Optimal cost design of water distribution networks using harmony search

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Abstract

This study presents a cost minimization model for the design of water distribution networks. The model uses a recently developed harmony search optimization algorithm while satisfying all the design constraints. The harmony search algorithm mimics a jazz improvisation process in order to find better design solutions, in this case pipe diameters in a water distribution network. The model also interfaces with a popular hydraulic simulator, EPANET, to check the hydraulic constraints. If the design solution vector violates the hydraulic constraints, the amount of violation is considered in the cost function as a penalty. The model was applied to five water distribution networks, and obtained designs that were either the same or cost 0.28 - 10.26% less than those of competitive meta-heuristic algorithms, such as the genetic algorithm, simulated annealing, and tabu search under the similar or less favorable conditions. The results show that the harmony search-based model is suitable for water network design.

Keywords: Water distribution network; Harmony search; Meta-heuristic algorithm

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1. Introduction

Today's highly capitalized societies require 'maximum benefit with minimum cost.' In order to achieve this goal, design engineers depend on cost optimization techniques. In this study, water distribution networks are optimized. This involves determining the commercial diameter for each pipe in the network while satisfying the water demand and pressure at each node. The optimal cost design is the lowest cost design out of numerous possibilities.

In order to find a low cost design in practice, experienced engineers have traditionally used trial-and-error methods based on their intuitive 'engineering sense'. However, their approaches have not guaranteed 'optimal' or 'near-optimal' designs, which is why researchers have been interested in optimization methods [1-2].

Alperovits and Shamir [3] proposed a mathematical approach (a linear programming gradient method) that reduced the complexity of an original nonlinear problem by solving a series of linear sub-problems. They formulated an optimization model with a two-stage (outer and inner) procedure, in which the outer procedure solved the flow status for a given network while the inner procedure determined the optimum solution of the network variables (pipe diameter) for the given flow distribution. This innovative approach was adopted and further developed by many researchers, such as Quindry *et al*. [4], Goulter *et al*. [5], Kessler and Shamir [6], and Fujiwara and Kang [7]. Schaake and Lai [8] used dynamic programming to search for a global optimum, while Su *et al*. [9] and Lansey and Mays [10] integrated gradient-based techniques with the hydraulic simulator KYPIPE [11], and Loganathan *et al*. [12] and Sherali *et al*. [13] introduced a lower bound.

However, Savic and Walters [14] pointed out that the optimum solution obtained by the aforementioned methods might contain one or two pipe segments of different discrete sizes between each pair of nodes because the methods are based on a continuous diameter approach. They asserted that the split-pipe design should be altered into only one diameter, and that the altered solution should then be checked to ensure that the minimum head constraints are satisfied. In addition, Cunha and Sousa [15] indicated that the conversion of the values obtained by the aforementioned methods into commercial pipe diameters could worsen the quality of the solution and might not even guarantee a feasible solution.

In order to overcome these drawbacks of mathematical methods, researchers such as Simpson *et al*. [16], Cunha and Sousa [17], and Lippai *et al*. [18] began to apply simulation-based meta-heuristic algorithms, such as the genetic algorithm (GA), simulated annealing (SA), and tabu search (TS) to water network design. These algorithms evolved into more robust optimization models because they could obtain split-free commercial diameters.

During the past decade, the GA has gained in popularity as a powerful meta-heuristic optimization technique. The GA is also increasingly used in water network design for problems that are difficult to solve using traditional techniques. Simpson et al. [16] presented a methodology for applying the GA technique to the optimization of water distribution network design. The model used a simple GA comprised of binary strings and three operators (reproduction, crossover, and mutation). Their results showed that the GA technique is effective at finding near-optimal or optimal solutions for an example network in relatively few function evaluations. The results have been compared with both complete enumeration and nonlinear algorithms. The advantages of the GA compared to those techniques are that the GA can consider the design of larger networks, and produce discrete pipe diameters and alternative solutions. Dandy *et al*. [19] proposed an improved genetic algorithm that used a variable power scaling of the fitness function. The exponent introduced into the fitness function increased in magnitude as the GA run proceeded. In addition, an adjacency mutation operator was introduced, rather than the commonly used bitwise mutation operator, using gray code. The computation results indicated that the improved GA performed better than the simple GA and traditional mathematical methods for the New York City water distribution network problem. Montesinos *et al*. [20] proposed a different improved GA with several changes in the selection and mutation processes as compared to the simple GA. In each generation, a constant number of solutions was eliminated, the selected ones were sorted for crossover, and the new solutions were allowed to undergo a maximum of one mutation. Their improved GA obtained the same lowest cost in fewer generations than the previous GA for the New York City water distribution network problem. Savic and Walters [14] developed the practical software GANET, which applied the GA to water network design problems. Two network examples (Hanoi and New York City) were used to illustrate the potential of GANET as a practical tool for water network design. Balla and Lingireddy [21] implemented an optimization model based on a distributed GA using a network of personal computers. The inherent parallelism associated with data exchange among the computers resulted in a significant reduction of the computing time for an 850-pipe network problem.

SA models have also been developed to obtain the least-cost solution for water network designs. Cunha and Sousa [15, 17] applied SA to the Hanoi and New York City network problems and obtained lower costs than the solutions previously reported in the literature. Costa et al. [22] developed an SA model for optimal network design that includes pumps. The pump size was also considered as a discrete decision variable.

Lippai et al. [18] introduced the TS to obtain the optimal design of a water distribution network using the commercial software OptQuest. They applied the TS model to the New York City network problem; however, the result obtained by OptQuest was not as good as the result obtained by the GA-based software Evolver.

Recently, Geem et al. [23] developed a harmony search (HS) meta-heuristic optimization algorithm that uses an analogy with the jazz improvisation process. The HS has been applied to various benchmarking and real-world optimization problems with success, including the traveling salesperson problem (TSP), the Rosenbrock function, hydrologic parameter calibration, two-loop network design, and truss structure design [23-27]. Although Geem et al. [26] tackled the design of a water distribution network, they used the original HS, which contains only memory consideration operations, and applied it to a simple test network. The purpose of this paper is to apply an improved HS algorithm, which adopts both memory consideration and pitch adjustment operations, to the design of various real-world water distribution networks while considering the pressure and demand constraints using a public hydraulic simulator. This will also serve to provide readers with the details of the HS calculation process.

2. Harmony Search Algorithm

Existing meta-heuristic algorithms are based on ideas found in the paradigm of natural or artificial phenomena. These include the biological evolutionary process in the GA [28-29], the physical annealing process in SA [30], and animal's behavior in TS [31]. The harmony search algorithm was conceptualized from the musical process of searching for a 'perfect state' of harmony, such as jazz improvisation.

Jazz improvisation seeks a best state (fantastic harmony) determined by aesthetic estimation, just as the optimization algorithm seeks a best state (global optimum) determined by evaluating the objective function. Aesthetic estimation is performed by the set of pitches played by each instrument, just as the objective function evaluation is performed by the set of values assigned by each decision variable. The harmony quality is enhanced practice after practice, just as the solution quality is enhanced iteration by iteration.

Consider a jazz trio composed of a saxophone, double bass, and guitar. Assume there exists a certain number of preferable pitches in each musician's memory: saxophonist {Do, Mi, Sol}, double bassist {Ti, Sol, Re}, and guitarist {La, Fa, Do}. If the saxophonist plays note Sol, the double bassist plays Ti, and the guitarist plays Do, together their notes make a new harmony (Sol, Ti, Do) which is musically the chord C^7. If this new harmony is better than the existing worst harmony in their memories, the new harmony is included in their memories and the worst harmony is excluded from their memories. This procedure is repeated until a fantastic harmony is found.

The steps in the procedure of harmony search are shown in Figure 1. They are as follows [23]:

Step 1. Initialize the problem and algorithm parameters.

Step 2. Initialize the harmony memory.

Step 3. Improvise a new harmony.

Step 4. Update the harmony memory.

Step 5. Check the stopping criterion.

2.1 Step 1: Initialize the problem and algorithm parameters

In Step 1, the optimization problem is specified as follows:

$$\text{Minimize } f(\boldsymbol{x}) \tag{1}$$

$$\text{Subject to } x_i \in \mathbf{X}_i,\ i = 1,2,...,N \tag{2}$$

where $f(\boldsymbol{x})$ is an objective function; $\boldsymbol{x}$ is the set of each decision variable x_i; N is the number of decision variables (the number of music instruments); $\mathbf{X}_i$ is the set of the possible range of values for each decision variable, that is, $\mathbf{X}_i = \{x_i(1), x_i(2),..., x_i(K)\}$ for discrete decision variables $(x_i(1) < x_i(2) < ... < x_i(K))$; and K is the number of possible values for the discrete decision variables (the pitch range of each instrument).

In the water network design, the objective function is the pipe cost function; the pipe diameter is the decision variable; the number of decision variables N is the number of pipes in the network; the set of decision variable values is the range of possible candidate diameters, for example, {300mm, 350mm, 400mm, 450mm, 500mm, 600mm, 700mm};

and the number of possible values for the decision variables K is the number of candidate diameters.

The HS algorithm parameters are also specified in this step. These are the harmony memory size (HMS), or the number of solution vectors in the harmony memory; harmony memory considering rate (HMCR); pitch adjusting rate (PAR); and the number of improvisations (NI), or stopping criterion.

The harmony memory (HM), shown in Figure 2, is a memory location where all the solution vectors (sets of decision variables) and corresponding objective function values are stored. The function values are used to evaluate the quality of solution vectors. This HM is similar to the genetic pool in the GA. The HMS for Figure 2 is four because the HM in the figure has four solution vectors. The meaning of the HMCR, PAR, and NI will be explained in the following steps.

In this study, an HMS of 30 - 100, an HMCR of 0.7 - 0.95, and a PAR of 0.05 - 0.7 were used based on the frequently used value ranges in other HS applications, as shown in Table 1 [23-25, 27]. However, the NI was determined based on the number of objective function evaluations from other competitive algorithms. NI is less than or equal to those of other algorithms.

2.2 Step 2: Initialize the harmony memory

In Step 2, the HM matrix is filled with as many randomly generated solution vectors as the HMS.

$$\mathbf{HM} = \begin{bmatrix} x_1^1 & x_2^1 & \cdots & x_{N-1}^1 & x_N^1 \\ x_1^2 & x_2^2 & \cdots & x_{N-1}^2 & x_N^2 \\ \vdots & \cdots & \cdots & \cdots & \cdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \cdots & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \cdots & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix} \begin{matrix} \Rightarrow & f(\boldsymbol{x}^1) \\ \Rightarrow & f(\boldsymbol{x}^2) \\ \Rightarrow & \vdots \\ \Rightarrow & f(\boldsymbol{x}^{HMS-1}) \\ \Rightarrow & f(\boldsymbol{x}^{HMS}) \end{matrix} \tag{3}$$

In the HS model for water network design, the randomly generated solution vectors undergo a hydraulic analysis to verify that they satisfy the minimum pressure requirements at each node. However, infeasible solutions that violate the minimum requirements still have a chance to be included in the HM in the hope of forcing the search towards the feasible solution area. The total design cost, including any penalty cost, is calculated for each solution vector.

2.3 Step 3: Improvise a new harmony

A new harmony vector, $\boldsymbol{x}' = (x_1', x_2', ..., x_N'),$ is generated based on three rules: (1) memory consideration, (2) pitch adjustment, and (3) random selection. Generating a new harmony is called 'improvisation' in this study.

In the memory consideration, the value of the first decision variable (x_1') for the new vector is chosen from any value in the specified HM range ($x_1^1 \sim x_1^{HMS}$). Values of the other decision variables ($x_2', ..., x_N'$) are chosen in the same manner. The HMCR, which varies between 0 and 1, is the rate of choosing one value from the historical values stored in the HM, while (1 − HMCR) is the rate of randomly selecting one value from the possible range of values,

$$x_i' \leftarrow \begin{cases} x_i' \in \{x_i^1, x_i^2, ..., x_i^{HMS}\} & \text{w.p.} \quad HMCR \\ x_i' \in \boldsymbol{X}_i & \text{w.p.} \quad (1\text{-}HMCR) \end{cases} \tag{4}$$

For example, an HMCR of 0.95 indicates that the HS algorithm will choose the decision variable value from historically stored values in the HM with a 95% probability or from the entire possible range with a (100 − 95)% probability. If the set of diameters stored in the HM is {300 mm, 500 mm, 500 mm, 700 mm} and the entire set of candidate diameters is {300 mm, 350 mm, 400 mm, 450 mm, 500 mm, 600 mm, 700 mm}, the algorithm chooses any diameter from the former set with a 95% probability, or any diameter from the latter set with a 5% probability.

Within the new harmony vector $\boldsymbol{x}' = (x_1', x_2', ..., x_N')$, every component obtained by the memory consideration is examined to determine whether it should be pitch-adjusted. This operation uses the PAR parameter, which is the rate of pitch adjustment as follows:

$$\text{Pitch adjusting decision for } x_i' \leftarrow \begin{cases} \text{Yes} & \text{w.p.} \quad PAR \\ \text{No} & \text{w.p.} \quad (1 - PAR) \end{cases} \tag{5}$$

If the pitch adjustment decision for x_i' is Yes, x_i' is replaced with $x_i(k)$ (the k^{th} element in $\mathbf{X}_i$) and the pitch-adjusted value of $x_i(k)$ becomes

$$x_i' \leftarrow x_i(k+m) \tag{6}$$

where m is the neighboring index, $m \in \{..., -2, -1, 1, 2, ...\}$. For example, a PAR of 0.1 indicates that the algorithm will choose a neighboring value with a 10% probability. If x_i' is 500 mm, m is -1 or 1 with equal chance, and the set of entire candidate diameters is {300 mm, 350 mm, 400 mm, 450 mm, 500 mm, 600 mm, 700 mm}, the algorithm will choose a neighboring diameter (450 mm or 600 mm) with a 10% probability, or keep the current diameter (500mm) with a (100 − 10)% probability.

In Step 3, HM consideration, pitch adjustment, or random selection is applied to each variable of the new harmony vector in turn. The HMCR and PAR parameters introduced in this step help the algorithm find globally and locally improved solutions, respectively.

2.4 Step 4: Update the HM

If the new harmony vector $\boldsymbol{x}' = (x_1', x_2', ..., x_N')$ is better than the worst harmony vector in the HM, judged in terms of the objective function value, and no identical harmony vector is stored in the HM, the new harmony is included in the HM and the existing worst harmony is excluded from the HM.

For the water network optimization problem, the new solution vector also undergoes a hydraulic analysis, just the same as in Step 2. Then, the total design cost of the vector is calculated. If the cost of the new vector is better (lower) than that of the worst vector in the HM, the new vector is included in the HM and the worst vector is excluded from the HM.

2.5 Step 5: Check stopping criterion

Steps 3 and 4 are repeated until the termination criterion (NI) is satisfied.

2.6 Numerical example

To easily understand the HS model for water network design, consider the example network shown in Figure 3. This network has three pipes and two demand nodes (nodes 1 and 2) with 10 cms (cubic meters per second) and 20 cms of flow, respectively. The set of candidate parameters is {100 mm, 200 mm, 300 mm, 400 mm, 500 mm}, and the corresponding cost set is {$100, $200, $300, $400, $500}. Whenever the pressure at a node violates the minimum pressure requirement, a penalty of $250 is added to the total cost. The HS uses the following algorithm parameter values: HMCR = 0.7; PAR = 0.5; HMS = 4; and NI = 2.

The HM is initially structured with four solution vectors randomly generated within the candidate diameters, such as (300 mm, 200 mm, 400 mm), (200 mm, 500 mm, 400 mm), (300 mm, 200 mm, 100 mm) and (100 mm, 200 mm, 200 mm). The corresponding total costs are $900 (= $300 + $200 + $400), $1100 (= $200 + $500 + $400), $850 (= $300 + $200 + $100 + ***$250***), and $1000 (= $100 + $200 + $200 + ***$250*** + ***$250***) if the third vector violates the pressure requirement at node 2 and the fourth vector violates the pressure requirements at both nodes.

In the next step, the diameter for the pipe 1 is chosen to be 300 mm if the HS selects a diameter from the HM where the candidate diameter set for pipe 1 is {300 mm, 200 mm, 300 mm, 100 mm}. This is the memory consideration. The diameter for pipe 2 is chosen to be 300 mm if the HS algorithm first chooses 200 mm from the HM of {200 mm, 500 mm, 200 mm, 200 mm} and then moves to the upper neighboring diameter. This is the pitch adjustment. The diameter for pipe 3 is chosen to be 200 mm if the HS algorithm randomly chooses the diameter from the original candidate set {100 mm, 200 mm, 300 mm, 400 mm, 500 mm}. This is the random selection.

The newly generated vector is then (300 mm, 300 mm, 200 mm), and the corresponding pipe cost is $800 if there are no pressure violations. The new vector is then substituted for the second vector (200 mm, 500 mm, 400 mm), which is the worst vector ($1100) in the HM.

As NI is two, the HS generates one more new vector. This could be (200 mm, 300 mm, 100 mm) after undergoing memory consideration, pitch adjustment, and random selection. The corresponding pipe cost is $600 if there are no pressure violations. The new vector is also included in the HM and the worst vector (100 mm, 200 mm, 200 mm) is eliminated from the HM.

Finally, the best solution vector (200 mm, 300 mm, 100 mm) stored in the HM with a cost of $600 is considered as the optimal solution for this water network design.

3. Problem Formulation

The least-cost design of a water distribution network can be stated as follows:

Minimize: Cost of the water network design

Subject to:

1. Continuity equation
2. Conservation of energy equation
3. Minimum pressure requirements

4. Other constraints (maximum pressure; flow velocity; reliability)

The objective function (cost of the water network design) is mathematically assumed to be a cost function of pipe diameters and lengths,

$$C = \sum_{i=1}^{N} f(D_i, L_i) \tag{7}$$

where $f(D_i, L_i)$ is the cost of pipe i with diameter D_i and length L_i, and N is the number of pipes in the network. A cost table is sometimes provided instead of the above cost function. The cost function is to be minimized under the following constraints.

3.1 Continuity equation

For each node, a continuity constraint should be satisfied,

$$\sum Q_{in} - \sum Q_{out} = Q_e \tag{8}$$

where Q_{in} is the flowrate to the node, Q_{out} is the flowrate out of the node, and Q_e is the external inflow rate or demand at the node.

3.2 Conservation of energy equation

For each loop in the network, the energy constraint can be written as follows:

$$\sum h_f - \sum E_p = 0 \tag{9}$$

where h_f is the head loss computed by the Hazen-Williams or Darcy-Weisbach formulae and E_p is the energy added to the water by a pump.

3.3 Minimum pressure requirement

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

$$H_j \geq H_j^{\min}; \quad j = 1, \ldots, M \tag{10}$$

where H_j is the pressure head at node j, $H_j^{\min}$ is the minimum required pressure head at node j, and M is the number of nodes in the network.

For the hydraulic analysis, in which each node pressure is investigated, the GA- and TS-based models [14, 18] interfaced with EPANET [32], and another GA-based model [33] interfaced with KYPIPE. Meanwhile, the SA-based and mathematical models [17, 34] adopted hydraulic simulation subroutines coded by the authors. The HS-based model in this study interfaced with EPANET for the hydraulic analysis. EPANET satisfies the continuity and energy conservation equations while calculating the flowrate Q_i in each pipe and the head H_j at each node. The Hazen-Williams formula was used as the pressure head loss equation in this study,

$$h_f = 4.72 C^{-1.85} Q^{1.85} D^{-4.87} L \tag{11}$$

where h_f is the head loss (ft or m), C is the Hazen-Williams roughness coefficient, Q is the flowrate (cfs), D is the pipe diameter (ft), and L is the pipe length (ft or m).

Savic and Walters [14] introduced a new constant ω to permit fair comparisons of hydraulic formulae among optimization models. Adopting this constant, the Hazen-Williams formula can be re-written in the following form:

$$h_f = \omega \frac{L}{C^{\alpha} D^{\beta}} Q^{\alpha} \tag{12}$$

where ω is a numerical conversion constant; α is a coefficient equal to 1/0.54 (or 1.85 in this study); and β is coefficient equal to 2.63/0.54 (or 4.87 in this study). The higher the constant ω, the greater the head loss, *i.e.*, higher ω values require larger diameters to deliver the same amount of water because they can violate the minimum pressure requirements while the lower ω values may just meet the constraint. Thus, higher ω values eventually require more expensive water network designs. If two researchers design the same network using different ω values, the researcher with the higher ω will have less favorable hydraulic conditions.

In the literature, Alperovits and Shamir [3] used ω values of 10.6792 and 10.7109, Quindry *et al*. [4] used 10.9031, Fujiwara and Khang [5] used 10.5088, Simpson *et al*. [16] used 10.6750, and Savic and Walters [14] used 10.5088 and 10.9031, and Cunha and Sousa [17] used 10.4973. In all these examples, the units of D and Q are m and m^3/s, respectively. The Hazen-Williams formula used in EPANET has an ω value of 10.5879; therefore 10.5879 as well as 10.5088 were chosen as the ω values in this study.

The penalty function is often introduced to effectively guide solution vectors from an infeasible solution area that only slightly violates the constraints to a feasible solution area. The penalty cost for an infeasible solution is calculated based on the distance away from the feasible solution area. In the water network design, a penalty cost function is introduced to prevent the algorithm from searching in the infeasible solution area, where pipes with small diameters that do not satisfy the minimum pressure head requirements at each node are located. The penalty function is in the form

$$f_p(H_j) = a\,\{\max(0, H_j^{\min} - H_j)\}^2 + b\,\mathrm{sgn}\{\max(0, H_j^{\min} - H_j)\} \tag{13}$$

where $f_p(\cdot)$ is a penalty function that has a value only when the node head H_j violates the minimum required head $H_j^{\min}$; $\max(\cdot)$ is the maximum function which compares two given numbers and then returns the larger value; $\mathrm{sgn}(\cdot)$ is the sign function, which extracts the sign of a real number; and a and b are penalty coefficients. Suggested values for the penalty coefficients are (a / approximate design cost) = 0.001 to 0.005 and (b / a) = 5 to 50, from experiments. The approximate design cost can be an original non-optimized cost or the design cost from another optimization algorithm. The penalty cost is added to the total design cost C_t,

$$C_t = \sum_{i=1}^{N} f(D_i, L_i) + \sum_{j=1}^{M} f_p(H_j) \tag{14}$$

4. Applications

The HS model was applied to the following five water distribution networks.

4.1 Two-Loop Water Distribution Network

The two-loop network, shown in Figure 4, was originally presented by Alperovits and Shamir [3], followed by Goulter *et al*. [5], Kessler and Shamir [6], Savic and Walters [14], and Cunha and Sousa [17]. The network has seven nodes and eight pipes with two loops, and is fed by gravity from a reservoir with a 210-m (= 689 ft) fixed head. The pipes are all 1,000 m (= 3,281 ft) long with a Hazen-Williams coefficient C of 130. The minimum head limitation is 30 m (= 98.4 ft) above ground level. Fourteen commercial pipe diameters and HS parameter values are listed in Table 2. Although this two-loop network looks small, a complete enumeration comprises $14^8 = 1.48 \times 10^9$ different network designs, thus making this illustrative example difficult to solve, as mentioned by Savic and Walters [14].

Table 3 compares the results obtained using the HS-based model with those obtained using other methods: column (2) the results from Alperovits and Shamir [3]; column (3) the results from Goulter *et al*. [5]; column (4) the results from Kessler and Sharmir [6]; and column (5) the results from Savic and Walters [14], Cunha and Sousa [17], and this study. From column (5), the optimal solutions obtained using the GA-, SA- ans HS-based models were exactly the same ($419,000). Previous research given in column (4) yielded an even better result. However, the solutions in column (2) - (4) allowed two segments with different discrete sizes. According to Savic and Walters [14], for a more realistic solution, the split-pipe design should be altered so that only one diameter is chosen for each pipe. They produced a non-split-pipe solution using the GA with up to 25,000 cost function evaluations and 10 runs. Cunha and Sousa [17] produced the same solution using SA with up to 70,000 evaluations and 1,500 runs. However, the HS in this study produced the same solution in only 5,000 evaluations (NI) and 5 runs. Furthermore, the HS used a less favorable hydraulic conversion constant (ω = 10.5879) than the GA (ω = 10.5088) and SA (ω = 10.4973). When the HS used the same constant as SA, it found the same solution after only 1,067 function evaluations, taking about 1 minute on an IBM 1.2-GHz processor.

4.2 Hanoi Water Distribution Network

Fujiwara and Kang [7] first presented the Hanoi network in Vietnam, shown in Figure 5. It consists of 32 nodes, 34 pipes, and 3 loops, and is fed by gravity from a reservoir with a 100-m (= 328 ft) fixed head. The pipe lengths are shown in Table 4, and have a Hazen-Williams *C* of 130. The minimum head limitation is 30 m (= 98.4 ft) above ground level. Six commercial diameters and HS parameter values are listed in Table 2.

Table 4 compares the results obtained using the HS-based model with those obtained using other methods: column (3) shows the results from Fujiwara and Kang [7], column (4) those from Savic and Walters [14], and column (5) those from this study. Fujiwara and Kang [7] solved the problem with ω = 10.5088 using a nonlinear programming gradient (NLPG) and local improvement method. They then converted their continuous diameters to discrete commercial diameters. They obtained \$6,320,000 for an optimal cost. Savic and Walters [14] solved the same problem with ω = 10.5088 using the GA, and obtained an optimal cost of $6,073,000 after 1,000,000 evaluations. The HS-based model tackled the problem with ω = 10.5088 and obtained an optimal cost of $6,056,000 after 200,000 function evaluations, which required about 5 hours on an IBM 333-MHz processor. Cunha and Sousa [17] also found the same cost as the HS-based model, but they used a more favorable hydraulic conversion constant (ω = 10.4973).

4.3 New York City Water Distribution Network

Schaake and Lai [8] first presented the New York City network, shown in Figure 6. It consists of 20 nodes, 21 pipes and 1 loop, and is fed by gravity from a reservoir with a 300-ft fixed head. The objective of the problem is to add new pipes parallel to existing ones because the existing network cannot satisfy the pressure head requirements at certain nodes (nodes 16 - 20). The pipe lengths are shown in Table 5, and have a Hazen-Williams constant C of 100. Fifteen commercial diameters and HS parameter values are listed in Table 2.

Table 5 compares the results obtained using the HS-based model with those obtained using other methods: column (3) shows the results from Schaake and Lai [8], column (4) those from Savic and Walters [14], column (5) those from Cunha and Sousa [15], and column (6) those from this study. Schaake and Lai [8] solved the problem using mathematical programming (LP and DP), and obtained $78,090,000 as the optimal cost. Savic and Walters [14] solved the problem with ω = 10.5088 using a GA-based model and obtained an optimal cost of $37,130,000 after 1,000,000 evaluations. Cunha and Sousa [15] solved the problem with ω = 10.5088 using an SA-based model and obtained the identical optimal solution with GA-based model. The HS-based model tackled the problem using ω = 10.5088 and obtained an optimal cost of $36,660.000 after 6,000 evaluations, which required about 20 minutes on an IBM 100-MHz processor. Table 6 represents corresponding nodal pressure comparison among GA, SA, and HS. Lippai *et al*. [18] also obtained a solution using a TS-based model, but they did not provide details because their optimum cost ($40,850,000) was higher than other solutions.

4.4 GoYang Water Distribution Network

Kim *et al.* [34] first presented the GoYang network in South Korea, shown in Figure 7. It consists of 22 nodes, 30 pipes, and 9 loops, and is fed by a pump (4.52 kW) from a reservoir with a 71-m fixed head. The water demands are shown in Table 7, and the pipe lengths are shown in Table 8, which have a Hazen-Williams coefficient *C* of 100. The minimum head limitation is 15 m above ground level. Eight commercial diameters and HS parameter values are listed in Table 2.

Table 8 compares the diameter solutions obtained using the HS-based model with those obtained using other methods: the third column shows the results from the original design, the fourth column those from Kim *et al*. [34], and the fifth column those from this study. Table 7 shows the corresponding node head results. Kim *et al*. [34] solved the problem using a projected Lagrangian algorithm supported by GAMS/MINOS, and then converted the continuous diameters to discrete commercial diameters. They obtained 179,142,700 Won (≈ $179,143), while the original cost was 179,428,600 Won (≈ $179,429). The HS-based model tackled the problem and obtained an optimal cost of 177,135,800 Won (≈

$177,136) after 10,000 function evaluations and 27 runs, which required about 12 minutes on an IBM 1.2-GHz processor.

4.5 BakRyun Water Distribution Network

Lee and Lee [33] first presented the BakRyun network in South Korea, shown in Figure 8. It consists of 35 nodes, 58 pipes and 17 loops, and is fed by gravity from a reservoir with a 58-m fixed head. The objective of the problem is to determine the diameters of new pipes (pipes 1 - 3) and parallel pipes (pipes 4 - 9) in addition to the existing network. The Hazen-Williams coefficient *C* is 100 for all pipes. The minimum head limitation is 15 m above ground level. Sixteen commercial diameters and HS parameter values are listed in Table 2. The last five corresponding costs shown in Table 2, represented by 'Max', indicate very large numbers that should not be selected. They are included to satisfy the 2^n-candidate condition (2^4 candidate diameters in this problem) in the GA.

Table 10 compares the diameter solutions obtained using the HS-based model with those obtained using other methods: the third column those from the original design, the fourth column those from Lee and Lee [33], and the fifth column those from this study. Table 9 shows the corresponding node pressure head results. Lee and Lee [33] solved the problem using a GA-based model and obtained an optimal cost of 903,620,000 Won (≈ $903,620) after 27 runs with different GA parameter values (mutation rate = 0.01 ~ 0.10; crossover rate = 0.3 ~ 0.7; and population size = 10 ~ 100). The original cost was 954,920,000 Won (≈ $954,920). The HS-based model tackled the problem and obtained the same cost (903,620,000 Won) after 27 runs with different HS parameter values (HMCR = 0.7 ~ 0.95; PAR = 0.3 ~ 0.7; HMS = 30 ~ 100) as shown in Table 11.

However, the HS-based model found the cost after 5,000 function evaluations, which required about 5 minutes on an IBM 1.2-GHz processor, while the GA-based model found after 15,000 - 350,000 function evaluations. Also, HS has reached the solution 24 times out of 27 runs as shown in Table 11, whereas the GA reached the solution 11 times out of 27 runs. The average cost of HS runs is 904,365,200 Won (0.08% difference from optimal cost) while that of GA runs is 917,492,800 Won (1.54% difference from optimal cost). Thus, HS-based model could find better results in terms of average cost from different values of the parameters within the less function evaluations.

5. Conclusions and Discussion

In this study, the meta-heuristic harmony search algorithm was introduced and applied to the least cost design of water distribution networks. HS mimics a jazz musician's improvisation behavior, which can be successfully translated into an optimization process. HS consists of three searching behaviors: memory consideration, pitch adjustment, and random selection. The parameter HMCR sets the rate of memory consideration and the parameter PAR sets the rate of pitch adjustment.

HS incorporates, by nature, the structure of existing meta-heuristic methods. It preserves the history of past vectors in the HM, similar to the TS, and is able to vary the adaptation rate HMCR from the beginning to the end of computation, resembling SA. It also manages solution vectors simultaneously in a manner similar to the GA.

However, there are advantageous features of the HS that distinguish it from other methods. Compared to the GA, HS (1) generates a new vector after considering all the existing vectors, rather than considering only two vectors (parents); (2) independently considers each decision variable in a vector; (3) considers continuous decision variable values without any loss of precision; and (4) does not require decimal-binary conversions or fixed number (2^n) of decision variable values. Compared to gradient-based methods, HS does not require any starting values of the decision variables nor does it require complex derivatives. These features improve the flexibility of the HS and help it to find better solutions [23].

In searching the solution space, the HS uses a ‘probabilistic-gradient’, which is a rate of inclination, to select the exact or neighboring values of decision variables for optimal solutions, while mathematical optimization techniques use mathematical-gradient to move better solutions, The probabilistic-gradient to the local or global optimal solution increases as the harmony memory is updated with better solutions, iteration by iteration.

In this study, the HS was successfully applied to the design of various water distribution networks, producing lower cost solutions than those of competing mathematical or meta-heuristic algorithms. The resulting costs obtained by the HS for the five water distribution were either the same or 0.28 - 10.26% less than those of competitive meta-heuristic algorithms, such as the GA, SA, and TS. For the BakRyun network design, although HS and GA reached the same cost, HS could find better average cost than GA, and the average cost of 27 HS runs differed from the optimal cost only by 0.08%.

The HS model also has other advantages over other approaches, not just the cost of the resulting design. The HS required fewer objective function evaluations than compatitive meta-heuristic algorithms. For the two-loop network design, the GA-, SA-, and HS-based models reached the same optimal cost ($419,000), but the GA- and SA-based models found the optimal solution after 25,000 and 70,000 evaluations, respectively, whereas the HS-based model found the optimal solution after only 5,000 evaluations (exactly after 1,095 evaluations). The HS-based model also found the same cost under less favorable hydraulic condition (ω = 10.5879) as compared to the GA-based model (ω = 10.5088) and the SA-based model (ω = 10.4973).

Unlike mathematical approaches, the HS-based model can suggest alternative solutions that are stored in HM after the computation. If a diameter contained in the best solution proves difficult to use, the engineer can choose another solution in the HM that contains a more reasonable diameter. This is in addition to the advantages of existing meta-heuristics models, which do not require starting value assumptions or mathematical derivatives.

From the good results and advantages illustrated in this study, the HS algorithm is particularly suited for combinatorial type problems such as water distribution network design.

References

[1] Walski, T. M., State-of-the-art pipe network optimization. in *Computer Applications in Water Resources*, ASCE, 1985, 559-568.

[2] Goulter, I. C., Systems analysis in water-distribution network design: from theory to practice. *Journal of Water Resources Planning and Management*, ASCE, 1992, **118**(3), 238-248.

[3] Alperovits, E. and Shamir, U., Design of optimal water distribution systems. *Water Resources Research*, 1977, **13**(6), 885-900.

[4] Quindry, G. E., Brill, E. D. and Liebman, J. C., Optimization of looped water distribution systems. *Journal of Environmental Engineering Division*, ASCE, 1981, **107**(EE4), 665-679.

[5] Goulter, I. C., Lussier, B. M. and Morgan, D. R., Implications of head loss path choice in the optimization of water distribution networks. *Water Resources Research*, 1986, **22**(5), 819-822.

[6] Kessler, A. and Shamir, U., Analysis of the linear programming gradient method for optimal design of water supply networks. *Water Resources Research*, 1989, **25**(7), 1469-1480.

[7] Fujiwara, O. and Kang, D. B., A two-phase decomposition method for optimal design of looped water distribution networks. *Water Resources Research*, 1990, **26**(4), 539-549.

[8] Schaake, J. and Lai, D., *Linear programming and dynamic programming – application of water distribution network design*. Report 116, 1969 (MIT Press: Cambridge, MA).

[9] Su, Y. C., Mays, L. W., Duan, N. and Lansey, K. E., Reliability-based optimization model for water distribution system. *Journal of Hydraulic Engineering*, ASCE, 1987, **114**(12), 1539-1556.

[10] Lansey, K. E. and Mays, L. W., Optimization model for water distribution system design. *Journal of Hydraulic Engineering*, ASCE, 1989, **115**(10), 1401-1418.

[11] Wood, D. J., *Computer analysis of flow in pipe networks including extended period simulations*. Report, 1980 (University of Kentucky: Lexington, KY).

[12] Loganathan, G. V., Greene, J. J. and Ahn, T. J., Design heuristic for globally minimum cost water-distribution systems. *Journal of Water Resources Planning and Management*, ASCE, 1995, **121**(2), 182-192.

[13] Sherali, H. D., Totlani, R. and Loganathan, G. V., Enhanced lower bounds for the global optimization of water distribution networks. *Water Resources Research*, 1998, **34**(7), 1831-1841.

[14] 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, 1997, **123**(2), 67-77.

[15] Cunha, M. C. and Sousa, J., Hydraulic infrastructures design using simulated annealing. *Journal of Infrastructure Systems*, ASCE, 2001, **7**(1), 32-39.

[16] Simpson, A. R., Dandy, G. C. and Murphy, L. J., Genetic algorithms compared to other techniques for pipe optimization. *Journal of Water Resources Planning and Management*, ASCE, 1994, **120**(4), 423-443.

[17] Cunha, M. C. and Sousa, J., Water distribution network design optimization: simulated annealing approach. *Journal of Water Resources Planning and Management*, ASCE, 1999, **125**(4), 215-221.

[18] Lippai, I., Heaney, J. P. and Laguna, M., Robust water system design with commercial intelligent search optimizers. *Journal of Computing in Civil Engineering*, ASCE, 1999, **13**(3), 135-143.

[19] Dandy, G. C., Simpson, A. R. and Murphy, L. J., An improved genetic algorithm for pipe network optimization. *Water Resources Research*, 1996, **32**(2), 449-458.

[20] Montesinos, P., Garcia-Guzman, A. and Ayuso, J. L., Water distribution network optimization using a modified genetic algorithm. *Water Resources Research*, 1999, **35**(11), 3467-3473.

[21] Balla, M. C. and Lingireddy, S., Distributed genetic algorithm model on network of personal computers. *Journal of Computing in Civil Engineering*, ASCE, 2000, **14**(3), 199-205.

[22] Costa, A. L. H., Medeiros, J. L. and Pessoa, F. L. P., Optimization of pipe networks including pumps by simulated annealing. *Brazilian Journal of Chemical Engineering*, 2000, **17**(4-7), 887-896.

[23] Geem, Z. W., Kim, J. H. and Loganathan, G. V., A new heuristic optimization algorithm: harmony search. *Simulation*, 2001, **76**(2), 60-68.

[24] Geem, Z. W. and Tseng, C. –L., New methodology, harmony search and its robustness, in *2002 Genetic and Evolutionary Computation Conference*, 2002, 174-178.

[25] Kim, J. H., Geem, Z. W. and Kim, E. S., Parameter estimation of the nonlinear Muskingum model using harmony search. *Journal of the American Water Resources Association*, 2001, **37**(5), 1131-1138.

[26] Geem, Z. W., Kim, J. H. and Loganathan, G. V., Harmony search optimization: application to pipe network design. *International Journal of Modelling and Simulation*, 2002, **22**(2), 125-133.

[27] Lee, K. S., and Geem, Z. W., A new structural optimization method based on the harmony search algorithm. *Computers and Structures*, 2004, **82**(9-10), 781-798.

[28] De Jong, K., Analysis of the behavior of a class of genetic adaptive systems. PhD thesis, University of Michigan, 1975.

[29] Goldberg, D. E., *Genetic algorithms in search optimization and machine learning*, 1989 (Addison Wesley: MA).

[30] Kirkpatrick, S., Gelatt, C. and Vecchi, M., Optimization by simulated annealing. *Science*, 1983, **220**(4598), 671-680.

[31] Glover, F., Heuristic for integer programming using surrogate constraints. *Decision Sciences*, 1977, **8**(1), 156-166.

[32] Rossman, L. A. *EPANET users manual*, 1994 (US Environmental Protection Agency: Cincinnati, OH).

[33] Lee, S. –C, and Lee, S. –I., Genetic algorithms for optimal augmentation of water distribution networks. *Journal of Korean Water Resources Association*, 2001, **34**(5), 567-575.

[34] Kim, J. H., Kim, T. G., Kim, J. H. and Yoon, Y. N., A study on the pipe network system design using non-linear programming. *Journal of Korean Water Resources Association*, 1994, **27**(4), 59-67.

Table 1. Harmony search parameters used for other problems.

Problem	Number of Variables	HMCR	PAR	HMS	NI
Rosenbrock function	2	0.95	0.7	10	40,000
Six-hump camelback function	2	0.85	0.45	10	5,000
Braken & McCormick function	2	0.8	0.1	30	40,000
Artificial neural network	6	0.9	0.3	30	20,000
Traveling salesperson problem	20	0.85 ~ 0.99	-	10 ~ 100	20,000
Generalized orienteering problem	27	0.3 ~ 0.98	-	1 ~ 10	50,000
Hydrologic parameter calibration	3	0.95	0.05	100	5,000
School bus routing	10	0.3 ~ 0.95	-	10 ~ 100	1,000
Truss structure design	10 ~ 29	0.8	0.3	20	50,000
Water pump switching problem	40	0.97	-	19	3,500

Table 2. Candidate pipe diameters and HS parameter values.

Network	Candidate Diameter	Corresponding Cost	# of Var.'s	HMS	HMCR	PAR	NI
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	8	100	0.95	0.05	5,000
Hanoi	{12, 16, 20, 24, 30, 40} in inches	{45.726, 70.4, 98.378, 129.333, 180.748, 278.28} in dollar/meter	34	50	0.93	0.18	200,000
New York	{36, 48, 60, 72, 84, 96, 108, 120, 132, 144, 156, 168, 180, 192, 204} in inches	{93.5, 134.0, 176.0, 221.0, 267.0, 316.0, 365.0, 417.0, 469.0, 522.0, 577.0, 632.0, 689.0, 746.0, 804.0} in dollar/foot	21	50	0.9	0.1	20,000
GoYang	{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	30	30 ~ 100	0.7 ~ 0.95	0.3 ~ 0.7	10,000
BakRyun	{300; 350; 400; 450; 500; 600; 700; 800; 900; 1,000; 1,100; 1,200; 1,350; 1,500; 1,600; 2,000} in millimeters	{118,000; 129,000; 145,000; 160,000; 181,000; 214,000; 242,000; 285,000; 325,000; 370,000; 434,000; Max; Max; Max; Max; Max} in won/meter	9 (pipes 1 ~ 9)	30 ~ 100	0.7 ~ 0.95	0.3 ~ 0.7	5,000

Table 3. Comparison of pipe diameters for two-loop network.

Pipe Number (1)	Alperovits and Shamir (2)	Goulter *et al.* (3)	Kessler and Shamir (4)	GA, SA and HS (5)
1	20 18	20 18	18	18
2	8 6	10	12 10	10
3	18	16	16	16
4	8 6	6 4	3 2	4
5	16	16 14	16 14	16
6	12 10	12 10	12 10	10
7	6	10 8	10 8	10
8	6 4	2 1	3 2	1
Cost ($)	497,525	435,015	417,500	419,000

(Diameter units are inches)

Table 4. Comparison of pipe diameters for Hanoi network.

Pipe Number (1)	Pipe Length (m) (2)	Fujiwara and Kang (3)	Savic and Walters (4)	Harmony Search (5)
1	100	40	40	40
2	1,350	40	40	40
3	900	40	40	40
4	1150	40	40	40
5	1450	40	40	40
6	450	40	40	40
7	850	38.16	40	40
8	850	36.74	40	40
9	800	35.33	40	40
10	950	29.13	30	30
11	1200	26.45	24	24
12	3500	23.25	24	24
13	800	19.57	20	20
14	500	15.62	16	16
15	550	12.00	12	12
16	2,730	22.50	12	12
17	1,750	25.24	16	16
18	800	29.01	20	20
19	400	29.28	20	20
20	2,200	38.58	40	40
21	1,500	17.36	20	20
22	500	12.65	12	12
23	2,650	32.59	40	40
24	1,230	22.06	30	30
25	1,300	18.34	30	30
26	850	12.00	20	20
27	300	22.27	12	12
28	750	24.57	12	12
29	1,500	21.29	16	16
30	2,000	19.34	16	12
31	1,600	16.52	12	12
32	150	12.00	12	16
33	860	12.00	16	16
34	950	22.43	20	24
Cost ($)	-	6,320,000	6,073,000	6,056,000

(Diameter units are inches)

Table 5. Comparison of pipe diameters for New York City network.

Pipe Number (1)	Pipe Length (ft) (2)	Schaake and Lai (3)	Savic and Walters (4)	Cunha and Sousa (5)	Harmony Search (6)
1	11,600	52.02	0	0	0
2	19,800	49.90	0	0	0
3	7,300	63.41	0	0	0
4	8,300	55.59	0	0	0
5	8,600	57.25	0	0	0
6	19,100	59.19	0	0	0
7	9,600	59.06	108	108	96
8	12,500	54.95	0	0	0
9	9,600	0.0	0	0	0
10	11,200	0.0	0	0	0
11	14,500	116.21	0	0	0
12	12,200	125.25	0	0	0
13	24,100	126.87	0	0	0
14	21,100	133.07	0	0	0
15	15,500	126.52	0	0	0
16	26,400	19.52	96	96	96
17	31,200	91.83	96	96	96
18	24,000	72.76	84	84	84
19	14,400	72.61	72	72	72
20	38,400	0.0	0	0	0
21	26,400	54.82	72	72	72
Cost ($1,000)	-	78,090	37,130	37,130	36,660

(Diameter unit are inches)

Table 6. Node pressure results for New York network.

Node Number	Water Demand (cfs)	Min. Pressure (m)	Pressure (GA&SA) (m)	Pressure (HS) (m)
1	-2017.5	300.0	300.00	300.00
2	92.4	255.0	294.34	294.38
3	92.4	255.0	286.47	286.57
4	88.2	255.0	284.17	284.28
5	88.2	255.0	282.13	282.27
6	88.2	255.0	280.56	280.71
7	88.2	255.0	278.08	278.26
8	88.2	255.0	276.52	276.40
9	170.0	255.0	273.77	273.70
10	1.0	255.0	273.74	273.67
11	170.0	255.0	273.87	273.80
12	117.1	255.0	275.16	275.10
13	117.1	255.0	278.12	278.08
14	92.4	255.0	285.59	285.56
15	92.4	255.0	293.34	293.33
16	170.0	260.0	260.17	260.15
17	57.5	272.8	272.87	272.80
18	117.1	255.0	271.30	261.29
19	117.1	255.0	255.21	255.22
20	170.0	255.0	260.82	260.80

Table 7. Node data and computational results for GoYang network.

Node Number	Water Demand (cmd)	Ground Level (m)	Pressure (Original) (m)	Pressure (NLP) (m)	Pressure (HS) (m)
1	-2550.0	71.0	15.61	15.61	15.61
2	153.0	56.4	28.91	28.91	24.91
3	70.5	53.8	31.18	31.15	26.32
4	58.5	54.9	29.53	29.10	24.11
5	75.0	56.0	28.16	27.47	22.78
6	67.5	57.0	26.91	25.44	20.67
7	63.0	53.9	30.46	30.75	25.34
8	48.0	54.5	29.80	29.48	24.41
9	42.0	57.9	26.05	24.84	20.01
10	30.0	62.1	21.50	20.17	15.43
11	42.0	62.8	20.92	19.79	15.06
12	37.5	58.6	24.34	22.95	18.16
13	37.5	59.3	23.54	22.07	17.38
14	63.0	59.8	21.43	20.84	15.27
15	445.5	59.2	21.59	20.78	15.42
16	108.0	53.6	31.06	30.65	25.88
17	79.5	54.8	29.05	28.97	24.29
18	55.5	55.1	28.76	28.87	23.99
19	118.5	54.2	29.49	29.14	24.89
20	124.5	54.5	28.80	27.96	24.43
21	31.5	62.9	21.06	20.18	16.89
22	799.5	61.8	21.47	20.07	17.21

Table 8. Comparison of pipe diameters for GoYang network.

Pipe Number	Pipe Length (m)	Diameter (Original) (mm)	Diameter (NLP) (mm)	Diameter (HS) (mm)
1	165.0	200	200	150
2	124.0	200	200	150
3	118.0	150	125	125
4	81.0	150	125	150
5	134.0	150	100	100
6	135.0	100	100	100
7	202.0	80	80	80
8	135.0	100	80	100
9	170.0	80	80	80
10	113.0	80	80	80
11	335.0	80	80	80
12	115.0	80	80	80
13	345.0	80	80	80
14	114.0	80	80	80
15	103.0	100	80	80
16	261.0	80	80	80
17	72.0	80	80	80
18	373.0	80	100	80
19	98.0	80	125	80
20	110.0	80	80	80
21	98.0	80	80	80
22	246.0	80	80	80
23	174.0	80	80	80
24	102.0	80	80	80
25	92.0	80	80	80
26	100.0	80	80	80
27	130.0	80	80	80
28	90.0	80	80	80
29	185.0	80	100	80
30	90.0	80	80	80
Cost (Won)	-	179,428,600	179,142,700	177,135,800

(1,000 Won ≈ 1 US Dollar)

Table 9. Node data and computational results for BakRyun network.

Node Number	Water Demand (cmd)	Ground Level (m)	Pressure (Original) (m)	Pressure (GA) (m)	Pressure (HS) (m)
1	0.0	24.9	32.76	32.76	32.76
2	4,231.0	29.9	26.95	26.95	26.95
3	3,257.0	31.4	25.33	25.25	25.25
4	4,528.0	40.8	15.13	15.05	15.05
5	1,784.0	24.3	20.88	20.59	20.59
6	20,023.0	28.0	27.08	27.00	27.00
7	5,673.0	22.4	31.68	31.10	31.10
8	2,516.0	31.4	21.01	20.43	20.43
9	860.0	21.9	23.44	23.13	23.13
10	334.0	17.6	29.55	29.20	29.20
11	1,512.0	17.8	34.56	34.56	34.56
12	901.0	22.9	28.24	28.00	28.00
13	853.0	14.1	37.02	36.80	36.80
14	966.0	17.4	33.44	33.15	33.15
15	2,270.0	19.4	31.21	20.81	20.81
16	1,255.0	17.1	35.01	34.85	34.85
17	1,526.0	19.9	31.43	30.84	30.84
18	1,497.0	20.6	30.63	30.05	30.05
19	716.0	36.4	15.26	15.05	15.05
20	6,900.0	23.5	27.36	26.93	26.93
21	10,000.0	26.3	24.35	23.90	23.90
22	636.0	34.3	16.31	15.91	15.91
23	809.0	20.8	30.15	29.64	29.64
24	2,069.0	26.3	24.76	24.23	24.23
25	1,761.0	15.4	35.89	35.30	35.30
26	2,279.0	11.4	30.08	29.65	29.65
27	1,795.0	11.4	38.86	38.56	38.56
28	1,968.0	11.1	29.48	29.06	29.06
29	2,986.0	10.5	40.22	39.75	39.75
30	2,078.0	11.6	39.53	38.96	38.96
31	1,587.0	25.2	23.94	23.38	23.38
32	4,085.0	12.9	35.83	35.31	35.31
33	4,701.0	12.9	30.04	29.51	29.51
34	0.0	18.2	29.44	28.88	28.88
35	667.0	25.2	25.79	25.22	25.22

Table 10. Comparison of pipe diameters for BakRyun network.

Pipe Number	Pipe Length (m)	Diameter (Original) (mm)	Diameter (GA) (mm)	Diameter (HS) (mm)
1	200.0	1,100	1,100	1,100
2	470.0	1,100	1,100	1,100
3	80.0	1,100	1,000	1,000
4	370.0	900	900	900
5	410.0	900	900	900
6	540.0	800	700	700
7	530.0	600	700	700
8	130.0	500	300	300
9	470.0	500	300	300
Cost (Won)	-	954,920,000	903,620,000	903,620,000

(1,000 Won ≈ 1 US Dollar)

Table 11. Results from different values of HS parameters

HMS	HMCR / PAR	0.7	0.9	0.95
30	0.3	903,620	903,620	*920,880*
	0.5	903,620	903,620	903,620
	0.7	903,620	903,620	903,620
50	0.3	903,620	903,620	903,620
	0.5	903,620	903,620	903,620
	0.7	*905,050*	903,620	903,620
100	0.3	903,620	903,620	903,620
	0.5	903,620	903,620	903,620
	0.7	*905,050*	903,620	903,620

(Unit: 1,000 Won)

Figure Captions

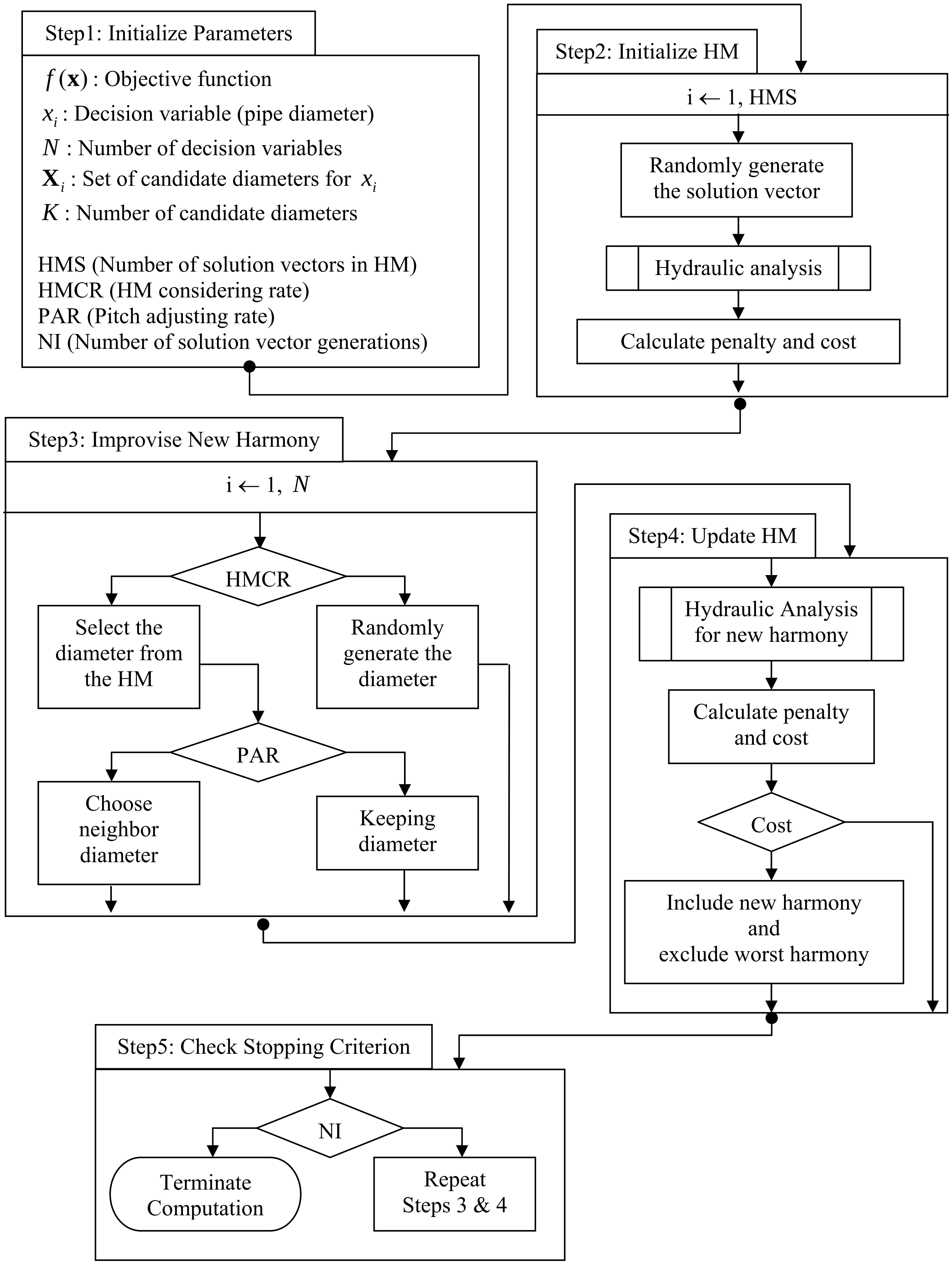

Figure 1. HS procedure for water distribution network design.

Objective Function $f(x) = (x_1-1)^2 + (x_2-2)^2 + (x_3-3)^2$

x_1	x_2	x_3	$f(x)$
1	2	3	0
1	3	5	5
2	4	2	6
3	2	1	8

Figure 2. Structure of harmony memory.

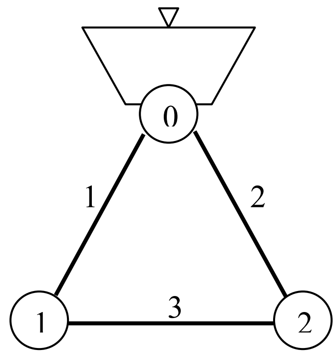

Figure 3. Example water distribution network.

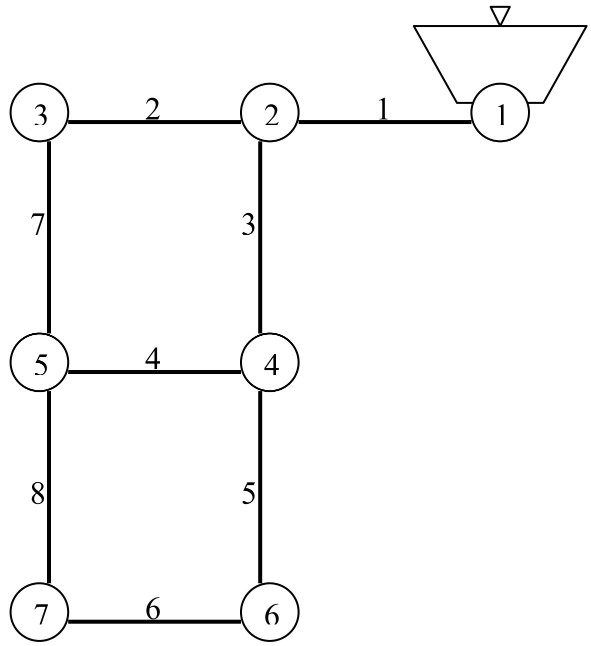

Figure 4. Two-loop water distribution network.

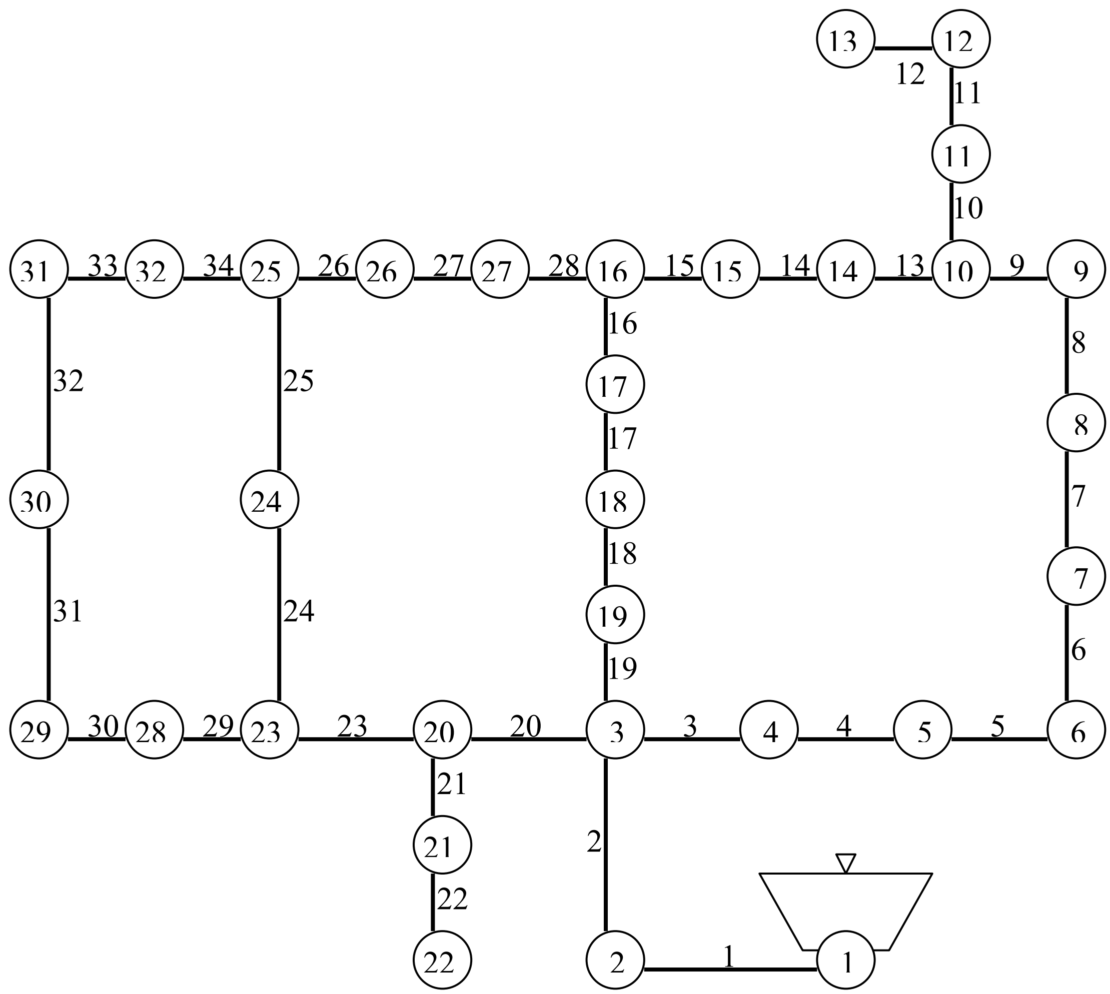

Figure 5. Hanoi water distribution network.

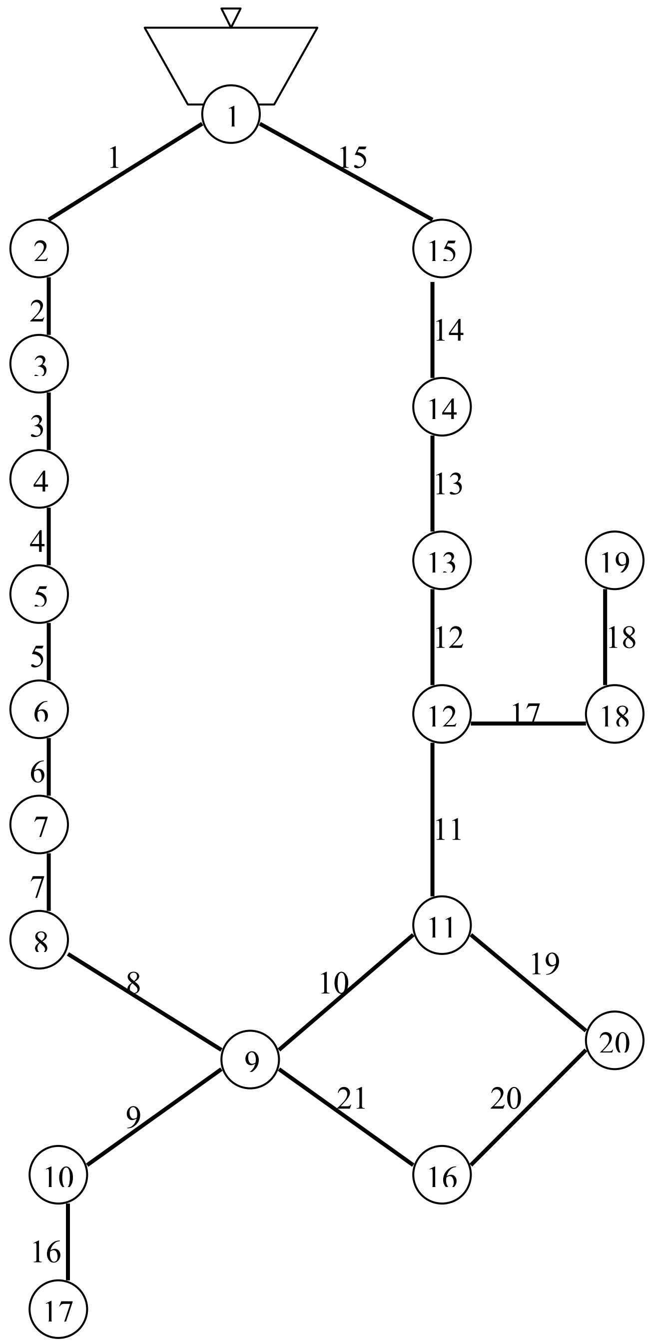

Figure 6. New York City water distribution network.

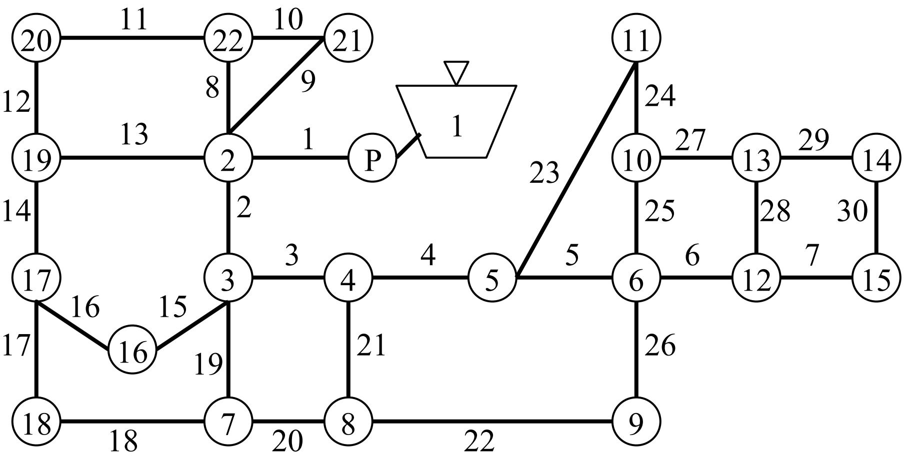

Figure 7. GoYang water distribution network.

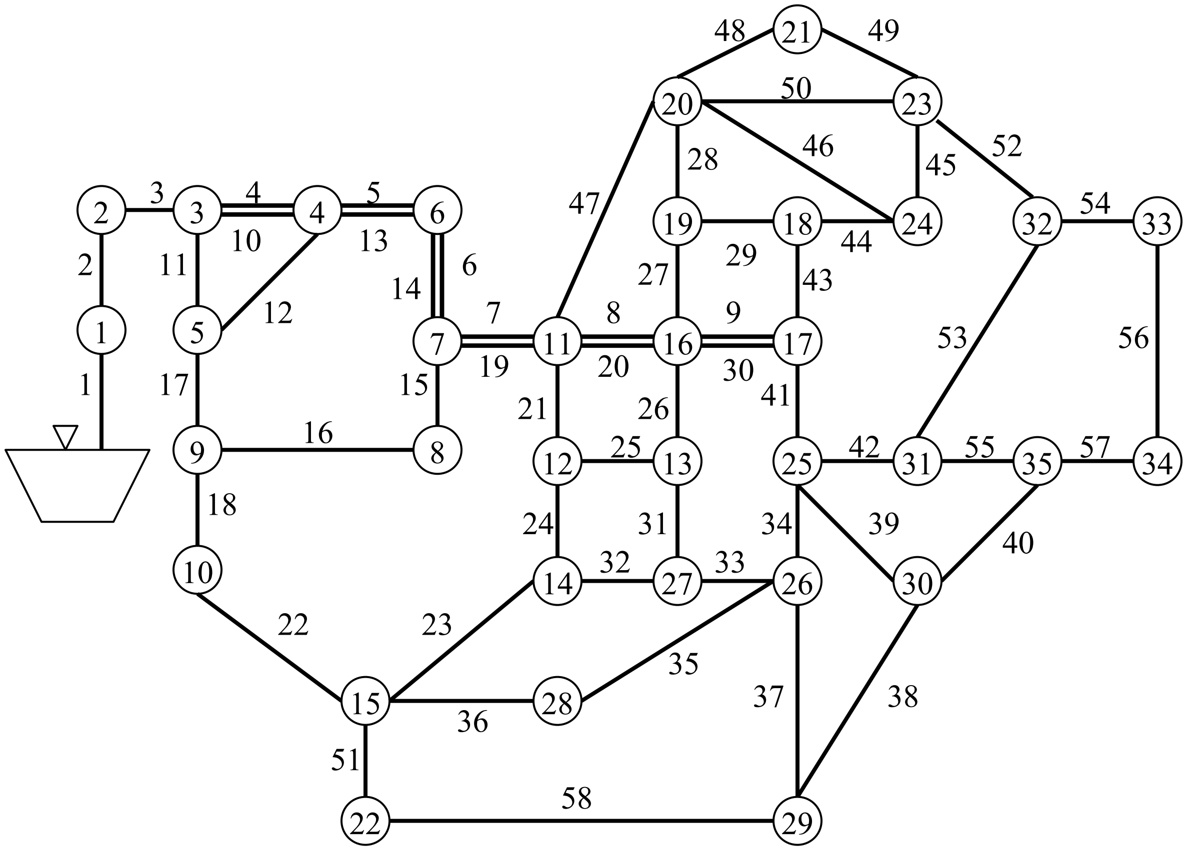

Figure 8. BakRyun water distribution network.