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A New Procedure for Optimal Design of District Metered Areas Based on the Multilevel Balancing and Refinement Algorithm

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Abstract A procedure for optimal design of District Metered Areas (DMAs) within a water distribution network based on a multilevel balancing and refinement algorithm to partition the network and determine the optimal meter positions, coupled with a pressure driven hydraulic simulator to quantify the hydraulic performance of the districtualized system, is presented. Unlike other procedures based on graph partitioning techniques proposed in the scientific literature, the two main issues involved in the design of the DMAs, namely a) how to partition the nodes into the required number of districts, and b) which pipes linking districts to leave open, and fitted with an assigned number of flow meters, and which to close, are simultaneously resolved. The application of this procedure to a real case shows that this approach provides design solutions well adapted to different numbers of measuring points, yielding superior performance indicator values to similar procedures reported in the literature and used here for comparative purposes.

Keywords District metered area · Water distribution system · Multilevel balancing and refinement algorithm

1 Introduction

In order to facilitate the monitoring and management of water distribution networks (WDNs), these can be partitioned into discrete zones, known as district metered areas (DMAs), interconnected only by conduits equipped with flow meters. The remaining pipes connecting the districts are closed by means of gate valves, so that flows to and from each DMA can be monitored, thereby enabling their trend in total water consumption over time to be calculated using a water balance equation. This makes partitioning systems a useful means of identifying

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leaks (Thorton 2004; Tabesh et al. 2009; Bettin et al. 2014; Xin et al. 2014), and can facilitate piezometric head control, bringing further benefits in terms of water loss containment (AWWA 2003; Ristovski 2011; Paskalev et al. 2011; Renaud et al. 2015). Q2

Operationally speaking, design of DMAs involves first fixing the number of DMAs to be created and defining their dimensions, in terms of the number of users to include in each, for example (WRc 1994). Subsequently it is necessary to determine how to subdivide the network nodes in order to create the assigned number of DMAs, whose user numbers must be as similar as possible to the desired ones, and to define how many and which pipes connecting the DMAs to leave open and fit with meters, and which to close by means of a gate valve without compromising the system's minimum service or acceptable hydraulic performance levels.

In real-world networks, this issue has often been tackled heuristically, relying heavily on the individual system managers' knowledge of the network. However, in recent years, several automated procedures have been proposed, alongside other helpful tools available to such decision-makers (see, for example Tzatchkov et al. 2006; Sempewo et al. 2008; Herrera et al. 2010; Perelman and Ostfeld 2011; Di Nardo and Di Natale 2011; Di Nardo et al. 2011; Gomes et al. 2012a, b; Perelman and Ostfeld 2012; Diao et al. 2013; Di Nardo et al. 2013a, b; Gomes et al. 2013; Alvisi and Franchini 2014; Di Nardo et al. 2014a, b; Ferrari et al. 2014; Perelman et al. 2015). These procedures are mainly based on techniques derived from Graph Theory (Tzatchkov et al. 2006; Di Nardo and Di Natale 2011; Gomes et al. 2012a, b; Di Nardo et al. 2013b, 2014a; Alvisi and Franchini 2014; Ferrari et al. 2014), clustering algorithms (Herrera et al. 2010; Perelman and Ostfeld 2011, 2012; Perelman et al. 2015), or the identification of community structures (Diao et al. 2013; Perelman et al. 2015). Another approach adopted is to combine graph-partitioning procedures, used in computer science for parallel computing, with hydraulic simulations to test the performance of the resulting solutions (Sempewo et al. 2008; Di Nardo et al. 2011, 2013a, 2014b). To this end, the previously mentioned authors (Sempewo et al. 2008; Di Nardo et al. 2011, 2013a, 2014b) have proposed and investigated the use of a particular graph-partitioning software package, METIS© (Karypis 2011), which uses a multi-level recursive bisection (MLRB) algorithm (Karypis and Kumar 1998a, b) purpose-designed to resolve the issue of allocating calculation processes uniformly between more than one machine/processor operating in parallel while minimizing the number/volume of information that needs to be exchanged between them. As observed by Sempewo et al. (2008) and Di Nardo et al. (2011, 2013b), this algorithm is also an effective means of uniformly partitioning water networks into an assigned number of districts, assuming that every network node within the districts is given a representative weight corresponding to the number of users connected to it, and each pipe connecting the districts is associated with a representative weight corresponding to its diameter or conductance, for example. By taking these factors into account, the software is able to allocate the nodes of a graph to a pre-established number of areas, each nearly containing a pre-assigned number of nodes (or sum of the weights assigned such nodes), and minimize the number of connections (pipes) between these areas (or sum of the weights thereof).

In particular, the METIS-based procedure proposed by Sempewo et al. (2008) merely enabled identification of the areas into which to partition the network, and made no attempt to tackle the problem of identifying which connections to open, and equip with meters, and which to close, whereas Di Nardo et al. (2011, 2013a, 2014b), did attempt to resolve this problem. More in details, in Di Nardo et al. (2011) once the DMAs and the set of pipes connecting them to each other have been identified, the number of connecting pipes that it is desired to leave open and therefore, by subtraction, the number of connecting pipes to be closed is fixed; all of the possible combinations of open and closed pipes are considered by enumeration and for each combination, by means of demand-driven hydraulic simulations (EPANET, Rossman 2000), a number of system performance indices are quantified (e.g., resilience index, minimum network pressure, etc.). These indices are used to identify the best solution, i.e., which links should be left open and have a meter placed in them and which should be closed. Recognizing, however, the laboriousness of this means of selecting which connections to meter and leave open and which to close, in order to limit the computer time required the same authors (Di Nardo et al. 2013a, 2014b) introduced an optimization process based on a genetic algorithm into the procedure. Indeed, fixed the number of connecting pipes that it is desired to leave open and therefore, by subtraction, the number of connecting pipes to be closed, the decision variables of the optimization process are the the positions of the meters, i.e., which pipes to keep open (and therefore also which to close), and the objective function to be minimized is the power dissipation across the network.

However, both procedures put forward by Di Nardo et al. (2011, 2013a, 2014b) solve the problem of the two critical phases in optimal district design (node allocation and meter positioning) by *uncoupling* them. In other words, first the graph-partitioning algorithm is used to identify the optimal solution in terms of node allocation to the assigned number of districts, respecting the required dimensions of each and minimizing of the total number of (weighted) pipes between them, and only in a second step is the number of meters assigned and their optimal position identified (i.e., which pipes to open and close). Although this approach is extremely pragmatic, it reduces the search domain of the optimal districtualization solution, and may therefore provide less than optimal results.

In order to overcome this aspect a new procedure is here presented for automated water network partitioning that is also based on the MLRB graph-partitioning algorithm and hydraulic simulation, but, unlike the procedure described above, is able to allocate the nodes and identify the best meter position simultaneously. In the following, after recalling the main characteristics of the multi-level recursive bisection (MLRB) algorithm, the proposed procedure is presented. Results obtained by the application of the procedure to a real complex water distribution are then discussed and compared with those generated by two well established methods for WDN districtualization, i.e., the procedure proposed by Di Nardo et al. (2011) which is similarly based on MLRB algorithm and hydraulic simulation but uncoupling node allocation and meter positioning, and the procedure Alvisi et al. (2014) which is based on a graph theory approach. Q3

2 The Multi-Level Balancing and Refinement Algorithm (MLBR)

The multi-level balancing and refinement algorithm (MLBR), is a method originally developed to resolve the issue of allocating calculation processes uniformly between more than one machine/processor operating in parallel, which can also be used to partition the nodes of a WDN into an assigned number of districts n_{DMA} of predefined size (i.e., serving a pre-established number of users). It consists of three main logical steps, namely 1) coarsening, 2) partitioning, and 3) partition expansion with balancing and refinement (Walshaw and Cross 2000), as described below.

2.1 Coarsening

The WDN is seen as a graph G_0 consisting of NN nodes and NT links. In essence, the coarsening procedure reduces the graph of the original network G_0 to a series of ever more simplified, coarser graphs, denoted G_1, G_2,… G_k, by coupling adjacent nodes and collapsing the links connecting them. The generic coarsening from graph G_i to graph G_{i+1} (e.g., from G_0 to G_1 or from G_1 to G_2, etc.) is achieved via the identification in graph G_i of a *maximum* set of *independent* links and collapsing the outermost nodes (i.e., the vertexes) of each. In this case *independent* means that no two links share an outermost node, while *maximum* denotes that it is impossible to reach any other trunk without violating the condition of independence.

In this way, each pair of collapsed nodes constitutes a new node in the simplified, coarser graph G_{i+1}, made up of only uncollapsed links. Assuming that each node in graph G_i is weighted, i.e., in this case according to the number of users it serves, the new node in the coarser graph G_{i+1} will have a weight equal to the sum of the users served by the collapsed nodes it contains.

One simple way of identifying the maximum set of independent network links is to create a list of the nodes in G_i in random order, taking each node in the list in turn and identifying the links connected to it, selecting and collapsing one of these links, thereby eliminating the other vertex of the selected link from the node list. This procedure is repeated until no more nodes can be eliminated from the list, and the coarser graph G_{i+1} is the result. If network links have not been assigned a weight, the choice of link to collapse is made randomly, but if each is given a weight *w* (e.g., relative to the diameter (Di Nardo et al. 2011) or conductance (Alvisi and Franchini 2014) of the corresponding pipe), the link with the greater weight is collapsed, as suggested by Karypis and Kumar (1998b).

The coarsening operation is repeated until a graph G_k, made up of a number of nodes N_{Gk} such as $n_{DMA} \le N_{Gk} < 2 \cdot n_{DMA}$ is obtained.

2.2 Partitioning

If the number of nodes N_{Gk} that make up graph G_k is equal to the number of districts n_{DMA} to be created, we can assume that each node in the graph corresponds to a district. Otherwise, graph nodes are randomly grouped two by two with adjacent nodes to obtain the required number of districts. It is important to note that coarsening and partitioning may create districts with very different numbers of users on the coarsest graph G_k. However, this non-uniformity in district size is not a problem (Walshaw and Cross 2000), and may indeed furnish better network partitioning at the end of the process (Walshaw et al. 1995; Simon and Teng 1997; Karypis and Kumar 1998b) through the balancing and refinement procedure outlined below.

2.3 Partition Expansion with Balancing and Refinement

In the partition expansion phase, the partition of graph G_k into n_{DMA} districts is iteratively linked to graphs G_{k-1}, G_{k-2}, etc., back to original network graph G_0. In practice, with reference to the generic iteration from $i+1$ to i, for each district all constituent nodes in graph G_{i+1} are considered, and, based on the association between the nodes in graph G_i and those in graph G_{i+1} (defined in the previous coarsening phase) the corresponding nodes in graph G_i are identified, and thereby the district in graph G_i. Obviously partition expansion alone cannot alter the size of the districts, and any non-uniformity generated in the network partitioning used to generate graph G_k is inevitably carried over to G_{k-1}, G_{k-2}, through to G_0. In order to obtain a more equal distribution of user numbers between the districts, therefore, an adjustment is performed during partition expansion from graph G_{i+1} to G_i, seeking out the nodes on the border between one district and another that need to be moved from one to the other (balancing).

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3 The Proposed Procedure

The procedure proposed is aimed at optimally partitioning a WDN into an assigned number of districts n_{DMA} of predefined size (i.e., serving a pre-established number of users), assuming that a certain number of meters, n_{meas}, will be placed. As the procedures proposed by Di Nardo et al. (2011; 2013a and 2014b), it is based on the MLBR algorithm but differently from these procedures it incorporates within the MLBR itself a rapid process for identifying near-optimal meter position. Indeed, Di Nardo et al. (2011, 2013a, 2014b) first identify, by using the MLBR algorithm, the optimal solution in terms of node allocation to the assigned number of districts (without taking into account the number and position of the meters), and only in a second step is the number of meters assigned and their optimal position identified (i.e., which pipes to open and close). Thus, the two critical phases in optimal district design, node allocation and meter positioning are *uncoupled*, reducing the search domain of the optimal districtualization solution, and therefore potentially providing less than optimal results. This is comprehensible by considering for sake of example the simple two-loops network shown in Fig. 1a, in which all nodes have equal weight (e.g., the same number of connected users) but all links are given different weights *w*, depending for example on their conductance (or diameter). If we want to uniformly allocate the 6 nodes to create 2 districts, positioning one flow meter, the previously mentioned procedures would lead to the identification of the solution shown in Fig. 1b as optimal. Indeed, in order to minimize the overall weight of connections, nodes 1, 2, and 3 would be allocated to the first district and the remaining three to the latter, yielding a total connection weight of 6+2+5=13 (any other uniform combination would yield a greater overall connection weight). Now, given this partition, the ideal position for the meter

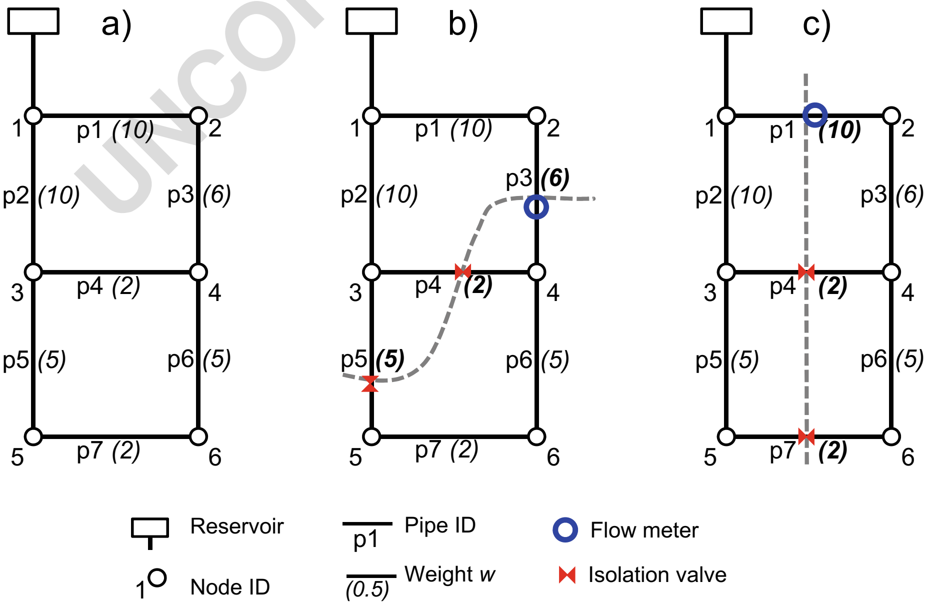

Fig. 1 **a** Two-loops network

would be at pipe p3, which has a greater weight (conductance /diameter), $w=6$, than the other two links ($w=2$ and $w=5$, respectively), which would be therefore closed. However, hydraulically speaking, the solution shown in Fig. 1c, also uniformly partitioned, would be more advantageous, with the single meter being positioned at a pipe (p1) with greater conductance (diameter), namely $w=10$, closing off the two (p4 and p7) with lower conductance (smaller diameter), both $w=2$. Despite the evident advantages of this solution, it would not be identified by the previously mentioned procedures, since its nodes allocation would be discounted during the first phase the sum of the connection weights (10+2+2=14) being greater than the abovementioned 6+2+5=13. Clearly then, uncoupling the problems of node allocation and meter positioning may cause valid partitioning solutions to be discounted from the outset, as the number of meters to be installed are not considered during the initial stage of the procedure.

The proposed procedure overcome this problem by taking into account the number of meters to be positioned within the partition expansion phase. Indeed, as previously observed in the partition expansion phase, the partition of graph G_k into n_{DMA} districts is iteratively linked to graphs G_{k-1}, G_{k-2}, etc., back to original network graph G_0 and an adjustment is performed during partition expansion from graph G_{i+1} to G_i, seeking out the nodes on the border between one district and another that need to be moved from one to the other. To this end, a maximum tolerance θ_i on the imbalance UB_i of number of users relative to the district partitioning solution in graph G_i, is fixed. The imbalance UB_i is defined as the percentage difference between the greatest number of users served by the largest district (partition), Nus^{max}, and that of the smallest district Nus^{min}, i.e.,:

$$UB_i = \frac{Nus_i^{\max} - Nus_i^{\min}}{Nus_i^{\min}} \tag{1}$$

The tolerance θ_i varies with the level i, and, in particular, we assume that it falls as i decreases, i.e., it will be very large for the partition solution defined in graph G_{k-1} (G_k being the coarsest), gradually diminishing towards the original graph G_0, at which it will reach its minimum value. It is important to note that by these means, even a very imbalanced user distribution in the coarsest graph G_k will be progressively evened out as border nodes are moved from one district to the next during the expansion process. Furthermore, while each district in the coarsest graph comprises two nodes at most, making it extremely difficult to optimize balancing, as partitioning expansion proceeds, the number of nodes in each district increases, thereby providing more degrees of freedom for moving nodes from one district to another, marrying well with the reduction in tolerance on the maximum imbalance.

During the adjustment procedure, the connections formed between the districts are also taken into account, as well as the question of which to close and which to leave open and fit with one of the n_{meas} meters. This enables the best partitioning solution, i.e., one that provides the best hydraulic performance, to be identified. In practice, in each partitioning expansion phase from graph G_{i+1} to graph G_i, the initial partitioning solution is transferred as is, and then opportunely improved as follows. First, all the nodes comprising each district in graph G_i are identified, and, among these the nodes bordering adjacent districts are picked out. The links connecting the districts are also identified, and it is assumed that the n_{meas} meters are placed on the connecting links of greatest conductance. All the other connecting links are henceforth

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considered closed. Next, pressure-driven hydraulic simulation is used to calculate the nodal heads, and therefore the resilience index, *Ir*, of the system (Todini 2000), given by:

$$Ir = \frac{\sum_{j=1}^{NN_i} q_j \left(H_j - H_j^* \right)}{\sum_{m=1}^{N0} Q_m H_m - \sum_{j=1}^{NN_i} q_j H_j^*} \tag{2}$$

where q_j, H_j and H_j^* are, respectively, the water demand, the available head, and the minimum reference head at the *j*-th node; NN_i is the total number of nodes of unknown head in graph G_i; Q_m and H_m are, respectively, the flow released and the head supplied by the *m*-th node, whose head is fixed; and $N0$ is the total number of nodes with fixed head. An optimization problem is thereby formulated with the aim of determining how best to allocate the border nodes, and therefore to identify a new set of connecting links, and where to position the meters so as to respect the size-balancing condition θ_i (in terms of users served) of the districts, while maximizing the resilience of the system.

It is important to note how the reallocation of one node from one district to another not only influences the size of the districts involved, and can therefore be used to bring the imbalance of a particular solution within the required margin of tolerance θ_i, but also affects the identification of pipes at which flow meters could potentially be positioned. To this end, consider, as an example, the scenario illustrated in Fig. 2, which features a boundary between two districts of a part of a partitioned graph. If we assume that each pipe is given a weight representative of or proportional to its conductance, as shown in Fig. 2, and that nodes 1 to 3 belong to DMA1 and nodes 4 to 7 to DMA2, the connecting pipes are p2, p4, p6, p7 and p8. Assuming that we are going to insert a meter between DMA1 and DMA2, judging by the weights/conductance

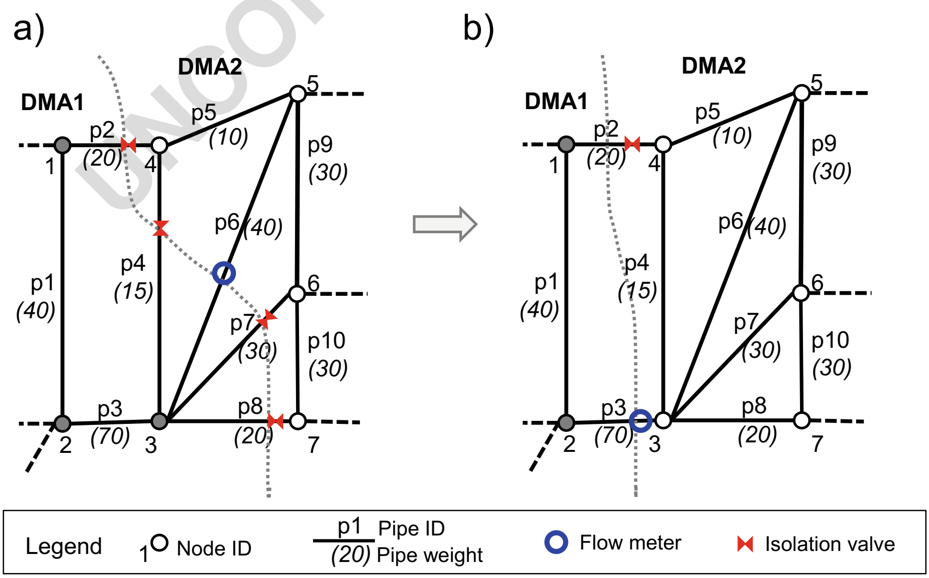

Fig. 2 Example network section bordering two districts whose nodes can be transferred from one to the other for better balancing and improve hydraulic performance of the districtualized system

shown in Fig. 2, these would be best placed at pipe p6 (i.e., that of greater conductance, namely 40), and all the other pipes between the districts would therefore be closed. By reallocating node 3 to DMA2, bearing in mind the inter-district balancing constraint, the connecting pipes would therefore be p2 and p3, and the meter would be positioned at pipe p3 (having a weight/conductance of 70). Therefore, only pipe p2 would need to be closed, conferring obvious benefits to the hydraulic performance of the system, quantified by pressure-driven hydraulic simulation calculation of the resilience index Ir (Todini 2000).

Formally speaking, the optimization process is formulated assuming that each of the border nodes represent a decisional variable that can take on the value representative of the district to which it belongs, or of the districts it is directly connected to. The maximization of the system resilience and compliance with the balancing constraint are synthesized in a single objective function, to be minimized, defined as follows:

$$OF = \frac{1}{Ir}\exp(\delta_i) \quad with \quad \delta_i = \begin{cases} 0 \ \ if \ \ UB_i \leq \theta_i \\ UB_i - \theta_i \ \ if \ \ UB_i > \theta_i \end{cases} \tag{3}$$

Operatively, this optimization process is performed by means of the SCE-UA algorithm (Shuffled Complex Evolution – University of Arizona; Duan et al. 1992).

4 Case Study

The proposed procedure was applied to a real life water distribution network serving a medium–large town in Emilia-Romagna (Italy) hereinafter referred to as AERnet (An Emilia-Romagna network – see Fig. 3). Its main characteristics are summarized in Table 1. The network is fed from a tank that guarantees an average load of 30 m with respect to the plane of the land. A minimum reference pressure head H_j^* of 25 m with respect to the plane of the land was assumed for each node (see also Eq. (2)), and, based on the pressure-driven hydraulic simulation, a resilience index Ir of 0.61 and a minimum pressure value of roughly 26.8 m were calculated for the non-partitioned network.

The procedure was applied in order to subdivide the network into 3 districts with uniformly distributed user numbers, assuming that 2 to 4 m – in addition to that already in situ at the feed

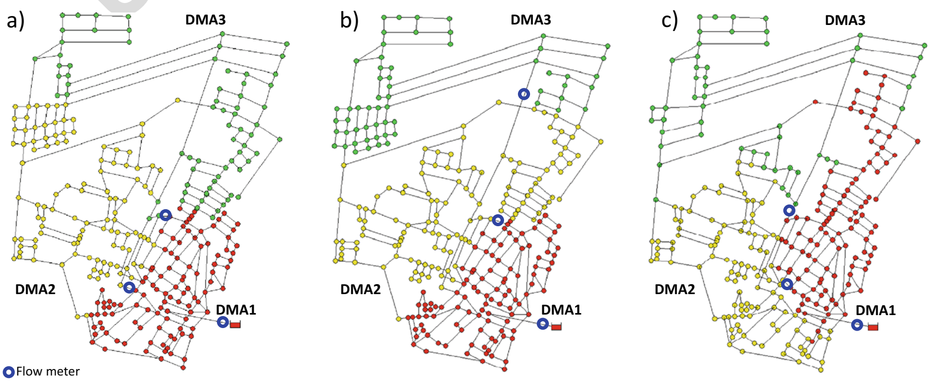

Fig. 3 Layout of AERnet water distribution network after partitioning into 3 districts by **a** the proposed procedure, **b** the M-Sym procedure and **c** the BFS-Sym procedure, assuming 3 m will be installed

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Table 1 Main characteristics of the AERnet water distribution network

Total pipe length *L*	90 km
# of inhabitants	≈30 000
# of network pipes *NP*	391
# of network nodes *NN*	273
# of loops	119
Average daily water demand	89 l/s

tank outlet – would be positioned (i.e., a total of 3 to 5 metering points). The partition expansion with balancing and refinement was performed assuming a tolerance θ_i (i=0:k-1, G_0 being the original graph and G_k the coarsest) that varied linearly from a minimum $\theta_{i=0}$=5 % corresponding to the original graph G_0 up to a maximum of $\theta_{i=k-1}$=(k-1)·$\theta_{i=0}$ for the partitioning solution described by graph G_{k-1}. The weight *w* of each pipes was fixed according to the pipe conductance (Alvisi and Franchini 2014).

The results obtained were compared with those yielded by two other partitioning procedures already proposed within the scientific literature. The first is the one proposed by Di Nardo et al. (2011), which, as previously observed is also based on a graph-partitioning software (METIS) and hydraulic simulation, but that uncouples the node-partitioning and meter-positioning problems in the optimal design process. This procedure will hereinafter be referred to as M-Sym. The latter is the one propped by Alvisi and Franchini (2014) which is mainly based on techniques derived from Graph Theory and in particular on the Bread First Search (BFS) algorithm. This algorithm is indeed used within this procedure to identify the near optimal node partitioning whereas hydraulic simulation is used to solve the meter positioning problem. This procedure will hereinafter be referred to as BFS-Sym. In order to make the comparison meaningful, within all these procedure the hydraulic simulation were performed by using a pressure driven simulator.

5 Analysis and Discussion of Results

Table 2 shows the performance indicator values calculated for the 3-district solution furnished by the proposed procedure for the AERnet, assuming 3, 4 or 5 metering points. In detail, for each partitioning solution the values for minimum pressure (*Pmin*) and resilience index *Ir* (see Eq.(2)) of the partitioned network was calculated, and the percentage reduction in resilience index with respect to the non-partitioned network (Di Nardo et al. 2011) was defined as follows:

$$Ird = \left(1 - \frac{Ir}{Ir_0}\right) \cdot 100 \tag{4}$$

where *Ir* is the resilience index of the partitioned network, and Ir_0 the resilience of the network before partitioning. For comparative purposes, the corresponding values yielded by the M-Sym procedure and by the BFS-Sym procedure are also reported, as are the corresponding resilience index and minimum pressure values for the non-partitioned network.

Considering first the case in which two meters, in addition to that at the tank outlet, are positioned, giving a total of three metering points, all the procedures yield partitioning solutions with a *Pmin* of less than 25 m. As this is not quite sufficient to meet the water

Table 2 Performance indicator values for the 3-district AERnet water distribution network solutions generated by the three partitioning procedures, assuming 3, 4 or 5 metering points

		Ir	*Ird (%)*	*Pmin (m)*
No districts		***0.61***	–	***26.8***
3 measuring points	**Prop. Proc.**	**0.40**	**34.6**	**23.1**
	M-Sym	0.12	80.3	21.8
	BFS	0.39	36.3	21.4
4 measuring points	**Prop. Proc.**	**0.51**	**17.48**	**25.1**
	M-Sym	0.43	29.5	24.2
	BFS	0.44	27.8	24.1
5 measuring points	**Prop. Proc.**	**0.59**	**3.87**	**26.5**
	M-Sym	0.55	10.4	25.7
	BFS	0.53	13.9	25.0

demand, it is clear that neither 3-m solution is able to provide adequate coverage of the three districts. Interestingly, however, comparison of the solutions reveals that the proposed procedure does yield a network in which the *Pmin* is just above 23 m, i.e., able to meet more than 99 % of the water demand, while *Pmin* in the M-Sym network and in the BFS-Sym network is lower than 22 m, i.e., able to meet less than 98 % of the water demand. Hence, although neither procedure is able to provide an ideal solution to the 3-m problem, the proposed procedure does provide a slightly superior partitioning solution in terms of performance, as confirmed by its higher *Ir*, value, 0.4, as compared to the 0.39 pertaining to the BFS-Sym solution and, in particular, to the 0.12 pertaining to the M-Sym solution. The performance gap with the M-Sym solution in particular is comprehensible by considering the partitioning solutions illustrated in Fig. 3. In the solution yielded by the procedure proposed here (Fig. 3a) and in the BFS-Sym solution (Fig. 3c), DMA1, which is directly feed by the tank, is also directly connected to both DMA2 and DMA3. In contrast, the three districts in the solution furnished by the M-Sym procedure (Fig. 3b) are connected in sequence, i.e., there is no direct connection between DMA1, which links to the feed tank, and DMA3, which must therefore be reached via DMA2 in order to supply its users. Indeed, it is worth remembering that the M-Sym solution is obtained first via node partitioning into three districts without at this point taking into account that an assigned number of links connecting the districts themselves will be left open and equipped with flow-meters, whereas the others will be closed; thus, without at this point taking into account the flow circulation within the network due to the closure of some link. In fact, only in a second step of the procedure, the best meters' position is identified, given the nodes' partition. On the contrary, within the proposed procedure, the two aspects, i.e., nodes' partition and meters' position, are simultaneously dealt with, taking into account the number and location of meters to be installed in the node partition phase of the procedure, and consequently also taking into account the flow circulation within the network due to the closure of some links.

Let us now consider a case of partitioning with 4 metering points; Table 2 shows that again the procedure proposed here provides a better solution in terms of minimum pressure *Pmin*, i.e., just over the threshold of 25 m, ensuring that it is able to fully meet the demand of network users, as compared with the M-Sym and BFS-Sym solutions, at just below 25 m, which is not. Likewise, the *Ir* values highlight this performance gap between the solution provided by the

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proposed procedure and those furnished by M-Sym and BFS-Sym (0.51 vs. 0.43 and 0.44, respectively). It is also interesting to note that (see Fig. 4) while the 4-m solutions yielded by M-Sym and BFS-Sym coincide, in terms of nodes allocation to form the 3 districts, with the 3-m solution yielded by M-Sym and BFS-Sym themselves respectively (see Fig 4b vs. 3b and Fig 4c vs. 3c), the procedure proposed here provides very different nodes partitions when 3- and 4-m are considered. This is comprehensible by considering once again that within the M-Sym and BFS-Sym procedures the district design problem is uncoupled into two subsequent steps, nodes partitioning and meter positioning; thus, the nodes allocation to form the 3 districts (step 1) is independent by the number of meters to be placed (considered in step 2). On the contrary, within the proposed procedure, the two aspects, i.e., nodes' partition and meters' position, are simultaneously dealt with, and thus the procedure allows adjusting the nodes partition to form the three districts according to the number of meters to be placed.

The inclusion of another meter, bringing the total to five, once again yields a difference in performance indicators, reported in Table 2, between the two systems. The *Ir* values calculated for the proposed procedure and the M-Sym and BFS-Sym approach (0.59 vs. 0.55 and 0.53, respectively) correspond to a percentage reduction in network resilience (*Ird*), as compared to the non-partitioned network, of 4 % in the former case and 10 % and 14 % in the other two cases.

Summing up, these results show that taking into account the pipes connecting the districts to be left open and close in the partition phase of the procedure provides DMAs design solutions better able to suit the number of available metering points, leading to network resilience indexes and minimum pressure higher than those provided by the uncoupled counterpart procedures.

6 Conclusions

Like others in the literature, the WDN partitioning procedure presented here is based on the combined use of graph partitioning and hydraulic simulation techniques to identify a) how best to partition network nodes into the assigned number of DMAs; and b) which connecting pipes between districts to leave open, and therefore where to position the assigned number of flow meters, and which to close. Unlike previously proposed graph-partitioning-based procedures, however, that presented here tackles these issues simultaneously, rather than first allocating the

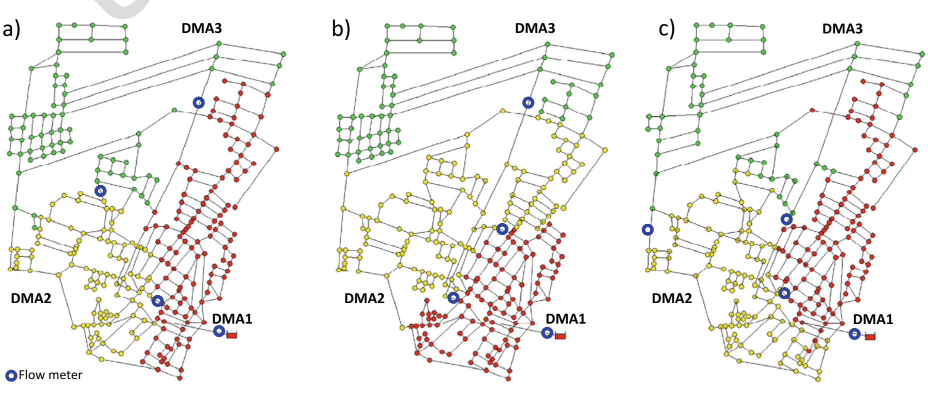

Fig. 4 Layout of AERnet water distribution network after partitioning into 3 districts by **a** the proposed procedure, **b** the M-Sym procedure and **c** the BFS-Sym procedure, assuming 4 m will be installed

nodes and only then positioning the meters. This innovation enables the open and closed connections, and therefore network flows, to be addressed during partitioning, ensuring that network node allocation can be adjusted to suit the number of available metering points and, likewise, the number of open and closed pipes between DMAs. Application of this procedure to a real-world network reveals that this approach furnishes partitioning solutions characterized by superior performance indicator values (*Pmin*, *Ir*, *Ird*,) to those yielded by a similar procedure in which node allocation and meter positioning are dealt with sequentially and to those yielded by another well-established partitioning approach based on graph theory.

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