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Optimal pressure management in water networks: increased efficiency and reduced energy costs

MATTEO NICOLINI*,
PAOLO CASSINA & MASSIMO BATTISTON**

Abstract. In this paper we address the problem of pressure management in water distribution systems with an aim to reduce pumping energy, water loss through leaks in the networks and the rate of pipe break repairs. After a brief introduction on the description of the problem and the "boundary conditions", we present a methodology based on single- and multi-objective genetic algorithms (GAs) which, starting from the numerical model of the network, performs calibration and then optimizes the location and control of pressure reducing valves (PRVs), according to some operational constraints that must be satisfied. In particular, the simulation model is calibrated with a real-coded, single-objective GA in order to obtain, on one hand, pipe roughness coefficient values and, on the other, an estimate of the subdivision of the total flow supplied to the network between actual customers demand and water loss. The multi-objective NSGA-II is implemented in order to find the Pareto optimal solutions representing different level of compromise between installation costs and leakage reduction. The application of the methodology to a real network allowed considerable energy and water savings, as evidentiated by the monitoring of the system. Two more advantages are also evident: firstly, the number of interventions for repairing pipes is more than halved, due to the reduced pressure regime (thus enabling the water utility to provide better service more efficiently and reliably); secondly, the surplus water is being diverted to a storage tank of a pumped network, thus allowing a notable reduction of pumping costs.

Key-words. Water supply, leakages, optimization, valves.

1. Introduction. Increasing energy costs, a reduction in water availability and the necessity of optimal performance are a few of the reasons which are leading

* Department of Chemistry, Physics and the Environment, University of Udine, Udine, Italy.
E-mail: matteo.nicolini@uniud.it
** CAFC S.p.A., viale Palmanova 192, Udine, Italy.

water utilities all around the world to find ever more effective instruments to reduce leaks in the network as a main issue for optimizing investments. For this reason, pressure control as a means to reduce water losses in water distribution networks has become a major concern for water utilities.

Water leaks imply:

- loss of water, which means
  - water which cannot be delivered,
  - and for this reason it cannot be accounted for;
- waste of the pumping energy used before it exits the pipe;
- waste of chemicals (e.g. chlorine) used to treat the water, possibly raising environmental problems;
- repairs, which in turn require
  - customer service defaults,
  - customer service reductions (loss of pressure, non conformance to service standards),
  - repair costs;
- all the general costs of the water utility which lie upon the water not delivered.

On one hand, systems characterized by high pressures:

- suffer from background leakages (which tend to increase with time);
- may be subjected to untolerable pipe break rates (with related service interruptions and customers complaints);

on the other,

- low pressure regimes often do not guarantee an adequate service to customers, and
- are often a consequence of the increasing level of leakage in the system.

Keeping an adequate pressure throughout the network is a difficult task, especially in rapidly growing cities or in situations with remarkable differences in ground elevations.

In the first case, the change in water demand makes the pipes in the network become insufficient too soon: since the pipes are dimensioned over an hypotesis of water demand, any increase in water demand makes some parts of the network become inadequate, because the flow rate required has become higher than the projected one. To deliver this flow, water must reach high speed values in the pipes, and consequently high head losses take place, due to friction. This leads to lower pressure delivered to the users.

In the second case, the difference in elevation means that two user branches on the same pipe may be subject to very different pressure values, due to different hydrostatic head. These two user branches will have different service standards (pressure and flow rate availability), but the water utility is bound to deliver the same service standards to every customer, so particular solutions must be found for this situations.

In addition, a key point to be considered is that water distribution systems are always designed in order to provide some standard pressures even under peak demand (or fire flow) conditions, thus constraining the network under excessive pressures during their lifetime.

As a result, energetic costs to manage a water distribution network tend to increase with time, very often leading to unsustainable situations that have to be faced. Water utilities can reduce electricity use by increasing pumping efficiency, for example by replacing inefficient motors on pumps, or by installing variable-speed drives and implementing operational controls such as those provided through SCADA (Supervisory Control And Data Acquisition) systems.

Anyway, pumping less water is even more effective in reducing power consumption. In order to reduce leakages, pressure management is now recognized as one of the most efficient and cost effective measures available to water utilities (Lambert 2001, Mckenzie 2002, Girard & Stewart 2007, Thornton et al. 2008). Replacing ageing infrastructures also reduces water loss and decreases water flow resistance due to corrosion and mineral build-up on pipe walls, thus lowering energy for pumping, but the investments required are often one order of magnitude higher.

One of the main solution used to control the pressure over the network is the installation of pressure reducing valves (PRV). These are devices capable of maintaining pressure within certain limits, with a feed-back action based on the differential pressure from upward to downward and with the possibility to set the working pressure at the required valute.

In order to rehabilitate a system, water utilities have to make decisions, often under a high degree of uncertainty. Decisions have to take into account several constraints, and it can be very difficult finding the correct trade-off between the opposite requirements above mentioned.

To help decision makers, hydraulic simulation models are widely adopted for analyzing the behavior of the network under different working conditions, but the predictive ability of a numerical model strongly depends on its calibration. A water network model, actually, is a mathematical description of the real situation. Data required concern

– pipes diameter,
– length and position of pipes, and
– inner roughness (which depends on age and pipe material).

Since these data (mostly the latter) are usually not known at the level of accuracy which would be required by the model, it is necessary to perform a certain amount of measurement and field work to calibrate the mathematical description of the system.

Summarizing:

pressure in water systems must be:

– not lower than a fixed value at any user branch, to grant the minimum pressure service standard to every customer, but
– as low as possible, to reduce pumping costs, water volume losses through

leaks, increase in the number of leaks which must be repaired, customer service defaults and so on.

An adequate pressure control can be obtained by the installation of pressure reducing valves, but the number, position and calibration of the valves must be accurately studied to optimize the trade-off between too-high and too-low pressure, on one side, as described above, and costs for PRVs procurement and installation.

From a mathematical point of view, both calibration and optimal pressure management may be considered as optimization problems with non-linear objective functions and constraints. In this paper, we consider a single-objective, real-coded Genetic Algorithm for solving the calibration problem (Nicolini et al. 2011), while we formulate pressure management as a two-objective optimization problem, in which the first criterion is the total number of pressure reducing valves (a surrogate for installation costs), while the second is represented by the total leakage in the system.

In particular, we implemented the multi-objective NSGA-II (Non-dominated Sorting Genetic Algorithm, Deb et al. 2002), in order to optimize the two conflicting criteria. In addition, the particular coding of the real variables allows the determination of both the location and the regulation of the valves, according to a number of predefined demand conditions (Nicolini & Zovatto 2009). The application of the methodology to a real network resulted in considerable water and energy savings, due to the fact that the surplus water arising from leakage reduction is being diverted to the storage tank of a pumped system, thus reducing costs for pumping.

As usual in the water networks calculation, the network is modelized through a set of branches connected together through nodes, where the flow demand and water losses are thought to be concentrated (this is a standard assumption, which does not affect significantly the model precision, while simplifies considerably the computation).

As is obvious, water demand, and consequently water pressure regimes in the network are subject to great variations in time, showing generally cycles of daily, weekly and yearly periods. This variation is not easily known and must be measured in critical points of the network.

Another relevant item to be kept into account in modeling the systems is that the main means to know water flows are:

- main meters at the intake plants; few in number, and rather easy to keep under control as to precision and calibration; they supply reliable flow measures;
- user-branch meters: very numerous, often rather aged and with a precision which cannot be easily estimated.

It must be underlined that an uncorrect measure of water flows often leads to an over-estimation of water leaks: if the water delivered to the users is measured through an old meter, it will tend to count a lower volume of water than the one which was really delivered.

The flow introduced in the network is delivered to different destinations, which can be summarized as follows:
- water supplied to normal users;
- water diverted for unmetered (but authorized) consumes (for example in maintenance or construction works, where new pipes are accurately flushed before putting them into service);
- water spilled for unauthorized consumes (stealing);
- water lost through leaks.

The optimization tools used to perform the mentioned tasks are Genetic Algorhytms (GAs). Genetic algorithms are derivative-free search procedures based on the mechanics of natural selection and natural genetics. They have been originally introduced by Holland in 1975, who explained the adaptive processes of natural systems and laid down the two main principles of GAs: the ability of a simple bit string representation to encode complicated structures, and the power of simple transformations to improve such structures.

Traditional GAs evolve a population of solutions through several operators. Encoding converts given parameter values (e.g. diameter sizes) to a string of bits (0 or 1), also called individual or chromosome. Decoding maps back the string to the corresponding parameter values. Each individual is evaluated according to its objective function, which plays the role of the environment (i.e. every individual is characterized by a fitness). After evaluation, selection, reproduction, crossover and mutation take place. Selection consists in choosing the individuals which are going to form a new generation, and in placing them in the mating pool; it is often proportional to fitness values: the higher the fitness, the higher is the probability for the individuals to be selected. Reproduction is the mechanism by which a string is copied in the subsequent generation: it may be copied with no change, but it may also undergo crossover and/or mutation, with prescribed probabilities. With crossover, two individuals are randomly selected and put in the mating pool; then, a position along the string is chosen, according to a uniform random law; finally, the paired individuals exchange all characters following the cross site. Mutation is a random alteration of a bit at a string position; in general, it enhances population diversity and enables the optimization process to get out of local optima. The procedure is iterated until a stopping criterion is met (in terms of total number of generations or convergence percentage).

The following part is organized as follows: section 2 describes the methodology, section 3 presents the application to a real network, while section 4 draws some concluding remarks.

2. Methodology.

2.1. Model calibration. Model calibration is based on a real-coded GA in which the objective function is defined as the minimization of the weighted sum of maximum absolute differences between observed and calculated values:

$$\min : f = W_h \cdot \max_{n,t}\left|H_n^{obs}(t) - H_n^{calc}(t)\right| + W_p \cdot \max_{p,t}\left|Q_p^{obs}(t) - Q_p^{calc}(t)\right|, \tag{1}$$

where $H_n^{obs}(t)$ and $H_n^{calc}(t)$ represent, respectively, the observed and calculated head at time t in node n, while $Q_p^{obs}(t)$ and $Q_p^{calc}(t)$ the observed and calculated flow at time t in pipe p. W_h and W_p are weighting factors for heads and flows, respectively.

The optimization problem is subjected to constraints defined by continuity equations ($\forall$ node i):

$$\sum_j Q_{ij}(t) - \alpha(t) Q_{b,i} - \ell_i(t) = 0, \qquad \ell_i(t) = c_i p_i(t)^\gamma \tag{2}$$

and energy loss equations ($\forall$link ij):

$$H_i(t) - H_j(t) = h_{ij}(t), \qquad h_{ij}(t) = \frac{10.668 Q_{ij}(t)^{1.852} L_{ij}}{C_{ij}^{1.852} D_{ij}^{4.871}} \tag{3}$$

where $Q_{ij}(t)$ indicates the flow from node i to node j at time t, $Q_{b,i}$ the (mean) metered consumption at node i (which can be calculated by billing information), $\alpha(t)$ a multiplier for nodal demands depending on time, $\ell_i(t)$ the leakage at node i, $p_i(t)$ the pressure at node i, while c_i and γ are two coefficients quantifying the relationship between water loss and pressure at node i. In particular, we assumed a unique typology of leakage, that is, the same value of γ for all nodes, and we express the coefficient c_i as:

$$c_i = c\frac{Q_{b,i}}{Q_b} = \frac{Q_{b,i}}{\sum_i Q_{b,i}} \tag{4}$$

In (3), $H_i(t)$ and $H_j(t)$ are the total heads at nodes i and j at time t, while $h_{ij}(t)$ is the head loss between nodes i and j; L_{ij}, D_{ij} and C_{ij} are the length, diameter and Hazen-Williams friction factor for pipe connecting nodes i and j, respectively. We chose the real coding of the decision variables, representing the Hazen-Williams pipe friction factors (four in this case) and the coefficient c (Figure 1). Hydraulic constraints are guaranteed by Epanet 2 (Rossman 2000), to which the optimization model has been coupled.

2.2. Optimal pressure management. The problem of optimal pressure management in a water distribution system is addressed through the introduction and regulation of pressure reducing valves. The determination of the number of valves, together with their location and setting, is formulated as a two-criterion optimization problem, and is based on the multi-objective genetic algorithm previously developed (Nicolini & Zovatto 2009).

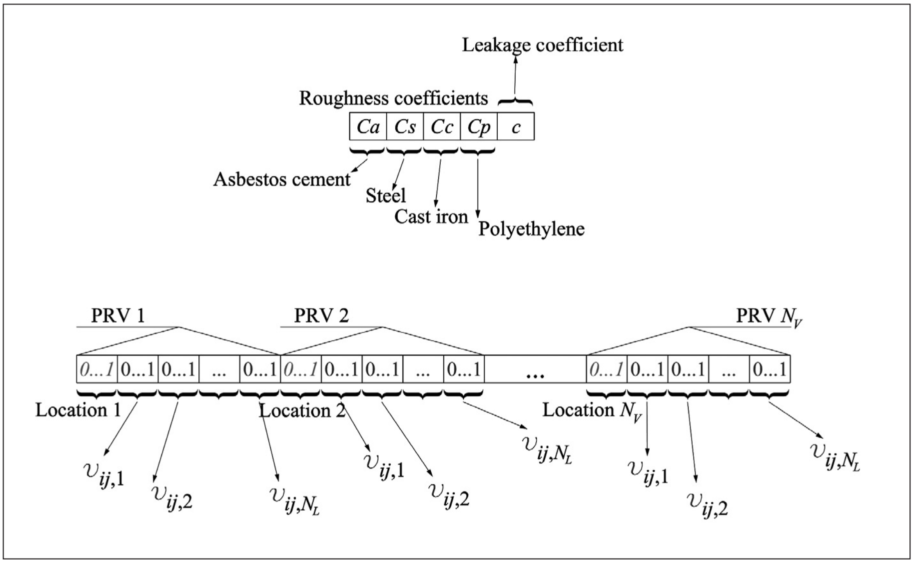

Figure 1. String coding in the genetic algorithms implemented: real coding of pipe roughness coefficients and leakage coefficient adopted in model calibration (above); real coding for NS-GA-II for multi-objective pressure management (below). The notation 0 indicates a real number in the range between 0 and 1. The meaning of the symbols is the following:
$\upsilon_{ij,k}$ = diameter multiplier simulating the presence of a valve in link connecting nodes i and j for load condition k;
N_L = number of load (demand) conditions;
N_V = maximum number of valves allowed.

The problem may be mathematically formulated as:

$$\min : f_1 = n_V \tag{5}$$

$$\min : f_2 = \frac{1}{N_L} \sum_{k=1}^{N_L} \sum_{i=1}^{N_S} w_k c_i p_{i,k}^{\gamma} \tag{6}$$

where n_V is the number of valves in a generic solution, N_S the number of nodes in the system and N_L the number of load (demand) conditions, each characterized by a weight, w_k.

Constraints are represented by three sets of equations: continuity for each node, hydraulic head loss relationship for each link (pipe or valve), and operational constraints, that is, the requirement that at each node pressure is for every load condition above a given level and the limit on the maximum number of allowed valves, N_V. With the same meaning of the symbols, but now with reference to load condition k instead of variation in time, t, we have:

1) Continuity at every node (conservation of mass), expressed as:

$$\sum_j Q_{ij,k} - \alpha_k Q_{b,i} - \ell_{i,k} = 0 \quad \text{for } k = 1, \ldots N_L \tag{7}$$

where the sum is extended to all links connected to node i. The subscript k refers to the k-th load (demand) condition.

2) Headloss in every link (conservation of energy), expressed as:

$$H_{i,k} - H_{j,k} = h_{ij,\,k} \tag{8}$$

According to the type of link, several expressions are possible for the head loss $h_{ij,k}$; in particular, we adopted the following equations useful to describe both pipes and pressure reducing valves.

– Pipes (Hazen-Williams formula in SI units):

$$h_{ij,k} = 10.668 C_{ij}^{-1.852} d_{ij}^{-4.871} L_{ij} Q_{ij,k}^{1.852} \tag{9}$$

– Pressure reducing valves:

$$h_{ij,k} = 10.668 C_{ij}^{-1.852} (v_{ij,k} d_{ij})^{-4.871} L_{ij} Q_{ij,k}^{1.852} \tag{10}$$

where $v_{ij,k}$ is a diameter multiplier (in the range 0, …, 1) which simulates the presence of a valve in the link connecting nodes i and j, and is dependent on load condition k.

3) Operational constraints:

– Required pressure at each node:

$$p_{i,k} \geq p_{req,i} \tag{11}$$

– Maximum number of valves:

$$n_V \leq N_V \tag{12}$$

where N_V represents a pre-defined chosen value.

3. Application to a real system. The methodology has been applied to the water distribution system of Buja (north-eastern Italy, Figure 2).

The whole system is composed of two networks (high and low), separated by closed gate valves: the high network is supplied by a main line and a gravity storage tank, while the low network before the application of pressure management was entirely served by a pumped storage tank. Due to the morphology of the area, the high network was also the one characterized by the highest values of pres-

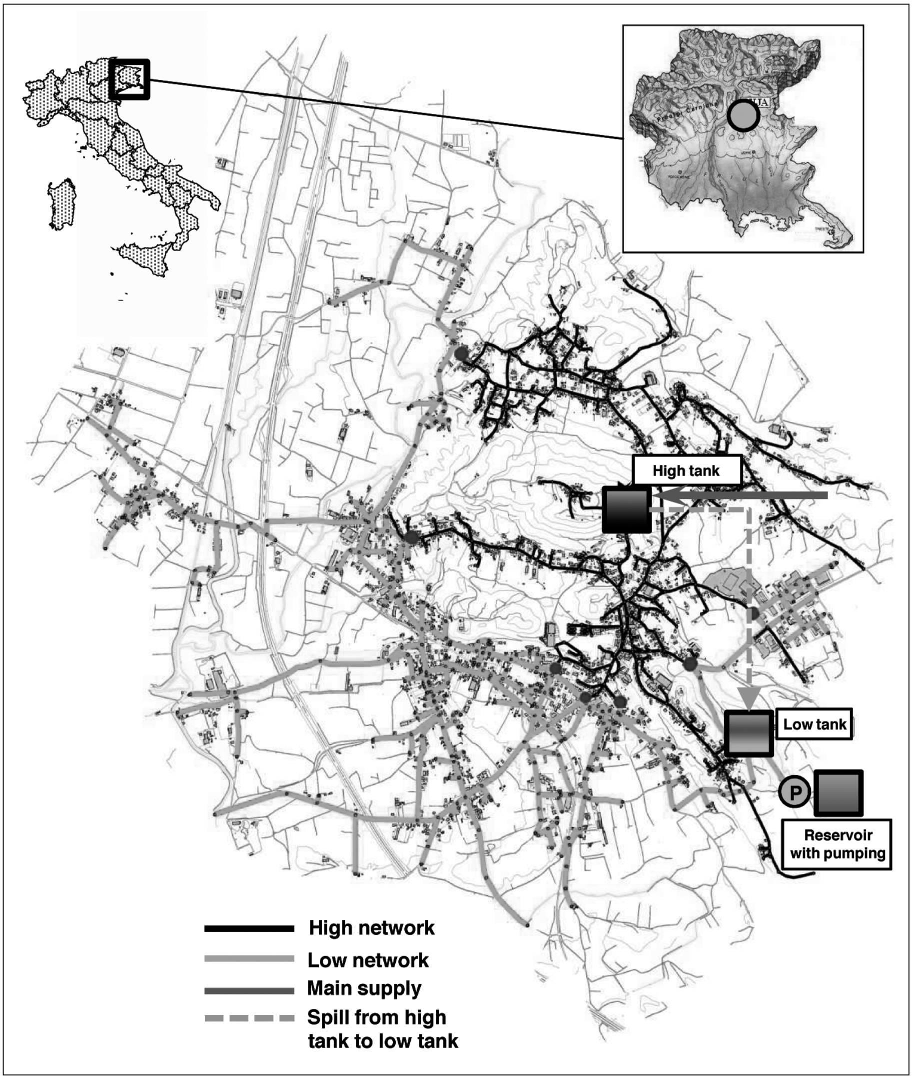

Figure 2. General view of Buja water distribution system, with distinction between the high (in black) and the low network (in grey).

sure (the average value was 7.5 bar, and in some points above 10 bar).

The high distribution network serves about 3500 inhabitants and is composed of several pipe materials: 45% of conduits is made of asbestos cement, 36% of steel, 10% of cast iron and 9% of polyethylene, for a total length of pipes of 35500 m.

Objective of the work was to reduce water loss in the high network through pressure management, and to transfer excess water coming from the main supply line to the low storage tank, in order to reduce electricity costs.

The simulation model was calibrated considering five decision variables (Nicolini et al. 2011), four Hazen-Williams friction factors and the coefficient c, introduced in (4).

Once the model had been calibrated, we applied the pressure management algorithm with a maximum number of allowed valves, N_V, equal to 10, and two load conditions, $N_L = 2$, representing respectively the minimum and maximum user demand (according to seasonal and diurnal variations).

At first we fixed at 2 bar the required level of pressure at every node in the system, thus resulting in an actual average pressure surplus of 5.5 bar.

In all the runs the NSGA-II algorithm used a population of 100 individuals evolving for 1000 generations. Uniform crossover probability was equal to 0.8, while mutation probability was equal to the inverse of the string length (Figure 1):

$$p_m = \frac{1}{(N_L + 1)N_V} = \frac{1}{30} \qquad (13)$$

in which p_m is the probability of mutation at the gene level.

The water utility managing the system (CAFC S.p.A.) adopted one of the optimal four-valve solutions identified by the algorithm, and in the period July-September 2008 four PRVs were installed in the network, as shown in Figure 3. In particular, pipes (265, 410, 577, 663) were chosen to place the PRVs. The monitoring of the reservoir in these two years after the installation of the valves allowed to give a precise estimate of the value of the water savings: from Table 1 it is evident the effect of the PRVs in reducing water supplied to the high network. In particular, the increment in water and energy savings during the year 2010 is due to a fine-tuning of PRV settings, which have been regulated in order to guarantee a minimum pressure between 1.5 an 1.8 bar in some portions of the network (instead of 2.0 bar initially fixed). The surplus water was transferred to the low network, thus achieving nearly 38% of energy saving in the

Table 1. Water supplied to the high network, energy for pumping in the low network, and number of interventions for pipe failure or joint breaks in the high network.

Year	*2008*	*2009*	*2010*
Average flow supplied (L/s)	18.93	13.99	10.47
Volume supplied ($m^3 \cdot 10^3$)	597.13	441.18	330.18
Energy for pumping (MWh)	130.34	82.71	60.91
Interventions on high network	95	67	45

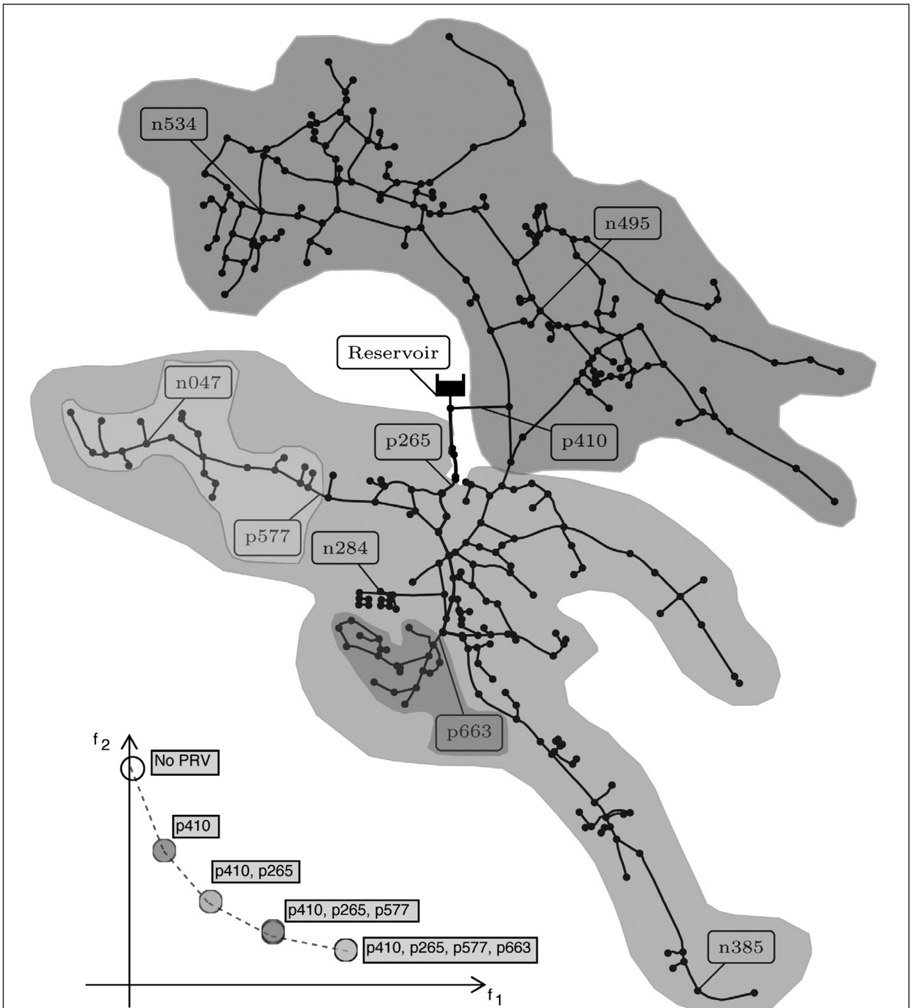

Figure 3. High network model: location of manometers used for calibration (prefix *n*), and pipes selected for PRV installations (prefix *p*). Areas under the influence of each PRV are also indicated. The lower left corner shows a schematic representation of the Pareto front with the optimal solutions representing different tradeoff between the two objective functions.

first year (2009) and 54% during the second year (2010), due to the reduced pumped volumes.

Another main advantage arising from pressure management is the reduction of the number of interventions for pipe failures or joint breaks, as evidentiated in Table 1: such opportunity allows the water utility to manage the system in a much more efficient way, thus avoiding numerous service interruptions which often lead to undesirable customers complaints.

4. Conclusion. In this paper we focused on optimal pressure management in water distribution networks, which is now recognized as one of the most efficient and cost effective measures for reducing real losses and operational costs. We presented a methodology based on genetic algorithms, in particular using a single-objective GA for model calibration and NSGA-II in order to solve the multi-objective problem characterized by the following two conflicting criteria: the minimization of the number of PRVs and the minimization of the total water loss in the network. The main advantages of the procedure are, on one hand, the possibility of relying on a calibrated model (of fundamental importance for evaluating beforehand the effects of any operation in the system) and, on the other, the availability of the Pareto optimal solutions representing the different level of compromise between costs and leakage reduction. An application to a real system proved the effectiveness of such approach, as evidentiated by the water and energy savings which, together with the reduction of intervention costs due to pipe or joint breaks, allow a more efficient and sustainable management of the system.

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