

Backup Design Optimization for Water Distribution Networks [†]

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Abstract: Rapidly growing cities need significant extensions to their water distribution networks to fulfil the water demands of the population. The design of such systems is still challenging to optimise between the robustness/reliability/vulnerability and the cost. This study presents an idea: If the network layout is already determined, how can optimal diameters be found that balance cost and service quality? On the one hand, the purpose is to determine the cheapest possible network that can still serve every consumer. On the other hand, we extend the idea by optimising all backups of the network.

Keywords: water distribution networks; backup optimisation; robustness; genetic algorithm



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1. Introduction

Since random pipe breaks are inevitable, their isolation is necessary [1,2]. As the pipelines in real-life networks do not have isolation valves on both ends, some part of the network (typically a few pipelines and nodes) is not operating during shutdowns. However, the rest of the system serves as a backup [3]. The introduced method considers every possible shutdown scenario for a water distribution network and optimises them simultaneously. The goal is to serve as many consumers with water as possible.

The proposed method applies a standard Matlab built-in genetic algorithm. The objective function (OF) includes the network cost according to the Battle of Intermittent Water Systems 2022 and the relative shortfall for each backup scenario. EPANET 2.2 is applied to determine the hydraulics with a pressure-driven solver. The goal is to minimise the cost while keeping the service quality as high as possible, even during a shutdown due to an accidental pipe burst. We demonstrate the method using EPANET sample network Net1.

2. Materials and Methods

The genetic algorithm (GA) is a widely used technique to find global minimum values of functions in the field of water distribution networks [3,4]. GA can overcome local minima by utilising the mutation and cross-over operators even if the OFs are mathematically not smooth. Regarding the optimisation of a network, a typical formulation of finding the proper diameters is to minimize the cost while ensuring an acceptable service level, [4] that is, to find the cheapest network with a given layout to supply every consumer. Although the diameters can be chosen from a predefined list of standardised values, the problem is still NP-hard, as by increasing the number of pipelines, the possible solutions tend to multiply exponentially.

This study applies the GA for two different OFs. The first follows the traditional optimisation, while the second includes the backup networks. If a pipe burst occurs and a shutdown is necessary to isolate some parts (a segment) of the network, the rest of the system is still operational, and we call this a backup. The idea is to find the cheapest network to serve every consumer, even if a network segment is isolated. The first OF is:

$$OF_1 = a \times CF + b \times RS \quad (1)$$

where a and b are constants—1 and 1000, respectively—and CF is the cost function:

$$CF = (A + B D + C D^2) / (A + B D_o + C D_o^2) \quad (2)$$

where CF is the relative cost in EUR/m, $A = 13$, $B = 29$ and $C = 1200$ according to the instructions for the Battle of Intermittent Water Supply 2022. D is the diameter and D_o is the original diameter in the network. RS stands for the relative shortfall:

$$RS = (d - c) / d, \quad (3)$$

where d is the overall nominal demand and c is the actual consumption in the network, i.e., if every consumer is served $RS = 0$. The value of a and b have been chosen as 1 and 1000 arbitrarily to ensure that even a small shortfall can increase the function value. The second OF is similar, but it considers the shortfalls of all the backups, i.e.,

$$OF_2 = a \times CF + b \times RSM, \quad (4)$$

where RSM is the relative shortfall mean, i.e., the average value of relative shortfalls of all the backups.

3. Results

The sample network of EPANET, Net1, is used to demonstrate the quality of the methods. Some isolation valves have been added to generate segments and shutdown plans (Figure 1). Overall, six isolation valves create five segments. The cost of the original network is EUR 2.46 million. Figure 2 presents the results of the optimisations, both the traditional (left side) and the backup ones (right side). The costs of both cases are significantly lower than the original. The traditional optimisation cost EUR 1.11 million, while the backup optimisation cost EUR 1.49 million.

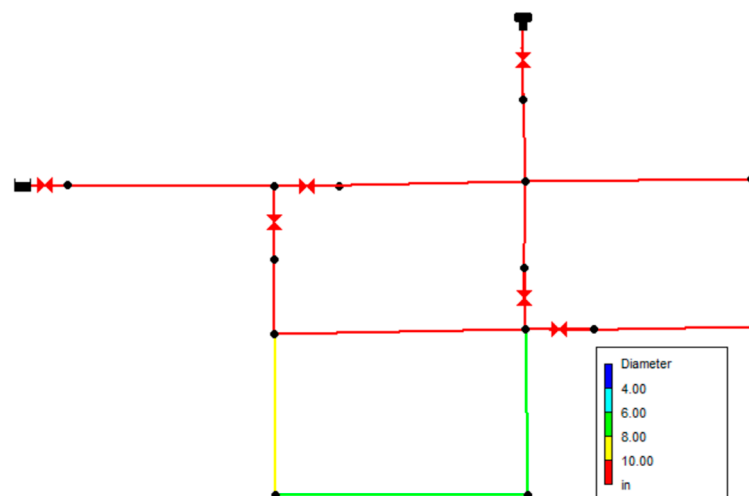


Figure 1. Net1 system coloured by the original diameters. The cost is EUR 2.46 million.

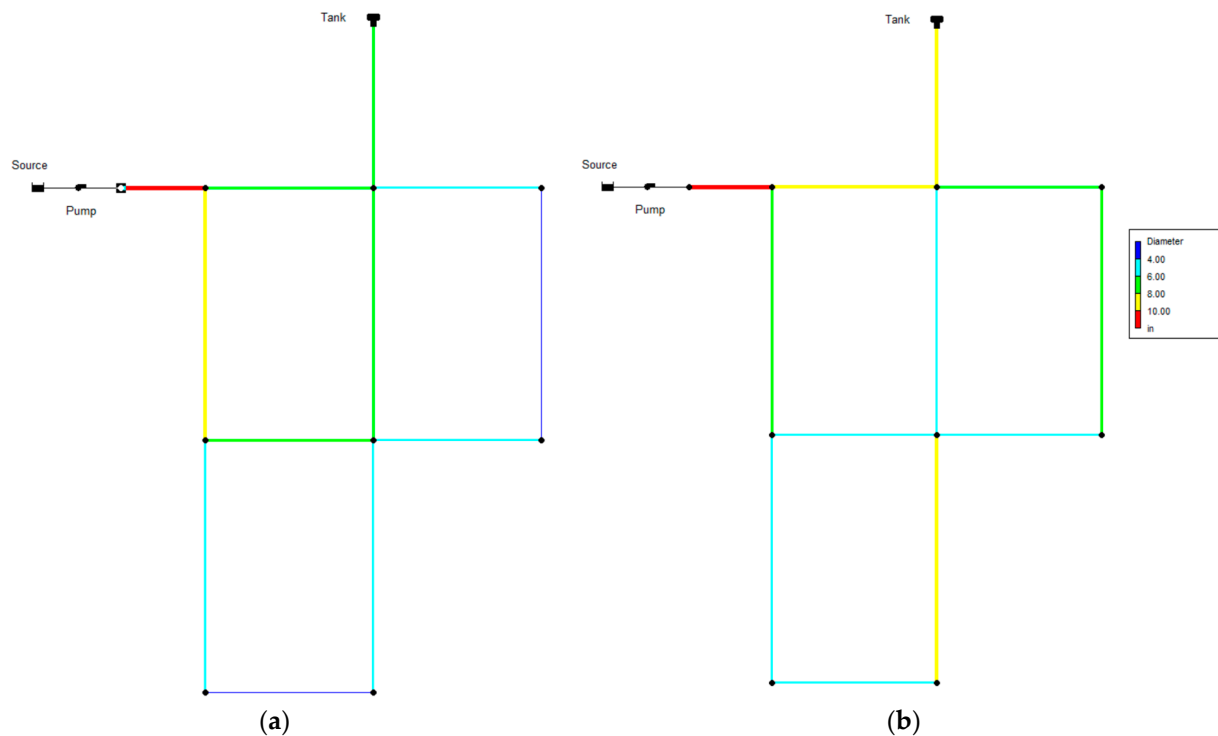


Figure 2. Results of the optimisation techniques. (a) Traditional optimisation for the cost and zero relative shortfall. The final cost is EUR 1.11 million. (b) Backup optimisation for all possible shutdown scenarios with minimal cost and zero relative shortfall for all cases. The final cost is EUR 1.49 million.

4. Discussion and Conclusions

This study presents an optimisation method for two objectives, a traditional diameter optimisation and a backup optimisation, both for the cost avoiding any shortfall. The methods are demonstrated using the EPANET example network, Net1, with some additional isolation valves.

Both methods can achieve a lower cost than the original, meaning the original network is oversized for both cases. While the traditional optimisation achieved a continuously reducing diameter distribution from the sources, the backup optimisation resulted in a more uniform one, creating the opportunity for some stable, looped backups.

The analysis can be further extended with additional real-life networks. Moreover, up to this point, the level of service is not considered; only the shortfalls are minimised to zero. An additional metric to the cost could increase the scope of the analysis, which counts in the quality of the water supply.

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

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