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Ant algorithm for smart water network partitioning

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Abstract

Applying ICT devices to WDS makes it possible to introduce also the new concept of Smart WAter Network (SWAN), as a key Smart City subsystem, improving the traditional management of WDS. The possibility of inserting remote-controlled valves and flow meters in a WDS allows to divide a water network into k smaller subsystems, in order to improve the management and protection of WDS. This study proposes a novel technique for water network partitioning based on an ant algorithm that allows to obtain a network partitioning compatible with the hydraulic performance. The technique is applied to a real water network.

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Keywords: water network partitioning, graph theory, district meter area, network sectorization, ant algorithm, multi agents.

1. Introduction

The Smart WAter Networks (SWAN) represent a subsystem of Smart Cities (Chourabi et al., 2012); indeed the availability at low cost of Information and Communication Technology (ICT), as remote-controlled monitoring and management devices allows to accelerate the alignment of WDS to other network utilities such as electricity, gas, Internet, etc. The application of ICT to Water Distribution Systems (WDS) makes it possible to introduce also the new concept of SWAN, as a key Smart City subsystem, transforming the traditional approach to analysis, design and management of WDS, from passive to smart actions. The possibility of inserting remote-controlled valves and flow meters in a WDS allows the implementation of the paradigm of "divide and conquer", that consists of dividing a large water network into k smaller subsystems, defining a Water Network Partitioning (WNP), in

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order to simplify and improve the management and protection of WDS (Water Industry Research Ltd,1999; AWWA 2003; Grayman et al. 2009; Di Nardo and Di Natale 2011; Di Nardo et al. 2013a).

The insertion of flow meters and the partitioning allow to simplify the water balance and pressure control that represent two important techniques for improving leakage search and reduction in WDS. The best results can be achieved by defining some permanent districts, called District Meter Areas (DMA), or isolated sectors (i-DMA) (Di Nardo et al., 2012 and 2013c), obtained by the insertion of boundary valves that modify the original network layout. The permanent partitioning changes the original topological layout of water systems traditionally designed with many loops in order to allow water network to be more reliable with respect to spatial and temporal variability of demand, as well as to mechanical and hydraulic failure conditions (Mays, 2000). Network sectorization achieved by pipe closure reduces the pipe diameter availability with the consequent decrease of network water pressure, especially during peak hours, worsening the level of service offered to users (Di Nardo and Di Natale, 2011).

WNP of existing networks is traditionally carried out on the basis of empirical suggestions (number of properties, length of pipes, etc.) and with approaches such as ‘trial and error’, even if used together with hydraulic simulation software (Water Authorities Association and Water Research Centre 1985; Water Industry Research Ltd 1999; Butler 2000; Twort et al. 2000). More recently, several approaches have been proposed in the literature for automatically performing the partitioning of an existing network, usually relying upon the application of topological and/or energetic constraints to support the choice of the links to be interrupted (Tzatchkov et al., 2006; Di Nardo and Di Natale 2011). The application of such procedures to real WDS is very difficult, since an exhaustive search of the optimal partitioning layout, i.e. the least affecting the hydraulic performance of the network, is impossible owing to the huge number of possible layouts (Di Nardo and Di Natale, 2012).

Therefore, several techniques have been proposed to search for a good layout, i.e. one of the least affecting the hydraulic performance, for assigned partitioning criteria. Herrera et al. (2010) have proposed a procedure based on spectral clustering using weighted kernel matrices, that are obtained from graphical and vector information (pipes, demand nodes and water constraints). Izquierdo et al. (2011) have proposed an original procedure, based on multi-agent systems (Wooldridge, 2002), to define the DMAs of a water supply network in which each agent is a consumption node with a number of associated variables (elevation and demand are most important). Recently, based on graph theory principles (Di Nardo and Di Natale, 2011) and graph partitioning techniques (Di Nardo et al., 2011; Di Nardo et al., 2013c) coupled with an energetic approach, some design procedures have been proposed to define DMAs that have significantly improved the automatic WNP.

This study proposes a novel technique for water network partitioning based on multilevel paradigm (Karypis and Kumar, 1998) that combines an ant algorithm (Comellas and Sapena, 2006) and a graph partitioning procedure coupled with a genetic algorithm (Di Nardo et al., 2013c), that allows to compare different WNPs of water system. The technique is applied to a real water network by considering various different constraints for the choice of the links to be interrupted.

2. Graph partitioning algorithm

Graph partitioning is a problem which appears in many different applications as data-mining, VLSI design, finite element and parallel computing. For example, large-scale numerical simulations on parallel computers, such as those based on finite element methods, require the distribution of the finite element mesh among the processors. This distribution must be done so that: 1) the number of elements assigned to each processor is the same, in order to balance the workload; 2) the number of adjacent elements assigned to different processors is minimized, to reduce the communication overhead. Graph partitioning is used to successfully satisfy these constraints that, in some ways, can be mapped on those of a water network sectorization problem: the workload balancing and the minimization of edge-cut can be likened to balance the number of nodes or flow for each DMA and to minimize the pipe-cut or the number of boundary valves, respectively.

Graph partitioning is an NP-complete problem (Garey and Johnson, 1979), for graphs with a large order it is not possible to obtain the best solution in a reasonable computation time: when the size of the graph increases, the execution time of an algorithm capable of solving the problem can be assumed to grow exponentially. Therefore the problem is practically unsolvable for most networks and heuristic and probabilistic methods are considered to obtain solutions close to the absolute minimum in a reasonable time (Comellas and Sapena, 2006).

Consider a simple weighted graph $G=(V,\mathrm{E})$, where V is the set of n vertices (or nodes) and E is the set of m edges (or links) and denote by ε_{ij} the non-negative weight of the edge $ij \in E$ and $\varepsilon_{ij}=0$ if $ij \notin E$. Let ω_i be a positive weight of vertex $i \in V$ and $\omega(D)=\sum_{i\in D}\omega_i$, where $D \subseteq V$. The k-way graph partitioning problem is to partition V vertices of G into k subsets, $D_1, D_2, \ldots, D_k$, such that $D_i \cap D_j = 0$ for i≠j, $|D_i| = n/k$, and $\cup_i D_i = V$ and the number of the edges $N_{ec} = \sum_{i\in D_n \Rightarrow j\notin D_n} e_{ij}$ (with e_{ij} called the edge-cut) that connect vertices in different partitions is minimized. In the cases in which the vertices and edges have weights associated, the goal is to partition the vertices into k disjoint subsets such that the sum of the vertex-weights in each D_i is the same and the sum of the edge-weights whose incident vertices belong to different subsets is minimized. In the last years some techniques have been proposed to graph partitioning, based on multilevel paradigm (Banos et al., 2003) that combines with evolutionary algorithm (Soper et al., 2004) and ant-colony (Korosec, 2004). The use of each one requires the problem codification and a criterion to "measure" the effectiveness of the found solution.

In this work, the authors proposes a novel methodology, defined WNP-Multilevel Algoritm (WNP-MA), for partitioning of a water supply system, based on multilevel paradigm composed by different steps, illustrated in the flow chart of Fig. 1, that combine graph theory, ant and genetic algorithms integrated in an original energetic approach.

Starting from network model as an INPUT (with node water demand distribution Q_i, with i=1..n, source heads H_s, with s=1..r reservoir, pipe length L_{ij} and node elevations z_i), pipe flow q_{ij}, node heads h_i and head losses ΔH_{ij} for each pipe can be calculated by a Demand Driven Approach, DDA (Rossmann, 2000). In order to obtain better results, the methodology can be performed with different weights ε_i for vertices and ω_{ij} for links using geometric and hydraulic properties of network. In this study (steps b1-b3), water demands have been adopted as weights of the vertices, while dissipated powers have been used as weights of the edges. This latter choice has been made owing to recent results indicating that indices based on the comparison between available and dissipated power are among the most suitable to be used as predictors of network capability of retaining its hydraulic performance after the interruption of one or more links (Greco et al., 2012).

Then, once the hydraulic simulation (step a) has been carried out in a peak demand condition (Di Nardo and Di Natale, 2011a), and once the number k of DMA of the water network has been chosen (step c), the proposed multilevel technique can be applied in order to find a k-way partitioning (step d). Specifically, the graph partitioning phase (step d) starts with recursive bisection (step d.1): first the starting graph G_0 is subdivided into *2*-way balanced partitions the $G_1=(V_1,E_1)$ and $G_2=(V_2,E_2)$, then each part further is subdivided in *2*-way balanced partitions (or bisections). To achieve balanced partitions the *Node Constrain* (1) must be satisfied:

$$NC = n/k \text{ or } NC = \sum_{i=1}^{n} \omega_i / k \tag{1}$$

This step d.1) is carried out with the aim of a DFS algorithm, proposed by Tarjan (1972), that starts from a node and explores as far as possible along each path (in "depth") until there are no more adjacent unvisited nodes; only then it starts a new path. The application of the DFS algorithm makes it possible to identify a new graph structure of the network, composed of *trees* and *branches,* called a *DFS forest graph* (Cormen et al. 1990), starting from a generic node of the graph.

Then *DFS forest graph* is divided in two subgraph (bisected): $G_1=(V_1,E_1)$ and $G_2=(V_2,E_2)$ that can be considered a possible bisection of G_0 if each one is a connected graph or, in other words, if for each couple of vertices u and v there is a path that links u and v, otherwise this condition is iteratively sought moving each not connected vertex from a subset to the other one until G_1 and G_2 are connected. Each bisection is followed by an optimization phase, performed by multiagent algorithm that generates new optimized bisection $G_1 = (V_1, E_1)$ and $G_2 = (V_2, E_2)$; the goal of this phase (step d.2) is *minimizing* the number of the edge-cut e_{ij} (or the associated weights ε_{ij}) and it is achieved by the ant algorithm of Comellas and Sapena (2006), adapted suitably to a water network with some novel modifications.

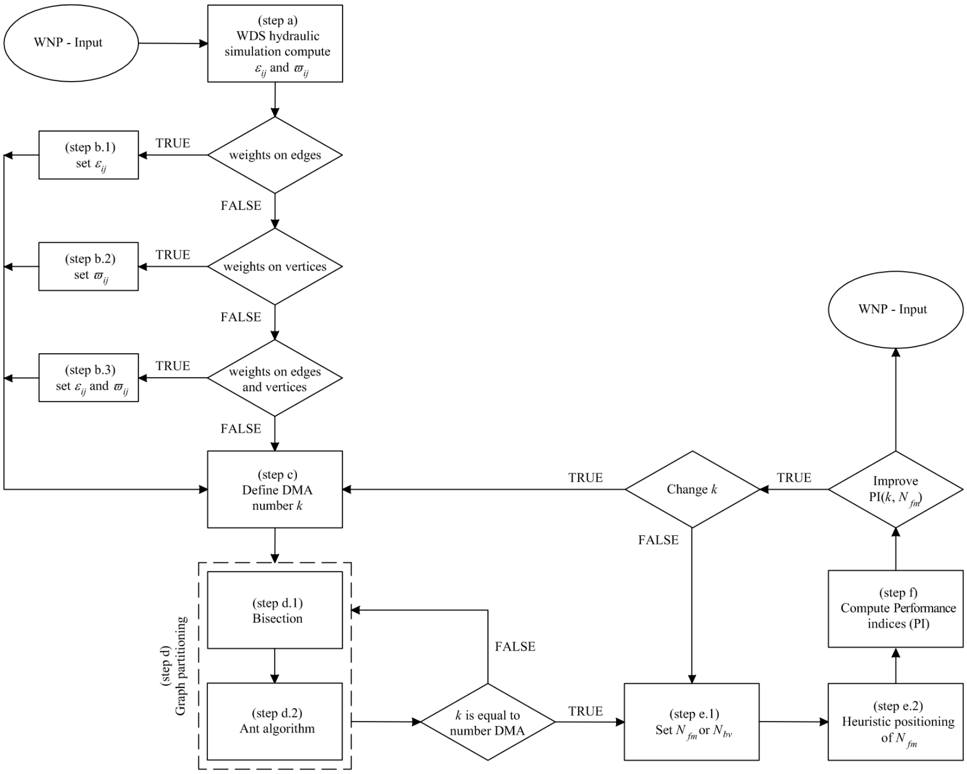

Fig 1. Different phases of the WNP-MA

Each phase of the ant algorithm is schematically reported in the following:

- each vertex of graph has a different colour in function of subgraph membership (defined by DFS algorithm);
- the number of ants (or agents), randomly assigned (or positioned) to vertices, is fixed;
- for each i-th vertex, a Local Cost function is defined:

$$LC_i = \frac{NA_j}{NA_i} \tag{2}$$

- in which, if the i-th vertex belongs to the subgraph G_1, NA_i is the total number of vertices adjacent and NA_j is the number of vertices adjacent to i-th vertex but belong to subgraph G_2;
- then for the graph G_0 the *Global Cost* function is initialized:

$$GC = \sum_{i \in G_1} \sum_{j \in G_2} e_{ij} \text{ or } GC = \sum_{i \in G_1} \sum_{j \in G_2} \varepsilon_{ij} \tag{3}$$

  that computes the number of the edges e_{ij}, or the associated weights ε_{ij}, that connect the vertices that belong to two different subgraph;
- the agents or ants move around the graph and change the colour according to a local optimization criterion: at each iteration, all the ants move from their position towards the adjacent vertex with the highest local cost, as illustrated in Fig. 2, with a probability p_m (otherwise it moves to any other adjacent vertex), and change its colour to decrease the local cost under probability p_c (otherwise it assigns any colour at random). Both probabilities are adjustable parameters;

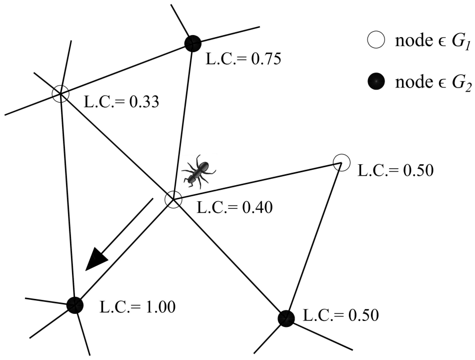

Fig. 2. Scheme of the ant movement

- at the same time, to keep balanced the number of vertices belonging to the various subgraphs, the algorithm chooses the vertex with the highest LC belonging to the subgraph to which the node changed colour was added, and changes its colour to the one previously assigned to the newly added vertex;
- the algorithm updates the value of the Global Cost function for the network and LC function for each node.

The process is repeated until the *Global Cost* function is minimized; the probabilistic nature of the algorithm allows it to escape from local minima and obtain partitions with *k-cuts* close to the absolute minimum. The number of ants in the algorithm is also an adjustable parameter that should increase with the diameter of the graph (maximum of the distances between pairs of vertices). Once the minimization of (3) is attained, another bisection of each subset is performed until the desired number k of subgraphs is obtained.

Then, once obtained the set N_{ec} of the edge-cuts, it is necessary to choose how many and which of these boundary pipes have to be interrupted with N_{bv} gate valves or, equally, have to be used for installing N_{fm}=(N_{ec}-N_{bv}) flow meters. In other terms, for assigned k districts, after finding the possible positions e_{ij} for flow meters and boundary valves, by the graph partitioning technique (step d), and choosing the number of N_{fm} and of N_{bv} (step e.1), one should define which pipes have to be interrupted among all the possible combinations of WNP layouts N_c expressed by binomial coefficient:

$$N_c = \begin{pmatrix} N_{ec} \\ N_{fm} \end{pmatrix} \tag{4}$$

which, evidently, grows enormously even for a relatively small number of districts. Therefore, also in this case, the problem is practically unsolvable with an exhaustive search of best solution and the recourse to heuristic methods is needed. So, fixed the number of N_{fm}, this phase (step e.2) is achieved by means of a heuristic procedure, based on a Genetic Algorithm (GA) (Goldberg, 1989), developed by the authors in Di Nardo et al. (2012) and in Di Nardo et al. (2013c). The GA allows the determination of the optimal position of each flow meter in the network by inserting gate valves in the pipes that belong to the *edge-cut* set, minimizing the following cost function:

$$\min\left(P_D^{bv} = \sum_{i=1}^{N_{bv}} P_{D_i} \right) \tag{5}$$

where P_D is the total dissipated power of the network and P_{Di} is the dissipated power in each i-th pipes (or edges). In particular, each GA individual is composed by a sequence of chromosomes corresponding to the number of pipes belonging to the set N_{ec}. Each chromosome assumes value 1 if a gate valve will be inserted in the j-th pipe otherwise value 0 if a flow meter will be inserted. GA is carried out with 50 generations and with a population composed of 100 individuals with a crossover percentage P_{cross}=0.8. So, once defined the optimal positions of flow meters (or the complementary positions of gate valves) (step e.2), it is possible to compute (step f) the Performance Indices (PI). Three categories of PI have been used to test different sectorization layouts using a DDA approach:

- resilience index I_r (Todini, 2000), based on the comparison between dissipated power and the maximum power which is necessary to satisfy the node demand constraints, and resilience deviation index I_{rd}, proposed in Di Nardo and Di Natale (2011), based on the comparison among resilience index of the original and of the sectorized network;
- pressure indices, traditionally measured by mean node pressure h_{mean}, maximum node pressure h_{max}, minimum node pressure h_{min} and standard deviation pressure h_{sd} (Di Nardo et al., 2013b);
- balance index:

$$I_B = \frac{k \cdot \max(d_p)}{n} \tag{6}$$

where $\max(d_p)$ can be the size of largest subset n_p (or the maximum weight ω_p) obtained by the k-way partitioning algorithm.

If the evaluated indices satisfy the performance requirements, the procedure stops, otherwise it is possible to modify the chosen number of gate valves N_{bv} (or the number of flow meters N_{fm}), as well as the number k of districts (Fig. 1).

3. Case study

The methodology has been tested for the real water system of Parete (Di Nardo and Di Natale, 2012) in the Province of Caserta (IT) with 10,800 inhabitants, in a densely populated area north of Naples (Italy), characterised by a low original resilience index (I_r=0.318), mean node pressure h_{mean}=31.05, maximum node pressure h_{max}=50.47 and minimum node pressure h_{min}=21.36.

In Fig. 3, the graph partitioning phase (step d) is illustrated with reference to the case without weight. Specifically Fig. 3a shows the first bisection of Parete network, the subsets G_1 (brown colour) and G_2 (yellow color) obtained with DFS algorithm. In Fig. 3b the results of first iteration of ant algorithm is illustrated, in which the minimization of the number of the edge-cut e_{ij} is performed. As shown in the Fig., the application of the ant algorithm can significantly affect the layout of the districts, even by keeping unchanged their number of nodes. Fig. 4a reports the recursive bisection applied to the subset G_1 and G_2 that generated four subset $G_{1,1}$ (pink colour) and $G_{1,2}$ (green color) and $G_{2,1}$ (red colour) and $G_{2,2}$ (blu color) corresponding to four DMAs (DMA1, DMA2, DMA3 and DMA4, respectively). Also in this phase (Fig. 4b) the graph partitioning process minimizes the number of edge-cuts N_{ec} in compliance with the constraint (1).

In this work, several different partitioning criteria have been compared, all based on the assumption of demand as vertex weight and dissipated power as edge weight, considering different weight conditions. Namely: without any weights (A); edge weights only, ε_{ij} (B); vertex weights only, ω_i, (C); edge and vertex weights simultaneously, ε_{ij} and ω_i, (D). The obtained WNPs have been compared in order to find the best weights for effective graph partitioning of a water network. This analysis has been carried out with the same choice of k=4 DMAs and the same number of flow meters N_{fm}=6. The obtained results are summarized in Table 1.

The evaluated performance indices show that, for case A, the resilience index is slightly lower than the one evaluated in a network without WNP, with a reduction I_{rd}=4.27%. Furthermore, the number of nodes for each DMAs is balanced, each one including 45 or 46 nodes; in this case without vertex weights, the index I_B is naturally computed only with the maximum number of nodes n_p=46 of DMA2 and DMA4. The result of case A is slightly improved, using the dissipated power $q_{ij}\Delta H_{ij}$ as edge weight (case B), as indicated by 3rd column of Table 1. In this case, in fact, the best performance index I_{rd}=3.99% is obtained, again with a perfect balance index equal to 1.00. Also the pressure indices are very good with a minimum pressure h_{min}= 21.55 and h_{min}=21.39, respectively, slightly higher than h_{min} of the network before partitioning. Other simulations, reported in the 4th column, have been carried out considering only vertex weights Q_i (without edge weights); in this case the result is slightly worse than for the two previous cases, with I_{rd}=11.96% but with a quite perfect balancing of $I_{B=}$1.03. In this case the possibility to move the nodes from a district to another is more constrained from relation (1) and, consequently, although the index I_B is very good, the resilience indices are slightly worse. This solution, with different number of nodes for each DMA but with a balanced district total flow, can evidently be very helpful for operators wanting to define DMAs with similar total water demand, useful for problems of water loss research.

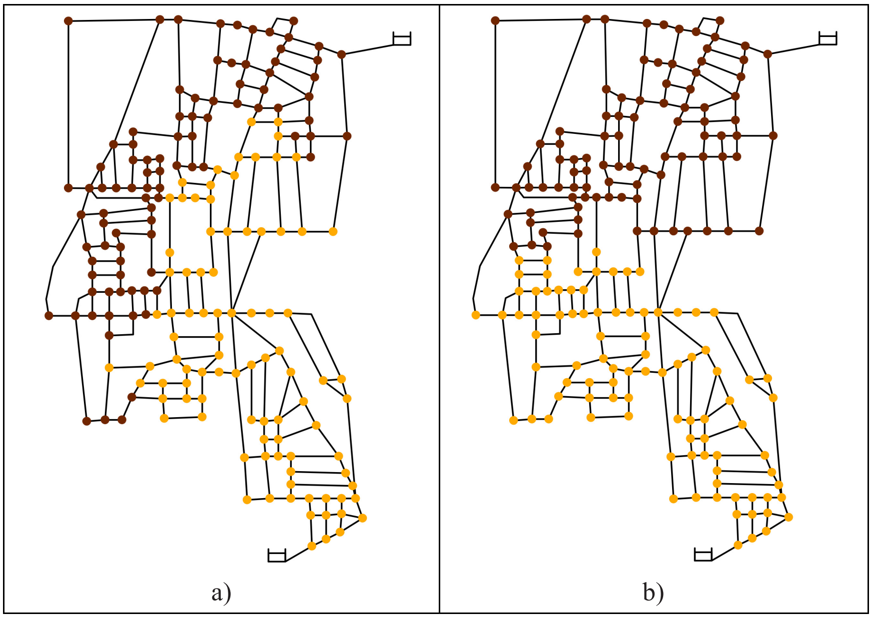

Fig. 3. First bisection of Parete network: a) DFS algorithm (step d.1) and b) ant algorithm (step d.2)

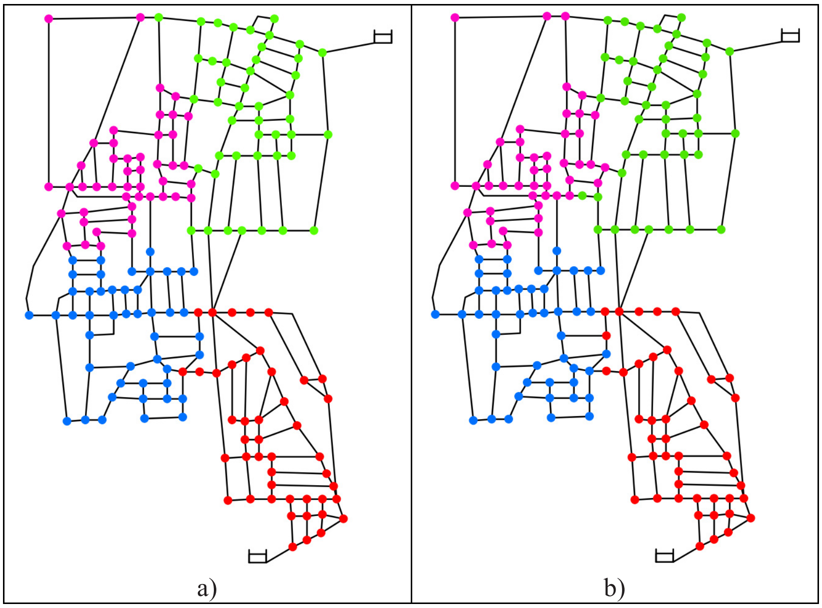

Figure 4. Second bisection of Parete network: a) DFS algorithm (step d.1) and b) ant algorithm (step d.2)

The last column of Table 1, shows that using both edge and vertex weights (case C) does not improve the results, but a slight performance worsening (I_r=0.308), compared to case (B), is obtained. This result may depend on the ineffectiveness of the chosen weights, as well as on the greater difficulty of the ant algorithm to investigate the solution space in the presence of many constraints.

The presented results have been obtained in all cases with the same number of ants and iterations and, possibly, better results could be found by increasing such numbers.

Table 1. Performance indices and main characteristics of each WNP

	No weight	Edge weights ε_{ij}	Vertex weights ω_i	Edge and vertex weights ε_{ij} and ω_i
	-	$q_{ij}\Delta H_{ij}$	Q_i	$q_{ij}\Delta H_{ij}$ and Q_i
WNP	A	B	C	D
k	4	4	4	4
n_1	45	46	30	67
n_2	46	45	26	54
n_3	45	45	67	30
n_4	46	46	59	31
N_{ec}	18	29	19	25
N_{fm}	6	6	6	6
N_{bv}	12	23	13	19
I_B	1.00	1.00	1.03	1.06
I_r	0.336	0.337	0.309	0.308
I_{rd} [%]	4.27	3.99	11.96	12.25
h_{min} [m]	21.55	21.39	21.68	20.95
h_{mean} [m]	30.73	30.62	30.19	29.94
h_{max} [m]	50.41	50.45	50.38	50.56
h_{sd} [m]	5.55	5.67	5.52	5.96

Anyway, the results reported in Table 1 indicate that all the obtained WNPs ensure retaining good network hydraulic performance, considering the large number of gate valves inserted in the water network, from N_{bv}=12 up to N_{bv}=23. Thus, the proposed methodology WNP-MA allows to find a good solution in compliance with the level of service for the users, as indicated by the values assumed by the pressure indices. In all cases the pressures of WNP layouts are similar to the pressure of original network; specifically also the minimum pressure h_{min}=20.95 of WNP4 is practically equal to the original value h_{min}=21.36 of the network without districts.
All the best WNPs obtained in the four considered cases with the proposed methodology are shown in Fig. 5a and Fig. 5b, in which the layout of DMAs and the location of flow meters and boundary valves are illustrated.

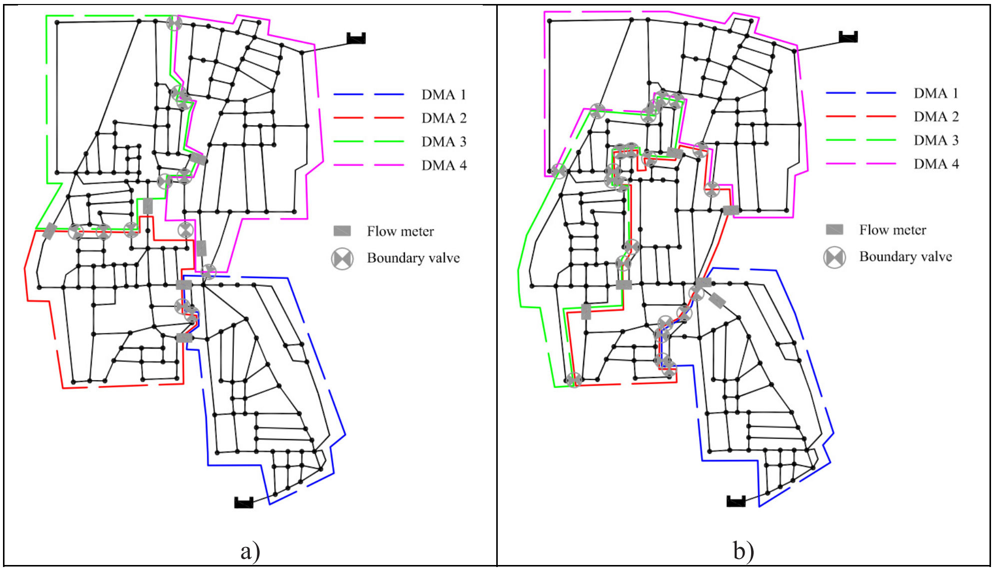

Figure 5a. WNPs with different weight combinations: a) no weights; b) on pipes

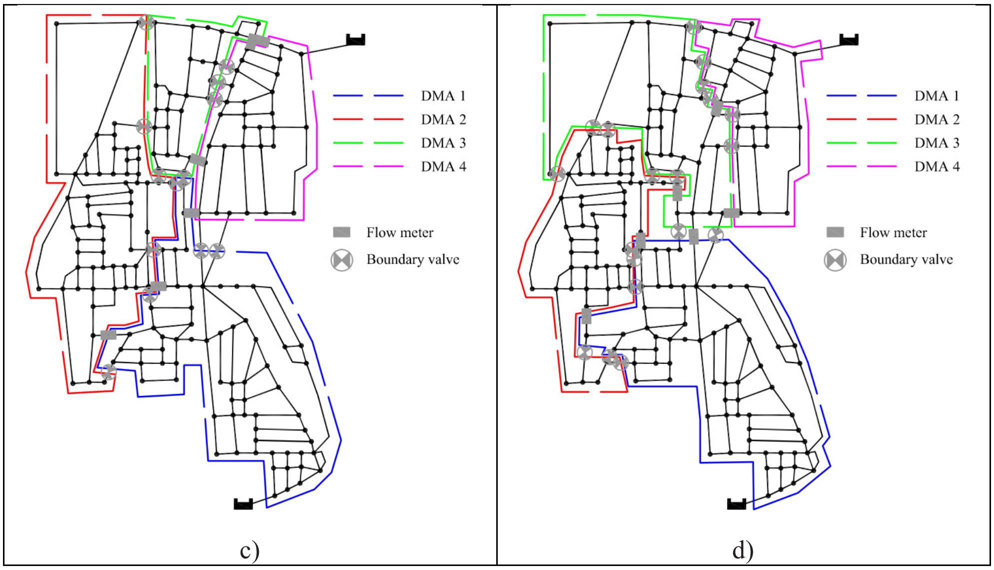

Figure 5b. WNPs with different weight combinations: c) on nodes; d) both weights

4. Conclusion

The proposed methodology, tested on the real case study of the network of Parete, is based on an original multilevel algorithm for water network partitioning, composed by different procedures that combine a DFS, an ant and a genetic algorithm integrated in an original energetic approach. After the hydraulic simulation of the network, that allows assigning weights to each node and pipe, WNPs, obtained with different partitioning criteria, based upon different combinations of weights, all based on assuming dissipated power as pipe weight and demand as node weight, have been compared using suitable performance indices. Simulation results show the effectiveness of the proposed multilevel algorithm because, automatically, the WNP-MA found different network partitioning of Parete network, all with 4 DMAs, compatible with the level of service for the users. The best results were obtained assigning weights only to edges, but all the other analyzed cases caused an alteration of the minimum network pressure of less than 1%. However, the maximum reduction of network resilience was obtained by assigning weights to both pipes and nodes. This result may depend on the ineffectiveness of the chosen weights, as well as on the greater difficulty of the ant algorithm to investigate the solution space in the presence of many constraints. In fact, the presented results have been obtained in all cases with the same number of ants and iterations and, possibly, better results could be found by increasing such numbers. Further simulations with larger number of ants and iterations should be carried out to investigate this aspect. In conclusion, the proposed methodology can be easily applied to large networks to define automatically optimal water network partitioning overcoming empiric approaches usually adopted by operators. Therefore, the proposed technique looks promising as a tool to investigate, for real networks, the effects of adopting different partitioning criteria.

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