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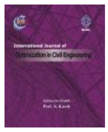

SIMULTANEOUS ANALYSIS, DESIGN AND OPTIMIZATION OF WATER DISTRIBUTION SYSTEMS USING SUPERVISED CHARGED SYSTEM SEARCH

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ABSTRACT

The present study encompasses a new method to simultaneous analysis, design and optimization of Water Distribution Systems (WDSs). In this method, analysis procedure is carried out using Charged System Search (CSS) optimization algorithm. Besides design and cost optimization of WDSs are performed simultaneous with analysis process using a new objective function in order to satisfying the analysis criteria, design constraints and cost optimization. Comparison of achieved results clearly signifies the efficiency of the present method in reducing the WDSs construction cost and computational time of the analysis. These comparisons are made for three benchmark practical examples of WDSs.

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KEY WORDS: analysis, design, optimization, water distribution system, supervised charged system search

1. INTRODUCTION

In this era, the growth of population in urban areas has increased the importance of the resource management. Diminishing of the resources has also increased the need for reducing the costs in the 21st century.

One of the most imperative fields in which the optimization and resource management needs special consideration is water distribution system. Water distribution system is an

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essential infrastructure, which consists of hydraulic components such as pipes, valves, and reservoir and pumps in order to supply water in the highly capitalized societies in desired quantity for consumers and in a reliable form. This configuration usually simplifies by the graph layout that has a number of nodes denoting the places in urban area, lines denoting the pipes, and other features such as reservoir and pumps. The construction and maintains of water distribution system pipelines to supply water can cost millions of dollars every year.

Traditionally water distribution system design is based on trial-and-error methods employing the experience. However, in the light of the optimization of cost and profits, designing the best layout of water supply system counting the best selection of water demands and pipe length and diameter within the millions of possible configuration, attracted a large amount of literature during the last decades. The majority of literatures have focused on cost; though, other ones deal with other aspects of design, such as reliability.

The nonlinear nature of equations involved in water distribution system, conservation of mass and energy (hydraulic head loss) equations, made this field of engineering as a fascinating challenging one. The research in optimization has attracted many researchers focusing on various programming methods such as linear and non-linear programming [1-3]. Alperovits and Shamir [4] reduced the complexity of an original nonlinear problem by solving a series of linear sub-problems. In this method a linear programming problem is solved for a given flow distribution, and then a search is conducted in the space of the flow variables. This method was followed and other methods were developed, examples of which are Quindry *et al*. [5], Goulter *et al*. [6], Kessler and Shamir [7], and Fujiwara and Kang [8] who used the two-phase decomposition method. Heuristic methods such as Genetic Algorithms [9-13], Ant colony optimization [14, 15], the Shuffled Frog-Leaping Algorithm [16] were also utilized in several optimization approaches for water distribution networks. Geem [17], who developed harmony search (HS) and particle-swarm harmony search (PSHS) and Eusuff and Lansey [18], who proposed an SFLA models are also employed their techniques for water distribution optimization. Tolson et al. [19] developed a hybrid discrete-dynamically dimensioned search (HD-DDS) algorithm to perform optimal design of water distribution system.

One of the most reliable meta-heuristic methods recently developed by Kaveh and Talatahari [20] is Charged System Search (CSS). The CSS algorithm is used in this study as an optimization algorithm together with performing as an analyzer instead of classic analyzer such as Newton-Raphson approach.

In the classic methods pipe demands are often calculated using indirect methods and pre-selected pipe sizes are utilized. However in the present work, the pipe sizes and demands are considered as the optimization variables leading to simultaneous analysis, design and optimization.

2. URBAN WATER DISTRIBUTION NETWORK OPTIMIZATION PROBLEM

The water distribution network optimization problem is defined as the selection of the most desirable configuration of circulation network considering the allowable pipe diameter and water demand in each point while satisfying various possible objectives such as network reliability, redundancy, water quality. One of the most common and favorable objective function of water distribution system is considered as minimizing the network arrangement cost, by suitable selection of pipe diameters and lengths. This can be expressed as

$$C = \sum_{i=1}^{N} f(D_i, L_i) \tag{1}$$

where $f(D_i, L_i)$ is the cost of the i_{th} pipe, with diameter D_i and length L_i, and N is the number of pipes in the network configuration.

In each engineering problem two phases should be performed to achieve a goal, analysis and design. In the Water distribution systems problem, which is a complex system of pipes, the goal is defined as the length and diameters of the pipes forming a complex configuration while obtain the required water demands at certain points of the network.

2.1. Analysis phase

In the analysis phase, the goal is to achieve a distribution of water for the postulated configuration of pipe lengths and diameters among an infinite number of distributions. This is achieved in the light of the fact that only our proposed distribution should satisfy the continuity equation in each nodes, and satisfy the hydraulic head loss principle in the system loops. In other word, only a few distributions can assure the continuity equation in each node and through these distributions, only one distribution can satisfy the hydraulic head loss equations.

Continuity equation or mass conservation at each node is given by

$$\sum Q_{in} - \sum Q_{out} = Q_e \tag{2}$$

where Q_{in} is the volumetric flow rate to the node, Q_{out} is the flow rate out of the node, and Q_e is the external inflow rate to the node.

Considering that each loop is actually a series of pipe of the configuration, where the differences between the head losses of the two end nodes of its pipes should be summed in order to find the head loss of the entire loop. For conservation of energy this sum should be equal to zero. Obviously if a loop has other features such as pumps, its energy interactions should also be added to the conservation equation formula as

$$\sum h_f - \sum E_p = 0 \tag{3}$$

where h_f is the hydraulic head loss calculated by Hazen-Williams formulae and E_p is the energy added to water at the loop by a pump. The above equation is also known as the hydraulic head loss equation.

For the analysis of a water distribution system fundamental principles of water systems are used. The principle of water branching has an interesting analogy with characteristics of electric circuit when rate of the flow corresponds to the electric current and the head loss correspond to the drop in potential. The hydraulic head loss, between two nodes *i* and *j*, can be expressed by Hazen-Williams formula as:

$$h_f = \omega \frac{L}{C^{\alpha} D^{\beta}} Q^{\alpha} \tag{4}$$

where ω is a numerical conversion constant; α is a coefficient equal to 1.85; and β is a coefficient equal to 4.87.

Based on the analogy between the electric circuits and the pipe branching, when two pipes are in the form of series, the head loss in this series configuration will equal to the sum of head losses of the constituting pipes (determined by Eq. (4)), and the flow is equal to the flow rate of each pipe.

$$\Delta h_t = \omega \frac{L_a}{C_a^{\alpha} D_a^{\ \beta}} Q^{\alpha} + \omega \frac{L_b}{C^{\alpha} D_b^{\beta}} \tag{5}$$

$$Q_t = Q_a = Q_b \tag{6}$$

where *a* and *b* denote the pipe *a* and pipe *b* which are used in the parallel configuration of pipe network.

Now considering the fact that each network may include a combination of parallel and series arrangement of branching pipes, the formulation of water distribution network is obvious. However a network configuration has other features such as loops and reservoir, which should be carefully dealt with, and as a result other equation should be set to achieve the best supply system.

2.1. Design phase

In the design phase of the water distribution system, the pipe diameters satisfying the water demand in each node and place of the urban area should be determined.

As previously mentioned, in this section the third imperative requirement of the water distribution system design should be set. This requirement is the minimum pressure requirement which is usually has a restricted limitation to prevent system failure. Thus during the network configuration assortment, the pressure in each point should be checked. Mathematically the minimum pressure requirement is presented in following form:

$$H_j \geq H_j^{\min}; j = 1,...,M \tag{7}$$

where H_j, $H_j^{\min}$ and M denote the pressure head at node *j*, minimum required pressure at node *j*, and the number of nodes in the network, respectively. Other requirements such as reliability, minimum and maximum limitation of the velocity and the maximum pressure

should be satisfied in the design phase.
To attain a network that satisfies the water requirement, conservation of mass and energy equations in each node and loop should be coupled and solved. These equations can be arranged in the following form:

$$\boldsymbol{H} \times \boldsymbol{q_p} - \begin{bmatrix} \boldsymbol{Q} \\ \boldsymbol{Null(M,1)} \end{bmatrix} = 0 \tag{8}$$

where $\boldsymbol{Q}$ is the demand in each node, and $\boldsymbol{Null(M,1)}$ is a M×1 zero vector with M being the number of loops. This zero vector indicates that in each loop the summation of pipe's head losses should be zero, as the conservation of energy implies. It can be seen that N demands node (N conservation of mass equation for each node) and M loop energy conservation equation, construct the above form of equations. $\boldsymbol{q_p}$ denote the flow rate of each pipe.

The matrix $\boldsymbol{H}$ consists of two essential parts. The first part corresponds to the equation of the conservation of mass consisting of some positive and negative 1, indicating the input and output flow rate of each node. Besides there are some 0 entries which obviously signify the pipes that are not relevant to considered node in that equation whose flow rate is considered in q matrix in the same row. The second part of $\boldsymbol{H}$, corresponds to M loops, containing some positive and negative coefficients which are determined considering the flow rate direct in each pipe, being assumed at the first step of the analysis (conservation of mass) and the postulated direction of the loops. These coefficients are determined using the Hazen-Williams formula. As previously mentioned the primary directions assigned to the pipes may not satisfy the conservation of energy equation, and the correct directions are decided in the process of design. As an example, Figure. 1 depicts a fundamental simple WDSs example whose satisfaction equations can be presented as follows:

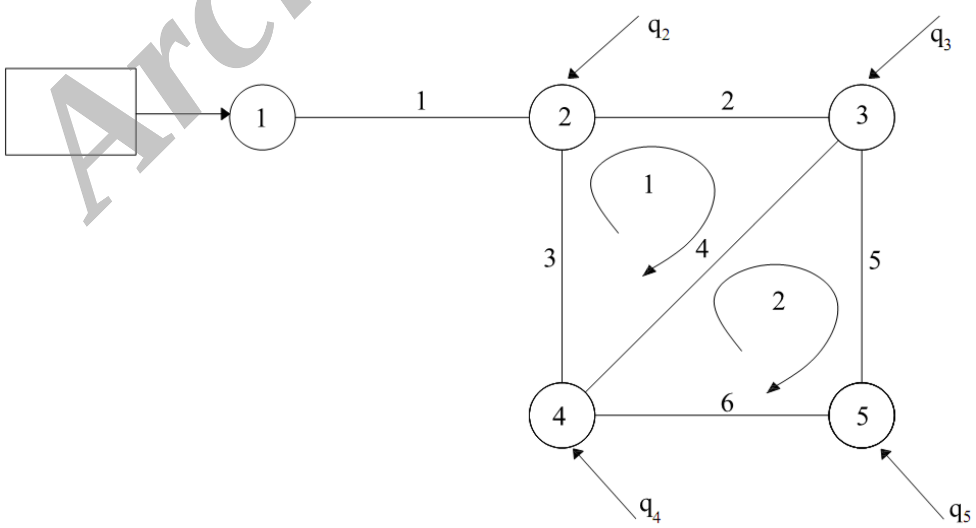

Figure 1. An example of simple fundamental WDSs

$$\sum_{l \to k} \pm q_l = -Q_K \quad k = 1,2,...,5 \tag{9}$$

$$\sum_{l \to m} \pm A_l |q_l|^{n-1} q_l = 0.0 \quad m = 1,2 \tag{10}$$

$$\begin{bmatrix} 1 & -1 & -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & -1 & -1 & 0 \\ 0 & 0 & 1 & 1 & 0 & -1 \\ 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & A_2|q_2|^{n-1} & -A_3|q_3|^{n-1} & A_4|q_4|^{n-1} & 0 & 0 \\ 0 & 0 & 0 & -A_4|q_4|^{n-1} & A_5|q_5|^{n-1} & -A_6|q_6|^{n-1} \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \\ q_5 \\ q_6 \end{bmatrix} = \begin{bmatrix} -Q_2 \\ -Q_3 \\ -Q_4 \\ -Q_5 \\ 0.0 \\ 0.0 \end{bmatrix} \tag{11}$$

where $A = \omega \dfrac{L}{C^{\alpha} D^{\beta}}$. As an example, in the first 4 rows of this H matrix (corresponding to 4 nodes where the water is being used) the first part of H is presented. In the first row of matrix, the entry for the pipe number 1 is positive since the direction of the flow in this pipe has an input role to the point. While the pipes 2 and 3 play the output role. As an illustration of the second part, bearing in mind the first loop, pipe numbers 2 and 4 and thus are negative. The second part of the matrix considering the loop 1, one can say that: the direction of the pipes 2 and 4 are the same as the direction of the loop 1, thus have positive signs. While the pipe number 2 acts in the reverse direction of the loop direction.

Finally it should be mentioned that, in this paper, similar to that of the Fujiwara and Kang [8], to achieve a better design, the configuration of series pipes which have the standard pipe diameters are used. For example if the program chooses the pipes with the 38 inch diameter for the system which does corresponds to neither the standard 30 inch nor to the 40 inch pipes, the later subroutine would change the pipe to two series pipes. One of the pipes would have diameter equal to 30 inch and the other will be 40 inch. This exchange should be made such that the sum of the lengths of two pipes is the same as the primary pipe. Since these two pipes should have the same demand as that of the primary pipe, and the total hydraulic head loss of these two pipes should be equal to the primary pipe.

3. THE CHARGED SYSTEM SEARCH ALGORITHM

3.1. The standard CSS

Charged System Search is one of the meta-heuristic search methods that is recently developed and utilized in many optimization problems. It is a population-based search approach, where each agent (CP) is considered as a charged sphere with radius a, having a uniform volume charge density which can produce an electric force on the other CPs. The force magnitude for a CP located in the inside of the sphere is proportional to the separation distance between the CPs, while for a CP located outside the sphere it is inversely proportional to the square of the separation distance between the particles. The resultant forces or acceleration and the motion laws determine the new location of the CPs [20, 21]. The pseudo-code for the CSS algorithm can be summarized as follows:

Step 1: Initialization.

The initial positions of CPs are determined randomly in the search space and the initial velocities of charged particles are assumed to be zero. The values of the fitness function for the CPs are determined and the CPs are sorted in an increasing order. A number of the first CPs and their related values of the fitness function are saved in a memory, so called charged memory (CM).

Step 2: Determination of forces on CPs.

The force vector is calculated for each CP as

$$\mathbf{F_J} = \sum_{i,i\neq j}\left(\frac{q_i}{a^3}.r_{i,j}.i_1 + \frac{q_i}{r_{i,j}^{\ 2}}.i_2\right)ar_{i,j}P_{i,j}\left(\mathbf{X_i}-\mathbf{X_j}\right)\left\langle\begin{array}{l} i_1 = 1, i_2 = 0 \Leftrightarrow r_{i,j} < a \\ i_1 = 0, i_2 = 1 \Leftrightarrow r_{i,j} \geq a \\ j = 1,2,\ldots,N \end{array}\right. \tag{12}$$

where F_j is the resultant force acting on the j th CP; N is the number of CPs. The magnitude of charge for each CP (q_i) is defined considering the quality of its solution as

$$q_i = \frac{fit(i) - fitworst}{fitbest - fitworst}, i = 1,2,\ldots,N \tag{13}$$

where *fitbest* and *fitworst* are the best and the worst fitness of all particles, respectively; *fit(i)*represents the fitness of the agent i; and N is the total number of CPs. The separation distance r_{ij} between two charged particles is defined as follows:

$$r_{i,j} = \frac{\left\|X_i - X_j\right\|}{\left\|\left(X_i - X_j\right)/2 - X_{best}\right\| + \varepsilon} \tag{14}$$

where X_i and X_j are respectively the positions of the ith and jth CPs, X_{best} is the position of the best current CP, and ε is a small positive number. Here, $P_{i,j}$ is the probability of moving each CP towards the others and is obtained using the following function:

$$P_{i,j} = \begin{cases} 1 & \dfrac{fit(i) - fitbest}{fit(j) - fit(i)} > rand \wedge fit(j) < fit(i) \\ 0 & else \end{cases} \tag{15}$$

In Eq. (30), $ar_{i,j}$ indicates the kind of force and is defined as

$$ar_{i,j} = \begin{cases} 1 & rand > 0.80 \\ 0 & else \end{cases} \tag{16}$$

where $rand$ represents a random number.

Step 3: Solution construction.

Each CP moves to the new position and the new velocity is calculated

$$X_{j,new} = rand_{j,1}.K_a.F_j + rand_{j,2}.K_V.V_{j,old} + X_{j,old} \tag{17}$$

$$V_{j,new} = X_{j,new} - X_{j,old} \tag{18}$$

where K_a is the acceleration coefficient; K_v is the velocity coefficient to control the influence of the previous velocity; $rand_{j,1}$ and $rand_{j,2}$ are two random numbers uniformly distributed in the rang (0, 1); K_a and K_v are taken as

$$K_a = 0.5 \times \left(1 + \frac{iter}{iter_{\max}}\right), K_v = 0.5 \times \left(1 - \frac{iter}{iter_{\max}}\right) \tag{19}$$

where $iter$ is the iteration number and $iter_{max}$ is the maximum number of iterations.

Step 4: Updating process.

If a new CP exits from the allowable search space, a harmony search-based handling approach is used to correct its position. In addition, if some new CP vectors are better than the worst ones in the CM; these are replaced by the worst ones in the CM.

Step 5: Termination criterion control.

Steps 2-4 are repeated until a termination criterion is satisfied.

3.2. An enhanced CSS algorithm

In the standard CSS algorithm, when the calculations of the amount of forces are completed for all CPs, the new locations of agents are determined. Also CM updating is fulfilled after moving all CPs to their new locations. All these conform to discrete time concept. In the optimization problems, this is known as iteration. On the contrary, in the enhanced CSS, time changes continuously and after creating just one solution, all updating processes are performed. Using this enhanced CSS, the new position of each agent can affect the moving process of the subsequent CPs while in the standard CSS unless an iteration is completed, the new positions are not utilized. All other aspects of the enhanced CSS are similar to the original one.

3.3. Supervised CSS algorithm

In the CSS algorithm, each vector of variables is an agent that moves through the search space and finds the minimal solutions. Throughout the search process, an agent might go to a coordinate in the search space that already has been searched by the same agent or another one. If this coordinates have a good fitness, it will be saved in the Charged Memory but if this coordinate does not have a good fitness, it will not be saved anywhere. Therefore, this step of the search process becomes redundant. This unnecessary step adversely affects the exploration ability of the algorithm. In this paper, the supervisor agents are introduced to improve the exploration ability of the CSS algorithm. The supervisor agent is an independent agent of constant values that repels the agent if its coordinate has a bad fitness or attracts the agents if its coordinate has a good fitness. This procedure is repeated in all of the iterations and gives an overall view of the search space. The number of supervisor agents is selected at the beginning of the algorithm, and then their constant coordinates in the search space are determined as follows:

$$xs_{j,i} = \frac{(i-1)[x_{max,j} - x_{min,j}]}{NOSA-1} + x_{min,j} \tag{20}$$

where NOSA is the number of supervisor agents, and $xs_{j,i}$ is the *j*th variable of the ith supervisor agent; $x_{min,j}$ and $x_{max,j}$ are the minimum and the maximum limits of the *j*th variable. The kind of the force for these agents is determined as

$$p = log(\frac{\overline{fit}}{fit_i}) \tag{21}$$

where *p* is the same as the parameter in the original version of the CSS, fit_i is equal to the fitness value of the *i*th supervisor agent and $\overline{fit}$ is the average value of the fitness of the normal agents. Calculating other properties of the supervisor agents such as force and radius are similar to the standard CSS algorithm. Supervisor agents do not move from their coordinate determined from Eq. (20), yet they apply additional forces on the normal agents. By doing so, they determine the fitness values of their fixed coordinate and its neighborhood, resulting in a better exploration ability of the CSS algorithm.

4. A NEW ALGORITHM FOR ANALYSIS AND DESIGN OF THE WATER DISTRIBUTION NETWORKS

As explained above, the matrix ***H*** known as the stability matrix of the network cannot be solved by a direct method. Thus this matrix is solved utilizing different indirect approaches such as Newton-Raphson and etc. Classic methods that use the above mentioned indirect approaches perform the analysis and design steps in separate steps requiring a considerable amount of computational time. But in the presented method analysis, design and optimization steps are performed simultaneously. In order to analyze a network we have to find a set of pipe demands that satisfies the Eq. (8) mentioned above.

In the present approach analysis phase is performed using the CSS algorithm by searching a vector of the pipe demands that satisfies the above equation. The left-hand side of this equation is a zero vector and should be changed to a scalar. The best is to find its norm. If this norm is zero all the entries should be zero. When the norm of a vector equals to zero then all the arrays of the vector equals to zeros. Considering the norm of the above matrix as the analysis constraints can be a reliable fundamental to this goal. Then simultaneous with the design, the analysis phase will be performed by considering the following objective function as the optimization goal function:

$$f(\mathbf{q_p}, D) = \sum_{i=1}^{L} l_i \times \cos t(D_i) \times (1 + norm(\mathbf{H} \times \mathbf{q_p} = \begin{bmatrix} \mathbf{Q} \\ \mathbf{Null(M,1)} \end{bmatrix})) + \sum_{i=1}^{L} g_i(q_i, D_i) \tag{22}$$

The following flowchart shows the schematic procedure of designing and analysis of a water distribution system using the CSS algorithm which is used in this study.

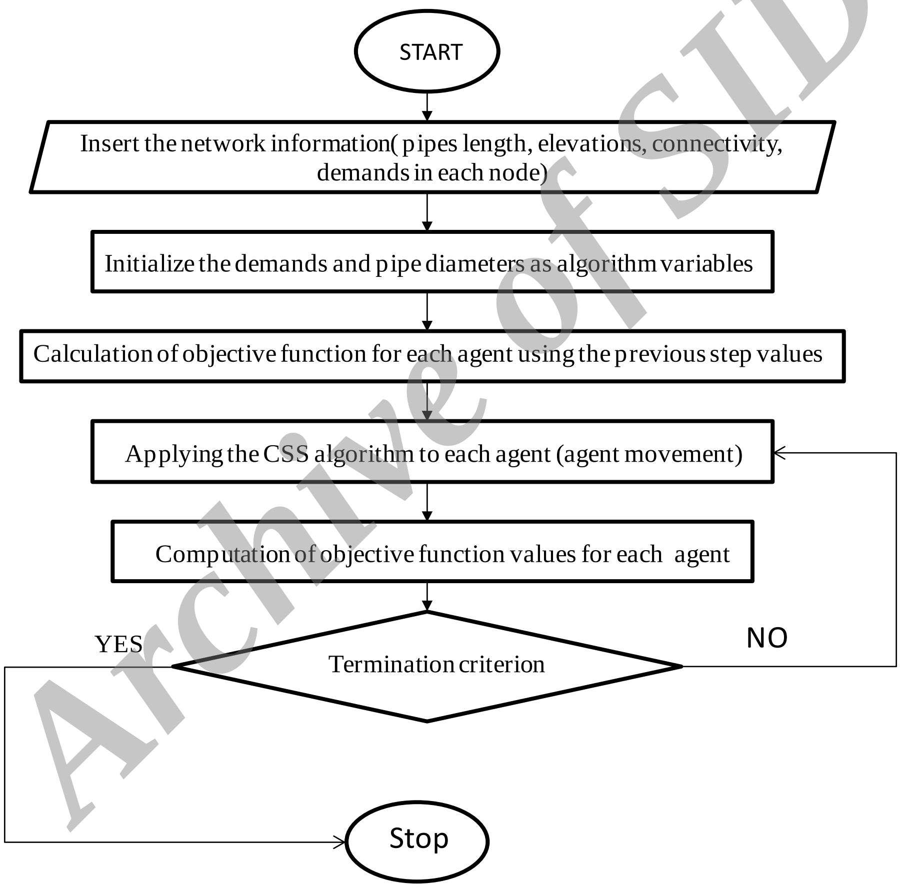

Figure 2. Flowchart of the present algorithm

5. DESIGN EXAMPLES

In order to assure that this method is reliable and capable in this field of science, the following sections explain the comparative study of cost optimization of water distribution system for some famous networks, which are studied by many other researchers.

5.1. A two-loop Network

The two loop network, depicted in Figure. 3, was studied by Shamir [7] for implementation of linear programming to acquire the least cost solution, considering the network pipes weight. Later this basic configuration was employed by different authors [2-7] for comparison of their results for optimal design of water distribution system as an illustrative simple network. This network is fed by gravity from a constant reservoir, which has 210 m fixed head. It consists of two-loop gravity flow pipeline, eight pipes, and seven study node for solving process. The length of all the pipes is assumed to be 1000 m with a Hazen-Williams coefficient (C) is equal to 130. Allowed pipe diameter and corresponding costs are available in Table 5 [17]. The Minimum head limitation in each pipe is set to 30 m above ground level. Here ω = 10.5088 is employed for the Hazen-Williams formulation as Savic and Walters [22]. Comparative results of the present study and those of the previous reliable 1 are shown in Table 1.

Table. 1. Comparison of the pipe diameters for the two-loop network

Pipe Number	Alperovits and Shamir	Goulter et al.	Kessler and Shamir	Present work	
				Pipe length (m)	Pipe Diameter (in)
1	20 18	20 18	18	L_1=595.52 L_2=404.48	D_1=18 D_2=16
2	8 6	10	12 10	L_1=602.78 L_2=397.22	D_1=10 D_2=8
3	18	16	16	L_1=94.36 L_2=905.64	D_1=20 D_2=18
4	8 6	6 4	3 2	L_1=582.75 L_2=417.25	D_1=8 D_2=6
5	16	16 14	16 14	L_1=806.91 L_2=193.09	D_1=16 D_2=14
6	12 10	12 10	12 10	L_1=174.46 L_2=825.54	D_1=10 D_2=8
7	6	10 8	10 8	L_1=934.91 L_1=65.09	D_1=8 D_2=6
8	6 4	2 1	3 2	L_2=978.63 L_1=21.37	D_1=2 D_2=1
Cost ($)	497,525	435,015	417,500	432,358	

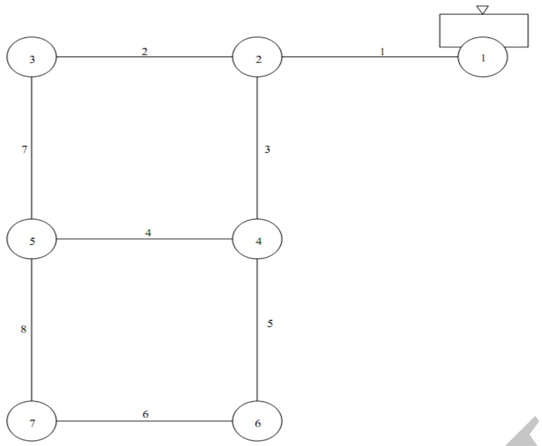

Figure 3. A two-loop water distribution network

5.2. Hanoi Water Distribution Network

The Hanoi arrangement, formerly studied by Fujiwara and Kang [8] in Vietnam, is shown in Figure. 4. This water circulation network can be considered as a medium size network by means of including 32 nodes, 34 pipes, 3 loops and 1 gravity reservoir with a 100m fixed head for its feeding. As the previous example, the Hazen-Williamz coefficient C=130 was employed for network water distribution equations. The tolerable of the pipe diameters, which have pronounced as the difference in upper limitation diameter with the two-loop network, is displayed in Table 5. The water required in this network is much higher than the accustomed demands for other ones so for satisfying these demands, the maximum velocity limitation is set to 7 m/s. As shown in Table 5, the present algorithm achieved very good results in comparison to those of the previous researches.

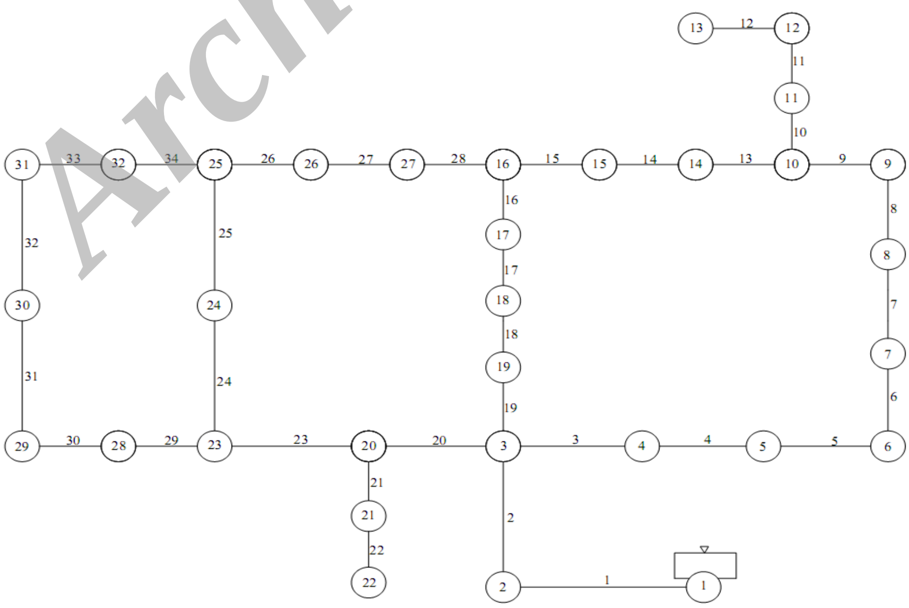

Figure 2. Hanoi water distribution network

Table. 2. Comparison of the pipe diameters and the total cost for the Hanoi network

Pipe number	Pipe length (m)	Fujiwara	Savic and Walters	Harmony	Present work	
					Pipe length (m)	Pipe diameter (in)
1	100	40	40	40	L_1=99.96 L_2=0	D_1=40 D_2=30
2	1,350	40	40	40	L_1=1349.75 L_2=0.24	D_1=40 D_2=30
3	900	40	40	40	L_1=852.17 L_2=47.82	D_1=40 D_2=30
4	1150	40	40	40	L_1=1084.35 L_2=65.65	D_1=40 D_2=30
5	1450	40	40	40	L_1=1299.37 L_2=150.62	D_1=40 D_2=30
6	450	40	40	40	L_1=360.93 L_2=89.06	D_1=40 D_2=30
7	850	38.16	40	40	L_1=496.46 L_2=353.53	D_1=40 D_2=30
8	850	36.74	40	40	L_1=399.38 L_2=450.61	D_1=40 D_2=30
9	800	35.33	40	40	L_1=224.15 L_2=575.85	D_1=40 D_2=30
10	950	29.13	30	30	L_1=258.49 L_2=691.51	D_1=30 D_2=24
11	1200	26.45	24	24	L_1=1002.79 L_2=197.2	D_1=24 D_2=20
12	3500	23.25	24	24	L_1=338.32 L_2=3161.68	D_1=24 D_2=20
13	800	19.57	20	20	L_1=684.30 L_2=115.70	D_1=20 D_2=16
14	500	15.62	16	16	L_1=402.94 L_2=97.06	D_1=16 D_2=12
15	550	12.00	12	12	L_1=6.99 L_2=543.01	D_1=16 D_2=12
16	2,730	22.50	12	12	L_1=2687.58 L_2=42.42	D_1=20 D_2=16
17	1,750	25.24	16	16	L_1=1480.29 L_2=269.70	D_1=24 D_2=20
18	800	29.01	20	20	L_1=475.23 L_2=324.77	D_1=30 D_2=24
19	400	29.28	20	20	L_1=246.80 L_2=153.20	D_1=30 D_2=24
20	2,200	38.58	40	40	L_1=1573.23 L_2=626.77	D_1=40 D_2=30

Pipe number	Pipe length (m)	Fujiwara	Savic and Walters	Harmony search	Present work	
					Pipe length (m)	Pipe diameter (in)
21	1,500	17.36	20	20	L_1=272.62 L_2=1227.38	D_1=20 D_2=16
22	500	12.65	12	12	L_1=2.82 L_2=497.18	D_1=16 D_2=12
23	2,650	32.59	40	40	L_1=2529.05 L_2=120.95	D_1=30 D_2=24
24	1,230	22.06	30	30	L_1=1112.98 L_2=117.02	D_1=20 D_2=16
25	1,300	18.34	30	30	L_1=223.13 L_2=1076.87	D_1=20 D_2=16
26	850	12.00	20	20	L_1=6.01 L_2=843.99	D_1=16 D_2=12
27	300	22.27	12	12	L_1=299.62 L_2=0.38	D_1=20 D_2=16
28	750	24.57	12	12	L_1=484.67 L_2=265.33	D_1=24 D_2=20
29	1,500	21.29	16	16	L_1=1258.09 L_2=241.91	D_1=20 D_2=16
30	2,000	19.34	16	12	L_1=848.55 L_2=1151.45	D_1=20 D_2=16
31	1,600	16.52	12	12	L_1=1309.85 L_2=290.15	D_1=16 D_2=12
32	150	12.00	12	16	L_1=0.28 L2=149.72	D_1=16 D_2=12
33	860	12.00	16	16	L_1=4.40 L_2=855.60	D_1=16 D_2=12
34	950	22.43	20	24	L_1=888.35 L_2=61.65	D_1=20 D_2=16
Cost ($)	-	6,320,000	6,073,000	6,056,000	5,562,343	

5.3. The Go Yang Water Distribution Network

Kim *et al.* [23] originally presented the GoYang network in South Korea, as depicted in Figure. 5. The system information such as elevations and water demand in each node are given in the Table 3. As the table and picture show, the system consists of 30 pipes, 22 nodes, and 9 loops and is fed by pump (4.75 KW) from a 71 m fixed head reservoir. Pipe length and their designed diameters are presented in Table 3 considering that the Hazen-Williams coefficient *C* is taken as 100, and 8 commercial pipe diameters that presented in Table 5 are used for this network. The minimum head limitation is assumed to be 15 m above the ground level.

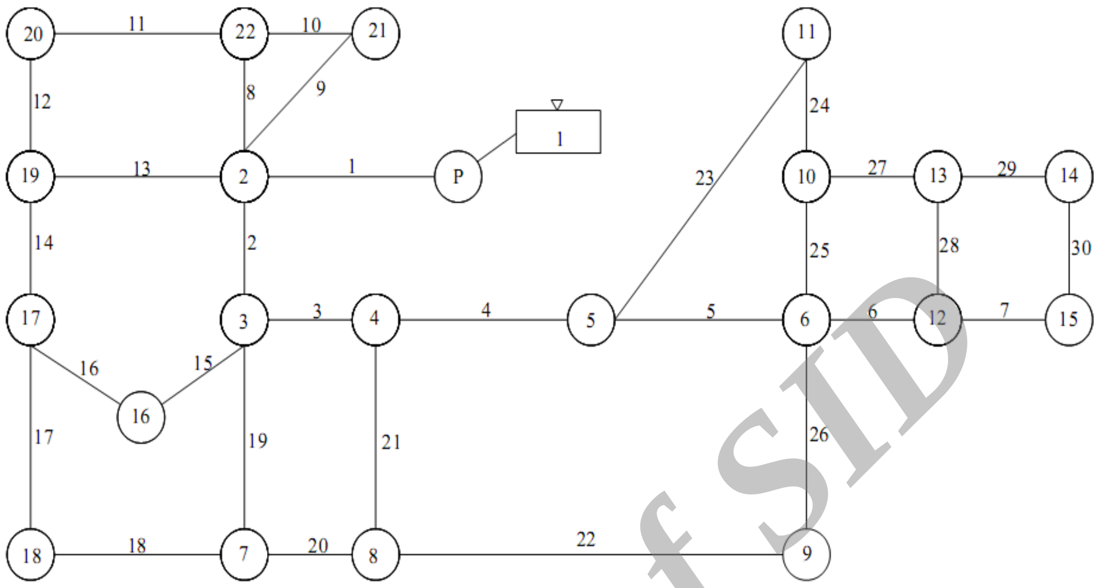

Figure 5. The Go Yang water distribution network

Table 3. Nodal data and the computational results for the GoYang network

Pipe Number	Water Demand(cmd)	Ground Level (m)
1	-2550.0	71
2	153.0	56.4
3	70.5	53.8
4	58.5	54.9
5	75.0	56
6	67.5	57
7	63.0	53.9
8	48.0	54.5
9	42.0	57.9
10	30.0	62.1
11	42.0	62.8
12	37.5	58.6
13	37.5	59.3
14	63.0	59.8
15	445.5	59.2
16	108.0	53.6
17	79.5	54.8
18	55.5	55.1
19	118.5	54.2
20	124.5	54.5

21	31.5	62.9
22	799.5	61.8

Table. 4. Comparison of the pipe diameters for the GoYang network

Pipe Number	Pipe Length (m)	Diameter (Original) (mm)	Diameter (NLP) (mm)	Diameter (HS) (mm)	Present Work	
					Pipe Length (m)	Pipe Diameter (in)
1	165.0	200	200	150	L_1=0.045 L_2=164.95	D_1=100 D_2=80
2	124.0	200	200	150	L_1=123.86 L_2=0.13	D_1=100 D_2=80
3	118.0	150	125	125	L_1=117.35 L_2=0.64	D_1=100 D_2=80
4	81.0	150	125	250	L_1=0.056 L_2=80.94	D_1=100 D_2=80
5	134.0	150	100	100	L_1=0.16 L_2=133.83	D_1=100 D_2=80
6	135.0	100	100	100	L_1=132.95 L_2=2.04	D_1=125 D_2=100
7	202.0	80	80	80	L_1=0.0024 L_2=201.99	D_1=100 D_2=80
8	135.0	100	80	100	L_1=2.20 L_2=132.80	D_1=100 D_2=80
9	170.0	80	80	80	L_1=69.78 L_2=100.22	D_1=125 D_2=100
10	113.0	80	80	80	L_1=108.86 L_2=4.14	D_1=125 D_2=100
11	335.0	80	80	80	L_1=132.75 L_2=202.25	D_1=100 D_2=80
12	115.0	80	80	80	L_1=0.051 L_2=114.94	D_1=100 D_2=80
13	345.0	80	80	80	L_1=0.016 L_2=344.98	D_1=100 D_2=80
14	114.0	80	80	80	L_1=1.39 L_2=112.60	D_1=100 D_2=80
15	103.0	100	80	80	L_1=0.0028 L_2=102.99	D_1=100 D_2=80
16	261.0	80	80	80	L_1=0.80 L_2=260.20	D_1=100 D_2=80
17	72.0	80	80	80	L_1=6.00 L_2=66.00	D_1=100 D_2=80
18	373.0	80	100	80	L_1=242.3 L_2=130.70	D_1=100 D_2=80
19	98.0	80	125	80	L_1=0.46	D_1=100

					L_2=97.54	D_2=80
20	110.0	80	80	80	L_1=0.005 L_2=109.99	D_1=100 D_2=80
21	98.0	80	80	80	L_1=0.003 L_2=97.99	D_1=100 D_2=80
22	246.0	80	80	80	L_1=0.38 L_2=245.62	D_1=100 D_2=80
23	174.0	80	80	80	L_1=56.01 L_2=117.99	D_1=100 D_2=80
24	102.0	80	80	80	L_1=7.41 L_2=94.59	D_1=100 D_2=80
25	92.0	80	80	80	L_1=90.60 L_2=1.40	D_1=100 D_2=80
26	100.0	80	80	80	L_1=0.009 L_2=99.99	D_1=100 D_2=80
27	130.0	80	80	80	L_1=108.93 L_2=21.07	D_1=100 D_2=80
28	90.0	80	80	80	L_1=71.08 L_2=18.92	D_1=100 D_2=80
29	185.0	80	100	80	L_1=85.11 L_2=99.89	D_1=100 D_2=80
30	90.0	80	80	80	L_1=11.6 L_2=78.40	D_1=100 D_2=80
Cost (Won)	-	179,428,600	179,142,700	177,135,800	176,720,977	

Table 5. Candidate pipe diameters

Network	Candidate Diameter	Corresponding Cost
Two-loop	{1, 2, 3, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24} in inches	{2, 5, 8, 11, 16, 23, 32, 50, 60, 90, 130, 170, 300, 550} in dollar/meter
Hanoi	{12, 16, 20, 24, 30, 40} in inches	{45.726,70.4,98.378, 129.333, 180.748, 278.28} in dollar/meter
Go Yang	{80, 100, 125, 150, 200, 250, 300, 350} in millimeters	{37,890; 38,933; 40,563; 42,554; 47,624; 54,125; 62,109; 71,524} in won/meter

6. CONCLUSION

In conclusion results show that the presented method leads to better designs than the existing approaches which usually utilize the WDSs design. One of the most important features of this method is the simultaneous analysis, design and optimization requiring less computational time. While the analysis and optimal design of WDSs are performed in two separate phases in the existing methods (some use a software such as Epanet 2, and some others employ different optimization methods). Charged System Search optimization algorithm is in good agreement with other optimization algorithms which are used in order to attain the optimal WDSs and has achieved better goal function than other algorithms in all of the examples. Therefore, this method is a reliable approach for optimal design of water distribution networks.

REFERENCES

1. Schaake J, Lai D. Linear programming and dynamic programming applications to water distribution network design, *Research Report, Department of Civil Engineering, Massachusetts Institute of Technology*, 1969; *No. 116*
2. Bhave PR, Sonak VV. A critical study of the linear programming gradient method for optimal design of water supply networks, *Water Resour Res,* 1992**; 28**(6): 1577-84.
3. Varma KVK, Narasimhan S, Bhallamudi SM. Optimal design of water distribution systems using an NLP method, *J Environ Eng, ASCE*, 1997; **123**(4): 381-88.
4. Alperovits E, Shamir U. Design of optimal water distribution systems. *Water Resour Res,* 1977; **13**(6): 885-900.
5. Quindry GE, Brill ED, Liebman JC. Optimization of looped water distribution systems. *J Environ Eng Div, ASCE*, 1981; **107**(EE4): 665-79.
6. Goulter IC, Lussier BM, Morgan DR. Implications of head loss path choice in the optimization of water distribution networks. *Water Resour Res*, 1986; **22**(5): 819-22.
7. Kessler A, Shamir U. Analysis of the linear programming gradient method for optimal design of water supply networks. *Water Resour Res*, 1989; **25**(7): 1469-80.
8. Fujiwara O, Kang DB. A two-phase decomposition method for optimal design of looped water distribution networks. *Water Resour Res,* 1990; **26**(4): 539- 49.
9. Simpson AR, Murphy LJ, Dandy GC. Genetic algorithms compared to other techniques for pipe optimisation, *J Water Resour Plan Man, ASCE*, 1994; **120**(4): 423-43.
10. Dandy GC, Simpson AR, Murphy LJ. An improved genetic algorithm for pipe network optimization, *Water Resour Res*, 1996; **32**(2): 449-58.
11. Savic DA, Walters GA. Genetic algorithms for least-cost design of water distribution networks, *J Water Resour Plan Man, ASCE*, 1997; **123**(2): 67-77.
12. Lippai I, Heany PP, Laguna M. Robust water system design with commercial intelligent search optimizers, *J Comp Civil Eng, ASCE*, 1999; **13**(3): 135-43.
13. Wu ZY, Boulos PF, Orr CH, Ro JJ. Using genetic algorithms to rehabilitate distribution system, *J Amer Water Works Ass*, 2001; **93**(11): 74-85.
14. Maier HR, Simpson AR, Zecchin AC, Foong WK, Phang KY, Seah HY, Tan CL. Ant Colony Optimization for the design of water distribution systems, *J Water Resour Plan Man, ASCE*, 2003; **129**(3): 200-09.
15. Zecchin AC, Simpson AR, Maier HR, Nixon JB. Parametric study for an ant algorithm applied to water distribution system optimisation, *IEEE Trans Evol Comput*, 2005; **9**(2): 175-91.
16. Eusuff MM, Lansey KE. Optimisation of water distribution network design using the shuffled frog leaping algorithm, *J Water Resour Plan Man*, 2003; **129**(3): 210-25.

17. Geem ZW. Optimal cost design of water distribution networks using harmony search, *Eng Optim*, 2006; **38**(3): 259-80.
18. Eusuff MM, lansey KE. Optimization of water distribution network design using shuffled frog leaping algorithm, *J Water Resour Plan Man*, 2003; **129**(3): 210-25.
19. Talson BA, Asadzadeh M, Maier HR, Zecchin AC. Hybrid discrete dynamically dimensioned search (HD-DDS) algorithm for water distribution system design optimization, *Water Resour Res*, 2009; **45**:W12416.
20. Kaveh A, Talatahari S. A novel heuristic optimization method: charged system search, *Acta Mech*, 2010; **213**(3-4): 267-89.
21. Kaveh A, Talatahari S. An enhanced charged system search for configuration optimization using the concept of fields of forces, *Struct Multidiscip Optim*, 2011; **43**(3): 339-51.
22. Savic DA, Walters GA. Genetic algorithms for least-cost design of water distribution networks. *J Water Resour Plan Man, ASCE*, 1997; **123**(2): 67-77.
23. Kim JH, Kim TG, Kim JH, Yoon YN. A study on the pipe network system design using non-linear programming, *J Korean Water Resour Ass*, 1994; **27**(4): 59-67.