A NEW ADAPTIVE PENALTY METHOD FOR CONSTRAINED GENETIC ALGORITHM AND ITS APPLICATION TO WATER DISTRIBUTION SYSTEMS

Berge Djebedjian *, Ashraf Yaseen **, and Magdy Abou Rayan *

* Mechanical Power Engineering Department, Faculty of Engineering,
Mansoura University, El-Mansoura, Egypt
** Damietta Drinking Water Company, Damietta, Egypt
E-mail: bergedje@mans.edu.eg , ashrafsayedyas@yahoo.com , mrayan@mans.edu.eg

ABSTRACT

This paper presents a new adaptive penalty method for genetic algorithms (GA). External penalty functions have been used to convert a constrained optimization problem into an unconstrained problem for GA-based optimization. The success of the genetic algorithm application to the design of water distribution systems depends on the choice of the penalty function. The optimal design of water distribution systems is a constrained non-linear optimization problem. Constraints (for example, the minimum pressure requirements at the nodes) are generally handled within genetic algorithm optimization by introducing a penalty cost function. The optimal solution is found when the pressures at some nodes are close to the minimum required pressure.

The goal of an adaptive penalty function is to change the value of the penalty draw-down coefficient during the search allowing exploration of infeasible regions to find optimal building blocks, while preserving the feasibility of the final solution. In this study, a new penalty coefficient strategy is assumed to increase with the total cost at each generation and inversely with the total number of nodes. The application of the computer program to case studies shows that it finds the least cost in a favorable number of function evaluations if not less than that in previous studies and it is computationally much faster when compared with other studies.

Key Words: Genetic Algorithm, Penalty Function, Water Distribution Systems

INTRODUCTION

A water distribution system consists of elements such as pipes, tanks, reservoirs, pumps, and valves etc. They are an essential part of all water supply systems. The cost of this portion of any sizable water supply scheme amount to more than 60% of the entire cost of the project. Also, the energy consumed in a distribution network supplied by pumping may exceed 60% of the total energy consumption of the system [1]. Water distribution system design optimization is one of the most heavily researched areas in the hydraulics profession. The optimization of pipe networks has been studied and various researchers have proposed the use of mathematical programming techniques in order to identify the optimal solution for water distribution systems. Hundreds of papers and reports on approaches have been developed over the past few decades. The optimization techniques can be categorized as follows:

i- Deterministic optimization techniques (linear, non-linear, dynamic and mixed integer programming)

ii- Stochastic optimization techniques (Genetic Algorithms, Simulated Annealing, GLOBE, Shuffled Complex Evolution and Shuffled Frog Leaping Algorithms).

For the deterministic optimization techniques, Alperovits and Shamir [2] proposed a linear programming gradient (LPG) in optimizing water distribution network and Kessler and Shamir [3] presented two stages LPG method. Eiger et al. [4] used the same formulation used in [3] and solved the problem using a nonsmooth branch and bound algorithms and duality theory. Other developments in LPG are used in Sonak and Bhave [5] and Sârbu and Borza [6]. Nonlinear programming (NLP) technique was developed and applied by Samani and Naeeni [7], Djebedjian et al. [8] and Sârbu and Kalmár [9].

The stochastic optimization methods deal with a set of points simultaneously in its search for the global optimum. The search strategy is based on the objective function. Simpson et al. [10] used simple Genetic Algorithms (GA). The simple GA was then improved by Dandy et al. [11] using the concept of variable power scaling of the fitness function, an adjacency mutation operator, and gray codes. Savic and Walters [12] also used simple GA in conjunction with EPANET network solver. Abdel-Gawad [13] studied the effect of different selection, crossover and mutation schemes of the GA on the network optimization. Instead of using a single optimization algorithm, Abebe and Solomatine [14] applied GLOBE that comprises several search algorithms and identified that very few algorithms reach to optimal or near optimal solutions. Many other researches on the water distribution network optimization using GA's can be found in Lippai et al. [15], Gupta et al. [16], Vairavamoorthy and Ali [17] and Wu and Simpson [18].

Cunha and Sousa [19] introduced the Simulated Annealing (SA) that is based on the analogy with the physical annealing process with Newton search method to solve the network equations. Eusuff and Lansey [20] proposed the Shuffled Frog Leaping Algorithms (SFLA). Liong and Atiquzzaman [21] used the Shuffled Complex Evolution (SCE) linked with EPANET network solver to identify the least cost of some water distribution pipe networks. The original SCE algorithm is modified to accommodate higher number decision variables; and the decision variables (pipe sizes) are converted to commercially available diameters in determining the cost of the network.

In the present investigation, a micro-genetic algorithm is applied for pipe network optimization. An adaptive penalty function is used to change the value of the penalty coefficient during the search allowing exploration of infeasible regions to find optimal building blocks, while preserving the feasibility of the final solution. The Newton-Raphson method is utilized for the hydraulic analysis of the network. The approach is applied to two water distribution networks to demonstrate its efficiency and effectiveness.

OPTIMIZATION MODEL FORMULATION

The water distribution network optimization aims to find the optimal pipe diameters in the network for a given layout and demand requirements. The optimal pipe sizes are selected in the final network satisfying all implicit constraints (e.g. conservations of mass and energy), and explicit constraints (e.g. hydraulic and design constraints).

The objective function is the total cost of the given network. The total cost C_T is calculated as:

$$C_T = \sum_{i=1}^{i=N} c_i\left(D_i\right).L_i \qquad (1)$$

where *N* is the total number of pipes, $c_i\left(D_i\right)$ the cost of pipe *i* with diameter D_i per unit length and L_i is the length of pipe *i*.

The objective function is to be minimized under the implicit constraints and explicit constraints. The implicit constraints are fulfilled as follows. The conservation of mass states that the discharge into each node must be equal to that leaving the node, except for storage nodes (tanks and reservoirs). This secures the overall mass balance in the network. For a total number of nodes *M* in the network, this constraint can be written as:

$$\sum_{j=1}^{M} Q_j = 0 \qquad (2)$$

where Q_j represents the discharges into or out of the node *j* (sign included).

The second implicit constraint is the conservation of energy according to which the total head loss around any loop must equal to zero or is equal to the energy delivered by a pump if there is any:

$$\sum h_f = E_p \qquad (3)$$

where h_f is the head loss due to friction in a pipe and E_p is the energy supplied by a pump. This embeds the fact that the head loss in any pipe, which is a function of its diameter, length and hydraulic properties, must be equal to the difference in the nodal heads.

Different forms for the head loss formula have been developed for practical pipe flow calculations. In this study, the head loss h_f in the pipe is expressed by the Hazen-Williams formula:

$$h_f = \frac{10.6744}{C_i^{1.852}} \frac{L_i \ Q_i^{1.852}}{D_i^{4.8704}} \tag{4}$$

where Q_i is the pipe flow (m^3/s), C_i is the Hazen-Williams coefficient, D_i is pipe diameter (m), and L_i is pipe length (m).

The explicit constraints are the design and hydraulic constraints. The design constraints (the pipe diameter bounds (maximum and minimum)) and the hydraulic constraints (the fluid velocity bounds and the pressure head bounds at each node) are given respectively as:

$$D_{\min} \le D_i \le D_{\max} \qquad i = 1,..., N \tag{5}$$

$$V_{\min} \le V_i \le V_{\max} \qquad i = 1,..., N \tag{6}$$

$$H_{j,\min} \le H_j \le H_{j,\max} \qquad j = 1,..., M \tag{7}$$

where V_i is the fluid velocity in pipe *i*, H_j is the pressure head at node *j*, and $H_{j,\min}$ and $H_{j,\max}$ are the minimum and maximum allowable pressure heads at node *j*.

The Newton-Raphson method, [22], is used to simulate hydraulically the given network. The technique used to solve the nonlinear set of equations. The flow rates in each pipe are assumed which satisfy continuity, then they are corrected so that the sum of the head losses around each loop approaches zero. The equations containing the correction factor are written for each loop and this nonlinear set of equations is solved successively for the final value of correction factor in each loop. Then, the initial flow rates in each pipe are adjusted to their final values.

NEW ADAPTIVE PENALTY METHOD

The idea underlying penalty function methods is to transform the problem of minimizing:

$$z = f(x) \tag{8}$$

subject to certain constraints on *x* into the problem of finding the unconstrained minimum of the objective function:

$$Z = f(x) + \mathrm{P}(x) \tag{9}$$

where $\mathrm{P}(x)$ is the penalty function. It is designed to penalize infeasible solution and to force the search towards the feasible solution region.

For the network optimization, the function $f(x)$ is the total cost C_T and the penalty cost C_P is used instead of $\mathrm{P}(x)$, so Eq. (8) yields:

$$Z = C_T + C_P \tag{10}$$

The design constraints in pipe network optimization that will be used in the penalty function is the minimum allowable hydraulic pressures at given nodes as the diameter of each pipe is chosen from a specified set of commercial pipes. When the pressure head condition at a node is not satisfied, then a penalty cost is added at that node,

$$C_P = \sum_{j=1}^{M} C_{P_j} = c \,.\sum_{j=1}^{M} \left(H_{j,\min} - H_j\right) \tag{11}$$

where c is the penalty draw-down coefficient. Choosing the penalty coefficient values for a penalty function is often arbitrary, [23]. A small coefficient will impose a smaller penalty than a large coefficient for the same magnitude of constraint violation. In the GA, a large penalty can quickly eliminate infeasible solutions from the search, which may contain schemas that are key elements of the optimal solution. Conversely, using a small coefficient may allow the survival of infeasible designs to the extent that the population converges at an infeasible point as the optimal fitness solution. Clearly, a compromise must be struck between these two extremes.

The goal of an adaptive penalty function is to change the value of the penalty coefficient during the search allowing exploration of infeasible regions to find optimal building blocks, while preserving the feasibility of the final solution, [23].

Crossley and Williams [23] defined three basic forms of draw-down coefficient strategies: constant penalty coefficient, generation number-based strategies (increasing the value of c with successive generations) and population fitness-based strategies (using the standard deviation and the variance of the population's fitness values).

The penalty costs used in the literature take many forms, [12], [14] and [18]. For example, Abebe and Solomatine [14] defined it as: $C_P = p.C_{\max}.\underset{j \text{ to } M}{Max}\left(H_{j,\min} - H_j\right)$ where p is the penalty cost coefficient, $C_{\max}$ is the maximum possible cost that the network can have, it is calculated based on the largest commercial pipe available. The penalty cost coefficient p must be selected carefully to provide a smooth transition from infeasible to feasible designs.

In this study, a new penalty coefficient strategy is assumed. The idea is to use a coefficient which depends on the total cost of network calculated at each generation and the total number of nodes. It is based on the important parameters having effect on the penalty cost. These parameters are the total cost C_T and the total number of nodes M. As the total cost is very large compared to the minimum cost; the penalty cost should be increased by the same amount. Also, as the number of nodes increases in large networks its importance on the penalty cost should be decreased. Consequently, the coefficient can be assumed to increase with the total cost at each generation and inversely with the total number of nodes. Then, the final form of the coefficient is $c = C_T / M$.

The new form of the penalty coefficient can be introduced in a different manner. Neglecting the effect of pipe length and treating it as a device, then the average cost of each pipe is (C_T / N). Similarly, assuming that each node plays the same role in the network, the average node cost is defined as (C_T / M). This term is multiplied to the nodal pressure head condition to obtain the penalty cost.

Applying the previous approach, the penalty cost is written as:

$$C_P = \frac{C_T}{M} \cdot \sum_{j=1}^{M} \left(H_{j,\min} - H_j \right) \tag{12}$$

and the objective function is calculated from:

$$Z = \begin{cases} C_T & \text{if } H_{j,\min} - H_j \le 0 \\ C_T \left[1 + \frac{1}{M} \sum_{j=1}^{M} \left(H_{j,\min} - H_j \right) \right] & \text{else} \end{cases} \tag{13}$$

The penalty cost is applied at the nodes where the pressure head at node is less than the minimum allowable pressure head at the same node.

The present adaptive penalty method has several advantages such as:

§ It does not contain any constant values. The penalty cost is function of the total cost, the number of nodes, and the node pressure head.
§ It is fast to reach the global optimization.
§ It decreases the number of evaluations.

GENETIC ALGORITHMS

Genetic algorithms are search techniques based on the concepts of natural evolution and thus their principles are directly analogous to natural behavior, Gen and Cheng [24]. The brief idea of GA is to select population of initial solution points scattered randomly in the optimized space, then converge to better solutions by applying in iterative manner the following three processes (reproduction/selection, crossover and mutation) until a desired criteria for stopping is achieved.

The micro-Genetic Algorithm (μGA), Krishnakumar [25], is a "small population" GA. In contrast to the Simple Genetic Algorithm, which requires a large number of individuals in each population (i.e., 30 - 200), the μGA uses a small population size.

The optimization program is written in FORTRAN language and called (GANRnet) as it depends on GA and Newton-Raphson simulation techniques. A brief description of the steps in using GA for pipe network optimization is as follows, Simpson et al. [26]:

1. ***Generation of initial population.*** The GA randomly generates an initial population of coded strings representing pipe network solutions of population size *N*. Each of the *N* strings represents a possible combination of pipe sizes.
2. ***Computation of network cost.*** For each *N* string in the population, the GA decodes each substring into the corresponding pipe size and computes the total material cost. The GA determines the costs of each trial pipe network design in the current population.
3. ***Hydraulic analysis of each network.*** A steady state hydraulic network solver computes the heads and discharges under the specified demand patterns for each of the network designs in the population. The actual nodal pressures are compared with the minimum allowable pressure heads, and any pressure deficits are noted. In this study, the Newton-Raphson technique is used.
4. ***Computation of penalty cost.*** The GA assigns a penalty cost for each demand pattern if a pipe network design does not satisfy the minimum pressure constraints. The pressure violation at the node, at which the pressure deficit is maximum, is used as the basis for computation of the penalty cost. The maximum pressure deficit is multiplied by a penalty factor, which is a measure of the cost of a deficit of one unit of pressure head.
5. ***Computation of total network cost.*** The total cost of each network in the current population is taken as the sum of the network cost (Step 2) plus the penalty cost (Step 4).
6. ***Computation of the fitness.*** The fitness of the coded string is taken as some function of the total network cost. For each proposed pipe network in the current population, it can be computed as the inverse or the negative value of the total network cost from Step 5.
7. ***Generation of a new population using the selection operator.*** The GA generates new members of the next generation by a selection scheme.
8. ***The crossover operator.*** Crossover occurs with some specified probability of crossover for each pair of parent strings selected in Step 7.
9. ***The mutation operator.*** Mutation occurs with some specified probability of mutation for each bit in the strings which have undergone crossover.

10. ***Production of successive generations.*** The use of the three operators described above produces a new generation of pipe network designs using Steps 2 to 9. The GA repeats the process to generate successive generations. The last cost strings (e.g., the best 20) are stored and updated as cheaper cost alternatives are generated.

These steps are illustrated in the flow chart of the GANRnet program, Fig. 1.

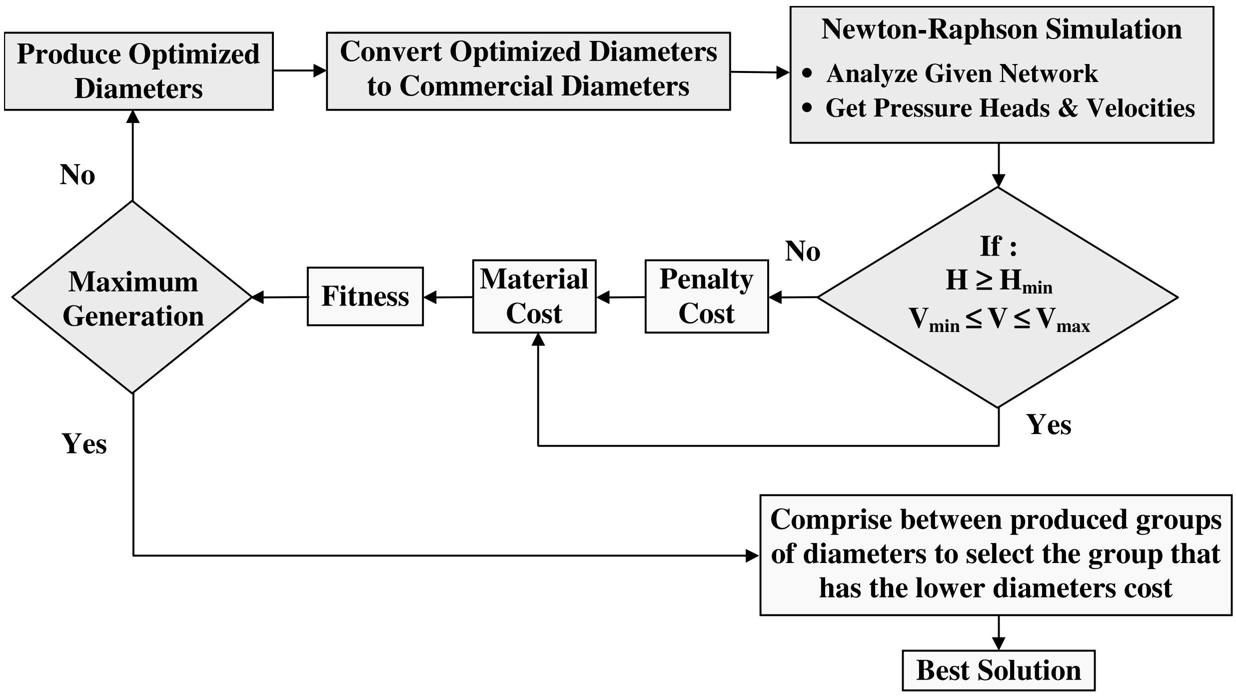

Fig. 1. Flow chart of the GANRnet program

APPLICATION TO WATER DISTRIBUTION SYSTEMS

The GANRnet program was applied to two case studies and the results were compared with other optimization methods and GA's. The hydraulic analysis results of the GANRnet program were compared with the EPANET (Rossman [27]) computer program. The EPANET program employs the "gradient method" (Todini and Pilati [28]) which was found to be the most sophisticated direct equation solving algorithm presented in the literature. EPANET is available in the public domain, so it is used to check the hydraulic solution accuracy of the GANRnet.

The genetic algorithm in the GANRnet program has several parameters that enable moving to different search regions to approach the global solution; these parameters are: *Npopsiz*: the population size of a GA run, *Idum*: the initial random number seed for the GA run, and it must equal a negative integer, *Maxgen*: the maximum number of generations to run by the GA, and *Nposibl*: the array of integer number of possibilities per parameter. The GA parameters are given in the two case studies.

Case Study 1: Two-Loop Network

The first case study is gravity fed two-loop network with 8 pipes, 7 nodes and one constant head reservoir. The layout of the network, the lengths of pipes and the node data are shown in Fig. 2. The two-loop network problem is originally presented by Alperovits and Shamir [2] and taken as a model network by many researchers. All the pipes are 1000 m long and the Hazen-Williams coefficient is assumed to be 130 for all the pipes. The demands are given in cubic meters per hour and the minimum acceptable pressure requirement for each node is 30 m above the ground level. There are 14 commercially available pipe diameters and Table 2 presents the total cost (in arbitrary units) per meter of pipe length for different pipe sizes.

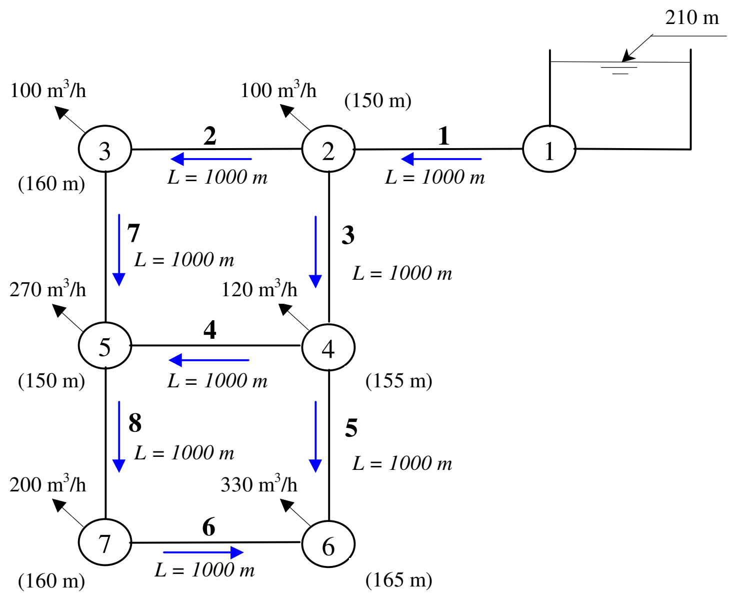

Fig. 2. The two-loop network (Case 1)

Table 1. Cost data for the two-loop network (Case 1)

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

The GANRnet program was applied to the two-loop network using the following values for μGA parameters: *Npopsiz* = 12, *Idum* = –1220, *Maxgen* = 62 and *Nposibl* = 32. The mutation and crossover rates were set to 0.2 and 0.5, respectively.

Figure 3 depicts the evolution of the solution as the GANRnet develops in a single run. A rapid decrease in the cost value for the first group of evaluation then quite slow changes in the later evaluations is observed.

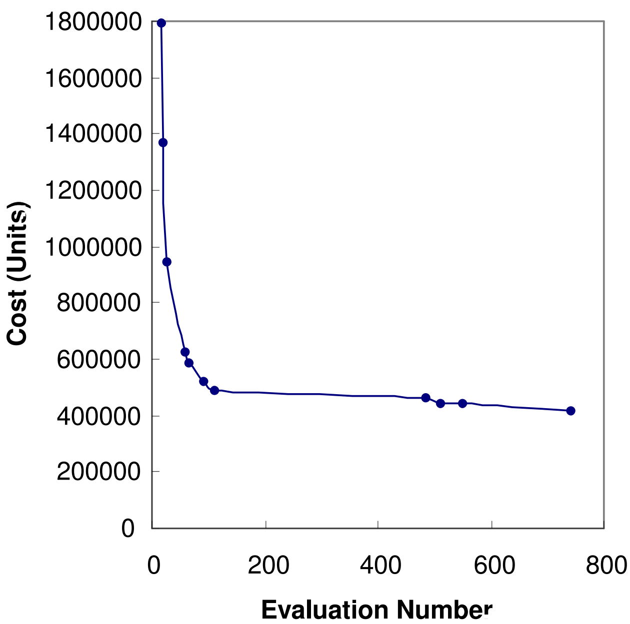

Fig. 3. Cost evolution (Case 1)

Table 2 lists the optimal network solutions, total network cost, number of function evaluations (F.E.N.), and the run time. It is important to note that some of the previous studies dealt with split-pipe solutions. These solutions are not included in this table. The minimum nodal head requirement is not violated in all cases mentioned in Table 2.

The two-loop network containing 8 pipes and with 14 available commercial pipe sizes has a total solution space of $14^8 = 1.48 \times 10^9$ different network designs, thus it is difficult to optimize it. Using the optimization techniques, it can be observed from Table 2 that only a small fraction of the total search space is searched (i.e. F.E.N.) by each algorithm to reach the optimal solution.

The GA solutions of the present study are similar to the least cost solutions (419,000 units) obtained by Savic and Walters [12], Abebe and Solomatine [14], Cunha and Sousa [19], Eusuff and Lansey [20], and Liong and Atiquzzaman [21]. The comparison between the different methods of optimization and the present study yields that the present study reaches to the least cost solutions faster than the other methods. It converges only after 741 evaluations with a computational time of 2 seconds.

The pressure at each node calculated by GANRnet and the EPANET are shown in Table 3. The results from the GANRnet (Newton-Raphson technique) are lower than that of EPANET within the acceptable accuracy.

Table 2. Results of the two-loop network (Case 1)

Pipe Number	**Pipe Diameter (in)**						
	Savic and Walters [12]		**Abebe and Solomatine [14]**	**Cunha and Sousa [19]**	**Eusuff and Lansey [20]**	**Liong and Atiquzzaman [21]**	**Present Study**
	GA1	**GA2**		**SA**	**SFLA**	**SCE**	**GA**
1	18	20	18	18	18	18	18
2	10	10	10	10	10	10	10
3	16	16	16	16	16	16	16
4	4	1	4	4	4	4	4
5	16	14	16	16	16	16	16
6	10	10	10	10	10	10	10
7	10	10	10	10	10	10	10
8	1	1	1	1	1	1	1
Cost	419,000	420,000	419,000	419,000	419,000	419,000	419,000
F.E.N. *	65,000	65,000	1,373	25,000	11,323	1,091	741
Run Time	10 min	10 min	7 min	40 sec	/	18 sec	2 sec **

* **F.E.N.:** Function Evaluation Number

** Run time in present study is produced on a computer with Pentium 4 (1.7 GHz) processor

Table 3. Node pressure head (m) for the two-loop network (Case 1)

Nodes	EPANET Simulation	Newton Raphson Simulation
2	53.25	53.23
3	30.46	30.43
4	43.45	43.42
5	33.81	33.76
6	30.44	30.41
7	30.55	30.51

Case Study 2: Hanoi Network

The second case study is the water distribution trunk network in Hanoi, Vietnam, Fig. 4. The data are given by Fujiwara and Khang [29] and summarized in Table 4. This network consists of one reservoir (node 1), 31 demand nodes and 34 pipes. The minimum pressure head required at each node is 30 m.

The set of commercially available pipe diameters (in inches) is (12, 16, 20, 24, 30, and 40) and their unit cost is given in [29] as: $C = 1.1\ D^{1.5}$ in which C is the cost per meter length in dollars and D is the pipe diameter in inches. The Hazen-Williams coefficient for all links is 130.

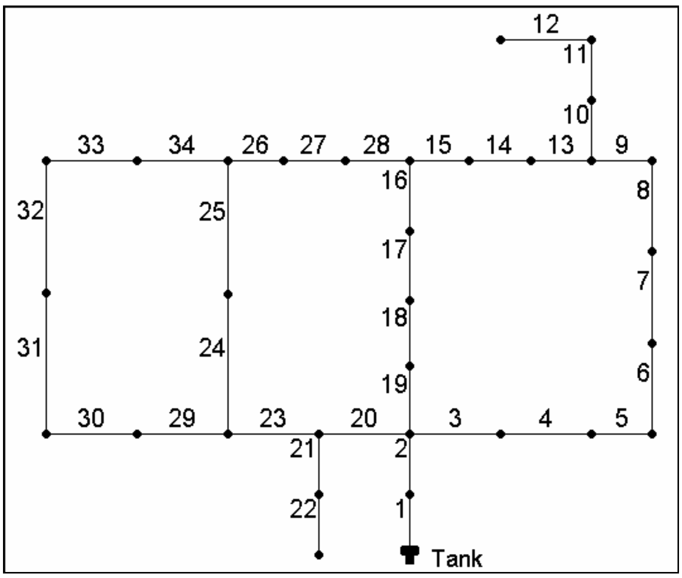

Fig. 4. Hanoi network (Case 2)

The GANRnet program was applied to Hanoi network. Two runs (trials) were performed using different values for μGA parameters:

Trial 1: *Npopsiz* = 17, *Idum* = –400, *Maxgen* = 1145 and *Nposibl* = 32.

Trial 2: *Npopsiz* = 23, *Idum* = –100, *Maxgen* = 1137 and *Nposibl* = 32.

The mutation and crossover rates were set to 0.2 and 0.5, respectively.

Figure 5 illustrates the cost evolution for the two trials. In the second trial, the decrease in the cost value for the first group of evaluation is slower than that of the first trial.

Table 4. Data for Hanoi network (Case 2)

Node	Demand (m^3/h)	Pipe	Start Node	End Node	Length (m)
1 Source	–19,940	1	1	2	100.00
2	890	2	2	3	1,350.00
3	850	3	3	4	900.00
4	130	4	4	5	1,150.00
5	725	5	5	6	1,450.00
6	1,005	6	6	7	450.00
7	1,350	7	7	8	850.00
8	550	8	8	9	850.00
9	525	9	9	10	800.00
10	525	10	10	11	950.00
11	500	11	11	12	1,200.00
12	560	12	12	13	3,500.00
13	940	13	10	14	800.00
14	615	14	14	15	500.00
15	280	15	15	16	550.00
16	310	16	16	17	2,730.00
17	865	17	17	18	1,750.00
18	1,345	18	18	19	800.00
19	60	19	3	19	400.00
20	1,275	20	3	20	2,200.00
21	930	21	20	21	1,500.00
22	485	22	21	22	500.00
23	1,045	23	20	23	2,650.00
24	820	24	23	24	1,230.00
25	170	25	24	25	1,300.00
26	900	26	25	26	850.00
27	370	27	26	27	300.00
28	290	28	16	27	750.00
29	360	29	23	28	1,500.00
30	360	30	28	29	2,000.00
31	105	31	29	30	1,600.00
32	805	32	30	31	150.00
		33	31	32	860.00
		34	25	32	950.00

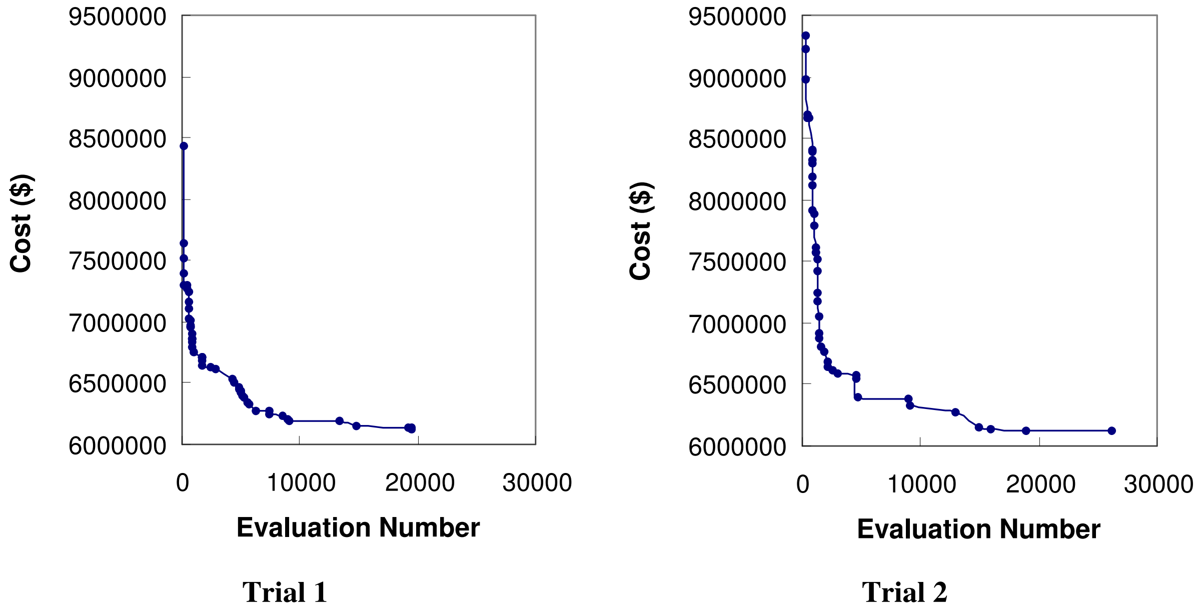

Fig. 5. Cost evolution (Case 2)

It should be mentioned that some of the previous studies dealt with split-pipe solutions. This kind of split-pipe design is less realistic, [12] and are not allowed in the present study.

Table 5 lists solutions for the Hanoi network found in the literature. The best network designs obtained by different authors are given in terms of cost (millions of dollars) and selected diameters (inches). Alongside these solutions, two solutions obtained by GANRnet are presented for comparison. The total search space for this network is $6^{34} = 2.87 \times 10^{26}$ different possible network designs. According to the number of function evaluations (F.E.N.) in Table 5, each algorithm reaches the optimal solution in a very small percentage of all possible designs.

The comparison between the network hydraulic simulation results of the present study with that of other researchers can be achieved by dealing with all the results of the different algorithms by EPANET network solver. This method will overcome the problem of the Hazen-Williams formula constant, which is a source of additional uncertainty associated with results obtained, [12].

Taking the EPANET solution as a reference solution and using the optimal diameters obtained by each study in the EPANET solver, the resulted pressure heads are given in Table 6. It can be observed that some of these solutions give infeasible solutions ($H < 30$m), such as Savic and Walters [12] - GA1 solution and Cunha and Sousa [19]. These two solutions are discarded, as the pressure head requirements are not fulfilled although these pressure heads are near from feasibility.

Table 5. Optimal diameters (in.) for Hanoi network (Case 2)

Pipe Number	Pipe Diameter (in)							
	Savic and Watters [12]		Abebe and Solomatine [14]		Cunha and Sousa [19]	Liong and Atiquzzaman [21]	Present Study	
							Trial 1	Trial 2
	GA1	GA2	GA	ACCOL	SA	SCE	GA	GA
1	40	40	40	40	40	40	40	40
2	40	40	40	40	40	40	40	40
3	40	40	40	40	40	40	40	40
4	40	40	40	40	40	40	40	40
5	40	40	30	40	40	40	40	40
6	40	40	40	30	40	40	40	40
7	40	40	40	40	40	40	40	40
8	40	40	30	40	40	30	40	40
9	40	30	30	24	40	30	40	30
10	30	30	30	40	30	30	30	30
11	24	30	30	30	24	30	24	30
12	24	24	30	40	24	24	24	24
13	20	16	16	16	20	16	16	20
14	16	16	24	16	16	12	16	12
15	12	12	30	30	12	12	12	12
16	12	16	30	12	12	24	12	12
17	16	20	30	20	16	30	20	16
18	20	24	40	24	20	30	24	24
19	20	24	40	30	20	30	20	24
20	40	40	40	40	40	40	40	40
21	20	20	20	30	20	20	20	20
22	12	12	20	30	12	12	12	12
23	40	40	30	40	40	30	40	40
24	30	30	16	40	30	30	30	30
25	30	30	20	40	30	24	30	30
26	20	20	12	24	20	12	20	20
27	12	12	24	30	12	20	12	16
28	12	12	20	12	12	24	12	12
29	16	16	24	16	16	16	16	16
30	16	16	30	40	12	16	16	16
31	12	12	30	16	12	12	12	12
32	12	12	30	20	16	16	16	20
33	16	16	30	30	16	20	16	20
34	20	20	12	24	24	24	20	20
Cost *	**6.073**	**6.195**	**7.000**	**7.800**	**6.056**	**6.220**	**6.127**	**6.120**
F.E.N.	/	/	16,910	3,055	53,000	25,402	19,455	26,132
Run Time	**3 hr**	**3 hr**	**75 min**	**15 min**	**2 hr**	**11 min**	**34 sec****	**45 sec****

* Cost in millions of Dollars.

** Run time is produced on a computer with Pentium 4 (1.7 GHz) processor.

Table 6. Pressure head for Hanoi network (Case 2)

Node Number	Nodal Pressure (m)							
	Savic and Watters [12]		Abebe and Solomatine [14]		Cunha and Sousa [19]	Liong and Atiquzzaman [21]	Present Study	
							Trial 1	Trial 2
	GA1	GA2	GA	ACCOL	SA	SCE	GA	GA
1	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00
2	97.14	97.14	97.14	97.14	97.14	97.14	97.14	97.14
3	61.63	61.63	61.67	61.67	61.63	61.67	61.67	61.67
4	56.83	57.26	58.59	57.68	56.82	57.54	57.12	57.11
5	50.89	51.86	54.82	52.75	50.86	52.43	51.49	51.45
6	44.62	46.21	39.45	47.65	44.57	47.13	45.58	45.51
7	43.14	44.91	38.65	42.95	43.10	45.92	44.20	44.13
8	41.38	43.40	37.87	41.68	41.33	44.55	42.59	42.50
9	39.97	42.23	35.65	40.70	39.91	40.27	41.31	41.21
10	38.93	38.79	34.28	32.46	38.86	37.24	40.38	37.41
11	37.37	37.23	32.72	32.08	37.30	35.68	38.82	35.85
12	33.94	36.07	31.56	30.92	33.87	34.52	35.39	34.69
13	<u>29.72*</u>	31.86	30.13	30.56	<u>29.66*</u>	30.32	31.18	30.48
14	35.06	33.19	36.36	30.55	34.94	34.08	32.44	34.64
15	33.07	32.90	37.17	30.69	32.88	34.08	31.56	30.79
16	30.15	33.01	37.63	30.74	<u>29.79*</u>	36.13	31.15	30.27
17	30.24	40.73	48.11	46.16	<u>29.95*</u>	48.64	41.11	34.88
18	43.91	51.13	58.62	54.41	43.81	54.00	48.44	53.41
19	55.53	58.03	60.64	60.58	55.49	59.07	54.27	58.83
20	50.39	50.63	53.87	49.23	50.43	53.62	50.53	50.32
21	41.03	41.28	44.48	47.92	41.07	44.27	41.18	40.98
22	35.86	36.11	44.05	47.86	35.90	39.11	36.01	35.81
23	44.15	44.61	39.83	41.96	44.24	38.79	44.37	43.99
24	38.84	39.54	30.51	40.18	38.50	36.37	39.14	38.51
25	35.48	36.40	30.50	38.95	34.79	33.16	35.85	35.02
26	31.46	32.93	32.14	36.01	30.87	33.44	32.02	30.72
27	30.03	32.18	32.62	35.93	<u>29.59*</u>	34.38	30.85	30.27
28	35.43	36.02	33.52	36.47	38.60	32.64	35.80	35.58
29	30.67	31.38	31.46	36.45	<u>29.64*</u>	30.05	31.18	31.09
30	<u>29.65*</u>	30.47	30.44	36.54	<u>29.90*</u>	30.10	30.28	30.31
31	30.12	30.95	30.39	36.64	30.18	30.35	30.40	30.36
32	31.36	32.24	30.17	36.76	32.64	31.09	31.69	30.81

* Infeasible solution (pressure head is less than 30 m) when EPANET network solver is used

Table 7 displays the corresponding nodal heads for the two trials of the present study obtained as a result of simulation by both EPANET and Newton-Raphson technique used in the GANRnet program. As previously observed in Case 1, the pressure heads resulted from the Newton-Raphson technique are smaller than that of EPANET by 0.03 to 0.05 m which is in the acceptable accuracy.

Table 7. Pressure head for Hanoi network (Case 2)

Node	Pressure Head (m)			
	Trial 1		Trial 2	
	EPANET	Newton-Raphson	EPANET	Newton-Raphson
1	00.00	00.00	00.00	00.00
2	97.14	97.14	97.14	97.14
3	61.67	61.64	61.67	61.64
4	57.12	57.09	57.11	57.07
5	51.49	51.45	51.45	51.41
6	45.58	45.54	45.51	45.47
7	44.20	44.16	44.13	44.09
8	42.59	42.54	42.50	42.46
9	41.31	41.27	41.21	41.17
10	40.38	40.34	37.41	37.36
11	38.82	38.78	35.85	35.80
12	35.39	35.35	34.69	34.64
13	31.18	31.14	30.48	30.43
14	32.44	32.39	34.64	34.60
15	31.56	31.51	30.79	30.75
16	31.15	31.11	30.27	30.23
17	41.11	41.08	34.88	34.84
18	48.44	48.41	53.41	53.37
19	54.27	54.24	58.83	58.80
20	50.53	50.49	50.32	50.29
21	41.18	41.14	40.98	40.94
22	36.01	35.98	35.81	35.77
23	44.37	44.33	43.99	43.95
24	39.14	39.09	38.51	38.47
25	35.85	35.80	35.02	34.97
26	32.02	31.98	30.72	30.67
27	30.85	30.81	30.27	30.22
28	35.80	35.76	35.58	35.54
29	31.18	31.13	31.09	31.05
30	30.28	30.23	30.31	30.27
31	30.40	30.35	30.36	30.31
32	31.69	31.64	30.81	30.76

The results from Tables 5 to 7 yields that using the cost as the assessment of the quality of the designs, then the solution by Cunha and Sousa [19] ($6.056 million) is superior among the results shown in Table 5. However, the pressure head requirement at nodes

13, 16, 17, 27, 29 and 30 is not met. Savic and Walters [12] obtained a slightly greater network cost ($6.073 million) but the resulting pressure heads at nodes 13 and 30 do not meet the head constraints, Table 6. Then according to the fulfillment of the pressure constraint, the best previous solution is the GA2 of Savic and Walters [12] ($6.195 million). It should be noted that the results of Vairavamoorthy and Ali [17] are similar to that of Cunha and Sousa [19] and therefore are not shown in Table 6.

The present study using the GANRnet program and the new adaptive penalty method shows two new optimal costs. The final network cost, Trial 1 ($6.127 million) requires 19,455 function evaluations and computational time of only 34 sec and the other is Trial 2, ($6.120 million) and requires 26,132 function evaluations and computational time of only 45 sec. These two optimal solutions which are the lowest costs and with the faster run time compared to previous studies make it possible to apply the GANRnet program to more complicated and actual networks.

The importance of the adaptive penalty coefficient can be illustrated when it is compared with the constant penalty coefficient c, Eq. (11). Figure 6 compares the convergence rates of the GA optimization for two different constant penalty coefficient values (1,000,000 and 10,000,000) and for the adaptive penalty coefficient $c = C_T / M$. For these GA runs, all the parameters of the GA have the same values as that of Trial 2. The figure shows that the optimality of the final solution depends on the penalty coefficient value being used. Also, the GA optimization with the adaptive penalty coefficient improves the search process very quickly in the early stages of the optimization compared with the constant penalty coefficient. This indicates that the adaptive penalty coefficient guarantees a reliable solution and improves the efficacy of GA optimization.

CONCLUSIONS

The determination of the optimal design for water distribution networks is computationally complex. In this paper, a binary-coded GA method coupled with the Newton-Raphson technique (the hydraulic solver) is proposed for the optimal design of water distribution systems. A new adaptive penalty function is presented. It has many advantages mainly it does not contain any constant values; the penalty cost is a function of the total cost, the number of nodes, and the node pressure head. Also, it is fast to reach the global optimization and it decreases the computational time.

The method was tested on two networks, the two-loop and the Hanoi networks, and has been shown to be efficient and robust. For the two-loop network, the results compared with that of other authors are favorable. For the Hanoi network, two solutions, which are the lowest costs, are achieved.

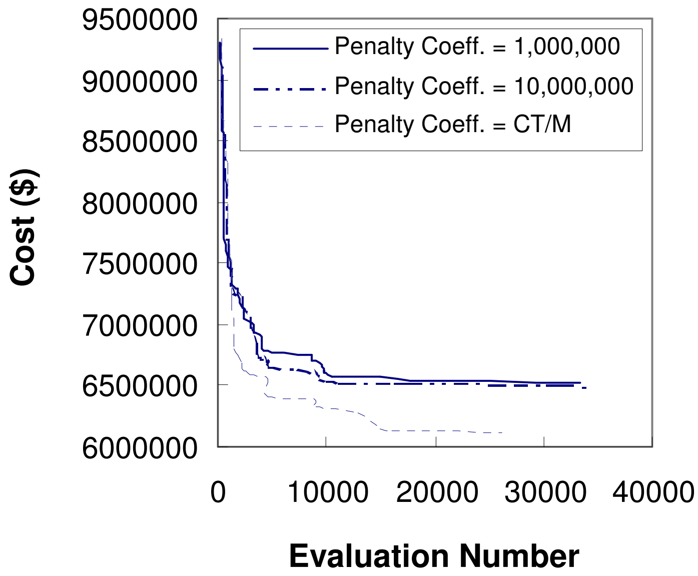

Fig. 6. Comparison between the cost evolution using constant and adaptive penalty coefficients (Case 2)

Generally, the proposed method produces good results quickly although; it is not appropriate to compare CPU times because of the different computer platforms used in the previous studies. The GANRnet program finds the least cost in a favorable number of function evaluations if not less than that mentioned in the other researches. The adaptive penalty function used in the GANRnet program helps to find least cost solutions in a small run time. This makes it possible to apply it to more complicated and actual networks.

NOMENCLATURE

C_i	Hazen-Williams coefficient of pipe *i*
C_P	penalty cost
C_T	total cost
c	penalty draw-down coefficient
$c_i(D_i)$	cost of pipe *i* with diameter D_i per unit length
D_i	diameter of pipe *i*, (m)
$D_{\max}$	maximum diameter, (m)
$D_{\min}$	minimum diameter, (m)
E_p	energy supplied by a pump, (m)
$f(x)$	function
F.E.N.	Function Evaluation Number
H_j	pressure head at node *j*, (m)

$H_{j,\max}$	maximum allowable pressure head at node *j*, (m)
$H_{j,\min}$	minimum required pressure head at node *j*, (m)
h_f	head loss due to friction in a pipe, (m)
Idum	initial random number seed for the GA run
L_i	length of pipe *i*, (m)
M	total number of nodes in the network
Maxgen	maximum number of generations to run by the GA
N	total number of pipes
Npopsiz	population size of a GA run
Nposibl	array of integer number of possibilities per parameter
$\mathrm{P}(x)$	penalty function
Q_i	flow in pipe *i*, (m^3/s)
Q_j	discharges into or out of the node *j*, (m^3/s)
V_i	fluid velocity in pipe *i*, (m/s)
Z	objective function

ABBREVIATIONS

ACCOL	Adaptive Cluster Covering with Local Search
GA	Genetic Algorithm
SA	Simulated Annealing
SCE	Shuffled Complex Evolution
SFLA	Shuffled Frog Leaping Algorithms

REFERENCES

[1] **Stephenson, D.,** *Pipeflow Analysis*, Elsevier Science Publishers B.V., 1984.

[2] **Alperovits, E., and Shamir, U.,** "Design of Optimal Water Distribution Systems," *Water Resources Research*, Vol. 13, No. 6, 1977, pp. 885-900.

[3] **Kessler, A., and Shamir, U.,** "Analysis of the Linear Programming Gradient Method for Optimal Design of Water Supply Networks," *Water Resources Research*, Vol. 25, No. 7, 1989, pp. 1469-1480.

[4] **Eiger, G., Shamir, U., and Ben-Tal, A.,** "Optimal Design of Water Distribution Networks," *Water Resources Research*, Vol. 30, No. 9, 1994, pp. 2637-2646.

[5] **Sonak, V.V., and Bhave, P.R.,** "Global Optimum Tree Solution for Single-Source Looped Water Distribution Networks Subjected to a Single Loading Pattern," *Water Resources Research*, Vol. 29, No. 7, 1993, pp. 2437-2443.

[6] **Sârbu, I., and Borza, I.,** "Optimal Design of Water Distribution Networks," *Journal of Hydraulic Research,* Vol. 35, No. 1, 1997, pp. 63-79.

[7] **Samani, H.M.V., and Naeeni, S.T.,** "Optimization of Water Distribution Networks," *Journal of Hydraulic Research*, Vol. 34, No. 5, 1996, pp. 523-632.

[8] **Djebedjian, B., Herrick, A., and Rayan, M.A.,** "Modeling and Optimization of Potable Water Network," *International Pipeline Conference and Technology Exposition 2000*, October 1-5, 2000, Calgary, Alberta, Canada.

[9] **Sârbu, I., and Kalmár, F.,** "Optimization of Looped Water Supply Networks," *Periodica Polytechnica* Ser. Mech. Eng., Vol. 46, No. 1, 2002, pp. 75-90.

[10] **Simpson, A.R., Dandy, G.C., and Murphy, L.J.,** "Genetic algorithms Compared to Other Techniques for Pipe Optimisation," *Journal of Water Resources Planning and Management*, ASCE, Vol. 120, No. 4, July/August, 1994, pp. 423-443.

[11] **Dandy, G.C., Simpson, A.R., and Murphy, L.J.,** "An Improved Genetic Algorithm for Pipe Network Optimization," *Water Resources Research*, Vol. 32, No. 2, 1996, pp. 449-458.

[12] **Savic, D.A., and Walters, G.A.,** "Genetic Algorithms for Least-Cost Design of Water Distribution Networks," *Journal of Water Resources Planning and Management*, ASCE, Vol. 123, No. 2, 1997, pp. 67-77.

[13] **Abdel-Gawad, H.A.A.,** "Optimal Design of Pipe Networks by an Improved Genetic Algorithm," Proceedings of the *Sixth International Water Technology Conference IWTC 2001*, Alexandria, Egypt, March 23-25, 2001, pp. 155-163.

[14] **Abebe, A.J., and Solomatine, D.P.,** "Application of Global Optimization to the Design of Pipe Networks," Proceedings of the *3rd International Conference on Hydroinformatics*, Copenhagen, August 1998.

[15] **Lippai, I., Heaney, J.P., and Laguna, M., 1999,** "Robust Water System Design with Commercial Intelligent Search Optimizers," *Journal of Computing in Civil Engineering*, Vol. 13, No. 3, pp. 135-143.

[16] **Gupta, I., Gupta, A., and Khanna, P.,** "Genetic Algorithm for Optimization of Water Distribution Systems," *Environmental Modelling & Software*, Vol. 14, 1999, pp. 437-446.

[17] **Vairavamoorthy, K., and Ali, M., 2000,** "Optimal Design of Water Distribution Systems Using Genetic Algorithms," *Computer-Aided Civil and Infrastructure Engineering*, Vol. 15, pp. 374-382

[18] **Wu, Z.Y., and Simpson, A.R.,** "A Self-Adaptive Boundary Search Genetic Algorithm and its Application to Water Distribution Systems," *Journal of Hydraulic Research*, Vol. 40, No. 2, 2002, pp. 191-203.

[19] **Cunha, M.D.C., and Sousa, J.,** "Water Distribution Network Design Optimization: Simulated Annealing Approach," *Journal of Water Resources Planning and Management,* ASCE, Vol. 125, No. 4, 1999, pp. 215-221.

[20] **Eusuff, M.M., and Lansey, K.E.,** "Optimization of Water Distribution Network Design Using the Shuffled Frog Leaping Algorithm," *Journal of Water Resources Planning and Management*, ASCE, Vol. 129, No. 3, 2003, pp. 210-225.

[21] **Liong, S-Y., and Atiquzzaman, Md.,** "Optimal Design of Water Distribution Network using Shuffled Complex Evolution," *Journal of the Institution of Engineers, Singapore*, Vol. 44, Issue 1, 2004, pp. 93-107.

[22] **Watters, G.Z.,** *Analysis and Control of Unsteady Flow in Pipelines*, 2nd Edition, Butterworth Publishers, 1984.

[23] **Crossley, W.A., and Williams, E.A.,** "A Study of Adaptive Penalty Functions for Constrained Genetic Algorithm Based Optimization," In *AIAA 35th Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, January 1997. AIAA Paper 97-0083. [http://www.cs.cinvestav.mx/~constraint/papers/crossley97.pdf]

[24] **Gen, M., and Cheng, R.,** *Genetic Algorithms & Engineering Optimization*, John Wiley & Sons, Inc., New York, 2000.

[25] **Krishnakumar, K.,** "Micro-Genetic Algorithms for Stationary and Non-Stationary Function Optimization," *Proc. Soc. Photo-Opt. Instrum. Eng.* (*SPIE*) *on Intelligent Control and Adaptive Systems*, Vol. 1196, Philadelphia, PA, 1989, pp. 289-296.

[26] **Simpson, A.R., Murphy, L.J., and Dandy G.C.,** "Pipe Network Optimization using Genetic Algorithms," Paper presented at ASCE, *Water Resources Planning and Management Specialty Conference*, ASCE, Seattle, USA, 1993.

[27] **Rossman, L.A.,** *EPANET, Users Manual.* U.S. Environmental Protection Agency, Cincinnati, Ohio, 1993.

[28] **Todini, E., and Pilati, S.,** "A Gradient Method for the Analysis of Pipe Networks," *Proceedings of the International Conference on Computer Applications for Water Supply and Distribution*, Leicester Polytechnic, Leicester, U.K., September 1987.

[29] **Fujiwara, O., and Khang, D.B.,** "A Two-Phase Decomposition Method for Optimal Design of Looped Water Distribution Networks," *Water Resources Researc*h, Vol. 26, No. 4, 1990, pp. 539-549.