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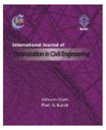

ANALYSIS AND DESIGN OF WATER DISTRIBUTION SYSTEMS VIA COLLIDING BODIES OPTIMIZATION

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ABSTRACT

This paper describes the application of the recently developed metaheuristic algorithm for simultaneous analysis, design and optimization of Water Distribution Systems (WDSs). In this method, analysis is carried out using Colliding Bodies Optimization algorithm (CBO). The CBO is a population-based search approach that imitates nature’s ongoing search for better solutions. Also, 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. A number of practical examples of WDSs are selected to demonstrate the efficiency of the presented algorithm. Comparison of obtained results clearly signifies the efficiency of the CBO method in reducing the WDSs construction cost and computational time of the analysis.

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KEY WORDS: analysis, design, optimization, water distribution system, colliding bodies algorithm

1. INTRODUCTION

Nowadays due to huge extension in size and dimension of the structures, there has been a great increase in weight and cost of construction materials used for structures. Therefore it is not surprising that a lot of attention is being paid by engineers to the optimal design of structures which lead to a significant decrease in cost of them.

One of the most imperative fields in which the optimization and resource management

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needs special consideration is water distribution system. Water distribution system is an essential infrastructure, which consists of hydraulic components such as pipes, valves, 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, line 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.

Due to the high costs associated with the construction of water distribution systems (WDSs) much research has been dedicated to the development of methods to minimize the capital costs associated with such infrastructure.

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 designing, 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 programing 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 developed, examples of which are Quindry *et al*. [5], Goulter *etal*. [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 system 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 new meta-heuristic methods that recently developed by Kaveh and Mahdavi [20] is Colliding Bodies optimization method (CBO). The CBO 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 this paper, the pipe sizes and demands are considered as the optimization variables leading to simultaneous analysis, design and optimization.

2. 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 *i*th pipe, with diameter D_i and length L_i, and N is the number of pipe 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 length 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 node, 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 the Hazen-Williams or Darcy-Weisbach 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 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 series 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.

2.2 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. For each node in the network, the minimum pressure constraint is given in the following form:

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

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 the 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:

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

where Q is the demand in each node, and $Null\,(M\,,1)$ 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 loss 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. q_p denotes the flow rate of each node.

The matrix ***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 ***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, Fig. 1 depicts a fundamental simple WDSs example whose satisfaction equations can be presented as follows:

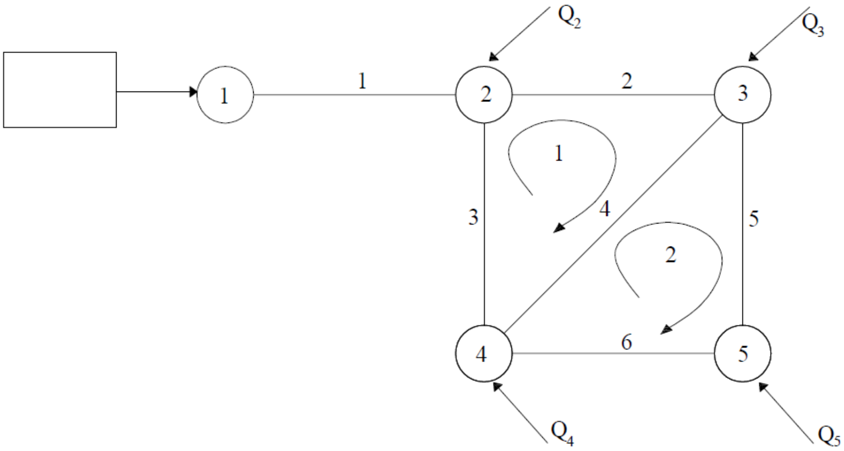


Figure 1. An example of simple fundamental WDSs

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

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

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

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 3 acts in the reverse direction of the loop direction.

Finally it should be mentioned that, in this study, 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 COLLIDING BODIES OPTIMIZATION ALGORITHM

Nature has always been a major source of inspiration to engineers and natural philosophers and many meta-heuristic approaches are inspired by solutions that nature herself seems to have chosen for hard problems. The collision is a natural occurrence, which it happens between objects, bodies, cars, etc. The Colliding bodies optimization algorithm is one of the meta-heuristic search methods that recently developed. It is a population-based search approach, where each agent (CB) is considered as a colliding body with mass m. The idea of the CBO algorithm is based on observation of a collision between two objects in one-dimension; in which one object collide with other object and they moves toward minimum energy level [20].

3.1 Collision laws

In physics, collisions between bodies are governed by: (i) laws of momentum and (ii) laws of energy. When a collision occurs in an isolated system, Fig. 2, the total momentum and energy of the system of object is conserved.

The conservation of the total momentum requires the total momentum before the collision to be the same as the total momentum after the collision, and can be expressed as:

$$m_1 v_1 + m_2 v_2 = m_1 v'_1 + m_2 v'_2 \tag{12}$$

Likewise, the conservation of the total kinetic energy is expressed by

$$\frac{1}{2} m_1 v_1^2 + \frac{1}{2} m_2 v_2^2 = \frac{1}{2} m_1 v'^2_1 + \frac{1}{2} m_2 v'^2_2 + Q \tag{13}$$

where v_1 is the initial velocity of the first object before impact, v_2 is the initial velocity of the second object before impact, v'_1 is the final velocity of the first object after impact, v'_2 is the final velocity of the second object after impact, m_1 is the mass of the first object, m_2 is the mass of the second object, and Q is the loss of kinetic energy due to impact.

The velocity after a one-dimensional collision can be obtained as:

$$v'_1 = \frac{(m_1 - \varepsilon m_2) v_1 + (m_2 + \varepsilon m_2) v_2}{m_1 + m_2} \tag{14}$$

$$v'_2 = \frac{(m_2 - \varepsilon m_1)v_2 + (m_1 + \varepsilon m_1)v_1}{m_1 + m_2} \tag{15}$$

where ε is the coefficient of restitution (COR) of two colliding bodies, defined as the ratio of relative velocity of separation to relative velocity of approach:

$$\varepsilon = \frac{|v'_2 - v'_1|}{|v_2 - v_1|} = \frac{v'}{v} \tag{16}$$

According to the coefficient of restitution, two special cases of collision can be considered as:

A perfectly elastic collision is defined as the one in which there is no loss of kinetic energy in the collision (Q=0 & ε=1). In reality, any macroscopic collision between objects will convert some kinetic energy to internal energy and other forms of energy. In this case, after collision the velocity of separation is high.

An inelastic collision is the one in which part of the kinetic is changed to some other form of energy in the collision. Momentum is conserved in inelastic collisions (as it is for elastic collision), but one cannot track the kinetic energy through the collision since some of it is converted to other forms of energy. In this case, coefficient of restitution does not equal to one (Q ≠ 0 & ε ≤ 1). Here, after collision the velocity of separation is low.

For most of the real objects, ε is between 0 and 1.

Figure 2. The collision between two bodies; (a) Before the collision. (b) After the collision

3.2 The CBO algorithm

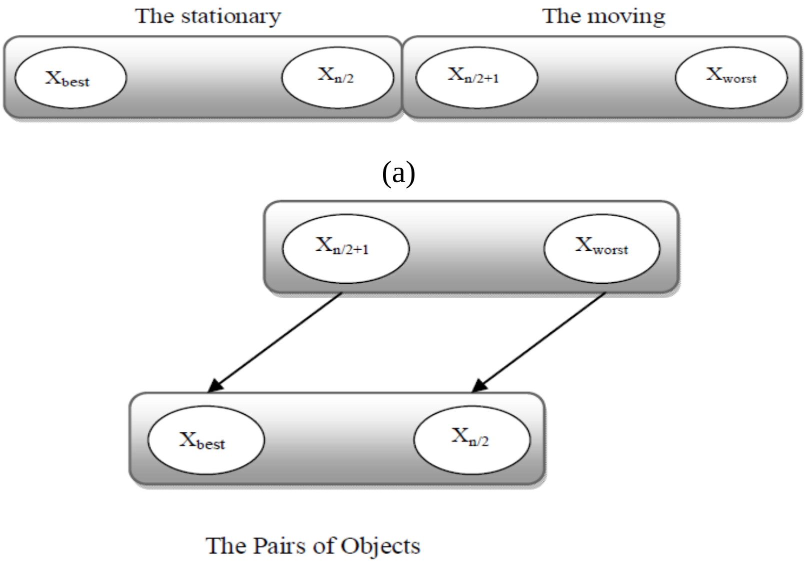
The Colliding Bodies Optimization algorithm is one of the meta-heuristic search methods that recently developed by Kaveh and Mahdavi [20]. In this method, each solution candidate X_i is considered as a colliding body (CB). The massed objects are composed of two main equal groups; i.e. stationary and moving objects, where the moving objects move to follow stationary objects and a collision occurs between pairs of objects. This is done for two purposes: (i) to improve the positions of moving objects; (ii) to push stationary objects towards better positions. After the collision, the new positions of the colliding bodies are updated based on the new velocity by using the collision laws as discussed in Section 3.1.

The pseudo-code for the CBO algorithm can be summarized as follows:

Step 1: Initialization. The initial positions of CBs are determined randomly in the search space:

$$x_i^0 = x_{\min} + rand.(x_{\max} - x_{\min}) \quad i = 1, 2, ..., n \tag{17}$$

where x_i^0 determines the initial value vector of the ith CB. $x_{\min}$ and $x_{\max}$ are the minimum and the maximum allowable values vectors of variables; rand is a random number in the interval [0,1]; and n is the number of CBs.



(a)

(b)

Figure 3. (a) The sorted CBs in an increasing order. (b) The pairs of objects for the collision

Step 2: Determination of the body mass for each CB. The magnitude of the body mass for each CB is defined as:

$$m_k = \frac{\dfrac{1}{fit(k)}}{\sum_{i=1}^{n} \dfrac{1}{fit(i)}}, \quad k = 1, 2, ..., n \tag{18}$$

where $fit(i)$ represents the objective function value of the agent i ; n is the population size. Obviously a CB with good values exerts a larger mass than the bad ones. Also, for maximizing the objective function the term $\frac{1}{fit(i)}$ is replaced by $fit(i)$.

Step 3: Arrangement of the CBs. The arrangement of the CBs objective function values is performed in ascending order (Fig. 3a). The sorted CBs are equally divided into two groups:

The lower half of CBs (stationary CBs); These CBs are good agents which are stationary and the velocity of these bodies before collision is zero. Thus:

$$v_i = 0 \quad i = 1, 2, \ldots, \frac{n}{2} \tag{19}$$

The upper half of CBs (moving CBs): These CBs move toward the lower half. Then, according to Fig. 3b, the better and worse CBs, i.e. agents with upper fitness value of each group will collide together. The change of the body position represents the velocity of these bodies before collision as:

$$v_i = x_i - x_{i-\frac{n}{2}} \quad i = \frac{n}{2} + 1, \ldots, n \tag{20}$$

where v_i and x_i are the velocity and position vector of the ith CB in this group, respectively; $x_{i-\frac{n}{2}}$ is the ith CB pair position of x_i in the previous group.

Step 4: Calculation of the new position of the CBs. After the collision, the velocity of bodies in each group is evaluated using Eq. (14), Eq. (15) and the velocities before collision. The velocity of each moving CB after the collision is:

$$v'_i = \frac{(m_i - \varepsilon m_{i-\frac{n}{2}}) v_i}{m_i + m_{i-\frac{n}{2}}} \quad i = \frac{n}{2} + 1, \ldots, n \tag{21}$$

where v_i and v'_i are the velocity of the ith moving CB before and after the collision, respectively; m_i is the mass of the ith CB; $m_{i-\frac{n}{2}}$ is mass of the ith CB pair. Also, the velocity of each stationary CB after the collision is:

$$v'_i = \frac{(m_{i+\frac{n}{2}} + \varepsilon m_{i+\frac{n}{2}}) v_{i+\frac{n}{2}}}{m_i + m_{i+\frac{n}{2}}} \quad i = 1, \ldots, \frac{n}{2} \tag{22}$$

where $v_{i+\frac{n}{2}}$ and v_i are the velocity of the ith moving CB pair before and the ith stationary CB after the collision, respectively; m_i is mass of the ith CB; $m_{i+\frac{n}{2}}$ is mass of the ith moving CB pair. As mentioned previously, ε is the coefficient of restitution (COR) and for most of the real objects, its value is between 0 and 1. It defined as the ratio of the separation velocity of two agents after collision to the approach velocity of two agents before collision. In the CBO algorithm, this index is used to control of the exploration and exploitation rate.

For this goal, the COR is decreases linearly from unit to zero. Thus, ε is defined as:

$$\varepsilon = 1 - \frac{iter}{iter_{\max}} \tag{23}$$

where $iter$ is the actual iteration number and $iter_{\max}$ is the maximum number of iterations, with COR being equal to unit and zero representing the global and local search, respectively.

New positions of CBs are obtained using the generated velocities after the collision in position of stationary CBs.

The new positions of each moving CB is:

$$x_i^{new} = x_{i-\frac{n}{2}} + rand \circ v'_i \quad i = \frac{n}{2}+1,...,n \tag{24}$$

where x_i^{new} and v'_i are the new position and the velocity after the collision of the ith moving CB, respectively; $x_{i-\frac{n}{2}}$ is the old position of the *i*th stationary CB pair. Also, the new positions of stationary CBs are obtained by:

$$x_i^{new} = x_i + rand \circ v'_i \quad i = 1,...,\frac{n}{2} \tag{25}$$

where x_i^{new}, x_i and v'_i are the new position, old position and the velocity after the collision of the ith stationary CB, respectively. $rand$ is a random vector uniformly distributed in the range (−1,1) and the sign ‘‘$\circ$’’ denotes an element-by-element multiplication.

Step 5: Termination criterion control. Steps 2-4 are repeated until a termination criterion is satisfied. It should be noted that, a body’s status (stationary or moving body) and its numbering are changed in two subsequent iterations.

Further explanation can be found in Kaveh and Mahdavi [20,21,22].

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

As explained in section 2, 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 in section 2.

In the present approach analysis phase is performed using the CBO 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:

$$f(\mathbf{q_p},D)=\sum_{i=1}^{L} l_i \times \mathrm{cost}(D_i)\times(1+norm(\mathbf{H}\times\mathbf{q_p}=\begin{bmatrix}\mathbf{Q}\\ \mathbf{Null(M,1)}\end{bmatrix}))+\sum_{i=1}^{L} g_i(q_i,D_i) \tag{26}$$

Fig. 4 shows the schematic procedure of designing and analysis of a water distribution system using the CBO algorithm which is used in this paper.

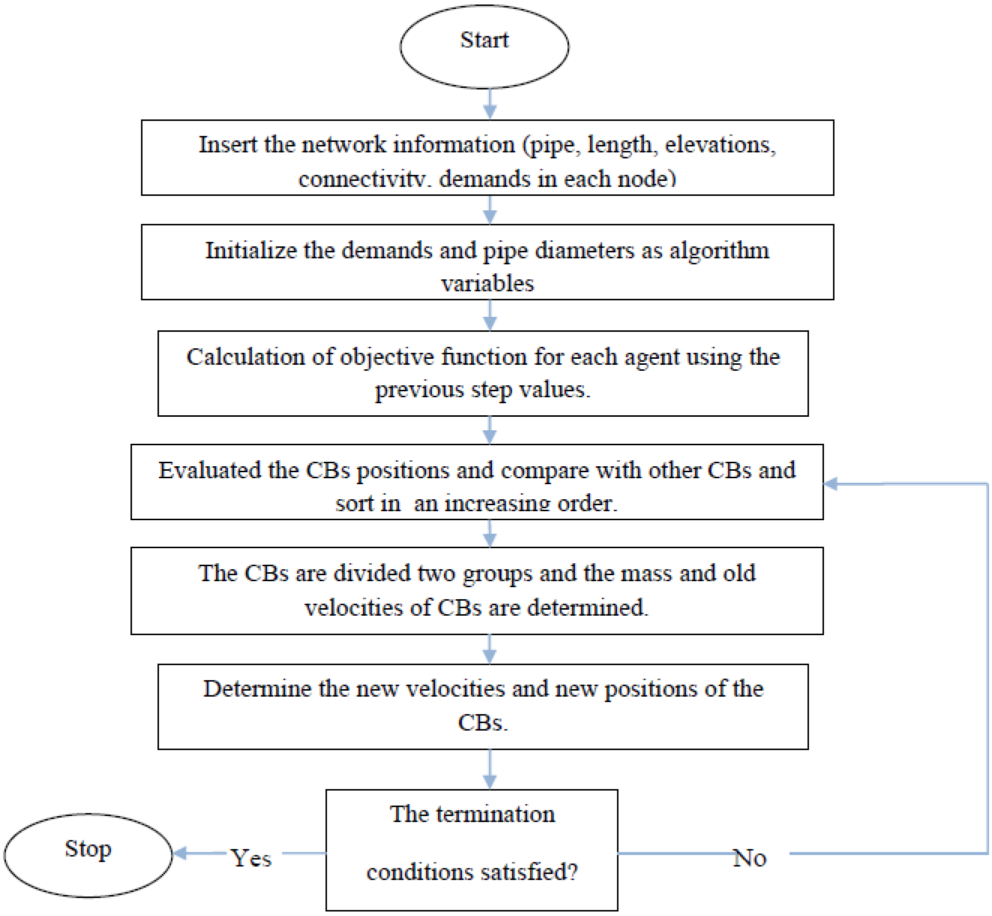


Figure 4. Flowchart of the present study procedure

5. DESIGN EXAMPLES

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

5.1 A two-loop Network

The two loop network, shown in Fig. 5, was first introduced by Alperovits and 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 consists of 8 pipes, 7 nodes, and 2 loops. The network is fed by gravity from a constant reservoir, which has 210 m fixed head. 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 6 [17]. The Minimum head limitation in each pipe is set to 30m above ground level. Here ω = 10.5088 is employed for the Hazen-Williams formulation as Savic and Walters [23].

Table 1 compares the results obtained using the CBO algorithm with those obtained using other methods. Also, Table 2 shows the corresponding nodal heads obtained in this study. As can be seen, in all nodes the minimum nodal head requirement is satisfied.

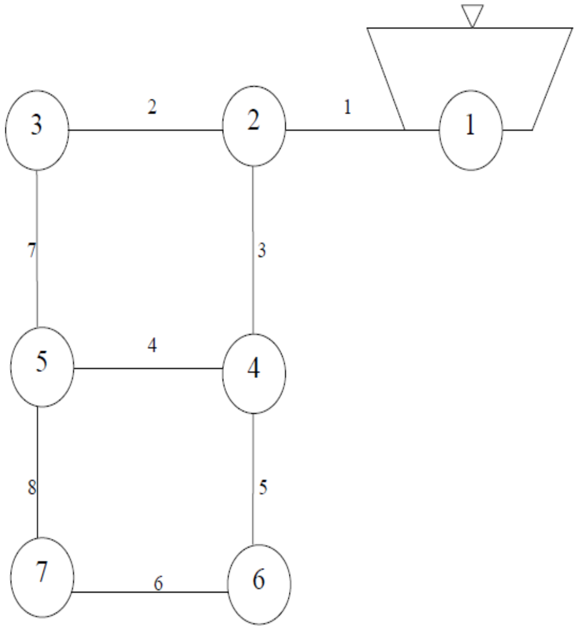


Figure 5. Two-loop water distribution network.

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

				Kaveh et al. [24]		Present work (CBO)	
Pipe Number	Alperovits and Shamir	Goulter et al.	Kessler and Shamir	Pipe length (m)	Pipe Diameter (in)	Pipe length (m)	Pipe Diameter (in)
1	20	20	18	L1=595.52	D1=18	L1=987.85	D1=18
	18	18		L2=404.48	D2=16	L2=12.15	D2=16
2	8	10	12	602.78	10	74.8	12
	6		10	397.22	8	925.2	10
3	18	16	16	94.36	20	998.25	16
				905.64	18	1.75	14
4	8	6	3	582.75	8	981.93	3
	6	4	2	417.25	6	18.07	2
5	16	16	16	806.91	16	934.62	16
		14	14	193.09	14	65.38	14
6	12	12	12	174.46	10	996.85	10
	10	10	10	825.54	8	3.15	8
7	6	10	10	934.91	8	751.14	10
		8	8	65.09	6	248.86	8
8	6	2	3	978.63	2	996.25	2
	4	1	2	21.37	1	3.75	1
Cost ($)	497,525	435,015	417,500	432,358		415,070	

Table 2: Optimal pressure heads for two-loop network

Pipe No.	Min Pressure Req. (m)	Pressure
1	-	-
2	30	53.21
3	30	30.80
4	30	43.38
5	30	30.87
6	30	30.08
7	30	30.02

5.2. Hanoi Water Distribution Network

The Hanoi network is a real network that formerly studied by Fujiwara and Kang [8] in Vietnam. This network is shown in Fig. 6. 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 6. 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 3, the CBO algorithm achieved good results in comparison to more of the previous researches.

The obtained results show that CBO has produced significant improvement in total cost of network, and it is one of the best solutions for this network.

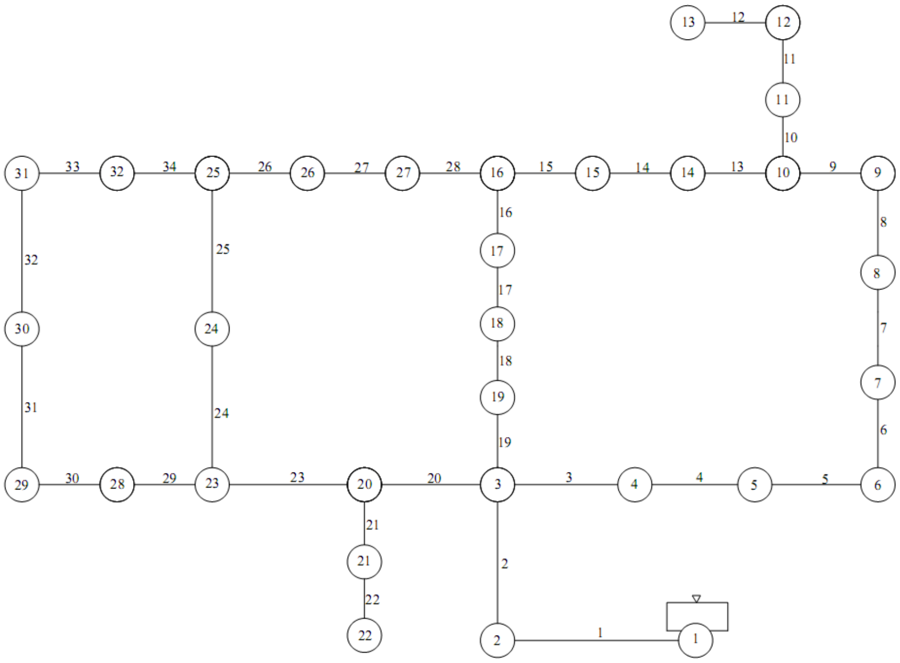


Figure 6. Hanoi water distribution network

Table 3: Comparison of the pipe diameters and the total cost for the Hanoi network

					Kaveh et al. [24]		Present work (CBO)	
Pipe Number	Pipe Length (m)	Fujiwara	Savic and Walters	Harmony	Pipe length (m)	Pipe Diameter (in)	Pipe length (m)	Pipe Diameter (in)
1	100	40	40	40	L1=99.96 L2=0.04	D1=40 D2=30	L1=99.70 L2=0.30	D1=40 D2=30
2	1,350	40	40	40	1349.75 0.25	40 30	1347.10 2.90	40 30
3	900	40	40	40	852.17 47.82	40 30	853 47	40 30
4	1150	40	40	40	1084.35 65.65	40 30	1084.40 65.60	40 30
5	1450	40	40	40	1299.37 150.62	40 30	1299.70 150.30	40 30
6	450	40	40	40	360.93 89.06	40 30	361.10 88.90	40 30
7	850	38.16	40	40	496.46 353.53	40 30	496.90 353.10	40 30
8	850	36.74	40	40	399.38	40	397.50	40

					450.61	30	452.50	30
9	800	35.33	40	40	224.15	40	789.40	40
					575.85	30	10.60	30
10	950	29.13	30	30	258.49	30	950	30
					691.51	24		
11	1200	26.45	24	24	1002.79	24	1200	24
					197.2	20		
12	3500	23.25	24	24	338.32	24	1016.90	30
					3161.68	20	2483.10	24
13	800	19.57	20	20	684.30	20	800	20
					115.70	16		
14	500	15.62	16	16	402.94	16	447.60	16
					97.06	12	52.40	12
15	550	12.00	12	12	6.99	16	550	12
					543.01	12		
16	2,730	22.50	12	12	2687.58	20	2730	16
					42.42	16		
17	1,750	25.24	16	16	1480.29	24	1750	
					269.70	20		20
18	800	29.01	20	20	475.23	30	800	24
					324.77	24		
19	400	29.28	20	20	246.80	30	15.30	24
					153.20	24	384.70	20
20	2,200	38.58	40	40	1573.23	40	1578.90	40
					626.77	30	621.10	30
21	1,500	17.36	20	20	272.62	20	1500	20
					1227.38	16		
22	500	12.65	12	12	2.82	16	500	16
					497.18	12		
23	2,650	32.59	40	40	2529.05	30	2534.90	30
					120.95	24	115.10	24
24	1,230	22.06	30	30	1112.98	20	1111.40	20
					117.02	16	118.60	16
25	1,300	18.34	30	30	223.13	20	222.30	20
					1076.87	16	1077.70	16
26	850	12.00	20	20	6.01	16	850	20
					843.99	12		
27	300	22.27	12	12	299.62	20	300	12
					0.38	16		
28	750	24.57	12	12	484.67	24	704.50	16
					265.33	20	45.50	12
29	1,500	21.29	16	16	1258.09	20	1500	12
					241.91	16		
30	2,000	19.34	16	12	848.55	20	834.80	20
					1151.45	16	1165.20	16
31	1,600	16.52	12	12	1309.85	16	1600	16

					290.15	12		
32	150	12.00	12	16	0.28 149.72	16 12	150	12
33	860	12.00	16	16	4.40 855.60	16 12	860	20
34	950	22.43	20	24	888.35 61.65	20 16	950	30
Cost ($)	-	6,320,000	6,073,000	6,056,000	5,562,343		5,741,900	

5.3 The Go Yang Water Distribution Network

Kim *et al.* [25] originally presented the GoYang network in South Korea, as shown in Fig. 7. The system information such as elevations and water demand in each node are given in the Table 4. As the table and picture show, the system consists of 30 pipes, 22 nodes, and 9 loops, and is fed by pump (4.52 KW) from a 71 m fixed head reservoir. Pipe length and their designed diameters are presented in Table 5 considering that the Hazen- Williams coefficient *C* is taken as 100, and 8 commercial pipe diameters that presented in Table 6 are used for this network. The minimum head limitation is assumed to be 15m above the ground level.

Table 4 shows the corresponding node pressure obtained using the CBO method. It can be observed that the minimum pressure limitation is satisfied in all nodes of network. Also, table 5 compares the selected diameters obtained using CBO with those obtained using other methods. It is apparent from table 5 that the CBO algorithm gives better results than other methods, and the corresponding cost obtained by this algorithm is equal to 176,946,211Won (≈ $176,946), while the original cost was 179,428,600 Won(≈ $179,429).

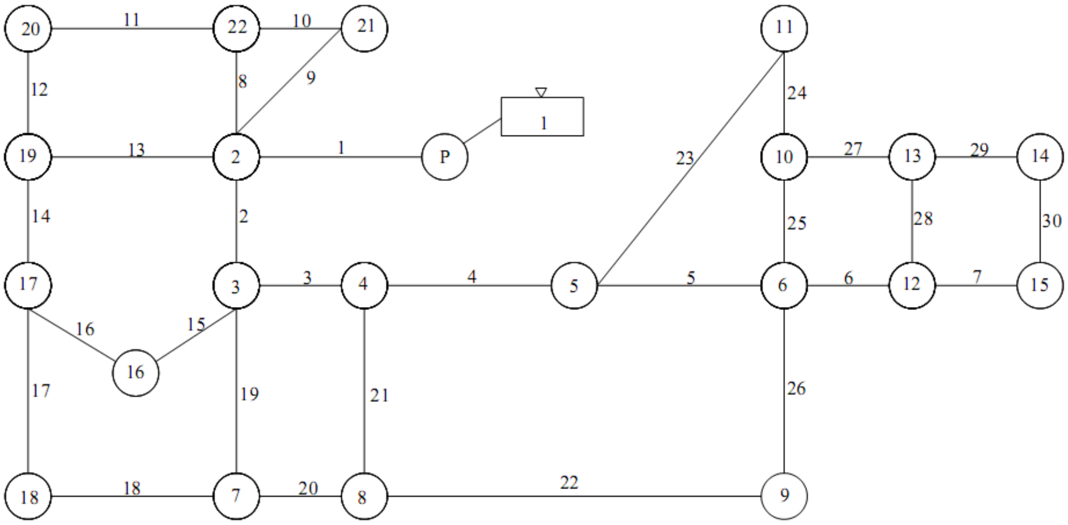


Figure 7. Go Yang water distribution network

Table 4: Nodal data and the computational results for the GoYang network

Pipe Number	Water Demand (cmd)	Ground Level (m)	Pressure (Original) (m)	Pressure (NLP) (m)	Pressure (HS) (m)	Pressure (CBO) (m)
1	-2550.0	71.0	15.61	15.61	15.61	15.61
2	153.0	56.4	28.91	28.91	24.91	28.18
3	70.5	53.8	31.18	31.15	26.32	27.58
4	58.5	54.9	29.53	29.1	24.11	26.31
5	75.0	56.0	28.16	27.47	22.78	24.92
6	67.5	57.0	26.91	25.44	20.67	23.36
7	63.0	53.9	30.46	30.75	25.34	27.18
8	48.0	54.5	29.80	29.48	24.41	26.17
9	42.0	57.9	26.05	24.48	20.01	20.16
10	30.0	62.1	21.50	20.17	15.43	15.16
11	42.0	62.8	20.92	19.79	15.06	15.18
12	37.5	58.6	24.34	22.95	18.16	20.50
13	37.5	59.3	23.54	22.07	17.38	17.67
14	63.0	59.8	21.43	20.84	15.27	16.0
15	445.5	59.2	21.59	20.78	15.42	16.54
16	108.0	53.6	31.06	30.65	25.88	26.8
17	79.5	54.8	29.05	28.97	24.29	24.7
18	55.5	55.1	28.76	28.87	23.99	24.18
19	118.5	54.2	29.49	29.14	24.89	27.54
20	124.5	54.5	28.80	27.96	24.43	27.2
21	31.5	62.9	21.06	20.18	16.89	20.04
22	799.5	61.8	21.47	20.07	17.21	20.28

Table 5: Comparison of the pipe diameters for the GoYang network

Pipe Number	Pipe Length (m)	Diameter (Original) (mm)	Diameter (NLP) (mm)	Diameter (HS) (mm)	Length (CBO) (mm)	Diameter (CBO) (mm)
1	165.0	200	200	150	L1=134.62 L2=30.38	D1=200 D2=150
2	124.0	200	200	150	108.54 15.46	125 100
3	118.0	150	125	125	0.15 117.85	125 100
4	81.0	150	125	150	15.21 65.79	100 80
5	134.0	150	100	100	120.91 13.09	100 80
6	135.0	100	100	100	113.74 21.26	100 80
7	202.0	80	80	80	202.0	80

8	135.0	100	80	80	135.0	80
9	170.0	80	80	80	170.0	80
10	113.0	80	80	80	113.0	80
11	335.0	80	80	80	335.0	80
12	115.0	80	80	80	115.0	80
13	345.0	80	80	80	345.0	80
14	114.0	80	80	80	114.0	80
15	103.0	100	80	80	103.0	80
16	261.0	80	80	80	261.0	80
17	72.0	80	80	80	72.0	80
18	373.0	80	100	80	373.0	80
19	98.0	80	125	80	98.0	80
20	110.0	80	80	80	110.0	80
21	98.0	80	80	80	98.0	80
22	246.0	80	80	80	10.96 235.04	100 80
23	174.0	80	80	80	174.0	80
24	102.0	80	80	80	55.62 46.38	100 80
25	92.0	80	80	80	40.28 51.72	100 80
26	100.0	80	80	80	100.0	80
27	130.0	80	80	80	130.0	80
28	90.0	80	80	80	18.79 71.21	100 80
29	185.0	80	100	80	185.0	80
30	90.0	80	80	80	90.0	80
Cost (Won)	-	179,428,600	179,142,700	177,135,800	176,946,211	

Table 6: 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 this paper, the CBO algorithm is applied to the least cost design of WDSs. 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 software such as Epanet 2, and some others employ different optimization methods). Also, the new algorithm, so-called CBO utilizes simple formulation and it requires no parameter selection. For water distribution network problem, choices of parameters are really hard works and appropriate parameter values are very difficult to select, while this algorithm does not internal parameter beside the COR. This feature of CBO is a definite strength of that. In order to show that this method is reliable and capable in this field of science; three famous WDSs are selected from literature, which are studied by many other researchers. It is observed that optimization results obtained by the colliding bodies optimization method have less cost in compare with more results obtained using other methods which usually utilize the WDSs design. Therefore, this method is a reliable approach for optimal design of water distribution networks.

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