Multi-object approach for WSN Partitioning in the framework of Pressure Driven Analysis

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ABSTRACT

This paper proposes a novel methodology for WSN (water supply network) partitioning, made up of two serial steps and aimed at investigating leakage reduction benefits as a dual-use value of water network partitioning (WNP). Step 1 makes use of a spectral clustering algorithm to define the optimal layout of the districts, exploiting the properties of the connectivity matrix and giving a mathematical elegance to the arduous problem of optimal cluster definition. Taking the partitioning results of step 1 as granted, Step 2 deals with closure of isolation valves and installation of flow meters in the boundary pipes between either district. In the context of Step 2, a bi-objective optimization, aimed at maximizing the daily water volume supplied to the WSN users and at minimizing the leakage, is performed, in which network behavior is tested in PDA (pressure driven analysis). The applicability of the methodology is shown in a real case study.

Keywords: Spectral Clustering, Pressure Driven model, Water Leakage.

1 BACKGROUND

The division of a Water Supply Network (WSN) into isolated supply clusters allows simplifying and improving the management of the whole system, defining sub-regions named District Meter Areas (DMAs) following the paradigm of "divide and conquer" [1], defining, in this way, a Water Network Partitioning (WNP).

In this regard, the physically division of system, by inserting hydraulic devices on proper pipes, shows to be an efficient strategy for the identification of water losses, for simplifying the control of water budget and the inspection area [2], for controlling district pressure to reduce the water leakage [3], and for protecting users from accidental and intentional contamination [4]. For these reasons, it is important to design the hydraulic districts in some optimal way.

In the last years, many methodologies were developed, from the 'trial and error' approaches to sophisticated heuristic procedures, based on graph and network theory. Generally, the problem is tackled in two steps: Step 1 - clustering (for the definition of shape and dimension of clusters, that is DMAs) and Step 2 - dividing (for the identification of pipes in which to insert isolation valves or flow meters). The objective of Step 2 is to limit the transfer of water from each DMA to its adjoining ones through a limited number of monitored pipes. This facilitates DMA management, especially as far as water balance calculations and leakage estimation are concerned.

In this work, the partitioning methodology proposed in work [5] was upgraded considering the two-step rationale described above. To this end, a bi-objective optimization was included in step 2.

Then, the methodology investigated the possible advantages in terms of leakage savings (considered as dual-use value [4]) obtained through water network partitioning.

In the following sections, the two steps of the methodology are described, and then the application to a real case study is shown.

2 METHODS

In this section, some information is provided about clustering (Step 1) and dividing (Step 2) algorithms used in this paper.

2.1 Clustering based on spectral theory (Step 1)

Water distribution network can be modelled as a strongly geographically constrained and sparse planar graph $G=(V,E)$, where V is the set of n vertices v_i (junctions and delivery nodes) and E is the set of m edges e_l (the pipes).

It is the starting point to apply any k-way graph clustering technique, which consists in partitioning the V vertices set of G into k subsets, $P_1, P_2, \ldots, P_k$ such that: $\cup_1^k P_k = V$ (the union of all clusters P_k must contain all the vertices v_i); $P_k \cap P_t = Ø$ (each vertex can belong to only one cluster P_k); $Ø \subset P_k \subset V$ (at least one vertex must belong to a cluster and no cluster can contain all vertices); $1<k<n$ **(**the number k of clusters must be different from one and from the number n of vertices).

Generally, the graphs are considered undirected and weighted assigning at each link a weight which express the strength of the link between nodes or similarity between elements.

Graph clustering can be achieved with many procedures finalized to define the optimal layout of each cluster through the minimization of an objective function (a large review is provided in [6]).

In the last years, spectral clustering algorithm, based on the Laplacian matrices spectrum (defined hereinafter) has attracted lots of interest in the scientific community due to its easy implementation. In fact, it can be solved by standard linear algebra software. Therefore, in this paper, the clustering phase for sub-region definition was carried out using spectral clustering and assuming graph G to be undirected and un-weighted. In this way, the elements of the adjacency matrix A (nxn), (which expresses the connectivity of the graph), are $a_{ij}=a_{ji}=1$ if nodes i and j are linked, 0 otherwise.

In this work, a recently proposed procedure based on spectral clustering was adopted [5], which leads automatically to the definition of balanced clusters layout (in terms of nodes) minimizing the edges cut set N_{ec} that allows the reduction of the investment cost and the potential hydraulic deterioration in the subsequent dividing phase.

In particular, the normalized spectral clustering according to Shi and Malik [7] was adopted, based on the eigenvalues of the normalized Laplacian matrix L_{rw} (nxn) [8]:

$$L_{rw} = D_k^{-1} L \quad (1)$$

where L is the unnormalized graph Laplacian (difference between the diagonal matrix D_k (nxn) of the nodes degrees k_i and the adjacency matrix A (nxn).

2.2 Dividing based on a bi-objective optimization (Step 2)

Step 2 is focused on the boundary pipes between either DMA. In order to limit the water transfer to each other district to a small number of monitored pipes, a certain number of isolation valves needs to be closed. Each of the pipes that stay open, instead, must be fitted with a flow meter, through which the exchange of water between either district can be thoroughly monitored.

The identification of the pipes in which the isolation valve must be closed and of the pipes to be fitted with a flow-meter was carried out through a bi-objective optimization, for which the algorithm NSGAII [9] was adopted. This algorithm operates as follows: first, at each generation starting from the initial population, the parent population is selected based on its fitness. The algorithm then generates the offspring population through crossover and mutation from the parent population. After being obtained as a combination of the parent and offspring populations, the new population is sorted according to fitness criteria, with the best individuals chosen in order to keep the total number of population individuals constant during generations. The process is repeated until the maximum number of generations.

Inside NSGA-II, a number of decisional variables equal to the number of boundary pipes, was considered. One gene was used for each decisional variable, taking on two possible values, that is 0 and 1, which encode the installation of the flow meter and the closure of the isolation valve, respectively. For each solution proposed by the optimizer, an extended period simulation (EPS) was performed through PDA [10], to analyze the hydraulic behavior of the WSN during the typical day of operation. Inside PDA, the important variables to set were h_{min} and h_{des}, which are the minimum pressure heads for having an outflow to the users larger than 0 and for fully satisfying the users' demand at the generic node, respectively. The objective functions (OF) to be assessed for each solution were:

- min(OF1) = minimization of the Total Leakage Volume;

- max(OF2) = maximization of the Total Water Volume supplied to the WSN users.

In this work, NSGAII was used in an iterative way, as described in [11], to improve the robustness of the end solutions found, which are expected to be close to the global optima. To this end, a certain number (n_{par}) of NSGAII runs was carried out in parallel. The ultimate solutions were then put together and some solutions were sampled based on their fitness. The sampled solutions were used inside the population of new parallel NSGAII runs. This process was repeated for a certain number of times (n_{iter}).

Finally, some performance indices were computed to choose the optimal WNP in terms of hydraulic performance and leakage savings computed in PDA, specifically: total leakage, daily consumption, demand statisfaction rate, and minimum, median and maximum daily values of the Global Resilience Failure index (GRF) proposed in [10]:

$$GRF = I_r + I_f \tag{2}$$

with

$$I_r = \frac{\max\left(\mathbf{q}_{\mathbf{user}}^{\mathbf{T}}\mathbf{H} - \mathbf{d}^{\mathbf{T}}\mathbf{H}_{\mathbf{des}}, 0\right)}{\mathbf{Q}_{\mathbf{0}}^{\mathbf{T}}\mathbf{H}_{\mathbf{0}} + \mathbf{Q}_{\mathbf{p}}^{\mathbf{T}}\mathbf{H}_{\mathbf{p}} - \mathbf{d}^{\mathbf{T}}\mathbf{H}_{\mathbf{des}}} \tag{3}$$

and

$$I_f = \frac{\min\left(\mathbf{q}_{\mathbf{user}}^{\mathrm{T}}\mathbf{H} - \mathbf{d}^{\mathrm{T}}\mathbf{H}_{\mathbf{des}}, 0\right)}{\mathbf{d}^{\mathrm{T}}\mathbf{H}_{\mathbf{des}}} \tag{4}$$

where $\mathbf{q}_{\mathbf{user}}$ and **d** are the vectors of the water discharges delivered to the users and the users' demands, respectively. **H**, $\mathbf{H}_0$ and **Hp** are the vectors of total heads at demanding nodes, water sources and pumps, respectively. $\mathbf{Q}_0$ and $\mathbf{Q}_p$ are the vectors of supplied water discharges by water sources and pumps, respectively. Finally, $\mathbf{H}_{\mathbf{des}}=\mathbf{z}+\mathbf{h}_{\mathbf{des}}$, where **z** and $\mathbf{h}_{\mathbf{des}}$ are the vectors of nodal ground elevations and nodal h_{des}, respectively.

3 APPLICATIONS

The real case study considered in this work is the WSN of Giugliano in Campania (Figure 1), a city of Southern Italy with 120,000 inhabitants. This network has 994 nodes with unknown head, 5 source nodes with assigned head and 1,077 pipes. In the typical day of operation, the users' demand adds up to 15,213 m^3. Before closure of isolation valves, leakage was equal to about 7,348 m^3, that is about 32.6% of the total outflow from the source nodes. The network has a low value of GRF (0.147) in the worst operation condition and, consequently, the system has "low capability" to be partitioned without a decrease in the hydraulic performance [12].

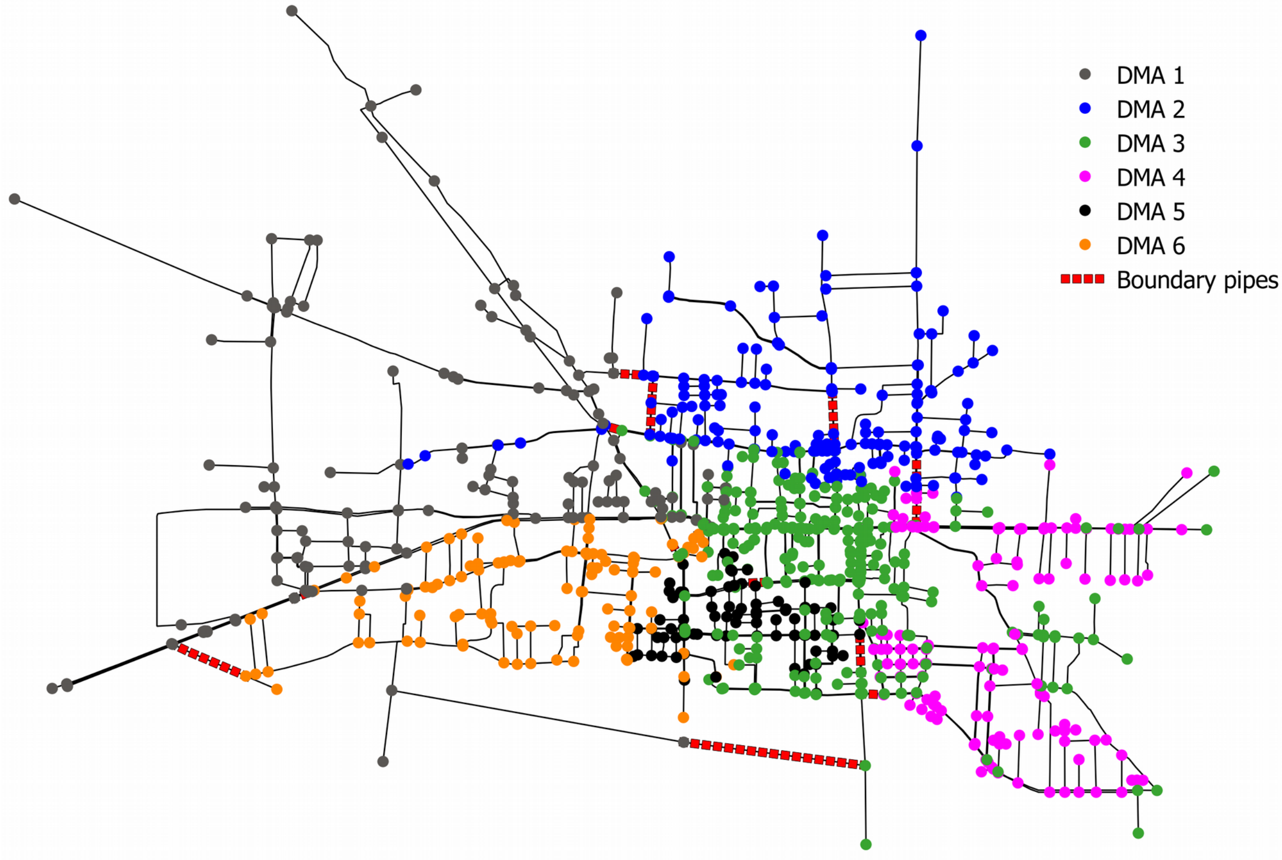

Figure 1. Spectral clustering (Step 1) of Giugliano in Campania network.

The application of Step 1 of the methodology enabled identification of 6 clusters as shown in Figure 1 with different colours, along with 20 boundary pipes. It is important to highlight that the choice of pipe weights is crucial, as different weights lead to significantly different layouts of the districts [5].

In this paper, no weights are assigned to links in order to have an edge cut set with pipes characterized by different hydraulic features, without the choice of a preferential attribute [5]. This was done in light of the principal aim of the work, which was just to balance as much as possible the clusters.

Step 2 was performed considering, inside NSGAII, a population of 50 individuals and a total number of 50 generations. Furthermore, both n_{par} and n_{iter} were set to 3. The PDA of the network was carried out setting h_{min} and h_{des} to 5 m and 25 m, respectively.

The application of Step 2 yielded the Pareto front in Figure 2a, representing optimal solutions in the trade-off between total daily leakage and total daily consumption of the users'. The graph in Figure 2a shows increasing values of leakage and consumption as the number of closed isolation valves and of installed flow meters vary at boundary pipes.

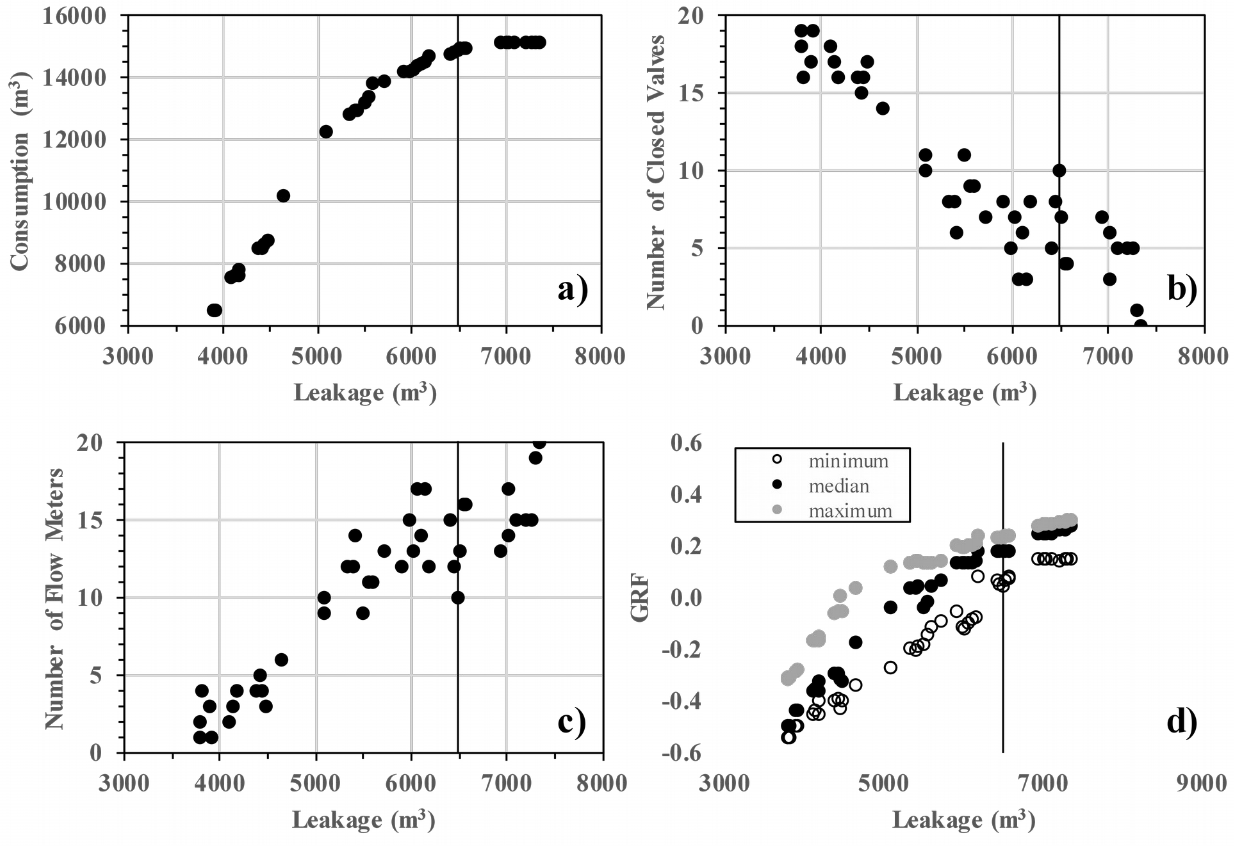

Figure 2. Pareto front of optimal solutions in the trade-off between users' consumption and total leakage (a). Re-evaluated solutions in terms of number of closed valves (b), number of flow meters (c) and GRF index (d). The vertical straight line indicates the chosen solution.

The proposed procedure can be handled as a Decision Support System, because the Pareto front provides the water utility with some possible solutions in terms of number of flow meters and gate valves, water savings and hydraulic performance.

Indeed, an important remark to be made on Figure 2a is that, by suitably choosing the isolation valves to close in the boundary pipes, leakage can be reduced from 7,307 m^3 (with 1 gate valves and 19 flow meters) to 6,146 m^3 (with 3 gate valves and 17 flow meters) that is a total leakage reduction from 0,55% to 16.35%, without prejudicing significantly the consumption (demand satisfaction > 95.0%) and energy resilience (0.00 $<GRF_{min}<$0.146).

In fact, thanks to the selection of suitable pipes for gate closure, the service pressure is reduced, thus enabling leakage mitigation. However, in most WSN nodes, it stays above h_{des} during the whole day, avoiding occurrence of demand shortfalls.

In the other graphs in Figure 2, the optimal solutions of the Pareto front were re-evaluated in terms of number of closed valves (graph b), number of installed flow meters (graph c) and Global Resilience Failure index (GRF) (graph d). In particular, as proposed in work [10], GRF is a power index ranging from 0 to 1 at each instant of WSN operation, with the negative and positive values representing power deficit and surplus conditions, respectively.
The analysis of the graphs in Figure 2 would lead to the choice of the solution with leakage=6,494 m^3 (with leakage reduction by 11.6%), daily consumption=14,852 m^3, demand satisfaction rate of 97.6%, 10 closed boundary pipes (pipes 23, 247, 447, 557, 696, 810, 929, 958, 969 and 1059), 10 flow meters, minimum, median and maximum GRF of 0.05, 0.18 and 0.23 respectively. This solution was highlighted with a straight vertical line in the graphs in Figure 2.

In the following Figure 3, this solution with 10 gate valves and 10 flow meters is reported highlighting the positioning of gate valves and flow meters on the Giugliano network.

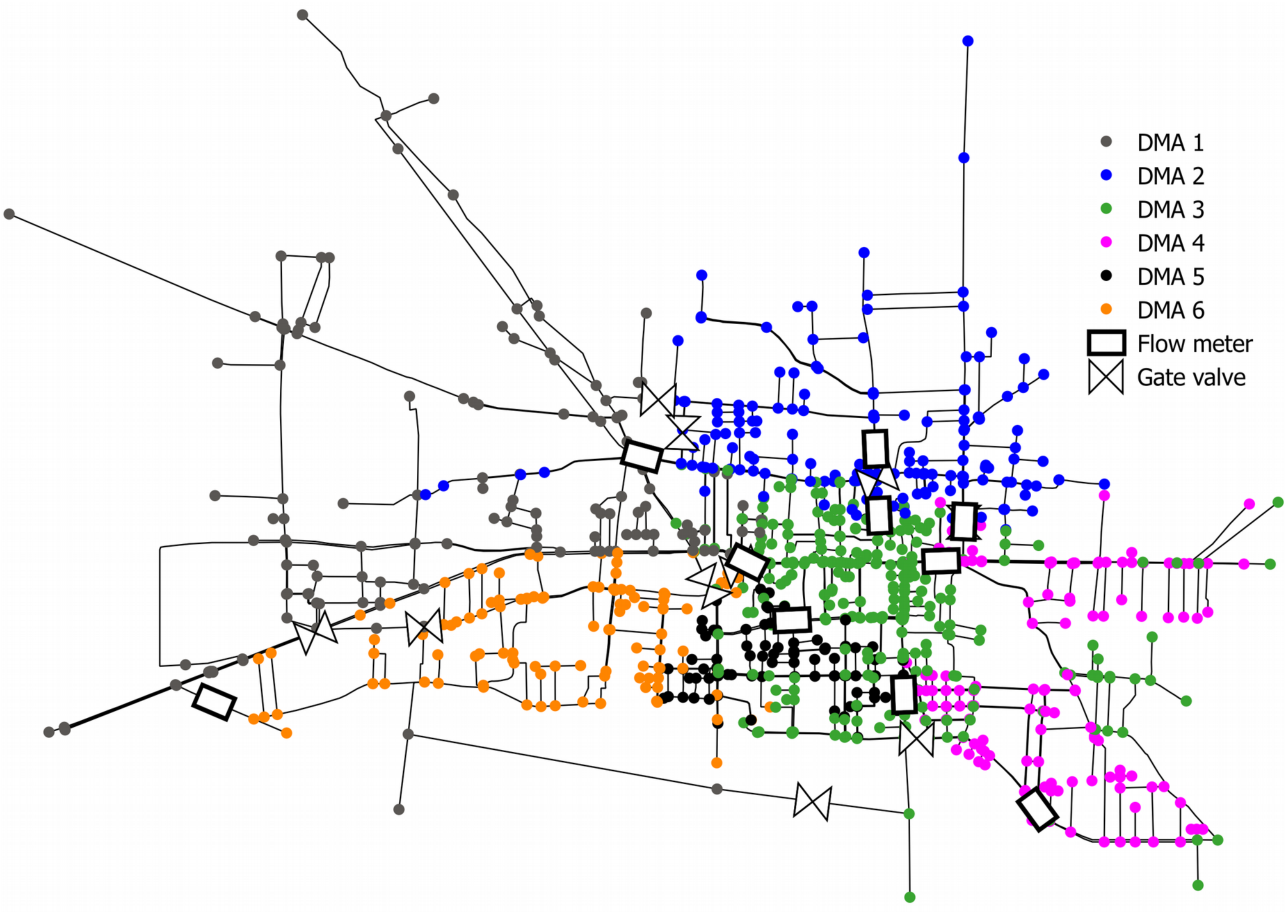

Figure 3. Dividing (Step 2) of Giugliano in Campania network.

4 CONCLUSIONS

This paper proposes a methodology, based on the innovative use of PDA in the water network partitioning design, which allows finding interesting solutions in terms of leakage savings and hydraulic perfomance (merasured with the demand satisfaction rate and global resilience failure index).

The coupling of spectral theory (for clustering phase) and the algorithm NSGAII with a bi-objective function (for dividing phase) was able to find a balanced clustering of DMAs and a wide choice of possible numbers and positioning of flow meters and gate valves corresponding to different leakage reduction (from 0.55% and to 16.30%) in compliance with hydraulic performance in terms of water demand satisfaction and energy resilience computed in PDA. Although the primary aim of water network partitioning is the water balance of DMA, this result shows that water saving can be considered as another dual-use value [4] of water network partitioning in addition to pressure management and water protection from accidental and intentional contamination.

Next studies will take into account also the economic aspects to better allocate the hydraulic devices using a multi-objective optimization, comparing the costs for the purchase and the installation of flow meters and gate valves, and the value of energy and water that can be saved.

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