 doi:10.20944/preprints202201.0430.v1

Article

Optimization of water distribution networks using Genetic Algorithm based SOP–WDN program

Uchit Sangroula [1], Kuk-Heon Han [2], Kang-Min Koo [1], Kapil Gnawali [1], and Kyung-Taek Yum [1, *]

[1] Graduate School of Water Resources, Sungkyunkwan University, Suwon 16419, Korea; uchit@skku.edu; koo00v@skku.edu; kapil@g.skku.edu
[2] Smart Water Technology and Consulting, Ltd., Incheon 21315, Korea; kuk0904@skku.edu
* Correspondence: kwfyum@skku.edu; Tel.: +82-31-290-7645

Abstract: Water distribution networks are vital infrastructure, needed for providing consumers with sufficient water of appropriate quality. The cost of construction, operation, and maintenance of such networks is extremely large. The problem of optimization of a water distribution network is governed by the type of water distribution network and the size of pipelines placed in the distribution network. This problem of the optimal diameter allocation of pipes in a distribution network has been heavily researched over the past few decades. This study describes the development of a computer program, 'Smart Optimization Program for Water Distribution Networks' (SOP–WDN), which applies Genetic Algorithm to the problem of the least-cost design of water distribution networks. SOP–WDN demonstrates the application of an evolutionary optimization technique, Genetic Algorithm, linked with a hydraulic simulation solver EPANET, for the optimal design of water distribution networks. The developed program was applied to three benchmark water distribution network optimization problems and produced consistently good results. SOP–WDN can be utilized as a tool for guiding engineers during the design and rehabilitation of water distribution pipelines.

Keywords: Water distribution networks, Optimization, Genetic Algorithm, EPANET

1. Introduction

A Water Distribution Network (WDN) is comprised of various elements, such as reservoirs, pumps, pipes, tanks, and valves. Around 80 % of the total cost of a water supply project is invested in its water distribution system [1]. Hence the design of a cost-effective and reliable water distribution network is a must. Optimization of the WDN involves the design of a reliable, efficient, and cost-effective distribution network that fulfils the necessary water demands, while maintaining adequate pressure heads.

Over the years, numerous researchers have presented many different methods for obtaining the optimal solution to the pipe network optimization problem. The Hardy cross method is considered as the oldest method for solving a pipe network. In this method, at any pipe junction, the algebraic sum of flow must be zero, and the algebraic sum of pressure drops at any loop must also be zero [2]. This method was improved upon by many other researchers. Alperovits and Shamir [3] proposed one of the most significant approaches for solving the problem of water distribution network design by utilizing the successive Linear Programming Gradient (LPG) method. This method was adopted and further expanded upon by other researchers [4, 5].

However, deterministic methods, such as linear programming and non-linear programming, presented drawbacks, such as entrapment in local minima, and dependence on the starting point. Hence, they failed to obtain near optimal solutions for complex, multi-objective, real-world pipe network problems. To overcome these drawbacks, researchers began to utilize meta-heuristic algorithms (Genetic Algorithms, Simulated Annealing, etc.) for water network design problems. These techniques include algorithms

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 28 January 2022 doi:10.20944/preprints202201.0430.v1

having some stochastic components. Goldberg and Kuo introduced stochastic methods for the optimization of water distribution networks using the principles of natural selection and genetics [6]. Simpson et al. used simple Genetic Algorithms (GA), and obtained near optimal solution [7], while Simpson et al. [8] compared the GA technique with other methods, such as complete enumeration and non-linear optimization, and concluded that the GA technique generates multiple alternative solutions that are both practical and close to the optimum. The results obtained by Ref. [7] were further improved upon by Dandy et al. [9] 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 [10] that utilizes GA for the least-cost design of pipe networks.

To avoid unfeasible solutions due to the violation of constraints, a penalty factor is necessary during the selection process of GA. Deb and Agrawal [11] developed a niched-penalty method to more effectively solve constrained optimization problems using GAs. Wu and Simpson [12] demonstrated significant improvements in efficiency and robustness for single-objective optimization utilizing a boundary search method. Liong and Atiquzzaman used the Shuffled Complex Evolution (SCE) linked with EPANET hydraulic network solver [13] to obtain the least cost of some well-known water distribution networks in the literature. SCE was demonstrated to be a potential alternative to other optimization algorithms, due to its faster computational speed. Other algorithms, like the Shuffled Frog-Leaping Algorithm (SFLA) by Eusuff [14] and Harmony Search Algorithm (HS) by Geem [15], have obtained comparable results, and proven to be effective tools for the optimal design of water networks.

Some studies consider a single economic objective (least-cost) to formulate the network optimization and rehabilitation problem, whereas others consider a multi-objective optimization approach that compares interesting trade-offs (e.g., a slight pressure deficit can sometimes be outweighed by substantial cost reduction) [16]. To improve network reliability, Chandramouli and Malleswararao [17] used fuzzy logic based on the excess pressure available at demand nodes. Jin et al. analyzed additional objectives, like considering both pressure and velocity violations [18]. More recent developments include improving algorithm convergence by using an engineered initial population, rather than a random one [19], and improvement of computational efficiency via the reduction of search space [20].

1.1. Problem Formulation

Cost-effective WDN design is a discrete optimization problem, as the individual pipe sizes are to be selected from a list of available commercial size diameters. The search space can be determined as the number of available diameters, raised to the power of the number of pipes in the network [21]; e.g., if 8 different commercial pipe sizes are available for the design of a WDN having 10 pipelines, the search space size would be 8^{10}, i.e., 1,073,741,824 different pipe combinations. Hence, even for a relatively small pipe network, the search space is large. The design of an economically optimal water distribution network is a difficult task, because it involves solving many complex, non-linear, and discontinuous hydraulic equations, while simultaneously optimizing pipe sizes and other network components [22, 23].

Optimization of a water distribution network aims to find the optimal pipe diameters in the network for the given layout and demand requirements. The optimal pipe sizes that satisfy all implicit constraints (conservations of mass and energy), and explicit constraints (hydraulic and design constraints) are selected in the final network.

The continuity equation is given as:

$$\sum_{i=1}^{n} q_i = 0 \tag{1}$$

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 28 January 2022 doi:10.20944/preprints202201.0430.v1

The continuity equation is applied to each node, with q_i being the flow rate (flow into and flow out of the node), and n the number of pipes connected at the node.

The energy equation is given as:

$$\sum_{i=1}^{m} h_i = 0 \tag{2}$$

The energy equation is applied to each loop in the distribution network, where h_i is the head loss in each pipe, and m the number of pipes in the loop.

The objective function is the total cost of the given network. The total cost CT is calculated as:

$$C_T = \sum_{i=1}^{N_p} C_i(D_i).L_i \tag{3}$$

where, N_P is the total number of pipes, $C_i\ (D_i)$ the cost per unit length of pipe i with diameter D_i, and L_i the length of pipe i. The objective function is to be minimized under the implicit constraints and explicit constraints.

The head loss is the sum of the local head losses and the friction head losses. The equation used to calculate the head loss is the Hazen–Williams (H–W) equation:

$$h_f = 4.72C^{-1.85}Q^{1.85}D^{-4.87}L \tag{4}$$

where, h_f is the head loss, Q the flow rate, C the Hazen–Williams coefficient, D the pipe inside diameter, and L the pipe length.

2. Materials and Methods

2.1. Genetic Algorithm

Genetic Algorithm (GA) is a search algorithm based on the mechanics of natural selection and natural genetics [24]. Although stochastic at certain aspects, genetic algorithm is not entirely random, as it utilizes historical information to determine new search points. GA has been widely utilized to solve optimization problems in multiple fields [25]. Following the concept of 'survival of the fittest', improvements in solutions evolve from past generations, until a near optimal solution is obtained. In Genetic Algorithm, the candidate solutions are represented by chromosomes (e.g., binary strings), and are collectively known as the population. The chromosomes are then evolved in each subsequent generation, according to their fitness. The fitness evaluation of each candidate solution depends upon how well it the meets the requirements of a pre-defined objective function (e.g., lowest cost). The fitter the candidate solution, the more probability it will have of being selected for reproduction. Hence, the fitter chromosomes replace the less fit chromosomes, and the process continues until a near optimal solution is found.

The general idea of GA in a pipe network optimization problem is to select a population of initial solution points, scattered randomly in the optimization space, and then converge iteratively to better solutions, until the desired criteria for stopping are achieved. The steps for using GA for pipe network optimization can be briefly described as follows [7]:

1. Generation of initial population

The GA randomly generates an initial population of coded strings (binary) representing pipe network solutions of population size N. Each of the N strings represents a possible combination of pipe sizes.

2. Computation of network cost

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 28 January 2022 doi:10.20944/preprints202201.0430.v1

For each N string in the population, the GA decodes each substring into the corresponding pipe size, and computes the total network cost (material cost, construction cost, etc.).

3. Hydraulic analysis of each network

A steady state hydraulic network solver computes the heads and discharges under the specified demand patterns for each of the network designs in the population. The actual nodal pressures are compared with the minimum allowable pressure heads, and any pressure deficits are noted. Similarly, maximum allowable velocities and velocity defects in the network are also noted.

4. Computation of penalty cost

The GA assigns a penalty cost for each individual network design in the population if a pipe network does not satisfy the pressure and velocity constraints (for example, pressure violation at a particular node if the pressure in the node is less or greater than the desired pressure).

5. Computation of total network cost

The total cost of each network in the current population is then taken as the sum of the network cost (Step 2) and the penalty cost (Step 4).

6. Computation of the fitness

The fitness of the coded string is taken as some function of the total network cost. For each proposed pipe network in the current population, fitness can be computed as the inverse or the negative value of the total network cost (Step 5).

7. Generation of a new population using the selection operator

The GA generates new members for the next generation by a selection scheme that depends on the fitness of the initial members.

8. The crossover operator

Crossover occurs with some specified probability for each pair of parent strings selected in Step 7. A uniform type of crossover operator is commonly used to accompany the comparatively large string size for pipe network optimization.

9. The mutation operator

Mutation occurs with some specified probability of mutation for each bit in the strings that have undergone crossover. The purpose of mutation operator is to maintain genetic diversity from one generation of a population to another.

10. Production of successive generations

The use of the three operators described above produces a new generation of pipe network designs using Steps 2 to 9. The GA repeats the process to generate successive generations. The final costs and pipe network designs are stored, and as cheaper cost alternatives that meet the required constrains are generated, updated.

2.2. EPANET

EPANET is a computer program that can perform extended hydraulic and water quality simulations for pressurized water distribution networks (Rossman, [26]). Generally, a water distribution network consists of many elements, such as pipes (links), pipe junctions (nodes), pumps, control valves, and tanks/reservoirs. EPANET solves the water distribution network for the flow of water in each pipe, pressure at each junction, water height in each tank, concentration of chemical species, etc. During the hydraulic analysis of the water distribution network, EPANET solves both the conservation of mass and energy equations.

EPANET–MATLAB Toolkit is an open-source software for interfacing a drinking water distribution system simulation library, EPANET, with the MATLAB technical computing language developed by Eliades [27]. The Toolkit allows users to access EPANET and EPANET-MSX through their shared object libraries, as well as their executables. EPANET can be called and used through a programming interface by an external software, which can be written in different programming languages (such as C/C++, Python, or MATLAB).

doi:10.20944/preprints202201.0430.v1

Generally, a large number of commands have to be written to achieve specific results, such as extracting the node pressures, pipe diameters, pipe roughness coefficients, or specifying demand patterns. However, in the EPANET–MATLAB toolkit, a significant part of the repetitive code is already included in the toolkit functions, and can be used directly.

2.3. SOP–WDN

Smart Optimization Program for Water Distribution Networks (SOP–WDN) is a computer program that has been developed by Smart Water Grid (SWG) research works for water distribution network optimization by using Genetic Algorithm. The program is written in MATLAB programming language. The program uses EPANET toolkit (a free open-source hydraulic solver) for steady state hydraulic simulation and solution. Before running the program, the network layout and network data must be imported as an .INP file from EPANET. Design parameters, such as available pipe sizes, respective cost of pipes, roughness coefficient, and required pressure and velocities for the network, should also be added. GA optimization parameters, such as population size, crossover probability, and mutation rate, are prerequisites to run the program, and are set to be altered by the user. Figure 1 shows a flowchart of the overall program:

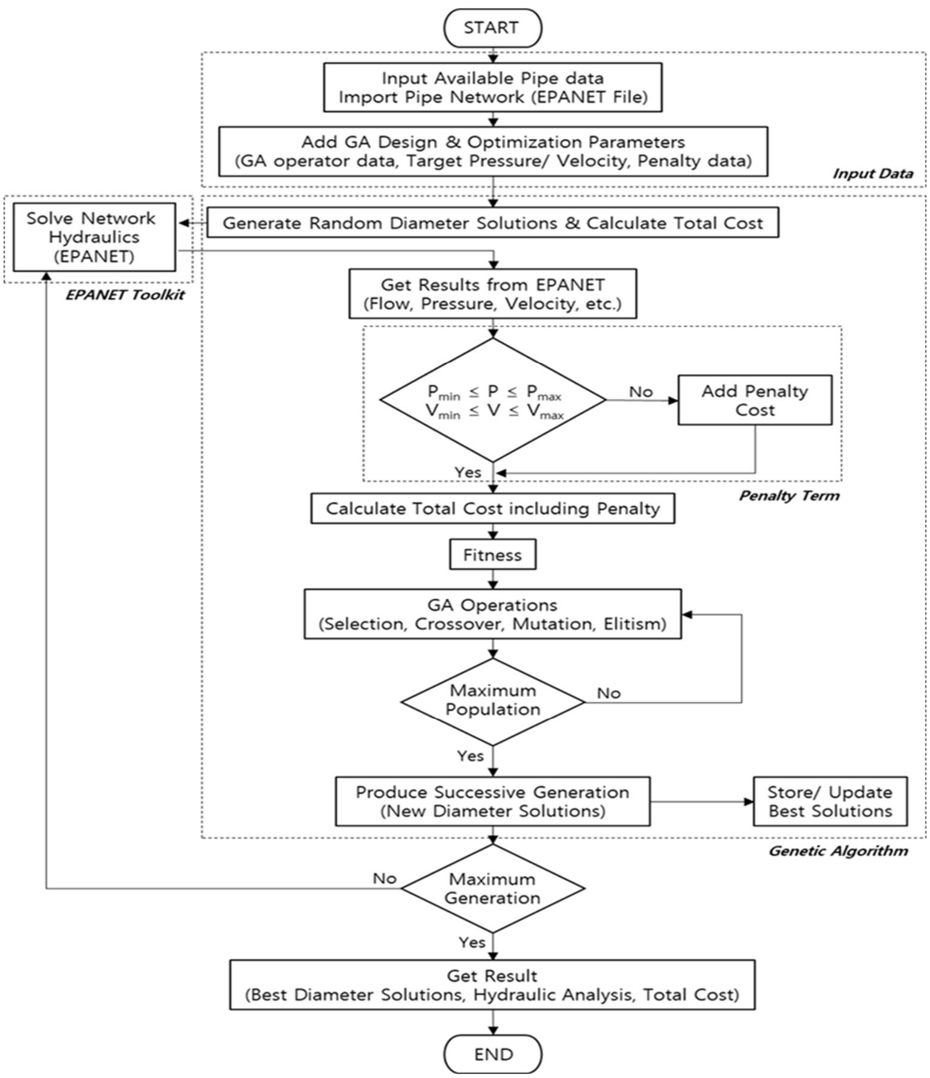

Figure 1. General Flowchart of the SOP–WDN program.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 28 January 2022 doi:10.20944/preprints202201.0430.v1

The following Eqs. (5) & (6) are used to calculate the penalty cost [28]. The penalty equation for violation of pressure constraint in the water distribution network implemented by SOP–WDN can be represented as:

$$P_P = 1 + \sum_{j=1}^{N_n} |T_P - P_j|.P_{P1} + \sum_{j=1}^{N_n} |T_P - P_j|.P_{P2} \quad (5)$$

where, N_n is the number of nodes in the network, P_P the pressure penalty, P_j the pressure of node j, T_P the target pressure, P_{P1} the pressure penalty coefficient if the pressure at the node is above the target pressure, and P_{P2} the pressure penalty coefficient if the pressure at the node is below the target pressure.

The penalty equation for the violation of velocity constraint in the distribution network implemented by SOP–WDN can be represented as:

$$V_P = 1 + \sum_{i=1}^{N_p} |T_V - V_i|.V_{P1} + \sum_{i=1}^{N_p} |T_V - V_i|.V_{P2} \quad (6)$$

where, N_p is the number of pipes in the network, V_P the Velocity penalty, V_i the flow velocity at link i, T_V the target velocity, V_{P1} the velocity penalty coefficient if the velocity at a given link is above target velocity, and V_{P2} the velocity penalty coefficient if the velocity at the link is below target velocity.

The program computes the fitness of each member of the population as the reciprocal of the total cost (including penalty) with an exponent that is based on the number of pipes in the distribution network. The fitness values of all the population are then normalized, and a multiplier (based on average fitness) is utilized to multiply each of the normalized fitness values of the population.

3. Results and discussion

The conventional approach when testing the functionality, validity, and efficiency of a developed optimization program is to choose some benchmark WDN problems, and obtain their solution. Benchmark water distribution networks have provided a common testbed for newly developed optimization algorithms and design approaches. To prove their significance, the developed Metaheuristic Optimization Algorithms are applied to benchmark WDN problems and are compared to the existing algorithms. Using SOP–WDN, some benchmark networks of the literature have been examined.

3.1. Example 1: Two-loop network

The two-loop network is an imaginary network introduced by Alperovitz and Shamir [3] that consists of 8 pipelines and 7 nodes (with reservoir), all fed by gravity flow from a single reservoir with an elevation of 210 m. All pipes in the layout are 1,000 m in length, and the Hazen–Williams coefficient is 130. The minimum head requirement in each node is 30 m above ground level. The commercially available diameters and the details of the distribution network are described below:

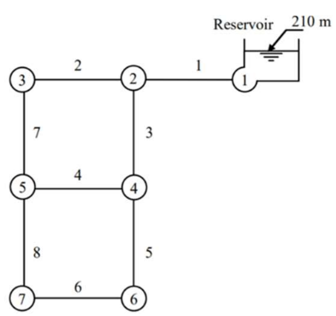

Figure 2. The Two-loop network layout.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 28 January 2022 doi:10.20944/preprints202201.0430.v1

Table 1. Node data for the Two-loop network.

Node No.	Elevation (m)	Demand (m³/h)
1	210	Reservoir
2	150	100
3	160	100
4	155	120
5	150	270
6	165	330
7	160	200

Table 2. Pipe data for the Two-loop network.

Pipe No.	Begin node	End node	Length (m)
1	1	2	1,000
2	2	3	1,000
3	2	4	1,000
4	4	5	1,000
5	4	6	1,000
6	6	7	1,000
7	3	5	1,000
8	5	7	1,000

Table 3. Available pipes for selection for the Two-loop network.

Diameter (in)	Diameter (mm)	Unit cost (USD/m)
1	25.4	2
2	50.8	5
4	101.6	11
6	152.4	16
10	254.0	32
14	355.6	60
16	406.4	90
18	457.2	130

Table 4 gives the solution obtained by SOP–WDN for the Two-loop network, while Fig. 3 shows the EPANET network layout of the solved network, and Table 5 compares the solution obtained from SOP–WDN with the solution obtained by other research reports:

Table 4. SOP–WDN results for the Two-loop network.

Pipe No.	Pipe diameter (mm)	Pipe length (m)	Cost (USD)
1	457.2	1,000	130,000
2	254.0	1,000	32,000
3	406.4	1,000	90,000
4	101.6	1,000	11,000
5	406.4	1,000	90,000

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 28 January 2022 doi:10.20944/preprints202201.0430.v1

6	254.0	1,000	32,000
7	254.0	1,000	32,000
8	25.4	1,000	2000
		Total Cost:	**419,000**

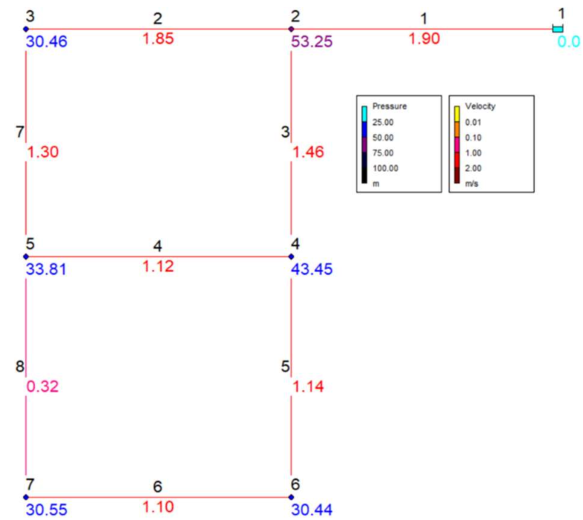

Figure 3. The Two-loop network solution (EPANET map) by SOP–WDN (pressure and velocity).

Table 5. Comparison of SOP–WDN results to past studies for the Two-loop network.

Studies	Alperovitz and Shamir	Savic and Walters	Geem	Van Dijk et al.	SOPWDN
Least cost obtained (USD)	479,525	420,000	419,000	419,000	419,000

The optimal cost of USD 419,000 was obtained, and the minimum pressure requirement of 30 m was fulfilled for all nodes. Table 5 shows the results obtained by other research reports for comparison. SOP–WDN obtained the optimal cost of USD 419,000 for the Two-loop network, which is same as the solution obtained by Geem and Van Dijk et al.

3.2. Example 2: Hanoi network

Hanoi network, located in Vietnam, was first presented by Fujiwara and Kang [29]. It consists of 32 nodes, 34 pipes, and 3 loops, and is fed by gravity from a reservoir with a 100 m fixed head. Table 7 shows the pipe lengths, which have a Hazen–Williams C of 130. The elevation of all nodes is 0 m, and minimum head limitation is 30 m above ground level. The details of the distribution network are described below:

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 28 January 2022 doi:10.20944/preprints202201.0430.v1

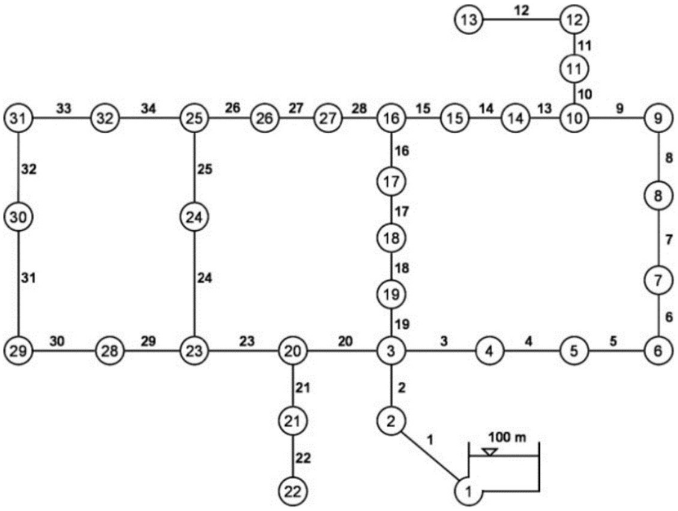

Figure 4. The Hanoi network layout.

Table 6. Node data for the Hanoi network.

Node No.	Demand (m^3/h)
1	Reservoir
2	890
3	850
4	130
5	725
6	1,005
7	1,350
8	550
9	525
10	525
11	500
12	560
13	940
14	615
15	280
16	310
17	865
18	1,345
19	60
20	1,275
21	930
22	485
23	1,045
24	820
25	170
26	900
27	370
28	290
29	360
30	360
31	105

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 28 January 2022 doi:10.20944/preprints202201.0430.v1

32	805

Table 7. Pipe data for the Hanoi network.

Pipe No.	Begin node	End node	Length (m)
1	1	2	100
2	2	3	1,350
3	3	4	900
4	4	5	1,150
5	5	6	1,450
6	6	7	450
7	7	8	850
8	8	9	850
9	9	10	800
10	10	11	950
11	11	12	1,200
12	12	13	3,500
13	10	14	800
14	14	15	500
15	15	16	550
16	17	16	2,730
17	18	17	1,750
18	19	18	800
19	3	19	400
20	3	20	2,200
21	20	21	1,500
22	21	22	500
23	20	23	2,650
24	23	24	1,230
25	24	25	1,300
26	26	25	850
27	27	26	300
28	16	27	750
29	23	28	1,500
30	28	29	2,000
31	29	30	1,600
32	30	31	150
33	32	31	860
34	25	32	950

Table 8. Available pipes for selection for the Hanoi network.

Diameter (in)	Diameter (mm)	Unit cost (USD/m)
12	304.8	45.73
16	406.4	70.40
20	508	98.38
24	609.6	129.33
30	762	180.75
40	1,016	278.28

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 28 January 2022 doi:10.20944/preprints202201.0430.v1

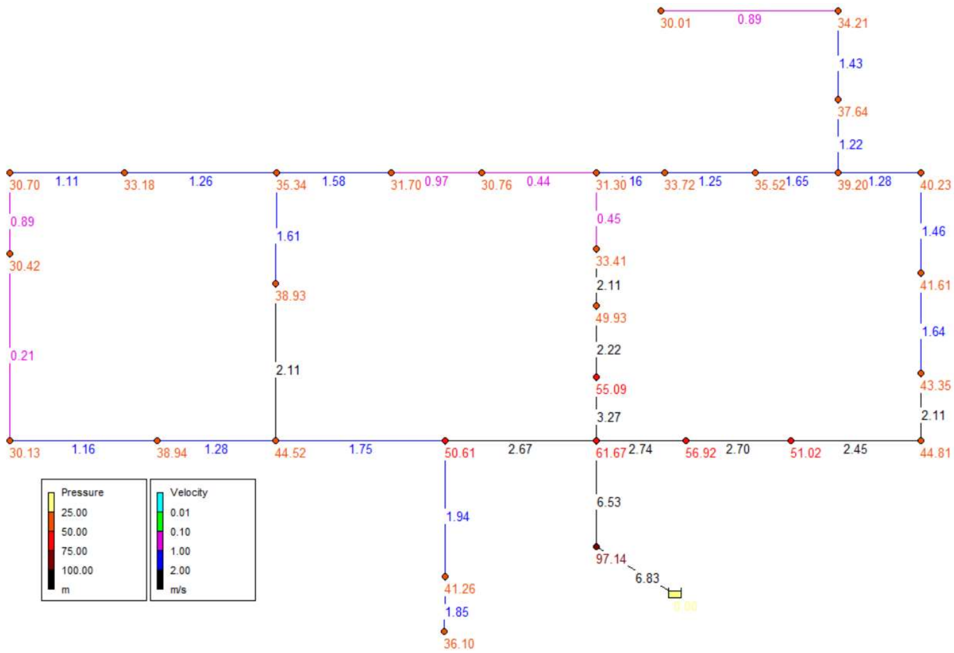

Figure 5. The Hanoi network solution (EPANET map) by SOP–WDN (pressure and velocity).

Table 9 gives the solution obtained by SOP–WDN for the Hanoi network, while Table 10 compares the solution obtained from SOP–WDN with the solution obtained by other research reports.

Table 9. SOP–WDN results for the Hanoi network.

Pipe No.	Pipe diameter (mm)	Pipe length (m)	Cost (USD)
1	1,016	100	27,828
2	1,016	1,350	375,678
3	1,016	900	250,452
4	1,016	1,150	320,022
5	1,016	1,450	403,506
6	1,016	450	125,226
7	1,016	850	236,538
8	1,016	850	236,538
9	1,016	800	222,624
10	762	950	171,712.5
11	609.6	1,200	155,196
12	609.6	3,500	452,655
13	508	800	78,704
14	406.4	500	35,200
15	304.8	550	25,151.5
16	304.8	2,730	124,842.9
17	406.4	1,750	123,200
18	609.6	800	103,464
19	508	400	39,352
20	1,016	2,200	612,216
21	508	1,500	147,570

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 28 January 2022 doi:10.20944/preprints202201.0430.v1

22	304.8	500	22,865
23	1,016	2,650	737,442
24	762	1,230	222,322.5
25	762	1,300	234,975
26	508	850	83,623
27	304.8	300	13,719
28	304.8	750	34,297.5
29	406.4	1,500	105,600
30	304.8	2,000	91,460
31	304.8	1,600	73,168
32	406.4	150	10,560
33	406.4	860	60,544
34	609.6	950	122,863.5
		Total Cost:	**6,081,115.4**

Table 10. Comparison of SOP–WDN results to past studies for the Hanoi network.

Studies	Savic and Walters	Liong and Atiquzzaman	Geem	Van Dijk et al.	SOPWDN
Least cost obtained (Million USD)	6.187	6.220	6.056	6.110	6.081

The optimal cost of USD 6.081 million was obtained, and minimum pressure constraint of 30 m was fulfilled for all nodes. It was observed to be the best solution without the violation of any constraints.

3.3. Example 3: GoYang network

The GoYang water network is located in South Korea, and consists of 30 pipes, 22 nodes, and 9 loops. This network was first introduced by Kim et al. [30] and is fed by a single fixed pump of 4.52 kW from a 71 m constant head reservoir. The H–W coefficient for all pipes in the network is 100. The minimum head limitation for this network is 15 m above ground level. The commercially available diameters for the distribution network and the details of the distribution are described below:

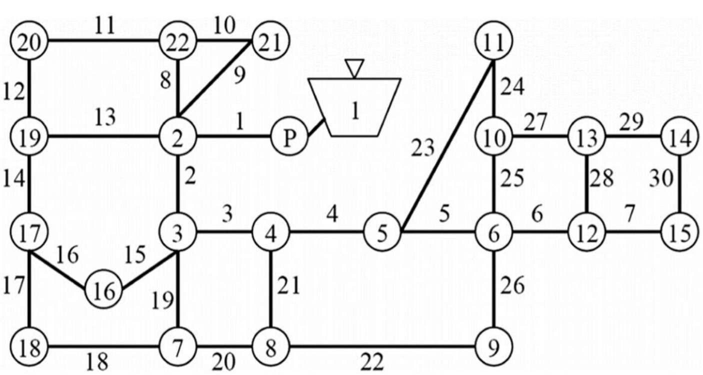

Figure 6. The GoYang network layout.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 28 January 2022 doi:10.20944/preprints202201.0430.v1

Table 11. Node data for the GoYang network.

Node No.	Elevation (m)	Demand (m^3/d)
1	71.0	Reservoir
2	56.4	153.0
3	53.8	70.5
4	54.9	58.5
5	56.0	75.0
6	57.0	67.5
7	53.9	63.0
8	54.5	48.0
9	57.9	42.0
10	62.1	30.0
11	62.8	42.0
12	58.6	37.5
13	59.3	37.5
14	59.8	63.0
15	59.2	445.5
16	53.6	108.0
17	54.8	79.5
18	55.1	55.5
19	54.2	118.5
20	54.5	124.5
21	62.9	31.5

Table 12. Pipe data for the GoYang network.

Pipe No.	Begin node	End node	Length (m)
1	1	2	165
2	2	3	124
3	3	4	118
4	4	5	81
5	5	6	134
6	6	12	135
7	12	15	202
8	2	22	135
9	2	21	170
10	21	22	113
11	22	20	335
12	20	19	115
13	2	19	345
14	19	17	114
15	3	16	103
16	16	17	261
17	17	18	72
18	7	18	373
19	3	7	98
20	7	8	110
21	4	8	98
22	8	9	246
23	5	11	174

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 28 January 2022 doi:10.20944/preprints202201.0430.v1

24	10	11	102
25	6	10	92
26	6	9	100
27	10	13	130
28	12	13	90
29	13	14	185
30	15	14	90

Table 13. Available pipes for selection for the GoYang network.

Diameter (mm)	Unit cost (Won/m)
80	37,890
100	38,933
125	40,563
150	42,554
200	47,624
250	54,125
300	62,109
350	71,524

Table 14 gives the solution obtained by SOP–WDN for the GoYang network, while Fig. 7 shows the EPANET network layout of the solved network. Table 15 compares the solution obtained from SOP–WDN with the solution obtained by other research reports.

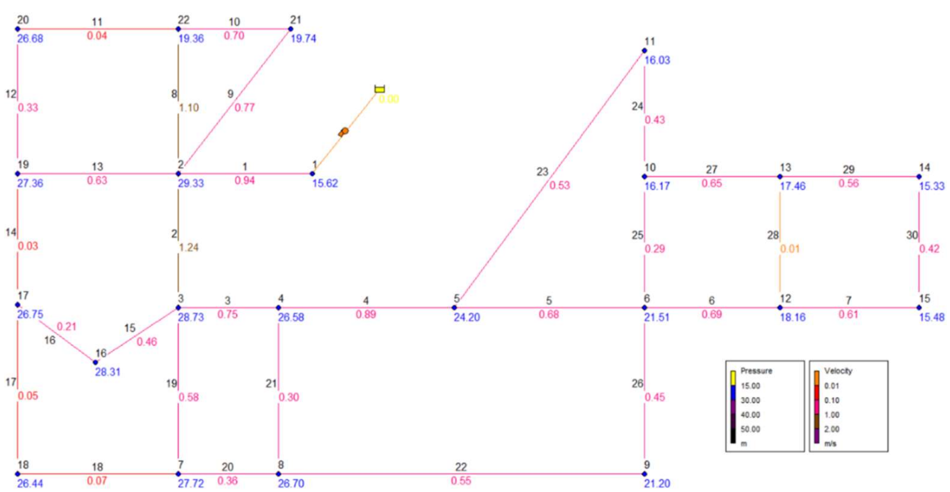

Figure 7. The GoYang network solution (EPANET map) by SOP–WDN (pressure and velocity).

Table 14. SOP–WDN results for the GoYang network.

Pipe No.	Pipe diameter (mm)	Pipe length (m)	Cost (Won)
1	200	165.0	7,857,960
2	125	124.0	5,029,812
3	125	118.0	4,786,434
4	100	81.0	3,153,573

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 28 January 2022 doi:10.20944/preprints202201.0430.v1

5	80	134.0	5,077,260
6	80	135.0	5,115,150
7	80	202.0	7,653,780
8	80	135.0	5,115,150
9	80	170.0	6,441,300
10	80	113.0	4,281,570
11	80	335.0	12,693,150
12	80	115.0	4,357,350
13	80	345.0	13,072,050
14	80	114.0	4,319,460
15	80	103.0	3,902,670
16	80	261.0	9,889,290
17	80	72.0	2,728,080
18	80	373.0	14,132,970
19	80	98.0	3,713,220
20	80	110.0	4,167,900
21	80	98.0	3,713,220
22	80	246.0	9,320,940
23	80	174.0	6,592,860
24	80	102.0	3,864,780
25	80	92.0	3,485,880
26	80	100.0	3,789,000
27	80	130.0	4,925,700
28	80	90.0	3,410,100
29	80	185.0	7,009,650
30	80	90.0	3,410,100
		Total Cost:	**177,010,359**

Table 15. Comparison of the SOP–WDN results to those of past studies of the GoYang network.

Studies	Original Network	Kim et al.	Geem	Menon et al.	SOPWDN
Least cost obtained (Million Won)	179.428	179.142	177.135	177.417	177.010

The lowest cost obtained by SOP–WDN was 177,010,359 Won, which compared to the other studies, is the cheapest cost. The obtained solution also has no nodes containing pressure violations, as all nodes in the distribution network have fulfilled the minimum pressure requirement of 15 m.

4. Conclusions

In this study, the developed Genetic Algorithm based optimization program SOP–WDN was tested on three benchmark water distribution networks, and in comparison to the other studies, it was able to produce competitive results. EPANET software, which was used for the hydraulic analysis and calculations of the water distribution systems is a well-accepted and utilized software. EPANET–MATLAB toolkit enabled the SOP–WDN program to perform EPANET based calculations directly in the MATLAB environment, which improved the overall speed, performance, and efficiency of the program. Hence,

 doi:10.20944/preprints202201.0430.v1

the EPANET–MATLAB toolkit can prove to be an important tool that enables the facile use of EPANET software in the MATLAB environment for many different research purposes. SOP–WDN can be used as a reliable program that can easily be implemented and adapted to aid engineers and designers during the design process of new water distribution networks, or the rehabilitation of existing water distribution networks.

Supplementary Materials: Not applicable.

Author Contributions: Uchit Sangroula developed the SOP–WDN program, and wrote the manuscript of this study; Kuk-Heon Han, Kang-Min Koo, and Kapil Gnawali made recommendations during the writing of the manuscript; Kyung-Taek Yum provided significant suggestions on the methodology and structure of the manuscript. All authors have read and approved the final manuscript.

Funding: This Research has been performed as Project of No A-C-002 supported by K-water.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Datasets that are restricted and not publicly available.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Swamee, P.K.; Sharma, A.K. *Design of water supply pipe networks*. John Wiley & Sons, **2008**.
2. Cross, H. *Analysis of flow in networks of conduits or conductors*. University of Illinois at Urbana Champaign, College of Engineering. Engineering Experiment Station. 1936.
3. Alperovits, E.; Shamir, U. Design of optimal water distribution systems. *Water resources research* **1977**, *13(6)*, 885-900.
4. Goulter, I.C.; Lussier, B.M.; Morgan, D.R. Implications of head loss path choice in the optimization of water distribution networks. *Water Resources Research* **1986**, *22(5)*, 819-822.
5. Quindry, G.E.; Liebman, J.C.; Brill, E.D. Optimization of looped water distribution systems. *Journal of the Environmental Engineering Division* **1981**, *107*(4), 665-679.
6. Goldberg, D.E.; Kuo, C.H. Genetic algorithms in pipeline optimization. *Journal of Computing in Civil Engineering* **1987**, *1*(2), 128-141.
7. Simpson, A.; Murphy, L.; Dandy, G. Pipe network optimisation using genetic algorithms. *American Society of Civil Engineers* **1993**.
8. Simpson, A.R.; Dandy, G.C.; Murphy, L.J. Genetic algorithms compared to other techniques for pipe optimization. *Journal of water resources planning and management* **1994**, *120*(4), 423-443.
9. Dandy, G.C.; Simpson, A.R.; Murphy, L.J. An improved genetic algorithm for pipe network optimization. *Water resources research* **1996**, *32*(2), 449-458.
10. Savic, D.A.; Walters, G.A. Genetic algorithms for least-cost design of water distribution networks. *Journal of water resources planning and management* **1997**, *123*(2), 67-77.
11. Deb, K.; Agrawal, S. A niched-penalty approach for constraint handling in genetic algorithms. *Artificial Neural Nets and Genetic Algorithms* **1996**, 235-243.
12. Wu, Z.Y.; Simpson, A.R. A self-adaptive boundary search genetic algorithm and its application to water distribution systems. *Journal of hydraulic research* **2002**, *40*(2), 191-203.
13. Liong, S.Y.; Atiquzzaman, M. Optimal design of water distribution network using shuffled complex evolution. *Journal of The Institution of Engineers, Singapore* **2004**, *44*(1), 93-107.
14. Eusuff, M.; Lansey, K.; Pasha, F. Shuffled frog-leaping algorithm: a memetic meta-heuristic for discrete optimization. *Engineering optimization* **2006**, *38*(2), 129-154.
15. Geem, Z.W. Optimal cost design of water distribution networks using harmony search. *Engineering optimization* **2006**, *38*(03), 259-277.
16. Di Pierro, F.; Khu, S. T.; Savić, D.; Berardi, L. Efficient multi-objective optimal design of water distribution networks on a budget of simulations using hybrid algorithms. *Environmental Modelling & Software* **2009**, *24(2)*, 202-213.

 doi:10.20944/preprints202201.0430.v1

17. Chandramouli, S.; Malleswararao, P. Reliability based optimal design of a water distribution network for municipal water supply. *International journal of engineering and technology* **2011**, *3(1)*, 13-19.
18. Jin, X.; Zhang, J.; Gao, J. L.; Wu, W. Y. Multi-objective optimization of water supply network rehabilitation with non-dominated sorting genetic algorithm-II. *Journal of Zhejiang University-SCIENCE A* **2008**, *9(3)*, 391-400.
19. Kang, D.; Lansey, K. Revisiting optimal water-distribution system design: issues and a heuristic hierarchical approach. *Journal of Water resources planning and management* **2012**, *138(3)*, 208-217.
20. Cisty, M.; Bajtek, Z.; Celar, L. A two-stage evolutionary optimization approach for an irrigation system design. *Journal of Hydroinformatics* **2017**, *19(1)*, 115-122.
21. Van Dijk, M.; van Vuuren, S. J.; Van Zyl, J. E. Optimising water distribution systems using a weighted penalty in a genetic algorithm. *Water SA* **2008**, *34(5)*, 537-548.
22. Lansey, K. E.; Mays, L. W. Optimization models for design of water distribution systems. *Reliability Analysis of Water Distribution Systems* **1989**. 37-84.
23. Keedwell, E.; Khu, S. T. A hybrid genetic algorithm for the design of water distribution networks. *Engineering Applications of Artificial Intelligence* **2005**, *18(4)*, 461-472.
24. Goldberg, D. E. *A Gentle Introduction to Genetic Algorithms*. Addison-Wesley Publishing Company, **1989**.
25. Abuiziah, I.; Nidal, S. A review of genetic algorithm optimization: operations and applications to water pipeline systems, **2013**.
26. Rossman, L. A. *EPANET 2: user's manual*, 2000
27. Eliades, D. G.; Kyriakou, M.; Vrachimis, S.; Polycarpou, M. M. EPANET-MATLAB toolkit: An open-source software for interfacing EPANET with MATLAB. *Proceedings of the 14th International Conference on Computing and Control for the Water Industry* **2016**.
28. Güç, G. Optimization of water distribution networks using genetic algorithm. Master's thesis, Middle East Technical Univ, **2006**.
29. Fujiwara, O.; Kang, D. B. A two-phase decomposition method for optimal design of looped water distribution networks. *Water Resources Research* **1990**, *26(4)*, 539-549.
30. Kim, J. H.; Kim, T. G.; Kim, J. H.; Yoon, Y. N. A study on the pipe network system design using non-linear programming. *J Korean Water Resource Association* **1994**, 27(4), 59-67.
31. Menon, K. K; Narulkar, S. M. Application of heuristic based algorithm in water distribution network design *Journal of Water Resource Pollution Study* **2016,** 1-14.