American Journal of Engineering Research (AJER)
e-ISSN : 2320-0847 p-ISSN : 2320-0936
Volume-03, Issue-01, pp-163-173
www.ajer.org

Research Paper Open Access

Optimal Design Of Existng Water Distribution Network Using Genetics Algorithms.

A Saminu[1], I Abubakar[2],H Sani [3]U Tsoho[4] I Suleman 5
*1, 3,4 5 Department of civil Engineering, Nigerian Defence Academy, Kaduna
2 Department of civil Engineering, Ahmadu Bello University Zaria

Abstract: - In this study EPANET, a widely used water distribution package was linked to OptiGa, a Visual Basic ActiveX control for implementation of genetic algorithm, through Visual Basic programming technique, to modify the computer software called OptiNetwork. OptiNetwork in its modifications, introduced means of selecting options for advanced genetic algorithm parameters (Top mate; Roulette cost; Random; Tournament methods; and one point crossover; two points crossover; uniform crossover methods and random seed number). Using Badarawa/Malali existing water distribution network consisting of 96 pipes of different materials, 75junctions, two tanks, and one overhead reservoir, and a source reservoir (i.e treatment plant) from which water is pumped through a pumping main to the overhead reservoir and later distributed to the network by gravity .The modified software optiNetwork was applied to Badarawa / Malali networks distribution designs. The results obtained were compared with those obtained using commercial software package (OptiDesigner), The modified software has been able to obtained almost equal result with OptiDesigner software for the first optimization i.e before the application of advance GA, after the application of Advance GA It was observed that the least-cost design of $195,200.00 that satisfies the constraints requirements was obtained using optiNetwork, which is much lower than $435,118.00 obtained from OptiDesigner software. The results obtained show that the introduction of the advanced genetic parameters of OptiNetwork is justified. This is because, it has been able to improve the search method in terms of achieving the "least-cost" designed water distribution system that will supply sufficient water quantities at adequate pressure to the consumers.

Keywords: - *Water, distribution, systems, least cost, design, optimization, genetic algorithms,*

I. INTRODUCTION

Pipe network optimization involves the design of new pipe network and rehabilitation of existing network. A water distribution system must sustain two hydraulic requirements: water demand and pressure head at the supply locations. There are three types of optimization models including least cost design, maximum benefit design, and cost-benefit tradeoff design, Wu et al. [1]: (a) least cost optimization searches for the optimal solution by minimizing the cost while satisfying the design constraints. The least cost optimization, however, produces the minimum pipe sizes that reduce the supply capacity and reliability. (b) Maximum benefit design optimization maximizes the return on every dollar spent by searching for the maximum benefit design solution within an available budget while still meeting hydraulic constraints.

Both the least cost and the maximum benefit optimization models identify the optimal or near-optimal solutions at the minimum cost and the maximum benefit (often corresponding to the maximum cost) respectively, using a single objective design model. (c) Cost-benefit tradeoff optimization is achieved using a multi-objective design model to minimize the cost and maximize the benefit while satisfying the constraints. Traditionally, most of the work on the design of water distribution networks has focused on developing optimization procedures for the least cost pipe-sizing problem. Numerous optimization techniques are used in water distribution systems. These
include the deterministic optimization techniques such as linear programming (for separable objective functions and linear constraints), and non-linear programming (when the objective function and the constraints are not all in the linear form), and the stochastic optimization techniques such as genetic algorithms and simulated annealing.

The problem of optimal design of water distribution network has various aspects to be considered such as hydraulics, reliability, water quality, and infrastructure and demand pattern. Though, each of these factors has its own part of the planning, design and management of the system despite the inherent dependence.

II. WHAT IS GENETIC ALGORITHM?

Genetic algorithms (GAs) are optimization techniques based on the concepts of natural selection and genetics. Genetic algorithms are inspired by Darwin's theory of evolution. In this approach, the variables are represented as genes on a chromosome. Solution to a problem solved by genetic algorithms uses an evolutionary process (it is evolved). GAs features a group of candidate solutions (population) on the response surface. Through natural selection and the genetic operators, mutation and recombination, chromosomes with better fitness are found. Natural selection guarantees that chromosomes with the best fitness will propagate in future populations. Using the recombination operator, the GA combines genes from two parent chromosomes to form two new chromosomes (children) that have a high probability of having better fitness than their parents. Mutation allows new areas of the response surface to be explored. This is repeated until some condition (for example number of populations or improvement of the best solution) is satisfied.

2.2. Steps in Using Genetic Algorithms for Network Optimization

The following steps summarize an implementation of a genetic algorithm for optimizing the design of a water distribution network system (based on Simpson, Murphy and Dandy 1993[2]; Simpson, Dandy and Murphy 1994) [3]

1. Develop a coding scheme to represent the decision variables to be optimized and the corresponding lookup tables for the choices for the design variables.
2. Choose the form of the genetic algorithm operators; e.g. population size (say N=100 or 500); selection scheme - tournament selection or biased Roulette wheel; crossover type - one-point, two-point or uniform; and mutation type - bit-wise or creeping.
3. Choose values for the genetic algorithm parameters (e.g. crossover probability – pc; mutation probability - pm; penalty cost factor *K*).
4. Select a seed for the random number generator.
5. Randomly generate the initial population of WDS network designs.
6. Decode each string in the population by dividing into its sub-strings and then determining the corresponding decision variable choices (using the lookup tables).
7. For the decoded strings, compute the network cost of each of the designs in the population.
8. Analyze each network design with a hydraulic solver for each demand loading case to compute network flows, pressures and pressure deficits (if any).
9. Compute a penalty cost for each network where design constraints are violated.
10. Compute the fitness of each string based on the costs in steps 7 and 9; often taken as the inverse of the total cost (network cost plus penalty cost).
11. Create a mating pool for the next generation using the selection operator that is driven by the "survival of the fittest."
12. Generate a new population of designs from the mating pool using the genetic algorithm operators of crossover and mutation.
13. Record the lowest cost solutions from the new generation.
14. Repeat steps 6 to 13 to produce successive generations of populations of designs stop if all members of the population are the same.
15. Select the lowest cost design and any other similarly low cost designs of different configuration.
16. Check if any of the decision variables have been selected at the upper bound of the possible choices in the lookup table. If so, expand the range of choices and re-run of genetic algorithm.
17. Repeat steps 4 to 16 for say, ten different starting random number seeds.
18. Repeat steps 4 to 17 for successively larger and larger population sizes.

The review of application of these techniques in the water distribution systems can be found in (Tospornsampon et al.2007) [4] applied a combination of Tabusearch (TS) and Genetic Algorithm (GA) to solve a problem of split-pipe design of water distribution network.

The first, is the two-loop network which was first introduced by (Alperovits and Shamir 1997) [5]. The system is to supply water to meet the required demand and to satisfy minimum pressure head at each node. Three different values of α are adopted in the study which consist of the maximum and minimum values. The unit of the "Q" (flow rate) and "D" (diameters) maintained in the study are m^3/h and centimeter "C". The results obtained using $\alpha = 10.5088$ and $\alpha = 10.6792$, produced a cost of $400, 337.97 and $403, 751.22, lower than that of simulated Annealing (SA) with a cost of $408,035.00.

The second network is the water distribution network in Hanoi, Vietnam, which was first introduced by (Fujiwara and Khang 1990) [6]. The problem is similar to the two-loop network that the network is fed by gravity from a single fixed head source and is to satisfy demands at required pressures. In this problem, six sizes of commercial pipe are available and the cost of each pipe with diameter Di and length Li is calculated from Ci = 1.1 X Di Xli in which cost is in dollars, diameter and length in meters. The Hazen Williams coefficient is fixed at 130 for all pipes. The result obtained shows that combined Tabu search and Genetic Algorithm (TS-GA) provide very

remarkable solutions, after satisfying all the demand and pressure requirements. All solutions obtained using different hydraulic constant α = 10.5088, and α = 10.6823, are superior to those obtained by simulated Annealing (SA) in the work of Tospornsampan et.al (2007) [4]. The total cost obtained by TS-GA are $6.022 and $6.111 for the values of α = 10.5088 and 10.0823 compared to that of SA, within the cost of $6.200 for the value of α 10.9031. The comparison of those solutions shows that the TS-GA has produced significant improvements in the network.

The third network is the New York City water supply network. The data of the New York City water supply tunnels are taken from (Fujirawa and Khang 1990) [6], and (Dandy et.al 1999) [7]. The challenge in the third network is to construct additional gravity flow tunnels parallel to the existing system to satisfy the increased demands at the required pressures. The results obtained from the TS-GA are $36.87 and $38.05 when compared to the work of (Tospornsampan et.al 2007) [4], with a cost of $40.04, after satisfying the demand pressure requirements at all nodes, the result shows that a combination algorithm is better than the SA for the design problem

Schaake and Lai [8] used the New York Tunnel system consisting of 21 pipes, 19 nodes and 1 reservoir. Walski et al. [9] set up the hypothetical Anytown water distribution system (USA) (40 pipes and 22 nodes) as a realistic benchmark to compare and test network optimization software, and has features and problems typical of those found in many real systems. Fujiwara and Khang [6] used the water distribution trunk network in Hanoi consisting of one reservoir, 31 demand nodes and 34 pipes. Halhal et al. [10] studied the optimization of a town in Morocco. The network consisted of 115 nodes, 158 existing pipes to be rehabilitated, and nine new pipelines to be designed (or sized) for the system.

From the previous review, it can be concluded that the application of the GA optimization model to existing network systems demonstrates the capability of the GA to incorporate real design concerns of water system planners, to systems of multiple pressure zones, and potentially identify significant cost savings.

III. METHODOLOGY

3.1 Introduction to Modified Program (OptiNetwork Software)

The modified program (Figure 3.1) is called OptiNetwork software and modified to:

1. Overcome all the shortcomings of the Demonstration Program.
2. It can handle a water distribution network up to 150 pipes.
3. Provide additional design parameters (pressure constrain, velocity constrain and diameter constrain).
4. Open and locate a water distribution network file that needs to be optimized.
5. Provide options for the selection of advanced genetic algorithm parameters (selection methods, crossover methods and random seed number).

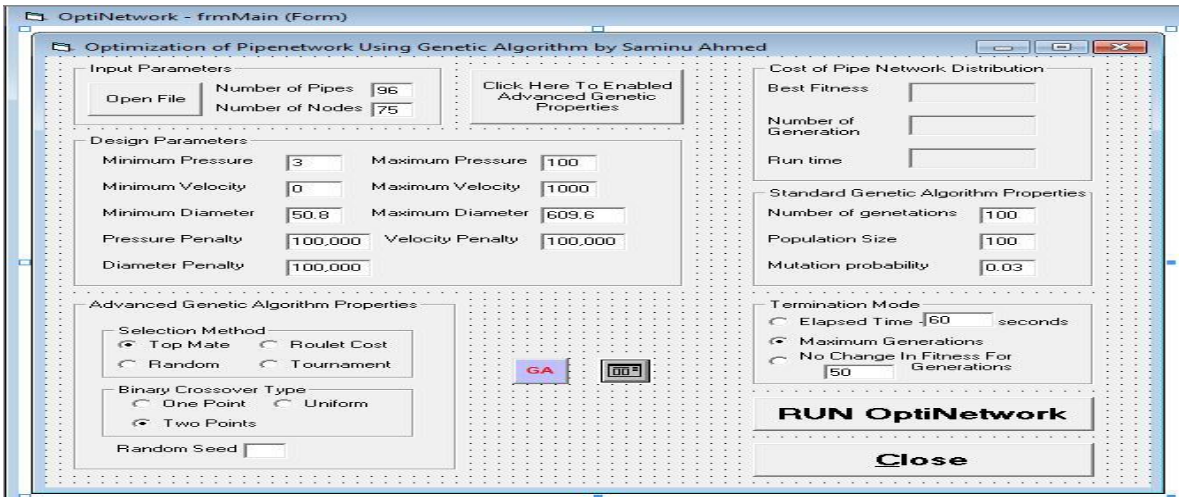

Figure 3.1 Modified Program (OptiNetwork Software)

3.2 Description of the Modified Software (OptiNetwork)

The flow chat for the software modified (OptiNetwork model) is shown in Figure 3.6. It is divided into two main stages, the first stage is hydraulic simulation, which involves the simulation of the water distribution network using the data collected / available. EPANET (Rossman, 2000)[11] a computer program that performs extended period simulation of hydraulic and water quality behavior within pressurized pipe networks is used, when a successful run is obtained, the network is then exported as an input file for optimization process.

The second stage is the implementation of the Genetic Algorithm. This is achieved by the use of EPANET TOOLKIT, which is a dynamic link library of functions that allows developers to customize EPANET's computational engine for their own specific needs, and OptiGA (Visual Basic ActiveX control for implementation of genetic algorithm) Solomons (2001) [12].

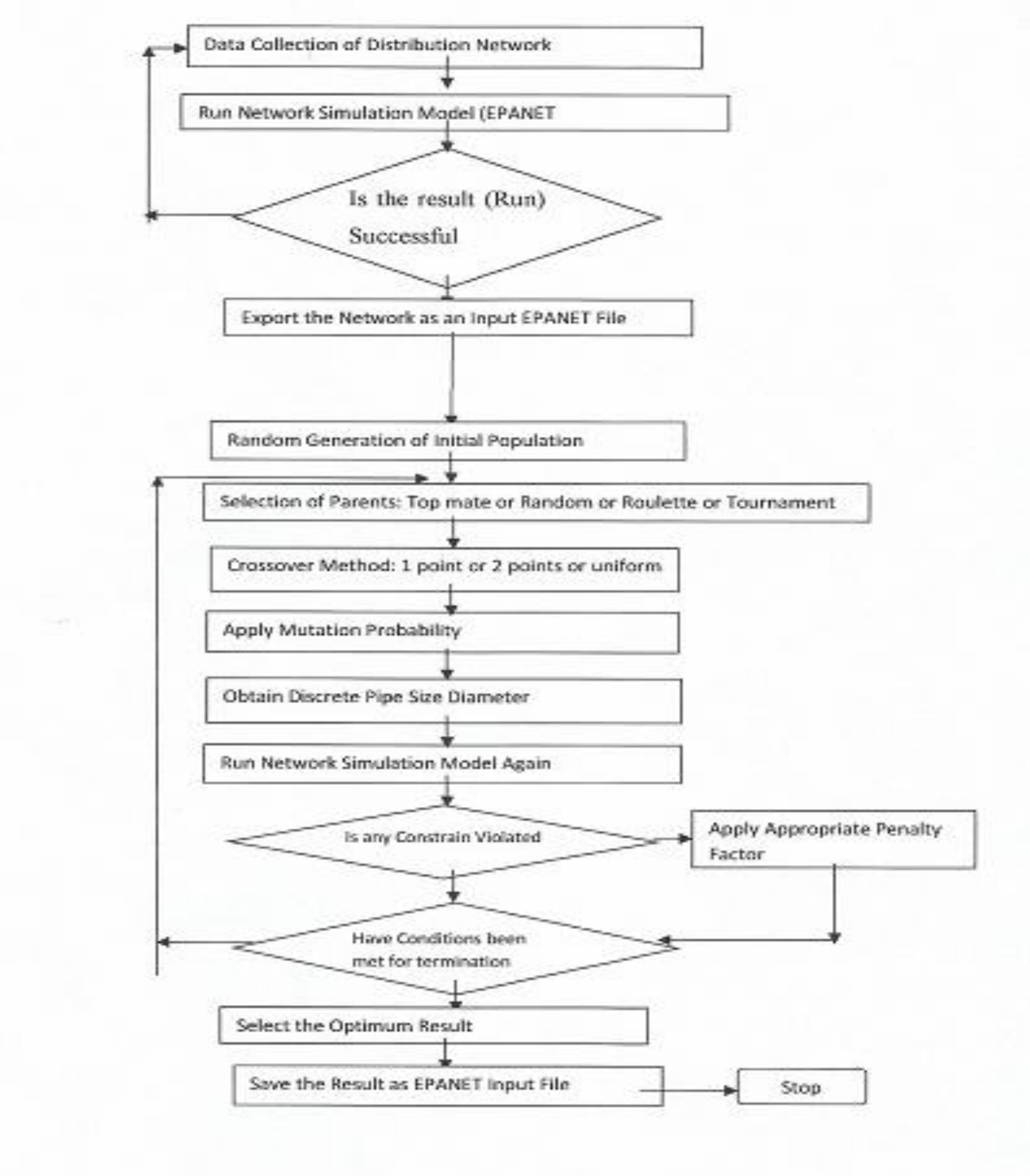

Figure 3. 3: Flowchart for the Modified Software…

3.3 Steps for optiNEtwork software

The following steps are to be taken for the use of OptiNetwork software:

1. Draw the system using EPANET and set system properties.
2. Export the network from EPANET as an INP file to OptiNetwork software directory.
3. Edit the text file called cost.text with appropriate commercial diameters pipes with corresponding cost.
4. Start the program by clicking OPEN, to select the imported file you want to work with and key in the correct number of pipes and nodes in the network.

5. Set constraint that is the design parameters i.e. pressures, velocities and diameters.
6. Set optimization parameters (standard genetic properties), you can change the defaults setting of advanced genetic properties by enabling it.
7. Set the termination mode.
8. Run the simulation.
9. View results using EPANET software.

3.4 THE CASE STUDY AREA

The existing distribution network of Badarawa/ Malali was studied and analyzed. It consists of 96 pipes of different materials,75junctions, two tanks, a source reservoir (i.e treatment plant) from which water is pumped through a pumping main to the overhead reservoir and later distributed to the network by gravity, as shown in (figure 4.1).

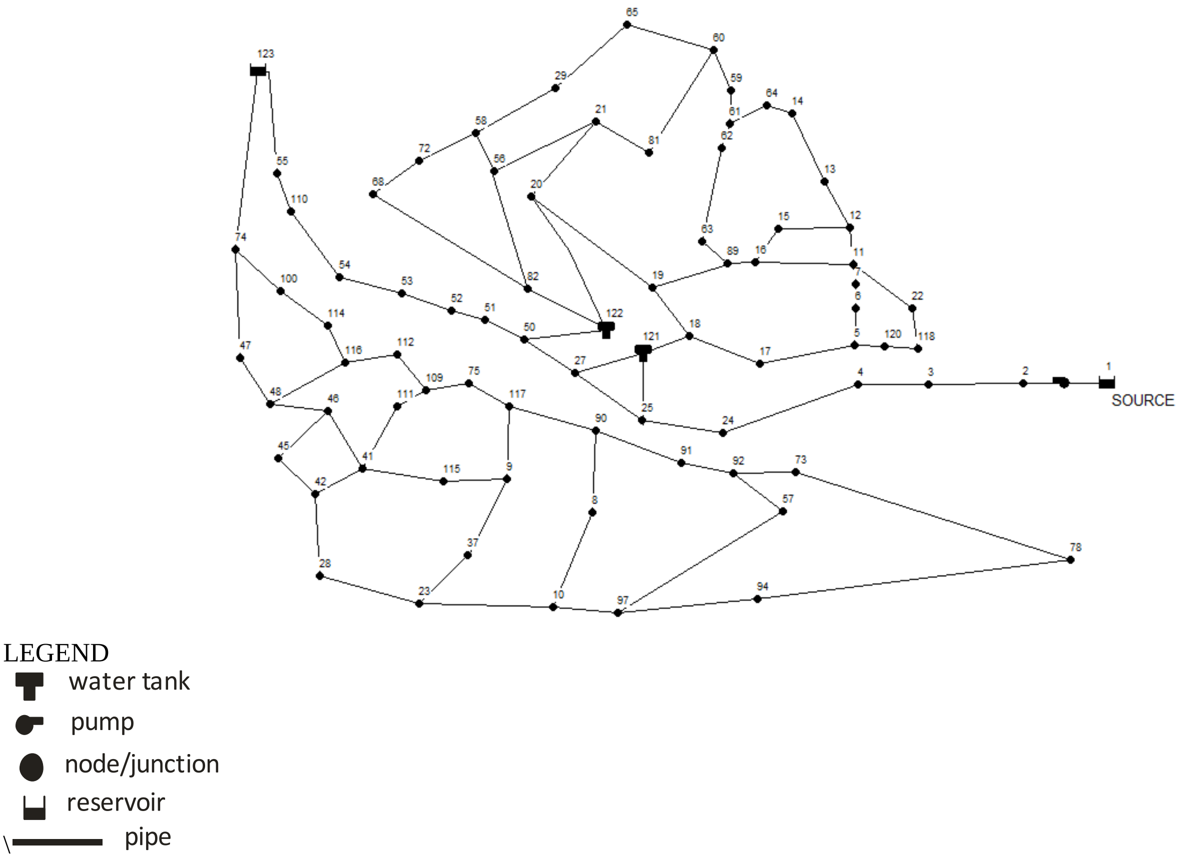

Figure 3.3 Badarawa/ Malali existing water distribution network

IV. RESULTS AND DISCUSSION

After several runs the least-cost obtained from this network using OptiNetwork software under advance genetics algorithm option is $195,200.00, which is much lower than $435,118.00 obtained from OptiDesigner software. Table 4.2 below shows the sample results of first five runs using 3 bits binary representative, different methods of selection and crossover with minimum pressure head of 3m, Pressure penalty of 200,000 and probability of mutation equal to 0.03, commercial diameters 4”, 6”, 8”, 10”, 12”, 14”, 16” 18” 20’’, 22’’and 24’’ d_{min} =4”, d_{max} = 24”. The optimum result from OptiNetwork software was achieved at Topmate selection method, two point crossover method and at mutation probability of 0.03. The commercial available diameters are shown in Table 4.1. And the data for the studied network is shown in Tables 4.3 (in the Appendix).

Table 4.1: Cost of Commercial Available pipe Diameter for Badarawa/ Malali water distribution

Diameter (mm)	Cost per Linear meter ($)
152.40	16
203.20	23
254.00	32
304.80	50
355.60	60
406.40	90
457.20	130
508.00	170
558.80	300
609.60	550

Table 4.2: Cost in $ of Badarawa and Malali Network With two Reservoir using 3 bits binary representative.

One point cross over method

No. of Runs	Top Mate	Roulette Cost	Random	Tournament
1	205,132	201,300	199,500	203,300
2	203,801	203,201	199,700	202,400
3	204,211	203,500	200,800	204,400
4	199,500	205,023	199,200	203,400
5	202,300	207,300	201,800	200,500

Table 4.2: Cost in $ of Badarawa and Malali Network With two Reservoir using 3 bits binary representative (continued).

Two points crossover method

No. of Runs	Top Mate	Roulette Cost	Random	Tournament
1	199,000	200,800	198,200	210,600
2	197,200	199,600	203,800	207,800
3	195,200	198,500	199,500	207,800
4	198,200	197,300	201,000	205,200
5	199,802	199,200	203,200	206,600

Uniform cross over method

No. of Runs	Top Mate	Roulette Cost	Random	Tournament
1	197,900	199,500	200,600	205,205
2	197,600	198,100	201,202	199,406
3	197,600	199,205	200,20.6	199,900
4	198,000	200,700	199,303	201,405
5	198,600	196,700	199,20.9	198,20.5

V. CONCLUSION

This study describes the modification of a computer program, called optiNetwork, which uses Genetic Algorithm for the least-cost design on existing of water distribution system. The modifications provide the options for selection of advanced genetic parameters (Top mate; Roulette cost; Random; Tournament methods; and one point crossover; two points crossover; uniform crossover methods and random seed number).

The performance of the OptiNetwork software was compared with OptiDesigner a commercial software package. The results obtained prove the introduction of the advanced genetics parameters by OptiNetwork is justified, as it has been able to improve the search in terms of achieving least cost of the distribution network.

VI. R ECOMMENDATIONS

Although the present software used only investment cost of pipes in the analysis, it is recommended that further research should be extended to include operational and maintenance cost. Also the use of OptiNetwork software should be encouraged in the design of water distribution network, as it has proved effective in obtaining optimal results satisfying the constraints requirements. Also recommended for solving similar problems in water distribution network

VII. REFRENCES

[1] **Wu, Z.Y., Walski, T.M., Naumick, G., Dugandzic, J., and Nasuti, R.,**"Optimizing Water System Improvement for a Growing Community," *International Conference of Computing and Control in the Water Industry*, Sept.5-7, 2005, Exeter, UK. http://www.genetic-programming.org/hc2005/ OptimalDGN4CCWI05.pdf

[2]. Simpson, A. R., Murphy, L. J., and Dandy G. C. (1993). "Pipe Network Optimization using Genetic Algorithms." Paper presented at ASCE, Water Resources Planning and Management Specialty Conference, ASCE, Seattle, USA.

[3] Simpson, A. R., Dandy G. C., and Murphy, L. J. (1994). "Genetic algorithms compared to other techniques for pipe optimization." J. Water Resour. Plng. and Mgmt., ASCE, 120(4), 423-443.

[4] Tospornsampan J, Kita J. Ishii M. and Kitamura. Y [2007]., Split-pipe Design of Water Distribution Networks using a Combination of Tobu Search and genetic Algorithm. International Journal of Computer, Information and Systems Science, and Engineering.

[5] Alperovists, E. and Shamir, U. [1997]. Design of Optimal water distribution systems. Water Resources Research, 1977, 13 (6), 885 – 900.

[6] Fujirawa, O. and Khang, D. B [1990]., A two phase decomposition method for optimal design of looped water distribution networks. Water Resources Research, 1990, 26 (4) 539 – 549.

[7] Dandy G.C, Simpson A. R, and L.J. Murphy L.J [1999]. An Improved Genetic Algorithm for Pipe Network Optimization. Water Resources Research, vol. 157, pp. 221.

[8] Schaake, J. and Lai, D., "Linear Programming and Dynamic Programming –Application of Water Distribution Network Design," Report 116, 1969 (MIT Press: Cambridge, MA).

[9] Walski, T.M., Brill, E.D., Gessler, J., Goulter, I.C., Jeppson, R.M., Lansey, K., Lee, H.L., Liebman, J.C., Mays, L.W., Morgan, D.R., and Ormsbee, L.E., "Battle of the Network Models: Epilogue," Journal of Water Resources Planning and Management, ASCE, Vol. 113(2), 1987,pp. 191-203.

[10] Halhal, D., Walters, G.A., Ouazar, D., and Savic, D.A**.**, "Water Network Rehabilitation with Structured Messy Genetic Algorithm," *J. Water Resources Planning and Management*, ASCE, Vol. 123(3), 1997, pp. 137-146.

[11] Rossman,L.A .(2000) EPANET2, LISERS MANUAL LI.S. Environmental protection Agency, Cincinnati Ohio.

[12] Salomons E. (2001). OptiDesigner Version 1, User Manual http://www.optiwater.com/optidesigner

Table 4.3: Network Data for Badarawa/Malali Water Distribution Network with two Reservoirs. After Optimization.(Using OptiNetwork)

Link ID	Length m	Diameter mm	Roughness mm	Flow LPS	Velocity m/s	Unit Headloss m/km	Friction Factor
Pipe 3	218.88	609.6	0.005	-38.32	0.13	0.03	0.019
Pipe 11	323.23	254	0.005	-6.64	0.13	0.08	0.023
Pipe 12	120.65	508	0.005	-1.41	0.01	0	0
Pipe 13	250.34	101.6	0.005	-6.09	0.75	5.44	0.019
Pipe 14	350.21	406.4	0.005	2.13	0.02	0	0.038
Pipe 15	230.23	101.6	0.005	-0.67	0.08	0.11	0.033
Pipe 19	388.48	101.6	0.005	-12.55	1.55	20.1	0.017
Pipe 20	145.68	101.6	0.005	-16.43	2.03	32.84	0.016
Pipe 22	151.33	355.6	0.005	30.9	0.31	0.24	0.018
Pipe 23	540.56	101.6	0.005	-40.97	5.05	176.89	0.014
Pipe 24	230.56	508	0.005	-43.32	0.21	0.08	0.018
Pipe 26	202.41	101.6	0.005	-13.38	1.65	22.6	0.017
Pipe 43	170.88	355.6	0.005	-17.25	0.17	0.09	0.02
Pipe 8	123.54	101.6	0.005	-5.24	0.65	4.16	0.02
Pipe 46	535.74	152.4	0.005	-37.16	2.04	20.42	0.015
Pipe 47	118.59	406.4	0.005	-29.27	0.23	0.12	0.018
Pipe 48	175.18	101.6	0.005	-20.18	2.49	47.84	0.015
Pipe 57	240.12	101.6	0.005	10.11	1.25	13.59	0.017
Pipe 58	134.77	101.6	0.005	12.27	1.51	19.29	0.017
Pipe 62	125.76	457.2	0.005	-20.96	0.13	0.04	0.02
Pipe 63	75.43	101.6	0.005	-18.71	2.31	41.67	0.016
Pipe 64	240.25	355.6	0.005	-2.47	0.02	0	0.035
Pipe 66	101.45	101.6	0.005	0.18	0.02	0.01	0.031
Pipe 67	278.9	508	0.005	13.69	0.07	0.01	0.023
Pipe 68	102.33	457.2	0.005	-7.42	0.05	0.01	0.026
Pipe 74	230.79	609.6	0.005	-3.16	0.01	0	0.033
Pipe 75	160.23	508	0.005	-5.51	0.03	0	0.031

Pipe 76	1350.68	203.2	0.005	75.45	2.33	18.51	0.014
Pipe 84	90.22	101.6	0.005	-14.91	1.84	27.52	0.016
Pipe 87	42.84	152.4	0.005	-26.92	1.48	11.33	0.016
Pipe 94	200.12	508	0.005	2.83	0.01	0	0.038
Pipe 16	1400	101.6	0.005	-51.71	6.38	273.03	0.013
Pipe 1	220.23	203.2	0.005	-233.18	7.19	150.89	0.012
Pipe 60	450.43	558.8	0.005	50.37	0.21	0.07	0.017
Pipe 77	250.12	609.6	0.005	48.02	0.16	0.04	0.018
Pipe 95	280.12	152.4	0.005	45.67	2.5	29.82	0.014
Pipe 96	1000	254	0.005	23.79	0.47	0.77	0.017
Pipe 97	200.65	101.6	0.005	21.44	2.64	53.47	0.015
Pipe 98	240.65	406.4	0.005	25.12	0.19	0.09	0.019
Pipe 99	230.65	304.8	0.005	22.67	0.31	0.29	0.018

Table 4.3: Network Data for Badarawa/Malali Water Distribution Network with two Reservoirs. After Optimization.(Using OptiNetwork)(continued).

Link ID	Length m	Diameter mm	Roughness mm	Flow LPS	Velocity m/s	Unit Headloss m/km	Friction Factor
Pipe100	150.77	152.4	0.005	21.94	1.2	7.81	0.016
Pipe101	200.99	406.4	0.005	12.65	0.1	0.03	0.022
Pipe102	200.12	254	0.005	10.3	0.2	0.17	0.021
Pipe103	230.43	254	0.005	4.55	0.09	0.04	0.025
Pipe123	100.54	101.6	0.005	-10.02	1.24	13.35	0.017
Pipe126	350.12	101.6	0.005	-46.76	5.77	226.25	0.014
Pipe127	400.12	101.6	0.005	-49.01	6.04	246.99	0.013
Pipe128	200	304.8	0.005	-6.23	0.09	0.03	0.024
Pipe129	280.79	254	0.005	-8.93	0.18	0.13	0.021
Pipe137	135.35	152.4	0.005	4.13	0.23	0.39	0.023
Pipe138	200.43	609.6	0.005	1.48	0.01	0	0.174
Pipe139	250.35	558.8	0.005	-1.22	0	0	0.131
Pipe140	120.32	254	0.005	3.62	0.07	0.03	0.027
Pipe141	110.11	101.6	0.005	1.07	0.13	0.25	0.029
Pipe142	100.32	101.6	0.005	-1.58	0.19	0.5	0.026
Pipe143	2600.54	203.2	0.005	-0.35	0.01	0	0.032
Pipe144	300.12	254	0.005	-3.05	0.06	0.02	0.028
Pipe 5	70.21	101.6	0.005	-25.03	3.09	71.09	0.015
Pipe 10	80.12	101.6	0.005	-36.16	4.46	140.23	0.014
Pipe 18	70.32	101.6	0.005	-38.86	4.79	160.3	0.014
Pipe 29	100.22	101.6	0.005	-41.66	5.14	182.44	0.014
Pipe 49	210.99	101.6	0.005	18.24	2.25	39.76	0.016
Pipe 51	100.43	558.8	0.005	15.99	0.07	0.01	0.021
Pipe 4	420	203.2	0.005	10.1	0.31	0.48	0.02
Pipe 6	400	406.4	0.005	3.2	0.02	0	0.029
Pipe 9	600	101.6	0.005	-44.11	5.44	202.93	0.014
Pipe 17	220	609.6	0.005	19.43	0.07	0.01	0.022
Pipe 50	220	101.6	0.005	8.47	1.05	9.86	0.018
Pipe 53	110	609.6	0.005	67.57	0.23	0.08	0.017
Pipe 55	110	254	0.005	34.42	0.68	1.5	0.016

Table 4.3: Network Data for Badarawa/Malali Water Distribution Network with two Reservoirs. After Optimization.(Using OptiNetwork) (continued).

Link ID	Length m	Diameter mm	Roughness mm	Flow LPS	Velocity m/s	Unit Headloss m/km	Friction Factor
Pipe 56	380	101.6	0.005	15.64	1.93	30.03	0.016
Pipe 59	89	101.6	0.005	1.53	0.19	0.47	0.026
Pipe 70	150	152.4	0.005	32.49	1.78	15.96	0.015
Pipe 73	260	101.6	0.005	4.5	0.56	3.18	0.021
Pipe 79	200	406.4	0.005	22.43	0.17	0.07	0.019
Pipe 80	380	254	0.005	2	0.04	0.01	0.031
Pipe 81	300	152.4	0.005	0.55	0.03	0.01	0.041
Pipe 82	60	558.8	0.005	10.99	0.04	0	0.027
Pipe 83	270	457.2	0.005	8.54	0.05	0.01	0.025
Pipe 86	200	152.4	0.005	-3.92	0.22	0.36	0.023
Pipe 90	380	101.6	0.005	8.06	0.99	9.01	0.018
Pipe 91	250	101.6	0.005	-1.62	0.2	0.52	0.026
Pipe 92	300	101.6	0.005	4.03	0.5	2.61	0.021
Pipe 93	260	304.8	0.005	6.94	0.1	0.04	0.023
Pipe104	200	101.6	0.005	6.87	0.85	6.77	0.019
Pipe105	300	355.6	0.005	4.17	0.04	0.01	0.027
Pipe106	390	254	0.005	3.31	0.07	0.02	0.027
Pipe107	200	304.8	0.005	4.85	0.07	0.02	0.026
Pipe108	300	203.2	0.005	4.24	0.13	0.1	0.024
Pipe109	1000	101.6	0.005	1.68	0.21	0.56	0.026
Pipe110	280	508	0.005	10.86	0.05	0.01	0.024
Pipe111	200	558.8	0.005	8.21	0.03	0	0.029
Pipe 2	350	152.4	0.005	35.97	1.97	19.23	0.015
Pipe 7	120	101.6	0.005	12.87	1.59	21.06	0.017
Pipe 21	110	609.6	0.005	-10.22	0.04	0	0.026
Pipe 25	200	101.6	0.005	8.95	1.1	10.9	0.018
Pump52	#N/A	#N/A	#N/A	197.21	0	-33.23	0

Table 4.3 Network Data for Badarawa/Malali Water Distribution Network with two Reservoirs. After Optimization.(continued)

Node ID	Elevation m	Demand LPS	Head m	Pressure m
Junc 2	600	0	615.23	15.23
Junc 3	610	2.35	621.96	11.96
Junc 4	611	2.65	621.97	10.97
Junc 5	655	2.35	712.03	57.03
Junc 6	660	2.55	712.03	52.03
Junc 7	665	2.65	712	47
Junc 11	667	2.55	712.05	45.05
Junc 12	650	2.55	712.05	62.05
Junc 13	703	2.45	713.41	10.41
Junc 14	704	2.45	713.41	9.41
Junc 15	700	2.8	712.05	12.05

Junc 16	675	2.7	712.07	37.07
Junc 17	685	2.45	712.23	27.23
Junc 18	710	2.35	720.04	10.04
Junc 19	715	2.35	724.83	9.83
Junc 20	720	2.25	724.99	4.99
Junc 21	700	2.55	724.95	24.95
Junc 22	660	2.7	711.98	51.98
Junc 24	650	2.35	717.59	67.59
Junc 25	700	2.55	717.61	17.61
Junc 27	718	2.7	722.18	4.18
Junc 37	1351	2.35	1404.36	53.36
Junc 41	1351	2.7	1405.14	54.14
Junc 42	1352	2.8	1405.16	53.16
Junc 45	1353	2.35	1405.64	52.64
Junc 46	1355	2.65	1405.66	50.66
Junc 47	1360	2.25	1424.98	64.98
Junc 48	1353	2.45	1416.6	63.6
Junc 50	700	2.65	727.17	27.17
Junc 51	720	2.7	738.41	18.41
Junc 52	730	2.8	749.68	19.68
Junc 53	755	2.45	767.96	12.96
Junc 54	800	2.65	889.72	89.72
Junc 55	1000	2.7	1067.76	67.76
Junc 56	700	2.35	721.69	21.69
Junc 58	700	2.55	719.09	19.09

Node ID	Elevation m	Demand LPS	Head m	Pressure m
Junc 59	690	2.25	716.56	26.56
Junc 60	712	2.45	716.56	4.56
Junc 61	693	2.55	713.42	20.42
Junc 62	685	2.65	713.42	28.42
Junc 63	692	2.65	713.42	21.42
Junc 64	696	2.7	713.41	17.41
Junc 65	713	2.8	716.57	3.57
Junc 68	701	2.55	719.09	18.09
Junc 72	701	2.35	719.09	18.09
Junc 73	1353	2.55	1403.79	50.79
Junc 74	1400	2.65	1424.99	24.99
Junc 75	1354	2.45	1405.08	51.08
Junc 78	1351	2.35	1403.78	52.78
Junc 81	709	2.25	716.57	7.57
Junc 82	700	2.35	722.52	22.52
Junc 89	673	2.8	713.42	40.42
Junc100	1380	2.35	1424.96	44.96
Junc109	1349	2.55	1405.1	56.1
Junc110	880	2.25	968.93	88.93
Junc111	1355	2.7	1405.11	50.11
Junc112	1355	2.35	1415.83	60.83
Junc114	1360	2.35	1424.95	64.95
Junc115	1351	2.65	1405.14	54.14
Junc116	1353	2.45	1416.6	63.6
Junc117	1353	2.35	1405.01	52.01
Junc118	654	2.7	711.98	57.98
Junc120	655	2.65	711.98	56.98
Junc 90	1352	2.35	1403.83	51.83
Junc 91	1351	2.35	1403.83	52.83
Junc 92	1351	2.55	1403.79	52.79
Junc 94	1350	2.7	1403.78	53.78
Junc 97	1349	2.35	1403.79	54.79
Junc 57	1350	2.65	1403.79	53.79
Junc 8	1350	2.7	1403.83	53.83
Junc 9	1352	2.55	1405.14	53.14
Junc 10	1350	2.7	1403.79	53.79
Junc 23	1349	2.55	1403.8	54.8
Junc 28	1350	2.7	1403.81	53.81
Junc 29	703	2.65	716.57	13.57
Resvr123	1450	-127.16	1450	0
Resvr 1	582	35.97	582	0
Tank 122	715	-74.01	725	10