Water Utility Journal 32: 3-13, 2023.
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Selective pipe replacement using Genetic Algorithms for long-term operating cost minimization in existing water distribution networks

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Abstract: This paper examines the reduction of pump energy consumption at existing water distribution networks through a selective pipes' replacement with new pipes of greater diameter. The selection of diameter is conducted via a Genetic Algorithm which searches for pipes and their diameters that will have the biggest impact in the increase of pressures, on condition that the pressure of each junction does not exceed a maximum value. By testing different budgets each time, we obtain different changes in diameters and consequently increase pressures. Then the pressures are reduced by decreasing the heads of the pumps in order to reach the initial pressure values. Thus, as the pump's head decreases, we have a different operational cost of the network, which translates into long-term energy and economic benefit. Tests are conducted in Python through the package Water Network for Resilience (WNTR), which can run EPANET models. The method proposed is applied in Evaggelistria in Thessaloniki (Greece) resulting in lower pumps' heads.

Key words: Water distribution networks; Genetic Algorithms; EPANET; energy reduction; pumping cost.

1. INTRODUCTION

The management of a water distribution system aims to satisfy water demands with minimum operational costs (Kanakoudis, 2004). Water supply networks to be reliable should have sufficient distribution capacity to meet the consumption requirements in terms of both quantity and pressure of the supplied water (Shinstine et al., 2002). In water distribution networks, the operating pressure should be maintained at levels that provide satisfactory pressure to all consumers regardless of their distance from the supply source or the elevation, in order to meet demand requirements (Farmani et al., 2005).

A common problem that affects the quality of water in the distribution networks of most countries is low water pressure. There are many causes that lead to low pressures, such as inadequate design of the water distribution system, choice of the supply system, pumping method, non-visible water losses, and unexpected high demand for water (Yahia, 2018). An additional problem is that most networks have been constructed many years ago and need renovation. Restoration strategies are necessary to ensure that water distribution networks continue functioning effectively and economically within defined functional requirements for a long period of time (Engelhardt et al., 2000).

The failure rate of pipelines is influenced not only by their age but also by their diameter. Regarding diameter, there is a strong linear correlation between the pipeline damage and their diameter (Kettler and Goulter, 1985). The failure rates of pipelines for some materials increase as the diameter decreases (US Environmental Protection Agency, 2006). In the case of insufficient pipelines, due to increased demand or hydraulic and structural degradation, it is recommended to replace them with other pipelines (Dandy and Engelhardt, 2001), but on a limited scale due to the high cost and long implementation time of replacement (Xu et al., 2014). Finally, increasing the initial budget for larger diameter pipes can reduce maintenance costs and improve the reliability of the network.

Minimizing energy consumption is the primary objective when optimizing energy in water systems with pumps, and this is achieved through solutions that provide the minimum required pressure at each water intake point (Pérez-Sánchez et al., 2017). The energy consumed by pumping is significant. The high costs of establishing a pumping station and the continuously increasing energy prices have made researchers more attentive to the optimal design and operation of these stations (Ormsbee et al., 1989). Consequently, efforts are made to improve the operational efficiency of existing pumping stations (Moradi-Jalal et al., 2003). The selection of efficient pump characteristics and curves minimizes the overall cost (construction and operational costs) and contributes to energy conservation (Moreno et al., 2009).

Different computational tools have been used in the optimization of water distribution networks, such as linear programming for minimizing costs and energy savings (Wang et al., 2021) and pseudo-genetic algorithms for limiting additional energy production in networks (Gutiérrez-Bahamondes et al., 2021). Additionally, stochastic methods have been employed using principles of biological genetics (Goldberg and Kuo, 1985), such as Genetic Algorithms, which became more popular in the 1990s (Simpson et al., 1994), and is now one of the most well-known optimization techniques in engineering problems (Dridi et al., 2005; Bennis and Kumar, 2020) and one of the most recognized numerical methods in water resource management (Nagkoulis et al., 2021; Nagkoulis, 2021). Some studies have shown that Genetic Algorithms find better solutions when applied in pipeline network problems compared to other optimization techniques (Savic and Walters, 1997).

Large pumps' heads lead to higher energy consumption and, consequently, an increase in the operational cost of the water distribution network. This study examines the replacement of certain pipes in the case of repair and improvement projects within existing networks, considering different budgets each time. By replacing pipes with new ones of larger diameter, an increase in the pressures at network nodes is achieved. Then, the heads of the pumps are reduced so that the new pressures approach the initial values. The new costs are then calculated after reducing the heads of the pumps to present the energy and economic benefits resulting from this reduction. Genetic Algorithms are employed for each different budget, which identify the replacements that optimize the investment's performance. Finally, this study conducts a real experiment on a subnetwork of the water distribution system of Thessaloniki to investigate the effect of replacing specific pipelines on the head of pumps, in order to present a picture of the energy and economic benefits.

2. METHODS

2.1 Mathematical formulation of the problem

In this section, the characteristics of the examined problem are described. Each water network can be represented as a Directed Weighted Graph G = (N, e, h_f), where N is the set of nodes and e is the set of edges that connect the nodes, and h_f: e $\rightarrow R_{\geq 0}$ is a weight function that assigns a positive weight value to each edge. In this specific case, nodes are used to represent water intakes and tanks, edges to represent pipes, and a weight function is used to incorporate the characteristics of these pipes into the problem. Specifically, the edges are vectors, as the direction of water flow in the pipes must be taken into consideration.

Consider an existing set of pipe diameters $SD_0 = \{D_{0,1}, D_{0,2}, \dots, D_{0,n}\}$ in the examined network, and a new set of pipe diameters $SD_{new} = \{D_{new,1}, D_{new,2}, D_{new,3}, \dots, D_{new,n}\}$, which contains at least one diameter different from the initial ones. Each graph can be associated with an average pressure value $\bar{p}/\gamma\ (m)$ of the network nodes during a day. The replacement of diameters will lead to a change in the average pressure. This way we get p_0 for the average pressure in the zero-case scenario and p_{new} for the average pressure obtained when the new set of diameters is implemented. We define the "performance" of the new graph G_{new} as the change in the average pressure due to the replacement of the initial diameters with the new ones (equation 1).

$$U(G_{new}) = \frac{\bar{p}_{new} - \bar{p}_0}{\gamma} \tag{1}$$

When the new set of pipe diameters leads to higher average pressures than the initial ones, then the performance is considered positive. The change in pressures is achieved through variations in the weight function h_f. The energy loss function in pipes h_f was chosen as the weight function, which is given by the classical Darcy-Weisbach equation (Equation 2), where Q (m^3/s) is the flow rate, L(m) is the length, f is the friction coefficient, and D(m) is the diameter of the pipe.

$$h_f = \frac{8LfQ^2}{D^5 g\pi^2} \tag{2}$$

A change in the diameters of pipes in the network will lead to a change in pressure through the alteration of the network's coefficients h_f. This study aims to increase the average pressure that appears in the network. However, it is not desirable for the pressure in the water intakes to exceed a certain critical value. To ensure this condition, the first constraint is introduced (equation 3).

$$\frac{p_i}{\gamma} \leq \frac{p_{critical}}{\gamma}\ ,\ \forall i \in \{NY\} \tag{3}$$

where |NY| is the number of water intakes, with NY ⊆ N. At the same time, there is a cost for the replacement of a pipeline. The cost is represented by Equation 4.

$$K(G_{new}) = \sum\nolimits_{\forall j \in \{e_{new}\}} K_j = \sum\nolimits_{\forall j \in \{e_{new}\}} \left(f(D_j)L_j + cL_j + c'\right) \tag{4}$$

In the above equation, the function $f(D_j)$ (€/m) represents a cost-diameter ratio per meter of pipe length, as shown in Table 1. There are 15 available diameter values from the set $\{D_{available}\}$ used in this study. This cost corresponds to the purchase/supply cost of the pipes. Regardless of the diameter and type of the pipe, there is a cost associated with its installation. The parameter c (€/m) is introduced to incorporate the construction cost into the algorithm. We have set c=5€/m, which means that for each extra "m" 5€ have to be paid for installation costs. Finally, regardless of the length of a pipe, there is a cost of installation that has to do with the connections. Thus, for example, 1000 m of 1 pipe have a lower installation cost than 20 pipes of 50 m. The parameter c' (€) corresponds to the unit installation cost of a pipe. To run the models proposed we have set c'=300€, which means that at least 300€ have to be spent for a pipe's replacement. These cost parameters should be considered indicative and can vary significantly between different regions worldwide, according to the labour cost and materials' supply chain.

Table 1. Representative market values for water supply pipelines.

No.	D (mm)	f (D) (€/m)
1	50	2.9
2	63	4.0
3	75	4.7
…	…	…
14	450	98.0
15	500	118.0

Finally, the cost of each possible solution cannot exceed a budget constraint $K(G_{new}) \leq \Pi$. Thus, equation 5 summarizes the optimization goal. Under these conditions, future research could introduce a new condition that defines a minimum pressure level. However, in this article, the aim is to increase pressures, and there is no reason to introduce a restriction for minimum pressure. For a given budget constraint, the Genetic Algorithms presented below find which pipes should be replaced with new ones with larger diameter to increase the average pressures of the nodes. A high pressure level is set to avoid increasing the pressure of some nodes so much that it would be dangerous for the pipes' condition.

$$\max_{D\in\{Davailable\}} U(G), \quad subject\ to\colon K(G) \leq \Pi,\ \frac{P_i}{\gamma} \leq \frac{p_{critical}}{\gamma}\ \forall i \in \{NY\} \tag{5}$$

When the optimization is completed, the average pressure is higher than in the zero-case scenario. The final step is to reduce the energy consumption of the pumps. Reducing the energy consumption of the pumps, the pressures are reduced until the average pressure becomes equal to the initial pressure. This way, the benefit obtained through pipes replacement is transformed to energy reduction and operational cost minimization. In Figure 1, a flow chart illustrates the methodology followed in this study in a simplified manner. The chart presents the actions that were conducted (e.g., selective replacement of the pipes) as well as the outcomes of these actions (e.g., increased pressures).

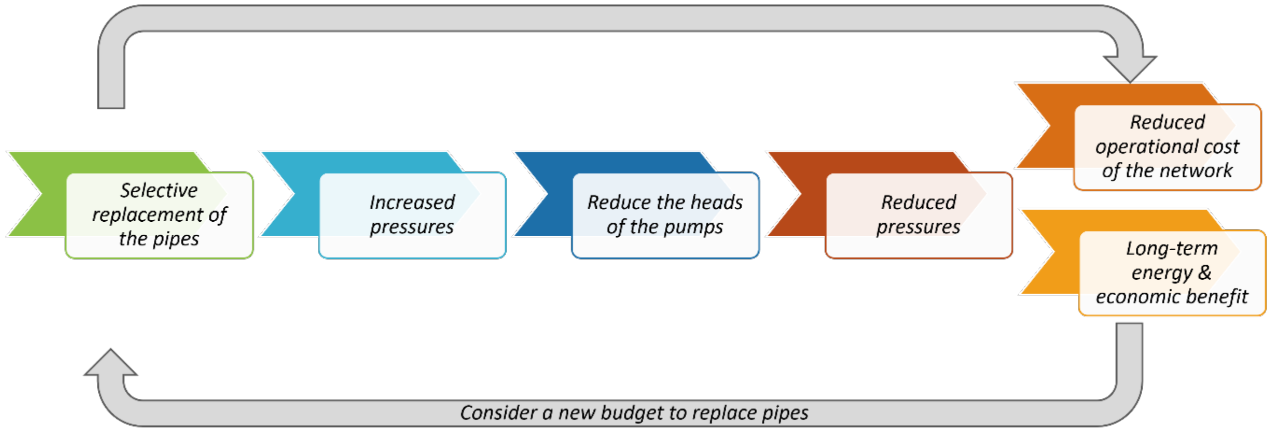

Figure 1. Flow chart presenting the methodology followed.

2.2 Optimization and genetic algorithms

The objective of optimization is to increase the average pressures in the network by replacing selected pipe diameters. The process is performed in Python using the packages “wntr” (Klise et al., 2017) and “geneticalgorithm2” (Pascal, 2023). The “wntr” package is used to establish a connection between python and the Epanet software. This package can read Epanet files (.inp) and execute Epanet hydraulic models using the “sim.EpanetSimulator( )” command. The “geneticalgorithm2” package is used to introduce Genetic Algorithms into the problem. The genetic algorithms’ package can use integer numbers instead of binary, making the modelling of the problem easier.

The initial average pressures are calculated using the “wntr” package for the existing pipe diameters. The new values for the average pressures are calculated using the “wntr” package for the new pipe diameters (chromosomes) SD_{new}. The difference between the existing and new pressure values will provide the performance (fitness value) of the set $\{SD_{new}\}$ from the function U(G). The process is repeated through a directed randomness (Genetic Algorithms), until the solution that maximizes the value of U(G) is found.

Specifically, in the problem examined in this study, 15 diameter values and 127 pipes are used. This implies a set of 15^{127} possible combinations of diameters. It is obvious from the number of solutions that without using an optimization method such as Genetic Algorithms, finding a satisfactory solution is not feasible.

Finally, we reduce the number of possible solutions to facilitate the algorithm in finding a desired solution. Thus, it is hypothesized that each pipe can only be replaced with pipes that are up to 4 categories larger than the existing diameter in Table 1. For example, for a pipe with a diameter of 55 mm, the algorithm is allowed to test diameters of 63 mm, 75 mm and the two immediately higher ones, and not the diameter of 500 mm, which is highly unlikely to be a desired solution. This way, the solutions are reduced to 5^{127} (4 possible new diameters for each pipe and 1 for the existing), making the problem solvable. The characteristics of the algorithm used to find the solution are shown in Table 2.

Table 2. Characteristics of Genetic Algorithms.

Iterations	5000
Population	400
Elitism	3%
Probability of Crossover	75%
Mutation Probability	20%
Type of Crossover	Homogeneous
Parent Selection Rate	0.3

Most of the values of these variables are typically set at that level by default (type of Crossover, parent Selection Rate, Elitism). The rest of the values were chosen after a small number of tests, in order to reach the optimization goal with the minimum computational cost. Increasing the iterations/generations did not result in any increase in the utility.

Finally, the most interesting point is the way constraints are introduced. Acceptable values for the solutions of U(G) are positive. Negative values for U(G) cannot be accepted as this would mean that the investment creates worse conditions in the network than the initial ones. Therefore, negative values will be used for defining penalties.

The first penalty targets on setting the limits for the available budget. In case that the construction cost (*K(G)*) of the diameters exceeds the available one (Π), negative values are assigned to the fitness of the chromosome. The fitness then becomes $U(g) = -K(G)/\Pi$. This condition leads the algorithm towards finding cheaper solutions. In this case, there is no need to calculate the pressures, as this solution will not be accepted. The second penalty concerns the maximum pressure limit. If the pressures are higher than expected, then the fitness get the following value $U(g) = \frac{p_i}{\gamma} - \frac{p_{critical}}{\gamma}$. Negative values are used again to get a relationship that will move the genetic algorithm away from a solution with those high pressures.

2.3 Description of the network

The area studied is the Evaggelistria zone in Thessaloniki, which is a hydraulically isolated sub-zone (DMA – District Meter Area). This means that it can function normally as a separate part of the water supply network, even though it is a component of the overall water distribution network of the city.

The hydraulic water supply system of the Evaggelistria area is defined by the Evaggelistria reservoir (start tank) and the Saranta Ekklisies reservoir (end tank), whose levels determine the boundary hydraulic conditions of the system. Water is transferred from the start tank to the end tank through a pressurized pipeline with a total length of approximately 1,317 m (total length of suction and pressurized pipeline), covering an elevation difference of about 90 m. In Figure 2, the pressurized pipeline is represented by dashed lines, as its length has been compressed for visualization purposes. This pipeline has no contact points with the water distribution network except for node 1, where it is connected to the network in order to supply water to the Evaggelistria neighborhood. This supply satisfies an average annual demand of about 7.5 m^3/h. After this connection, the main pipeline continues to the Saranta Ekklisies tank without intersecting with any other points. In Figure 2, the maximum pressures' hour is presented at 10:30 pm, as it is the hour with the highest water demand. It can be noticed that the pressures of the internal network range between 50-80 m, and the highest pressures are located at the left side of the network since they are at a lower elevation.

To meet the pressure and elevation requirements of the water supply hydraulic system of Evaggelistria, a pumping station with three parallel-connected pumps is utilized. During a typical day, the three pumps never operate simultaneously. The system operates on a daily basis with one pump, while the second pump is activated during peak demand hours.

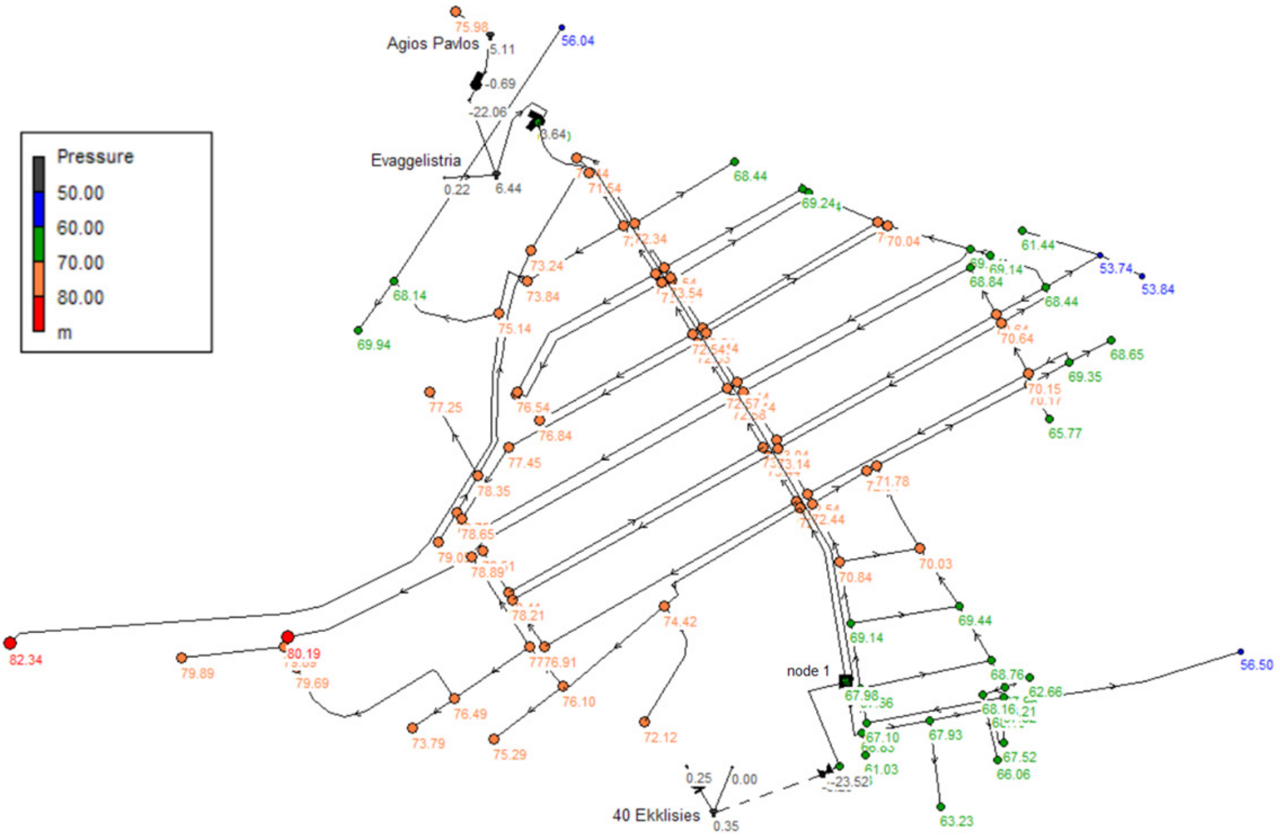

Figure 2. Maximum node pressure in the studied water distribution network.

The overall network under study includes the tank of Agios Pavlos, which is supplied by the tank of Evaggelistria. Therefore, the system has a total of three tanks, a pumping station with five pumps (two for the Agios Pavlos tank and three for the Saranta Ekklisies tank), two pressurized pipelines (from the pumping station to the two tanks) and 127 distribution pipes.

The average height of all nodes in the distribution network is 47.7 m. Furthermore, regarding the external aqueduct, the elevation of the Evaggelistria tank is lower than that of the Agios Pavlos and Saranta Ekklisies tanks.

In this study, the simulation is conducted for a 24-hour period (one day) with a time step of half an hour. This simulation is based on the 30-minute demand data provided by the water supply company. The 24-hour period represents a typical (average) day. The same methodology can be used to model other time discretization without any loss of generality.

Table 3 presents the basic characteristics of the pipes in the studied network. The characteristics have been provided by the water supply company, together with the network structure. These characteristics can be used to get an overall view of the network. In the modelling stage, the characteristics of the network have been inserted in detail for each pipe and node separately.

Table 3. *Pipe characteristics of the studied network*

Pipe characteristics	**Value**
Diameter (mm)	20-600
Age (years)	20 (the majority of pipes)
Total length of all pipes (km)	6.7
Material	PVC (77.6%), Ductile iron (16%)

3. RESULTS

In the present study, a Genetic Algorithm was utilized to determine which pipes, along with the respective diameters, should be replaced in order to achieve an increase in pressures, while considering a given budget. In the following Figure 3, the best solution of each iteration is depicted. It can be observed that the solution transitions from negatives to positives values. This occurs because in the initial iterations, the algorithm surpasses one of the two constraints, resulting in negative performances.

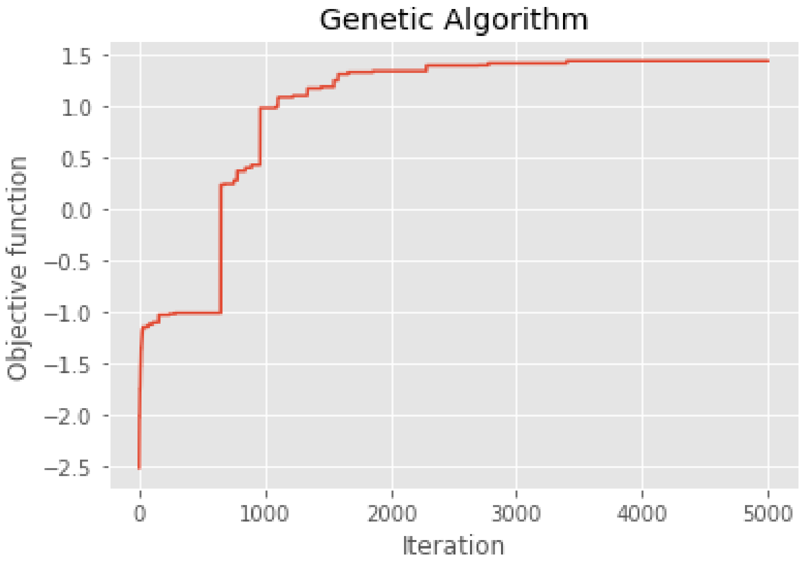

Figure 3. Optimal solution of Genetic Algorithm for each iteration.

For each available budget, the long-term operational cost of the network for the next 30 years was calculated. Each long-term cost was computed according to the following Equation 6.

$$C = 30years * 365days * 24hours * \frac{\gamma Q h}{3600} \quad (kWh) \tag{6}$$

where $\gamma = 9.81$ kN/m^3 is the specific weight of water, Q (m^3/h) is the pump flow rate, and h (m) is the head of the pump. Since there are two pumps in the network under study, the long-term costs were calculated for both pumps. Table 4 presents the long-term energy consumption for each available budget.

Table 4. Available budgets and the corresponding long-term energy consumption.

Scenario	Available Budget (€)	Energy Consumption (GWh)
0	0	81.40
1	40,000	81.30
2	50,000	81.09
3	60,000	81.05
4	70,000	81.04
5	80,000	81.02
6	90,000	81.00
7	100,000	81.02

Figure 4 (left panel) presents the construction costs given for each scenario. In scenario 0, we do not have any extra budget as we refer to the existing water distribution network. As the scenarios increase, the budget for constructing the network also increases.

Figure 4 (right panel) presents the reduction in operational costs of investment for three different kWh charge cases over the next 30 years for each scenario. Additionally, there is a dashed curve representing the construction costs, similar to the curve in the left panel. Profit is observed in the region above the green dashed curve. It is evident that as the energy price increases, the profit becomes greater. In this case, investments in improving the network conditions are economically advantageous. Similarly, as the energy cost decreases, there is no economic incentive to allocate a budget for network improvement. However, in all cases, energy savings are achieved. The conclusion is that when dealing with an aging network, it is worthwhile to allocate a certain amount of funds to replace it. In addition to the well-known benefits in water quality, there are also cost advantages in terms of pumping cost.

It is clear from Figure 4 (right panel), that the benefit per budget increase is maximized near scenarios 2 and 3. This is due to the fact that the derivative of the function in the diagram is maximized in that range. Specifically, in the area where the curves have a steep slope, even a small increase in the budget results in a significant energy saving. Conversely, for scenario 7 we invest a large amount of money to achieve a small benefit. Hence, the difference between the green dashed and the grey line (■) is minor. Therefore, if we seek the maximum economic gain, we should invest between scenarios 2 and 6.

It is a fact that the larger the budget we allocate, the more energy we save. Therefore, if we aim to minimize energy consumption without exceeding our financial limits, we choose scenario 7 for an energy cost of 0.3 €/kWh and scenario 4 for 0.2 €/kWh.

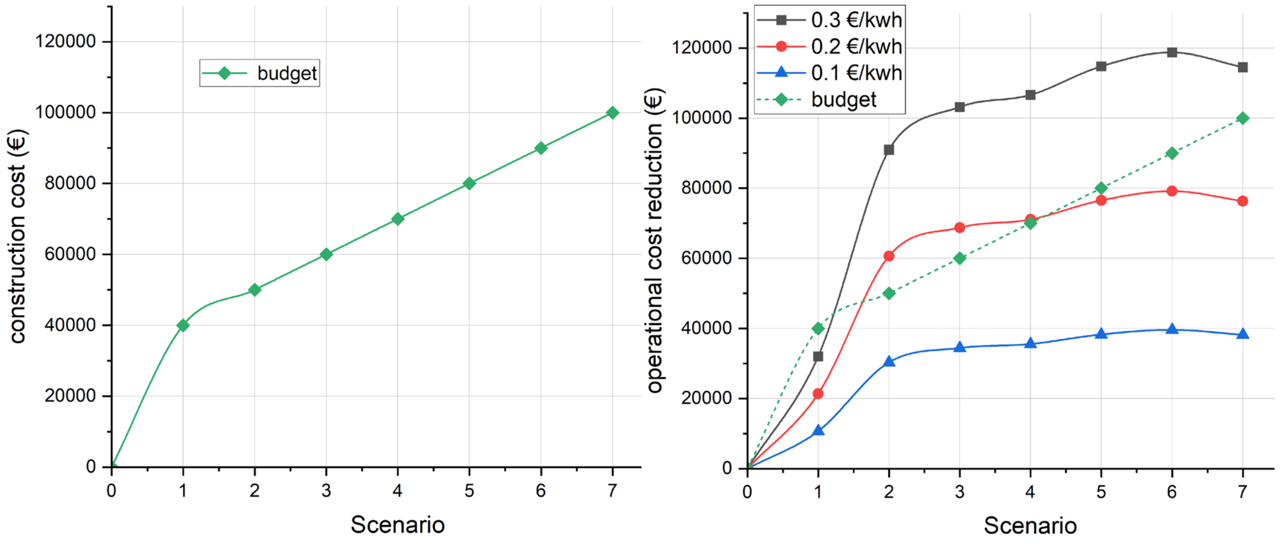

Figure 4. The construction cost for each scenario (left panel) and the operational cost reduction for each case of kWh charge for each scenario (right panel).

Subtracting the available budget from the operational cost reduction we get the “overall economic outcome” (Figure 5) for each scenario. When this outcome is positive, the pipes’ replacement has resulted in an economic benefit in a long term basis, as the budget spent has resulted in higher energy consumption reduction. For high energy costs it is indeed profitable to replace pipes in order to reduce long term economic costs from pumps’ operation. In Figure 5, we can clearly see that the overall benefit is maximized around scenarios’ 2 and 3. The gradual reduction of benefit reflects a phenomenon known as “diminishing marginal returns” in economics (adding an additional factor of production results in smaller increases in output).

Figure 6 illustrates the pump’s head reduction for each available budget. It is evident that as the budget increases, the pump’s head reduction also increases. This is because a higher budget leads to a greater increase in pressures, requiring a higher amount of pump’s head to be removed in order to bring the pressures closer to their initial levels. However, beyond a certain point, the curve tends to stabilize. This occurs because the pump’s head cannot be further reduced without causing pressure issues. The only case where the pump’s heads get lower with increasing the budget is the last case.

However, such variations are a result of the genetic algorithms' non-deterministic operation, as a metaheuristic method does not guarantee that the optimum solution is always reached.

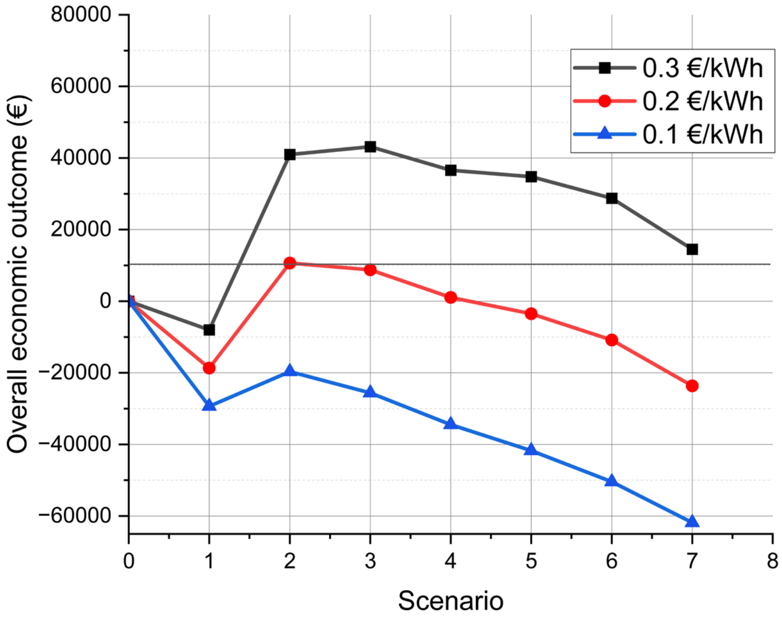

Figure 5. The overall economic outcome for each case of kWh charge for each scenario.

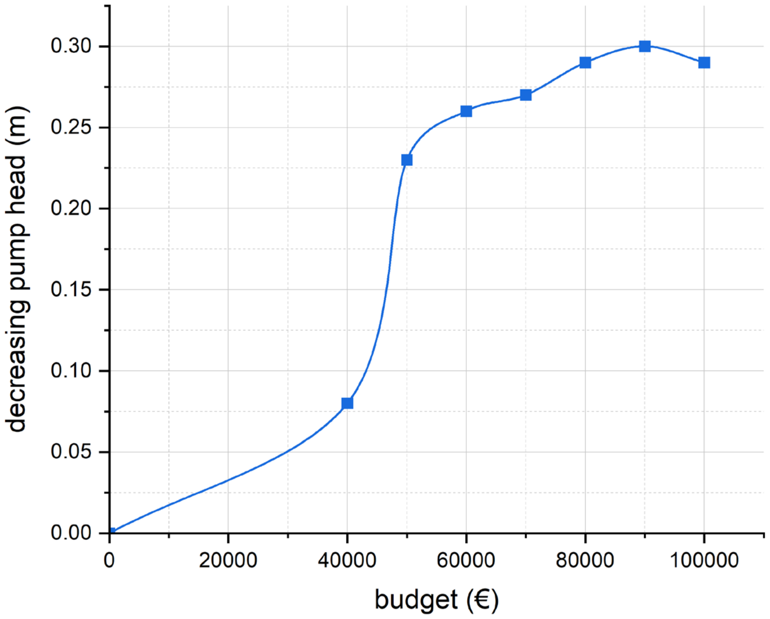

Figure 6. The increasing amount of pump's head subtracted for each increased available budget.

4. CONCLUSIONS

A new optimization method for existing water distribution networks was proposed and applied to the isolated hydraulic network of Evaggelistria (Thessaloniki). Specifically, using Genetic Algorithms, the pipes were identified that, if replaced with larger diameter pipes, would have a significant impact on increasing the pressures and thus resulting in a substantial reduction in the pump's head that need to be carried out to bring the new pressures closer to the initial values. This leads to long-term cost savings in the network.

The results indicate that the method can be successfully implemented to water distribution networks, leading to larger node pressures. This is a consequence of reducing energy losses in the pipes. In this paper, the aim is to increase pressures through diameters replacements, but the final goal is to decrease the head of the pumps, leading to a decrease in pressures. Specifically, a variety of possible available budgets are examined in order to find the amount of investment that will maximize the efficiency in reducing the operating and energy costs of the pumps. Furthermore, the method used to employ the Genetic Algorithm in selecting the appropriate pipes is useful for other applications as well. For instance, apart from reducing energy consumption, it can identify pipes that can create more favorable conditions for the movement of a pollutant. Moreover, this method can be implemented to existing water networks for pipe rehabilitation or utilized in new networks to determine the optimal diameter for new pipes.

The conclusion is that when dealing with an aging network, it is worthwhile to allocate a certain amount of funds to replace it. Therefore, we can recover our investment by reducing long-term pumping costs. Indeed, energy prices vary and can decrease or increase in the future. This means that if the energy cost increases significantly, the cost of investment will be high and unprofitable. Energy reduction can be achieved in any case, but the profit can only be maximized within a certain range of investment.

ACKNOWLEDGMENTS

The authors express their gratitude to the Thessaloniki Water Supply and Sewerage Company S.A. (EYATH S.A.) for providing the necessary initial data for the implementation of this study. Special thanks are also given to Ms. Panagiota Galiatsatou of the Department of Strategic Planning, Hydraulic Works & Development of EYATH for her significant contribution to the acquisition of the data. The hydraulic model in the EPANET software was created as part of Anna Antoniou’s master dissertation.

An initial, shorter version of the paper has been presented at the 15th Conference of the Hellenic Hydrotechnical Association (Thessaloniki, Greece, June 2-3, 2022).

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