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Automatic Multi-Objective Sectorization of A Water Distribution Network

F. De Paola[a], N. Fontana[b], E. Galdiero[a]*, M. Giugni[a], D. Savic[c], G. Sorgenti degli Uberti[d]

[a]*Department of Civil, Architectural and Environmental Engineering, University of Naples "Federico II", Naples, Italy*
[b]*Department of Engineering, University of Sannio, Benevento, Italy*
[c]*Centre for Water Systems, University of Exeter, Exeter, United Kingdom*
[d]*ABC Azienda Speciale, Naples, Italy*

Abstract

This paper deals with optimization of Water Distribution Networks (WDNs) by establishing District Metered Areas (DMAs). A methodological approach for the automatic partitioning of a WDN into DMAs is presented and discussed. Several design criteria are taken into account for the definition of the problem objectives and constraints. The optimization methodology applies adjustable weights to various objectives to allow flexible decisions to be made. The proposed approach combines graph theory and an evolutionary multi-objective algorithm, whose parameters were calibrated through extensive tests. The results of the application to a real case study are presented, as well.

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Keywords: District Metered Areas; water distribution network sectorization; multi-objective optimization; pressure management; water losses.

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1. Introduction

The sectorization of a Water Distribution Network (WDN) consists of the partitioning of the whole system into smaller hydraulically discrete areas called District Metered Areas (DMAs), which are used for monitoring of system flow and pressure. As stated in literature [1], the DMA approach is one of the most effective management techniques commonly used for improved understanding of WDN behaviour. Among the many benefits achievable through the establishment of DMAs, the most interesting effects are increased system control and leakage reduction and better

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* Corresponding author. Tel.: +39-081-768-34-63.
E-mail address: enzo.galdiero@unina.it

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pressure management. However, in real cases, to achieve the optimal design of DMAs may be challenging because of the number of design criteria, the natural complexity of WDNs, and the number and the non-linearity of the involved equations. Therefore, a Decision Support System (DSS) able to provide the best solution in an automatic way would be required. Several approaches can be found in the literature on this topic, most of them showing the effectiveness of graph theory principles in such kind of problems [2,3,4,5,6]. The use of graphs for modeling WDNs significantly reduces the number and the complexity of the required calculations. Moreover, the availability of well-known and reliable algorithms for the exploration of the network graphs is very useful for the software implementation of the design methodology. Nevertheless, the approaches only based on graph theory applications may result in an inefficient investigation of the domain of feasible solutions. Such approaches are normally limited to considerations of node connectivity within the DMAs and of reachability of each node from the water supply sources [7]. In further studies this issue is tackled through the adoption of heuristics [8] or machine learning techniques [9]. A procedure based on the use of Simulated Annealing (SA) is described in [10], while a Genetic Algorithm (GA) is introduced in [11]. However, although evolutionary algorithms are widely acknowledged among the most effective techniques for solving optimization problems, their use for this type of application does not appear to have been sufficiently investigated.

Therefore, in the present paper, the methodology by De Paola et al. [12] is comprehensively revised and developed, and an Evolutionary Multi-Objective algorithm (EMO) is introduced. Starting from a large selection of the design criteria described in the proposed approach [12], a two-objective optimization problem is formulated for the automatic sectorization of a WDN. Adjustable weights are introduced in the objective functions in order to provide some preference articulation to the decision maker. The description of the methodology is followed by the discussion of the results of the application to a real case study, namely the WDN of Pianura, a neighborhood in the city of Naples, Italy.

2. Methodology

2.1. Problem formulation

Sectorization projects are implemented in WDNs by permanently closing pipes at boundaries of DMAs through the use of shut-off valves. Following the assumptions from the classical approach [1], the DMAs should supply a number of customers (i.e., served water demand) and have a limited number of connections with the main trunks (or with other DMAs). This approach reduces the number of flow meters required for monitoring the input and output flows. Elevations of the network nodes within each DMA should also be considered in order to identify a unique pressure target level against for reducing leakage without violating the minimum pressure requirement at demand nodes. In addition to the above mentioned criteria, which are mainly related to the topology of the network, the cost of the DMA creation project should be taken into account. The most of the methodologies proposed so far only consider the cost of the shut-off valves and of the flow meters required for setting the DMAs boundaries. The approach here presented aims to deal with the total operative cost for the partitioned WDN, which involves also the water leakage costs and of the energy consumed by pumps, if present. Finally, the hydraulics of the problem must be taken into account. The compliance with hydraulic constraints must be verified, as well as the minimum service requirements at nodes (in terms of both demand and pressure). Furthermore, it must be pointed out that the partitioning of the WDN significantly reduces the redundancy of its layout. This may lead to an excessive loss in the system resilience against significant changes in the spatial or temporal distribution of water demands (e.g. fire service). Given the above mentioned criteria, the mathematical formulation of the problem follows the approach by Gomez et al. [13], where a total cost function is compared to the change in the hydraulic performance of the WDN. The Total Cost Function (TCF) is defined as follows:

$$TCF = w_B\left(r \cdot C_B\right) + w_L\left(365 \cdot C_L\right) + w_P\left(365 \cdot C_P\right) = \min! \qquad (1)$$

where C_B is the amount of the required investment for setting the boundaries of the DMAs, C_L is the daily cost due to the water leakages, C_P the cost due to the energy use and r is an annual discounting rate. The above definition allows the decision maker put the desired emphasis on each cost item by changing weights w_B, w_L, w_P. Their values must satisfy the followings:

$$w_B; w_L; w_P \in [0;1] \quad ; \quad w_B + w_L + w_P = 1 \tag{2}$$

Apart from the weights, Eq. (1) represents a sort of total annual operations cost for the partitioned network. The evaluation of C_L and C_P requires the availability of a WDN hydraulic model that takes into account pressure dependent leakage. On the other hand, the hydraulic performance is evaluated in terms of the change in WDN hydraulic reliability before and after the sectorization. This is expressed by the "Resilience Deviation Index" (I_{rd}), which is proposed in [14] and adapted as follows:

$$I_{rd} = \frac{\sum_{i=1}^{N_n} q_i \left(H_{i,ND} - H_i\right)}{\sum_{i=1}^{N_n} q_i \left(H_{i,ND} - H_{t,i}\right)} \tag{3}$$

where i is the generic demand node, N_n is the number of demand nodes in the WDN, q_i is the water demand, $H_{t,i}$ is the minimum required head, while $H_{i,ND}$ and H_i are the actual heads in the original and in the new configuration of the WDN, respectively. Since the closure of pipes causes a reduction in the redundancy provided by multiple flow paths into an area, the reliability of the partitioned network is expected to be lower than that in the original network configuration. Consequently, a large value of I_{rd} would indicate a worse hydraulic performance. Therefore, the objective that would be aimed at preserving reliability levels could be achieved by minimizing the maximum value of I_{rd} over time:

$$I_{rd,\max} = \max_t \left\{I_{rd}\right\} = \min! \quad ; \quad t \in \left\{1,...,T\right\} \tag{4}$$

where t is the generic time step t and T is the number of time steps in the hydraulic simulation.

As for problem constraints, the hydraulic feasibility of the provided solutions must be considered first. Therefore, in addition to the hydraulic equations (i.e., head-loss formulas, mass balance equations, pump curves, etc.) the achievement of the minimum pressure target at demand nodes (P_{min}) must be verified:

$$P_{i,t} \geq P_{\min} \quad \forall i \in \left\{1,...,N_n\right\}, \forall t \in \left\{1,...,T\right\} \tag{5}$$

where $P_{i,t}$ is the pressure at i-th node at the end of the time step t. Furthermore, in case of limited budget for the required investment (C_{Bmax}), the following constraint must be satisfied:

$$C_B \leq C_{\mathrm{Bmax}} \tag{6}$$

Finally, in order to achieve a reasonably sized DMAs, it is commonly assumed that the number of customer connections per each DMA should be in the range between 500 (*MinConn*) and 5,000 (*MaxConn*). Assuming that the customers have the same requirements in terms of water demand, this criterion can be also formulated as follows:

$$\begin{aligned} &\min Q_d \le Q_d \le \max Q_d \\ &\min Q_d = \frac{MinConn}{TotConn} \cdot Q_{tot} \\ &\max Q_d = \frac{MaxConn}{TotConn} \cdot Q_{tot} \end{aligned} \tag{7}$$

where Q_d is the sum of the base demands at demand nodes within the d-th DMA, Q_{tot} is the sum of the base demands of all the network nodes and *TotConn* is the total number of customer connections. However, given the purely informative nature of the best practice limits, in the proposed approach just a corresponding "flexible" constraint is defined. In brief, when the values of Q_d for all the DMAs are in the above mentioned range, the solutions are considered feasible. Otherwise, if at least one Q_d falls outside the range, but within the 50% bounds, the solutions are accepted with a probability that linearly decreases with the distance from the limit. In all the other cases, the solutions are considered infeasible.

2.2. Optimization model

The domain of possible solutions for the two-objective problem outlined in the previous section is investigated through the use of the Non-dominated Sorting Genetic Algorithm (NSGA-II), which is proposed in [15]. Rounding functions are introduced in the creation function because of the presence of integer variables. Constraint handling is implemented, as well, and the tournament selection is adopted. The simulated binary crossover [16] and the polynomial mutation are used as reproduction operators. A schematic of the optimization algorithm is showed in Fig. 1. Besides the network features (layout, number of customer connections, target pressure at nodes) and the unit costs (shut-off valves, flow meters, water leakage, energy use), the input parameters that must be provided are the settings of the NSGA-II (size of the population, number of generations, tournament size, crossover fraction, distribution indices for crossover and mutation) and the upper bound for the number of DMAs (D_{max}). It is worth noting that this approach explores a broad space of solutions and allows that the most convenient number of DMAs is found. The set of decision variables consists of the followings:

- the number of DMAs (D) in the current solution (integer);
- the node indices for a number of DMA centroids equal to D (integer);
- a blending factor (φ) ranging from 0 to 1 for the evaluation of a "topological distance" between nodes (real).

At each evaluation, the DMAs are created by adding every WDN node to the DMA of the closest centroid. The distances on the network graphs are computed as the lengths of the shortest paths between each pair of nodes evaluated using the Floyd-Warshall Algorithm (FWA) [17,18]. In order to meet the "topological criteria" discussed in section 1.1, the weight on the graph edge (l_{ij}) connecting the nodes i and j is computed as follows:

$$\begin{aligned} &l_{ij} = \varphi \cdot \frac{Q_{ij}}{\max\limits_{ij}\left\{Q_{ij}\right\}} + (1-\varphi) \cdot \frac{\Delta z_{ij}}{\max\limits_{ij}\left\{\Delta z_{ij}\right\}} \\ &Q_{ij} = \frac{Q_i}{n_i} + \frac{Q_j}{n_j} \quad ; \quad \Delta z_{ij} = \left|z_i - z_j\right| \end{aligned} \tag{8}$$

where q_i and z_i are the water base demand and the elevation at node i, while n_i is the number of edges linked to the same node. Once the DMAs are defined, the solution is brought into the hydraulic simulation model by closing the pipes connecting different DMAs. If there is any DMA that is completely isolated from the water sources, the algorithm allows that the supply is provided by opening the most appropriate connection between different DMAs.

The FWA is used again to calculate the shortest paths from the source nodes to the boundary nodes of the isolated DMA. However, in order to ensure a sufficient pressure head at the entry point of the DMA, the weight on the graph edges are set equal to the hydraulic resistance of the pipes. For further details, see the procedure described in [12]. Then, the hydraulic simulation is run using the updated model of the WDN. This allows the full evaluation of objective functions (1) and (4) and of constraint functions (5), (6), (7). The evaluation of the effect of the provided solutions on the amount of water losses requires that pressure-dependent leakages are properly modeled in the hydraulic simulation model. On the contrary, because the pressure at demand nodes is required to exceed the minimum target value, modeling of pressure-dependent demands is not required. The described steps are repeated for all the evaluations required by the NSGA-II to develop the final configuration of the Pareto front.

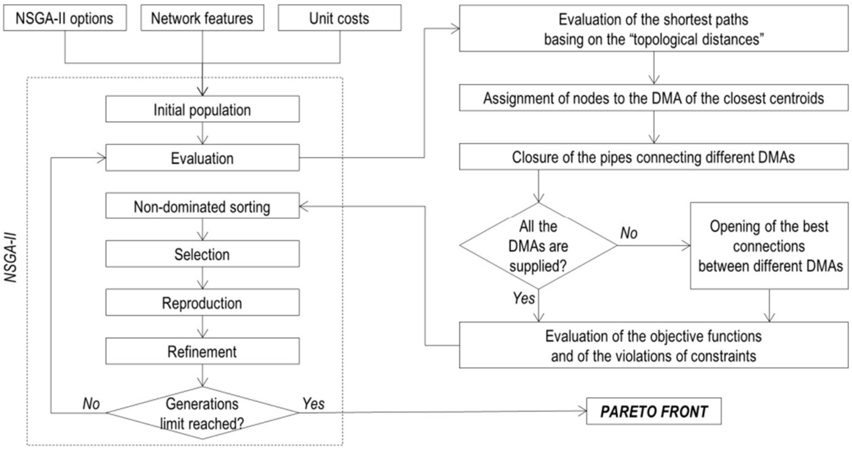


Fig. 1. Schematic of the optimization algorithm.

3. Case test

The results of the application of the proposed methodology are presented in this section. A real case test is analyzed, namely the WDN of Pianura, a neighborhood in the city of Naples, Italy. The WDN consists of 268 nodes, 313 pipes and a single reservoir as water source (see Fig. 2).

The minimum required pressure at demand nodes is 20 meters. The most of the background water losses is located in the northern area and they are modeled through the use of calibrated emitters in demand-driven analysis. The results come from the software implementation of the optimization algorithm in Matlab® environment, while the revised version of EPANET [19] described in [20] is adopted as a hydraulic simulator. Given the absence of pumping stations, the analysis is only focused on the optimization of investment costs and water leakage costs. Without a loss of generality, the weights in the TCF are set equal to 0.5. Moreover, a budget limit of 50,000 euros is considered, while the upper limit for the number of DMAs in each solution is assumed equal to five. The cost of the water losses is quantified in 0.18 €/m^3, while the unit costs of shut-off valves and flow meters are reported in Table 1.

The selection of the parameters of the NSGA-II is based on the results of a sensitivity analysis, which is not reported here for the sake of brevity. The size of the population and the number of generations are both fixed at 100, so that 10,000 evaluations are required per each run. The tournament selection with size equal to 2 and a crossover probability of 0.9 are used for the reproduction. Due to the presence of integer variables, and in order to provide sufficient differentiation in the generation of child solutions, very low values (equal to 1) are adopted as distribution indices for crossover and mutation. Fig. 3a shows the Pareto fronts for 10 independent runs of the optimization algorithm, thus involving a total of 100,000 evaluations of the objective functions. The quality of the performance can be evaluated by considering the empirical first-order attainment function (EAF), as reported in [21]. The very narrow band indicated by the traces of the attainment surfaces corresponding to the 25th and the 75th percentiles (Fig.3b) denotes the very good performance of the optimization.

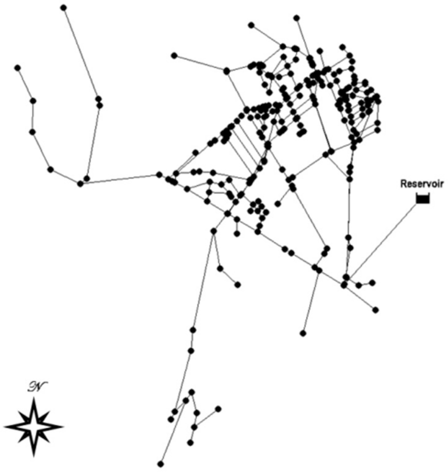


Fig. 2. Layout of the WDN of Pianura.

Table 1. Unit costs of shut-off valves and flow meters .

Diameter (mm)	Shut-off valve (€)	Flow meter (€)
40	120.00	1,665.00
60	135.00	1,675.00
65	160.00	1,700.00
80	175.00	1,730.00
100	215.00	1,770.00
150	340.00	1,950.00
200	560.00	2,245.00
250	845.00	2,430.00
300	1,315.00	2,860.00
400	3,755.00	5,345.00
500	8,070.00	6,470.00
600	9,665.00	7,950.00

The solutions obtained show that a decrease in the hydraulic resilience is limited to 20%, which can be considered reasonably satisfactory for this kind of application. From a technical point of view, the feasibility of the solutions is evidenced by the number of pipes that needs to be closed, which is always below 20. More frequently the number of closed pipes is between 7 and 13.

However, the most interesting outcomes are shown in Fig. 4a, in which the solutions are detailed basing on the required investment and on the percentage reduction of the annual cost due to the water leakage. It can be noted that the maximum value of the required investment is far from the fixed budget limit, with most of the solutions involving expenditures less than 50% of the limit. At the same time, the Fig. demonstrates that the closure of a limited number of pipes in the WDN is able to provide significant reductions in the amount of the water losses, here estimated between 0.3% and 8%.

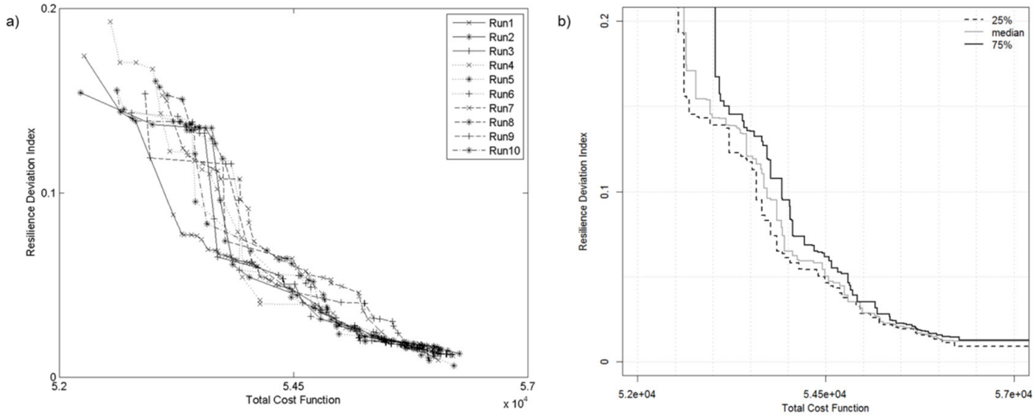
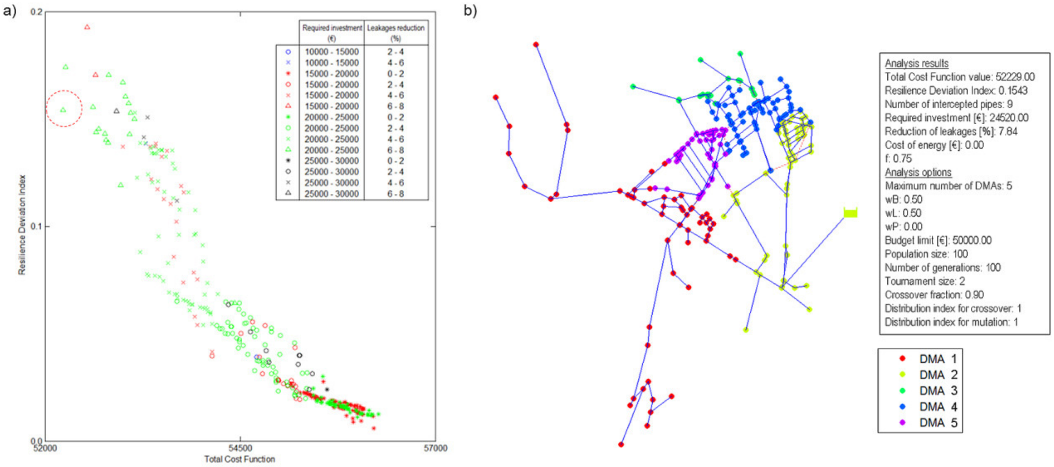


Fig. 3. Overlapped Pareto fronts (a) and attainment surfaces (b) for 10 independent runs of the optimization algorithm.

The bulk of the solutions consists of 4 or 5 DMAs, and only in few cases 3 DMAs are contemplated. The solution with the best overall value of the TCF (highlighted by the red circle in Fig. 4a) involves the delimitation of 5 DMAs, with a reduction in the percentage of water losses equal to 7.84% against a required investment of approximately half of the budget (Fig. 4b).



Analysis results
Total Cost Function value: 52229.00
Resilience Deviation Index: 0.1543
Number of intercepted pipes: 9
Required investment [€]: 24520.00
Reduction of leakages [%]: 7.84
Cost of energy [€]: 0.00
f: 0.75
Analysis options
Maximum number of DMAs: 5
wB: 0.50
wL: 0.50
wP: 0.00
Budget limit [€]: 50000.00
Population size: 100
Number of generations: 100
Tournament size: 2
Crossover fraction: 0.90
Distribution index for crossover: 1
Distribution index for mutation: 1

Fig. 4. Required investment and reduction of water losses (a) and layout of the solution with the best TCF value (b).

Conclusions

The comprehensive methodology presented in this paper is developed to provide a powerful tool for the design of effective DMAs in WDN. The formulation of the problem is oriented to the optimization of the main design criteria, namely the total cost and the hydraulic reliability, but several other issues are taken into account in the implementation of the model. In particular, the best practice principles for sizing the DMAs are considered (number of customers, node elevations, limited number of connections between different DMAs), as well as the hydraulic feasibility of the solutions. The NSGA-II is adopted as the optimization algorithm and the results obtained from its application to a real case study are encouraging. In future works, the sensitivity analysis with respect to the input parameters will be addressed. Further investigations will be also performed on the optimization of the energy consumption [22,23], which is not addressed in the present paper.

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