A PRACTICAL APPLICATION OF WDNETXL SYSTEM TO DMA DESIGN OF APULIAN NETWORKS

Spagnuolo S.1, Perrone G.2, Berardi L.3, Laucelli D.3, Simone, A.3, Giustolisi O.3

1Acquedotto Pugliese S.p.A., via S. Cognetti, 36, Bari, Italy
2IA. Ing Srl, v.le M. Chiatante, 60, Lecce, Italy
3Technical University of Bari, Dept. of Civil Engineering and Architecture via Orabona n.4, 70125, Bari, Italy

luigi.berardi@poliba.it

ABSTRACT

The design of district metering areas (DMA) in water distribution networks (WDNs) is a key action for supporting decisions aimed at improving system knowledge, control and asset management. This contribution reports a novel practical strategy to support DMA design that was developed and customized for a consultant company working for Acquedotto Pugliese s.p.a., which is a large water utility in southern Italy. Based on DMA design solution that contains the positions of “closed gate valves” at DMA boundaries aimed at reducing pressure and leakages, the methodology allows designing the most effective location of flow meters accounting for budget and practical constraints. The resulting procedure was implemented as additional functionalities of the WDNetXL platform and answers the technical request of the water utility for an integrated, robust and flexible design process for DMA aimed at supporting WDN monitoring, pressure control, leakage reduction and asset management.

Keywords: DMA design, Leakage reduction, Practical applications

1 Introduction

Urban Water Distribution Networks (WDNs) are complex systems that pervades our cities providing a vital service for all human activities. The majority of WDNs in Europe were built in the last century and nowadays are experiencing the combined effects of increasing water requests and asset deterioration that result into raising level of water losses and higher frequency of major pipe failures that, ultimately, exposes citizens to increasing risk of unreliable access to water. Considering limited financial resources, WDNs are public infrastructures that requires continuous investments to ensure reliable water supply to customers. The design of district metering areas (DMAs) in WDNs is of strategic relevance for supporting management, operation and planning decisions.

A recent survey of WDN in Italy [1], reported that only 9% of water distribution systems use districts for monitoring and control purposes. In addition, in face of the continuous investments on such infrastructure, the average rate of water losses in some regions still exceeds 50% of total inlet volume. In order to improve the quality of investments, the Italian Authority for Regulation of public service networks in the last year introduced a novel regulatory framework where WDN service performances are evaluated using measurable indicators, with direct consequences on water tariff and, ultimately, on revenues for water companies.

In this context, Acquedotto Pugliese s.p.a. (AQP), that is one of the biggest water supply company in Europe managing WDNs in about 300 cities in Apulian region (Southern Italy), started a new
process for asset management aimed at “passive” and “active” control of the WDNs. It aims at a rational engineering of DMAs as functional for monitoring of hydraulic quantities, implementing pressure control and planning the replacement of aged pipes. As an essential pre-requisite for AQP, the DMA design procedure should be measurable, verifiable, repeatable and scalable in order to be applied on various size WDNs following a structured non-heuristic approach.

IA.Ing s.r.l. as a technical consultant for AQP on this call, tuned to IDEA-RT s.r.l (registered innovative start-up company, spin-off of the Technical University of Bari) as a unique international provider of innovation with high technical-scientific content in the field of water network systems management. This contribution presents the proposed practical approach for DMA design that is being implemented by AQP in some WDNs. As such, it reports advanced technical-scientific fundamentals and tools, while demonstrating a tangible research transfer process to support technical consultant actors (i.e. IA.Ing s.r.l.) that daily operate with water companies (i.e. AQP).

2 Background on DMA design

The technical literature reports several approaches for supporting the division of the hydraulic systems into districts for monitoring purposes. Jacobs and Goulter [2] and Yang et al. [3] consider the WDN reliability; Perelman and Ostfeld [4] proposed a segmentation framework for WDNs analysis. Perelman et al. [5] proposed a strategy to decompose the system into the main subsystems identifying the boundary valves in the edge cuts while minimizing the number of open boundary valves. Alvisi and Franchini [6] suggested a procedure for the creation of DMAs accounting for resilience and minimum pressures, in peak demand and fire-flow conditions. Ferrari and Savic [7] introduced the concept of leakage reduction by means of DMA definition. In fact, closing gate valves changes hydraulic paths in the system and the implementation of DMAs could reduce pressure with potential leakages reduction. Recently, Laucelli et al. [8] proposed a two-step strategy for optimal DMA design. The first step, based on optimal segmentation design, aims at achieving “conceptual cuts” dividing the network into modules [9][10]. In the second step, the optimal DMA design starts from one of the optimal segmentation solutions and returns the decision on installing flow meters or closed gate valves in each “conceptual cut”, accounting for customers’ water requests, maximizing leakages reduction and minimizing the number of meters. The novel practical approach presented in this contribution exploits the abovementioned strategy to provide an integrated, robust and flexible process for supporting DMA design for WDN monitoring, pressure control, leakage reduction and pipe replacement as of direct relevance for AQP. In order to make the entire procedure available to technical consultants (i.e. IA.Ing. s.r.l.) it was implemented within the WDNetXL system [11][12].

3 The DMA design strategy

The strategy implemented for designing DMAs in WDNs follows a structured approach based on two logical steps, namely (i) the conceptual subdivision of the system topology as the main domain for the hydraulic behavior, and (ii) the identification of DMAs driven by the advanced hydraulic analysis. In order to provide a set of technically optimal alternatives, each step is formulated as a multi-objective optimization problem where conflicting technical objectives are simultaneously optimized.

3.1 Topological segmentation

The topological segmentation aims at identifying the minimum number of conceptual cuts that maximize the infrastructure modularity index [10] as a metric of the efficiency of WDN subdivision
into segments. Eq. (1) reports the general formulation of the infrastructure modularity index used to drive the topological segmentation.

$$Q(w_p) = \left\{ \frac{n_p}{n_p} \right\} + \frac{1}{n_m} \sum_{m=1}^{n_m} \left( \frac{w_p}{\delta(M_m,M_k)} \right)^2 = Q_1 + Q_2$$

Where, $n_p$ is the number of pipes; $n_c$ is the number of conceptual cuts close to WDN nodes; $n_m$ is the number of the identified segments/modules; $w_p$ is a vector of weights, whose sum is $W$; $\delta$ is the Kronecker’s operator allowing to select pipes belonging to the $m$-th module ($\delta=1$ if $M_m=M_k$, $\delta = 0$ otherwise). It is worth noting that, differently from the original modularity index developed in the complex network theory, the infrastructure modularity in Eq. (1), allows accounting for the technical constraint that cuts (i.e. device like valves or meters) in WDNs are located close to nodes, thus leaving the entire pipe into one segment.[9] Moreover, the index $Q(w_p)$ was developed to overcome the resolution limit of the original modularity index [10], thus allowing to achieve higher number of segments/modules.

Since the WDN subdivision in network managed by AQP are intended to support both operational (i.e. monitoring and pressure control) and strategic (i.e. rehabilitation) management, the topological subdivision aim as identifying segments with similar “risk of failure”.

The two-objectives optimization procedure implemented in the WDNetXL, returns a number of Pareto-optimal topological segmentation solutions with increasing number of conceptual cuts in face of increasing value of $Q(w_p)$. A key property of such segmentation solutions is that smaller segments/modules are nested into larger ones; this, in turns, means that conceptual cuts (i.e. virtual locations for valves/meters) at the boundaries of some segments are still in segmentation solutions with higher number of cuts including nested segments. Such property match the technical prerequisite of identifying segments through a smaller number of devices (i.e. small investments), while providing the optimal location of additional devices in the near future (i.e. as soon as the budget will be available) or considering innovation (e.g. internet of things (IoT), 5G internet, etc.)

### 3.2 Hydraulic DMA design

Based on the original strategy in [8], the hydraulic DMA design takes conceptual cuts from one of the topological segmentation solutions as candidate positions for installing closed gate valves or flow meters. The hydraulic rationale behind this phase is that closing some gate valves at the boundaries of segments leaves less water paths into the network where head losses will be higher than the original WDN configuration; this, in turns, reduces leakages from the WDN while preserving water supplied to customers with sufficient pressure. In addition, from district monitoring perspective, this strategy minimizes the number of flow meters at the boundaries of each district, thus making easier to perform water balance at DMA level.

The hydraulic DMA design phase is a multi-objectives optimization where the number of installed flow meters and the leakage volume from WDN are minimized, while guaranteeing the total water volume unsupplied to customers. As such, the optimization exploits the advanced hydraulic simulation embedded in the WDNetXL system [11]. It encompasses pressure-dependent models for customers demand as well as the “volumetric” leakages distributed along pipes also referring to property connections, i.e. those having major impact on water volume balance (i.e. background leakages and unreported bursts).

The candidate locations for flow meters (i.e. the decision variables of the optimization) are the conceptual cuts of the topological segmentation solution with the highest number of segments. On the one hand, this solution allows exploring the maximum number of feasible locations for
installing closed gate valves, entailing various volumetric leakage reduction performance. On the hand, a larger number of hydraulic DMA design solutions will enable the flexible strategy for installing meters, as described in the next section. In other words, planning of closed gate valves has two main purposes: (i) allows designing DMA for water balance using the minimum number of flow measurements and (ii) allows reconfiguring the fluxes into the network, which is a global pressure control to reduce volumetric leakages depending on the residual hydraulic with respect to the need for a “conservative” correct service.

In order to account for the peculiarities of Apulian region, where some WDNs are fed by gravity and pressure reduction valves (PRVs) regulate pressure right upstream of the distribution network, the original hydraulic DMA design strategy was modified to take the setting points of these PRV as additional decision variables of the problem. In fact, highest global reduction of pressure through these PRVs leaves less room for pressure reduction by flux reconfiguration, thus requiring more flow meters at DMA boundaries.

4 Decision support for DMA implementation

The structured DMA design strategy described above shows two main technical advantages of direct relevance for the water utilities. (i) It provides objective measures (i.e. the infrastructure modularity index) to evaluate and compare different topological segmentation solutions thus overcoming the empirical approaches commonly adopted in these systems. (ii) It allows combining the need for planning system monitoring with the opportunity of reducing leakages, as one main target of WDN management, providing various alternative solutions. Actually, the strategy usually returns a number of DMA configurations with customers demands fully supplied (i.e. null pressure deficit) related to various leakage reduction performance, i.e. flux reconfiguration into the hydraulic system, obtained by closing various gate valves in some conceptual cuts.

In order to make strategy of practical relevance to support decisions/planning for the water company, the original DMA design was exploited to allow the introduction of the following criteria to drive the flexible planning of DMAs, which reflect various constraints in real decision contexts: (i) identification of the most effective location of a maximum number of meters, i.e. reflecting a limited budget available; (ii) introduction of the expertise from technicians that daily operates on the system and know possible constraints that would make infeasible the installation of flow meters at some locations; (iii) verification of effective metering accounting for the expected hydraulic status, as simulated using the advanced hydraulic model. These criteria, that will be detailed in the following sections, do not exclude each other since reflect different practical constraints, providing optimal DMA design alternatives.

4.1 Flexible DMA identification based on maximum number of meters

Once the hydraulic DMA solution, implying the maximum reduction of volumetric leakages by closing some gate valves has been chosen, the budget available for flow meters is constrained by the current management cost of the devices. Let’s recall that the topological segmentation procedure returns a number of (Pareto-optimal) solutions that are nested into each other. This means that is possible to consider some parsimonious segmentation solutions with progressively larger segments and lower number of conceptual cuts than the segmentation solution used to search the optimal DMA design (i.e. that with the highest number of segments and conceptual cuts). Accordingly, such parsimonious segmentation solutions include smaller segments. The novel methodology exploits the topological properties of the conceptual segments/modules to find the most effective nf location of flow meters that do not coincide with closed gate valves.
This means that, assuming $n_c$ maximum number of conceptual cuts, with $n_v$ of them hosting closed gate valves, it is possible to find $n_f$ flow meters for straight installation among at the boundaries of DMAs. Since this rationale process resorts to metrics from complex network theory for infrastructure systems, it provides a repeatable and verifiable design of DMAs that, at the same time, allows reducing volumetric leakages following a flexible planning of flow meters that provides a road map to increase the monitoring resolution with innovation referring to IoT and 5G networks.

### 4.2 Introducing expert judgement

In real WDN management contexts, there are could be practical constraints for installing measurement stations that cannot be known in advance or, sometimes, come up during the executive project phase when design details are discussed with technical divisions working at water company that daily operate on these systems. The decision support tool in WDNetXL allows introducing at any time the constraints coming from experts’ judgement based on technical feasibility of installing the planned measurement stations. The topological properties of the segments/modules behind the DMA design enables to reconfigure DMA boundaries even when some of the flow meters are removed from the design based on expert’s judgement.

It is worth to remark that the introduction of expert selection criterion is independent from the application of the strategy for accomplishing the maximum number of meters and can be applied at any stage of the DMA planning process.

### 4.3 Supporting effective metering

As mentioned above, the DMA design strategy intends to support the location of flow meters at the boundaries of WDN districts for many purposes, including the water balance at district level (e.g. for accurate leakage assessment/detection). As such, the compatibility of commercial flow meters with the flows and diameters in the selected pipes is of primary importance. From metering perspective, pipes with low minimum flow or possible reverse flow should be avoided in order to avoid inconsistent measurements considering the sensitivity and accuracy of commercial meters. For this reason, each hydraulic DMA design solution in WDNetXL systems provides, as additional output, the flow patterns at all pipes that are candidate location for flow meters accounting for the gate valves that will be closed. Therefore, the user, after selecting the DMA solution with the highest leakage reduction with respect to the original configuration, check for possible deletion of candidate meter location with high risk of inconsistent measurement. Also the implementation of this decision criterion is independent on the previous two (i.e. based on the maximum number of meters and introducing expert judgement).

### 5 Case study

The abovementioned DMA design procedure was implemented to support panning in some cities in Apulian region. One of them is the city of Taranto, which is the second biggest city in the region, with a population of about 200,000 inhabitants. The DMA design was based on a preliminary implementation of the WDN hydraulic model developed by AQP, within the advanced hydraulic framework in WDNetXL, which allowed pressure-driven analysis of customers’ demands and volumetric leakages. The WDN model includes 7297 nodes and 8025 pipes, representing a pipeline length of about 390 km. In addition, the model includes three pressure reduction valves (PRV) reported as red circles in Figure 1.

The first phase identified over 100 topological segmentation configurations, with a maximum number of 51 segments/modules and 170 conceptual cuts, which is that reported in Figure 1.
The second phase of hydraulic DMA design resulted into nine solutions entailing various leakage reduction as percentage of the original leakage volume. Since the pressure regulation through the three PRVs affects the pressure reduction achievable by closing gate valves at DMA boundaries, the pressure settings for these valves are included as decision variables in the hydraulic DMA design optimization phase.

**Figure 1. Topological segmentation of Taranto WDN**

**Table 1. Hydraulic DMA design solutions**

<table>
<thead>
<tr>
<th>Segmentation</th>
<th>Leakage reduction [%]</th>
<th># Closed gate valves</th>
<th># DMA</th>
<th># Flow meters</th>
<th># Perspective meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>18.1</td>
<td>19.2</td>
<td>19.3</td>
<td>19.5</td>
<td>19.9</td>
</tr>
<tr>
<td>2</td>
<td>21.9</td>
<td>22.1</td>
<td>22.3</td>
<td>23.9</td>
<td>-</td>
</tr>
</tbody>
</table>

The first column in Table 1, i.e. hydraulic DMA design solutions headed as “0”, reports the number of conceptual cuts and segments/modules of the topological segmentation solution. For instance, considering the hydraulic DMA solution n.9 resulting into 23.9% leakage volume reduction, it requires the closure of 67 gate valves among a total of 170 conceptual cuts. Since the pressure regulation through the PRVs affects the pressure reduction achievable by closing some gate valves at DMA boundaries, the pressure settings for these valves are included as decision variables in the hydraulic DMA design optimization phase. Table 1 reports 9 DMA design solutions (i.e. columns from 1 to 9), entailing various leakage reduction as percentage of the original leakage volume. Such values are obtained as a consequence of pressure reduction through the combined effects of three PRVs and a number of closed gate valves, as reported in the same table. The first column in Table 1, i.e. hydraulic DMA design solutions n.0, reports the number of conceptual cuts and segments/modules of the topological segmentation solution. In the hypothetic scenario that no budget/technical constraints affect the design solution, all conceptual cuts in the segmentation n.1
that are not closed gate valves, will host flow meters (i.e. installation of 103 flow meters for DMA design solution n.9). Vice versa, in case the limited budget would allow purchasing 25 flow meters only, the strategy enables to reconfigure the DMAs while preserve the same leakage reduction performances. In case of solution n.9, such DMA reconfiguration allows, with 25 flow meters and 67 closed gate valves, to identify 10 DMAs. The remaining 78 conceptual cuts will be equipped flow meters in the future or, due to their location, identify strategic topological points for temporary measurements (e.g. using portable meters). This DMA solution is reported in Figure 2 along with the location of flow and pressure meters. It is worth to remark that the DMA strategy assumes that pressure meters can be installed at DMA boundary at the same location of flow meters, since they are cheaper and have less installation constraints. In addition, collecting pressure values at DMA boundaries would provide useful information of both WDN model calibration purposes and for monitoring purposes (e.g. for early detection of anomalies due to new pipe bursts).

![Figure 2](image_url)

**Figure 2. DMA design solution with 25 flow/pressure meters.**

Finally Figure 3 shows, for the same solution, the patterns of discharge predicted through the 25 conceptual cuts where flow meters are planned to be installed. This information together with the knowledge of pipe diameters is useful to understand whether there will be any flow inversion and/or very low velocity over a typical operating cycle compared with the sensitivity of the instruments, thus supporting the decision on meters purchasing and installation.

![Figure 3](image_url)

**Figure 3. Flow and velocity in 25 candidate flow meters locations.**
6 Conclusions

This contribution presents a practical approach to DMA design that was developed and customized to match innovation requests from a consultant company of a large water utility in southern Italy. The structured methodology proved to be measurable, repeatable and scalable. It also allowed to match the needs for the water company of verifying the impact of decision process at any step, support short to long term planning of DMA design and incorporate practical constrains and filed expertise at any time. Applications like that demonstrated on the case study on several WDNs also showed that DMA design solutions often have a ratio between the number of flow observations and the number of DMAs close to unit. This means having technically effective solutions where, on average, only one flow meter connects two DMAs. In addition, the identification of the optimal location of flow meters to be installed in the future, will prompt water utilities for the next implementation of IoT paradigm in the WDN sector, where a rational approach will be essential to deploy more and more sensors. The entire procedure was implemented in the WDNeXL system as an innovation transfer platform for technicians and consultants.

7 Acknowledgements

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8 References