

CHAPTER 4: OPTIMISATION OF PIPE NETWORK FOR NEWTONIAN FLUID (WATER) USING GENETIC ALGORITHM

4.1 Introduction

Rehabilitating and maintaining water (Newtonian Fluid) infrastructure is a costly and important effort for cities around the world by UN Habitat (2012). Most of the requirement in a pipe network is in substituting and rehabilitating deteriorated water mains in water distribution systems. The design of a pipe network carrying water is to determine the minimum cost while satisfying the demands and required pressure heads at different nodes. The cost of the system consist of the initial investment for the accessories, such as pipes, valves, tanks, pumps and the operating cost for driving the water throughout the network by Mays and Tung, (1992). The main constraints are that the anticipated discharge are supplied with adequate pressure heads at nodes. Also, the flow of water in a pipe network and the pressure heads at nodes must fulfil the laws of conservation of mass and energy. The pipe network design problem can be specified as Mays (2000).

Minimize: - Initial capital cost + operations cost

Subject to

1. Conservation laws of mass and energy
2. Water demand constraints
3. Meet nodal head requirements

The author cover excellent description of the hydraulics of water distribution system. It can be designed using conventional trial and error methods or more intelligent optimization methods. So as to attain this goal, design engineers rely on cost optimisation techniques. The optimal cost design is the lowermost cost design out of several options. The veteran engineers have conventionally used trial-and-error methods to find a low cost design. However, this methods has not assured 'optimal' or 'near-optimal' designs, which is why researchers have been concerned in stochastic analysis of uncertainty (probabilistic modelling) methods Walski (1985), and Goulter (1992).

4.2 Design Components

The task of decision making requires choosing between numerous alternatives. Optimisation is crucial to any problem involving decision making, whether in engineering or in economics. The selection is governed by the desire to make the best decision. The measure of goodness of the alternatives is described by an objective function. Optimisation theory and methods address the selection of the best alternative through the given objective function. The optimisation problems (for water distribution systems) occur when it is desired to solve the design problem at minimum total cost, subject to a set of constraints such as maximum and (or) minimum operating pressures, minimum pipe diameters, and use of a discrete set of commercially available pipe sizes. The design or optimisation problem can be stated as minimisation of total cost which is sum of initial capital cost and operations cost.

The optimisation is subjected by constraints:

- a. Conservation laws of mass and energy
- b. Water demand constraints
- c. Fulfil nodal head requirements

In fact, additional complexities have also to be included for a multiple loadings. The design of a water distribution network (WDN) is based on the various demands such as industrial, residential, commercial etc. in the given area. Therefore, for proper design of a WDN, it is necessary to consider several loadings, including fire requirements, to provide reasonable flexibility to the network by Bhave (2003). The low demand loadings also have to be well-thought-out to make sure the tanks are filled during low demand periods by Alperovits and Shamir (1977).

The optimisation of the network design problem is the identification of the commercial pipe size diameters combination that give the minimum cost under certain conditions such as the specified demands and prescribed range of pressures at given nodes. The minimisation of cost for a network is expressed by the objective function which is assumed to be a function of pipe diameters and lengths, by Savic and Walters (1997):

4.2.1 Objective function: Objective function of water distribution pipe network can be defined as the minimisation of the total cost of the pipe network:

$$f(D, L) = \sum_{i=1}^N c(D_i, L_i) \quad (4.1)$$

Where $c(D_i, L_i)$ is the cost of the pipe i with the diameter D_i and the length L_i and N is the total number of pipes in the network.

Subjected to:

The minimisation of cost for a network is categorized by the following conservation laws and constraints:

1. Law of conservation of mass at each node:

$$\sum Q_{in} - \sum Q_{out} = Q_e \quad (4.2)$$

Where Q_{in} = flow into the junction; Q_{out} = flow out of the junction; and Q_e = external inflow or demand at the junction node.

2. Energy conservation in each loop can be written as

$$\sum h_f = 0 \quad (4.3)$$

The Hazen-Williams head loss (h_f) equation for pipe i connecting node j and k

$$H_j - H_k = \frac{-10.675 L_i Q_i |Q_i|^{0.852}}{C_i^{1.852} D_i^{4.8704}} \text{ For all pipes } i=1,2,\dots,N. \quad (4.4)$$

Where L_i = length of pipe, Q_i = discharge inflow in pipe, N = total number of pipes in the network and C_i = Hazen Williams coefficient for pipe i of diameter D_i .

3. Minimum pressure head requirements at each node in the network is given in the form:

$$H_m \geq H_{m,\min} \quad \text{For } m=1,2,3,\dots,M \quad (4.5)$$

Where H_m the head at node m is, $H_{m,\min}$ is the minimum required head at the same node m and M is the total number of nodes in the network.

4. Minimum size of pipe (diameter) requirement is defined by:

$$D_i \geq D_{\min} \quad \text{For } i=1,\dots,N \quad (4.6)$$

Where, N = total number of pipes in the network, D_i = diameter of pipe i of network, D_{\min} is the minimum diameter of pipe (size) required in the pipe i of network (condition if any).

The objective function may be linear or nonlinear, depending upon the type of problem formulation. The conservation laws of mass and energy are nonlinear equations. These constraints can be written for multiple loading conditions. The constraints D design variables can be discrete or continuous. The discrete nature of the design variables, such as commercially available pipe sizes.

4.3 Case Study

Researchers have applied GA to a diverse range of scientific, engineering, economic, and also artistic search problems. The design purpose of a water distribution system is to deliver water, satisfy various water pressure and demand at all nodes. To evaluate the interrelationships among several components, a water distribution system is transformed into a network representation called water distribution network (WDN) by Yang et al. (1996). Using Genetic Algorithm as optimisation tool a computational code has been developed here by means of MATLAB\2012a software for optimisation of pipe network.

To validate the mathematical model developed, it has been tested with Gessler (1985) pipe network as shown in figure-4.1. The optimized data is compared with Simpson (1994) optimisation design the known solution given in literature who used the same pipe network. All other data such as objective function, cost function of pipe, pipe sizes, and cost of the pipe are taken from Simpson (1994).

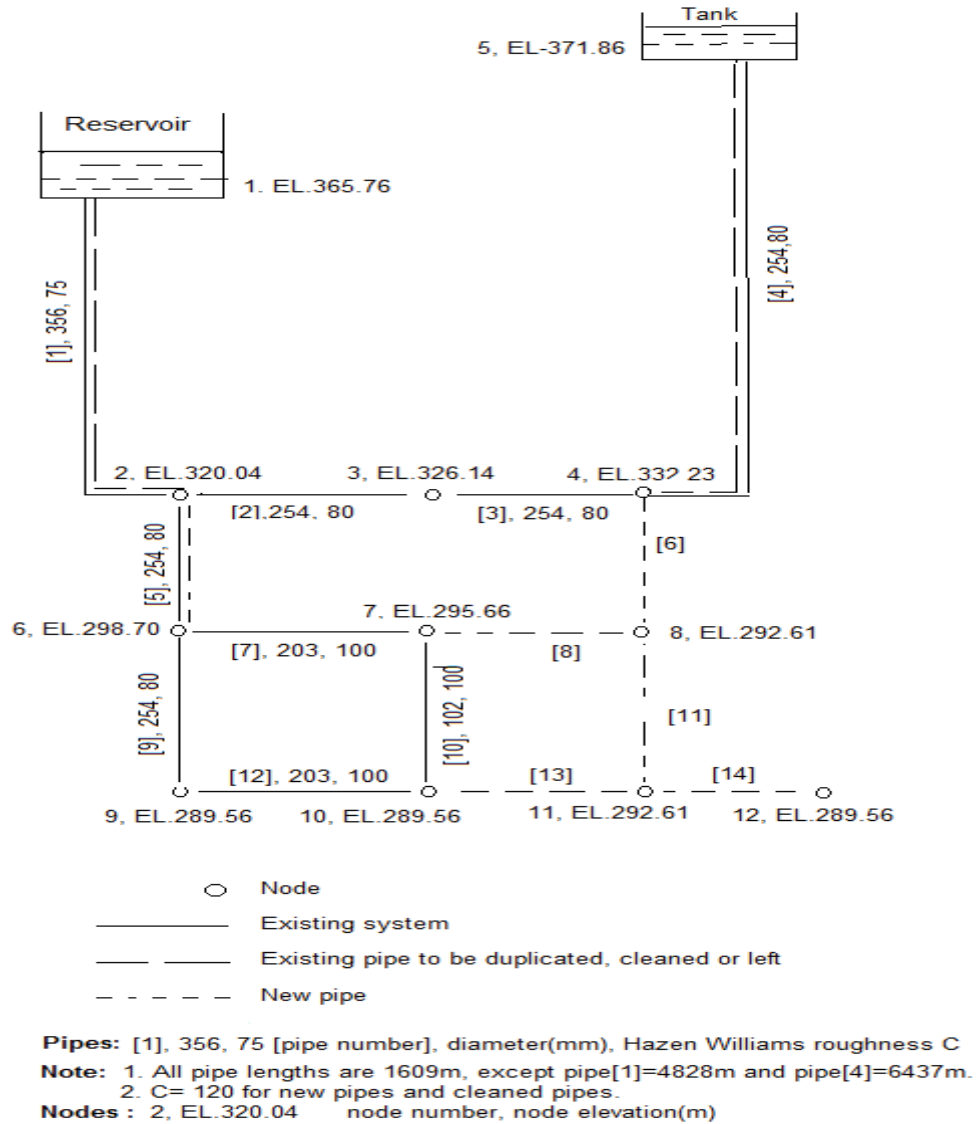


Figure-4.1 Layout of Gessler (1985) pipe network

Network shows solid lines, representing the existing system, dashed lines depicting the new pipes and Elevations, pipe lengths, diameters and Hazen-Williams coefficients (C) are also shown in the network. The pipe network has following features.

- a. All pipes are 1609 m long, except pipe [1] =4828m and pipe [4] =6437m.
- b. The Network must fulfil these conditions.
 - 1. Selection of five new pipes [6], [8], [11], [13] and [14] from commercially available pipe. Given in table-4.1
 - 2. Three pipes [1], [4] and [5] may be cleaned duplicated or left as it is.
 - 3. Three demand patterns and associated minimum pressure for network is given in table-4.2.
- c. It is given, Hazen-Williams coefficients (C) =120 for new pipes and cleaned pipes.
- d. Available pipe sizes and associated cost is mentioned below.
- e. The value of penalty function multiplier, $K = \$70,000/m$ has been taken from literature of Simpson (1994).
- f. Fitted Cost Functions for Nonlinear Optimisation Model of pipes is shown in table-4.3.

Table 4.1 Available Pipe Sizes and Costs for Case Study of Simpson (1994)

Sl no.	Diameter (mm)	Cost of new pipe (dollars/m)	Cost of cleaning existing pipe (dollars/m)
1	152 ^a	49.54	47.57
2	203	63.32	51.51
3	254	94.82	55.12
4	305	132.87	58.07
5	356	170.93	60.70
6	407	194.88	63.00
7	458	232.94 ^b	----
8	509	264.10 ^b	----

^aTaken as the lowest size (lower bound) for new pipes.
^bApproximated using linear extrapolation.

Table 4.2 Demand Pattern and Associated Minimum Pressure for Network by Simpson (1994)

Node (1)	Demand Pattern-1		Demand Pattern-2		Demand Pattern-3	
	Demand (L/S) (2)	Minimum Pressure Head (m) (3)	Demand (L/S) (4)	Minimum Pressure Head (m) (5)	Demand (L/S) (6)	Minimum Pressure Head (m) (7)
2	12.62	28.18	12.62	14.09	12.62	14.09
3	12.62	17.61	12.62	14.09	12.62	14.09
4	0	17.61	0	14.09	0	14.09
6	18.93	35.22	18.93	14.09	18.93	14.09
7	18.93	35.22	82.03	10.57	18.93	14.09
8	18.93	35.22	18.93	14.09	18.93	14.09
9	12.62	35.22	12.62	14.09	12.62	14.09
10	18.93	35.22	18.93	14.09	18.93	14.09
11	18.93	35.22	18.93	14.09	18.93	14.09
12	12.62	35.22	12.62	14.09	50.48	10.57

Table 4.3 Fitted Cost Functions for Nonlinear Optimisation Model Pipes of Simpson (1994)

Sl. No.	Pipes	Cost function (dollars/m length)
1	New	$C_1 = 611.0D - 52.9$
2	Pipe [1]	$C_2 = 420.1 \log(D_e) + 447.9$ (for $D_e \geq 0.356$ m)
3	Pipes [4] and [5]	$C_3 = 278.3 \log(D_e) + 385.0$ (for $D_e \geq 0.254$ m)
	Note: D = diameter of new pipe (meters); and D_e = equivalent diameter of pipe (meters).	

4.4 Application of Genetic Algorithm for Gessler (1985) Pipe Network

4.4.1 Objective Function

The objective of the pipe network is to minimize the total network cost. Neglecting the other factors, it is assumed that actual cost of the network is solely depending upon pipe geometry (commercially available pipe). To tackle the minimum head constraint and minimum discharge constraint, penalty cost is added to the actual cost of the network.

4.4.1.1. Minimum Network Cost (z)

$$z = C_1L_1 + \sum_{i=new} C_iL_i + \sum_{K \in [4] [5]} C_KL_K \quad (4.8)$$

Here, C1, C2 and C3 are shown in table-4.3, L represent length of the pipe. i represent five new pipes [6], [8], [11], [13] and [14]. Similarly k represent pipe [4] and [5].

4.4.2.2. Penalty Cost

The penalty cost is superimposed on top of the actual cost of the network in such a way that it will discourage the search in the infeasible direction.

$$\text{Objective function} = \text{minimum (Total cost)} \quad (4.9)$$

$$\text{Total Network cost (TC)} = \sum_{i=1}^n C_iL_i + \text{Penalty} \quad (4.10)$$

Subjected to:

$$\sum Q_{in} - \sum Q_{out} = Q_e \quad \text{For all Nodes} \quad (4.11)$$

$$Q_{\min} \leq Q_k \leq Q_{\max}, \quad \text{For all Nodes} \quad (4.12)$$

$$H \geq H_{\min} \quad \text{For all Nodes} \quad (4.13)$$

Where Q_{in} = flow into the junction; Q_{out} = flow out of the junction; and Q_e = external inflow or demand at the junction node, n is the number of pipe in network, k represent node number. Q and H represent the discharge and Pressure head required at nodes respectively. Q_{\min} is the minimum and Q_{\max} is the maximum discharge at any node. Similarly, H_{\min} is minimum pressure head required at any node, L represent length of the pipe and C_i represent cost function of pipe i as shown in table-4.3.

4.4.2.3. Constraints

In practice it is difficult to find a penalty function which is an effective and efficient substitute for the constraints, (section-3.2.9).The GA allocates a penalty cost for each demand pattern if a network does not fulfil the minimum pressure constraints. The maximum pressure deficit is multiplied by a penalty factor (e.g., $K = \$70,000/\text{m}$ of head). Here, the value of penalty factor is taken from the literature of Simpson (1994).

4.4.2 Design Variables

Various design alternatives which relate to minimum cost of pipe network need to be considered to ensure that a good global optimal design is achieved. The decision variable (parameters) for each pipe (pipe number [1], [4], [5] [6], [8], [11], [13] and [14]) was its diameter as given in table-4.4.

Table 4.4 Design Option for Case Study

Sl No.	Variables (Pipe Diameter)	Description of Variables Option (in mille-meter)	Total Number of Option
1	Pipe [1] as x_1	Clean, Leave, Duplicated with pipe diameter (152, 203, 254, 305, 356, 407)	Eight (8)
2	Pipe [4] as x_2	Clean, Leave, Duplicated with pipe diameter (152, 203, 254, 305, 356, 407)	Eight (8)
3	Pipe [5] as x_3	Clean, Leave, Duplicated with pipe diameter (152, 203, 254, 305, 356, 407)	Eight (8)
4	Pipe [6] as x_4	152, 203, 254, 305, 356, 407, 458, 509	Eight (8)
5	Pipe [8] as x_5	152, 203, 254, 305, 356, 407, 458, 509	Eight (8)
6	Pipe [11] as x_6	152, 203, 254, 305, 356, 407, 458, 509	Eight (8)
7	Pipe [13] as x_7	152, 203, 254, 305, 356, 407, 458, 509	Eight (8)
8	Pipe [14] as x_8	152, 203, 254, 305, 356, 407, 458, 509	Eight (8)

4.4.2.1 Binary Coding for Commercially Available Pipes

In the GA formulation for test problem, eight variables ($x_1, x_2, x_3, x_4, x_5, x_6, x_7$ and x_8) were each represented by a three-bit binary substring were selected. Since, eight number of commercial pipes are available, hence three bit substring length were selected representing eight possible alternatives as shown in table-4.5. The binary

coding for different pipes are taken arbitrary. e.g. - the binary coding for pipe 152 mm diameter is taken (000) randomly and so on.

Table 4.5 Options for Each Decision Variables

Sl no.	If new pipes (mm)	If existing pipes	Binary coding
1	152	Leave as exist	000
2	203	Duplicate with 152 mm	001
3	254	Clean existing pipe	010
4	305	Duplicate with 203mm	011
5	356	Duplicate with 254mm	100
6	407	Duplicate with 305mm	101
7	458	Duplicate with 356mm	110
8	509	Duplicate with 407mm	111

A binary substring of three bits can be used to represent the options for each of the eight decision variables (table-4.5). Here, optimisation has done with eight variables (genes). A 24-bit binary string represents (as chromosomes) the network to be optimized which is made up of the eight by three-bit substrings for each decision variable. (Figure -4.2).

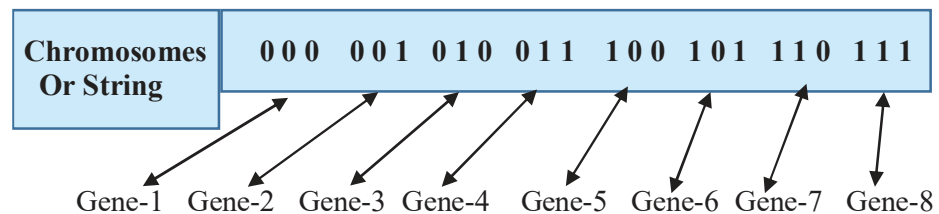


Figure-4.2 Formation of Chromosomes with Different Variables

4.4.3 Generation of Initial Population

The Genetic Algorithm (GA) generates the initial population of solutions (say, size $n = 100$, see table-4.6) using a random number generator. Each bit location in the 24-bit string for this (case study) problem takes on a value of either 1 or 0. Each successive three bits represent a specific variables for the eight pipes under consideration (i.e., for pipes [1], [4], [5], [6], [8], [11], [13], and [14]). For example, if the 24 bits were **1 0 1 0 1 1 0 1 0 1 1 0 0 1 0 0 1 0 0 1 0 1 1 0**, then following Table-4.5 notation, the existing pipe [1] has to be duplicated with 305 mm pipe, pipe [4] has a parallel pipe of diameter with 203 mm, Pipe [5] was cleaned, Pipe [6], pipe [8], Pipe [11], Pipe [13] and Pipe [14] are used 458 mm, 254mm, 254mm, 254mm and 458 mm pipe diameter respectively. The population size, which is typically a user-specified parameter, is one of the significant factors affecting the performance of genetic algorithms. For example, small population sizes might lead to premature convergence and yield substandard solutions. On the other hand, large population sizes causes to unnecessary spending of valuable computational time. The size of population size depend upon the complexity of problem.

Table-4.6 Initial Solution (Population) Randomly Generated by GA

Chromosome-1	001 110 101 011 000 110 101 111
Chromosome -2	111 100 101 001 101 100 001 100
Chromosome -3	101 110 001 111 010 110 101 011
...	...
...	...
Population-100	110 010 101 011 011 000 111 000

4.4.4 Hydraulic Analysis of Network

Computation of the heads and discharges under the three specified demand patterns has been shown in table-4.2, for each of the networks in the population. For the initial generation (n=100) networks are examined. The actual heads are compared with the minimum allowable pressure heads and any pressure deficits are noted. The total number of constraints for three demand patterns (table- 4.2) are 110 as explained below.

- a.** Continuity of flow equation i.e. The sum of inflow and outflow at all ten nodes (Node number as 2,3,4,6,7,8,9,10,11 and 12) in the network should be equal. (10 linear equations i.e. 10 constraints per demand pattern)

$$\sum Q_m = q_m \quad \text{Where all nodes } m= 1, 2, 3, \dots, 10$$

Where Q_m is the discharge in pipe meeting at node m and q_m is nodal withdrawal at node m.

- b.** The Hazen-Williams head loss equation for each pipe i connecting nodes j and k (14 nonlinear equation i.e. 14 constraints per demand pattern)

$$H_j - H_k = \frac{-10.675 L_i Q_i |Q_i|^{0.852}}{C_i^{1.852} D_i^{4.8704}} \quad \text{For all pipes } i=1, 2, \dots, 14$$

Where L_i =Length of pipe, Q_i = Discharge inflow in pipe and C_i = Hazen Williams coefficient for pipe i of diameter D_i .

- c.** Minimum Pressure head constraints (H_{\min}) at each nodes as shown in table-4.2 (10 linear inequalities for each loading case i.e. 10 constraints per demand pattern)

$$H_m \geq H_{\min} \quad \text{For all node } m = 1, 2, \dots, 10$$

Where, H_m is the pressure head at any node (m).

- d. In addition there are eight lower bounds (minimum size 152 mm diameter pipe, table-4.1) for the pipe diameters. Five new pipes (6, 8, 11, 13 and 14) are selected from the commercially available pipe as given in table-4.1, (second column) and three pipes (pipe number viz. 1, 4 and 5) that could be left as it is, duplicated or cleaned. (8 constraints)

$$D_{\text{new}} \geq \bar{D}_{\text{new},\text{min}} \quad (\text{for all new pipes}), \quad \text{new} = 1, 2, 3, \dots, \text{new (total)}$$

Where, ($\bar{D}_{\text{new},\text{min}}$) is the minimum equivalent diameter for each pipe that could be duplicated (pipes [1], [4], and [5]) is its existing diameter (figure-4.1).

For single demand pattern there were 34 constraints (10+14+10=34, from section-i, section-ii and section-iii). However for three demand patterns, there were a total of 110 constraints (i.e., 3x34 + 8 (section-iv) =110) for the given problem.

4.4.5 Computation of Network Cost

Once the population is initialized or an offspring population is created, the fitness values of the candidate solutions are evaluated. It decodes each substring into the corresponding pipe size and calculates the total material and construction cost. One can also include operation and maintenance costs if required. Likewise, all the fitness values of the chromosomes in a particular generation are calculated. The maximum, minimum and average fitness values of the chromosomes in a population are calculated. Then the termination criterion is checked. If the termination criterion is not reached, GA operators are applied to create a new population.

4.4.6 Computation of Total Network Cost

The total cost of the network in the population is taken as the summation of the network cost and the penalty cost.

4.4.7 Fitness

The GA computes the fitness for the network in the population. The GA examines for the minimum total network cost formation in the case of a pipe network. It has the following form:

$$\text{Fitness} = \text{Minimum of (Total network cost)} \quad (4.14)$$

4.4.8 Generation of New Population Using Reproduction Operator

The GA produces new members of the new generation by a selection system. Good individuals will possibly be selected a number of times in a generation but poor ones may not be at all. Having selected two parents, their chromosomes are recombined, typically using the mechanisms of crossover and mutation. Selection allocates more copies of those solutions with higher fitness values and thus imposes the survival-of-the-fittest mechanism. The main idea of selection is to prefer better solutions to worse ones, and many selection procedures have been proposed to accomplish this idea, including roulette-wheel selection. A weighted roulette wheel has spaces that are sized according to the fitness of each member in the population. The selection operator allocates each string in the population to a fragment of the roulette wheel. The size of the fragment is proportional to fitness f_i of the string. The probability of selection of a particular string is

$$P_i = \frac{f_i}{\sum_{i=1}^n f_i} \quad (4.15)$$

Where n is the number of population. Strings with higher fitnesses (i.e., lower costs) have a higher probability of being nominated.

4.4.9 Crossover Operator

Crossover is the partial interchange of bits between two parent strings to form two offspring strings. Crossover is not usually applied to all pairs of individuals selected for mating. A random choice is made, where the likelihood of crossover being applied is typically between 0.6 and 1.0. Consider a crossover probability of $P_c = 0.80$. The GA randomly choose two strings from the new population. An evenly distributed random number is then generated in the range 0.0 to 1.0. The GA applies the crossover operator if the random number is less than 0.8. Otherwise, the GA does not apply crossover for these two particular strings. To perform crossover, a crossover point is randomly selected along the strings (e.g., location 10). The crossover operator moves the last fourteen digits (out of 24 bits in a chromosomes) of the first string in the pair to the digit positions 11 to 24 of the second string, while the last fourteen digits of the second string are moved to end part of the first string.

4.4.10 Mutation Operator

Mutation performs a random walk in the vicinity of a candidate solution. While recombination operates on two or more parental chromosomes, mutation locally but randomly modifies a solution. Again, there are many variations of mutation, but it usually involves one or more changes being made to an individual's trait or traits. Mutation ensures no significant genetic material is lost. Consider a mutation probability of $P_m = 0.01$. The GA considers each string bit by bit in the new generation designed as a result of reproduction and crossover. An evenly distributed random number in the range 0.0 to 1.0 is then produced. The GA applies mutation if the random number is less than 0.01. Otherwise the GA does not apply mutation to that particular bit. The mutation operator interchanges the value of the bit to the opposite value (i.e., 0 to 1 or a 1 to 0).

The GA repeats the process to generate successive generations. The least cost strings (e.g., the best 10) are kept and informed as cheaper cost alternatives.

4.4.11 Computation of Network Cost Using Matlab Software

Pipe network optimisation is achieved by using Genetic Algorithm comprising reproduction, crossover and mutation. A software programming has been developed on MATLAB for getting optimal or near optimal solution for this case study.

In GA, the value of five parameters (population size, crossover point, mutation rate, number of iteration and percentage of crossover) necessity to be tuned when it is applied to several optimisation problems (Tolson et al. (2009)). The performance of the GA has been established to be heavily dependent on the parameter values used and appropriate parameter values are dependent on the optimisation problem under consideration. Thus, it requires substantial effort, normally by trial and error, for practitioners to decide the most appropriate parameter values for GA in order to apply them to various optimisation problems. To establish the parameter values of GA, trial and error methods is considered.

4.4.11.1 Convergence Study for Percentage of Cross over

In table-4.7, the population size (50), crossover point (single), and mutation rate (0.05) are kept constant and number of iterations and crossover percentage goes on changing. It is observed from convergence study (figure-4.3) that fitness value are very close at crossover percentage of 80% and 100%. As number of iteration increases, the fitness values are converging. The fitness value at iteration rate 300 and 500 are very close. Crossover percentage as 80% and number of iteration as 300 for further convergence of fitness value has been selected.

Table 4.7 Fitness Value (Total Cost in Dollars) Vs. Percentage of Crossover

Number of Iterations	Percentage of crossover			
	20	50	80	100
50	1,887,211	1,834,860	1,813,863	1,811,690
100	1,861,109	1,834,860	1,810,971	1,759,005
200	1,818,718	1,761,552	1,727,740	1,715,984
300	1,816,260	1,736,797	1,722,451	1,715,984
500	1,816,260	1,722,451	1,722,451	1,715,984

Note:- population size=50, Crossover point=1, Mutation rate=0.05

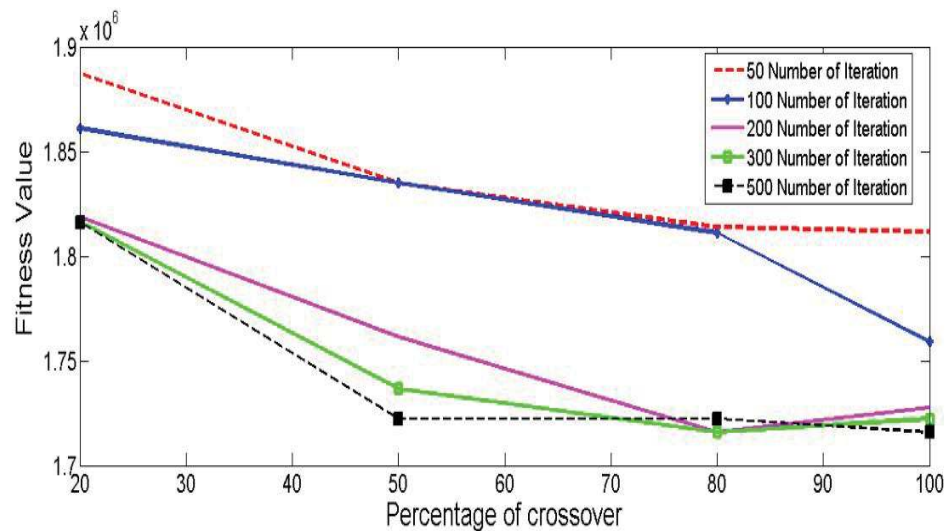


Figure-4.3 Fitness Value vs. Percentage of Crossover

4.4.11.2 Convergence Study for Mutation Rate

In table-4.8, the number of iteration (300), crossover point (single), and percentage of crossover (80%) are kept constant and mutation rate as well as population size goes on changing. It is observed from convergence study (figure-4.4) that fitness value at population size at 300 and 500 are very close. Similarly, the fitness value at different mutation rates, are almost similar but it is minimum at 0.05. Population

size as 300 and mutation rate as 0.05 has been selected for further convergence of fitness value.

Table 4.8 Variation of Fitness Value (Total Cost in Dollars) at Different Mutation

Mutation Rate	Population Size				
	100	150	200	300	500
0.02	1766122	1722451	1715984	1710695	1710695
0.05	1796176	1736078	1715984	1677602	1677602
0.1	1822727	1766122	1760833	1715984	1715984
0.5	1761552	1760833	1727740	1702985	1702985

Note:- Number of iteration=300, Crossover point=1, Percentage of crossover=0.8

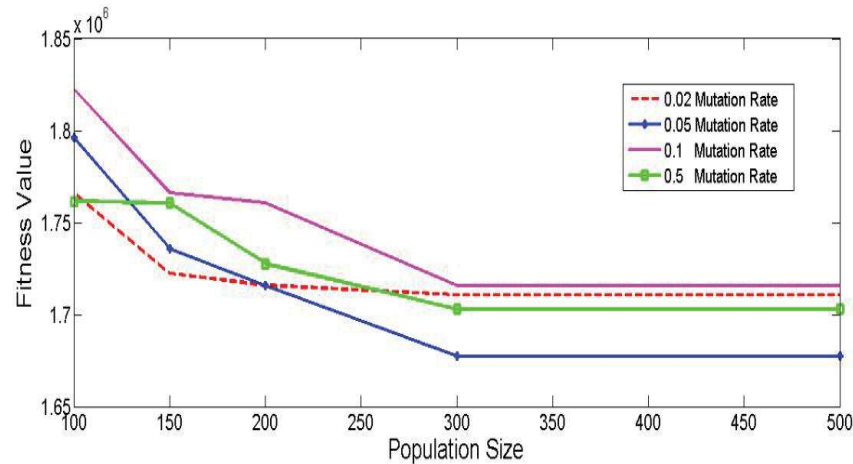


Figure-4.4 Fitness Value vs. Different Mutation

4.4.11.3 Convergence Study for Crossover Point

In table-4.9, the fitness values are very close at one point, two point and three point crossover as shown in convergence study (figure-4.5). Here, Single crossover point has been selected.

Table 4.9 Fitness Value (Total Head Loss in Dollars) Vs. Different Crossover Point

Crossover Point	Population Size	
	150	300
1-point	1,724,624	1,677,602
2-point	1,715,984	1,677,602
3-point	1,677,602	1,677,602

Note:- Number of iteration=300, Percentage of crossover=0.8, Mutation Rate= 0.05

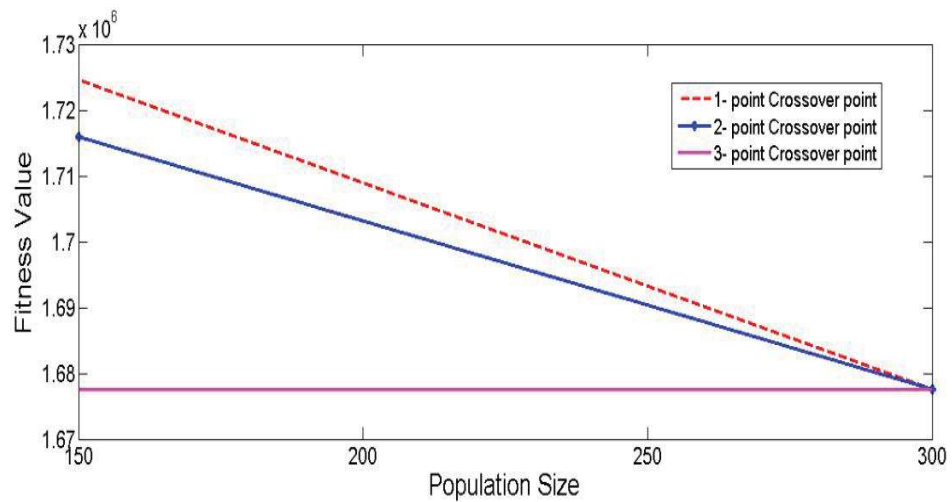


Figure-4.5 Variation of Fitness Value vs. Crossover Point

However, Population size (300), percentage of crossover (80%), number of iteration (300), mutation rate (0.05) and single point crossover have been selected to find the optimum value (minimum value) of network cost. The best nine solutions (Total cost of network in Dollars) that satisfy all Constraints are given in table-4.10. The optimum value of Gessler (1985) pipe network is **1,467,008 Dollars** which is much lower than earlier calculated fitness value (**1,750,300 Dollars**) in literature.

Table 4.10 Best Nine Solutions that Satisfy Pressure and Demand Constraints

Sl. No	Total Cost (dollars) x 10 ⁶	Pipe ^{bcd} [1]	Pipe ^{bcd} [4]	Pipe ^{bcd} [5]	Pipe [6]	Pipe [8]	Pipe [11]	Pipe [13]	Pipe [14]
1	1.467	203	254	203	152	152	356	152	152
2	1.715	Dup 254	Dup 254	clean	152	203	152	203	254
3	1.715	Dup 254	Dup 254	Dup 254	152	203	152	203	254
4	1.722	Dup 254	clean	clean	152	152	152	305	254
5	1.736	Dup 254	clean	Dup 203	152	152	152	254	305
6	1.760	Dup 254	leave	leave	152	203	152	305	254
7	1.711	Dup 254	leave	leave	152	152	152	254	305
8	1.722	Dup 254	clean	Dup 254	152	152	203	254	254
9	1.722	Dup 254	Dup 254	leave	152	152	203	254	254

^b[eave = leave existing pipe as it is.

^cclean = clean existing pipe.

^ddup356 = duplicate existing pipe with a 356 mm pipe.

Notes:

1. The table shows that pipe number [1], [4] and [5] may be leaved as it is, cleaned or duplicated with available pipe sizes.
2. Pipe number [6], [8], [11], [13] and [14] can be chosen from commercially available pipes given in table-4.1
3. All pipe sizes mentioned above are diameter in millimetre.

From table-4.10, the best results (minimum total cost of given network) is 1.467×10^6 dollars as shown in figure-4.6.

Fitness Value (Best Cost Results in Dollars) Vs. Population Generation

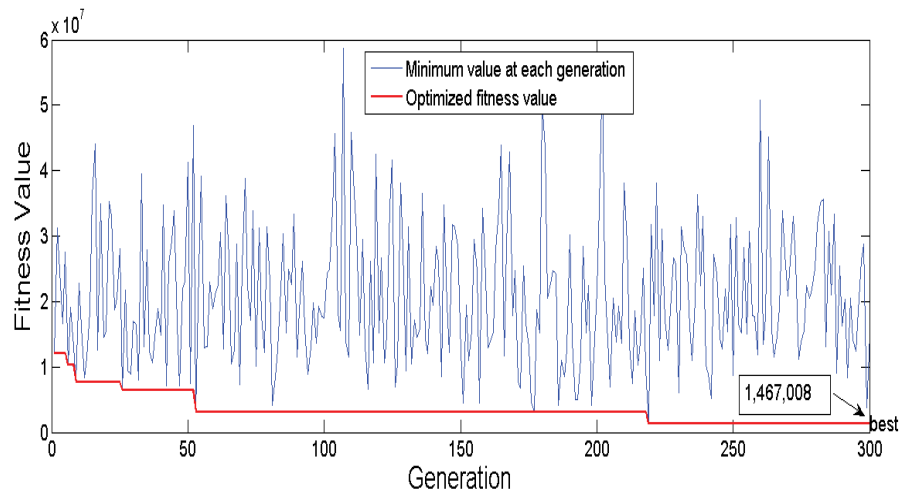


Figure-4.6 Generation vs. Fitness Value (Best Cost Results)

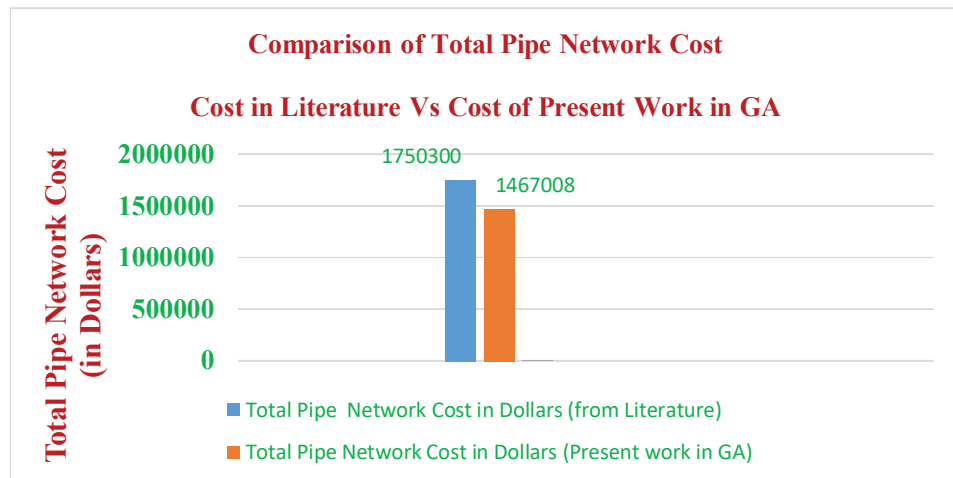


Figure-4.7 Comparison of Pipe Network Cost

4.4.12 Results

The Genetic algorithm deals the eight decision variables in the Gessler (1985) pipe network. Each variable is represented by a three bit binary substring. The three bit represents eight possible alternatives for new pipes, duplicated pipes or cleaning of an existing pipe (table-4.5). A 24-bit binary string represents the network to be optimized. The fact that the problems considered do not have pumping facilities is simply because these problems were taken from literature. The MATLAB (Appendix A) computer programming of a standard three operator GA has been developed here. There are nine alternatives solutions are shown in table-4.10.

4.5 Concluding Remarks

The GA finds the minimum cost configuration of Pipe network. The authors establish that the genetic algorithm method using the standard three operators comprising reproduction, crossover, and mutation, is particularly effective in finding global optimal or near optimal solutions for the water pipe network.

The genetic algorithm technique is appropriate to discrete variables such as selection of commercially available pipe sizes and hydraulic constraints. The genetic algorithm technique is in its research stage, and further developments can improve the search methods for large size practical problems.