OPTIMAL DESIGN OF WATER DISTRIBUTION NETWORKS UNDER A SPECIFIC LEVEL OF RELIABILITY

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ABSTRACT

In this paper the chance constrained model was adopted to incorporate a pre-specified level of reliability for optimal design of pipe networks. Uncertainties were considered for the following design parameters: 1) required demand from every node, 2) minimum permissible pressure head at each node, and 3) roughness coefficient for each pipe. Uncertain parameters were presented by random variables that have a normal distribution. The innovation in this paper is the adopting of the Genetic Algorithm (GA) method to obtain the optimal design of the network system. GA is a stochastic optimization method that can easily handle any nonlinear constrained problem without any necessity to evaluate derivatives of the optimized function with respect to the unknown decision variables. A hypothetical example was tested against different levels of uncertainties and different levels of reliability. The results showed that the minimum cost, for the studied pipe network system, increases as the reliability level or the uncertainty level increases. Also, the final layout of the pipe networks system is greatly affected by the levels of uncertainty and reliability. A FORTRAN code was developed to apply the present methodology on water distribution networks.

Key words: Pipe Networks - Reliability - Optimal Design - Genetic Algorithm - Chance Constrained Model.

INTRODUCTION

Water distribution systems are designed to service consumers over a long period of time. Due to the unknown number and types of future consumers, the excepted future required demands and required pressure heads for design are uncertain. Another uncertain parameter in the design of a system is the system capacity. The capacity is affected by corrosion of pipes, deposition of pipes, physical layout and installation of the system. The change in capacity can be reflected in the roughness coefficient of the pipes. Since the impact of the different mechanisms that decrease system capacity is not known, there is uncertainty in the projection of the coefficients of roughness [8]. Uncertainty in different parameters within a pipe network, indeed causes uncertainties in output results. So, it is more realistic to consider the desired reliability of the network during the design process. Explicit consideration of reliability is one of the most difficult tasks facing researchers working on the development of least-cost optimization design models for water distribution networks.

There is currently no universally accepted definition or measure of the reliability of water distribution systems. In general, reliability is defined as the probability that a system performs its mission within specified limits for a given period of time in a specified environment [11]. The issue of water distribution system reliability concerns the ability of the system to supply the demands at the nodes within the system at pressure head levels greater than or equal to a pre-specified level [3, 8, 12].

Several optimization models for pipe network have been reported in the literature. Most of them are devoted to optimal design of pipe network under a deterministic/constant magnitudes of different design parameters. Goulter [5] published a review of different optimization technique developed to design pipe networks. He mentioned that in spite of the considerable development of models in the literature, they have not been accepted in practice. Goulter attributed that to the lack of acceptance of several factors. One of these factors is ignoring the reliability concept during the design process.

Su (1987) developed a model to determine the least-cost design of a pipe systems under reliability of pipe failure (mechanical failure). Reliability of pipe failure was measured with the concept of the minimum cut set method. Optimal cost was determined from a generalized reduced gradient method [12]. In 1990, Lansey applied the chance constrained method for the optimal design of pipe networks under uncertainties in: 1) nodal demands, 2) pipe roughness, and 3) minimum pressure head levels. The method considered the optimal design under a pre-specified level of reliability. The idea of the chance constrained method is to convert the required stochastic model (for pipe network design) to a simple deterministic model. Also, Lansey [8] utilized the reduced gradient method to solve the converted deterministic model. The concept of the chance constrained was also adopted for aquifer remediation design under uncertainties in hydraulic conductivities [9].

Duan [3] developed a reliability-based optimization model for water-distribution systems. He studied the design of a pipe networks taking into consideration number, location and size of pumps and tanks within the systems under study. Two optimization methods were used in combination, the pure 0-1 integer programming method and the generalized reduced gradient method.

Goulter [4] studied optimal design of pipe systems under reliabilities in both pipe failure and required demands. The chance constrained method was adopted to constrain the probability of pipe failure of each link and the probability of demand exceeding design values at each node. The gradient method was adopted to perform the optimization process.

Cullinane [2] presented a new vision of the reliability-based optimal design. He included all types of mechanical failure and created the concept of availability. Availability is the percentage of time that the demand can be supplied at or above the required pressure head.

Khang, [7] developed a model for optimal design of pipe networks subjected to both reliability constraints and the condition that each link consists of two segments with adjacent diameters. Xu [14], developed a new methodology to assessment reliability of a pre-existed pipe system under uncertainties in nodal demands, pipe capacity, reservoir/tank levels and availability of system components.

Guercio [6] adopted the first-order Taylor series expansion to linearize the optimization model that required for the reliability-based design of water systems. The optimal search was done in two steps. The first step was to search for an optimal design and then the reliability and pressure heads, evaluated on assumed configuration, were compared with the constraint values. If there still exists a possibility that the cost of the system can be further decreased a new iteration is performed. Effect of mechanical failure can be incorporated for different configurations.

Xu, [15] presented a new approach that considered uncertainty in nodal demands, pipe capacity and mechanical failure of system components. He combined the first order Taylor series approximation with the design point concept to relax the optimization model.

The objective of the present paper is to provide a methodology which incorporates the uncertainties in: 1) nodal demands, 2) minimum pressure heads at different nodes, and 3) roughness coefficients in the design of pipe distribution networks. Similar to Goulter and Lansey [4, 8], the chance constrained method was adopted. The new innovation here is utilizing a power stochastic optimization method to solve the problem instead of the gradient methods. All previous researches adopted the gradient approach within the optimization process. That approach usually returns with different local minimums depending on its starting point/ initial solution. Genetic algorithm (GA) is utilized in the present work.

PROBLEM FORMULATION

The optimization problem for the design of water distribution networks can be summarized as follows:

$$Minimum\ Cost = minimum \sum_{i,j \in M} f\left(D_{i,j}\right) \tag{1}$$

subjected to the following constraints:

$$\sum_j q_{i,j} = \sum_j KC_{i,j}\left[\frac{h_i - h_j}{L_{i,j}}\right]^{0.54} D_{i,j}^{2.63} = Q_j \qquad \textit{for nodes } j=1,2,\ldots,n \tag{2}$$

$$\sum_{i,j \in k} h_{i,j} = 0.0 \qquad \textit{for loops } k=1,2,..,N \tag{3}$$

$$h_j \geq H_j \qquad \textit{for nodes } j=1,2,\ldots,n \tag{4}$$

$$D_l \geq 0 \qquad \textit{for pipes } l=1,2,\ldots,M \tag{5}$$

where $f(\ )$ is an objective function represents construction cost of the network, $q_{i,j}$ is the flow rate between nodes i and j which calculated by the Hazen-Williams equation, Σ_j represent summation of all nodes/pipes connecting to node j, K is a conversion factor for units, $C_{i,j}$ is roughness coefficient for pipe between nodes i and j, h_p is the pressure head at node p, $L_{i,j}$ represents the length of pipe between nodes i and j, $D_{i,j}$ is the unknown diameter for pipe connecting node i to node j, Q_j is the required demand at node j, $h_{i,j}$ is the head loss between nodes i and j, H_j is the allowable lower level of pressure head at node j, D_l is the diameter of pipe l, n is the number of nodes in the system, N is the number of loops in the system, and M is the number of pipes in the network system. Equation 2 is the continuity equation used to satisfy demands at different nodes of the pipe system, while Eq. 3 represents the energy conservation within any loop. Satisfying any equation makes the other one unnecessary.

Considering for design purpose that future demands Q, minimum desirable level of pressure heads H, and pipe roughness coefficient C, are uncertain, consequently they can be represented by independent normal random variables. Any normal random variable can be completely specified with its mean μ and standard deviation σ. The uncertain parameters can be expressed as:

$$Q \sim N(\mu_Q, \sigma_Q) \tag{6}$$
$$H \sim N(\mu_H, \sigma_H) \tag{7}$$
$$C \sim N(\mu_C, \sigma_C) \tag{8}$$

where, $N(\ )$ means a normal random distribution variable. Substituting the random variables in Eqs. 6 to 8 in the optimization problem complicate the problem. Due to uncertainties the optimization problem must be solved thousands of times to include the erratic behavior of the designed parameters. That procedure is named by the Monte Carlo approach, which is adequately simple, accurate and has no approximation. Unfortunately, it requires an intensive computing time especially for large pipe systems. So, it is desirable to find a quicker approach to handle the present problem. In this paper, the chance constrained method was adopted. That method can transform different random variables to deterministic values by utilizing the concept of the cumulative probability distribution. Thus, the constraints in Eq. 2 can be reformulated as:

$$P\left[\sum_j KC_{i,j}\left[\frac{h_i - h_j}{L_{i,j}}\right]^{0.54} D_{i,j}^{2.63} \geq Q_j\right] \geq \alpha_j \qquad \textit{for nodes } j = 1, 2, \ldots, n \tag{9-a}$$

or
$$P\left[\sum_j KC_{i,j}\left[\frac{h_i - h_j}{L_{i,j}}\right]^{0.54} D_{i,j}^{2.63} - Q_j \leq 0\right] = P\left[W_j\right] \leq 1 - \alpha_j \qquad \textit{for nodes } j = 1, 2, \ldots, n \tag{9-b}$$

where, P[A] is the probability of occurrence event A with a probability level equal to α_j. The term W_j is also a random normal distribution variable with the following mean and standard deviation:

$$\mu_{Wj} = \sum_j K\mu_{Ci,j}\left[\frac{h_i - h_j}{L_{i,j}}\right]^{0.54} D_{i,j}^{2.63} - \mu_{Qj} \qquad \textit{for nodes } j = 1, 2, \ldots, n \qquad (10)$$

$$\sigma_{Wj} = \left\{\left[\sum_j K\left[\frac{h_i - h_j}{L_{i,j}}\right]^{0.54} D_{i,j}^{2.63}\right]^2 \sigma_{Ci,j}^2 + \sigma_{Qj}^2\right\}^{1/2} \qquad \textit{for nodes } j = 1, 2, \ldots, n \qquad (11)$$

Using the above two equations the constraints in Eqs. 9 can be transformed to:

$$P\left[\frac{W_j - \mu_{Wj}}{\sigma_{Wj}} \le \frac{0 - \mu_{Wj}}{\sigma_{Wj}}\right] \le 1 - \alpha_j \qquad \textit{for nodes } j = 1, 2, \ldots, n \qquad (12)$$

or, $$\frac{\mu_{Wj}}{\sigma_{Wj}} \le \phi^{-1}(1 - \alpha_j) \qquad \textit{for nodes } j = 1, 2, \ldots, n \qquad (13)$$

where, ϕ^{-1} is the inverse of the cumulative distribution function. Under the assumption of normality $\phi(\ )$ is the standard normal distribution function.
In a similar manner the constraint of the pressure head at different nodes, Eq. 4, can be rewritten in a probabilistic form as:

$$P\left[\frac{H_j - \mu_{Hj}}{\sigma_{Hj}} \le \frac{h_j - \mu_{Hj}}{\sigma_{Hj}}\right] \ge \beta_j \qquad \textit{for nodes } j = 1, 2, \ldots, n \qquad (14)$$

or, $$h_j \ge \mu_{Hj} + \sigma_{Hj}\phi^{-1}(\beta_j) \qquad \textit{for nodes } j = 1, 2, \ldots, n \qquad (15)$$

where, β_j is the probability level at which the actual pressure heads equal to or exceed the desired pressure head. Equation 1 represents the objective function that must be optimized to find the optimal solution. While equations 5, 13, and 15 are the deterministic form of the constraints, bounded the optimization domain, that concluded from the chance constrained method. The above constraints concluded under the assumption of normality of the random variables and the assumption of no correlation between different variables. However, the above procedure is applicable for any random distribution with a correlation effect between different variables.

The achieved model is a nonlinear problem in which Eqs. 5 and 13 are treated as simple bound constraints. Nonlinearity arises from the expressions of μ_{Wj} and σ_{Wj}. That nonlinear problem consists of one nonlinear constraint for every node, Eq. 13, and a simple linear bound for each pipe (diameter), Eq. 5, and for every node (pressure head), Eq. 15. A powerful method should be adopted to handle the high nonlinearity of the present model. The Genetic algorithm method was selected.

GENETIC ALGORITHM (GA)

Genetic algorithm is a search technique developed by Holland in [10] that uses the mechanism of natural selection to search through decision space for optimal solutions.

GA has been shown to be valuable tool for solving complex nonlinear constrained optimization problems in a broad spectrum of fields. That algorithm consists of three basic operations: 1) selection, 2) crossover (mating), and 3) mutation. In using GA, several chromosomes or strings which represent different solutions (decision set) are formed. These strings are evaluated on their performance with the desired objective function. Using this fitness value the strings compete in a selection tournament, where strings having high fitness value enter the mating population and strings with low fitness value are killed off. Penalty functions are usually used to assign poor fitness values to strings that violate the problem constraints.

Different formulations for the genetic algorithm have been studied by Abdel-Gawad [1]. The best formulation that is adopted in this paper, composed from uniform crossover, modified uniform mutation, constant value of penalty and tournament strategy for both selection/reproduction and replacement steps. Also, the real code was adopted to different decision variables. Genetic algorithm is superior to any gradient algorithm due to its erratic behavior within the optimization process.

Gradient methods, always, start with one initial guess/solution and stuck down with surface of the optimization space. Initial solution sweep down with the gradient of the objective function till reach the nearest local minimum. Consequently, the final design depend on the initial guess and require the analytical form of the gradient of the objective function with respect to the decision variables (pipe diameters). On the other hand, GA starts with a huge number of candidate solutions and search in erratic ways. Consequently, a high probability of catching the global solution can be achieved. Another more advantage is that the GA depends only on the objective function without any need for its gradients.

STEPS OF SOLUTION

A Fortran code for GA, previously written by Abdel-Gawad [1], was modified to incorporate the chance constrained method, for optimal design of pipe networks. The following steps illustrate the solution procedure:

1. Determine the cost of the pipe network for pre-selected magnitudes of the pipe diameters. That cost is used to estimate a reasonable penalty function.
2. Generate an initial population with number of strings/solutions equal to *NG*. Each string contains number of genes equal to number of the designed pipes within the system. Every gene has a suggested magnitude for the unknown diameter of the corresponding pipe.
3. Calculate the corresponding construction/material cost for every string from using the objective function settled in Eq.1.
4. Generate a uniform random pressure heads at different demand nodes. These random heads are restricted with a lower bound that can be calculated from Eq. 15, and a higher bound equal to the pressure head at the source. In general, an infeasible pressure heads are initiated to get an accepted pattern of the pressure heads, along the pipe system, so, several iterations must be repeated. During the

iteration process, if there is any pressure head pattern satisfy the constraints in Eq. 13, the iteration process stops with a feasible string/solution. Otherwise, the iteration process continues to 1000 iteration and ended with the minimum number of constraints violations within the iterations process. Number of constraints violations must be used to calculate the penalty cost. At each iteration, a check must be included to determine if any h_i is less than h_j because of term $(h_i-h_j)^{0.54}$ in the constraints. If h_i is less than h_j, then the absolute value of $(h_i-h_j)^{0.54}$ must be multiplied by –1 to indicate the change in flow direction.

5. Check if there is any violation for the constraints. A penalty cost must be added to the construction cost to weak strings that contains infeasible solutions. A constant penalty cost is added for every intruded constraint without consideration to its value.
6. Calculate the corresponding fitness of every string. GA computes the fitness for each proposed network in the current population as the inverse of the total network cost. Total cost is equal to the construction cost plus the penalty cost.
7. Create a mating pool from the initial population. Different strings in the mating pool must be selected from the initial pool with a probability proportional to their fitness value. Then, apply crossover and mutation to different strings within the mating pool.
8. Select the fittest strings from both the initial/father chromosomes and the children chromosomes in the mating pool, and set them again in the father pool (initial population). The principle of tournament selection is used to the replacement policy. Then return to step 3. The optimization process stops when number of generations reaches a pre-specified number, or the fittest chromosome is constant for ten consecutive generations [1].

HYPOTHETICAL EXAMPLE AND DISCUSSION

A simple hypothetical pipe network, see Fig. 1, was used to test the present methodology. That example was previously solved by Lansey [8]. He used the gradient optimization method instead of the genetic algorithm method.

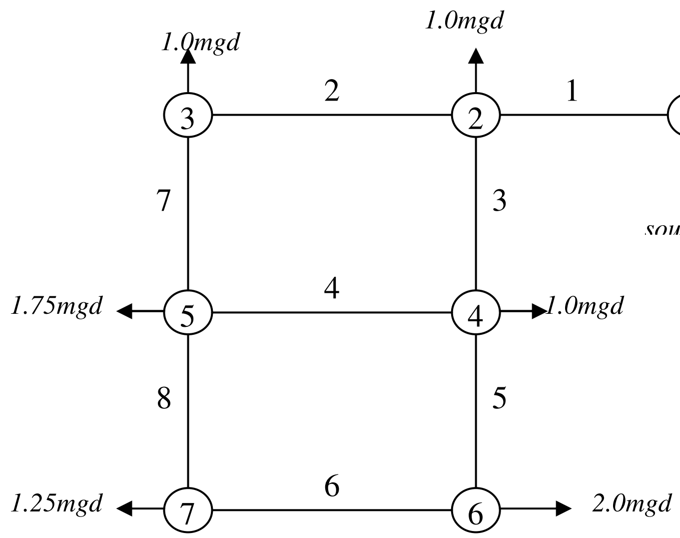

Figure 1. A plan of the network system

The pipe network under study consists of two loops with eight pipes each has a length equal to *3280ft*, the mean demands are shown in Fig. 1. All nodes are assumed to be at the same elevation and the pressure head at the source is taken equal to *196.8 ft*. The nodal pressure head requirement at each node is *100ft*, and the mean Hazen-Williams roughness coefficient is *100* for each pipe. The objective function used to determine the total cost is:

$$Cost = 0.331L\,D^{1.51} \tag{16}$$

where D is the pipe diameters in inches, and L is the length of the pipe in *ft*. Demands were converted to cubic meter per hour to be consistent with the Hazen-Williams equation.

The following parameters were used to solve the present problem: 1) *the conversion factor for Hazen-Williams equation K = 0.062, number of strings =150, maximum number of generation = 75, crossover ratio = 0.5, mutation ratio = 0.25, seed number = 19, penalty = 800473 / every violated constraint* (equivalent to the construction cost of the system with diameters equal to 20 inch for each).

Twenty three runs were carried out for different levels of uncertainty and different required levels of reliability. Standard deviation for pressure heads were taken equal to *0.0, 5 and 10 ft*, while standard deviation of the nodal demands were assumed equal to *0.0, 0.1 and 0.25 mgd* (*1.0mgd = 189.42 m^3/hour*). Finally, standard deviation of the roughness coefficients were adopted equal to *0.0, 5.0 and 10.0*. Different reliability levels were considered α, β *= 0.7, 0.9, 0.8 and 0.99*.

Table 1 presents a comparison between the present results and the corresponding results obtained from using the gradient method [8]. Comparisons were made for design parameter with certainty, that means standard deviations of different parameters were taken equal to zeros. From that table it can be concluded, that several mistakes were incorporated within the computation process of Lansey [8]. Both the estimated pressure heads and the calculated cost were found in wrong values. In spit of the GA ended with a higher cost, the final design satisfies the required minimum pressure heads at all nodes. For that run number of generation were taken equal to *200* and minimum cost was reached after *29801* iterated strings/ solutions. The required minimum pressure head was settled equal to *100 ft*, which is lower than calculated pressure heads at different nodes of the optimal design. This means that the GA needs more iterations to reach to global solution.

Table 1. Comparison between optimal design from the present work and the corresponding results of Lansey, [8]. {σ_H =0.0, σ_Q = 0.0, σ_C =0.0, α =β =0.0}

Diameters of pipes in inches			*Pressure head at nodes in ft.*		
Pipe	***The present GA method***	***Gradient method [8]***	***Node***	***The present GA method***	***Gradient method [8]***
1	*19.0*	*18.0*	*1*	*196.8*	*196.8*
2	*9.3*	*6.8*	*2*	*148.4*	*133.8*
3	*22.1*	*16.3*	*3*	*115.17*	*-19.8**
4	*11.4*	*9.2*	*4*	*134.8*	*73.87**
5	*15.9*	*13.0*	*5*	*127.99*	*55.45**
6	*12.6*	*9.9*	*6*	*113.07*	*-1.65**
7	*0.0*	*0.0*	*7*	*101.55*	*-71.0**
8	*0.0*	*0.0*	*Infeasible pressure heads were calculated from the gradient method*		
Cost	*403,814*	*331,160[x]*			

* *means infeasible pressure head (<100 ft).*

[x] *means wrong calculated value for the cost, the correct value = 296,224.*

Figure 2 shows the effect of uncertainty of the demand requirements and the roughness coefficients on the optimal cost of the pipe system. The trade off relation between reliability level and the construction cost for different degree of uncertainties were shown in the figure. Figure 3 traces the relation between uncertainty in the pressure head and the optimal cost. Finally, Figure 4 represents the effect of uncertainties for all the design parameters (minimum pressure, demand nodes, and roughness coefficients) against different levels of reliability.

Figures 2 to 4 show an increase in construction cost as the reliability level increases. Also, the construction cost increases with the increase in uncertainty of any design parameter. From these figures it can be noticed that the construction cost increases with increasing rate, as the reliability level increases.

Tables 2 to 5 list the optimal design for all runs, which show a change in cost and system layout due to different reliability requirements. It can be noticed that all solutions ended with zero diameters for pipes 7 and 8, which changes the pipe network configuration. The present problem handles the unknown diameters as a continuous variable for sake of comparison with previous work. In reality, pipes have discrete commercial diameters, so it is more accurate to use these discrete diameters within the optimization process. In contrast to the gradient methods, GA can handle that problem easily and a straightforward.

From the following figures and tables it can be seen that the construction cost change considerably with different levels of uncertainties and reliability requirements. The construction cost ranges from *403,814 to 623,462.* Uncertainties in either demand nodes or roughness coefficients have a greater effect on the final cost, than the uncertainty in the required minimum pressure heads.

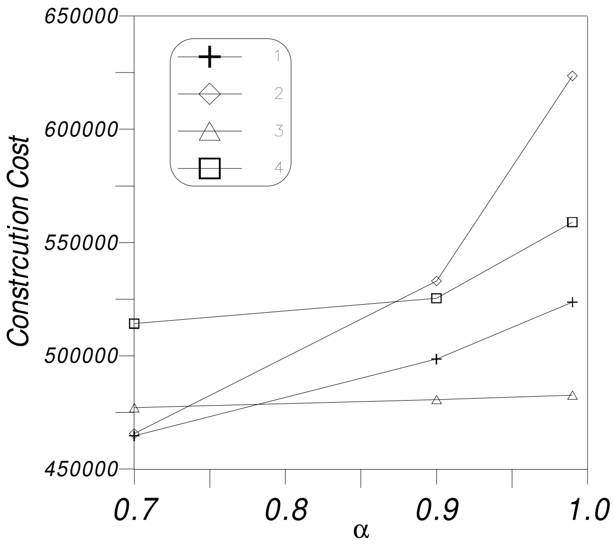

Figure 2. Construction cost against reliability for certain pressure heads (σ_H=0), 1) σ_Q = 0, σ_C = 5, 2) σ_Q = 0, σ_C = 10, 3) σ_Q = 0.1mgd, σ_C = 0, 4) σ_Q = 0.25mgd, σ_C = 0.

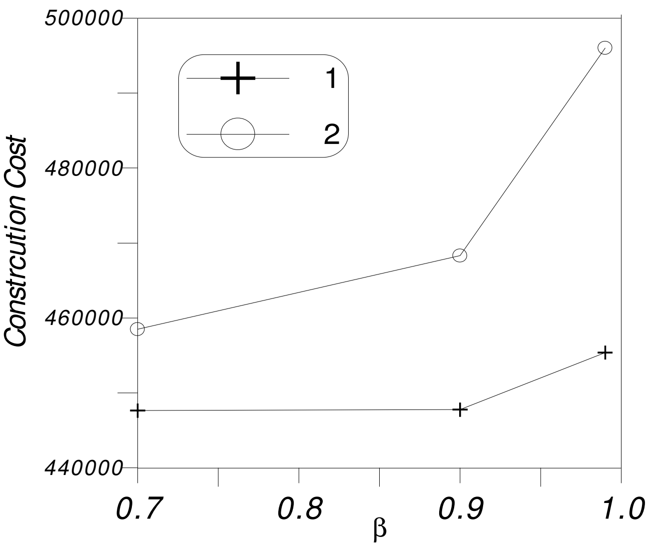

Figure 3. Construction cost against reliability for certain values of demand nodes and roughness coefficients (σ_Q = σ_C = 0.0), 1) σ_H=5.0 ft, 2) σ_H=10.0 ft.

CONCLUSIONS AND RECOMMENDATIONS

A general method for approaching the reliability issue in the design of optimization-based network design models has been presented. That method depends on using the chance constrained model to convert uncertainties in the design parameters to form a deterministic formulation of the problem. Then the GA method was adopted to solve the nonlinear optimization problem settled in a deterministic form.

A hypothetical example was solved and compared with previous solution from the gradient approach [8]. From the results it can be found that the construction cost of the pipe system increases, with an increasing rate, as the reliability requirement increases.

Uncertainties in demand nodes or roughness coefficients have a more pronounced effect on final construction cost, than the effect of the required minimum pressure heads.

Through the optimization process GA needs an iterative repetition of random generations for the unknown pressure heads at different nodes, till a feasible pattern was achieved. This process increases considerably the computation time. Also, the optimal solution needs more iteration to catch the global design. So, it is more realistic to incorporate a gradient method with the GA method. In that case, GA will provide the solution pool with different reasonable/feasible solutions close to different local minimums, then the gradient algorithm can exploit these solutions as an initial guesses to catch a better ones.

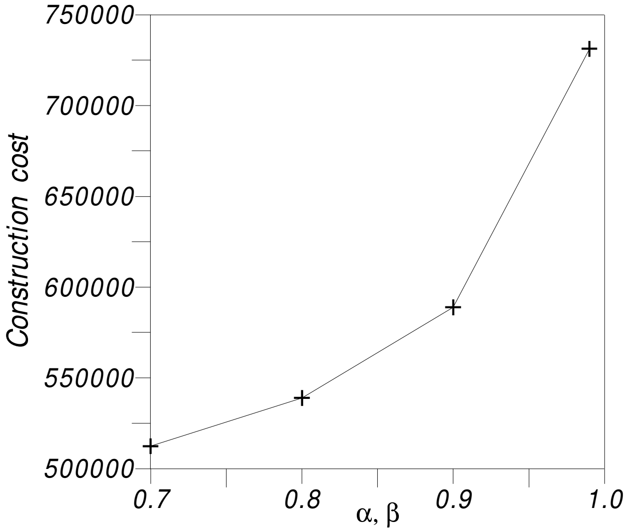

Figure 4. Construction cost against reliability for σ_Q = 0.25mgd, σ_C = 10.0 , and σ_H =10.0 ft.

Table 2. Optimal design of pipe diameters in inches, due uncertainty in pipe roughness.

	σ_H=0.0, σ_Q= 0.0, σ_C=5.0, β=0.5			σ_H=0.0, σ_Q=0.0, σ_C=10.0, β=0.5		
Pipe	***α=0.7***	***α=0.9***	***α=0.99***	***α=0.7***	***α=0.9***	***α=0.99***
1	*22.0*	*25.4*	*23.6*	*24.9*	*26.3*	*33.0*
2	*9.9*	*12.3*	*10.3*	*9.0*	*10.8*	*12.3*
3	*22.8*	*22.4*	*23.2*	*21.3*	*24.1*	*27.4*
4	*12.9*	*12.1*	*16.8*	*12.6*	*13.0*	*12.6*
5	*16.6*	*17.4*	*20.3*	*16.7*	*20.2*	*19.1*
6	*15.1*	*14.3*	*13.3*	*14.3*	*13.6*	*13.5*
7	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
8	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Cost	*464,683*	*498,532*	*523,673*	*465,613*	*533,036*	*623,462*
No. of strings	*10518*	*11386*	*10240*	*10228*	*9681*	*8459*

Table 3. Optimal design of pipe diameters in inches, due uncertainty in nodal demands.

	σ_H=0.0, σ_Q= 0.1, σ_C=0.0, β=0.5	σ_H=0.0, σ_Q= 0.25, σ_C=0.0, β=.5

Pipe	α=0.7	α=0.9	α=0.99	α=0.7	α=0.9	α=0.99
1	21.3	22.7	24.9	26.5	27.0	29.9
2	10.7	11.0	10.6	8.3	12.2	10.8
3	20.9	21.2	20.5	27.2	24.6	23.9
4	13.9	14.6	13.5	14.2	14.2	13.7
5	19.0	19.1	17.3	16.4	16.6	18.0
6	15.9	13.3	15.1	11.2	12.4	15.3
7	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0
Cost	464,683	480,566	482,637	514,236	525,425	558,572
No. of strings	10518	10881	9581	12936*	5400	6705

* *number of generations were taken equal to 100.*

Table 4. Optimal design of pipe diameters in inches, due uncertainty in the permissible minimum pressure heads.

	σ_H=5.0, σ_Q= 0.0, σ_C=0.0, α=0.5			σ_H=10.0, σ_Q= 0.0, σ_C=0.0, α=0.5		
Pipe	β=0.7	β=0.9	β=0.99	β=0.7	β=0.9	β=0.99
1	23.5	23.2	23.6	25.3	23.3	27.4
2	9.7	9.2	10.1	10.3	10.3	11.2
3	21.8	21.4	19.5	22.1	19.4	20.7
4	12.4	13.3	13.3	11.9	14.4	13.7
5	16.3	16.9	16.3	16.9	18.3	16.7
6	12.7	12.5	15.4	10.8	14.5	13.5
7	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0
Cost	447,651	447,783	455,379	458,511	468,306	496,032
No. of strings	21632*	14723*	9508	9598	7612	10204

* *number of generations were taken equal to 100.*

Table 5. Optimal design of pipe diameters in inches, due uncertainty of the required pressure heads, demands, and roughness coefficients.

	σ_H=10.0, σ_Q= 0.25, σ_C=10.0			
Pipe	$\alpha=\beta=0.7$	$\alpha=\beta=0.8$	$\alpha=\beta=0.9$	$\alpha=\beta=0.99$
1	23.3	25.4	29.1	33.7
2	11.4	10.1	11.4	12.8
3	22.4	23.2	25.7	30.2
4	15.0	16.4	14.1	15.4
5	19.7	20.0	20.4	23.8
6	14.6	14.3	14.5	16.7
7	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0
Cost	512,381	538,910	588,895	731,186
No. of strings	10145	6733	11259	9719

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