Optimal design of looped water supply network by GA-NLP hybrid approach

Srinivasa Prasad A¹ and Leela Krishna K¹

¹Dept. of Civil Engineering, R.V.R. & J.C. College of Engineering, Chowdavaram, Guntur, Andhra Pradesh, India – 522019, Ph.No: 9490223827
E-Mail: annavarapu_sp@yahoo.com (corresponding Author)

Abstract
Any Municipal distribution system consists of pipe network, valves and pressure generating facilities etc. Around 70% of total cost of any water distribution system is towards cost of pipe network only. Therefore, the cost of pipe network is to be reduced by selecting the appropriate lengths of candidate diameter pipes between the nodes in a pipe network.

In the present study, a municipal looped water distribution network is designed for least cost by Genetic Algorithm – Non Linear Programming (GA-NLP) hybrid approach. In the present study, optimal lengths of sub pipes of various discrete diameters (sizes) available in the market making the link between the nodes are obtained by minimising the total cost of pipe network. In order to obtain the optimal solution of a looped network, non-linear hydraulic analysis and optimization of network is to be performed. In this study, non-linear hydraulic analysis is made a part of optimization by adding loop head loss and node continuity equations as constraints to the objective function. The model developed is solved by GA-NLP hybrid approach in MATLAB. Near optimal solution obtained by GA is taken as initial solution of NLP for obtaining optimal solution. By adopting GA-NLP hybrid approach, convergence is faster when compared to GA avoiding the complexity in selection of suitable trial values of GA parameters.

Many researchers applied different techniques like linear programming, integer linear programming, linear programming gradient method and branch & bound algorithm etc. and optimized the looped pipe network by minimizing the cost. The results obtained by proposed model are compared with that of other investigators and found to be superior. It is also concluded that the proposed model may be applied to any larger municipal looped pipe network through demonstration by applying proposed model to a case study of Rajiv Gandhi Nagar of Guntur Municipal Corporation.

1. Introduction
Large municipal water supply distribution system consists of looped pipe networks with pressure generating devices like pumps and elevated service reservoirs. Any municipal water distribution system is to be designed to satisfy the demands with sufficient pressure. Major share of the total cost of the system goes just for pipes. When higher pipe sizes are selected, head loss in the system can be decreased maintaining higher residual heads but the cost of pipe network increases. To minimise pipe cost, if lower pipe sizes are selected, head loss will be more and minimum residual heads cannot be maintained in the system. Therefore appropriate sizes of the pipes are to be selected minimizing the cost while maintaining the residual head at each node in the allowable range. This necessitates the application of optimization while designing the water supply looped networks minimizing the cost subject to constraints. The complexity with looped pipe network increases as the flow distribution in pipes is unknown and pipe
flow distribution takes place satisfying the nonlinear loop energy equations and node continuity equations for the given set of pipe sizes.

Many researchers addressed this problem adopting different optimization techniques. Some of the researchers developed linear programming models [1-8]. In linear programming for the optimization of pipe sizes, the lengths of commercial pipes are unknowns. This approach allows split pipe solutions whereby the length of pipe between two nodes can consist of sub lengths of pipes of different diameters available in the market. Hydraulic analysis is linked to linear programming while selecting optimal lengths [9]. Some of the investigators adopted nonlinear programming techniques [10, 11]. The hydraulic analysis and optimization analysis are linked through an iterative process and solved by branch and bound integer linear programming technique [12]. The optimal design of a water distribution network is formulated as a two-stage decomposition model and can be solved by Branch and bound algorithm using non-smooth optimization and duality theory [13]. Optimization of cost of pipe networks is addressed by Genetic Algorithms [14, 15]. GA has drawback of, sometimes, converging to the values which may not be optimum, and NLP methods have drawback of converging to local optimum values, if initial choice is nearer to the local optimum [16]. GA-NLP hybrid approach overcomes the drawbacks of GA and NLP methods. GA-NLP hybrid approach is widely being used in many fields, optimizing nonlinear problems for global optimal solutions with quicker convergence [16-19].

In the present study, GA-NLP hybrid approach is adopted to minimize the total cost of the pipe network satisfying the nonlinear constraints of loop energy loss equations, permissible limits on residual pressure heads at nodes and linear continuity equation at each node. The decision variables are pipe flows between nodes and lengths of sub pipes from the given set of selected candidate diameters between nodes.

2. Methodology
The objective of the present study is to develop a method to obtain optimal lengths of sub pipes of available diameters in the market making link between nodes in such a way that overall cost of the pipe network is minimum. The optimal values are to be obtained satisfying flow continuity at nodes, length constraints between nodes, loop energy equations and residual pressure heads at nodes. As the loop equations and permissible residual head constraints at nodes are of nonlinear nature, NLP optimizing technique is to be adopted. In the present study, an attempt is made using GA-NLP hybrid approach in the design of water distribution networks for least cost.

2.1 GA-NLP hybrid approach
A genetic algorithm (GA) is a search and optimization method which works by mimicking the evolutionary principles and chromosomal processing in natural genetics. A GA begins its search with a random set of solutions usually coded in binary strings. Every solution is assigned a fitness which is directly related to the objective function of the optimization problem. Thereafter, the population of solutions is modified to a new population by applying three operators similar to natural genetic operators- reproduction, crossover, and mutation. Reproduction (or selection) is usually the first operator applied to a population. Reproduction selects good strings in a population and forms a mating pool. The crossover operator is applied next to the string of the mating pool. In crossover operator, two strings are picked from the mating pool at random and some portion of the strings is exchanged between the strings. The need for mutation is to maintain diversity in population by changing 0 to 1 or vice versa within the gene with a small probability. After reproduction, crossover, and mutation are applied to whole population, one generation of GA is completed. It works iteratively by successively applying these three operators in each generation till a termination criterion is satisfied. Over the past decade and more, GA has been successfully applied to a wide variety of problems, because of their simplicity, global perspective, and inherent parallel processing. The difficulty that lies with GA is selection of its parameters suitable to the given problem for faster convergence and to get near global optimal solution.

When non linearity is involved either in objective function or in constraints, NLP techniques have been successfully applied in nonlinear optimal models. An initial feasible solution is required to start
search for optimal solution in NLP methods. But obtaining initial feasible solution itself is difficult in complex systems where large number of decision variables and constraints are involved. This problem can be avoided if any feasible near optimal solution obtained by GA is adopted as initial feasible solution to NLP technique to obtain optimal solution in a faster manner. Therefore, in the present study GA-NLP hybrid approach is considered. Fig.1 shows the flow chart of GA-NLP hybrid approach.

2.2 Formulation of problem
The design problem is formulated as a nonlinear optimization problem minimizing the total cost of the pipe network subject to constraints. The decision variables are flows between successive nodes and length of sub pipes of competing candidate diameters between the nodes.

2.2.1 Objective function
Objective function is
Minimize $Z = \sum_{x} \sum_{m} C_{mx} X_{mx}$  \hspace{1cm} (1)
Where \( X_m \) is the length of \( m^{th} \) candidate diameter in section \( s \) between nodes \( i, j \) and \( C_m \) is the cost of \( m^{th} \) candidate diameter pipe per unit length.

### 2.2.2 Constraints

#### Length constraints: The sum of lengths of competing sub pipes considered must be equal to the total length of the section between nodes \( L_s \).

\[
\sum_{m} X_m = L_s \quad \forall s
\]  

#### Flow continuity equations at nodes: Algebraic sum of flows in sections joining at each node \( i \) must be equal to the demand \( U_i \) at that node.

\[
\sum_{s} Q_s = U_i \quad \forall i
\]

#### Loop equations of energy: If \( X_m \) is the length of the \( m^{th} \) sub pipe of diameter \( D \) with Hazen - Williams’s coefficient \( C_h \) in pipe section \( s \), then the algebraic sum of the head losses in all pipe sections engaged in each loop \( l \) must be zero.

\[
\sum_{s} \sum_{m} K_{sm} X_m Q_s^{1.852} = 0 \quad \forall l
\]

Where \( K_{sm} = \frac{10.67}{D^{4.87}C_h^{1.852}} \)

#### Constraints on minimum residual head: To maintain minimum residual pressure head above ground level at each node, upper allowable limit \( H_{\text{max}} \) on algebraic sum of head loss in all sections \( s \) connected from source to each node \( i \) is imposed.

\[
\sum_{s} \sum_{m} K_{sm} X_m Q_s^{1.852} \leq H_{\text{max}} \quad \forall i
\]

### 2.3 Example

The method described above is illustrated with an example of a two looped simple network as shown in the Fig. 2. This network has been studied by other researchers also [4, 12 & 13]. It consists of two basic loops. Total number of nodes are 7 and number of sections are 8. The length of each section is 1000m. Each section is proposed to have sub pipes of a set of candidate diameters. Details of proposed candidate diameters for each section are shown in Table 1. The ground levels and demands at each node are given in Table 2. The minimum residual pressure head at each node is 30 m. Details of commercially available pipe sizes and their cost per unit length are shown in Table 3. The Hazen William coefficient of all pipes is assumed to be 130.
Figure 2. Layout of the example problem

Table 1. Details of proposed candidate diameters for each section

| Pipe Section (s) | Link From Node (i) | To Node (j) | Pipe Numbers | Respective Candidate Diameters in inches (D) |
|------------------|--------------------|-------------|--------------|--------------------------------------------|
| 1                | 1                  | 2           | 1, 2         | 18, 20                                     |
| 2                | 2                  | 3           | 3, 4, 5, 6   | 6, 8, 10, 12                               |
| 3                | 2                  | 4           | 15, 16       | 16, 18                                     |
| 4                | 4                  | 5           | 10, 11, 12, 13, 14 | 1, 2, 3, 4, 6 |
| 5                | 4                  | 6           | 25, 26       | 14, 16                                     |
| 6                | 6                  | 7           | 22, 23, 24   | 8, 10, 12                                  |
| 7                | 3                  | 5           | 7, 8, 9      | 6, 8, 10                                   |
| 8                | 7                  | 5           | 17, 18, 19, 20, 21 | 1, 2, 3, 4, 6 |

Table 2. Details of elevation and demands at each node

| Node Number | Elevation (m) | Demand (m³/s) |
|-------------|--------------|---------------|
| 2           | 150          | 0.028         |
| 3           | 150          | 0.075         |
| 4           | 155          | 0.033         |
| 5           | 160          | 0.028         |
| 6           | 165          | 0.092         |
| 7           | 160          | 0.055         |
Table 3. Details of available pipe sizes and their costs

| Pipe Sizes | Cost (units/m) |
|------------|----------------|
| Inches     | meters         |
| 1          | 0.025          | 2              |
| 2          | 0.051          | 5              |
| 3          | 0.076          | 8              |
| 4          | 0.102          | 11             |
| 6          | 0.152          | 16             |
| 8          | 0.203          | 23             |
| 10         | 0.254          | 32             |
| 12         | 0.305          | 50             |
| 14         | 0.356          | 60             |
| 16         | 0.406          | 90             |
| 18         | 0.457          | 130            |
| 20         | 0.508          | 170            |

The method described above is followed to obtain optimal lengths of sub pipes of each section. The decision variables are length of 26 sub pipes X1 to X26 and flows in 7 sections Q2 to Q8. The total number of decision variables is 33. The elevation of service reservoir is considered constant and is equal to 210 m.

2.3.1 Objective function:
Minimize total cost of pipes of looped pipe network
Minimize
\[ Z = 130X_1 + 170X_2 + 16X_3 + 23X_4 + 32X_5 + 50X_6 + 16X_7 + 23X_8 + 32X_9 + 5X_{10} \]
\[ + 8X_{11} + 11X_{12} + 16X_{13} + 2X_{14} + 90X_{15} + 130X_{16} + 2X_{17} + 5X_{18} + 8X_{19} + 11X_{20} + 16X_{21} + 23X_{22} + 32X_{23} + 50X_{24} + 60X_{25} + 90X_{26} \] (6)

2.3.2 Constraints
Length constraints: The sum of lengths of competing sub pipes in a section must be equal to the total length of the section between nodes.
X1 + X2 = 1000 \hspace{2cm} (7)
X3 + X4 + X5 + X6 = 1000 \hspace{2cm} (8)
X7 + X8 + X9 = 1000 \hspace{2cm} (9)
X10 + X11 + X12 + X13 + X14 = 1000 \hspace{2cm} (10)
X15 + X16 = 1000 \hspace{2cm} (11)
X17 + X18 + X19 + X20 + X21 = 1000 \hspace{2cm} (12)
X22 + X23 + X24 = 1000 \hspace{2cm} (13)
X25 + X26 = 1000 \hspace{2cm} (14)

Node flow continuity equations:
Q2 – Q3 = 0.028 \hspace{2cm} (15)
Q4 + Q7 + Q8 = 0.075 \hspace{2cm} (16)
Q3 - Q4 - Q5 = 0.033 \hspace{2cm} (17)
Q5 - Q6 = 0.092 \hspace{2cm} (18)
Q6 – Q8 = 0.055 \hspace{2cm} (19)
Loop equations of energy: Considering clock-wise flow as positive, the nonlinear loop energy equations are as follows.

For loop 1:
\[-12.519X3Q2^1.852 - 3.059X4Q2^1.852 - 1.027X5Q2^1.852 - 0.421X6Q2^1.852 - 12.519X7Q7^1.852 - 3.059X8Q7^1.852 - 1.027X9Q7^1.852 + 82257.109X10Q4^1.852 + 2554.316X11Q4^1.852 + 366.083X12Q4^1.852 + 87.349X13Q4^1.852 + 12.519X14Q4^1.852 + 0.105X15Q3^1.852 + 0.059X16Q3^1.852 = 0.0 (20)\]

For loop 2:
\[-82257.109X10Q4^1.852 - 2554.316X11Q4^1.852 - 366.083X12Q4^1.852 - 87.349X13Q4^1.852 - 12.519X14Q4^1.852 + 82257.109X17Q8^1.852 + 2554.316X18Q8^1.852 + 366.083X19Q8^1.852 + 12.519X21Q8^1.852 + 0.105X23Q6^1.852 + 0.421X24Q6^1.852 + 0.198X25Q5^1.852 + 0.105X26Q5^1.852 = 0.0 (21)\]

Constraints on head loss: Constraints on maximum head loss to maintain minimum residual pressure head of 30 m above ground level at each node are imposed for all nodes. Restriction on maximum total head loss in pipes from source to each node is as follows.

Node 1:
\[0.007X1 + 0.004X2 <= 30.0 (22)\]

Node 2:
\[0.007X1 + 0.004X2 + 0.105X15Q3^1.852 + 0.059X16Q3^1.852 <= 20.0 (23)\]

Node 3:
\[0.007X1 + 0.004X2 + 0.105X15Q3^1.852 + 0.059X16Q3^1.852 + 0.198X25Q5^1.852 + 0.105X26Q5^1.852 <= 15.0 (26)\]

Node 4:
\[0.007X1 + 0.004X2 + 0.105X15Q3^1.852 + 0.059X16Q3^1.852 <= 25.0 (25)\]

Node 5:
\[0.007X1 + 0.004X2 + 0.105X15Q3^1.852 + 0.059X16Q3^1.852 + 0.198X25Q5^1.852 + 0.105X26Q5^1.852 <= 20.0 (27)\]

Results and discussion

The problem formulated is optimized by GA-NLP technique using MATLAB software. Values of GA parameters adopted for solving the problem are as follows. Population size = 150; Maximum No. of generations = 100; Error tolerance = 0.001; Crossover probability = 0.8; Roulette Wheel method for selection process and single point method for crossover are considered in GA process. Optimal value of the objective function is found to be 401,610 units. Optimal solution obtained by the proposed model is shown in Table 4 and Table 5. The rate of flows in sections 2 to 8 are shown in Table 4. Least cost of pipe network and optimal lengths of sub pipes of different diameters obtained by proposed model are compared with the results obtained by other researchers and are shown in Table 5. From the table, it is clear that the cost of pipe network obtained by the proposed GA-NLP model is least.
Table 4. Flow distribution in the network

| Flows in Pipe Sections | Q2  | Q3  | Q4  | Q5  | Q6  | Q7  | Q8  |
|------------------------|-----|-----|-----|-----|-----|-----|-----|
| m$^3$/s                | 0.00954 | 0.1876 | 0.0074 | 0.1472 | 0.0552 | 0.0674 | 0.000184 |

Table 5. Comparison of results of proposed model with other models

| Link | Samani and Mottaghi[12] | Goulter et. al.[7] | Kessler and Shamir [8] | Eiger et. al.[13] | Proposed GA-NLP model |
|------|------------------------|--------------------|------------------------|-------------------|-----------------------|
|      | L (m) | D (in) | L (m) | D (in) | L (m) | D (in) | L (m) | D (in) | L (m) | D (in) |
| 1    | 1000.0 | 18   | 383.0 | 20   | 1000.0 | 18   | 1000.0 | 18   | 1000.0 | 18   |
| 2    | 1000.0 | 10   | 1000.0 | 10   | 660.0 | 12   | 238.02 | 12   | 1000.0 | 10   |
| 3    | 1000.0 | 16   | 1000.0 | 16   | 1000.0 | 16   | 1000.0 | 16   | 1000.0 | 16   |
| 4    | 1000.0 | 4    | 687.0 | 6    | 713.00 | 3    | 1000.0 | 1    | 998.16 | 6    |
| 5    | 1000.0 | 16   | 1000.0 | 16   | 836.00 | 16   | 628.86 | 16   | 792.68 | 16   |
| 6    | 1000.0 | 10   | 98.0  | 12   | 109.00 | 12   | 989.05 | 10   | 979.15 | 10   |
| 7    | 1000.0 | 10   | 492.0 | 10   | 819.00 | 10   | 921.86 | 10   | 779.10 | 10   |
| 8    | 1000.0 | 1    | 990.93 | 2    | 920.00 | 3    | 1000.0 | 1    | 1000.0 | 1    |
|      | Cost | 419,000 | 417,500 | 417,500 | 402,350 | 401,610 |

3. Application of model to a case study

The model developed is demonstrated through a case study of Rajiv Gandhi Nagar which comes under Guntur municipal corporation, Andhra Pradesh, India. The proposed water supply looped pipe network for the Rajiv Gandhi Nagar is shown in Fig.3. The network consists of 24 nodes and 14 basic loops and 37 pipe sections. Water is supplied from an elevated tank by gravity from node number '0' to the network through the main supply section of number '0'.

Details of outer diameter, wall thickness, inner diameter and cost of pipe per running meter of various sizes available in the market are shown in Table 6. Hazen William’s coefficients for the HDPE pipes are taken as 150 for all pipes.
Table 6. Details of proposed HDPE pipes (6 kg/cm²)

| S.No. | Outer Diameter (mm) | Wall Thickness (mm) | Inner Diameter (mm) | Cost (Rs./m) |
|-------|---------------------|---------------------|---------------------|--------------|
| 1     | 75                  | 5.3                 | 64.4                | 207.61       |
| 2     | 90                  | 6.3                 | 77.4                | 310.25       |
| 3     | 110                 | 7.7                 | 94.6                | 458.92       |
| 4     | 125                 | 8.8                 | 107.4               | 596.93       |
| 5     | 140                 | 9.8                 | 120.4               | 744.08       |
| 6     | 160                 | 11.2                | 137.6               | 972.83       |
| 7     | 180                 | 12.6                | 154.8               | 1228.15      |
| 8     | 200                 | 14.0                | 172                 | 1513.09      |
| 9     | 225                 | 15.7                | 193.6               | 1909.65      |
| 10    | 250                 | 17.5                | 215                 | 2364.17      |
| 11    | 280                 | 19.6                | 240.8               | 2962.98      |
| 12    | 315                 | 22.0                | 271.0               | 3736.99      |
It is proposed to design system keeping residual head at each node in the range of 7 m to 17 m. Ground levels, projected population, demand and allowable maximum & minimum head above ground level of source at each node are shown in Table 7.

**Table 7. Details of demand, ground levels and allowable residual heads**

| Node No. | Consumption (Demand) (m³/s) | Ground level (m) | Residual head | Maximum (m) | Minimum (m) |
|----------|-----------------------------|------------------|---------------|-------------|-------------|
| 1        | 0                           | 99.62            | 16.00         | 6.00        |
| 2        | 0.00103                     | 99.27            | 15.65         | 5.65        |
| 3        | 0.001218                    | 99.11            | 15.48         | 5.48        |
| 4        | 0.002943                    | 98.66            | 15.04         | 5.04        |
| 5        | 0.002925                    | 97.77            | 16.15         | 6.15        |
| 6        | 0.003113                    | 97.66            | 16.13         | 6.13        |
| 7        | 0.004144                    | 97.75            | 16.12         | 6.12        |
| 8        | 0.002531                    | 97.77            | 16.15         | 6.15        |
| 9        | 0.002813                    | 97.88            | 16.26         | 6.26        |
| 10       | 0.001331                    | 100.01           | 16.39         | 6.39        |
| 11       | 0.000769                    | 100.11           | 16.48         | 6.48        |
| 12       | 0.001688                    | 100.12           | 16.50         | 6.50        |
| 13       | 0.002625                    | 99.91            | 16.29         | 6.29        |
| 14       | 0.004406                    | 99.83            | 16.21         | 6.21        |
| 15       | 0.002794                    | 99.76            | 16.13         | 6.13        |
| 16       | 0.003975                    | 99.30            | 15.68         | 5.68        |
| 17       | 0.005475                    | 99.69            | 16.07         | 6.07        |
| 18       | 0.002429                    | 99.26            | 15.63         | 5.63        |
| 19       | 0.004050                    | 99.82            | 16.19         | 6.19        |
| 20       | 0.001650                    | 99.87            | 16.25         | 6.25        |
| 21       | 0.000994                    | 99.87            | 16.25         | 6.25        |
| 22       | 0.002382                    | 99.80            | 16.18         | 6.18        |
| 23       | 0.001200                    | 99.75            | 16.12         | 6.12        |
| 24       | 0.002288                    | 99.41            | 15.79         | 5.79        |

**4. Results**

The optimization problem is formulated for the study area and is solved by GA-NLP model in MATLAB. The optimal lengths of the sub pipes obtained are presented in Table 8 and the corresponding least cost of the pipe network is Rs. 45,42,000.
Table 8. Details of candidate diameters for each section

| Section number | Link From Node | Link To Node | Total length of section (m) | Optimal length in meters (diameter in mm) |
|----------------|----------------|--------------|-----------------------------|------------------------------------------|
| 0              | 0              | 1            | 1300                        | 626(225),245(280),429(315)              |
| 1              | 1              | 12           | 43                          | 43(160)                                  |
| 2              | 12             | 11           | 31.5                        | 31.5(160)                                |
| 3              | 11             | 2            | 40.2                        | 35(75),5.2(90)                           |
| 4              | 2              | 1            | 31.5                        | 6.5(140),25(160)                         |
| 5              | 11             | 10           | 24                          | 23(160),1(140)                           |
| 6              | 10             | 3            | 36                          | 36(75)                                   |
| 7              | 3              | 2            | 24.3                        | 1.2(110),12(125),1(140),10.2(160)        |
| 8              | 10             | 9            | 28.5                        | 28.5(160)                                |
| 9              | 9              | 4            | 36                          | 33.16(75),2.84(160)                      |
| 10             | 4              | 3            | 28.5                        | 9.15(140),19.35(160)                     |
| 11             | 9              | 8            | 90.7                        | 11.57(125),33.3(140),46.83(160)          |
| 12             | 8              | 5            | 28.5                        | 28.5(75)                                 |
| 13             | 5              | 4            | 91.0                        | 2.2(75),13.67(110),21.33(125),25.51(140),28.29(160) |
| 14             | 8              | 7            | 86.5                        | 6.95(110),20.14(125),27.34(140),32.07(160) |
| 15             | 7              | 6            | 24.3                        | 4.45(75),3.33(110),4.93(125),5.88(140),5.71(160) |
| 16             | 6              | 5            | 86                          | 25.05(75),9.54(110),14.82(125),17.71(140),18.89(160) |
| 17             | 8              | 15           | 30.3                        | 30.3(75)                                 |
| 18             | 15             | 16           | 91.0                        | 62.98(75),4.34(110),6.73(125),8.06(140),8.89(160) |
| 19             | 16             | 7            | 30.3                        | 2.1(110),10.73(140),17.47(160)           |
| 20             | 9              | 14           | 32.5                        | 21.8(75),2.15(90),3.38(140),5.16(160)    |
| 21             | 14             | 15           | 90.0                        | 50.19(75),6.33(110),9.69(125),11.53(140),12.26(160) |
| 22             | 12             | 13           | 33.0                        | 2.13(140),30.87(160)                     |
| 23             | 13             | 14           | 82.5                        | 53.82(75),4.46(110),6.87(125),8.23(140),9.12(160) |
| 24             | 13             | 20           | 29.5                        | 11.47(140),18.03(160)                    |
| 25             | 20             | 19           | 82.0                        | 5.06(75),8.58(110),17.92(125),23.41(140),27.03(160) |
| 26             | 19             | 14           | 30.4                        | 27.67(75),2.73(160)                      |
| 27             | 19             | 18           | 91.0                        | 7.1(75),2.03(90),8.7(110),10.53(125),26.17(140),36.48(160) |
| 28             | 18             | 15           | 30.0                        | 30(75)                                   |
| 29             | 18             | 17           | 91.0                        | 67.36(75),4.32(110),5.5(125),6.61(140),7.2(160) |
| 30             | 17             | 16           | 30.0                        | 2.21(110),6.76(140),21.03(160)           |
| 31             | 18             | 23           | 30.2                        | 20.34(75),3.96(125),2.8(140),3.1(160)    |
| 32             | 23             | 24           | 89.0                        | 86.05(75),2.95(160)                      |
| 33             | 24             | 17           | 30.2                        | 2.34(75),8.58(140),19.28(160)            |
| 34             | 19             | 22           | 30.0                        | 30(75)                                   |
| 35             | 22             | 23           | 90.8                        | 80.92(75),7.81(90),2.08(160)             |
| 36             | 20             | 21           | 30.0                        | 30(75)                                   |
| 37             | 21             | 22           | 83.5                        | 81.05(75),2.45(160)                      |

5. Conclusions
A GA-NLP hybrid model is applied to design a looped water supply pipe network for least cost. The results obtained by proposed model for a standard example network is compared with that of obtained by other researchers and proposed GA-NLP model is found to be superior. It is also demonstrated that the model developed can be applied to larger networks through a case study.
6. References

[1] Dantzig G B 1963 Linear programming and extensions (Princeton: Princeton University Press)
[2] Gupta I 1969 Trans. Am. Inst. Ind. Eng. 1(1) 56-61
[3] Gupta I and Hassan M Z 1972 Trans. Am. Inst. Ind. Eng. 4(3) 200-204
[4] Alperovits E and Shamir U 1977 Water Resour. Res. 13(6) 885-900
[5] Quindry G Brill E and Leibman J 1981 J. Environ. Eng. 107(4) 665-679
[6] Bhave P and Sonak V 1992 Water Resour. Res. 28(6) 1577-1584
[7] Goultier I C, Lassier B M and Morgan D R 1986 Water Resour. Res. 22(5) 819-822
[8] Kessler A and Shamir U 1989 Water Resour. Res. 25(7) 1469-1480
[9] Morgan D and Goultier I 1985 Water Resour. Res. 21(5) 642-652
[10] Ormsbee L E 1989 J. Water Resour. Plan. Manage. 115(2) 243-257
[11] Samani H M V and Naeeni 1996 J. Hydraul. Res. 34(5) 623-632
[12] Samani H M V and Mottaghi A 2006 J. Hydraul. Eng. 132(5) 501-509
[13] Eiger G, Shamir U and Ben-Tal A 1994 Water Resour. Res. 30(9) 2637-2646
[14] Savic D A and Walters G A 1997 J. Water Resour. Plan. Manage., 123(2) 67-77
[15] Simpson A R, Dandy G C and Murphy L J 1994 J. Water Resour. Plan. Manage. 120(4) 423-443
[16] Bedekar P P and Bhide S R 2011 IEEE Transactions on Power Delivery 26(1) 109-119
[17] Moreno-Beneto M and Espuna A 2012 Computer Aided Chemical Engineering 30 1332-1336
[18] Leela Krishna K, Umamahesh N V and Srinivasa Prasad A 2018 ISH Journal of Hydraulic Engineering 24(2) 258-265
[19] Shakya S and Patel G R 2014 International Journal of Engineering Development and Research 2(2) 1635-1641