work

While there were 34 pipes in the system, the problem was solved as 34-dimensioned. Having different values were tried in the algorithm for the number of bees, and for the maximum number of cycles, the most suitable value was consequently attained as 70 bees (35 employed bees + 35 onlooker bees), 10,000 iteration, and as the limit value of 2380. Final values are shown in Table 8 comparatively with other methods. Optimum cost in Hanoi water distribution network was found by means of ABC method as 6.123×10^6 units. Change in the total cost throughout iteration is shown in Figure 5.

Table 5 Number of Evaluations and Cost Obtained by Different Approaches for Alperovits&Shamir Network

Approach	Number of evaluations	Cost (units)
HBA [4]	43	445,000
RBGA [39]	250,000	419,000
SA [18]	25,000	419,000
SFLA [38]	11,323	419,000
PSO-DE [41]	3,080	419,000
ABC (Present Work)	**2,873**	**429,000**

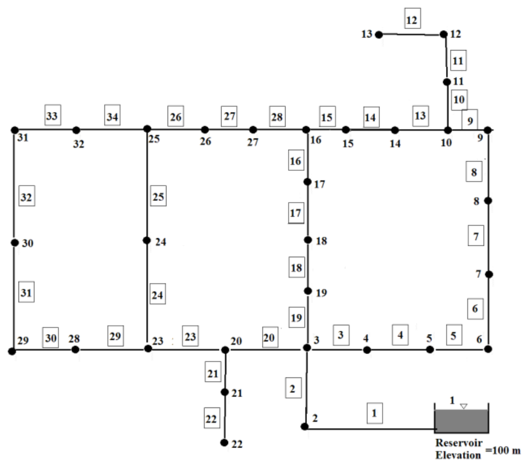

Figure 4. Hanoi Water Distribution Network [18]

Table 8 shows the values obtained out of the use of ABC algorithm. Main pipes Nos.1 and 2 in Hanoi network are those which deliver the water from the reservoir to the network. Due not only to the high values of the flows they carried, but also to the longer length of pipe no.2 than that of the pipe no.1, too much energy loss was incurred until arriving at the node no.3. This not only complicated the provision of the desired pressure at each and every point of the network, but also affected the solution.

The results obtained for water distribution network of Hanoi by different methods are shown in Table 8. It is apparent that the best (feasible) results were obtained as 6.081x10^6 units for this network by CE ([44]) and PSO-DE ([41]) methods. Optimum cost was obtained as 6.123x10^6 units by ABC method. As seen in Figure 5, although the algorithm ran for 10,000 iterations, a lower value could not be found after iteration 2,505. Therefore, the algorithm ran the objective function for 35+(35+35)*2505=175,385 times until reaching the optimum value.

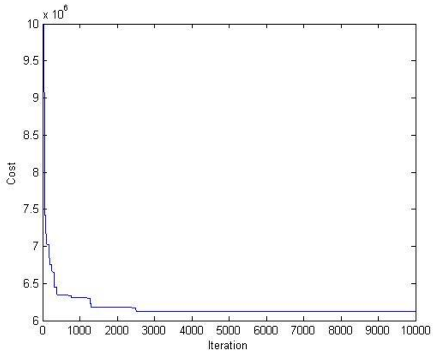

Figure 5. Cost graph of Hanoi Network for ABC

Optimum value was obtained as 6.123x10^6 units by ABC method. It is clear that this value approached the best result (6.081x10^6 units) obtained so far, by a difference of less than 1%, and a result better than those of SFLA [38] and HBA [4] methods were achieved. In addition, the algorithm solely obtained a value which is very similar to the value of PSO-GA ([45]), a hybrid method, suggesting that it is a successful method and can be applied to this type of problems. In ABC method, the large size of the colony increased the number of evaluations, which decreased the success of the method, but nevertheless the algorithm is thought to give better results in development process.

3.3. NewYork water distribution network

New York water distribution network, which was first included in the study of Schaake and Lai in 1969 [44], has later become a benchmark network, and researchers utilizing various methods ([8];[13]; [38]; [41];[47];[48]) tested their methods on this network.

Table 6. Data for Hanoi Network [18]

Node	Demand (m^3/h)	Pipe	Length (m)	Node	Demand (m^3/h)	Pipe	Length (m)
2	890	1	100	23	1,045	22	500
3	850	2	1,350	24	820	23	2,650
4	130	3	900	25	170	24	1,230
5	725	4	1,150	26	900	25	1,300
6	1,005	5	1,450	27	370	26	850
7	1,350	6	450	28	290	27	300
8	550	7	850	29	360	28	750
9	525	8	850	30	360	29	1,500
10	525	9	800	31	105	30	2,000
11	500	10	950	32	805	31	1,600
12	560	11	1,200			32	150
13	940	12	3,500			33	150
14	615	13	800			34	950
15	280	14	500				
16	310	15	550				
17	865	16	2,730				
18	1,345	17	1,750				
19	60	18	800				
20	1,275	19	400				
21	930	20	2,200				
22	485	21	1,500				

Table 7. Commercial Pipe Data for Hanoi Network [18]

Diameter (mm)	Cost per m (unit)
304.8	45.726
406.4	70.400
508.0	98.378
609.6	129.333
762.0	180.748
1,016.0	278.280

New York Water Distribution Network (Figure 6), which is comprised of 20 nodes and 21 tunnels, is different from the other two networks (i.e. Alperovits &Shamir, Hanoi) in that it is a rehabilitation project.

In line with the growing needs in the network, since desired minimum pressure values can not be provided in nodes 16, 17, 18, 19 and 20, it is aimed to ensure desired pressure values with minimum cost by adding extra pipes of the same length in parallel to existing tunnels in the network. CWH coefficient was considered 100 for all pipes to be added in the network. Information to be used for node points in the network, information to be used for existing pipes and unit cost values of pipes to be used in the network are given in Table 9, Table 10 and Table 11, respectively.

In order to identify parallel to which tunnels new pipes will be added in New York water distribution network, firstly, head loss values were considered in the existing state, and different combinations were initially tried by taking the parts with high head loss.

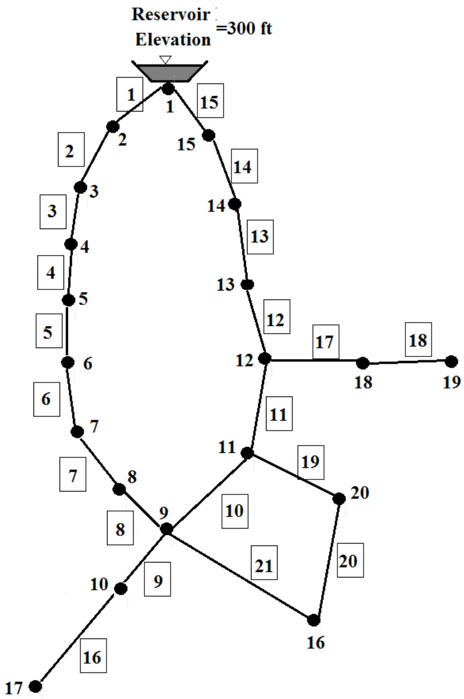

Figure 6. New York City water supply tunnels [18]

At the end of the study, it was concluded that optimum cost is achieved by laying parallel pipes to tunnels 7, 16, 17, 18, 19, and 21.

Different values were tried for the number of bees and maximum number of loops in the implementation of ABC for New York water distribution network and as a result, the most suitable value was obtained with the solution which includes 60 bees (30 onlooker bees + 30 employed bees), 2,000 iterations, and 1,260 as the limit value.

Table 9. Nodal data for New York City Water Supply Tunnels [8]

Node	Demand, (feet^3/s)	Minimum Total Head, (feet)
1	Reservoir	300.0
2	92.4	255.0
3	92.4	255.0
4	88.2	255.0
5	88.2	255.0
6	88.2	255.0
7	88.2	255.0
8	88.2	255.0
9	170.0	255.0
10	1.0	255.0
11	170.0	255.0
12	117.1	255.0
13	117.1	255.0
14	92.4	255.0
15	92.4	255.0
16	170.0	260.0
17	57.5	272.8
18	117.1	255.0
19	117.1	255.0
20	170.0	255.0

Table 8. Number of Evaluations and Cost Obtained by Different Approaches for Hanoi Network

Approach	Number of evaluations	Cost (units)
GA [37]	-	$6.073x10^{6}$ [a]
SA [18]	53,000	$6.056x10^{6}$ [a]
SFLA [38]	27,546	$6.195x10^{6}$
CE [44]	97,000	$6.081x10^{6}$
HBA [4]	70	$6.701x10^{6}$
PSO-DE [41]	40,200	$6.081x10^{6}$
PSO-GA [45]	15,200	$6.117x10^{6}$
ABC (Present Work)	175,385	**$6.123x10^{6}$**

[a]Refers infeasible solution

Variation of the cost value with the number of iterations is shown in Figure 7. At the end of the study, an optimum cost value of $38.96x10^6 was obtained. Although the algorithm ran for 2,000 iterations, optimum value was achieved at iteration 125 (Figure 7). Therefore, the algorithm ran the objective function for 30+(30+30)*125=7,530 times until reaching the optimum value.

Diameter values obtained for extra pipes from the implementation of ABC and the values from other studies are shown in Table 12, Optimum cost values and evaluation figures obtained from various methods for New York water distribution network are shown in Table 13.

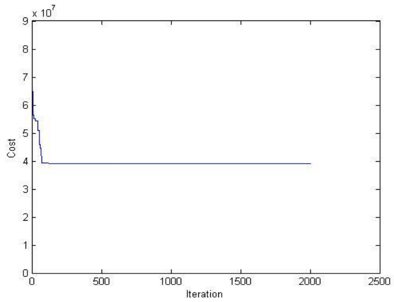

Figure 7. Cost graph of New York Network for ABC

An optimum cost value of $38.96x10^6 was obtained for New York water distribution network. In this network, the lowest cost value obtained by PSO-DE method [41] was $38.52x10^6. A difference of around 1% exists between the value obtained from the ABC study and the best value obtained so far. It is clear that this value is very similar to those obtained by previous studies conducted using ABC method in this network. On the other hand, the optimum cost was obtained by lower number of evaluations compared to other cost values, suggesting that ABC method is a more successful and applicable method.

Table 10. Pipe data for the New York City Water Supply Tunnels [8]

Pipe	Start Node	End Node	Lenght (feet)	Existing Diameter (inch)
1	1	2	11,600	180
2	2	3	19,800	180
3	3	4	7,300	180
4	4	5	8,300	180
5	5	6	8,600	180
6	6	7	19,100	180
7	7	8	9,600	132
8	8	9	12,500	132
9	9	10	9,600	180
10	11	9	11,200	204
11	12	11	14,500	204
12	13	12	12,200	204
13	14	13	24,100	204

14	15	14	21,100	204
15	1	15	15,500	204
16	10	17	26,400	72
17	12	18	31,200	72
18	18	19	24,000	60
19	11	20	14,400	60
20	20	16	38,400	60
21	9	16	26,400	72

Table 11. Available pipe size and pipe costs for New York City Tunnels dublication [8]

Diameter (inch)	Pipe Cost ($/feet)
0	0
36	93.5
48	134.0
60	176.0
72	221.0
84	267.0
96	316.0
108	365.0
120	417.0
132	469.0
144	522.0
156	577.0
168	632.0
180	689.0
192	746.0
204	804.0

Table 12. Solutions for New York water distribution systems obtained by different techniques

Pipe	**[8]**	**[38][a]**	**[13]**	**[48]**	**[41]**	**Present Work**
	GA	**SFLA**	**ACO**	**DE**	**PSO-DE**	**ABC**
			Pipe diameters (in.)			
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	0	132	144	144	0	108
8	0	0	0	0	0	0
9	0	0	0	0	0	0
10	0	0	0	0	0	0
11	0	0	0	0	0	0
12	0	0	0	0	0	0
13	0	0	0	0	0	0
14	0	0	0	0	0	0
15	120	0	0	0	96	0
16	84	96	96	96	96	96

17	96	96	96	96	96	96
18	84	84	84	84	84	96
19	72	72	72	72	72	84
20	0	0	0	0	0	0
21	72	72	72	72	72	72

[a] this solution results in infeasible pressures at Nodes 16, 17 and 19 when the network is simulated using EPANET hyraulic solver

Table 13. Number of Evaluations and Cost Obtained by Different Approaches for New York Water Distribution System

Approach	**Number of evaluations**	**Cost ($x10^6$\$)**
GA [8]	96,750	38.80
SFLA [38]	31,267	38.13[a]
ACO [13]	13,938	38.64
DE [48]	30,701	38.64
PSO-DE [41]	3,540	38.52
ABC (Present Work)	7,530	**38.96**

[a] this solution results in infeasible pressures at Nodes 16, 17 and 19 when the network is simulated using EPANET hyraulic solver

4. CONCLUSIONS

Cost optimization was performed in 3 different benchmark networks using the ABC method, which wasn't previously reported to have been implemented to water distribution networks, and the results were presented.

At the end of the study, it was revealed that the implementation of ABC to Alperovits&Shamir network has produces near optimal solutions, while results has shown similar performace over New York network near the other methods and for the Hanoi network ABC algorithm has shown a better performance near the other two networks. Particularly, it should be noted that the results obtained in Hanoi network are better than the results obtained so far by several methods applied on this subject, and yielded a result which is very similar to the best result. Although the best result could not be achieved by ABC method for New York network in this study, it is apparent that the resulting value is very similar to the best result ever found and it was obtained with less number of evaluations compared to most other methods.

Optimization practice in water distribution systems is essentially a very complicated matter. On one hand, satisfaction of many constraints is required for the network, and on the other hand, there is a large number of decision variables, making it difficult to obtain a global optimum value. ABC method includes decision variables such as size of colony, number of iterations and the objective function coefficients as well as a series of hydraulic variables such as location of zero points, establishing optimum flows that pass through pipes in the network and direction of water flow in the pipes. During the implementation, it was seen that these hydraulic variables have a big influence on the solution. There are many possibilities for such hydraulic variables, however, they should be constrained so that it becomes easier to reach the solution, which is thought to be the reason for not being able to achieve more successful results in the implementation of ABC method.

On the other hand, although there are less control parameters in ABC method near the other algorithms, ABC is also dependent on the control parameters' self structures. Better solutions can be obtained for different control parameters. And this algorithm can be strengthened by using differeny algorithms such as PSO in a hybrid applications.

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