Optimum rehabilitation strategy of water distribution systems using the HBMO algorithm

Omid Bozorg Haddad, Barry J. Adams and Miguel A. Mariño

ABSTRACT

The honey-bee mating optimization (HBMO) algorithm is applied to extracting the optimal rehabilitation strategy for water distribution systems. Deterioration of water distribution networks due to aging and stress, causes increased operation and maintenance costs, water losses, reduction in the quality of service, and reduction in the quality of water supplied. Since the most expensive component of water supply systems is the distribution network, their increased costs can be substantial. A well-known two-loop network is presented to demonstrate the application of the proposed algorithm. The significance of this algorithm is its ability to identify an optimal rehabilitation strategy in a combinatorial solution space considering the deterioration of both structural integrity and hydraulic capacity of the entire network. A previously developed methodology is presented to implement this approach into a decision support system which facilitates the identification of an optimal rehabilitation strategy. The problem is considered as the present value of an infinite stream of costs for 30 and 100 operational years. The results indicate that the proposed HBMO algorithm readily finds the feasible solution for the problem and goes towards the optimal solution. Furthermore, results prove the cost-effectiveness of such a strategy compared with those not considering the rehabilitation strategy.

Key words | honey-bee mating optimization, optimization, rehabilitation alternatives, water distribution system

Omid Bozorg Haddad (corresponding author)
Department of Irrigation & Reclamation,
Faculty of Soil & Water Engineering,
College of Agriculture & Natural Resources,
University of Tehran,
Karaj, Tehran,
Iran
E-mail: *OBHaddad@ut.ac.ir*

Barry J. Adams
Department of Civil Engineering,
University of Toronto,
35 St., George Street,
Toronto, ON, M5S 1A4,
Canada

Miguel A. Mariño
Department of Civil & Environmental Engineering, and Department of Biological & Agricultural Engineering,
University of California,
139 Veihmeyer Hall, University of California,
Davis, CA 95616-8628,
USA

INTRODUCTION

Aging water supply infrastructure, coupled with the continuous stress placed on pipes by operational and environmental conditions, have led to system deterioration which manifests itself in increased operation and maintenance costs, water losses, reduction in the quality of service, and reduction in the quality of water supplied. Given the reality of scarce capital resources, it is imperative that a comprehensive methodology be developed to assist planners and decision makers in selecting the most cost-effective rehabilitation policy which addresses the issues of safety, reliability, quality, and efficiency. Water distribution network design and/or rehabilitation problems belong to a group of inherently intractable problems referred to as NP-hard. Essentially, NP-hard means that a rigorous algorithm aimed at finding an optimum design using discrete diameters is not a practical possibility. It is well known that when diameters are used as the decision variables, the constraints are implicit functions of the decision variables and require solving conservation of mass and energy equations to determine the network's pressure heads. In addition, the feasible region is non-convex, and the objective function is multimodal. Cost-effective expenditure on the design and rehabilitation is essential to achieve a sufficient quality service due to an ever-tightening budget. In Canada, the Canadian Water and Wastewater Association CWWA (1997) estimated that $11.5 billion (Canadian dollars) will be required for water main upgrading over the next 15 years. The state of practice in the long-term planning of water main renewal is still evolving.

For a given network layout, demand loading conditions, and an operation policy, the optimal design and rehabilitation of a water distribution system is to determine the least

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cost combination of: (1) new pipe diameters; (2) pipe rehabilitation actions; and (3) setting a new pipe which can be either an expansion (subdivision) to, a replacement of, or a parallel pipe (duplication) to an existing pipeline. The total cost of a design and rehabilitation solution is minimized while satisfying a set of prescribed system criteria.

Because the performance of the distribution system depends on the performance of each pipe, the decision on pipe rehabilitation or renewal should consider an individual pipe in the context of the network performance. Several models have been developed for this purpose (e.g., Woodburn *et al.* 1987; Su & Mays 1988; Male *et al.* 1990; Kim & Mays 1994; Arulraj & Suresh 1995; Schneiter *et al.* 1996; Kleiner *et al.* 1998*a*,*b*).

Although there are previous works which guide the prioritization of maintenance actions in relation to several pipes within a water distribution network (Quimpo & Shamsi 1991; Arulraj & Suresh 1995; Quimpo & Wu 1997), it is not simple to find an optimal maintenance policy and furthermore an allocation program for the entire network. This is due to the complexity in solving large-scale nonlinear programming problems which usually result from the determination of such an optimal policy. Much research has been conducted to help determine the optimal maintenance policy for water distribution networks (e.g., Andreou & Marks 1987; Li & Haimes 1992*a*,*b*). The model proposed by Li & Haimes (1992*a*) is difficult to apply in actual water distribution networks due to the complex relationship between nodal availability and availability of a network's pipes, especially when the network is rather large. Another impractical aspect of the model proposed by Li & Haimes (1992*b*) is that in the optimal maintenance schedule resulting from their approach, the maintenance action taken when the pipe is at some failure state is not a deterministic one, it is randomly selected among a predefined set of actions with the selection probability for each action determined from a discrete distribution. The cost-based approach is also employed in Kleiner *et al.* (1998*a*,*b*) to construct a long-term rehabilitation strategy for water distribution networks. Following this definition, the resulting model is a complex, large-scale nonlinear program.

Honey-bee mating optimization algorithm may also be considered as a tool for selecting rehabilitation alternatives for water distribution systems. A detailed description of the HBMO algorithm has been presented by Bozorg Haddad *et al.* (2006). The latter presented a successful application of the algorithm in solving a mathematical optimization problem as well as the optimal operation of a single reservoir in a discrete domain. Moreover, Afshar *et al.* (2007) applied the proposed HBMO algorithm to the same single reservoir in a continuous domain to evaluate its capability in solving optimization problems with a continuous solution space.

In this paper, we explore the application of full features of the HBMO algorithm (Bozorg Haddad *et al.* 2006) to enhance the capability of the algorithm to the optimal rehabilitation strategy (ORS) of a water distribution system. This paper focuses on the application of a new optimization method to the ORS problem. In the present work, an approach based on Kleiner (1996), Kleiner *et al.* (1998*a*,*b*) is proposed in which the network economics and hydraulic capacity are analyzed simultaneously over a pre-defined analysis period, while explicitly considering the over time deterioration of both the structural integrity and the hydraulic capacity of every pipe in the system. The approach of Kleiner *et al.* (1998*a*,*b*) leads to a methodology by which a decision to implement a rehabilitation action at a certain time is determined not only by the current state of the system but also by future rehabilitation actions. In this methodology, the cost associated with each pipe in the network is calculated as the present value of a stream of costs. Although an all-encompassing, quantitative decision model is yet to be developed, the approach described in this paper considers the structural and hydraulic state of the network while providing a framework for the future inclusion of other considerations as well.

The contribution of this paper can be considered twofold: (1) a new and recently developed evolutionary algorithm has been applied and tested in an important problem of water distribution network rehabilitation where a few other evolutionary algorithms have been used in this field and the traditional optimization approaches are least effective in this problem. Problem complexity consists of a discrete solution domain which increases the difficulty for gradient-based approaches such as nonlinear programming (NLP) solvers and the curse of dimensionality for discrete global optimization approaches such as dynamic programming (DP) algorithms. (2) although the foundation of the rehabilitation concept has been borrowed completely from Kleiner (1996), Kleiner *et al.* (1998*a*,*b*), some innovation is considered in the present paper. For instance, the rehabilitation alternatives period which has been assumed to be fixed (constant operational years) in previous studies by Kleiner (1996), Kleiner *et al.* (1998*a*,*b*) is now considered to be only one year in this paper. So, it is not necessary for a rehabilitation alternative to follow a constant period and it can be changed during the operational period. Thus, the flexibility of the rehabilitation scheduling increases and the rehabilitation costs decrease. In the approach considered in this paper, the dimensionality of the problem increases and the efficiency of the DP-category solvers decrease. Therefore, in this paper both innovation in solution approach and rehabilitation modeling are considered.

HONEY-BEE MATING OPTIMIZATION (HBMO) ALGORITHM

The honey-bee mating optimization (HBMO) algorithm is a hybrid optimization algorithm involving simulated annealing, genetic algorithm (GA), and local search. These features are combined together in an effective way to enhance the abilities of each one individually. Bozorg Haddad *et al.* (2006) presented a detailed description of the HBMO algorithm. However, an overview of the proposed algorithm is presented in this paper. The HBMO process consists of three repetitive features: (1) selection, (2) reproduction, and (3) improvement. The selection process is borrowed from simulated annealing (SA) which provides the proposed HBMO algorithm with a powerful selection procedure. The SA algorithm is a mapping of the mating flight behavior of bee colonies in nature, between the queen and the drones to nominate selected drones for mating. Using SA allows only the potential drones to be nominated to mate with the queen and therefore decreases the unnecessary objective function evaluation. The reproduction process, which is the act of generating broods (new trial solutions), is between the genomes of the queen (the best up to now solution) and the selected drones (some test solutions selected). Drones can be either the best broods of the previous generation or some selected solutions by the mating flight (SA process). In the reproduction process, the queen's and the selected drones' genomes, mix (produce new solutions) by different genome combinations (cross-over operators). The reproduction process is mainly borrowed from the principles of genetic algorithm (GA). The improvement process, which applies workers (different mutation operators) on queen and broods, generates some potential broods (test solutions) to be used as the queen or as drones for the next generation. The improvement process is basically taken from the idea of local search. Contribution of all the operators (cross-over and mutation) to generate new solutions according to the improvement each one has made in the previous generation is one of the main aspects of the algorithm. This is one of the advantages of the algorithm, which decreases the unnecessary computation of the objective function by unsuited operators. To improve the new generalized set of solutions, the feeding process of broods and the queen with royal jelly performed by the worker bees is mapped into the algorithm.

PROBLEM STATEMENT

Consider a water distribution network with p pipes (links) and n nodes. Every pipe in the network may be rehabilitated by one of R rehabilitation alternatives, including relining or replacement with the same or with a larger diameter pipe. For the purpose of formulating the proposed approach, rehabilitation techniques are classified in one of two ways: (1) those which only improve pipe hydraulic capacity, and (2) those which provide added structural integrity as well. The first class of techniques is considered here as the "reline alternative", meaning that only the pipe's friction coefficient changes and possibly its inside diameter. The techniques in the second class are equivalent in their effect to pipe replacement and are considered as the "replace alternative".

For a given time horizon of H years, minimizing the present value of the total cost of maintaining and rehabilitating the pipe network (total cost = maintenance + capital investment costs) is subject to the following: (1) Mass conservation of flow in all nodes (continuity equations); (2) energy conservation of flow in all pipes (links); (3) residual supply pressure in every node is above a stated minimum; (4) as the network ages, the hydraulic carrying capacities of the pipes diminish; (5) as the network ages, the breakage rates of the pipes increase; (6) a pipe can be replaced more than once during the analysis time period, but all subsequent replacements are identical to the initial replacement (a limitation discussed later); and (7) when a pipe is relined, it is assumed that it will eventually be replaced at a later time; however, consecutive relining is not considered for a given analysis period.

DETERIORATION OF PIPE HYDRAULIC CAPACITY

Luong & Nagarur (2001) modeled the deteriorating behavior of a pipe as a semi-Markov process in which the state-space represents the states of the pipe as new, operating with n repairs undergone, under repair, or under replacement. They assumed that the pipe will be replaced according to the following criteria: (1) the pipe will be replaced if it has experienced more than N breaks regardless of its age; and (2) if the pipe is experiencing a break, it will be replaced if its operation time in the previous operating state has reached a specified threshold duration for replacement. Otherwise, the pipe will be repaired.

The head loss h (m) in any pipe i is calculated using the Hazen-Williams equation:

$$h_i = 10.653\left(\frac{Q_i}{C_i^{\mathrm{HW}}}\right)^{1.852} D_i^{-4.87} L_i \tag{1}$$

where Q_i = flow rate in pipe i ($\mathrm{m^3\,s^{-1}}$); C_i^{HW} = Hazen-Williams hydraulic coefficient in pipe i; D_i = diameter of pipe i (m); and L_i = length of pipe i (m).

The equation of Sharp & Walski (1988) is used in the present work to model the effect of aging on the carrying-capacity of pipes in the distribution network. The equation is written for the pipe in two forms, before and after rehabilitation, as follows:

$$C_i^{\mathrm{HW}}(t) = 18.0 - 37.2\log\left(\frac{e_{0_i} + a_i(t+g_i)}{D_i}\right) \tag{2}$$

where $C_i^{\mathrm{HW}}(t)$ = Hazen-Williams coefficient in pipe i at year t (before rehabilitation); e_i^0 = initial roughness in pipe i at the time of installation when it was new (m); a_i = roughness growth rate in pipe i ($\mathrm{myr^{-1}}$); D_i = diameter of pipe i (m); g_i = age of pipe i at the present time (time of analysis) (years); and t = time elapsed from present time to future periods ($t < T_{ij}$) (years).

After rehabilitation with alternative j, the H-W coefficient, C^{HW} in pipe i at year t is:

$$C_{ij}^{\mathrm{HW}}(t) = 18.0 - 37.2\log\left(\frac{e_{0_{ij}} + a_{ij}(t - T_{ij})}{D_{ij}}\right) \tag{3}$$

where e_{ij}^0 = initial roughness in pipe i at the time of implementing rehabilitation alternative j (m); a_{ij} = roughness growth rate in pipe i with rehabilitation alternative j ($\mathrm{myr^{-1}}$); D_{ij} = diameter of pipe i with rehabilitation alternative j (m); T_{ij} = rehabilitation timing of pipe i with alternative j (years elapsed from present time); and t = time elapsed from present time to future periods ($t > T_{ij}$) (years).

REPLACEMENT ALTERNATIVES

In a water distribution network with p pipes (links) and n nodes, every pipe in the network may be rehabilitated by one of R rehabilitation alternatives which may be implemented any number of times, at any year from the present to the end of the planning horizon H. Pipe relining is considered as a hydraulic capacity improvement measure, whereas pipe replacement (with the same or larger diameter pipe) improves both the structural integrity and the hydraulic capacity of the link.

The total cost comprises capital cost for rehabilitation and maintenance, which consists primarily of breakage repair costs. An exponential relationship based on field data analysis is used between the breakage rate and the age of a pipe (Shamir & Howard 1979; Kleiner 1996) as follows:

$$N(t)_i = N(t_0)_i \cdot \mathrm{e}^{A_i(t+g_i)} \tag{4}$$

where t = time elapsed (from present) in years; $N(t)_i$ = number of breaks per unit length per year in pipe i ($\mathrm{km^{-1}\ year^{-1}}$); $N(t_0)_i = N(t)_i$ at the installation year of pipe i (i.e., when the pipe is new); g_i = age of pipe i at the present time; and A_i = coefficient of breakage rate growth in pipe i ($\mathrm{year^{-1}}$).

RELINING ALTERNATIVES

When pipe relining is considered with the assumption that no structural improvement occurs, the steady-state approach is modified. From an engineering point of view, it may be economically feasible to reline a pipe whose hydraulic capacity deteriorates much faster than its structural integrity. Since maintenance costs of a relined pipe continue to increase with age, it is assumed that the relined pipe will have to be replaced at some future time. Consequently, if the hydraulic capacity of a pipe needs to be improved well before this time in the future, relining should be considered as a feasible alternative.

NETWORK HYDRAULICS

The residual pressure at the demand node is determined by the demand flow rate, the supply pressure at the source node, the demand node elevation (constant), and the hydraulic capacity of the distribution network. By assuming a constant demand and supply pressure at the source node, the residual pressure at the demand node depends only on the hydraulic capacity of the "distribution network". Since the hydraulic capacity of the pipes diminishes over time, so does the residual pressure at the demand node. Suppose that $P_{\min}$ is the minimum residual pressure required at the demand node to maintain adequate service. It is clear that the diminished hydraulic capacity in one of the pipes will have to be increased to avoid the residual pressure at the demand node dropping below $P_{\min}$. This increase in pipe hydraulic capacity is achieved by implementing a rehabilitation project. Possible projects could be (1) relining the pipe, (2) replacing the pipe with a new pipe of the same diameter, or (3) replacing the pipe with a larger diameter pipe.

The hydraulic framework described above determines the latest implementation time which is allowed for any rehabilitation project which happens once in a sequence of projects. It should be emphasized that the hydraulic behavior of the network is determined simultaneously by all pipes and the interactions among them, because any change in the hydraulic properties of any pipe in the network causes a redistribution of flows in all pipes in the network.

In the proposed model, selecting a least-cost rehabilitation policy is subject to the supply system's conformity to all physical/hydraulic laws and to adequate supply criteria as outlined below.

Conservation of mass:

$$Q_{\mathrm{in}_y} = Q_{\mathrm{out}_y} \text{ for all nodes } y \in \{1, 2, \ldots, n\} \text{ in the network,} \quad (5)$$

where Q_{in} = flow rate into a node and Q_{out} = flow rate out of a node.

Conservation of energy:

$$\sum_{l} h = c \quad (6)$$

for all paths which either form closed loops in the network or connect two nodes with fixed hydraulic grade (e.g. reservoirs, etc.), where h = head changes in a pipe or a component in the network; l = all pipes and components included in a path; and c = a constant (= 0 for a path that is a closed loop).

Minimum supply pressure:

Junction pressure is often required to maintain greater than a minimum pressure level to ensure adequate water service and less than a maximum pressure level to reduce water leakage within a system.

$$P_{yT} \geq P_{\min_y} \text{ for all nodes } y \in \{1, 2, \ldots, n\} \text{ in the network and all years } T \in \{0, 1, 2, \ldots, H\} \text{ in the analysis period,} \quad (7)$$

where P_{yT} = residual supply pressure, at node y in year T; and $P_{\min_y}$=minimum residual pressure allowed at node y in the system.

INDIVIDUAL PIPE ECONOMICS

Within the hydraulic framework, the actual timing of the rehabilitation project is determined using economic considerations as well. The total cost of a pipe comprises (a) the maintenance costs of the existing pipe until it is initially replaced (including possible pipe relining), (b) the cost of the first replacement, and (c) the costs of maintenance and replacement in subsequent replacements. This total cost function is convex with respect to the timing of the first replacement, and has a minimum cost point depicting a time at which, if the first replacement of a pipe is indeed implemented, the total cost of this pipe is minimized. Consequently, in determining the timing of a replacement project there are two "motivations": (a) implement it as late as possible (without violating hydraulic integrity) in order to delay the time of minimum pressure (TMP) as much as possible, and (b) implement the replacement as close as possible to the pertinent minimum cost replacement timing (MCRT) in order to reduce cost.

The relining of a pipe is assumed to be hydraulically equivalent to replacing it with the same diameter pipe, although this is only an approximation. From a structural integrity viewpoint however, the relining alternative is different to replacement because it provides no reduction in breakage rate. It is consequently assumed that if a pipe is relined, it will eventually be replaced, and this time of (eventual) replacement is assumed to be the MCRT of the replacement with same diameter alternative. Details of this approach can be found in Kleiner (1996), Kleiner *et al.* (1998*a*,*b*).

Consider a water distribution network with p pipes (links) and n nodes. A rehabilitation project is defined as (a) relining a pipe, or (b) replacing a pipe. In addition, the "do nothing" alternative is defined as a rehabilitation alternative which is implemented at or after the end of the analysis period. Consequently, it can be assumed that the number of rehabilitation projects which are undertaken for the network within the analysis period is equal to the number of pipes (p) in the network. For every pipe there are R alternatives for the type of rehabilitation, e.g., $R = 1$ reline pipe, $R = 2$ replace pipe, and $R = 3$ replace with a pipe one nominal diameter larger. T_{ij} is the time at which pipe i is rehabilitated with rehabilitation alternative $j(0 \le T_{ij} \le H \quad \text{for}\, j \in \{1, 2, \ldots, R\})$.

The total cost (objective function) of s is:

$$C = \sum_{T=1}^{H} \sum_{i=1}^{P} \sum_{j=1}^{R} C_{T_{ij}} \tag{8}$$

where j can only take one value for every i ($i \in S, j \in R$) and $C_{T_{ij}}$ = cost of jth alternative for pipe i in year T. Assume that C is minimized. The objective is to add projects to s until all pipes are rehabilitated and the total cost is kept minimal.

ALGORITHM APPLICATION

The HBMO algorithm is a recently-developed optimization approach. The authors are trying to test and demonstrate its capability and introduce the HBMO algorithm as an alternative tool for optimization. The main purpose of this paper is to check the performance of the HBMO algorithm and introduce it as a potential alternative to the optimization methods in the case of NP-hard problems.

It should be noted that: (1) the HBMO algorithm is in the early stages of its development, (2) this paper is the first application of the HBMO algorithm in water distribution networks rehabilitation, and (3) the rehabilitation strategy used in this paper is the first time of its usage in water distribution systems. Thus, these three considerations dictate the authors to test the new methodology as well as the new optimization algorithm in a low-sized system. In the future, modest or even high-sized systems would be examined.

TWO-LOOP NETWORK

The following example numerically illustrates the concepts described in the previous sections. The example network, namely two-loop network, was first studied by Alperovits & Shamir (1977). Other investigators have worked on this well-known benchmark example by applying different traditional and evolutionary algorithms and have reported various results as the least-cost design of this network. The network consists of eight pipes and seven nodes, including one supply node and two demand nodes. The layout of the network with a single source at a 210 m total fixed head and eight pipes arranged in two loops is shown in Figure 1.

The two-loop network has been considered as the case study, where the results of its least-cost design is available and can be a reference point for comparison with the rehabilitation strategy and breakage repair costs. Thus, the results are not comparable with those of Kleiner (1996), Kleiner *et al.* (1998*a*,*b*). Moreover, because of the complexity of the new strategy considered in this manuscript, the two-loop problem is difficult to solve by DP methods because of the curse of dimensionality. So, as a case study, the two-loop network has been considered to be

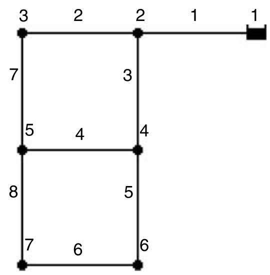

Figure 1 | Schematic of two-loop network problem.

the first experience in extracting the rehabilitation strategy for this benchmark design problem. Clearly, in the future other methodologies and algorithms can be applied to this problem in order to test their efficiencies compared to those of HBMO. The main reason for considering the two-loop network as the case study is its simplicity and popularity among designers to check the associated least-cost design against its rehabilitation cost.

The demand flows are peak demands and are assumed constant throughout the design period. The pipes are all 1,000 m long. The minimum acceptable residual pressure requirements for nodes 2 to 7 are defined as 30 m above ground level for most of the cases described in this paper. There are 14 commercially available diameters. The analysis periods are 30 and 100 years, the discount rate (r) used is 0.05, and the breakage growth rate (A_i) is 0.1 per year. Other pertinent data are presented in Table 1. Furthermore, the variation of the Hazen-Williams coefficient in operational years is illustrated in Figure 2. It should be noted that the deterioration action rate is identical for every pipe in the network.

Since this network is considered to be in service for a long-term operational period, the initial design diameters are achieved with the Hazen-Williams coefficient equal to 100. The reason for this initial design selection is to have a safety margin for violation of the nodal pressure from the desired head at each joint in the early operational years. Consequently, the initial design pressures will accept a higher threshold and after some time (year) arrive at a pressure below the required nodal head. Figure 3 demonstrates the variation of nodal pressures for each joint of the network in operational years for the proposed system where the network has been designed with the Hazen-Williams coefficient equal to 100. It shows that after 5 years the network does not satisfy the expected nodal pressure for demand nodes. Although initial network design with higher Hazen-Williams coefficient will cause a greater (more

Table 1 | Cost and roughness data for different commercial pipe diameters

No.	D	D	Installation Cost	Relining Cost	Single breakage repair cost Cb_i	Initial roughness e_{0_i}	Roughness growth rate A_i
	in	Mm	$\$m^{-1}$	$\$m^{-1}$	$\$break^{-1}$	mm	$year^{-1}$
1	1	25.4	2	0.7	500	0.02	0.03
2	2	50.8	5	1.75	522	0.05	0.05
3	3	76.2	8	2.8	543	0.07	0.08
4	4	101.6	11	3.85	565	0.10	0.11
5	6	152.4	16	5.6	609	0.15	0.16
6	8	203.2	23	8.05	652	0.20	0.22
7	10	254	32	11.2	696	0.25	0.27
8	12	304.8	50	17.5	739	0.30	0.33
9	14	355.6	60	21	783	0.35	0.38
10	16	406.4	90	31.5	826	0.40	0.44
11	18	457.2	130	45.5	870	0.45	0.49
12	20	508	170	59.5	913	0.50	0.54
13	22	558.8	300	105	957	0.55	0.60
14	24	609.6	550	192.5	1000	0.59	0.65

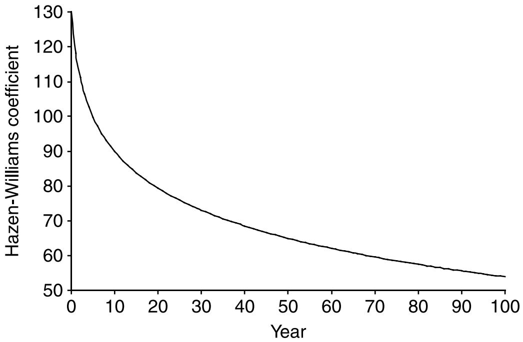

Figure 2 | Variation of Hazen-Williams coefficient in operational years.

expensive) investment cost, however, it will prevent the infeasible solutions and states in the primary operational periods. The variation of annually and cumulative maintenance cost associated with each pipe in the network in operational years is presented in Figure 4, which is due to the breakage repair in the network. In the same figure, the initial investment is presented. It can be observed that in the 38th operational year, the cumulative repair cost will be equal to the initial investment with a rapid increase rate after that time.

The rehabilitation alternatives considered are relining, replacement with same diameter pipe, and replacement with a pipe one nominal diameter larger (alternatives $j = 1, 2$, and 3, respectively). The solution space comprises $(R+1)^{pH}$ possible combinations of rehabilitation alternative selection and scheduling. Even for this simple example, the total enumeration of this network, with three rehabilitation alternatives and 1-year time step (30-year planning horizon) is 3×10^{144}. For comparison, if one could examine 1 trillion

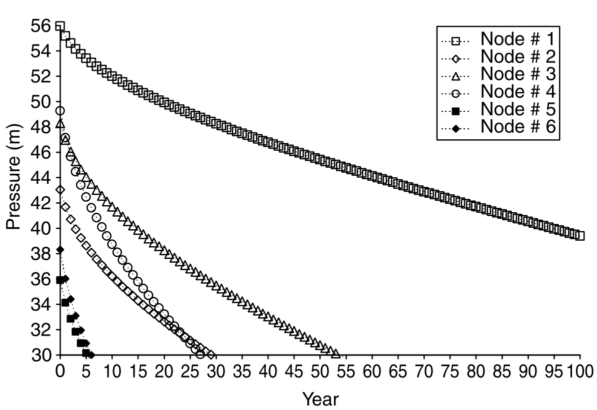

Figure 3 | Variation of nodal pressure in operational years.

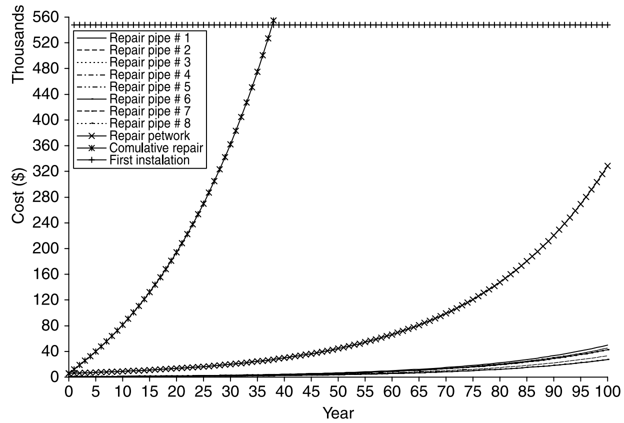

Figure 4 | Variation of maintenance cost in operational years.

alternatives per second, it would take about 10^{123} centuries to examine all alternatives. The proposed HBMO algorithm solved this network in about 30 minutes using a 1500-MHz Pentium IV PC. The dimensionality and run time of the problem can be reduced by using longer time steps. The total cost of the optimal solution declines as the time step increases in length. This may, at first glance, seem counterintuitive because longer time steps would be expected to result in a less accurate thus a higher cost solution. However, it is possible to reduce total run time by using a long time step to filter out improbable states and then running the system with a short time step and reduced set of alternatives for the final results. The run time of the HBMO algorithm is also affected by the network's minimum allowed pressure. Of course, things could even be more complex if, for instance, a booster pump was to be considered as an alternative, but this is beyond the scope of the current study. The network simulator used for calculating nodal residual pressures is EPANET (Rossman 1993).

a) 30-year operation

In this case, 10 different runs of the HBMO algorithm with different initial seed numbers have been conducted and the results are presented in Table 2. The robustness of the algorithm has been tested by presenting the results of 10 different runs for the 30-year problem and as can be seen, there is a slight difference between the final results of 10 different runs, which indicates the capability of the algorithm to converge to a near optimal solution. From now on, the results presented in this section are those for the best out of 10 runs.

Table 2 | Objective function value and number of function evaluations at the end of 10 different runs of the HBMO with 3,000 mating flights

Number of run	Objective function value	Number of function evaluations
1	1,102,575	323,283
2	1,098,281	323,361
3	1,105,754	323,430
4	1,105,080	323,421
5	1,100,943	323,274
6	1,104,517	323,199
7	1,124,065	323,352
8	1,108,119	323,412
9	1,136,200	323,415
10	1,116,355	323,409
Min	1,098,281	323,199
Max	1,136,200	323,430
Average	1,110,189	323,356

For a 30-year operational period, the HBMO algorithm convergence rate for the best run out of 10 runs conducted has been plotted in Figure 5. It shows that the HBMO algorithm is sufficiently capable of handling this problem. After about 20,000 function evaluations, the proposed algorithm converges to the local optimal solution and gives a final objective function equal to 1,098,281 which is 21% more than the cost associated without considering the rehabilitation alternatives (910,332). Although the cost is marginally greater than those considering only the breakage repair, the advantage of the recent solution is having a feasible solution in all operational periods without any violation from the minimum required pressure in demand nodes, while the other solution presents undesired pressures after the 4th year of operation. The cumulative costs of rehabilitation alternatives as well as the cost of cumulative breakage repair in operational periods are presented in Figure 6. It can be observed that in the four first operational years both curves show the same cumulative cost, which is due to satisfying the minimum required pressure in those years. Thus, there is no need for activation of the rehabilitation alternatives and so the only associated cost is the breakage repair cost for both curves. The activated rehabilitation alternatives for all pipes in the operational years are presented in Figure 7. Since alternative 3, which is a replacement for the pipe with one nominal greater diameter, has the most expensive associated cost among the rehabilitation alternatives, it has the least contribution in the final solution reported by the proposed algorithm. Moreover, in the four early operational years there is no rehabilitation alternative, which is again due to satisfaction of the desired pressure in those years. Figure 8 illustrates the variation of pipe diameters in operational years which is a result of the activation of the 3rd rehabilitation alternative. Figure 7 illustrates the activated rehabilitation alternatives in the planning horizon, whereas Figure 8 shows each pipe diameter of the network in operational years. Although the information in Figure 8 can be gleaned from Figure 7, in the operational years it is not easy to follow. Figure 8 gives a very quick and explicit view of pipe-diameter change trend for all pipes in the planning horizon.

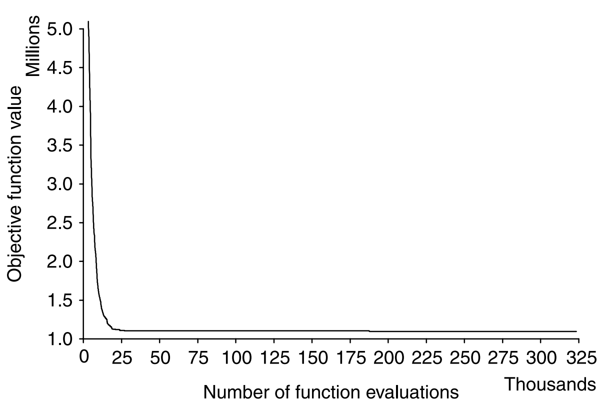

Figure 5 | Variation of objective function value along with number of function evaluation for the 30-year operation case.

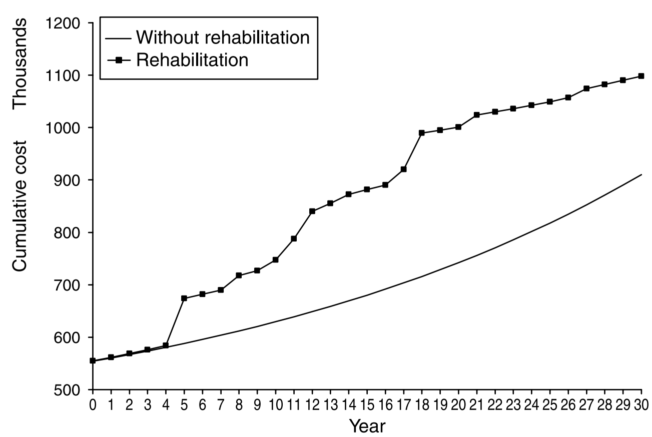

Figure 6 | Variation of cumulative cost as well as cumulative breakage repair cost in operational years for the 30-year operation case.

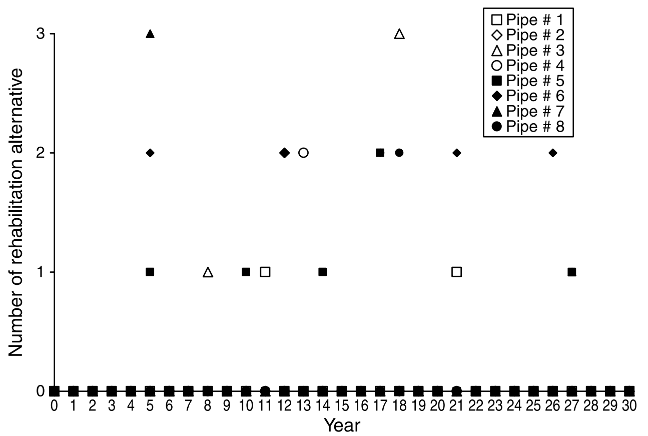

Figure 7 | Performance of rehabilitation alternatives in operational years for different pipes for the 30-year operation case.

The changes in Hazen-Williams coefficient which are due to deterioration of the pipes hydraulic characteristics is presented in Figure 9. Clearly, whenever the rehabilitation alternative for each pipe is activated, it indicates that relining or replacement of the pipe is conducted, and subsequently the Hazen-Williams coefficient chooses the amount of 130 which is the characteristic of the new pipes. Finally, in Figure 10 the variation of nodal pressures of all the pipes in the network are presented. This figure is a proof for the feasibility of the final solution, because all pipes of the network fulfill the minimum required pressure in demand nodes which is 30 for all pipes. It shows that whenever the pressure in a node drops below 30 m, a rehabilitation alternative will be activated and will affect the characteristic of the network in such a manner to bring the pressure of that node into the feasible region.

b) 100-year operation

To demonstrate the capability of the proposed algorithm and also to observe the performance of the network in longer operational periods, the optimization model has been considered with 100 operational periods. The complexity of the network and its dimensionality has been increased in this case. The proposed HBMO algorithm converges to a near-optimal solution in more function evaluations compared with those of 30-year operational periods. Figure 11 illustrates the convergence rate with respect to number of function evaluations. It shows that in about 70,000 function evaluations, the algorithm finds a near-optimal solution and reports a final solution of 1,331,389. The cost associated without considering rehabilitation alternatives is 8,785,327, which is much more expensive than that of considering rehabilitation alternatives. Figure 12 compares the cumulative annual costs for both rehabilitation strategy and breakage repair. The cost relating to "do nothing" or "without considering rehabilitation strategy" is due to breakage repair costs.

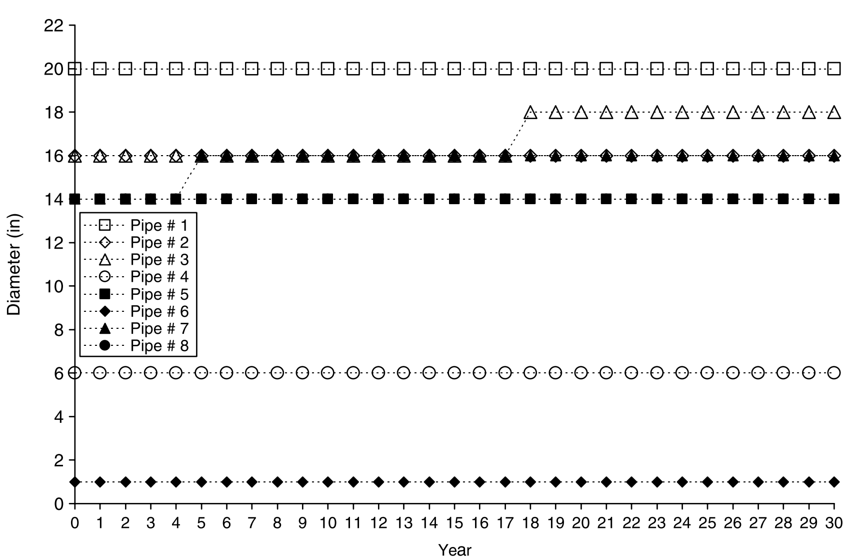

Figure 8 | Changes in pipe diameter in operational years for the 30-year operation case.

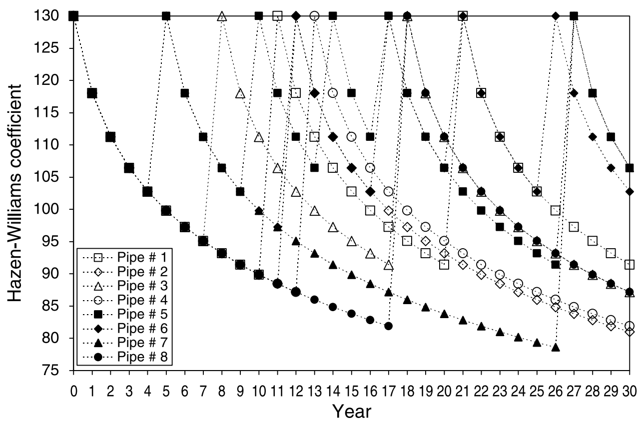

Figure 9 | Variation of Hazen-Williams coefficient in operational years for the 30-year operation case.

Hence, the breakage repair cost follows an exponential trend in the operational years, it will end up with a cost of 8,785,327, which is relatively more than the cost considering the rehabilitation strategy. After the 42nd year, the rehabilitation strategy arrives at a cheaper cost than that of breakage repair situation which is due to the effect of exponential breakage growth rate on the breakage repair cost curve to make the slope of the latest curve in such a sharp rate. Although "do nothing" and replacement alternatives are both affected by discount rate but the increase of "do nothing" is more significant which is the cause of the rapid and progressive increase of the breakage rate as time goes on which results in a higher cost. Obviously, considering different combinations for economic and hydraulic data will produce some other characteristics for these curves which are due to the effects of discount rate. Moreover, there are slight changes in the pipe diameters after the 50th year and the rehabilitation costs are insignificant considering the time past, therefore without the need of replacement and change of diameters, the remaining pipes are just rehabilitated. Figure 13 presents the activated rehabilitation alternatives for this problem. It shows that the most concentration belongs to the rehabilitation alternative 2 which replaces the pipe with the same diameter in all operational periods, whereas the other alternatives, 1 and 3, rarely appear in the years after the 50th year. The variation of the pipe diameter for the network's pipes is presented in Figure 14. In order to have a perspective of deterioration of pipe hydraulic characteristics, variation of Hazen-Williams coefficients in operational years is presented in Figure 15 for all the pipes of the network. Figure 16 demonstrates the variation of nodal pressures for all the pipes of the network in operational years. There is no violation of minimum required pressure in the network, which is a proof of feasibility for the final solution reported by the algorithm.

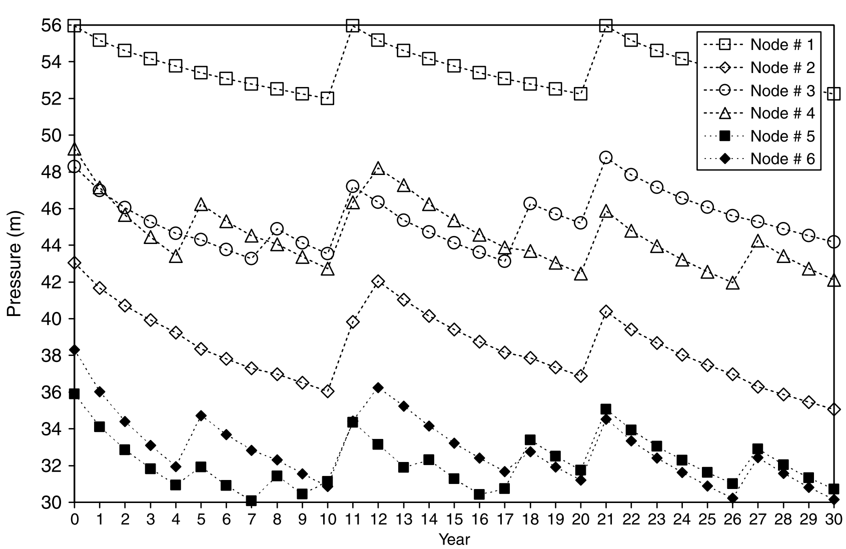

Figure 10 | Nodal pressure changes in operational years for the 30-year operation case.

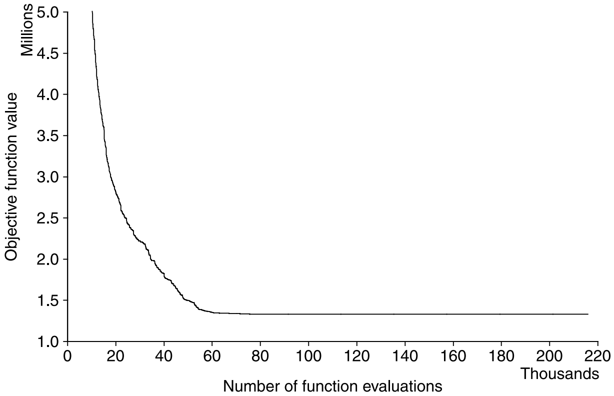

Figure 11 | Variation of objective function value along with number of function evaluations for the 100-year operation case.

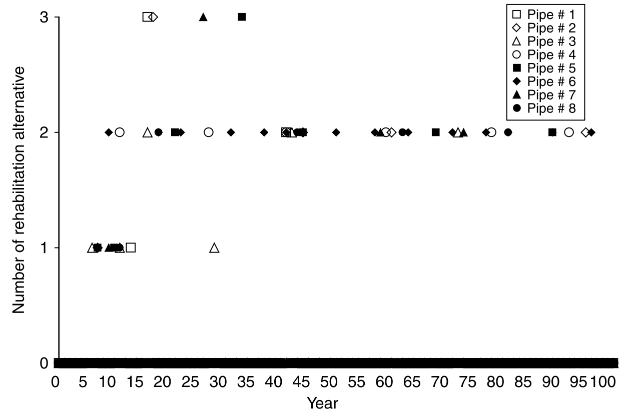

Figure 13 | Performance of rehabilitation alternatives in operational years for different pipes for the 100-year operation case.

CONCLUDING REMARKS

The long-term planning of rehabilitating and upgrading a water distribution system involves the selection of an appropriate rehabilitation measure for each pipe in the network and considering its implementation timing while maintaining adequate supply pressures in the system. This paper addressed this need to find an optimal strategy for extracting a minimum cost solution among a vast combinational (and not "well-behaved") solution space. The network economics and hydraulic capacity are analyzed simultaneously over a predefined analysis period while explicitly considering the over-time deterioration of both the structural integrity and the hydraulic capacity of every pipe in the system. A pipe cost function was developed which considers a finite time stream of costs that are associated with finite rehabilitation alternatives for every pipe. The methodology contains two implicit assumptions regarding the hydraulic behavior of a water distribution network: (1) the minimum residual pressure of a water distribution network is non-increasing with respect to the time due to deterioration in the Hazen-Williams coefficient of all pipes, and (2) increasing the Hazen-Williams coefficient in any pipe in a water distribution always improves the system's hydraulic capacity.

To test the efficacy and robustness of the proposed methodology, a test problem from the literature was chosen. This problem has been studied using other optimization methods by several researchers. The HBMO algorithm can identify an optimal rehabilitation strategy for the water distribution network. The advantages of HBMO algorithm are its ability to (1) explicitly consider the deterioration over

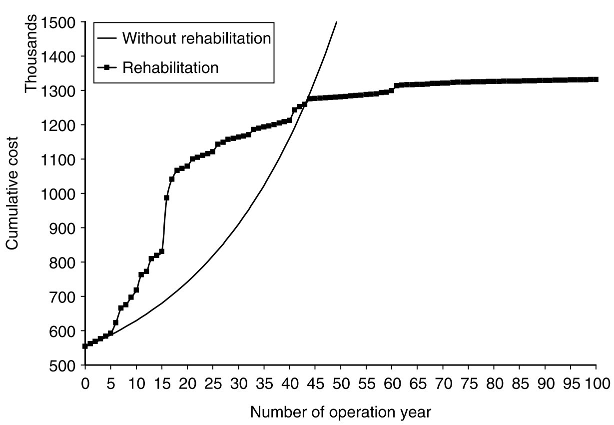

Figure 12 | Variation of cumulative cost as well as cumulative breakage repair cost in operational years for the 100-year operation case.

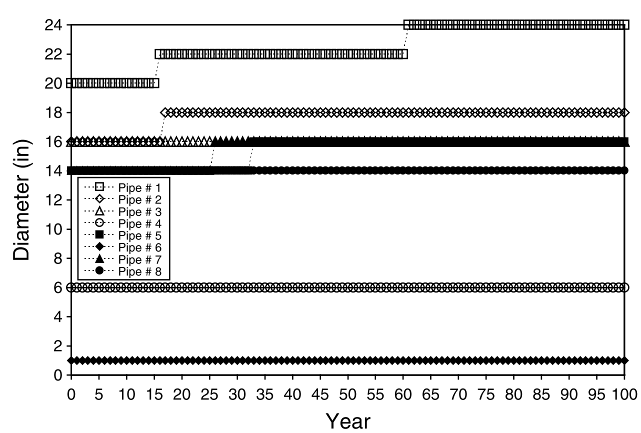

Figure 14 | Changes in pipe diameter in operational years for the 100-year operation case.

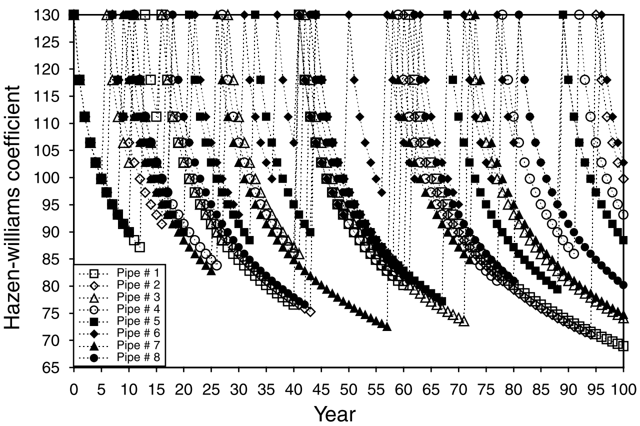

Figure 15 | Variation of Hazen-Williams coefficient in operational years for the 100-year operation case.

time of both the structural integrity and the hydraulic capacity of the pipes in the water distribution network; (2) compare projected cost streams which are independent from the selected analysis period; (3) consider the economic and performance of the entire network while regarding each pipe as a separate entity with its own characteristics and parameters; and (4) determine each rehabilitation action not only by the current state of the system, but also by future rehabilitation actions. It is, however, suitable for distribution systems with the present computational techniques and equipments.

The HBMO algorithm can be applied to the system using various time step sizes. With a single year time step, the system is hydraulically evaluated every year within the specified analysis period. In general, the shorter the time step, the more likely the results are to be closer to the true

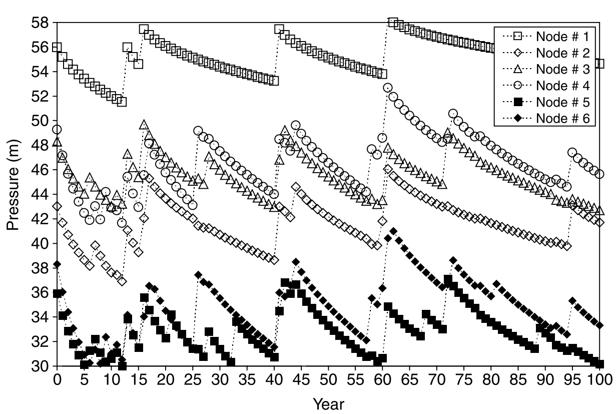

Figure 16 | Nodal pressure changes in operational years for the 100-year operation case.

minimum cost solution, but the longer it takes to arrive at this solution. Consequently, running the system with longer time steps can be useful to screen out inferior alternatives, thus reducing runtimes of shorter time steps. The application of the HBMO algorithm to the optimal rehabilitation of the two-loop water distribution system particularly shows its capability of optimizing water distribution systems. It is therefore concluded that the HBMO algorithm provides a competent approach for the optimization of a water distribution system. The approach allows the least-cost solution to be located more efficiently. It enables the optimal design and rehabilitation solution to be achieved for a water distribution system in a rapid manner. The approach provides a potentially valuable decision support system for engineers and decision-makers in devising long-term water distribution network rehabilitation plans. It would be interesting to investigate the HBMO algorithm's performance for optimizing other system elements, such as pumps, tanks, and valves in a water distribution system.

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