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A GENETIC ALGORITHM BASED APPROACH FOR OPTIMIZATION OF REAL TIME PIPED FLOW WATER DISTRIBUTION NETWORK TO MINIMIZE THE COST OF PROJECT IMPLEMENTATION

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Abstract

Water Distribution Systems (WDS) are one of the major infrastructure assets of the society, designing economically effective WDSs is a complex task, which involves solving a large number of simultaneous nonlinear network equations, and at the same time, optimizing sizes, locations, and operational statuses of network components such as pipes, pumps, tanks and valves. The objective of this study is to minimize the implementation cost of real time water distribution network(WDN)by minimizing the diameters of the pipes. In this study first EPANET 2.0 analysis of the target WDN is carried out to determine the pipes size.The diameters of the pipe required for EPANET analysis is obtained by theoretical calculations. The system is analyzed using EPANET 2.0 hydraulic solver to determine the pressure heads at each node and velocities in each pipe. Next Genetic algorithm (GA) is developed implemented in MATLAB to analyze the target WDN. The required pressure head at each junction and velocities obtained from the EPANET Hydraulic solver is given to GA for the further analysis. The developed GA will select optimal pipe sizes taking care of minimum required pressure heads and other operating conditions at each nodes. Based on the analysis WDN is redesigned using lower level pipe sizes and hence minimizing the cost of pipes. Cost of pipe plays major role in minimizing the implementing cost of water distribution network projects and it is observed that there is a significant around 4.3% reduction in pipe cost and around 1% reduction in project cost.

Keywords: Water distribution network, optimization, head loss, pressure, EPANET, friction Coefficient. Genetic Algorithm

Introduction:

Water is the Critical infrastructure of the society. Optimal usage of the water is the necessity of every human being. Water distribution systems play very important role in effective distribution of water from the sources to required stations. Water can be distributed through canal networks. These systems have major drawbacks like evaporation losses, major cost of implementation, land requirements, unauthorized usage of water. Piped flow systems are the remedy for drawbacks associated with canal based water distribution networks. Piped flow water distribution networks (WDN) can be gravity flow or pumped flow, branched flow or looped flow. Design and optimization of looped pipe flow water distribution network is complex compared to branched flow WDN.

Water distribution network (WDN) Fig 1.1, considered for the present study is aimed at supplying water through the pipes to fill up the natural water tanks (water bodies). It consists of 1 reservoir, 7 junctions 8 tanks and 18 pipes to carry the water to fill up the tanks. Water will flow from the reservoir 1 and flow towards junction 3. At junction 3 some volume of water will flow through pipe 9 to fill up tank 10 and remaining water will flow towards junction 4. The water will flow through all the pipes to fill up all the 8 tanks. This water distribution system carries the water by gravity flow and it has 3 loops. Mild steel (MS) pipes are used to carry water between junctions. Ductile iron (DI) and High density polyethylene (HDPE) pipes are used to carry water from junctions to tanks. Based on the capacity of tanks demand at each node is calculated. When the water flow in the pipes frictional and minor losses occurs and this is to be minimized.In order to maintain required flow in each pipe corresponding junctions should have minimum pressure. Pipe cost is the major part of the total implementation cost of the project which depends on pipe material, length and diameter of the pipe. In this study an effort is made to minimize the cost involved with the pipes by reducing the diameters of the pipes through Genetic Algorithm approach. In this study first EPANET 2.0 analysis of the target WDN is carried out to determine the pipes size. The system is analyzed using EPANET 2.0 hydraulic solver to determine the pressure heads at each node and velocities in each pipe. Next Genetic algorithm (GA) is developed and implemented in MATLAB to analyze the target WDN. The required pressure head at each junction and velocities obtained from the EPANET Hydraulic solver is given to GA for the further analysis. The developed GA will select optimal pipe sizes taking care of minimum required pressure heads and other operating conditions at each nodes. Based on the analysis WDN is redesigned using lower level pipe sizes and hence minimizing the cost of pipes

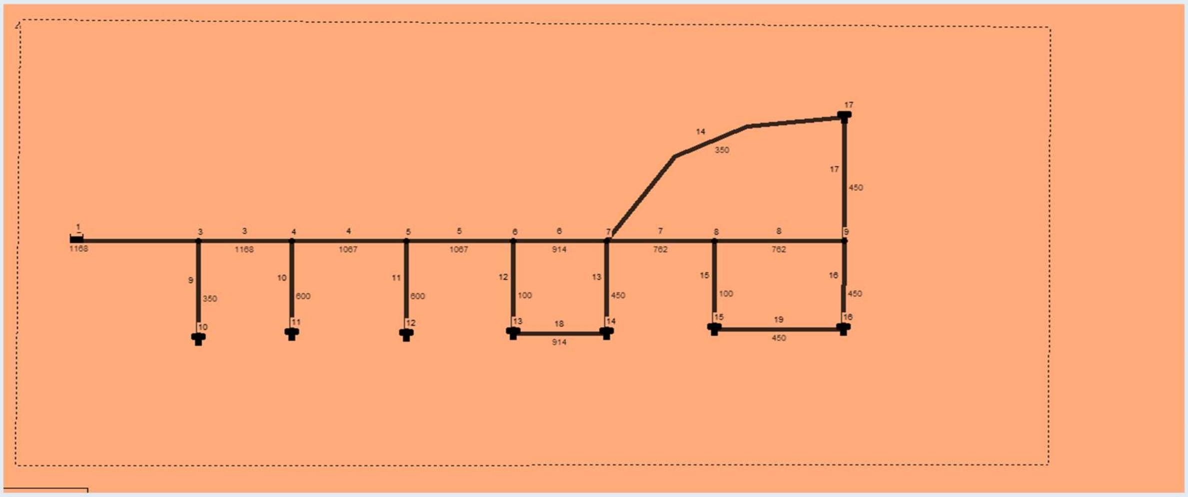

Fig 1.1: Target water distribution network (WDN)

EPANET is a computer program that performs extended period simulation of hydraulic and water quality behavior within pressurized pipe networks. A network consists of pipes, nodes (pipe junctions), pumps, valves and storage tanks or reservoirs. EPANET tracks the flow of water in each pipe, the pressure at each node, the height of water in each tank, and the concentration of a chemical species throughout the network during a simulation period comprised of multiple time steps. In addition to chemical species, water age and source tracing can also be simulated. EPANET is designed to be a research tool for improving our understanding of the movement and fate of drinking water constituents within distribution systems. It can be used for many different kinds of applications in distribution systems analysis

Genetic Algorithms (GA) are search techniques based on the concepts of natural evolution and their principles are directly analogous tonatural behavior, the brief idea of GA is to select population of initial solution points scattered randomly in the optimized space, then converge to better solutions by applying initerative manner the following three processes (reproduction/selection, crossover and mutation) until a desired criterion for stopping is achieved.

MATLAB (**Mat**rix **Lab**oratory), a product of Math works, is a scientific softwarepackage designed to provide integrated numeric computation and graphics visualizationin high-level programming language. MATLAB has a wide variety of functions useful to the genetic algorithm practitionerand those wishing to experiment with the genetic algorithm for the first time.Given the versatility of MATLAB's high-level language, problems can be codedin m-files in a fraction of the time that it would take to create C or Fortran programsfor the same purpose. Couple this with MATLAB's advanced data analysis,visualization tools and special purpose application domain toolboxes and the user ispresented with a uniform which to explore the potential of geneticalgorithms.

1. Literature Review:

Many of the researcher used GA based approach for design of water distribution network. simple genetic algorithms (GA) is used to obtain near optimal solution [1], while Simpson et al. [2] compared GA technique with other methods, and concluded that the GA technique generates multiple alternative solutions which are optimum. The results obtained by Simpson

Dandy et al. [3] improved the solutions obtained by Simpson using the concept of variable power scaling of the fitness function, an adjacency mutation operator, and gray codes. Savic and Walters developed the computer model GANET [4] to obtain least cost of water distribution system. Prasad and Park considered both minimization of cost and maximization of network reliability [5] in GA, Harmony search method is used [6] by Geem for optimization of water distribution network. Multi objective approach is used [7] in optimization. G C Dandy further improved GA [8] for obtaining better solutions. Chandramouli and Malleswararao [9] used fuzzy logic based approach to improve the reliability of network. Cisty [10] used search space reduction approach to improve computational efficiency, minimization of electricity cost [11] is also considered in optimization, combining GA and mathematical programming with the inclusion of new elements such as pressure reducing valves [12];Surco et al. utilized a modified particle swarm optimization (PSO) algorithm for the optimization of water distribution networks [13], Antonowicz used EPANET solver for solving water distribution network[14], [15], [21],Beatriz, Martinez-Bahena used GA for optimizing real time water distribution network [16],Wu and Simpson [17] demonstrated significant improvements in efficiency and robustness for single-objective optimization utilizing a boundary search method, Bilal and Pant utilized a hybrid metaheuristic algorithm[18].Comparison of searching behaviour of evolutionary algorithms [19], Investigating the Impacts of Water Conservation on Water Quality in Distribution Networks Using an Advection-Dispersion Transport Model [20], Tanyimboh, T.T. “Redundant binary codes in genetic algorithms [22], Pant, M used novel differential techniques for optimizing WDN [23], Sangroula, U. carried out Optimization of Water Distribution Networks Using Genetic Algorithm Based SOP–WDN [24].

2. Theoretical Analysis of the Target Network:

It is desirable to supply water up to the tanks through pipelines than letting water in to the streams/canals to feed to the other smaller tanks. Supply through pipes is the best option considering that it eliminates water losses in that of canal due to evaporation, seepage and unauthorized lifting. After conducting detailed geographical and hydrological survey of the location of the tanks and pipe alignment following tasks is carried out. Full tank capacities are collected, Junction levels and full tank level (FTL) are measured, by using Bernoulli’s equation and continuity equation diameter of the main and branched pipe is calculatedand Pressure drop in each pipe is calculated using Hazen- William’s equation

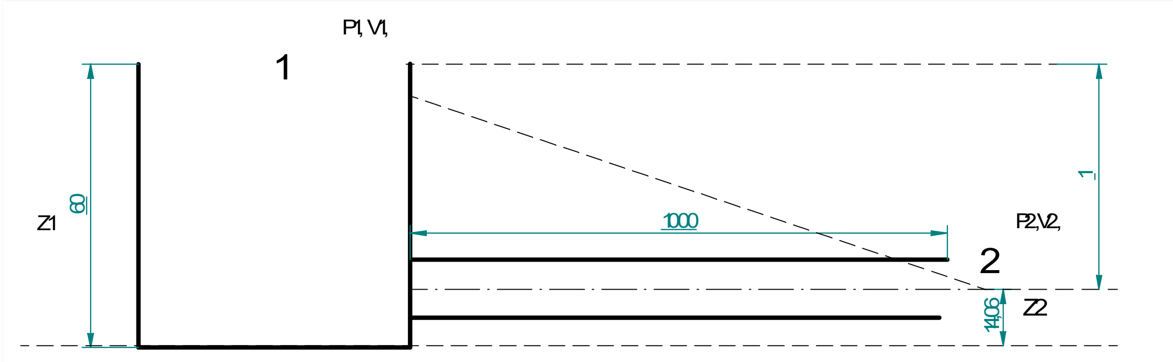

Fig 3.1: Flow through pipe

Fig 3.1 shows an arrangement of reservoir and pipe. The water will flow from point 1 to point 2 as there is a difference in the pressure head between two. According to Bernoulli's theorem energy at any point in incompressible fluid field is constant.

$P/\rho g + V^2/2g + Z$ =Constant -----------(1)

Where $P/\rho g$ is pressure energy or pressure head in m

V2/2g is kinetic energy or kinetic head in m

Z is datum energy or datum head in m

Applying Bernoulli's theorem at point 1 and point 2

$P1/\rho g + V1^2/2g + Z1 = P2/\rho g + V2^2/2g + Z2 + hf + hm$------(2)

Wherehf is major head losses or frictional lossesin m

hm is minor energy losses or minor head losses in m

Total head loss H = hf + hm------------(3)

When water flows point 1 to point 2 there is a loss of energy takes place due to head losses. Major energy losses occur due to friction and minor losses occurs due to inlet of pipe, exit of pipe, elbow, bend in pipe, sudden contraction in pipe, sudden enlargement in pipe and various pipe fittings.

Total head available at point 2 will be calculated by Applying Bernoulli's theorem at point 1 and point 2

0+0+Z1 =0+0+Z2+ hf + hm

Total head loss H =hf + hm = Z1-Z2 --------------(4)or Z2 = Z1- losses

Frictional losses hfis calculated using Hazen- Williams's equation and minor losses is taken as 10% of major losses.

$hf = 10.65(Q^{1.85} /C^{1.85})(L/d^{4.87})$-----------(5) Hazen Williams equation

Where hf is major head losses or frictional losses in m

Q is the discharge in m3/s, L is length of the pipe in m,

d is the diameter of the pipe in m,

C is friction or roughness coefficient its value is (120 for MS pipes, 130 for DI pipes and 150 for HDPE pipes)

$V=0.849*C*R^{0.63}*S^{0.54}$--------------------(6) Hazen Williams Equation for velocity

Where V is velocity in m/s, C is roughness coefficient, R is the hydraulic radius

S is the slope of pipe

Q = AV----------------(7) Continuity equation

Where A is the velocity of fluid in m/s and A is the area of pipe in m2

Target water distribution network is theoretically analyzed using above relations to determine the diameters and velocities of each pipe.

- Based on the tank capacities the required discharge (Demand) of each pipe connecting to corresponding tanks are calculated.
- Using reservoir, junction and tank elevations head at each junctions and head loss in each pipe is calculated. This head loss is used in the Hazen Williams equation to determine the velocities in each pipe. Velocity plot of theoretical analysis is shown in fig 3.2.

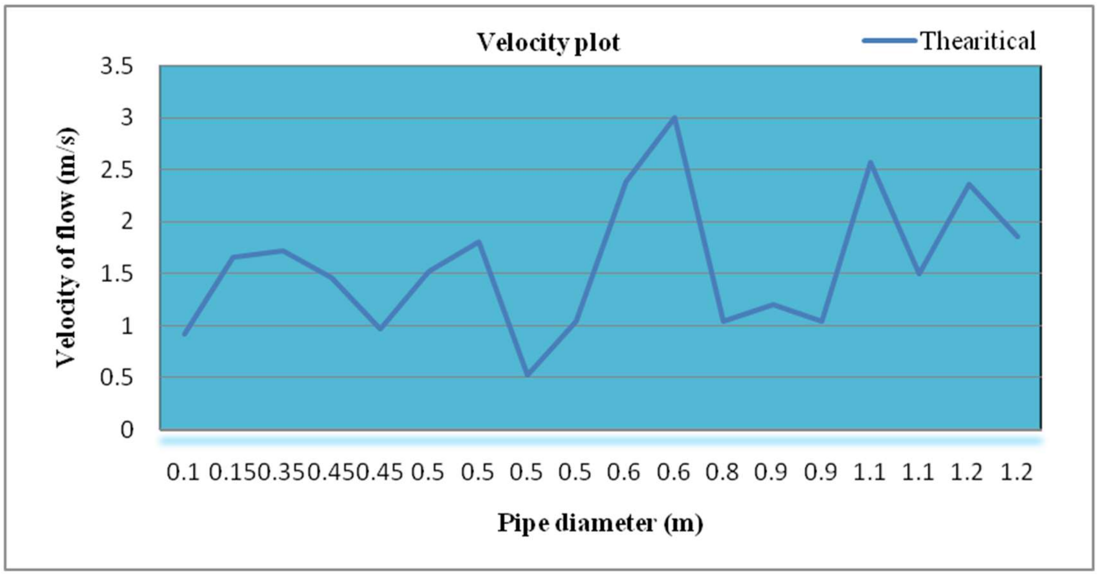

Fig 3.2: Velocity plot of theoretical analysis

3. Hydraulic Analysis of WDN using EPANET:

Hydraulic analysis of the water distribution network is carried out using the diameters obtained by theoretical analysis keeping all other input values same. The WDN is drawn by adding reservoir, nodes, Tanks and pipes. Input values for the reservoir, pipes, nodes and tanks are added and the system is analyzed. Since the peak demand occurs initially corresponding values are recorded and tabulated. It is also important to understand the unit head loss in each pipe as the head available at next junction is the difference of between head at previous junction and head loss in corresponding pipe.Unit head loss plot for different diameters is shown in fig 4.1.

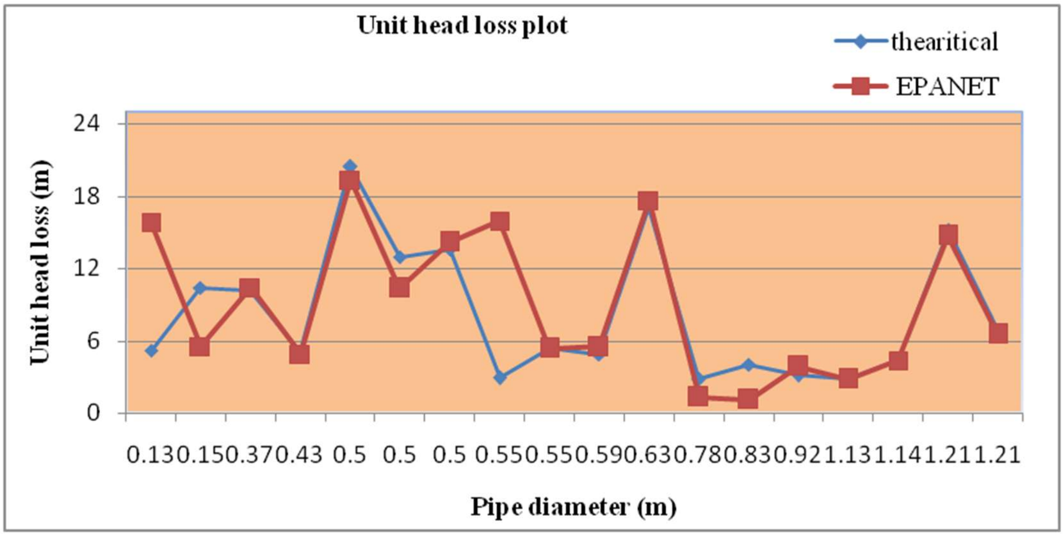

Fig 4.1: Unit head loss comparison plot

It is observed that for most of the pipes unit head loss is minimized in case of EPANET analysis as compared to theoretical analysis. Fig 4.2, 4.3, 4.4 and 4.5 shows the output of EPANET analysis.

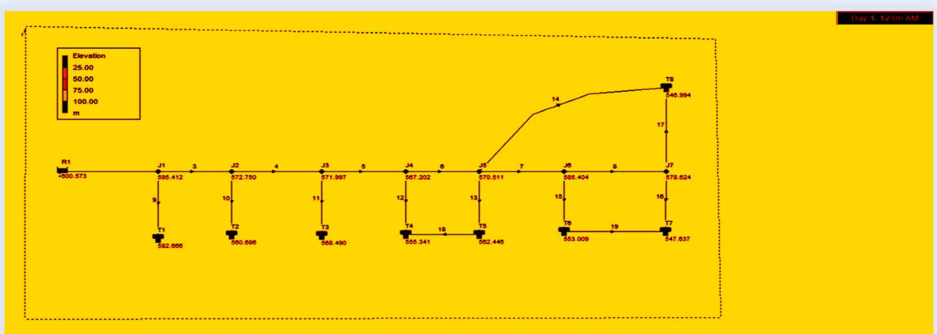

Fig 4.2: Elevations at junctions and Tanks

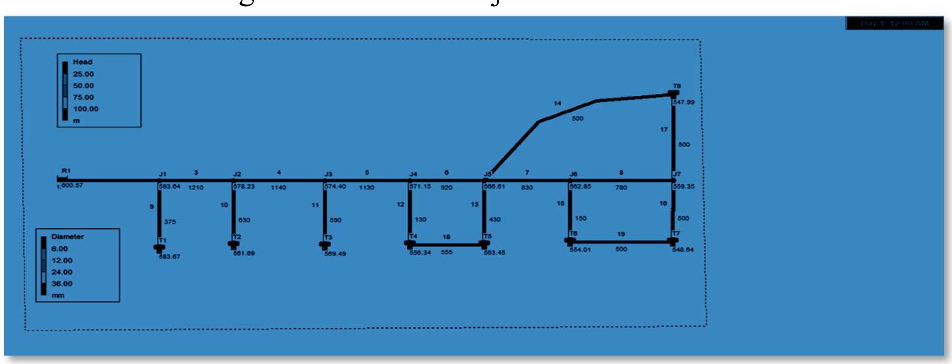

Fig 4.3: Pressure head and diameter value

4. Development of Genetic Algorithm(GA) and implemented in MATLAB2016:

To carry out this study we developed GA and is implemented in the MATLAB 2016. Developed algorithm works on the following Logic.

i. GA reads the input file for necessary data for processing

ii. It is suggested to use larger diameter pipes to minimize the head loss. Larger diameter pipes increase the cost of pipe. This GA selects the optimal pipe diameters in the pipe network to minimize the pipe cost maintaining required head at each junction in the pipe network so as to allow the required discharge to fill the tanks.

iii. This GA performs 6 iterations to optimize the values

iv. It considers the flow between Reservoir and junction J1. Initially in first iteration it selects maximum diameter pipe out of available diameter steps. Using Hazen Williams formula calculates frictional losses. It adds 10 percent of frictional losses to calculate total losses in the flow from Reservoir to junction J1. It deducts the total head loss from the head available at reservoir. The result will be compared with head available at J1. If the resulted head is more than the junction head GA selects next lower diameter values and perform the above steps. This will repeat for all the junctions.

v. Based on the selected values of pipe diameter it will calculate the total optimized cost of the pipe.

We created the input file to run the developed GA. Following input files in the form of matrix is created

i. Head Required at each junctions
ii. Start and End elevations
iii. Conversion factor for Hazen- Williams equation
iv. Theoretical diameter of pipes
v. Roughness coefficients of pipe material
vi. Pipe lengths
vii. Commercially available Standard Diameter of Pipe and Cost/meter

5. Pseudo Code of GA

```
% Genetic Algoritm Code
% Main File
% 12.04.2021

%% Problem Definition

clc;clear;close all
CostFunction=@(x) Cost(x);     % Cost Function
nVar=18;                       % Number of Decision Variables
VarSize=[1 nVar];              % Decision Variables Matrix Size
VarMin=1;                      % Lower Bound of Variables
VarMax= 25;                    % Upper Bound of Variables

%% Diameter of pipes
```

```
% Standard Diameter available
D=xlsread('C:\Users\Hp\Desktop\HP_Final\Input_Data\','Standard_Dia','C3:AB3');

%% GA Parameters
MaxIt=6;            % Maximum Number of Iterations
nPop=6;             % Population Size (Swarm Size)
pc=0.7;             % Crossover Percentage
nc=2*round(pc*nPop/2);  % Number of Offsprings (also Parnets)
pm=0.3;             % Mutation Percentage
nm=round(pm*nPop);      % Number of Mutants

beta=8;
%%
empty_individual.Position=[];
empty_individual.Cost=[];
GlobalBest.Cost=inf;
empty_particle.Position=[];
empty_particle.Cost=[];
empty_particle.Velocity=[];
empty_particle.Best.Position=[];
empty_particle.Best.Cost=[];

%%
for i=1:nPop

% Initialize Position

    m=randi([1 25],VarSize);

    pop(i).Position=m;
    pop(i).Position=D(m);

% Evaluation
   pop(i).Cost=CostFunction(pop(i).Position);

   particle(i).Position=pop(i).Position;

% Evaluation
   particle(i).Cost=pop(i).Cost;
```

```
% Update Personal Best
   particle(i).Best.Position=particle(i).Position;
   particle(i).Best.Cost=particle(i).Cost;

% Update Global Best
if particle(i).Best.Cost<GlobalBest.Cost

      GlobalBest=particle(i).Best;

end
end
Costs=[pop.Cost];

[Costs, SortOrder]=sort(Costs);

pop=pop(SortOrder);
% Store Best Solution
BestSol=pop(1);
% Array to Hold Best Cost Values
BestCost=zeros(MaxIt,1);
% Store Cost
WorstCost=pop(end).Cost;
%% Loop for Iterations
for it=1:MaxIt

   P=exp(-beta*Costs/WorstCost);
   P=P/sum(P);

   popc=repmat(empty_individual,nc/2,2);
for k=1:nc/2

% Select Parents Indices
      i1=RouletteWheelSelection(P);
      i2=RouletteWheelSelection(P);
      p1=pop(i1);
      p2=pop(i2);

% Apply Crossover
     [popc(k,1).Position, popc(k,2).Position]=Crossover(p1.Position,p2.Position);
```

```
%%
% Evaluate Offsprings
        popc(k,1).Cost=CostFunction(popc(k,1).Position);
        popc(k,2).Cost=CostFunction(popc(k,2).Position);

end
    popc=popc(:);


%%

% Mutation
    popm=repmat(empty_individual,nm,1);
for k=1:nm

% Select Parent
        i=randi([1 nPop]);
        p=pop(i);

% Apply Mutation
        popm(k).Position=Mutate(p.Position,mu,VarMin,VarMax);

% Evaluate Mutant
        popm(k).Cost=CostFunction(popm(k).Position);

end
%%
% Create Merged Population
    pop=[pop
        popc
        popm]; %#ok

% Sort Population
    Costs=[pop.Cost];
    [Costs, SortOrder]=sort(Costs);
    pop=pop(SortOrder);
%---------------------------------------------------
% for population and cost iterationwise details
    populationPosition=vertcat(pop.Position);
```

```
    PopulationCost=vertcat(pop.Cost);
    Population_Cost=[populationPosition PopulationCost];
%-----------------------------------------------------
% Update Worst Cost
    WorstCost=max(WorstCost,pop(end).Cost);

% Truncation
    pop=pop(1:nPop);
    Costs=Costs(1:nPop);

% Store Best Solution Ever Found
    BestSol=pop(1);

%----------------------------------------------------------
% Store Best Cost Ever Found

for i=1:nPop
if pop(i).Cost<=particle(i).Cost
            particle(i).Position = pop(i).Position;
            particle(i).Cost = pop(i).Cost;
end
        Cx(i) = particle(i).Cost;
end
    [BestCost(it),r]=min(Cx);
    GlobalBest.Cost=particle(r).Cost;
    GlobalBest.Position=particle(r).Position;

    BstCostGA(it)=BestCost(it);
    disp(['Iteration ' num2str(it) ': Best Cost = ' num2str(BestCost(it))]); % Displaing Iteration
number and solution
end

% Ploting Graph
BestSol = GlobalBest;
figure;
plot(BestCost,'LineWidth',2);
%semilogy(BestCost,'LineWidth',2);
xlabel('Iteration');
ylabel('Best Cost');
grid on;
```

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```
%--------------------------------------------------------
%  Best Selected Diameter Output to Excell Shee
BestSol= struct2table(BestSol);   %Convert Structure to Numeric
BestSol=vertcat(BestSol.Position);  % Taking only one field
xlswrite('C:\Desktop\HP_Final\Input_Data\Best_Sol.xlsx',BestSol,'C4:T4');  % Writing to excell
```

6. Result and Discussion:

Usually it is suggested to use larger diameters pipe to allow higher discharge with reduced velocity which minimizes the head loss. Using larger diameter pipes in WDN increase the cost of pipes and project cost. Smaller diameters pipedecreases the cost of pipe and project cost but increase the head loss resulting in lowering of head at next junction. Here optimization is required to select lowest possible values of the pipe diameter to maintain operating condition like minimum head loss, minimum head at junctions and maintaining required velocities in the pipes. In this study first theoretical analysis of the target WDN is carried out to determine the pipes size. The results are plotted in fig 3.2. The system is analyzed using EPANET 2.0 hydraulic solver to determine the pressure heads at each node and velocities at each pipe considering the calculated values of diameters. After the analysis the result is plotted in fig 4.1, 4.2 and 4.3. From the result it is observed that the diameters used in the analysis gives more discharges than required and hence decided to reduce the diameters in order to minimize the cost.To carry out further analysis we developed genetic algorithm (GA) and implemented in MATLAB 2016. We set 6 iterations for each run and carried out 30 runs using the diameters obtained from EPANET analysis. We got minimum cost value in the 6th run and next minimum cost value in the 2nd run. Based on the diameters availability and ease of layout arrangement 2nd run costs and diameters are decided as optimal and selected for implementation. Theobtained results of 2nd run and 6th run is shown in fig 7.1 and 7.2.

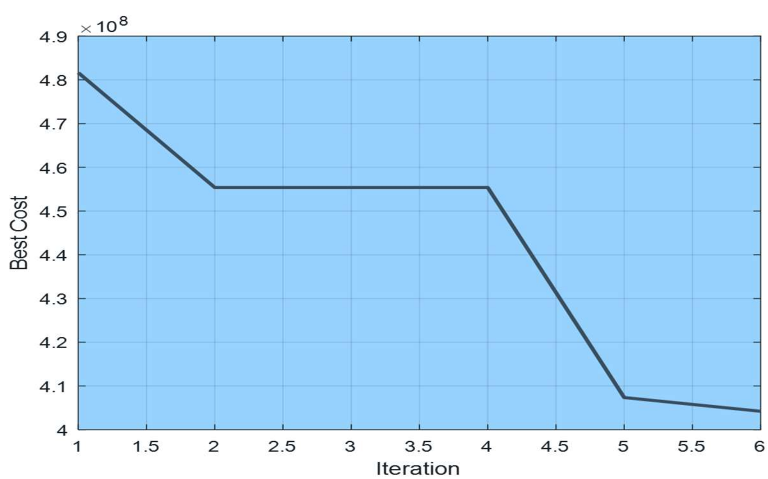

Fig: Fig 7.1: Run 2 Best cost v/s Iterations

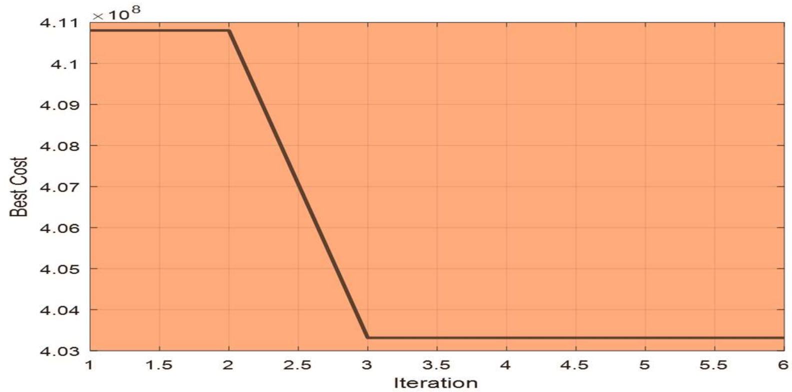

Fig 7.2: Run 6 Best cost v/s Iteration

Table 7.1: Pipe cost comparison for both methods

From	To	Pipe No	Length (m)	EPANET Analysis		GA Analysis	
				Diameter(m)	Cost(Rs)	Diameter(m)	Cost(Rs)
R	J1	2	1710	1.2	35773200	0.9	18485100
J1	J2	3	4342	1.2	90834640	0.4	19243744
J2	J3	4	1590	1.1	28092120	1.9	59679060
J3	J4	5	3893	1.1	68781524	0.55	27729839
J4	J5	6	2038	0.9	22030780	0.45	10970554
J5	J6	7	2789	0.9	30149090	0.25	7494043
J6	J7	8	1972	0.8	1787520	0.25	5298764
J1	T1	9	1314	0.35	5240232	1.1	23215752
J2	T2	10	2020	0.6	17008400	0.25	5427740
J3	T3	11	419	0.6	3427980	0.15	504476
J4	T4	12	3511	0.1	3862100	0.7	27912450
J5	T5	13	947	0.45	5097701	0.5	5973676
J6	T8	14	4342	0.5	27389336	1.0	63927266
J6	T6	15	1814	0.15	2184056	1.8	64663658
J7	T7	16	5762	0.45	31016846	0.25	15482494
J7	T8	17	2038	0.5	12855704	0.35	8127544
T4	T5	18	4563	0.45	24562629	0.35	18197244
T6	T7	19	1972	0.45	10615276	0.65	19088960
Total pipe cost (EPANET)					419762574		
Total pipe cost in Rs (GA)							401422364
Reduction in pipe cost (Rs)					4.3%		18340210

After GA analysis it is observed that minimum required velocity in each pipe is maintained and also head loss is minimized. By carrying out this analysis we recommended lower values of diameters for the pipes. Cost of pipe plays major role in minimizing the implementing cost of water distribution network projects. From the table 7.1 it is observed that there is a significant around 4.3% reduction in pipe cost and around 1% reduction in project cost.

7. Conclusion and Future scope:

Water supply systems are the major infrastructure of the society. This type of project is usually implemented for public service. Implementation cost of this type of projects is huge and is to be reduced. Pipe cost attains major percentage of project cost. Proper analysis of water distribution system is required. Optimization of water distribution network can be accomplished by many methods. In this study a GA based approach is used to analyze the real time WDNand achieved around 4.3% reduction in pipe cost and around 1% reduction in project implementation cost. Further research can be carried out for optimization of diameters sizes by hybridization of optimization techniques. Hybridization of Heuristic search methods like Genetic algorithms, Particle swam optimization,frog leaping algorithm, ant colony optimization etc. Complex water distribution network increases the maintenance cost and hence required to design simple networks. This can be carried by using GA and other optimization techniques. Both existing and new WDN can be analyzed and redesigned. Optimized WDN reduce the cost and maintenance work.

8. Acknowledgment:
The authors are grateful to The Principal, JSS Academy of Technical Education Bengaluru, for his support in carrying out this study. We acknowledge Head of Department and all Professors and staff of Mechanical Engineering department for their valuable comments and helpful suggestions which greatly improved the quality of this research.

9. Data Availability statement

The data that support the findings of this study are available in the form of tables and graphs. Data related to Theoretical, EPANET and GA analysis are stored in the file. Related data of this research can be viewed or downloaded from the url: https://data.mendeley.com/drafts/jdhh62ww3p?folder=841440ef-52e9-4696-bafb-ff7ddb15f409
http://dx.doi.org/10.17632/jdhh62ww3p.1
These can be available on request from the corresponding author, [Prakash Hanumanthappa]. The data are not publicly available as further research has to be carried using data as a part of improvement.

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