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Optimal Design of District Metering Areas

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Abstract

The search for optimal segmentations aimed at defining district metering areas (DMAs) is a challenging and crucial issue in the analysis, planning and management of water distribution networks (WDNs). The need to select optimal segmentations relates to a number of important technical reasons. Today, the most relevant one is the leakage management by means of pressure-control zones. This contribution proposes a novel two-steps strategy for DMAs planning. The strategy is based on the segmentation design as first step, to achieve a scenario of optimal locations of "conceptual cuts"; during the second step, these are the candidate for the location of (closed) gate valves or flow measurement devices that gave rise to district monitoring areas (DMAs). The segmentation step is performed solving a multi-objective optimization problem (i.e. WDN-oriented modularity maximization versus the number of "conceptual cuts" minimization).

The second step accomplishes the real DMAs design by solving a three-objective optimization, i.e. the minimization of the background leakages versus the unsupplied customers demand versus the flow observations. This means that the procedure will search for a set of scenarios having a number of closed gate valves installed at the "conceptual cuts" that do not decrease the WDN hydraulic capacity below that necessary for a sufficient service to customers, while contemporarily reducing the background leakages. A pressure-driven modelling approach is used to predict background leakage reduction and the unsupplied customers demand. The procedure is explained on a benchmark network from literature, the Apulian network.

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Keywords: Segmentation; District metering areas; Infrastructure modularity index; Background leakages; Unsupplied customer demand.

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1. Introduction

Water distribution networks (WDN) are key infrastructures for all human activities in modern cities. Their complexity is due to many factors including their large size (up to thousands of pipes), the hydraulic functioning and the alteration of asset conditions from their original installation (i.e. obsolescence). Moreover, the expansion of urban areas and the growing amount of field information (i.e. streams of data) on WDNs are increasing the complexity of their analysis, management and planning. From this perspective, the division of WDN into districts (i.e. modules, segments, etc.) is a common practice for multiple technical purposes, generally aiming at simplifying system analysis, planning and management problems, as for example, support model calibration, plan efficient metering systems, etc.. WDN districtualisation is not a trivial problem since it depends on the network size, topology and hydraulics. Additionally, there are technical and practical issues for water companies that can influence the problem solution. For example, water companies are usually interested in integrated and dynamical planning which permits to increase the resolution of segments over time by adding new segmenting devices, based on incoming budget and/or increasing system knowledge.

The literature reports many research works where segmentation is analyzed from various perspectives including reliability analysis [1][2], location of isolation valves [3], and analysis of contaminant spread [4]. Other researchers exploited the concepts of graph theory for the identification of the main structure in WDN for monitoring and control purposes, as for example model calibration, metering water consumption, early contaminant detection, control of pressure/leakages and network vulnerability analysis [5][6][7][8][9][10]. Recently, innovative approaches have been investigated to support WDN management and planning, taking inspiration from their nature of complex networks. Therefore, paradigms from community detection [11] in complex network theory [12][13] has been applied to WDN segmentation, considered as technological infrastructures different from other spatial networks in size, density of connections and technical constraints [14][15]. Among the various metrics used to identify communities that form the large-scale structure of the network (real or immaterial) [11], the modularity index is one of the most popular [16]. Nonetheless, some authors observed [17][18] strong differences between the immaterial networks (e.g., food web, trade, World Wide Web) for which the classical modularity concept was conceived, and material networks (e.g., urban infrastructure networks). In particular, among these networks, WDN are nearly planar graphs and, considering their hydraulic functioning, they can be viewed as weighted directed graphs, where direction of links reflects flows through pipes. Then, they have material links (pipes), spatial constraints (two dimensionality, urban layout, location of water sources/demands, etc.), and real devices installed along links (e.g. valves, pumps, meters, etc.).

For this reason, Giustolisi and Ridolfi [18] tailored the classic modularity in order to achieve a WDN-oriented modularity index accounting for the WDN infrastructural peculiarities, such as the fact that the “conceptual cuts” of the segmentation cannot be assumed in the middle of the pipe. In fact, the devices for the creation of the DMAs are actually installed close to ending nodes of the pipes. Such WDN-oriented modularity index, weighted with specific pipe characteristics [18], permits to identify segments that are similar to each other (i.e. modules). From a technical perspective, this is relevant for length-based pipe characteristics (e.g. total water demand distributed along pipes, propensity to pipe background leakages, etc.). Indeed, maximizing such WDN-oriented modularity index is likely to return modules suitable for many technical purposes as, for example, water consumption metering and leakage monitoring. However, the WDN-oriented modularity index is affected by a resolution limit that increases with network size. This limit stems from classic modularity index [19] and causes the drawback of non-identifiability of smaller modules depending on the size of the network, i.e. increasing the size of the hydraulic system in term of number of pipes increases the smaller modules that can be identified using a metric based on the modularity paradigm. Therefore, Giustolisi and Ridolfi [20] proposed a new infrastructure modularity index to overcome the resolution limit of the classic modularity index (WDN-oriented or not). The framework of the WDN-oriented modularity indexes has been completed and explicitly outlined from technical perspective by the work of Giustolisi et al. [21] introducing the attribute-oriented infrastructure index, thus extending the strategy for solving the resolution limit to the attribute-based index.

This paper implements the infrastructure modularity index [20] as a metric to maximize during the WDN segmentation design in a multi-objective optimization framework. The modules defined by means of “conceptual cuts” becomes real DMAs during the second phase of the presented procedure, establishing which “conceptual cuts” will represent flow measurements or closed valves, in a three-objective optimization scheme. The aim here is to reduce leakages without deteriorating the quality of the service (i.e. limiting the unsupplied demand) by using the minimum possible number of flow observations for the DMA definition, because they are more expensive than closing gates from both economic and management perspective.

2. Methodology

The WDN segmentation problem has generally three drivers: (i) network features; primarily the topology, but also the hydraulic and asset characteristics; (ii) specific technical purposes (e.g. monitoring water consumption); and (iii) technical constraints related to uncertainty or limitation of the budget, preexisting segmentations and devices, and/or other objectives generally related to capital/operational costs. Finding a tradeoff among these different goals is not an easy task. A general-purpose approach to the WDN segmentation is not available at date, and empirical methods are generally used resorting to expertise of technicians on the WDN in hand. Giustolisi and Ridolfi [18] proposed a multi-objective optimization strategy for segmentation, implementing a WDN-oriented modularity index considering pipe attributes, i.e., the need for obtaining modules composed of pipes having similar attributes.

Starting from this multi-objective optimization strategy, this work proposes the following design paradigm, based on the multi-objective optimization strategy and composed of two main phases:

A. bi-objectives optimal network segmentation using the infrastructure modularity index [20], minimizing the number of "conceptual cuts" versus the maximization of the infrastructure modularity index; each segmentation solution consists of a set of "conceptual cuts" into the network, which are the candidate positions for flow measurements or closed gate valves. Among the optimal segmentation scenarios from the resulting Pareto front, one scenario is selected as starting point for the next phase;
B. starting from the selected segmentation solution, a three-objectives optimal design of the network DMAs is performed by simultaneously minimizing the number of flow observations, the background leakages reduction and the unsupplied customer demand. The last two objectives are based on advanced WDN hydraulic modelling [22] encompassing pressure-driven analysis for both customers' demands and pipe level background leakages.

2.1. Optimal network segmentation (Phase A)

As above said, the infrastructure modularity index has further good features with respect to the weight-based modularity index [18], which makes it more effective for multi-objective segmentation design for WDNs as discussed by [20]. The infrastructure modularity index can be written as follows,

$$IQ\left(\mathbf{w}_p\right)=\left(1-\frac{n_c}{n_p}\right)+\frac{\left(n_m-1\right)}{n_p}-\sum_{m=1}^{n_m}\left[\sum_{k=1}^{n_p}\frac{\left(\mathbf{w}_p\right)_k\,\delta\left(\mathrm{M}_m,\mathrm{M}_k\right)}{W}\right]^2=Q_1+\frac{\left(n_m-1\right)}{n_p}+Q_2 \qquad (1)$$

where n_p is the number of network links/pipes, n_c is the number of cuts in the network (i.e. the number of pipes linking the modules) that are also the decision variables of this first phase of the WDN segmentation problem. n_m is the number of network modules; the summation inside the square brackets is related to pipe weights stored in the vector $\mathbf{w}_p$, whose sum is W, and Kronecker's delta function δ makes that the sum refers only to the weights of pipes belonging to the m^{th} module (i.e. $\delta = 1$ if $\mathrm{M}_m = \mathrm{M}_k$ and $\delta = 0$ otherwise). The added term $(n_m - 1)/n_p$, representing the minimum theoretical fraction of pipes to be cut to obtain n_m modules, is the difference between the *weight-based* and the *infrastructure modularity* indexes, which was demonstrated to overcome the resolution limit. This means that in Eq. (1) the term Q_1 starts dominating the term Q_2 when the number of modules n_m increases; therefore, one further cut in the network will decrease Q_1 more than any increase of Q_2 due to an optimal identification of a further module [20][21]. Note that the word "weight" (afterwards substituted by the word "attribute") indicates a specific pipe characteristic that can be considered to drive the segmentation process. In fact, Eq. (1) is able to measure the similarity of modules with each other.

The bi-objectives network segmentation (i.e. the phase A of the proposed strategy) can be formulated as follows,

$$\begin{cases} [M, n_c, n_{act}] = \text{Connectivity}\left(I_c, \left|\bar{\mathbf{A}}_{np}\right|\right) \\ f_1 = \max\left\{IQ\left(\mathbf{L}_p\right)\right\} = \max\left\{\left(1 - \dfrac{n_c}{n_p}\right) + \dfrac{(n_{act} - 1)}{n_p} - \displaystyle\sum_{m=1}^{n_{act}}\left[\sum_{k=1}^{n_p}\dfrac{\left(\mathbf{L}_p\right)_k \delta\left(\mathrm{M}_m, \mathrm{M}_k\right)}{L}\right]^2\right\} \\ f_2 = \min\left\{n_c\right\} \end{cases} \tag{2}$$

where $\bar{\mathbf{A}}_{np}$ is the incidence matrix, I_c is the set of n_c cuts in the network, the $\text{Connectivity}\left(I_c, \left|\bar{\mathbf{A}}_{np}\right|\right)$ stands for component analysis of the graph for the given cuts, and n_{act} indicate the cuts that are *actually* used to separate modules [18][20]. In this work, the length of pipes is used as attribute for the network pipes, thus in Eq. (2) such information is stored in the vector $\mathbf{L}_p$, and the sum of pipes lengths is L. It should be emphasized that the choice of the pipe length as attribute for the modularity herein has a technical meaning linked to all the WDN phenomena related in some way to pipe length, as for example the water distributed to private properties connected to pipes, the occurrence of background leakages [22], the probability of pipe bursts [23], etc.. Therefore, using length as “weight” is expected to identify segments that are similar from these technical viewpoints.

The procedure allows introducing some constraints that make the resulting segments consistent with technical meaning of the segmentation. In fact, it would make no sense to have very small segments although the infrastructure modularity is powerful for identifying very small modules. Possible constraints to be considered during this first optimization are the following C_1, C_2 and C_3:

$$C_1 = \frac{\sum_{k=1}^{n_p}\left(\mathbf{L}_p\right)_k \delta\left(\mathrm{M}_m, \mathrm{M}_k\right)}{L} \geq x\% \quad C_2 = \max\left(\text{pipe diameter of cuts}\right) \geq y \quad C_3 = n_{m,p} \geq z \tag{3}$$

where C_1 limits the smallest module length; C_2 limits the minimum diameters of cut pipes; and C_3 defines the minimum number of pipes belonging to a module. It is worth noting that the constraints act as a pressure to exclude the smaller modules during the segmentation design, but if they are optimal, despite the constraint, they results identified in any case.

The optimization procedure returns a Pareto front of segmentation solutions that are optimal with respect to the number of “conceptual cuts”, thus generating modules that are similar to each other as total length. At the end of this first phase, one of the Pareto-optimal segmentation solutions is selected, according to technical/economic criteria provided by the water utility as well as to the purposes of the segmentation. This optimal segmentation solution will be the starting point for the second phase of the design procedure.

2.2. Optimal design of the network DMAs (Phase B)

The second phase of the proposed design procedure defines the actual DMAs starting from the selected segmentation solution from phase A. This means that the procedure will determine which cuts related to the chosen solution can be “conceptual,” i.e. flow measurements, or “real”, i.e. valves (closed) and such decision has to account for some operative objectives related to the final purpose of the districts planning. Indeed, closing gate valves is likely to change the original water paths, thus resulting into higher flow rates and head losses along pipes still “open”, while reducing background leakages in the WDN. Closing pipes that connect different segments is likely to results into major alterations of the original flow paths and reduction of leakages. On the other hand, pipes that are not closed should be equipped with flow meters, e.g. for WDN monitoring or WDN model calibration purposes. Therefore, the second step (i.e. phase B) of the proposed methodology will accomplish this task by means of a three-objectives optimization procedure implementing the following objective functions: (F1) the minimization of the number of flow observations; (F2) the minimization of the background leakages; and (F3) the minimization of the unsupplied customer demand. The first objective aims to find the optimal DMAs using the minimum possible number of flow observation, since they are more expensive than gate valves (to be closed) also from a management perspective. Note that the procedure assumes flow observations anyway along pipes joining tanks and reservoirs, downstream pumps and along pipes of control devices (i.e. flow control valves, pressure control valves). Existing flow observations are also accounted for during optimization. The objective function F2 consists in the minimization of the ratio between the background leakages volumes calculated in the ith solution (i.e. set of closed valves) and in the original WDN configuration, i.e. where no gate valve is closed. The objective function F3 is formulated as the ratio between the unsupplied demand volume computed for the ith solution and the supplied demand volume computed in the original WDN configuration.

3. Case study

The proposed design strategy is here presented on a simple network in order to show and discuss its main features. Apulian network is a small network having one reservoir feeding by gravity all nodes (for details see [24]), whose layout is in Figure 1 (left).

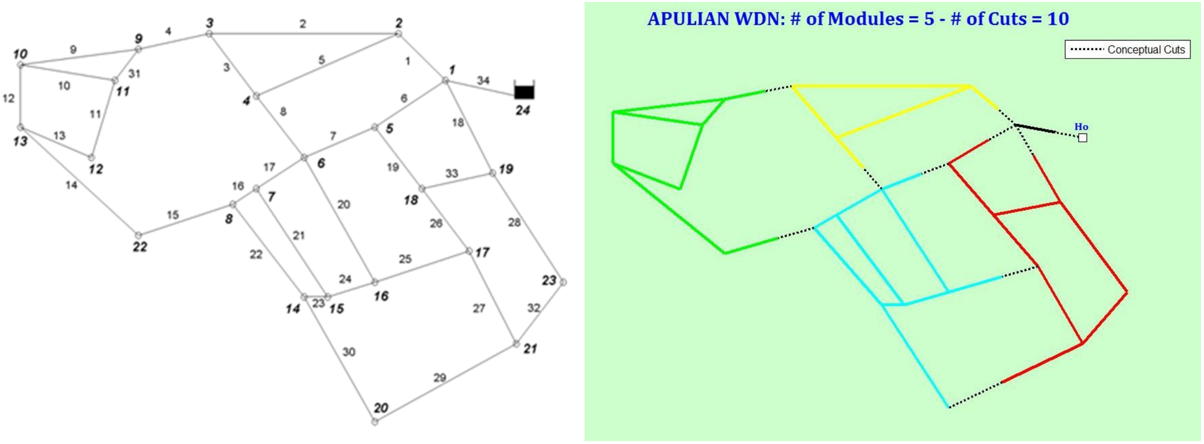

Fig. 1. Apulian network layout (left); optimal segmentation selected solution for the Apulian network (right).

The optimization problems above described are solved using the OPTImized Multi-Objective Genetic Algorithm (OPTIMOGA) [25] and all tests were performed by means of a specific function for WDN segmentation implemented as part of WDNetXL [26][27] system, that integrates OPTIMOGA. Referring to the above reported description of the DMA design paradigm, the first phase requires the definition of some constraints related to the objective functions in Eq. (2). In particular, with reference to Eq. (3), two out of three constraints are here used, namely C_1 = 0.5% and C_3 = 4, which is the minimum number of pipes belonging to a module.

3.1. Results discussion

The first optimization procedure (phase A) returned the Pareto front of optimal segmentations for the Apulian network. Note that, in this example, Apulian network has no pre-existing segmentation. The optimal (Pareto-efficient) segmentation configurations based on the objective functions in Eq. (2) have a number of cuts ranging from 4 to 10, where the maximum of the modularity (i.e. the infrastructure modularity index) is obtained for a number of cuts equal to 10. For the phase B of the proposed strategy, the less parsimonious segmentation solution (i.e. with 10 "conceptual cuts") is here chosen as starting point, as showed in Figure 1 (right). Actually, this choice reflects the illustrative purpose of this example, since the selected solution allows for several combinations of flow measurements and closed gate valves.

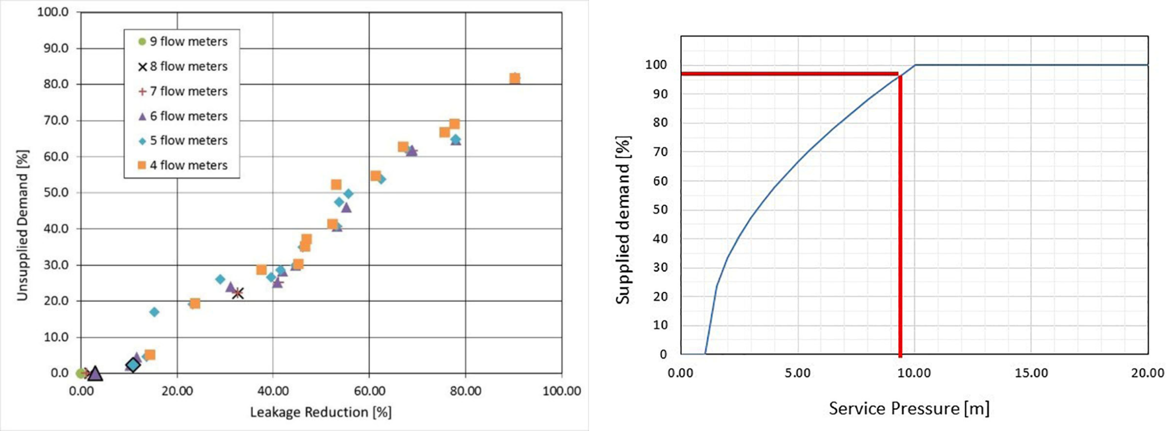

Fig. 2. Pareto front of optimal DMAs (left), as projection in the plan [leakage reduction rate, unsupplied demand rate]; diagram showing the supplied demand rate as function of the service pressure (right) [22].

The phase B returned for various number of flow observations few alternative configurations resulting into different leakage reduction rates, depending on the location of (closed) valves. As arguable by Figure 2 (left), the number of closed gate valves ranges from 6 (i.e. 4 flow meters) to 1 (i.e. 9 flow meters), whereas high leakage reduction can be obtained for high number of closed valves. Note that, for all the solutions in the Pareto front in Figure 2 (left), the modules/segments always consist in the same pipes; what changes is the allocation of flow meters and closed valves only.

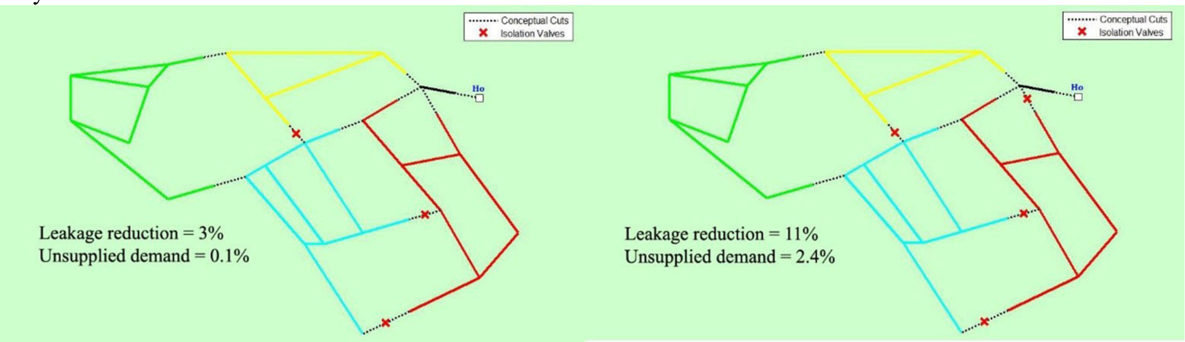

Fig. 3. Two solutions of optimal DMAs design for the Apulian network.

Figure 3 reports the two optimal DMAs solutions highlighted on the Pareto front reported in Figure 2 (left). That on the left of Figure 3 has three closed valves, and thus seven flow meters, while the solution on the right has four closed valves, and six flow meters. Figures report also the leakage reduction and the unsupplied demand as percentages with respect to the original network functioning (original status with no unsupplied demand). The districtualisation solution on the left Figure 3 substantially does not change the quality of service (i.e., the unsupplied demand after closing valves and inserting flow meters) with respect to the original status. The situation is almost unchanged also in terms of background leakages. In other words, the location of closed gate valves does not result into a relevant pressure deficit and the network is still able to supply almost all the required demand to customers.

The DMA solution on the right Figure 3 is more effective in reducing the background leakages through the closure of one more valve. This is likely due to the position of this additional closed valve, which is located on a very important flow path in the network (i.e. a pipe with a large diameter) thus forcing the water to follow longer routes with respect to the solution on the left Figure 3. However, the consequent pressure deficit does not cause a relevant detriment of the service quality, so that a slight relaxation with respect to the required level of service (97.6% vs. 100% of supplied demand), the hydraulic capacity of the network remains the same, see the red line on the diagram on Figure 2 (right). This diagram shows that the slight reduction of pressure still results into acceptable supplied demand rate according the function here used for pressure-driven modelling of nodal demands [22], where the pressure for correct service is assumed = 10m. Therefore, the procedure can be considered as a useful tool for decision support that, considering different technical aspects related to the purposes of the districtualisation, enables the managers to be aware about the best configuration for DMAs, being able to immediately evaluate the pros and cons of their choice.

Finally, it is to note that all the solutions returned by the phase B of the presented paradigm, as exemplified by the two solutions shown in Figure 3, allow assessing the mass balance for each segment through flow metering, thus helping to understand the hydraulic functioning of the DMAs and support WDN operation, as for example for leak detection.

4. Summary and conclusions

A multi-objective design strategy for optimal DMAs design has been presented. It proceeds from a first phase in which the network is optimally segmented in conceptual DMAs by maximizing the infrastructure modularity index [20] against the minimization of the number of “conceptual” pipe cuts, in a multi-objective optimization scheme. A second phase identifies the actual DMAs of the network by establishing the position of flow meters and closed gate valves among the “conceptual cuts” of an optimal segmentation solution returned by the first phase. In particular, the design of DMAs is accomplished in a multi-objective scheme accounting also for the reduction of flow meters number, background leakages and unsupplied demand to customers, exploiting an advanced pressure-driven modelling approach to predict leakage reduction and unsupplied demand [22].

The procedure can provide a wide range of district metering solutions, which take into account various technical and management aspects, such as those related to the asset (length of the pipeline, thus probability of failure, presence of background leakage, etc.) and those related to the hydraulic functioning of the network (leakages, unsupplied demand, pressure deficit, etc.). Among such solutions, the water utilities can make the most suitable choice always having an immediate quantification of operative effectiveness of the districtualisation. Moreover, taking into account existing devices makes it easily repeatable over time, potentially allowing a dynamic planning accounting for the actual availability of budget and network development dynamics.

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