Optimal Design of District Metering Areas for the Reduction of Leakages

OPTIMAL DESIGN OF DMAs FOR LEAKAGES REDUCTION

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ABSTRACT

The division of water distribution networks (WDNs) into district metering areas (DMAs) is a challenging issue and can be effective for analysis, planning and management purposes. This contribution proposes a novel two-steps strategy for DMA planning. The first step is the *optimal segmentation design*, by maximizing the WDN-oriented modularity index versus minimizing the number of "conceptual cuts" (i.e. not accounting for devices). The second step is the actual *optimal DMA design*, returning the positions of flow meters and closed valves at the "conceptual cuts". Since closed valves change hydraulic paths of the system, the implementation of DMAs could allow reducing pressure and leakages through the WDN. *Optimal DMA design* is therefore achieved by

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solving a three-objective optimization minimizing the number of flow meters and the total unsupplied customer demand while maximizing the reduction of background leakages; thus, pressure-driven modelling is mandatory. The effectiveness and flexibility of the procedure is demonstrated using the Apulian and Exnet networks. Results shows that DMA implementation can allow leakage reduction on systems with excess of hydraulic capacity.

INTRODUCTION

The expansion of urban areas is increasing the complexity of the water distribution networks (WDNs) analysis, planning and management, while the growing amount of field information for WDNs, nowadays available from Information Communication Technology (ICT), could be helpful. Nonetheless, this new source of information is expanding the technical tasks that water companies could consider in order to increase service reliability and quality (e.g., vulnerability, performance, resilience, water losses, planned and unplanned works, energy consumptions, etc.). In fact, WDNs are key infrastructures, which are important in modern cities for several socio-economic reasons. They are complex network structures due to factors like their size (thousands of pipes) and hydraulic behaviour for the presence of non-linear devices.

Recently, several studies have been proposed in order to reduce the management complexity of WDNs by dividing the hydraulic systems into districts for monitoring purposes.

This contribution proposes a novel and flexible procedure which disjoints the phase related to network division in modules, named segmentation, and the engineering decision on the hydraulic system, i.e. on the installation of flow meters or closed gate valves supporting the segmentation and creating the actual district metering areas (DMAs). In fact, the network segmentation does not requires the decision on the position of devices because it is a conceptual action on the network structure of a WDN, although it can consider the devices that are already installed as existing cuts close to pipe nodes (Giustolisi and Ridolfi, 2014a).

The community detection is the most popular approach to divide a WDN into modules, also named segments or districts. The segment became district metering areas (DMAs) after installing flow meters and closed gate valves. DMAs allow managing pressures, demands, leakages, rehabilitation works, etc. by simplifying the hydraulic system analysis into smaller sub-networks, monitored in terms of mass balance.

The technical literature reports several works dealing with DMA planning from various perspectives. Considering WDN reliability analysis, Jacobs and Goulter (1988) proposed the division of the networks into smaller sections, which can be analysed by using procedures that best exploit the common features of the network and Yang et al. (1996) proposed a mechanical reliability index computed using the minimum cut-set method.

The graph theory concepts were used for the identification of the network structure of the hydraulic systems for monitoring and control purposes, as for example model calibration, metering water consumption, early contaminant detection, control of pressure/leakages. Very recently, Torres al. (2016) investigated the graph-based structural patterns and linkages with engineered performance using a library of lattice-like pipe networks. Nonetheless, in literature, many algorithms and metrics were used to define the optimal WDNs division with respect to topology and asset characteristics such as pipes length and diameter, nodal elevations, leakages, etc..

Perelman and Ostfeld (2011) proposed a segmentation framework for topological/connectivity analysis with the objective of developing and demonstrating a connectivity based algorithm for WDNs analysis. Most recently, Perelman et al. (2015) proposed a strategy to decompose the system into the main subsystems, approximating the network reconfiguration as a linear problem, where the decision variables are the boundary valves in the edge cut and the objective function minimizes the number of open boundary valves. Alvisi and Franchini (2014) suggested a procedure for the automatic creation of DMAs in a WDN to identify good solutions in terms of resilience and minimum pressures, accounting for the peak demand and fire-flow conditions. Ferrari et al. (2014) proposed a methodology to design a given number of districts in looped WDNs considering some important

DMA design criteria as the maximum and minimum size recommended for a district, the connectedness of each district to the water supply source and the absence of links between the districts. Therefore, it allows the creation of DMAs that are independent one from each another. Di Nardo et al. (2014) proposed a methodology aimed at defining the shape and dimension of network DMAs based on topology using different segmentation procedures; thereafter, the location of flow meters or gate valves was selected based on a partitioning technique using a real WDNs and a large set of performance indices.

It has to remark that such literature contributions, although providing various approach, did not account for all the characteristic of WDNs as infrastructure system. For example, devices are usually assumed in the middle of the pipes although they are practically located close to pipe ending nodes. Also such work rarely resort to hydraulically consistent pressure-driven simulation of background leakages, besides demand supplied to customers.

Ferrari and Savic (2015) introduced the concept of leakage reduction by means of DMA definition. In fact, closing gate valves changes hydraulic paths of the system and the implementation of DMAs could allow reducing pressure with potential leakages reduction. It is worth noting that the implementation of DMAs does not prevent from installing pressure reduction valves (PRVs) to achieve larger leakage reduction. Rather, the effective planning of PRVs should account for the districts in the network.

As mentioned above, this work proposes a novel two-steps strategy for optimal DMA design. The strategy is based on the *optimal segmentation design*, as first step, aimed at achieving scenarios of “conceptual cuts” dividing the network into modules (Giustolisi and Ridolfi, 2014a). “Conceptual cuts” are defined as the locations of cuts that segment the WDN graph without accounting for devices to be installed. In the second step, the *optimal DMA design* starts from one of the optimal segmentation solutions and returns the decision on installing a flow meter or a closed gate valve in each “conceptual cut”, accounting for the change of the WDN hydraulic behavior with respect to the delivered customer demand and background leakages.

Optimal segmentation is here performed using a paradigm from complex network theory (Albert and Barabasi, 2002; Fortunato, 2010; Newman, 2010). In fact, one possible approach to network segmentation is referring to community detection strategies, while the most popular one is based on modularity index (Newman, 2004). The modularity index is the most widely accepted and used metric to measure the propensity of the network division into modules (or communities, consistently with the earliest applications of the index) (Newman and Girvan, 2004). The modularity is a descriptive measure of topology and relies strictly on the network structure. The advantage of the modularity is that it is a topological index, which depends only on the identification of network adjacency matrix (Steinhaeuser and Chawla, 2010) and whose assessment does not require high computational costs. For a given network, a higher value of the maximum modularity index indicates a better identification of communities; therefore, the maximum value of the modularity corresponds to the maximum degree of segmentation.

Recently, Scibetta et al. (2013) and Diao et al. (2013) applied the modularity index to the segmentation of a WDN using the original Newman's formulation. Unfortunately, the original formulation was proposed for immaterial networks and Barthélemy (2011), for example, pointed out the strong difference between immaterial networks (e.g., food web, trade, World Wide Web) and material networks (e.g., urban infrastructure networks).

For this reason, Giustolisi and Ridolfi (2014a) tailored the original modularity index in order to obtain a WDN-oriented modularity index accounting for the features of WDNs which are infrastructure systems. The modification of the original modularity index consists in considering the "conceptual cuts" segmenting the network close to ending nodes (instead of the middle of pipes) and in introducing pipe weights in the formulation of the WDN-oriented modularity index. Furthermore, Giustolisi and Ridolfi (2014b) proposed an infrastructure modularity index, modifying the WDN-oriented modularity index, in order to overcome the resolution limit of the original modularity index (Fortunato and Barthélemy, 2007), which causes the non-identifiability of smaller modules depending on the size of the network. Finally, Giustolisi et al. (2015) reported a comprehensive framework of the WDN-oriented modularity indexes.

The WDN *segmentation* provides the initial step to solve the *DMA design* problem, since “conceptual cuts” represent candidate locations of closed gate valves or flow measurement devices. For this reason the optimal segmentation design is driven by the minimization of the number of cuts versus the maximization of one of the modularity metrics proposed by Giustolisi and Ridolfi (2014a;b), which is selected according to the most important technical task driving the actual DMA design (during the second phase).

Thereafter, during the second step of the procedure, the modules identified by “conceptual cuts” becomes actual DMAs establishing which “conceptual cuts” will represent the location of flow measurements or closed valves.

Following the idea of exploiting the potentiality of DMA implementation to reduce background leakages while preserving adequate water supply service, the procedure proposed herein for planning DMAs is solved as a three-objective optimization problem, which minimizes the number of flow meters and the total unsupplied customer demand while maximizing the reduction of background leakages. This way, deciding the “conceptual cuts” where to install the closed gate valves (*vice versa* where to install flow meters) contemporarily avoids the worsening of the service quality (i.e. searching for solutions with null or negligible unsupplied demand) and pursues the reduction of leakages (i.e. searching for solutions with significant pressure reduction through the hydraulic system).

Therefore, the optimal DMA design approach introduced by Ferrari and Savic (2015), is here expanded using a two-step optimization in order to segment first, using the findings of the complex network theory, and then to introduce the hydraulic behaviour of the system using a pressure-driven hydraulic modelling computing leakages and unsupplied demand in order to achieve effective technical solutions. The proposed procedure proves quite flexible and general since allows selecting from among the optimal segmentation solutions in the first step and to introduce any technical/engineering constraint or objectives to drive the effective allocation of devices in second step.

A small size test case, the Apulian network (Giustolisi et al., 2008), will allow presenting the procedure and clarifying the concept of "conceptual cuts", "optimal conceptual scenario" and "actual DMA". A real medium size test case, the Exnet network (Giustolisi and Ridolfi, 2014b), will allow demonstrating and analysing from the hydraulic standpoint the overall DMA design strategy.

FROM SEGMENTATION TO DMA DESIGN

The concept of DMA management was first introduced to the UK water industry in the early 1980s (UK Water Authorities Association, 1980), where a district was defined as an area of a distribution system specifically distinct, e.g. by the closure of valves, and in which the quantities of water entering and leaving the district are metered. The subsequent analysis of flow calculates the level of leakage within the district, not only to plan whether works should be undertaken to reduce leakages, but also to compare the level of leakages among different districts, thus assessing where it is most beneficial to undertake leak location activities.

From such perspective, the division of WDN into districts 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, demand and leakage management, etc. Walski et al. (2001) reported many technical aspects related to the installation of a system for water sub-metering as well as ancillary works and activities in a real WDN, thus emphasizing the need to support the effective planning of DMAs.

As said above, Giustolisi and Ridolfi (2014a) tailored the original modularity (Newman, 2004) in order to define the WDN-oriented modularity index accounting for hydraulic networks, which are infrastructure networks. To this purpose, they introduced the notion of "conceptual cuts", which are assumed close to the ending nodes of pipes where devices that create DMAs are actually installed. In addition, they proposed a multi-objective segmentation design using WDN-oriented modularity indexes.

Starting from such findings, in the proposed two-step optimal DMA design strategy, the first step focuses on the structure of the hydraulic system as network, in order to segment/divide the hydraulic domain, and in the second step focuses on the hydraulic behaviour, in order to define operative districts. In fact, the network connectivity structure of the hydraulic system dominates the district design with respect to the hydraulic behaviour. In fact, the network connectivity structure is the main driver of the hydraulic behaviour.

It is worth noting that, searching for positions of devices (flow meters or closed gate valves), which divide the network into modules and contemporarily satisfy the hydraulic requirements (service quality and background leakage reduction) would be cumbersome because computationally very expensive. In fact, it would be necessary to perform the extended period simulation using pressure-driven analysis for all candidate segmentation alternatives during the optimization in order to compute the hydraulic performance. The search space itself would increase exponentially with the size of the WDN, making less and less effective the optimization.

On the contrary, the division of the design problem in the abovementioned two steps guarantees better optimization performance and flexibility. In fact, when the segmentation solution, which is weakly dependent on hydraulics, is selected, the DMA design can be simply and rapidly performed also varying the hydraulic behaviour of the network (e.g. demands, installed control devices, etc.) and accounting for peculiar technical objectives like, for example, system reliability.

METHODOLOGY

The subdivision of hydraulic systems into districts represents a technically structured approach for several management purposes including monitoring, control and operations that might require the isolation of some portion of the system (e.g. in case of planned or accidental interruptions). The district design problem of WDNs has generally three drivers: (i) network structure (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, pre-existing segmentations and devices, and/or other objectives generally related to capital/operational costs. Finding a trade-off among these different goals is a complex management task and is a relevant issue for water utilities to ensure adequate service for customers, increasing the benefits of the planned investments. A general-purpose approach to the district design is not available at date and empirical methods are generally used resorting to expertise of technicians.

The modularity index represents ultimately the most popular index used to divide networks into modules by means of “conceptual cuts”, which are the candidate positions for installing devices creating actual DMAs and even for designing isolation valve systems (Giustolisi and Savic, 2010). In fact, incidentally, the segmentation problem might entail directly the optimal location of gate valves only.

This work proposes the following district design paradigm, based on two main phases:

A. Two-objective optimal network segmentation, minimizing the number of “conceptual cuts” versus the maximization of the WDN-oriented modularity index. Each segmentation solution consists of a set of “conceptual cuts” dividing the network structure of the WDN into modules. It is possible to constraint the multi-objective optimization to search for nested solutions. This means each segmentation solution can be generated starting from the one having the lowest number of modules by progressively increasing number of modules, so that solutions with higher resolution (with more “conceptual cuts”) are nested in the more parsimonious segmentations (with less “conceptual cuts”), i.e. subdividing the modules of the more parsimonious segmentation. This fact provides flexibility to the segmentation design because it is possible to start from any optimal scenario, depending on the preferred resolution of the districts, which is generally driven by the available budget. Such feature allows the dynamic planning of the segmentation, increasing over time the resolution of the districts, considering the budget uncertainty and the growing knowledge of the system. Therefore, although one solution needs to be selected among the *optimal* *segmentation solutions* as the basis for the actual DMA design, a "nested" segmentation design makes the procedure flexible from a technical perspective. It is to remark that the devices already installed in the system are constraints for the optimal segmentation design (Giustolisi and Ridolfi, 2014a; b), therefore the proposed procedure is flexible also with respect to the applications in real hydraulic systems where DMA or devices already exist;

B. starting from the *selected segmentation solution*, a three-objectives optimization is performed by simultaneously minimizing the number of flow observations and the unsupplied customer demand while maximizing the reduction of leakages. The minimization of the number of flow meters instead of their total cost, which depends on diameter, represents a pressure for the optimization to install a lower number of flow meters on pipes having greater flow rates, as reported later in the text. The minimization of background leakages entails a driver towards installing closed gate valves in strategic positions, which changes the water paths resulting into reduced pressures through the hydraulic system. Finally, the minimization of the total unsupplied customer demand guarantees solutions, which are technically effective with respect to service quality.

Optimal network segmentation (Phase A)

The WDN-oriented modularity index is the basis of the optimal segmentation; its formulation is,

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

where n_c is the number of pipes linking modules of the infrastructure network, namely the number of "conceptual cuts" in the network (i.e. the decision variables of the segmentation problem) and n_m is the number of 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 δ function 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).

It is worth to note that the term Q_1 of Eq. (1) decreases with the number of cuts, while Q_2 generally increases with the number of modules and, for a given number of modules, it increases with the similarity of modules to each other with respect to the assumed pipe weights.

The modularity index measures the similarity of the segments/modules with respect to selected pipe weights (e.g.; in the case of lengths the similarity of segment lengths) for a given number of "conceptual cuts" dividing the network in n_m segments. Therefore, its maximization provides the maximum number of modules, which are similar with respect to pipe weights, obtained with the minimum number of cuts.

The formulation of the two-objective optimal segmentation is,

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

where $\mathbf{A}_{np}$ is the incidence matrix, I_c is the set of n_c cuts in the network, decision variables of the optimization, the Connectivity(I_c,|$\mathbf{A}_{np}$|) stands for component analysis of the undirected graph for the given cuts, and n_{act} indicate the cuts that are *actually* used to separate modules (Giustolisi and Ridolfi, 2014a). Note that being the decision variables related to "conceptual cuts", the already existing flow measurements corresponding to control valves, pumps, tank and reservoir, could be considered as constraints, i.e. already existing "conceptual cuts", which are the initial basis of the network segmentation. Similarly, closed valve or pressure reduction valves locations can be considered as constraints, i.e. already existing "conceptual cuts".

Although several formulation of the WDN-oriented modularity index have been developed (Giustolisi et al., 2015) the use of a specific index does not impair the generality of the multi-objective optimization described in Eqs. (2). In this work the length of pipes stored in the vector $\mathbf{L}_p$, is reported in Eqs. (2), therefore L is the sum of pipes lengths. Actually, this selection is consistent with the main purpose of reducing leakages while guaranteeing adequate water supply in next DMA design. In fact, pipe lengths significantly influence the WDN hydraulic behavior having a technical meaning also with respect to background leakages for a given deterioration of the system (Giustolisi et al., 2008).

Solving the optimization problem in Eq. (2) 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 in terms of total length for a given number of cuts. As said, the optimal segmentation could be constrained to search for nested solution providing flexibility to the entire procedure. At the end of this first phase, the selected optimal segmentation solution, for example based on available budget, will be the basis for the second phase related to the actual design of DMAs.

Optimal design of the network DMAs (Phase B)

The optimal DMA design procedure aims at determining the position of flow meters and closed gate valves in the "conceptual cuts" dividing the network structure of the WDN in modules. Therefore, the optimization problem has binary decision variables, one for each "conceptual cut", corresponding to the decision of installing a flow meter or a closed gate valve. It is worth noting that the procedure could be constrained by existing flow meters (e.g. close to tanks, reservoirs, pump installations, etc.) and existing closed gate valves, (i.e. considered as constrained "conceptual cuts" during the first phase) are assumed as fixed variables during the second phase. In addition, between the first and second phase, a connectivity analysis is performed to check whether the closure of each candidate isolation valve would determine the disconnection of some WDN portions; unfeasible locations of gate valves are then automatically removed from the set of candidates assuming flow meters.

As said above, the installation of closed gate valves alters the original flow paths reducing the pressure status into the WDN due to the increase of head losses along other flow paths. In other words, the procedure is conceived to obtain a double effect, the design of districts in the hydraulic system and the leakage reduction (Ferrari and Savic, 2015).

The formulation of the three-objective optimal segmentation problem is,

$$\begin{cases} f_1 = \min\left\{n_{fm}\right\} \\ f_2 = \max\left\{1 - \dfrac{V_T^{leak}(\mathbf{v})}{V_T^{leak}}\right\} \\ f_3 = \min\left\{1 - \dfrac{V_T^{cust}(\mathbf{v})}{V_T^{cust}}\right\} \\ \\ \text{subject to:} \\ \begin{bmatrix} \mathbf{A}_{pp}\mathbf{Q}_p(t) + \mathbf{A}_{pn}\mathbf{H}_n(t) & = & -\mathbf{A}_{p0}\mathbf{H}_0(t) + \mathbf{H}_p^{pump}(t) \\ \mathbf{A}_{np}\mathbf{Q}_p(t) - \left[\mathbf{d}_n^{leaks}(\mathbf{H}_n, t) + \mathbf{d}_n(\mathbf{H}_n, t)\right] & = & \mathbf{0}_n \end{bmatrix} \quad \forall t = 1,\dots,T \\ \\ \text{and} \quad \textit{Technical Constraints} \end{cases} \tag{3}$$

where n_{fm} is the number of flow meters; V_T^{cust} and V_T^{leak} are namely the total customer demand and leakages over T-steps extended period simulation (EPS), in the original WDN configuration (i.e. without accounting for devices); $V_T^{cust}(\mathbf{v})$ and $V_T^{leak}(\mathbf{v})$ are the same figures, but referred to the set $\mathbf{v}$ of closed gate valves located at "conceptual cuts" (i.e. representing the implementation of the DMAs). $\mathbf{d}_n$ and $\mathbf{d}_n^{leaks}$ are the vectors of water demand and background leakages (lumped at nodes) which depend on time and current pressure status. Further details on the hydraulic model used for the following case studies are reported in Giustolisi et al. (2008).

In order to account for the emptying/filling process of tanks during optimal DMA design the following constraints have to be added to the formulation (3),

$$\begin{cases} H_s^{ini} \le H_s^{final} \\ H_s(t) \ge H_s^{\min} \end{cases} \tag{3a}$$

where s is the subscript of the sth tank node; $H_s^{\min}$ is the minimum head level at the sth tank node; H_s^{ini} is the initial head level at the sth tank node varying over time t and H_s^{final} is the final level at the sth tank node. The constraints in (3a) guarantee system reliability because the first equation states that the initial level (i.e. volume) in each tank should be lower than the final of the EPS, while the second states that the tank level cannot be lower than the minimum during EPS.

The minimization of the number of flow meters does not account for their cost of purchasing, which depends on pipe diameter, for two main reasons: (i) the flow meters management cost is much higher than the initial cost of purchasing; and (ii) it drives the search towards a lower number of flow meters installed on pipes with greater flow rates. In other words, it drives towards the installation of closed gate valves on pipes with lower flow rates, whose interruption that does not impair the service quality while allowing leakage reduction.

The reduction of the background leakages is formulated as the fraction of saved water volume with respect to the original WDN configuration (i.e. without closing the valves). The maximization of the leakages volume reduction, obtained through the positioning of closed valves, is assessed by means of extended period simulation of the hydraulic system behavior, i.e. during a selected operative cycle. It is relevant to note that pressure-driven analysis is compulsory for hydraulic modelling (Giustolisi et al., 2008; Giustolisi and Walski, 2012).

Finally, the minimization of the total unsupplied customer demand is formulated as fraction of the water volume unsupplied to customers with respect to that required during a selected operative cycle. This objective function is relevant in order to obtain the leakage reduction with null or negligible unsupplied demand, i.e. without decreasing service quality. Once again, pressure-driven analysis represented with the matrix equations in (3) is compulsory to compute the unsupplied demand, e.g. using the Wagner model (Wagner et al., 1988).

It has to remark that the abovementioned pressure-demand model permits also to consider the pressure requirements of hydrants when the WDN serves for fire protection. In the case of accounting for fire protection, in the hydraulic model of Eqs. (3) the component of hydrants in demands is added, i.e. $\mathbf{d}_n + \mathbf{d}_n^{leaks} + \mathbf{d}_n^{hydr}$, and a scenarios of fire protection based on specific national regulation should be considered (Giustolisi and Walski, 2012). Another possible approach is to increase the pressure for a correct service considering the pressure requirement for hydrant and an excess of pressure in order to consider the increased flow in the network during a fire event.

However, it is to remark that fire protection is not an issue for all water distribution networks, depending on the specific national regulations and on the leakage rate, which can suggest renouncing to the higher pressure required for fire protection. For this reason, the case study, without loss of generality, will be performed to discuss and demonstrate the two steps for DMA design methodology considering the requirements for customer demands only.

Finally, phase B allows introducing any *Technical Constraint* (last Eq. (3)) in order to drive DMA design towards engineering sound solution as, for example, excluding transmission mains (i.e. diameters larger than a given threshold) form candidate location of closed gate valves.

Accordingly, the proposed strategy shows two levels of flexibility to support DMA design.

In phase A segmentation can be driven to return segments that are nested, thus permitting flexibility in the selection of the conceptual cut that are candidate for the next step or to account for existing devices. In phase B, it permits to introduce any technical/practical constraints entailing engineering considerations or even other objective functions to match peculiar technical purposes, even different from those reported in this work (e.g. minimize the possible spread of contaminants (e.g. Grayman et al., 2016) while minimizing background leakages and matching the required demand).

CASE STUDIES

All tests were performed by means of a specific function for WDN segmentation implemented as part of WDNetXL system integrating a genetic algorithm, named OPTIMOGA (see Acknowledgements). The methodology is presented on three different case studies, Apulian network, Apulian oversized network and Exnet network.

Apulian Case study

The proposed design strategy is here presented on a simple network in order to show and discuss its main features. The Apulian network (Giustolisi et al., 2008) is a small network having one reservoir feeding by gravity 23 nodes and 34 pipes, whose layout is reported in Figure 1. The parameters of the leakage model (Germanopoulos, 1985; Giustolisi et al., 2008) are set as $\alpha = 1.2$ and $\beta = 1.06\times10^{-7}$ $m^{2-\alpha}s^{-1}$ for all the pipes, which leads to a leakage rate of about 24% of the total WDN inflow. The pressure assumed to get a correct water supply service is 10 m at every demand node. The first optimization procedure (phase A) returned a Pareto front of optimal segmentations by solving the problem of Eqs. (2). The optimal configurations are characterized by a number of cuts ranging from three to nine. It is to remark that all configurations share a common "conceptual cut" close to the unique reservoir of the network, which should be candidate to be flow meter in the final DMA solutions/configurations.

Results and discussion - Apulian case study

The solution with the maximum number of cuts, reported in Figure 2, corresponds to the maximum value of the WDN-oriented modularity index. This last solution is here selected as the basis for the second phase (phase B), the actual DMA planning.

As reported in Table 1, the phase B returned several "DMA configurations", i.e. location of flow meters and closed valves, resulting into different leakage reduction rates and total unsupplied customer demand. Table 1 shows that the number of closed gate valves for different "DMA configurations" ranges from 5 (i.e. 4 flow meters) to 2 (i.e. 7 flow meters). Due to the hydraulic capacity of the original network (i.e. optimized for normal working conditions without closed valves), few solutions in Table 1 (i.e., 1, 10, 11, 17, 20, 30 and 35) show null or negligible unsupplied demand in spite of closed gate valves. Those "DMA configurations" are characterized by a small leakage reduction of about 4% on average. Therefore, the optimization provides information about the actual possibility of reducing leakages by installing closed valves, accounting also for the residual hydraulic capacity of the system.

It is worth noting that the maximum percentage of leakage reduction (70%) is achieved with five closed gate valves and that, in general, the reduction of background leakages involves the increase of unsupplied demand, consistently with the reduction of pressure due to the change of water paths in the network.

From management perspective, accepting values of unsupplied demand lower than 1% (e.g. equal to 0.35%), it is possible to achieve about 4% of leakage reduction.

Figure 3 reports two optimal DMAs configurations corresponding to solutions number 12 and 13 in Table 1 having three closed valves and six flow meters. It is evident that to a high value of leakage reduction corresponds a high value of unsupplied demand, while the unsupplied demand value grows up when a configuration with a higher leakage reduction is considered as solution. In fact, pipe sizes in Apulian WDN were optimally designed (Giustolisi et al., 2008) in order to provide sufficient hydraulic capacity without closing any valve. This, in turns, leaves little room to reduce losses without increasing the unsupplied demand.

Furthermore, the two configurations of Figure 3 differ for a closed valve installed on pipe 7 and 1 (see Figure 1) having the similar diameters (i.e. 327 mm and 368 mm,). Despite this fact, the configurations returns different technical conditions. This observation hints that an important driver of an effective DMA design is the network topological structure of the hydraulic system. In other words, given a diameter, i.e. a cost of valve installation, the hydraulic effect on the WDN can be greatly influenced by the topological position of that valve as well as the position of the other valves, thus changing the flow paths in the system. In order to prove further this point, the only phase B of the procedure was performed on an oversized version of the Apulian network. Such oversizing was obtained by assuming internal diameters equal to 184 mm for all pipes in bold in Figure 1 in place of the optimized diameters equal to 100 mm for all such pipes except for pipes 15 and 27, whose optimized diameters were 164mm. This way, the network is assumed to represent real systems, which are generally oversized with respect to the customer water requests.

Table 2 reports the three Pareto efficient solutions returned for the optimal DMA design of the oversized Apulian WDN. It is evident that the increased hydraulic capacity due to pipe oversizing allows finding solutions with null or negligible unsupplied demand with respect to the previous case, although showing sensible leakage reduction.

Indeed, Figure 4 shows that the leakage reduction values are similar even if the positions of the closed valves change among different solutions. Each solution creates different flow paths inside the hydraulic network and for this reason the WDN functioning needs to be considered globally and not looking at a single closed valve.

It is worth remarking that, for the oversized Apulian, the same segmentation configuration (i.e. “conceptual cuts”) used for the original Apulian is the basis of the optimal DMA design. This fact demonstrates the flexibility of the procedure that does not require repeating the optimal segmentation design (phase A) when the network topology does not change.

Exnet Case study

Exnet network (Giustolisi et al., 2008) is a real medium size network composed of 1.894 nodes and 2.471 pipes. Figure 5 reports the network layout. Actually, for the sake of the example all valves in the original Exnet data were eliminated, while five reservoirs were added at original inflow nodes 3003, 3004, 3005, 3006 and 3007; the head of all such new reservoirs and the original reservoir 3001 were assumed equal to 70 m. Finally, the elevation of junctions 1107, 1084, 726, 55, 41, 186, 1092, 120 and 5555 (i.e. close to reservoirs 3001 and 3002) was put equal to 10 m. All such changes guarantee hydraulically consistent simulation of inlet flow using pressure-driven analysis."Also, it is assumed a leakage model with parameters α = 1.1 and β = 10^{-8} $m^{2-\alpha}s^{-1}$ for all the pipes (Germanopoulos, 1985; Giustolisi et al., 2008), which leads to a leakage rate of about 28% with respect to the total water inflow. The hydraulic system was analyzed during a daily operating cycle using the same daily pattern of customer demands reported in Figure 1, because the original real pattern was not available.

Without loss of generality for the following discussion, as explained in the section entitled "Optimal design of the network DMAs (Phase B)", the fire protection is not here considered.

Figure 6 shows the Pareto front of *optimal segmentations* returned by the first optimization procedure of the methodology (phase A) for Exnet network. The maximum value of the WDN-oriented modularity corresponds to ninety-nine "conceptual cuts" dividing the network in 32 modules, as reported in Figure 7, while the minimum number of "conceptual cuts" is constrained by the eight pipes delivering water from the seven reservoirs. The segmentation scenario of Figure 7 was used as basis for the second phase (phase B) in order to design the actual DMAs.

It is to remark that the selected solution for phase B has some cuts, which are either close to the reservoirs or separate branched portions from the rest of the WDN. For these cuts, the installation of a flow meter is mandatory, because otherwise one or more reservoirs or network portions would be disconnected.

Moreover, for the sake of the example, the optimal DMA design of Exnet was constrained to pipes with diameters no higher than 500 mm. From hydraulic standpoint, this constraint avoid closing major transmission mains that would result into massive reduction of system hydraulic capacity for which the WDN was originally designed, although oversized.

Therefore, considering that all abovementioned technical constraints results into 31 mandatory flow meters, the DMA design phase will provide the decision about installing a closed gate or a flow meter for 68 out of 99 "conceptual cuts".

Results and discussion - Exnet Case study

The optimization procedure returned 12 solutions (Figure 8), all characterized by null unsupplied demand. In fact, as for the oversized Apulian case, Exnet hydraulic system is oversized and the returned solutions dominate the technically unfeasible ones.

The twelve solutions shows a number of flow meters ranging from 16 to 27 (i.e. closed gate valves decreasing from 52 to 41), that correspond to a leakage reduction between about 11% and 15% with respect to the original configuration.

Figure 9 shows the percentage of times that each candidate "conceptual cuts" is selected for installing a closed valve, over the twelve optimal DMA design solutions. Consistently with previous constraints, the maximum pipe diameter in Figure 9 is 500 mm. 33 out of 68 "conceptual cuts" are selected in all solutions (i.e. 100% of times) for installing closed gate valves. This means that such "conceptual cuts" are in strategic topological position to change water paths in the WDN, irrespectively on their diameter.

Figures 10 and 11 show the pressure drop, with respect to the original pressure status, of the solutions 1 and 12, which are obtained with a different number of flow meters, 27 and 16 respectively (corresponding to 41 and 52 closed valves). The leakage reduction is about 15.4% and 11%, respectively. Therefore, a significant difference between the reported solutions exists in terms of ratio valves/meters and positioning at "conceptual cuts". This generates a different hydraulic behaviour of the WDN, as shown by pressure drop in Figures 10 and 11. In other words, each solution generates a different distribution of flow paths with respect to the original ones of the hydraulic system (i.e., without DMAs definition), which need to be carefully simulated considering a pressure-driven analysis and a consistent background leakages model. Figures 12 and 13 show the significant difference in terms of diameters of closed valves with respect to flow meters of the solutions 1 and 12. In terms of leakage reduction, it can be observed that a solutions with a larger number of closed valves installed on smaller diameter pipes (i.e. up to 319 mm) (solution 12) is less effective than a solution with a lower number of valves installed on larger diameter pipes (solution 1).

Therefore, bearing in mind that none of the solutions have unsupplied demand, the trend of increasing leakage reduction as the number of closed valves decreases indicates that a lower number of valves can be more effective for leakage reduction, because installed in strategic topologic positions (i.e., more important flow paths) with respect to the original flow paths of the hydraulic system. *Vice versa,* a greater number of valves can be less effective for leakage reduction, if their positioning is driven only by the need of topological division of the network structure, i.e. they are installed in positions that do not change significantly the original system configuration. From this perspective, it is worth noting that a realistic hydraulic modelling is strategic in order to predict the WDN behaviour. Thus, leakage and pressure-driven analysis are compulsory. In the opposite case, considering pressure drops in demand-driven analysis as surrogate of their actual effect on leakage reduction might result in a solution with many closed valves driven by the topologic division of the network structure, because negative pressures returned by demand-driven modelling need to be avoided, with the result of a negligible actual leakage reduction.

Finally, considering that all the proposed solutions are optimal as resulting from the solution of problem in Eqs.(3), the best selection among the DMA design solutions depends on constraints/options of the decision maker, e.g. the number of flow meters versus leakage reduction, DMA configuration, etc. Therefore, consistently with results, the authors' opinion is that DMA design should be accomplished on the base of a decision support tool providing Pareto efficient solutions, which are all effective with respect to the objective functions explicitly accounted in the problem definition. Such solutions could be significantly different from a more comprehensive technical standpoint when additional criteria are adopted, that are not considered while solving in the problem statement. Our procedure, thanks to the flexibility, see e.g. problem formulation in Eqs. (3), allows designing technically consistent DMAs.

CONCLUSIONS

The paper presents a two-phase design strategy for *optimal DMAs design*. The first phase entails a multi-objective optimization, where the network is segmented by maximizing the infrastructure modularity index (Giustolisi and Ridolfi, 2014b) against the minimization of the number of "conceptual" pipe cuts. The second phase starts from an *optimal segmentation* solution returned by the first phase, and searches for the actual DMAs of the network by establishing the position of flow meters and closed valves among the "conceptual cuts", accounting for the reduction of the number of flow meters, background leakages and unsupplied demand to customers, within a multi-objective optimization. Moreover, the second phase is able to incorporate any technical constraint driven from engineering or management needs.

An advanced pressure-driven modelling approach to predict leakage reduction and unsupplied demand (Giustolisi et al., 2008) is embedded in both phases.

The procedure proves able to deliver many district metering solutions, taking into account of various technical and management aspects, as well as those related to the hydraulic functioning of the network (leakages, unsupplied demand, pressure deficit, etc.) and engineering insight as technical constraints. In particular, from the background leakages reduction perspective, results from the case study related to a real WDN, highlighted the different impact of placing closed valves in few strategic positions rather than in many locations as obtained looking at network topological division only.

The proposed approach, based on separating the segmentation of the WDN from the planning of devices at DMA boundaries allows great flexibility to provide technically feasible alternatives. Besides the possibility of including prior "conceptual cuts" or selecting among "nested" segmentation solutions in the phase A, the DMA design optimization problem in phase B can be easily extended including other objective functions and/or technical constraints.

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The case studies reported herein has been accomplished by means of the WDNetXL Design Module, which implement the proposed optimal DMA design strategy. The system tool WDNetXL can be requested free of charge for students and research purposes at www.idea-rt.com. The network data used in WDNetXL can be obtained contacting Prof. Orazio Giustolisi (orazio.giustolisi@poliba.it).

Notations list

The following symbols are used in this paper:

$\mathbf{A}_{pn}$ = general topological matrix of the network ($\mathbf{A}_{pn} = \mathbf{A}_{np}^T$);

F_i = objective function;

I_c = set of n_c cuts in the network;

K_i = node degree of the i-th node;

L = connectivity matrix of the edges/pipes;

$(\mathbf{L}_p)_k$ = vector of pipe length values in module *k;*

L = sum of pipes length values;

M_i = identifier of network modules;

N = network;

n_{act} = actual number of modules satisfying the constraints;

n_c = number of pipes linking modules of the infrastructure;

n_m = number of network modules;

n_p = number of network links/pipes;

Q = WDN-oriented modularity index;

$\mathbf{w}_p$ = vector of pipe weights;

W = sum of pipe weights;

α = exponent of the leakage model;

β = coefficient of the leakage model;

δ = Kronecker's delta function;

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Table 1. List of forty-two DMA optimal solutions for Apulian case study.

Solution	Closed Valves	Leakage Reduction [%]	Unsupplied Demand [%]
1	1	3,58	0,33
2	1	27,27	7,60
3	2	3,56	0,33
4	2	29,83	11,05
5	2	31,27	13,77
6	2	27,08	7,93
7	2	45,55	29,70
8	2	36,22	19,68
9	2	27,08	7,95
10	3	3,91	0,33
11	3	1,09	0,00
12	3	34,55	19,14
13	3	47,78	34,28
14	3	36,24	19,70
15	3	29,56	11,81
16	3	40,07	29,24
17	3	7,70	0,90
18	3	48,80	37,87
19	3	36,64	19,70
20	3	4,78	0,35
21	3	30,93	14,76
22	3	31,07	19,11
23	3	40,44	29,26
24	3	39,66	20,22
25	3	26,78	8,46
26	3	68,52	50,94
27	4	17,53	13,60
28	4	50,92	44,98
29	4	36,75	19,76
30	4	4,78	0,34
31	4	40,50	29,26
32	4	69,84	57,33
33	4	47,26	40,78
34	4	39,82	20,23
35	4	8,66	0,91
36	4	29,95	16,88
37	4	45,46	30,55
38	4	43,84	29,77
39	4	70,48	61,54
40	4	70,35	61,53
41	4	66,91	53,70
42	4	26,25	13,67

Table 2. List of three DMA optimal solutions for Apulian oversized case study.

Solution	Closed Valves	Leakage Reduction [%]	Unsupplied Demand [%]
1	5	18.23	0.02
2	5	17.23	0.00
3	4	17.22	0.00