Optimal Water Distribution Network Design with Honey-Bee Mating Optimization

S. Mohan[1] and K. S. Jinesh Babu[2]

Abstract: Water distribution network is a costly infrastructure and plays a crucial role in supplying water for the consumers especially for those who are living in the urban areas. The importance and huge capital cost of the system leads to considerable attention on seeking the optimal cost design. The necessity for such a sound research attention arises from the complexity associated with the problem. In the recent years, stochastic optimization algorithms like genetic algorithm, simulated annealing, ant colony optimization etc. are found to be successful in exploring the optimal combination of pipe diameters that can satisfy the hydraulic-head requirements with least cost. In this paper, the details on the optimal water distribution network design with a novel technique called honey-bee mating optimization and its validation with two benchmark water distribution networks are presented. From the results, it is observed that the proposed algorithm identifies the optimal solution with relatively less number of evaluations than the other well-established stochastic optimization algorithms.

DOI: 10.1061/(ASCE)CP.1943-5487.0000018

CE Database subject headings: Optimization; Algorithms; Stochastic models; Water distribution systems; Water supply.

Author keywords: Optimization algorithms; Stochastic models; Water distribution systems; Water supply.

Introduction

Water distribution network (WDN) includes supply reservoir or source node, storage tanks or sumps, pumps, consumer withdrawal points or demand nodes, control valves, and interconnecting pipes. Among these components, the interconnecting pipes that transport water from the source node to the demand nodes account for the major fraction of the capital cost. Thus, exploring the pipe diameters that satisfy the hydraulic-head requirements at least cost assume the primary concern of the WDN design.

The optimal combination of pipe diameters should be able provide the hydraulic heads greater than that of the minimum required values at all the demand nodes. The hydraulic head available at a particular demand node depends on head-loss values associated with the supply pipes of that node and the hydraulic head(s) available at the upstream node(s). The head-loss value associated with a pipe varies with pipe material, length, diameter, and discharge. Among these, pipe material and length are fixed and the discharge carried by a pipe depends on its diameter. Thus, the pipe diameters become the logical decision variables. The main bottleneck associated with the WDN design is the nonlinear relationship between the pipe diameter and the head-loss value.

Up to date, there is no universally accepted method for optimal WDN design. In this paper, honey-bee mating optimization (HBMO), a stochastic optimization algorithm that replicates the biological behavior of the honey bees, has been proposed. The analysis reveals that HBMO has the capability of exploring the optimal pipe diameters from the discrete choices with relatively less number of evaluations.

Literature Review

The past studies related on optimal WDN design are presented in this section. Alperovits and Shamir (1977) applied linear programming gradient (LPG) method for the design of WDN, and in this method the nonlinear problem was converted into linear one by taking the pipe lengths as decision variables. The stretch between the adjacent nodes was divided into different segments and then the lengths of the segments were optimized to minimize the cost. Later, the LPG method was improved by different writers (Quindry et al. 1981; Fujiwara and Khang 1990). Savic and Walters (1997) concluded that, getting single discrete pipe diameter between the adjacent nodes is necessary for the more realistic and practical design.

The nonlinear optimization methods were also adopted for getting the optimal combination of pipe diameters (Su et al. 1987; Lansey and Mays 1989; Duan et al. 1990). The pipe diameters obtained by these methods are continuous and thus it is required to replace the resulted values with the nearest pipe sizes available in the market. This rounding off may lead to suboptimal solutions.

Since 1990, the application of stochastic optimization algorithms has been retained as an active research area for optimal WDN design. In the stochastic optimization algorithms, the objective function calls for evaluation at every trial made with different values on decision variables. Based on the objective function value obtained, the search progresses until the convergence is achieved.

Genetic algorithm (GA), an adaptive stochastic algorithm

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[1] Professor, Dept. of Civil Engineering, Indian Institute of Technology Madras, Chennai 600036, India (corresponding author). E-mail: smohan@iitm.ac.in

[2] Research Scholar, Dept. of Civil Engineering, Indian Institute of Technology Madras, Chennai 600036, India. E-mail: er_jinesh_babu@yahoo.co.in

Note. This manuscript was submitted on July 31, 2008; approved on March 3, 2009; published online on December 15, 2009. Discussion period open until June 1, 2010; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Computing in Civil Engineering***, Vol. 24, No. 1, January 1, 2010. ©ASCE, ISSN 0887-3801/2010/1-117–126/$25.00.

J. Comput. Civ. Eng. 2010.24:117-126.

based on natural selection and genetics (Goldberg 1989) had been successfully applied for the optimal WDN design (Simpson et al. 1994; Savic and Walters 1997; Halhal et al. 1997; Gupta et al. 1999; Prasad and Park 2004; Kadu et al. 2008). Simulated annealing (SA) (Kirkpatrick et al. 1983) is a metaheuristic algorithm that simulates the physical annealing process (by which the metal gradually cools down from a very high temperature to attain a solid crystalline form), also successful in exploring the optimal pipe diameters (Loganathan et al. 1995; Cunha and Sousa 1999). Ant colony optimization (ACO) is another stochastic optimization algorithm, which is based on the foraging behavior of ants (Dorigo et al. 1996). Adaptability of ACO for optimal WDN design was demonstrated by Maier et al. (2003). Tabu search that mimics the human memory process (Glover 1986) was used by da Conceição Cunha and Rebeiro (2004) for optimal design of WDNs.

The detailed literature review revealed that the stochastic optimization algorithms had been successful in exploring the optimal combination of pipe diameters from the available discrete pipe sizes than the deterministic optimization methods. But the stochastic optimization algorithms require large number of iterations to arrive at the optimal solution as these algorithms ignore the gradient information. Also, till date there is no globally accepted method for optimal water distribution network design.

HBMO

This section describes the biological basis of the honey-bee colony and the computational adaptation of the HBMO technique.

Biological Basis of Honey-Bee Colony

A honey-bee colony includes queens, drones, and workers or nurses. Division of labor, individual and group level communications, and cooperative behavior are the peculiar features of the honey-bee colony. The number of queen bees in a colony may be either one (monogynous) or more (polygynous) and queens are the main reproductive sources of individuals. Drones are fathers of the colony and they are haploids. The role of drone is to inject the sperm into queen's spermatheca. The nurse bees take care of broods' growth and they secrete the royal jelly from their glands and feed it to their future queen(s). This royal jelly feeding makes the queen bees bigger in size than that of others in the colony.

The queen bee used to gear up the mating flight with a dance and it will travel far away from the nest. In the beginning of the mating flight, the queen's speed is very fast and the speed gradually gets reduced as the mating processes hold on. During the mating flight, drones used to follow the queen bee and mate with her in the air. A queen bee can have several mating with different drones even in a single mating flight. But a drone's life ends up with a single mating. Eventual death of the drone indicates the successful insemination. The sperms accumulated in the queen's spermatheca make a genetic pool of the new colony. The queen sets off a mating flight with an empty spermatheca but while back to the nest its spermatheca gets filled with sperms either fully or partially.

After a mating flight, the queen bee turns on to fertilize the eggs by retrieving the sperms that are accumulated in the spermatheca. The worker bees can lay unfertilized eggs. Thus, a brood may arise from either a fertilized egg or an unfertilized egg. But, the brood that becomes the next queen comes from the fertilized egg only.

Computational Adaptation

With the biological background described in the above subsection, the HBMO was developed by Abbass (2001). Haddad et al. (2006) demonstrated the applicability of the HBMO with different benchmark mathematical problems. Afshar et al. (2007) applied HBMO for optimal reservoir operation problem and reported that the results obtained were promising and HBMO method holds good match with that of the results obtained by the other methods including GA.

For the execution of HBMO algorithm, the number of queens, drones, and workers need to be fixed in the beginning. The parameters associated with the queens that require prespecification are maximum number of broods that can be produced after a mating flight, spermatheca size, initial speed, speed reduction factor, and the maximum number of mating flights. Each honey bee in a colony represents a trial in the solution space. Here in after, the words honey bee and solution are used synonymously. To lead off the search, the ancestors of the honey-bee colony need to be initialized. The individuals are represented by the string of genes and the string length is equal to the number of decision variables. The genes of the individuals can be represented by binary coded or real coded values. To initialize the gene values, it can be assigned at random from the available discrete set of choices available in the list.

After initialization, the fitness of the individuals has to be evaluated. For minimization problems, the inverse of the objective or cost function value can be taken as the fitness of a honey bee. As analogous to the real honey-bee colony, the solution with more fitness value would act as queen.

The queen sets off the mating flight with an empty spermatheca and with the high initial speed. The mating flight can be treated as a set of transitions in a state space (the environment) where the queen moves between the different states in some speed and mates with the randomly selected drones one by one. The mating can takes place only when the probabilistic rule of mating described in Eq. (1) gets satisfied

$$P = \exp[-\Delta(f)/S(t)] \tag{1}$$

where P=probability of mating; $\Delta(f)$=absolute difference between fitness values of the queen bee and the selected drone; and $S(t)$=speed of the queen. After each transition in the space, speed of the queen gets reduced as per Eq. (2)

$$S(t) = \alpha S(t-1) \tag{2}$$

where α=speed reduction factor. To replicate the death of a drone after insemination, the solution which represents the drone that successfully mates with the queen bee has to be removed from the drone population. The mating process of a queen can hold on until the spermatheca gets filled with sperms or the speed falls below the threshold value. The mating flight is postulated for all the queens if more than one queen exists.

After the mating flight, the new broods can be bringing forth by coupling the queen's and drone's genes. In HBMO, the function of nurse bees is limited to brood care only as the new queens arise from the fertilized egg only. To simulate the royal jelly feeding, nurse bee's gene can be mutated with the brood's gene to improve the brood's fitness. After bringing forth the specified numbers of broods, the objective function requires to be evaluated to subsequently compute the fitness values of the broods. The broods with higher fitness values than that of current queens' fitness have to be replaced as queens of the next generation. The routine of mating flight and subroutine of brood generation need to be continued until the termination criteria met. The termination criteria may be either arrival of maximum number of mating flights or no more improvement in solution over certain number of mating flights. The pseudocode for this algorithm is given below.

Pseudo Code

```
1. initialization:
  define the number of queens, drones and workers.
  define the number of genes of the individuals.
  define the maximum number of mating flights.
  define the spermatheca size of the queens.
  define the queen's initial speed and speed reduction factor.
  define the number of broods that can be produced by a queen after a mating flight.

2. generation of ancestors (initial colony)
  initialize the queens, drones and workers gene values from the list of discrete variables at random.
  classification of honey-bees:
  evaluate the objective function and subsequently the fitness of the individuals.
  based on the fitness value, arrange the individuals in an ascending order.
  $n=1$;
  while n less than the number of queens
    individuals are queens.
    $n=n+1$.
  end while
  while n less than the number queens+drones
    individuals are drones.
    $n=n+1$.
  end while
  while n less than the number queens+drones+workers
    individuals are workers.
    $n=n+1$.
  end while

3. generation of new colony:
  while maximum number of mating flight or no improvement in solution observed
    mating Flight:
    for each queen in the queen list
      while the queen's spermatheca has space or speed>min value
        queen moves between states and randomly chooses drones
        if a selected drone satisfies the probabilistic rule of mating,
          add its sperm to the queen's spermatheca
          remove the selected drone from the drone list
        end If
        update the queen's speed
      end While
    end for each queen

    fertilization:
    for each queen in the queen list
      while the queen's spermatheca empty
        randomly retrieve the sperm from the spermatheca using uniform random number generator
        generate a brood by crossover the queen's and drone's genotypes
        remove the used sperm from the spermatheca
      end while
    end for each queen

    fitness improvement:
    for each brood
      use workers to improve broods fitness through mutation
    end for each brood

    update the queens:
    while the best brood is better than the worst queen
      replace the least–fittest queen with the best brood
      remove the best brood from the brood list
    end While

      update of drones list

    end while
```

Individual Representation

The number of genes in an individual is taken as the number of decision variables involved in the problem. For demonstration, it is assumed that the number of decision variables is 8. The queen-bees are represented as follows:

Q1 Q2 Q3 Q4 Q5 Q6 Q7 Q8

where Q1, Q2, …, Q8 are the genes of a queen. The gene values of the individuals have to be initialized from the list of discrete variables at random.

The drones are haploid in nature and in the mathematical form, a drone is represented by the genes and the genotype marker. A genotype marker is used to randomly mark half of the genes, leaving the other half unmarked. The drone's gene and genotype marker can be represented as follows:

Gene Value	D1	D2	D3	D4	D5	D6	D7	D8
Genotype marker	u	m	u	m	m	u	m	u

where D1, D2, …, D8 are genes of the drones. u and m indicate an unmarked and a marked genes, respectively. The unmarked genes are those that form a sperm to be randomly used in the mating process and thus the drone's sperm takes the following form:

D1 D3 D6 D8

The empty boxes represent the nonexisting genes. The workers or nurse bees are represented as follows:

N1 N2 N3 N4 N5 N6 N7 N8

where N1, N2, …, N8 are genes of the workers and in the similar way the broods are represented as follows:

B1 B2 B3 B4 B5 B6 B7 B8

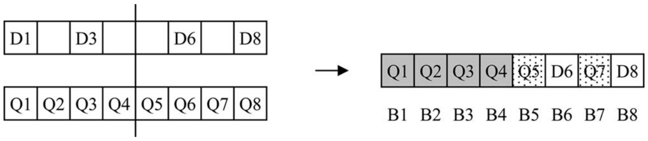
where B1, B2, …, B8 are genes of the broods.

Crossover Operation

Fertilization has to be carried out by crossover of the queen's and drone's genes. Random retrieval of sperms can be achieved through the use of uniform random number generator. Each sperm stored in the spermatheca has a unique identification number (ID) ranging from 1 to spermatheca size (number of sperms that can be stored is queen's spermatheca size). To retrieve a sperm, an integer random number ranging from 1 to spermatheca size is generated and the sperm ID that equals the random number generated can be used for the fertilization. After the crossover process, the retrieved sperm should be removed from the list. In the present research approach three types of crossover operators are analyzed: (1) single-point crossover; (2) multipoint crossover; and (3) uniform crossover.

Single-Point Crossover

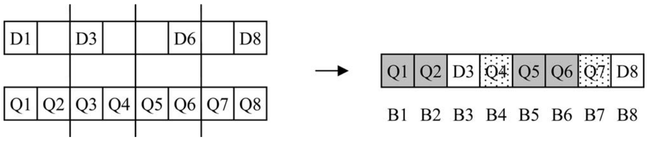
A single cutoff point has to be selected at random. For the brood's string, queen's genes have to be placed up to the cutoff point, after that the drone's sperm have to be placed. In the second part, the nonexisting genes of the sperm need to be filled by the queen's genes



where B1, B2, …, B8 are genes of the broods. The shaded boxes show the part of the string formed by the queen's genes. The dotted boxes show the nonexisting genes replaced by the queen's genes.

Multipoint Crossover

Two or more cutoff points have to be selected at random. In the brood's chromosome string, queen's genes have to be placed in the alternate subsections. In the remaining subsections drone's sperm have to be placed and the non-existing genes of the sperm require to be filled by the queen's genes



The shaded boxes show the part of the string formed by the queen's genes. The dotted boxes show the nonexisting genes replaced by the queen's genes.

Uniform Crossover

The nonexisting genes of the sperm have to be filled by the queen's genes

D1 D3 D6 D8
Q1 Q2 Q3 Q4 Q5 Q6 Q7 Q8
→ D1 Q2 D3 Q4 Q5 D6 Q7 D8
B1 B2 B3 B4 B5 B6 B7 B8

Mutation

Mutation process enhances the fitness of the broods by flipping the genes of the brood and a worker. Mutation rate needs to be fixed as low. On an average only one gene or no gene has to be changed. Probability of mutation can be checked as the same way used in doing GA

D1 Q2 D3 Q4 Q5 D6 Q7 Q8
N1 N2 N3 N4 N5 N6 N7 N8
→ D1 Q2 D3 Q4 Q5 N6 Q7 D8
B1 B2 B3 B4 B5 B6 B7 B8

The shaded box shows the way by which the brood's gene flipped by the workers' genes.

Optimization Model for WDN Design

In any WDN, the source head, elevation of demand nodes, demand values, and pipe lengths and layout are known in advance. The objective is exploration of the pipe diameters from the available list, which would satisfy the stated conditions or constraints with least cost. Thus, the objective function has been defined as follows:

$$\text{Min } Z=\sum_{i=1}^{N} C_i(L,\Phi) \tag{3}$$

where N=number of pipes in the WDN; $C_i(L,\Phi)$=cost of the pipe i that has a length "L" and diameter "Φ."

The hydraulic head available at all the demand nodes should be greater than that of the minimum required value. This minimum hydraulic-head requirement constraint can be mathematically expressed as shown in Eq. (4)

$$H_j \geq H_j^{\min} \quad j=1,2,3,\ldots,\text{nd} \tag{4}$$

Flow enters the node j should be equal to the flow that leaves node j through pipes and the demand at node j and this condition is referred as nodal mass balance [Eq. (5)]

$$q_j^{\text{in}}-q_j^{\text{out}}-q_j=0 \quad j=1,2,3,\ldots,\text{nd} \tag{5}$$

Head loss around a loop must be 0. This condition is known as loop energy balance and it is mathematically represented as shown in Eq. (6)

$$\left(\sum_{i=1}^{\text{np}_L}\text{HL}_i\right)_L=0 \quad L=1,2,3,\ldots,\text{nL} \tag{6}$$

where H_j=hydraulic head available at node j; $H_j^{\min}$=minimum hydraulic head required at node j, nd=number of demand nodes; q_j^{in} and q_j^{out}=flow entering and leaving the node j, respectively; q_j=demand satisfied at the node j, HL_i is head loss in pipe i; np_L=number of pipes in a loop; and nL=number of loops in the WDN.

HBMO for WDN Design

The way by which the HBMO used for the optimal WDN design is presented in Fig. 1. To set forth, the WDN parameters that include: source head, nodal elevations and demands, minimum hydraulic-head value to be maintained at the demand nodes, pipe layout, length of the individual pipes, commercially available pipe sizes, and unit cost associated with the commercial pipes are initialized.

After specifying these parameters, the initial colony of honey bees (ancestors) is evolved. To evolve the ancestors, the gene values are assigned from the list of commercially available pipe sizes. After initialization, the fitness values are computed as fol-

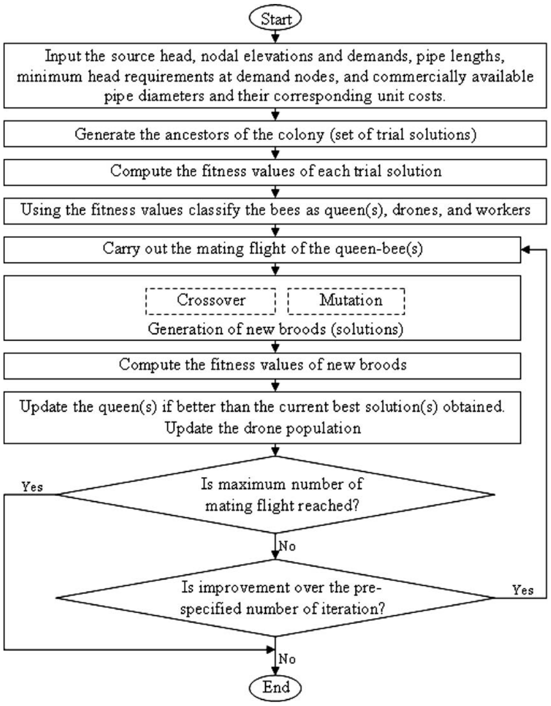


Fig. 1. Flowchart for optimal design of WDNs with honey-bee mating optimization

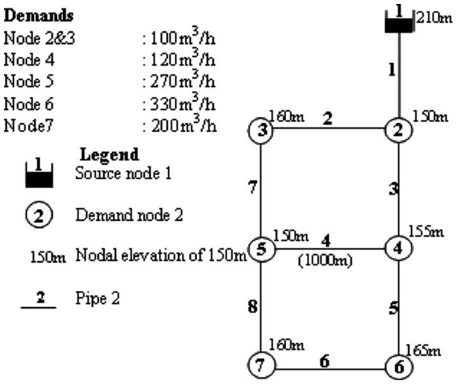


Fig. 2. WDN-I [adapted from Cunha and Sousa (1999)]

lows. The hydraulic head available at the demand nodes are computed using EPANET (Rossman 2000), a hydraulic simulation model developed by the Environmental Protection Agency, United States. Though, there are three sets of constraints stated in the optimization model, only the minimum hydraulic-head constraint is considered explicitly. The other two constraints, namely, nodal mass balance and loop energy balance are implicitly taken into account in the hydraulic simulation model. The penalty is added with the objective function value of the solutions that do not satisfy the minimum hydraulic-head constraint. The penalty value added for the constraint violation is modeled through Eq. (7)

$$\text{Penalty Value} = \text{Max}[(H_j^{\min} - H_j),0]^{*}\text{Penalty Factor} \quad j = 1,2,\ldots,\text{nd} \tag{7}$$

Eq. (7) evinces that the solution does not satisfy the minimum hydraulic-head constraint is penalized in proportion to the hydraulic-head deficit $(H_j^{\min} - H_j)$ values. The inverse of objective function value is taken as the fitness value of the solution.

To facilitate the computations, the individuals are provided with a unique ID. The honey bees are then arranged in an ascending order based on the fitness values. The individuals with more fitness values (for the number of queens) are taken as queens and the honey bees next to the queens (for the number of drones) are treated as drones. The rest of the honey bees are placed in the worker population.

Once the initial colony of honey bees becomes ready, the mating flights of the queens are fired on. During the mating flight, the queen mates with the drones that are randomly selected from the drone population only when the probabilistic rule of mating gets satisfied. As soon as the successful mating, the solution that represents the particular drone is removed from the drone population.

After return back to the nest, the queen starts to fertilize the eggs through crossover process. The sperms those stored in the spermatheca are retrieved using the uniform random number generator. To improve the fitness of the broods, mutation operation is carried out by flipping the broods and workers' genes. The fitness values of some of the newly developed broods may be higher than that of the fitness of current queens. If better broods appeared, replacement of the queens by the better fit broods is carried out. The drone population requires to be updated after each mating flight as the drones that breed with the queens are removed from the drone population. The processes of mating flight, new brood generation, replacement of queens, and update of drone population are continued either the maximum number of mating flight or no improvement in solution over the pre-specified number of mating flight is noticed.

Case Examples

The applicability of the proposed HBMO for the optimal design of WDN has been demonstrated through two benchmark networks.

WDN-I

The WDN-I was introduced by Alperovits and Shamir (1977) and it has been considered as a benchmark network by different authors to demonstrate the applicability of the many developed methods. In this study also, WDN-I is taken as a benchmark system for validating the applicability of the HBMO method and to comparatively evaluate the relative performance of the proposed method. The layout of WDN-1 and the demanded quantity of water at the consumer withdrawal points are presented in Fig. 2. It can be seen from Fig. 2 that the system has one source node, six demand nodes, and eight pipes. The hydraulic head required to be maintained at all the demand nodes is 30 m above the nodal elevation. All the pipes are of equal length of 1,000 m. The list of commercially available pipe sizes and their unit costs are given in Table 1 and the Hazen William's coefficient is taken as 130 for all pipes.

The first step in the optimal WDN design using HBMO is to evolve the ancestors. Toward this the genes of individuals are assigned with the randomly selected pipe sizes. The number of genes of an individual is made equal to the number of pipes in the system. Thus, for WDN-I, the honey bees are provided with eight genes. The sensitivity analysis has been carried out with different combination of number of queen bees, drones, and worker bees and the following combination is identified as best for WDN-I;

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Table 1. Commercial Pipe Data for WDN-I [Adapted from Cunha and Sousa (1999)]

Diameter (mm)	Cost (units)
25.40	2
50.80	5
76.20	8
101.60	11
152.40	16
203.20	23
254.00	32
304.80	50
355.60	60
406.40	90
457.20	130
508.00	170
558.80	300
609.60	550

number of queens=3; number of drones=200; and number of nurse bees=100. The maximum number of mating flights is taken as 100. The spermatheca size of queen bee is taken as 20. The initial speed and speed reduction factor (α) are taken as 0.6 and 0.95, respectively.

The significance of number of queen-bees (number of drones =200; number of workers=100) on the least-cost solutions obtained for WDN-I is shown in Fig. 3. The least-cost value of 459,000 units is obtained by a single-queen colony and this value appeared in the 20th mating flight. The two-queen colony ended up with a least-cost value of 453,000 units and this value appeared at the 39th mating flight. The optimal cost of 419,000 units is obtained by the three-queen colony and this cost first appeared in the 11th mating flight and all the three queens yielded the optimal value at 13th mating flight.

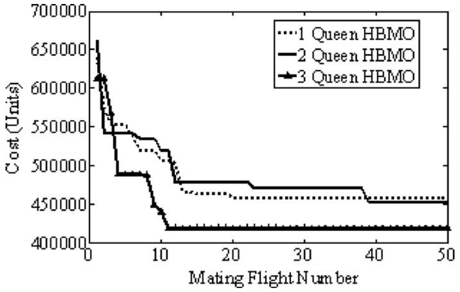

Fig. 3. Significance of number of queens on least-cost solution for WDN-I

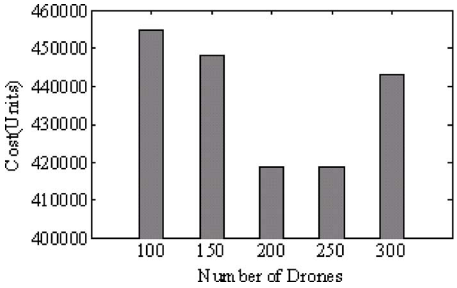

Fig. 4. Significance of number of drones on least-cost solution for WDN-I

The effect of number of drones on a three-queen colony (number workers=100) is shown Fig. 4. From Fig. 4, it can be inferred that the optimal cost of 419,000 is obtained when the number of drones are in the range of 200 to 250. The optimal value appeared at 11th and 17th mating flight when the number of drones is taken as 200 and 250, respectively. Thus the number of drones is taken as 200. Fig. 5 visualizes the significance of number of workers on the solution when the number of queens and drones are kept as 3 and 200, respectively. Fig. 5 shows that the optimal cost of 419,000 is obtained when the numbers of workers are ranging from 100 to 125. The optimal value appeared at 11th and 15th mating flight when the number of workers is taken as 100 and 125, respectively. Thus the number of workers is taken as 100.

To reach the optimal value of 419,000 units, the maximum number of calls for hydraulic simulation run is found to be 1,293. The value of 1,293 includes: evaluation of 303 ancestors (3 queen-bee+200 drones+100 workers), a total evaluation of 660 new broods (3 queen bees×20 new broods at each mating flight×11 mating flights), and evaluation of 50% of the drones (330 numbers) that are updated with randomly evolved drones [3 queens×(0.5×20)×11 mating flights]. The randomly evolved drones are subjected to hydraulic simulation because their fitness values are essential for checking the probabilistic rule of mating in the next mating flight.

When the number of queens exceeds three the optimal cost of 419,000 units is retained. But the number of mating flights taken to arrive at the optimal cost gets increased. This is due to the reason that when the number of queens increases, the solution space also increases and thus requires more number of evaluations to arrive at the optimal solution. By the four-queen colony, the optimal value is obtained in the 19th mating flight and the number of evaluation taken to achieve this is 2,584. Thus, it can be concluded that the three-queen colony is the best one for the optimal design of WDN-I and the remaining part of this discussion is limited to the results associated with the three-queen colony.

The fertilization has been carried out with single-point, multipoint, and uniform crossover operations. Fig. 6 shows the least cost obtained at the successive mating flights with these different crossover operators. The single-point crossover and multipoint crossover yielded the least-cost values of 441,000 and 438,000 units, respectively. The optimal value of 419,000 is obtained only with the uniform crossover operator. Thus it is considered that uniform crossover is better than that of other two methods.

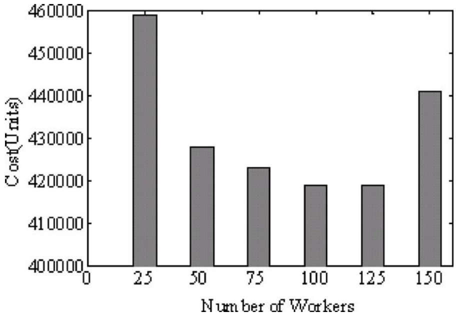

Fig. 5. Significance of number of workers on least-cost solution for WDN-I

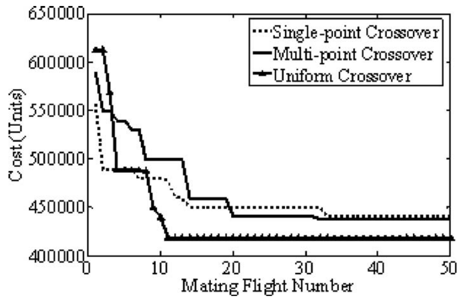

Fig. 6. Comparison of the convergence with different crossover operation for WDN-I

Since the mutation step simulates the royal jelly feeding, the terms mutation, and royal jelly feeding are used synonymously here. Mutation is admitted only when the probability of mutation gets satisfied. The value for probability of mutation is assumed as 0.1. If there is a chance for mutation, then it is carried out by replacing the randomly selected gene of the brood with randomly chosen nurse bee's gene. Fig. 7 visually compares the costs obtained by the three-queen HBMO with and without royal jelly feeding. Fig. 7 ascertains that the optimal cost of 419,000 units is obtained only when the mutation process is included in the optimization. If the mutation process is excluded, then the least cost resulted is 444,000 units and it requires 22 mating flights in order to obtain this value. The similar kind of observation is noticed when the analysis has been carried out with different number of queens.

Table 2 lists the cost associated with each queen of the three-queen colony in the successive mating flights. From Table 2, it can be observed that after each mating flight at least one of the queens is getting replaced with the better new brood(s). In Table 3 the optimal pipe diameters obtained with the three- queen HBMO are listed. The optimal pipe diameters obtained by HBMO is same as the one obtained by GA (Savic and Walters 1997) and SA (Cunha and Sousa 1999). Table 3 also presents the hydraulic-head values available at the demand nodes corresponding to the optimal pipe diameters obtained from the HBMO. From the numerical values, it can be seen that the hydraulic head available at all the demand nodes are greater than that of 30 m above the nodal elevation.

WDN-II

The WDN-II selected for the study was originally introduced by Fujiwara and Khang (1990) and the same network is shown in Fig. 8. This network has one source node, 31 demand nodes, 34 pipes, and the elevations of all the demand nodes is 0. The demanded quantity at the consumer withdrawal points and length of the pipes for WDN-II are listed in Table 4. The hydraulic head available at the source node is 100 m. The minimum hydraulic-head value that needs to be maintained at all the demand nodes is 30 m. The pipe sizes available in the market and the unit costs associated with them are given in Table 5. The Hazen William's coefficient for all the pipe size is taken as 130.

For WDN-II, each honey bee has been assigned with 34 genes as the number of pipes in the system is 34. The sensitivity analysis has been carried out as demonstrated for WDN-I and based on the observations, the following parameters are taken for the optimization; number of queens=5, number of drones=100, and number of workers=100. The spermatheca size of the queen is taken as 20. The initial speed and the speed reduction factor (α) are assumed as 0.6 and 0.95, respectively. The maximum number of mating flight is fixed as 150. Though the number of pipes in WDN-II is greater than that of WDN-I, it is found that for the design of WDN-II, less number of drones are required than that of WDN-I. This may be due to the fact that the number of commercial pipe sizes for WDN-I design is 14 whereas for WDN-II design the number of pipe sizes is only 6. The least-cost values of 6.80×10^6, 6.51×10^6, and 6.11×10^6 units are obtained with three-queen, four-queen, and five-queen colonies, respectively.

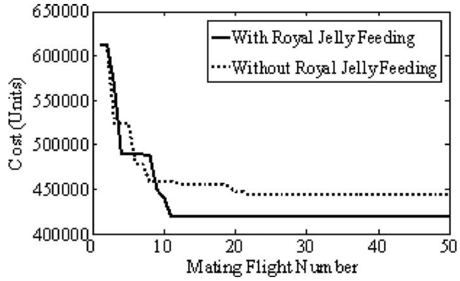

Fig. 7. Comparison of convergence to least-cost with and without feeding of royal jelly for WDN-I

Table 2. Variation of Cost Associated with the Queens at Successive Mating Flights

Mating fight number	Cost (units)		
	Queen 1	Queen 2	Queen 3
1	612,712.02	651,000.00	662,268.62
2	612,712.02	637,017.41	649,682.32
3	568,000.00	584,039.95	608,000.00
4	489,000.00	544,000.00	551,000.00
5	489,000.00	489,000.00	517,000.00
6	489,000.00	489,000.00	494,000.00
7	489,000.00	489,000.00	494,000.00
8	488,000.00	489,000.00	489,000.00
9	450,000.00	461,000.00	478,000.00
10	440,000.00	440,000.00	450,000.00
11	419,000.00	422,000.00	440,000.00
12	419,000.00	419,000.00	422,000.00
13	419,000.00	419,000.00	419,000.00
14	419,000.00	419,000.00	419,000.00
15	419,000.00	419,000.00	419,000.00

Table 3. Optimal Pipe Diameters and the Hydraulic-Head Values for WDN-I

Pipe number	Diameter (mm)	Node number	Hydraulic head (m)
1	457.20	1	210.00
2	254.00	2	203.25
3	406.40	3	190.46
4	101.60	4	183.45
5	406.40	5	183.81
6	254.00	6	195.44
7	254.00	7	190.55
8	25.40		

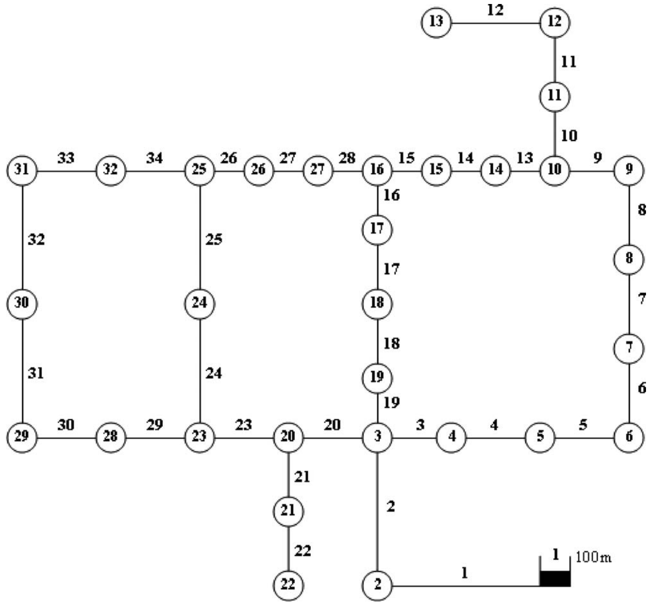

Fig. 8. WDN-II [adapted from Cunha and Sousa (1999)]

When the number of queen bees exceeds five, the same cost of 6.11×10^6 units is retained but the number of evaluations becomes more. The increase in number of evaluations is due to the reason that though the number of queens is increased there is no significant decrease in the number of mating flights required for the arrival of optimal cost.

Savic and Walters (1997) assigned the values of 10.5088 and 10.9031 for the conversion factor "*a*" in the head-loss equation and obtained the designs of the same network for these two cases and these cases are here in after referred as GA-I and GA-II, respectively. For WDN-II, Savic and Walters (1997) reported that the least cost obtained by GA-I and GA-II were 6.076×10^6 and 6.195×10^6 units, respectively. The least-cost value reported by Cunha and Sousa (1999) for the same network was 6.056×10^6 units. Eusuff and Lansey (2003) showed that the pipe diameters reported by Savic and Walters (1997) for GA-I had hydraulic-head deficit at node-13 and node-30. Similarly, the pipe diameters presented by Cunha and Sousa (1999) had hydraulic-head deficit at node-13, node-16, node-17, node-27, node-29, and node-30 while running with EPANET. Table 6 shows the least-cost pipe diameters obtained from the proposed HBMO and the hydraulic-head values at the demand nodes corresponding to the least-cost diameters. It can be seen from Table 6, that all the demand nodes are having hydraulic-head values greater than that of the required value of 30 m.

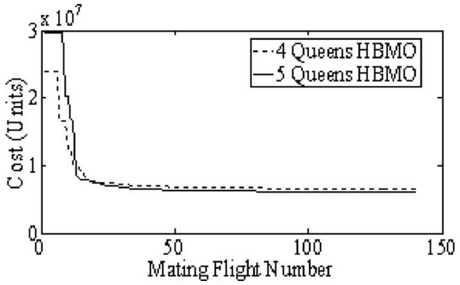

Fig. 9. Convergence curve for WDN –II

Table 4. Nodal Demand and Pipe Length for WDN-II [Adapted from Cunha and Sousa (1999)]

Node	Demand (m^3/h)	Pipe	Length (m)
2	890	1	100
3	850	2	1,350
4	130	3	900
5	725	4	1,150
6	1,005	5	1,450
7	1,350	6	450
8	550	7	850
9	525	8	850
10	525	9	800
11	500	10	950
12	560	11	1,200
13	940	12	3,500
14	615	13	800
15	280	14	500
16	310	15	550
17	865	16	2,730
18	1,345	17	1,750
19	60	18	800
20	1,275	19	400
21	930	20	2,200
22	485	21	1,500
23	1,045	22	500
24	820	23	2,650
25	170	24	1,230
26	900	25	1,300
27	370	26	850
28	290	27	300
29	360	28	750
30	360	29	1,500
31	105	30	2,000
32	805	31	1,600
		32	150
		33	860
		34	950

The variation of least cost resulted at successive mating flights of the four-queen HBMO and five-queen HBMO is shown in Fig. 9. For both the cases, there are 100 drones and 100 workers. In the five-queen colony, the least-cost value appeared in the 105th mating flight. Each of the queens can bring forth a maximum of 20 new broods after every mating flight. Thus, the number of calls for hydraulic simulation runs by the five-queen HBMO is 15,955.

Table 5. Commercial Pipe Data for WDN-II [Adapted from Cunha and Sousa (1999)]

Diameter (mm)	Cost (units)
304.80	45.726
406.40	70.400
508.00	98.378
609.60	129.333
762.00	180.748
1,016.00	278.28

Table 6. Optimal Pipe Diameters and the Hydraulic-Head Values for WDN-II

Pipe number	Diameter (mm)	Node number	Hydraulic head (m)
1	1,016.00	1	100.00
2	1,016.00	2	97.14
3	1,016.00	3	61.67
4	1,016.00	4	56.97
5	1,016.00	5	51.14
6	1,016.00	6	45.00
7	1,016.00	7	43.56
8	1,016.00	8	41.85
9	1,016.00	9	40.49
10	762.00	10	39.49
11	609.60	11	37.93
12	609.60	12	34.50
13	508.00	13	30.30
14	406.40	14	36.07
15	304.80	15	34.52
16	304.80	16	32.74
17	508.00	17	38.74
18	508.00	18	45.30
19	609.60	19	58.77
20	1,016.00	20	50.73
21	508.00	21	41.38
22	304.80	22	36.21
23	1,016.00	23	44.74
24	762.00	24	39.27
25	762.00	25	35.78
26	508.00	26	32.40
27	304.80	27	31.74
28	304.80	28	39.19
29	406.40	29	30.52
30	304.80	30	30.83
31	304.80	31	31.12
32	406.40	32	33.62
33	406.40		
34	609.60		

The analyses are carried out with different crossover operations including single-point crossover, multipoint crossover, and uniform crossover and it is reinforced that the uniform crossover operator out-performs the other two crossover operators. The significance of the mutation process is examined by carrying out the design with and without mutation process and the results indicated that the inclusion of mutation process is crucial in the HBMO. The queen would terminate the mating flight when the spermatheca gets filled with drones sperms or when the speed falls below the threshold level. A closer look at the results indicate that most of the times the queen bees return back to the nest after getting filled with drones sperm.

The statistical results of the multiple random trials made for the WDN-I and WDN-II are given in Table 7. For WDN-I, the number of drones and workers have been allowed to vary from 175 to 275 and 75 to 150, respectively. Similarly for WDN-II, the drones and workers count varying from 50 to 150 and 75 to 125, respectively. The least-cost, mean, and standard deviation (SD) values unveil that the proposed HBMO method is highly robust and efficient in finding the least-cost combination of pipe diameters.

Table 7. Statistical Results of Sensitivity Analysis

System	Number of queens	Least-cost (units)	Mean (units)	SD (units)
WDN-1	1	459,000	468,270	8,098.95
WDN-1	2	453,000	456,470	5,719.81
WDN-1	3	419,000	420,620	1,727.85
WDN-1	4	419,000	422,340	3,508.20
WDN-1I	3	6.80×10^6	7.05×10^6	0.19×10^6
WDN-1I	4	6.51×10^6	6.72×10^6	0.14×10^6
WDN-1I	5	6.11×10^6	6.18×10^6	0.08×10^6
WDN-1I	6	6.11×10^6	6.27×10^6	0.10×10^6

Note: WDN refers to water distribution network and SD refers to standard deviation.

Table 8 lists the costs associated with the least-cost pipe diameters and the number of evaluations taken by the proposed HBMO, GA, SA, shuffled frog leaping algorithm, and modified GA with reduction in search space. From Table 8, it can be inferred that the number of evaluation needed for the proposed HBMO method accounts only the small fraction of evaluations taken by the other methods. Thus, it can be concluded that the HBMO has the capability of identifying the feasible optimal combination of pipe diameters with relatively less number of evaluations. The major differences of the HBMO method over the other methods like GA is that since the queen stores a number of different drone's sperm in her spermatheca she can use parts of the genes of different drones to create different new solution which gives the possibility to have many more fittest broods.

Conclusions

The HBMO which replicates the biological nature of the honey bee had been successfully applied for the optimal WDN design. The applicability of the algorithm was demonstrated with two benchmark WDNs. From the application of the algorithm to the WDN design, the following conclusions were made.

For optimal WDN design the multiple-queen colony is essential. The number of queen bees required increases with the increase in number of pipes in the WDN. The number of drones increases with the increase in number of commercially available pipe sizes. Probabilistic rule of mating works well only when the normalized values of queen's and drone's fitness were used. The study reveals that more than 90% of the time the mating flight gets terminated when the spermatheca gets filled by drones' sperm.

For HBMO it is recommended that uniform crossover operator may be adopted than single-point and multipoint crossover operators. The mutation process is very crucial to reach the optimal cost configuration. Better update of the drone population can be achieved through replacement of 50% of the new drones with the newly generated broods and the remaining with the randomly evolved drones.

It is concluded that, the HBMO has the ability to identify the optimal combination of pipe diameters with relatively less number of evaluations or iterations when compared with that of other stochastic optimization algorithms like GA, SA, and shuffled frog leaping algorithm.

Table 8. Optimal Costs Resulted and Number of Evaluations Taken by Different Algorithms

	WDN-I		WDN-II	
Approach	Number of evaluations	Cost (units)	Number of evaluations	Cost (units)
HBMO	1,293	419,000	15,955	6.117×10^6
GA-I (Savic and Walters 1997)	250,000	419,000	—	6.073×10^6 [a]
GA-II (Savic and Walters 1997)	250,000	420,000	—	6.195×10^6
SA (Cunha and Sousa 1999)	25,000	419,000	53,000	6.056×10^6 [a]
Shuffled frog leaping algorithm (Eusuff and Lansey 2003)	11,323	419,000	27,546	6.195×10^6
Modified GA (Kadu et al. 2008)	—	—	18,000	6.056×106 [a]
Complete enumeration	1.48×10^9		2.87×10^{26}	

[a]Refers infeasible solution.

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