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Optimization model the pipe diameter in the drinking water distribution network using multi-objective genetic algorithm

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Abstract

Under conditions of gravity flow, the performance of a distribution pipe network for drinking water supply can be measured by investment cost and the difference in real and target pressures at each node to ensure fairness of the service. Therefore, the objective function for the optimization in the design of a complex gravity flow pipe network is a multi-purpose equation system set up to minimize the above-mentioned two parameters. This article presents a new model as an alternative solution to solving the optimization equation system by combining the Newton–Raphson and genetic algorithm (GA) methods into a single unit so that the resulting model can work effectively. The Newton–Raphson method is used to solve the hydraulic equation system in pipelines and the GA is used to find the optimal pipe diameter combination in a network. Among application models in a complex pipe network consisting of 12 elements and 10 nodes, this model is able to show satisfactory performance. Considering variations in the value of the weighting factor in the objective function, optimal conditions can be achieved at the investment cost factor (ω_1) = 0.75 and the relative energy equalization factor at the service node (ω_2) = 0.25. With relevant GA input parameters, optimal conditions are achieved at the best fitness value of 1.016 which is equivalent to the investment cost of USD 56.67 thous. with an average relative energy deviation of 1.925 m.

Key words: diameter, genetic algorithm, network, Newton–Raphson method, optimum, pipe

INTRODUCTION

One of complexity factors in the design of a drinking water distribution pipe network is caused by the non-linear relationship between the discharge of pipe elements and the difference in relative energy at each network node. In a branched pipe network system, the technical analysis is relatively simpler compared to a closed pipe network system (loop). In a branched network, the hydraulic equation system can be simplified into a linear function, but in a closed network, the solution of the equation system must use a non-linear function approach. Since a complex distribution pipe network is a combination of branched and closed networks, the solution of the equation system must use a non-linear function approach. The design of a complex pipe network system with a large number of pipe elements and service nodes will certainly cause its own prob-

lems in finding the right solution. Various constraints in an effort to achieve optimal conditions also adds complexity to the design process. These problems attract attention of researchers and stimulate in-depth studies, especially concerning the optimization of pipe network performance.

This article is a response to frequent disparities in drinking water supply in developing regions, e.g. the Malang City, East Java, Indonesia. During peak hours of water use, the distribution of the flow is uneven. Some service nodes show little outflow and pressure (under design criteria), whereas as others are redundant. These problems generally occur in small pipelines in small new cluster areas built by developers. In such an area, the partial water supply system utilizes local water sources, most of which abstract water from boreholes. The solution to overcome this problem is actually quite simple. It is sufficient to install valves to regulate discharge and pressure, or to install

pumps in certain places to reduce discharge and pressure gaps. However, the solution is inefficient in terms of investment and operational costs. In our opinion, the problem of even distribution of discharges and water pressures in service nodes can be solved by the application of proportional pipe dimensions. The right combination of pipe diameters is expected to produce pressures on each service nodes that are evenly distributed, follow design criteria, and efficient from the point of view of investment costs.

The determination of the optimum pipe diameter has become an important part in the design of drinking water distribution network, because the cost efficiency and operational performance of the network system remains under a strong influence of pipe diameter combinations. In pipe network systems that rely on gravity flow, optimal pipe diameters can only be determined through optimization techniques that have two objective functions simultaneously. These are the minimization of investment costs and the reduction of the difference in relative energy at each service node with a relative energy target. The constraint function includes the network hydraulic equation system, physical characteristics of the pipe elements and relevant design criteria. The determination of the optimum diameter in a branched pipe network is simpler. The hydraulic pipe network equation system and optimization equations can be brought into a linear form so that linear programming methods with objective functions of minimum investment cost are relevant to solve the developed equation system [BELLO *et al.* 2015; SULIANTO 2015a]. The branched pipe network optimization model that encompasses advantages of the genetic algorithm (GA) also show satisfying results [SULIANTO 2015b].

The revolutionary development of the metaheuristic method turned it into a reliable tool for solving optimization problems in various fields. In water resource development, metaheuristic methods are often used in hydrological modelling, groundwater modelling and optimization of water supply. SOETOPO *et al.* [2018] successfully implemented the GA to build models of the reservoir release rule for irrigation in the Sutami reservoir, Indonesia. KUMAR *et al.* [2015] proposed a hybrid metaheuristic technique for multi-objective optimization of in-situ bioremediation of groundwater. A hybrid metaheuristic technique is a new method developed from the differential evolution algorithm, genetic algorithm and simulated annealing algorithm. In hydrological modelling, the differential evolution (DE) algorithm can effectively optimize the DISPRIN model which encompasses 25 parameters used to transform rainfall into runoff data [SULIANTO *et al.* 2018].

The use of metaheuristic methods to build pipe diameter optimization models in a complex pipe network has also been widely proposed by researchers in various parts of the world in recent decades. The proposed optimization model basically consists of two elements, namely the hydraulic simulation of a pipe network and the process of optimizing the pipe diameter to minimize cost. BELLO *et*

al. [2015] developed a pipe diameter optimization model in a complex pipe network by combining EPANET-based hydraulic simulation methods and pipe diameter optimization using the loop function in Matlab. SOMAIDA *et al.* [2011] has developed the GANEO application program for optimizing pipe diameters. The model is the result of combining the EPANET-based hydraulic simulation and GA-based pipe diameter optimization. MTOLERA *et al.* [2014] developed an optimization model of the irrigation pipe network to optimize the layout of the network and the pipe diameter, but the model was limited to a branching pipe network. The objective function in the form of cost minimization is analysed by involving the GA method and particle swarm optimization (PSO). SHRIVATAVA *et al.* [2015] proposed a pipe diameter optimization model by combining the finite element method for hydraulic simulation and the PSO for the pipe diameter optimization process.

The all-in-one model developed by AKLOG and HOSOI [2017] is an application package for pipe diameter optimization that combines the EPANET application package with the optimization method based on linear programming, GA and the one-by-one heuristic reduction method (OBORM). AFSHAR [2006] proposed the merging of the element-by-element algorithm for solving the hydraulic equation of the pipe and the ant colony optimization (ACO) for the pipe diameter optimization process. ABEBE and SOLOMATINE [1998] proposed a combination of GLOBE optimization methods and EPANET-based network hydraulic simulation models. The GLOBE optimization method was developed by ABEBE and SOLOMATINE [1998] to solve optimization problems with the objective function of cost minimization. The GLOBE optimization method involves four methods, namely: Controlled Random Search (CRS2) [PRICE 1983], CRS4 [ALI, STOREY 1994], GA [GOLDBERG 1989] and Adaptive Cluster Covering with Local Search (ACCOL) [SOLOMATINE 1998]. Results of the study suggest that the GA and ACCOL algorithms show their efficiency and effectiveness. MEMON and NARUKLAR [2016] have reviewed a variety of articles related to the pipe diameter optimization and concluded that the GA is the most desired method by researchers even though it has almost the same performance as other metaheuristic methods.

This article presents a new model for optimizing pipe diameters in a complex pipe network under gravity flow. In this model, the hydraulic equation system of the pipe network is compiled using a non-linear matrix system which is solved using the Newton–Raphson method and the optimization of pipe diameter using the GA. The simulation of hydraulic equation system and the optimization equation system of multi objective based on the GA are arranged as a whole so that the optimization process is accelerated. The model built was then solved by using the program code from M-FILE MATLAB 7.0 due to its practicality, as well as ease in matrix operations and graphic data management.

MATERIALS AND METHOD

SOLUTION OF HYDRAULIC EQUATION SYSTEM IN PIPE NETWORK

The basic principle of flow in the pipe network. The analysis of flow in a pipe network must meet the following basic principles of energy continuity and conservation: 1) flow in the pipe must comply with the laws of high energy loss for a single pipe flow, 2) inflow to the network must equal outflow, and 3) inflow to a node must be the same as the outflow.

Hydraulic equation system in pipe elements. High energy is needed to overcome friction resistance that occurs when water flows in the pipe. The relationship between high energy loss and discharge according to Hazen–William is stated by ABEBE and SOLOMATINE [1998]:

$$Q = \frac{0.278 (C_{HW} D^{2.63}) h f^{0.54}}{L^{0.54}} \quad (1)$$

Where: Q = discharge ($\text{m}^3 \cdot \text{s}^{-1}$), D = pipe diameter (m), hf = energy loss due to boundary friction (m), L = length of pipe elements (m), and C_{HW} = coefficient of pipe wall roughness by Hazen–William.

Furthermore, if

$$k = 0.2785 (C_{HW} D^{2.63} / L^{0.54}), \text{ and } Z = hf \quad (2)$$

then Equation (1) can be simplified into:

$$Q^i = k^i (Z^i)^{0.54} \quad (3)$$

or

$$Q^i = Kt^i (Z^i) \quad (4)$$

Where:

$$Kt^i = \frac{k^i}{(Z^i)^{0.46}} \quad (5)$$

Equation (5) shows that the Kt^i value is not constant, and it is also influenced by the high loss of energy (Z^i) so that the analysis leads to a system of non-linear equations. By using Equation (5), the discharge of element i , which is a function of the high loss of energy in that element, can be calculated. Discharge from an element marked positive (+) if it leaves node k or it is marked negative (–) if it goes to node j that corresponds to energy at node k , which is greater than node j . Discharge entering a node is marked positive (+) and marked negative (–) when leaving the node.

$$Q_k^i = Kt^i dZ_i = Kt^i (Z_k - Z_j) \quad (6)$$

$$Q_j^i = Kt^i dZ_j = Kt^i (Z_j - Z_k) \quad (7)$$

Where: Q_k^i = discharge at node k element i , and Q_j^i = discharge at node j element i .

If the equation system is transformed into a matrix, then:

$$Kt^i \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \begin{bmatrix} Z_k \\ Z_j \end{bmatrix} = \begin{bmatrix} Q_k^i \\ Q_j^i \end{bmatrix} \quad (8)$$

or

$$Q^i = Kt^i Z^i \quad (9)$$

Where: Q^i = node i vector discharge, Kt^i = matrix characteristic element i , and Z^i = a vector of absolute energy at node i .

Hydraulic equation system in a pipe network. According to the law of flow balance, the discharge to a node must be the same as the discharge leaving it. In or out discharge of network is stated in Q_n , it will be positive (+) if the inflow and negative (–) if the flow leaves the node (meaning there is real use). Based on the description the value of discharge from the elements connected to the node value must be the same as the number of discharge exiting the node, thus for each node applies:

$$F_i = \sum Q_k + \sum Q_n = 0 \quad (10)$$

Where: F_i = discharge balance at node i , and $\sum Q_n$ = increase or decrease of discharge at node i .

If the Equation (9) is changed into a matrix symbol then it applies:

$$F = K(Z)Z \quad (11)$$

The solution of a hydraulic equation system in a pipe network with the Newton–Raphson method. The procedure for solving the flow equation system in a pipeline using the Newton–Raphson method is schematically shown in Figure 1. Analysis steps under the Newton–Raphson method are as follows:

- 1) determine the initial Z of any value (Z^i),
- 2) calculate the gradient of line i (Kt^i),
- 3) calculate the F^i from the equation $F^i = Kt^i Z^i$,
- 4) calculate the difference in the balance discharge ΔF^i from the equation $\Delta F^i = F - F^i$,
- 5) calculate ΔZ^i based on the Kt^i equation $\Delta F^i = F - F^i$,
- 6) calculate Z^{i+1} from the equation $Z^{i+1} = Z^i + \Delta Z^i$,
- 7) repeat step (2) to step (6) until the desired tolerance limit is found.

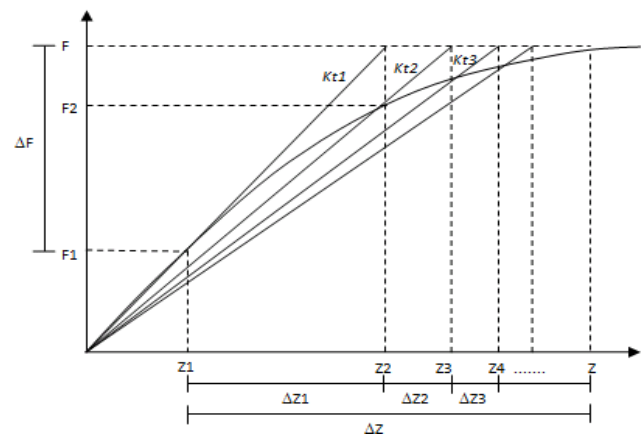


Fig. 1. Iteration in the Newton–Raphson method; source: own elaboration

OPTIMIZATION OF PIPE DIAMETER BASED ON GA

The optimization problem discussed in the article assumes that the pipe network, service node elevation, pipe type and the actual discharge requirements at each node, and the elevation of the water level in reservoir are con-

stant. The flowing system relies on the force of gravity. The purpose of the optimization model is to minimize the pipe network investment cost to ensure efficiency in construction and to minimize the difference between the real relative energy and the target relative energy at each node in the network to ensure fair service. As the limiting function is the continuity of the flow, network hydraulic equations are met, and the minimum diameter and the maximum diameter are applied. The objective function of the optimization model is as follows:

Minimize:

$$f(D_1, \dots, D_m) = \omega_1 \sum u(D_k)L_k + \omega_2 \left(\frac{\sum (Er_j - Er_{target})}{n} \right) \quad (12)$$

subject to the following constraints;

– flow balance at the node:

$$\sum Qin_j = \sum Qout_j \quad (13)$$

– flow balance in the network:

$$F_i = \sum Q_k + \sum Qn_i = 0 \quad (14)$$

– minimum and maximum diameters required, according to available pipe diameter candidates:

$$D_k \in (D_{min}, \dots, D_{max}); k = 1, 2, \dots, m \quad (15)$$

Where: D_k = pipe diameter of element k , L_k = pipe length of element k , ω_1 = weighting factor of cost investment, ω_2 = weight factor of relative energy deviation at each node, $u(D_k)$ = unit price of investment pipe element, Er_j = height of relative energy at node j , Er_{target} = height of relative energy to the targeted at service nodes, n = number of node, m = number of pipe element, D_{min} = minimum pipe diameter, D_{max} = maximum pipe diameter, F_i = flow balance in the pipe network.

The GA is an algorithm that utilizes a natural selection known as the evolutionary process. In the process of evolution, individuals constantly undergo changes in genes to adapt to their environment. “Only strong individuals can survive.” This natural selection process involves changing genes that occur in individuals through the reproductive process. In this genetic algorithm, the breeding process becomes the basic process of primary concern which can be expressed as: “How to get a better offspring”.

The implementation of the GA for solving this case contains eight components analysed consecutively, namely: initialization of population, decoding of chromosome, fitness values, parental selection, crossover, mutation, elitism and population replacement. The relationship between these components is schematically explained in Figure 2. The characteristics of each GA component chosen to resolve the case in this paper can be explained as presented below.

Population initialization. This function aims to generate a population that contains a number of individuals. In the GA implementation, individuals are called chromosomes. Chromosomes represent a candidate for problem solving in a coded form. As in the process of natural evolution, chromosomes are assessed for their fitness level. Only chromosomes with a high fitness level are selected to survive in the population. In this article, chromosomes are

a representation of optimized variables, namely the diameter of pipe elements in the pipe network, so that the number of chromosomes is the same as the number of pipe elements. A genotype (Gen) is a part of the chromosome, which is a value that states the basic unit that forms a certain meaning in the chromosome. In this case, the genes are expressed in binary values. Each chromosome contains a gene, so the mathematically generated population can be expressed in terms of the size matrix [Population x Number of Genes].

Decoding of chromosome. This function aims to decode a chromosome containing binary numbers into an individual with real values in the desired interval. In this function, the term chromosome refers to row vectors containing binary numbers, while individuals refer to the x variable which contains real numbers. The input of this function is a chromosome [matrix measuring = 1 x number of genes], number of variables, number of bits that encode a variable, lower limit of the interval, upper limit of the interval, whereas the output of this function are individual results of chromosome decoding. In solving this case, $x(i)$ is a series of optimal pipe diameters whose values will be sought.

Evaluate individual. This function is to calculate the fitness value of individual x . In this case, the Equation (16) is used:

$$f = \frac{1}{(h+a)} \quad (16)$$

Where: f = fitness value, a = small number, and h = minimize function from Equation (12).

Parental selection. The parental selection process uses the roulette-wheel selection method. As the name implies, this method mimics the roulette-wheel in which each chromosome occupies a circle piece on the wheel, proportionally according to its fitness value. Chromosomes that have a larger value occupy larger pieces of circles compared to chromosomes with low fitness values. In this function, input variables include population size and linear fitness, while the output is P_{index} , which is the index of the selected chromosome or the index of the individual selected as a parent.

Crossover. A chromosome that leads to a good solution can be obtained from the process of crossing two other chromosomes. Cross moves are arranged using a certain probability (pc), meaning that cross moves can be done only if a random number (0, 1) is generated less than the specified pc . In general, the pc is set close to 1. The method of crossing that can be used is to cross one point crossover, which is a cut point that is chosen randomly.

Elitism. Elitism is the process of multiplying one or several individuals. Due to the random selection, there is no guarantee that an individual with the highest fitness value will always be chosen. Even if the individual with the highest fitness value is chosen, it is possible that the individual will be damaged (his fitness value decreases) due to the process of crossing over. To keep the individual with the highest fitness value from being lost during the evolution, an elitism process is needed. The procedure used for this is to make the best copy of one chromosome

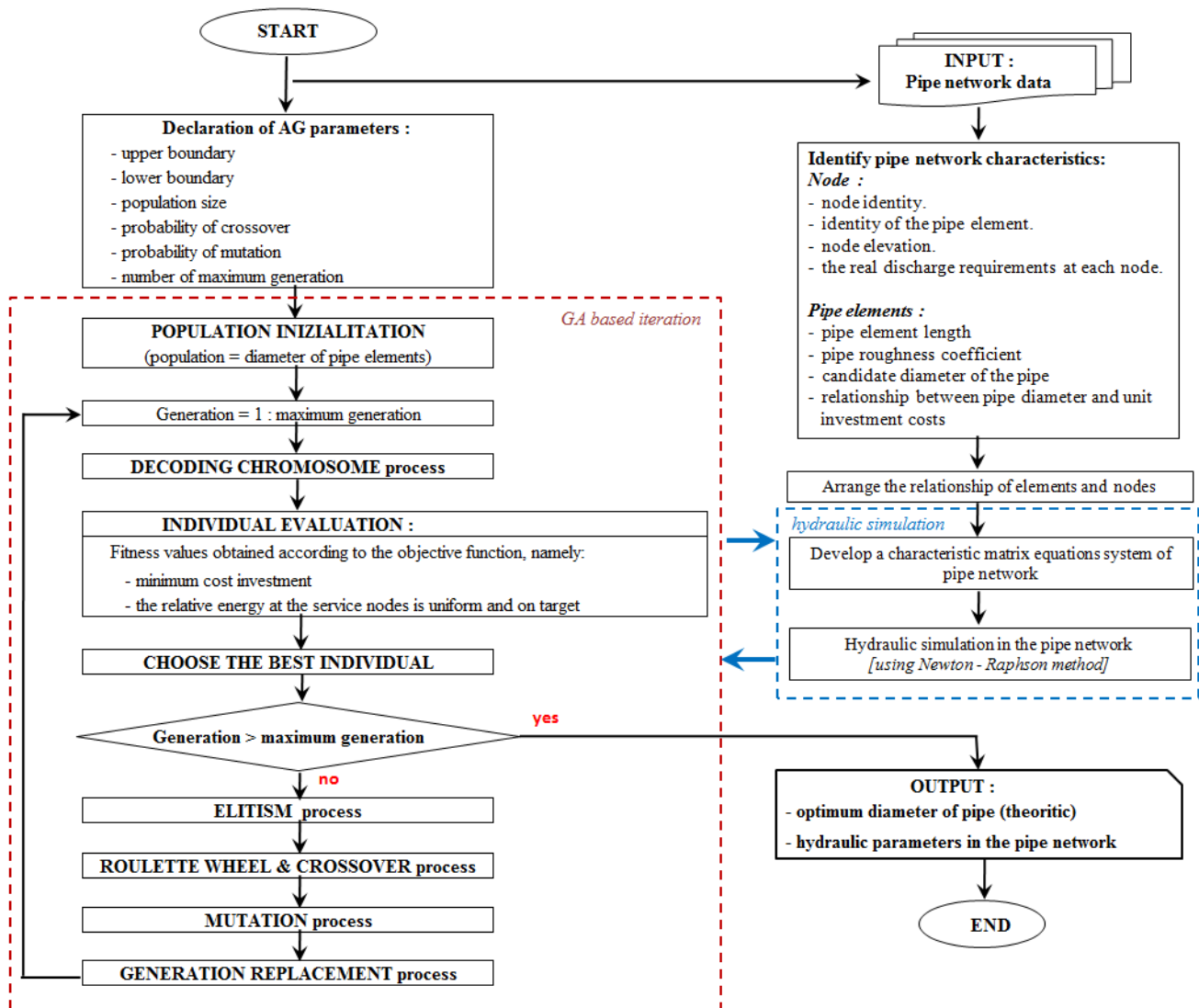


Fig. 2. The optimization model algorithm; source: own elaboration

if the population size is odd and make the two best chromosomes if the population size is even.

Population replacement. In this function, all individuals (e.g. N individuals in population) of a generation are replaced simultaneously by new N individuals resulting from crossing and mutations. In general, population replacement schemes can be formulated based on a measure called the generational gap G . This measure shows the percentage of population replaced in each generation. In this generational replacement scheme, $G = 1$. The most extreme replacement scheme is to only replace one individual in each generation, namely $G = 1/N$, where N is the number of individuals in the population. This replacement scheme is referred to as a steady-state reproduction. In this scheme, G is usually the same as $1/N$ or $2/N$. In each generation, a number of individual NGs must be removed to maintain a steady population size N . There are several individual removal procedures, namely the elimination of individuals with the lowest fitness value or the elimination of the oldest individuals. Elimination can apply only to individual parents or can also apply to all individuals in the population.

PIPE NETWORK TECHNICAL DATA

The pipe network data in this article are hypothetical, schematically shown in Figure 3. The network is a combi-

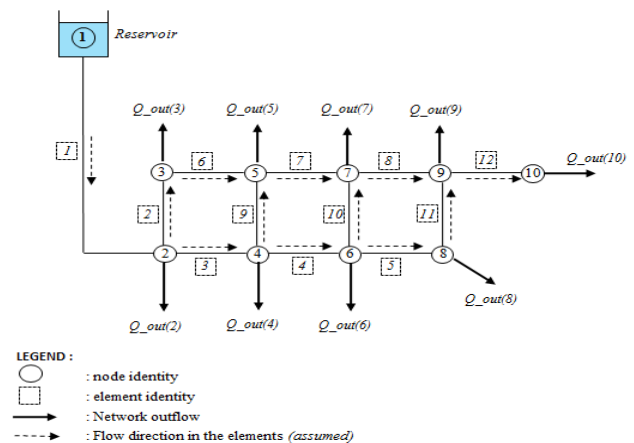


Fig. 3. Pipe network data; Q_{out} = the real requirement at nodes; source: own elaboration

Table 1. Characteristics of nodes on the network

Parameter	Value for node service number									
	1	2	3	4	5	6	7	8	9	10
Elevation (m)	5.00	4.00	3.00	2.00	4.00	6.00	8.00	8.00	7.00	6.00
The real requirement ($\text{dm}^3 \cdot \text{s}^{-1}$)	–	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Source: own elaboration.

Table 2. Characteristics of pipe elements

Parameter	Value for pipe element number											
	1	2	3	4	5	6	7	8	9	10	11	12
Length (m)	50	150	200	250	300	350	400	450	500	550	600	700
Roughness pipe coefficient (C_{HW})	130	130	130	130	130	130	130	130	130	130	130	130

Source: own elaboration.

Table 3. Candidate of pipes diameter

Specification	Candidate of pipe diameter and estimated investment cost							
Pipe diameter (inch)	0.50	0.75	1.00	1.50	2.00	2.50	3.00	4.00
Unit price of pipe investment ($\text{USD} \cdot \text{m}^{-1}$)	4.42	5.00	5.58	6.72	7.84	8.93	10.01	12.10
Pipe diameter (inch)	6.00	8.00	9.00	10.00	12.00	14.00	16.00	18.00
Unit price of pipe investment ($\text{USD} \cdot \text{m}^{-1}$)	16.04	19.66	21.34	22.94	25.89	28.52	30.82	32.78

Source: own elaboration.

Table 4. Relationship between elements and nodes identities in the network

Node	Number of element											
	1	2	3	4	5	6	7	8	9	10	11	12
The begin node	1	2	2	4	6	3	5	7	4	6	8	9
The end node	2	3	4	6	8	5	7	9	5	7	9	10

Source: own elaboration.

Table 5. Matrix characteristic network (K^i)

Node number	Node number									
	1	2	3	4	5	6	7	8	9	10
1	K^1	$-K^1 + K^2 + K^3$	$-K^2$	$-K^2 + K^4$	0	$-K^4$	0	0	0	0
2	$-K^1$	$K^1 - K^2 - K^3$	K^2	K^2	0	0	0	0	0	0
3	0	0	K^2	0	$-K^2$	0	0	0	0	0
4	0	0	0	$-K^2 + K^4$	$-K^4$	K^4	0	0	0	0
5	0	0	$-K^2$	$-K^4$	$K^2 + K^4 + K^5$	0	$-K^4$	0	0	0
6	0	0	0	0	0	$K^5 + K^6$	$-K^6$	$-K^5$	0	0
7	0	0	0	0	$-K^5$	$-K^6$	$K^5 + K^6 + K^7$	0	$-K^6$	0
8	0	0	0	0	0	$-K^6$	0	$K^6 + K^7$	$-K^7$	0
9	0	0	0	0	0	0	$-K^7$	$-K^7$	$K^7 + K^8 + K^9$	$-K^8$
10	0	0	0	0	0	0	0	0	$-K^8$	$+K^8$

Source: own elaboration.

nation of closed and branched networks that have 12 pipe elements and 10 service nodes. The elevation of a service node and the real need target at each service node are shown in Table 1. The length of the pipe element is shown in Table 2 and the candidate pipe diameter along with the estimated unit price of work are described in Table 3. The reservoir water level is at +30.00 m, so that the water flow can be gravitational. Each pipe element has the same material with the Hazen–William roughness coefficient (C_{HW}) of 130. In this case, the problem is to find the optimum pipe diameter combination to produce relative energy at service nodes that is close to the relative energy value being drawn (i.e. as high as 10.00 m) but at a minimum pipe investment cost.

HYDRAULIC EQUATION SYSTEM OF A PIPE NETWORK

Based on data in Figure 3, the relationship between the identity of elements and nodes can be arranged as shown in Table 4, as well as matrix characteristics of the network as shown in Table 5, and equilibrium flow equations in nodes can be expressed as presented below.

$$\begin{aligned}
 F1 &= Q_{in} - Q(1) = 0 \\
 F2 &= Q(1) - Q(2) - Q(3) - Q_{out}(2) = 0 \\
 F3 &= Q(2) - Q(6) - Q_{out}(3) = 0 \\
 F4 &= Q(3) - Q(4) - Q(9) - Q_{out}(4) = 0 \\
 F5 &= Q(6) + Q(9) - Q(7) - Q_{out}(5) = 0 \\
 F6 &= Q(4) - Q(5) - Q(10) - Q_{out}(6) = 0 \\
 F7 &= Q(7) + Q(10) - Q(8) - Q_{out}(7) = 0
 \end{aligned}$$

$$\begin{aligned} F8 &= Q(5) - Q(11) - Q_{out}(8) = 0 \\ F9 &= Q(8) + Q(11) - Q(12) - Q_{out}(9) = 0 \\ F10 &= Q(12) - Q_{out}(10) = 0 \end{aligned}$$

Where: $F1, F2, \dots, F10$ = equilibrium flow at nodes 1, 2, ..., 10; $Q_{in} = F1 + F2 + \dots + F10$; $Q_{out} = Q_{in}$.

RESULTS AND DISCUSSION

Efforts to find combinations of pipe diameters at optimum conditions involved two stages. The first step was to analyse such combinations by utilizing a model which merges the pipe network hydraulic equation system based on the Newton–Raphson method and the optimization equation system based on the genetic algorithm (GA). This analysis uses continuous pipe diameter data so that the optimal diameter found is considered theoretical. The second stage justified the theoretical pipe diameter obtained to be the optimal diameter according to a reserved pipe size as shown in Table 3. The justification process approximated the theoretical pipe diameter size to the available pipe diameter. The resulting diameter is the actual optimal pipe diameter that can be implemented in the network. Furthermore, to determine the performance of the justified pipeline, the cost of the pipe and the relative energy at each node need to be recalculated.

In this discussion, the model is run five times by using input of various weight factor values on the objective function. This is done to study the impact of changing the weight value on the resulting fitness value. The fitness function as an objective function representation of the GA based optimization process is calculated by the Equation (17):

$$f = \frac{1}{(\omega_1 Cp + \omega_2 \varepsilon + a)} \quad (17)$$

Where: f = fitness value, a = small number (= 0.01), Cp = total investment cost of the pipe (USD), ε = mean deviation of relative energy heights at service nodes with respect to the targeted height of relative energy (m), ω_1 = weighting factor of cost aspect, ω_2 = weighting factor of relative energy aspect.

The value ω indicates the level of importance of the aspects reviewed in deciding the optimal conditions. If ω_1 is small and ω_2 is large, it means that the cost aspect is not an important consideration in deciding the optimal conditions, and vice versa. However, if both parameters have the same value (= 0.50), it means that both parameters are equally important in determining the optimal decision. The combination of ω_1 and ω_2 values involved in this discussion is shown in Table 6.

Table 6. Variations in values ω_1 and ω_2

Weighting factor	run-1	run-2	run-3	run-4	run-5
ω_1	0.99	0.75	0.50	0.25	0.01
ω_2	0.01	0.25	0.50	0.75	0.99

Source: own study.

The optimization process uses input GA parameters in the form of minimum diameter = 2 cm, maximum diameter = 50 cm, population size = 750, probability of crossover =

0.9, probability of mutation = 0.01 and the number of generations = 400. The model performance indicators reflected by the best fitness value, minimum costs and minimum relative energy deviation results from run-1 to run-5 are presented in Table 7, whereas the progress of the best fitness value from generation to generation is shown in Figure 4. The progress of the best fitness value shows a growing trend from generation to generation with increasingly convergent conditions at the end of the generation. This indicates that the GA is able to work well and successfully achieve optimum conditions. Table 7 shows the tendency of the smaller weighting factor of cost aspect (ω_1) to produce the best value of fitness; the smaller the relative energy deviation is at each service node, the higher the investment cost of the pipe. This reinforces the hypothesis that the models developed are in accordance with the planned scenario. When the weighting factor of cost is getting smaller, we expect the relative energy equalization factor in each service node to be the first priority and the cost factor to be the second priority, and vice versa. The statement is proven as shown in Table 7. Run-1 prioritizes the cost factor so that it produces a small pipe investment cost but the relative energy deviation of each node is very large. Run-5 prioritizes the energy equalization factor at each node so that the relative energy deviation in each service node is relatively small but the investment cost of the pipe network is relatively large compared to other results.

Table 7. The best fitness values, cost minimum and relative energy deviation minimum

Indicator	The value of the genetic algorithm-based analysis				
	run-1	run-2	run-3	run-4	run-5
The best fitness value	1.549	1.016	0.920	0.850	0.811
Average of deviation relative energy at nodes (m)	7.463	1.925	1.821	1.904	1.799
Total cost of pipe investment (USD thous.)	38.872	56.125	59.045	63.470	70.293

Source: own study.

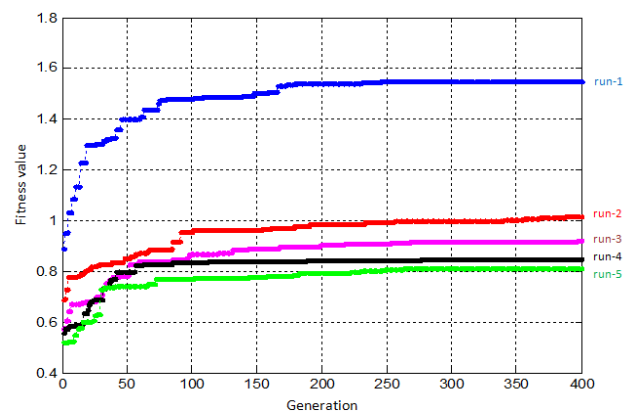


Fig. 4. Progress of the fitness value; source: own study

In the best fitness conditions, the optimum theoretical pipe diameter and the diameter of pipe justified are as shown in Table 8. The table shows that the pipe diameter differs from the theoretical pipe diameter. The diameter of the average pipe justified tends to be smaller than the

Table 8. Optimum diameter of pipe elements (inch)

Element	Optimum diameter from genetic algorithm-based analysis and result of justification									
	run-1		run-2		run-3		run-4		run-5	
	theoretical	justification	theoretical	justification	theoretical	justification	theoretical	justification	theoretical	justification
1	2.93	3.00	2.20	2.00	2.19	2.00	2.21	2.00	2.19	2.00
2	1.12	1.00	0.80	0.75	1.40	1.50	1.50	1.50	1.21	1.00
3	3.27	3.00	17.59	16.00	19.60	18.00	8.81	8.00	18.37	18.00
4	2.13	2.00	19.27	18.00	18.95	18.00	15.61	14.00	19.57	18.00
5	2.05	2.00	3.16	3.00	3.70	4.00	17.15	16.00	19.55	18.00
6	0.90	0.75	2.08	2.00	1.74	1.50	1.03	1.00	1.91	2.00
7	3.12	3.00	1.45	1.50	1.30	1.00	1.65	1.50	2.49	2.50
8	2.61	2.50	5.51	5.00	19.61	18.00	0.97	1.00	19.47	18.00
9	3.17	3.00	2.58	2.50	2.31	2.00	1.71	1.50	0.84	0.75
10	0.80	0.75	6.26	6.00	18.95	18.00	5.41	5.00	18.62	18.00
11	0.80	0.75	0.88	0.75	0.91	0.75	10.37	10.00	6.44	6.00
12	1.82	1.50	3.22	3.00	4.19	5.00	3.17	3.00	5.22	5.00

Source: own study.

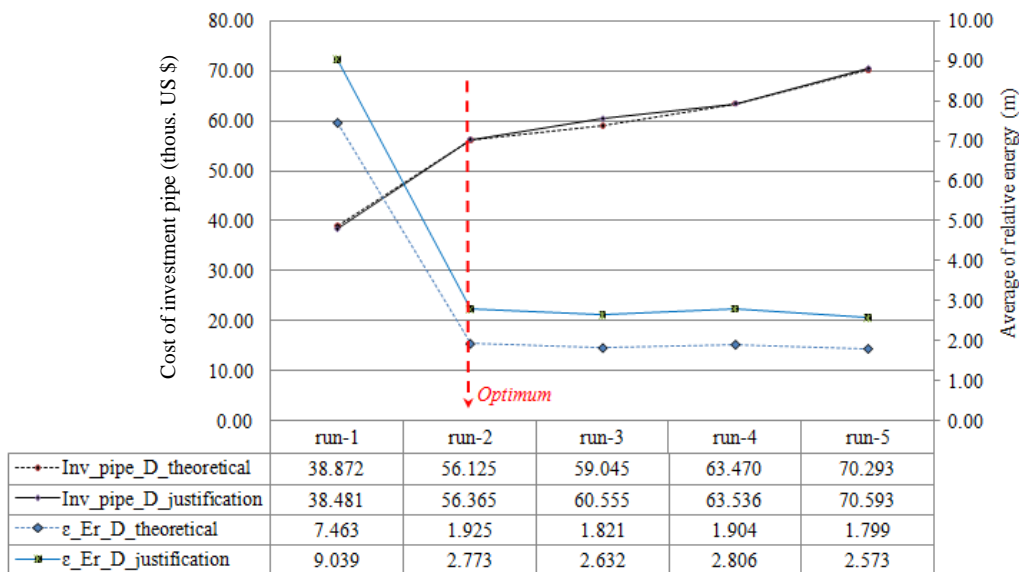


Fig. 5. Determination of optimum conditions; source: own study

diameter of the theoretical average pipe. This condition will certainly have implications for the smaller cost of the pipe, but the deviation of the average relative energy at a node is greater as shown in Figure 5. In terms of cost, there is a slight decrease, especially in run-3 and the relative energy deviation in the service node tends to increase from run-1 to run-5. This result means a deviation from optimal conditions and, at the same time, it can be used as a control that the developed algorithm model has been in line with expectations because the change in the theoretical optimum pipe diameter to the pipe diameter justification does not translate into better network performance indicators.

When viewed at the diameter of the justification input condition, which is the real diameter, then setting run-2 with $\omega_1 = 0.75$ and $\omega_2 = 0.25$ as the optimum condition is the most realistic choice. In this condition, the best fitness value was obtained by 1.016, as shown in the best fitness progress in Figure 4. Run-2 results also showed that the investment cost for the pipe of a theoretical diameter was USD 56.125 thous., whereas for the diameter of the justi-

fied pipe USD 56.365 thous. The average relative energy deviation and the target relative energy for the theoretical pipe diameter is 1.925 m and for the justification pipe diameter as much as 2.773 m. The comparison of the relative energy at nodes generated from hydraulic analysis using the theoretical diameter and justification diameter inputs and their position to the relative energy of the target is shown in Figure 6. At service nodes, the average relative energy deviation from the theoretical diameter input is 13.72% and the justification diameter input is 24.86%. Based on the analysis using input theoretical diameter and justification diameter, the comparison of discharge, head loss and velocity values for each pipe element is presented in Table 9. In the discharge and velocity column, positive values indicate the flow moving from small to large node indices, whereas negative values indicate the flow moving from large to small node indices. The table shows that pipe element 1 has a predominant effect on hydraulic parameters in the pipe network. If higher pressure target is needed at each service node, it can be easily done by increasing the diameter of pipe 1 so that the head loss becomes smaller.

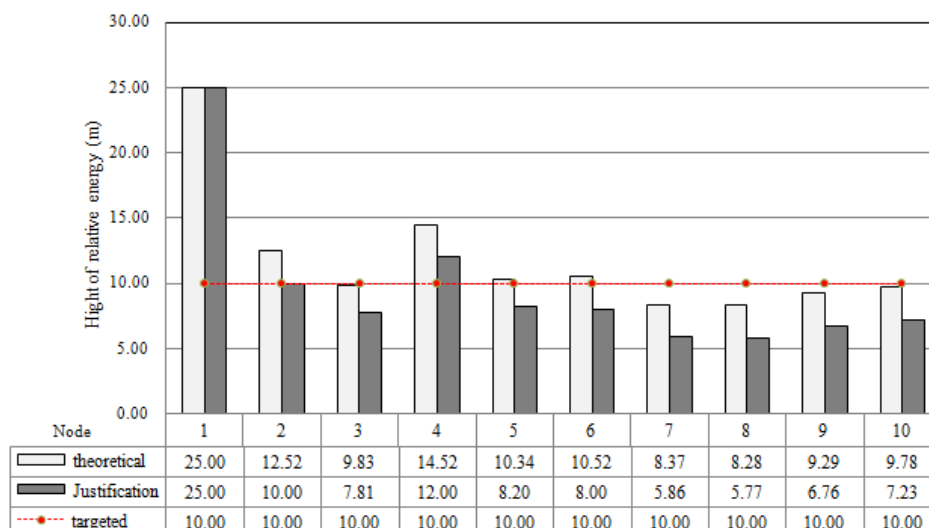


Fig. 6. Comparison of the relative energy of theoretical and justification optimum diameters; source: own study

Table 9. Discharge, head loss and vector velocity in the pipe element

Element	Discharge (dm ³ ·s ⁻¹)		Head loss (m)		Velocity (m·s ⁻¹)	
	theo	just	theo	just	theo	just
1	9.000	9.000	13.479	15.996	3.665	4.443
2	0.174	0.158	3.695	3.199	0.533	0.555
3	7.826	7.842	0.002	0.002	0.050	0.060
4	5.355	5.405	0.001	0.001	0.028	0.033
5	0.998	1.003	0.237	0.229	0.197	0.220
6	-0.826	-0.842	1.509	1.392	-0.378	-0.416
7	-0.355	-0.405	2.035	1.666	-0.331	-0.356
8	2.002	1.997	0.086	0.102	0.130	0.158
9	1.471	1.437	2.184	1.805	0.437	0.454
10	3.357	3.402	0.148	0.138	0.169	0.187
11	-0.002	0.003	0.003	0.011	-0.006	0.012
12	1.000	1.000	0.507	0.531	0.190	0.219

Explanations: theo = theoretical, just = justification.
 Source: own study.

CONCLUSIONS

The combined model of solving a non-linear matrix based on the Newton–Raphson method for hydraulic simulation of a pipe network and the GA in the process of optimizing the performance of a pipe network shows satisfactory results. Efforts to find the optimal solution in the form of a minimum investment cost of a pipe and a relative energy distribution at service nodes according to established criteria can produce desired effects. The GA-based multi objective optimization, which is accomplished by giving a weighting factor to the objective function to solve the case of finding the optimum diameter in a complex pipe network, shows expected results. The running of the model when input ω_1 is large and ω_2 is small shows that cost is an important factor in determining of the optimum condition, and vice versa. In the case of a pipe network considered in this article, optimum conditions are achieved at the cost factor (ω_1) = 0.75 and the relative energy equalization factor (ω_2) = 0.25. If the developed model is used to solve different pipe network cases, it is possible that the optimum weight factor value is also different depending on the

network characteristics, unit cost of the pipe, and the criteria for the relative energy at each targeted node.

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