Reliability Based Optimization of Water Distribution System Using Hybrid Method

Priyanshu Jain, Ruchi Khare

Abstract: ***In present world, water distribution network has a considerable role in maintaining the required living standard. It has various components such as pipe, pump, and control valve to deliver water to the consumer withdrawal point from its source point. Among these elements, more than 70% of the project cost depends on the pipe cost, which justifies the need of optimal sizing of pipes. Unfortunately, optimal pipe sizing is a non-linear problem. Importance and complexity of the pipe flow problem makes it popular in research field. The literature unfolds that the stochastic optimization algorithms are successful in examining the combination of least-cost pipe diameters from the commercially available distinct diameter set, but with the liability of considerable computational effort. The hybrid method i.e. Genetic -Fuzzy System, presented in this research work has a main focus to develop a parameter for increasing the reliability of the overall network using fuzzy logic concepts based on the difference in simulated pressure and acceptable pressure limits in demand nodes and to incorporate this parameter in a bi-objective optimization model for water distribution network design using Genetic Algorithms, hence attaining the optimized pipe diameters with minimum computational effort. The method is applied for optimizing three different water distribution systems [1, 13]. The variation of reliability index with the optimal cost is presented in graphical form.***

Index Terms: ***Optimization, water distribution system, fuzzy logic, genetic algorithm, reliability index***

I. INTRODUCTION

Water is a vital commodity for all living beings on earth surface next to air. Therefore water distribution system is most important public utility for safe and potable water. To supply the adequate amount of water at desired pressure with minimum cost is the challenge for researchers. The pipes of network are interconnected at junction and change in size of any one pipe affect the pressure and velocity in complete network. The minimization of cost of the network often compromises with the reliability. A reliable network at minimum cost to full fill all the necessities of pressure and demands at all junction is an important task. For achieving this goal various optimization techniques are applied. Many papers and applications combining fuzzy concepts and GAs have appeared, and there is growing concern about the integration of these two topics. Specifically, a large number of publications investigate the use of Genetic Algorithms for designing fuzzy systems. These approaches get the general name of Genetic Fuzzy Systems (GFSs). Alperovits & Shamir, [1977] applied linear programming for the economical design of water distribution system (WDS). The solution is obtained via a hierarchical decomposition of the optimization problem [1]. Subsequently, Chandramouli, S. and Malleswararao, P. [2011] used two quantitative approaches for the incorporation of reliability measures in the economical design of looped water distribution networks [9]. Gupta et al [1999] used genetic algorithm [3]. Suribabu, C.R. and Neelakantan, T.R. [2006] applied particle swarm optimization in design of a water distribution pipeline network [6]. Minakshi et al. [2014] introduced various optimization techniques that have been used by different investigators to analyze and optimize pipe network problem such as Genetic Algorithms, Ant Colony Method, Particle Swarm Optimization and Hybrid Methods [11, 12]. Jinesh Babu K. S. and Vijayalakshmi D. P. [2013] presented a hybrid model that couples PSO and GA [10]. Geem Z.W. [2015] applied fuzzy theory for optimizing WDN [13]. In the present work a method of reliability enhancement is proposed for water distribution networks. The ratio of demand at each node to the total demand of the system and a membership function of the difference in simulated pressure and required pressure range is employed as a measure of reliability. Reliability is improved by increasing pipe size. The effectiveness of the introduced reliability measure is examined by assessing the final solutions for required nodal pressures at each node and having reliable loops. Identification of the payoff between cost and reliability is also another aim of this study.

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II. PROBLEM FORMULATION

The main purpose of this study is to minimize the cost and maximize the reliability of the water distribution network.

A. Minimization of cost

The commercially available pipes are used in design of network and objective function for minimization of pipe cost is:

Min $C_1 = \Sigma f(D_i, L_i)$ (i)

Where $f(D_i, L_i)$ is cost function which has two arguments of pipe diameter D_i and pipe length L_i.

The objective is to minimize this cost function by fulfilling the following constraints:

$\Sigma Q_{in} - \Sigma Q_{out} = Q_e$ (ii)

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Where Q_{in} is discharge entering to a specific node; Q_{out} is discharge exiting from the specific node; and Q_e is external demand of discharge at the node. This is the continuity constraint which is to be satisfied for every node in a network.

$$\Sigma h_f = 0 \qquad \text{(iii)}$$

Where h_f is head loss because of friction in pipe, which is calculated using Darcy-Weisbach or Hazen-Williams formulae. This energy conservation constraint must be satisfied for each loop in the network [12].

B. Maximization of Reliability

All WDSs have a minimum permissible pressure value due to the local topography and their nodal demands. The network experience failures when the supplied nodal pressures during the running period fall down from the minimum required level. Thus, by having higher values of nodal pressures, the network is more capable of facing hydraulic failures and its reliability in supplying required pressure will increase. In addition, nodal pressure in each network has a maximum permissible value which is based on the capability of network components. Nodal pressure larger than the maximum permissible value causes leakage and breakage, which leads to a considerable decrease in the serviceable life of the network. Hence, the optimal value of the design nodal pressure in the network should fall between the minimum and maximum permissible values.

Here, MFj is fuzzy membership value for node j; hj is simulated pressure head in node j; hj* is minimum required pressure head for node j; and hj** is maximum permissible pressure head for node j. The fuzzy membership value for each node in the WDS is calculated with Equation iv and this equals the Fuzzy Reliability Index (FRI) for that node. Thus, due to the definition of MFj, the reliability of the network nodes increases if their pressure values are close to the average.

The most favorable value of fuzzy membership is obtained when the pressure head is equal to the average of the minimum and maximum of permissible values [14].

This study bring up a fuzzy function in the range amidst the minimum and maximum permissible pressure heads and represents the fuzzy reliability index (FRI) as follows:

$$MF_j = \begin{cases} 0 & ;\ \text{if } hj<hj^* \\ 2(hj-hj^*)/(hj^{**}-hj^*) & ;\ \text{if } hj^* <hj< (hj^{**} + hj^*)/2 \\ 2(hj^{**}-hj)/(hj^{**}-hj^*) & ;\ \text{if } (hj^{**} + hj^*)/2 <hj<hj^{**} \\ 0 & ;\ \text{if } hj<hj^{**} \end{cases} \qquad \text{(iv)}$$

Two more terms demand coefficient (equation v) and redundancy coefficient (equation vi) are developed

$$C_{1j}= 1- q_{ij}/\Sigma q_{ij} \qquad \text{(v)}$$

Where C_{1j} is demand coefficient in each node j; q_{ij} = nodal demand in node j; By multiplying C_{1j} and MFj, the membership value of high consumption nodes decreases and the membership value of low consumption nodes increases.

$$C_{2j}= \Sigma D_{ij}/ (NP_j*D_{ijmax}) \qquad \text{(vi)}$$

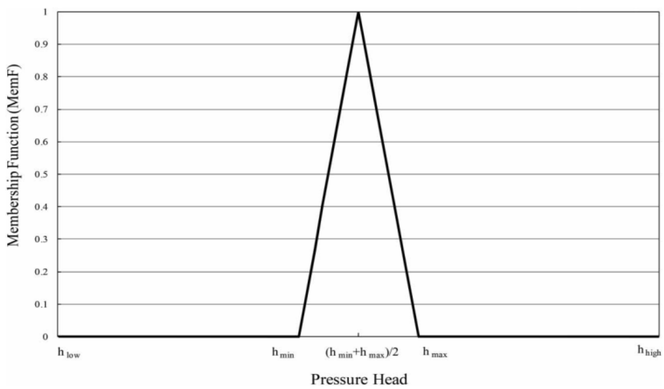

Figure 1 Fuzzy membership function (Triangular)

Where C_{2j} is coefficient introduced by Prasad & Park [2003] to ensure redundancy in network loops, calculated at each node j; D_{ij} = diameter of pipe i connected to node j; NP_j = number of pipes connected to node j; and D_{ijmax} is diameter of the largest pipe connected to node j. C_{2j} equates to one when the diameters of all the pipes connected to a node are equal to each other; otherwise, it is less than its optimal value [4]. Dependency on Equations iv, v and vi provides the Fuzzy Reliability Index (FRI).

$$FRI_{2j}= MF_j*C_{1j}*C_{2j} \qquad \text{(vii)}$$

The concluding value of the FRI index for each node takes into account the magnitude of pressure reliability achieved in supplying the total network water demand and also includes the redundancy of the network loops. The reliability of the network is considered as a function which takes into account the sum and the minimum values of FRI indices at all nodes in the calculations.

$$\text{Reliability} = RI_2= \Sigma FRI_{2j}*(FRI_2j_{min}) \qquad \text{(viii)}$$

III. METHODOLOGY

1. Initially the network is optimized by using in built Genetic Algorithm optimization available in commercial software.
2. Than the system is further optimized by calculating fuzzy membership function at each node by considering the difference between simulated pressure and required pressure range.
3. Calculation of coefficient C_{1j} at each node for analyzing demand distribution at the node.
4. Calculation of coefficient C_{2j} for the redundancy in the diameters for each pipe in a loop of the network.
5. Determination of reliably of the network.
6. Repeating steps 1 to 5 by changing the GA parameters.

IV. RESULTS AND DISCUSSIONS

Two standard basic networks referred by various researchers i.e. Shamir's Two Loop Network [1] and Hanoi network [2] are optimized and validated by using present hybrid methodology. One more tree type network of School of Planning and Architecture, Bhopal (M.P) campus is also optimized by using this hybrid method.

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a. Shamir network

The two loop network was primarily used by Alperovits and Shamir [1977]. They used linear programming for calculating the optimal design. Afterwards many researchers used this network for optimization and reliability study. The two loop network working under gravity as shown in Fig. 2 comprises of 6 demand nodes, 8 links and single reservoir. Node 1 is a supply node with hydraulic gradient level of 210 m and a demand of 1120 m3/hr. Hazen-Williams coefficient (CH_w) is assumed as 130 and length of all the links in the network is 1000m [1].

Table 1 show the cost of pipes which is used for the validation as used by various researchers in the network [1].

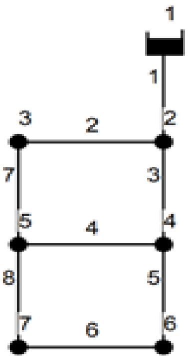

Figure 2 Shamir network [1]

Table 1 Available pipe sizes for Shamir network

Diameter (mm)	Cost per meter (units)
25.4	2
50.8	5
76.2	8
101.6	11
152.4	16
203.2	23
254.0	32
304.8	50
355.6	60
406.4	90
457.2	130
508	170
558.8	300
609.6	550

Table 2 shows the nodal demands which should be satisfied during optimization procedure.

Table 2 Nodal input parameter for Shamir network

Label	Elevation (m)	Demand (m^3/h)
J-1	150	100
J-2	160	100
J-3	155	120
J-4	150	270
J-5	165	330
J-6	160	200

The proposed hybrid method is applied to solve this network and it is found that the reliability correspond to the minimum cost (419,000) is 0.015 which is very low in comparison with the reliability of the optimal cost (633,000) that is, 0.58. Thus it can be seen that by increasing the cost 1.5 times of the least cost, the reliability of the network is increased 37 times. The variation of reliability with cost is shown in Fig. 3.

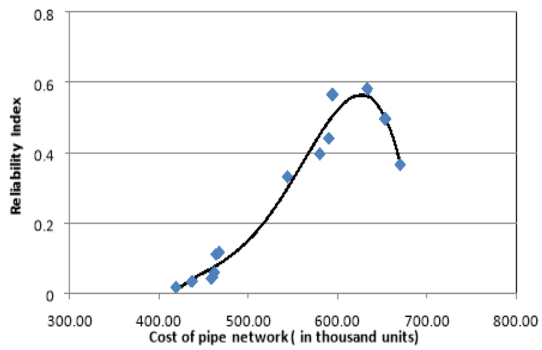

Figure 3 Variation of reliability with unit cost in Shamir's two loop network

b. Hanoi network

II. The network was primarily optimized by Fujiwara and Khang [1990] using two phase non linear programming method. It has subsequently been used as a case study for a number of optimization techniques. This network is comprised of 31 nodes, 34 pipes and single reservoir. The available pipe sizes with their unit cost are made known in Table 3 [13].

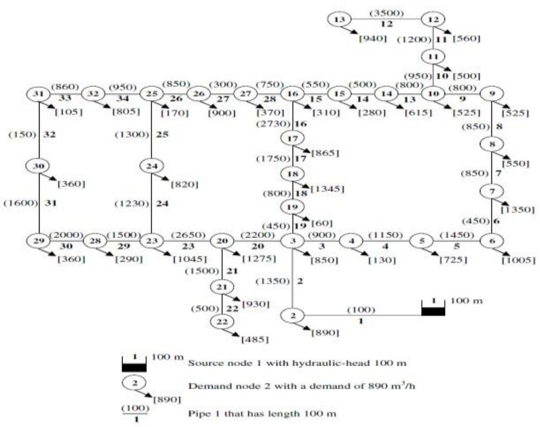

Figure 4 Hanoi network [2]

Table 3 Available pipe sizes for Hanoi network

Diameter (mm)	Cost per meter (units)
304.8	45.726
406.4	70.400
508.0	98.378
609.6	129.333
762.0	180..748
1016.0	278.280

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In case of Hanoi Network, the similar trend can be seen and the optimal reliability is found to be 0.177 in comparison to the reliability corresponding to least cost which is 0.096, the optimal cost is 7,602,90 units and least cost is 6,125,600 units. Hence, the optimal cost is only 1.24 times of the least cost whereas the reliability is increased by 1.84 times.

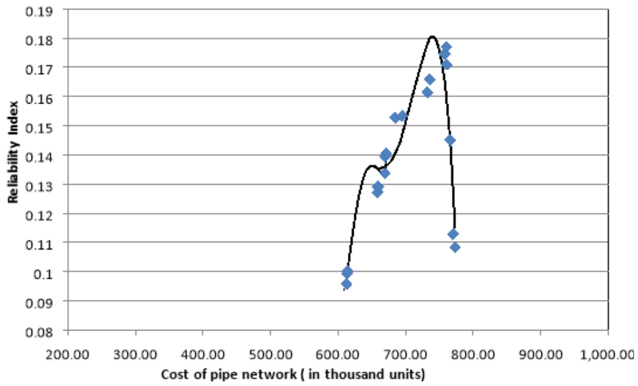

Figure 5 Variation of reliability with unit cost in Hanoi network

c. SPA tree type network

The water supply network of the hostel sector of School of Planning and Architecture is shown in Fig. 6. The details of pipes cost used in this network are given in Table 4.

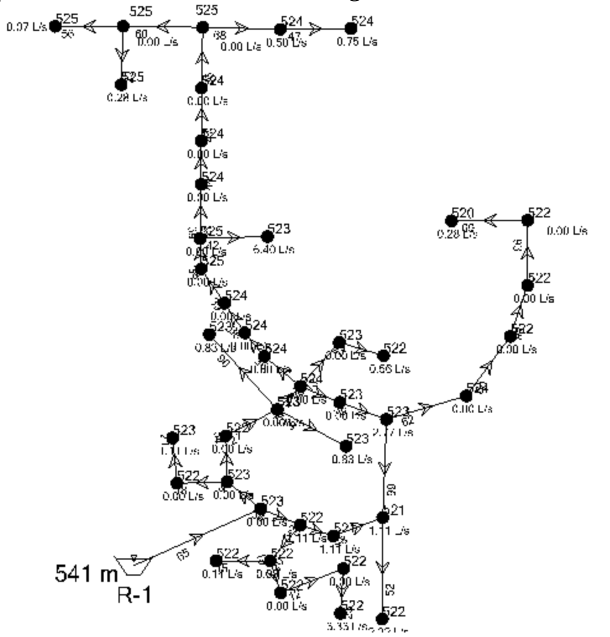

Figure 6 SPA tree type network

The variation of least cost with reliability index is shown in case of SPA network is shown in Fig. 7. In case of tree type network the least cost is equal to 17,302,598 units as calculated in this study and the RI value corresponding to this cost is 0.26. The optimal cost found from the study is 19,344,796 corresponding to RI value 0.44. Thus increasing the cost by just 1.11 times the RI value is increased by 1.665 times.

Table 4 Available pipe sizes for SPA tree type network

Material	Diameter (mm)	Cost per meter (units)
CPVC	15	35
CPVC	20	54
CPVC	25	78
CPVC	32	117
CPVC	40	160
CPVC	50	268
CPVC	62.5	651
CPVC	75	730
DI	100	800
DI	150	1,200
DI	200	1,650
DI	250	2,300
DI	300	2,860
DI	350	3,510
DI	400	4,500
DI	450	5,200
DI	500	6,580
DI	600	7,930
DI	700	11,000
DI	750	11,900
DI	800	12,000
DI	900	14,500
DI	1,000	16,300
RCC	1,100	1,875
RCC	1,200	1,677

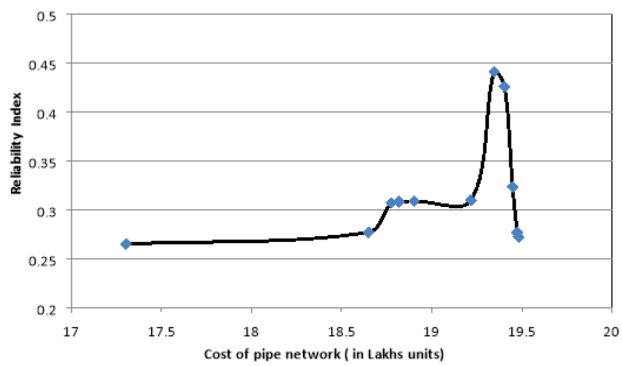

Figure 7 Variation of reliability with unit cost for SPA tree type network

V. CONCLUSIONS

This research work presents the hybridization of the concepts of two conventional systems, that is Fuzzy Logic Systems and Genetic Algorithms, which are combined in a very handy way, hence suppresses the complexity involved in previous research works.

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A simple procedure is proposed for the optimization with the predefined coefficients for reliability, Fuzzy Logic Concepts and WaterGEMS.

It can be observed that the performance of this method varies for all the three network examples, but the final results are acceptable, for each case, when compared with the previous works. This method is user-friendly and the requirement of the input parameters is almost same as required in hydraulic simulation models. Few additional data requirements are some genetic algorithm parameters the values of which are taken by referring various literatures [4, 9, 11].

The cost obtained for the optimum solution in each network is found to be compatible than the cost found by other researchers with a minor difference in reliability index for the respective studies. Thus this study shows better results when coefficient of demand and coefficient of redundancy in pipe sizes is included in multi-objective optimization.

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