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Location and Calibration of Valves in Water Distribution Networks Using a Scatter-Search Meta-heuristic Approach

S. Liberatore · G. M. Sechi

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Abstract Recently, there has been an increase in the use of meta-heuristic techniques addressing water distribution network design and management optimization problems. The meta-heuristic approach applied to water distribution systems has provided interesting results both for optimum pipe diameter sizing and for the location and management of network pressure control devices (i.e., pumps and valves). Regarding the insertion and calibration of pressure regulation valves, the use of meta-heuristic techniques is relatively recent. We search to strategically placing the valves in order to achieve pressure control in the network and, therefore, the valves must be calibrated in relation to water demand trends over time. In the Pressure Reference Method (PRM) described in this paper, the search for valve location is restricted to pipe-branch sets defined on the basis of hydraulic analysis and considering the range between minimum and maximum acceptable pressures in the network. In the PRM approach, the Scatter-Search (Glover and Laguna, 1997) meta-heuristic procedures are applied to obtain the optimal location and calibration of valves in the water distribution network.

Keywords Water distribution networks · Pressure management · Pressure regulating valves · Metaheuristic optimization · Scatter search technique

1 Introduction

Operating requirements linked to pressure control in water distribution systems may involve the insertion of pressure reduction valves in the pipes network. To ensure

S. Liberatore · G. M. Sechi (✉)
Department of Land Engineering, University of Cagliari, Cagliari, Italy
e-mail: sechi@unica.it

S. Liberatore
e-mail: saverio@unica.it

optimal use of valves, different problems must be solved: the choice of the number of valves, their location, and the determination of the optimal adjustment for opening of valves for different demand patterns. These aspects are discussed in the paper, together with the techniques used to achieve the optimal solution for these problems using meta-heuristic procedures. Even if we are discussing the case of pressure reducing valves (PRV), the optimization procedures can also be applied largely in the same manner as flow regulation valves.

The development and applications of meta-heuristic optimization methodologies for design and management problems in water distribution networks have been proposed in recent years (Murphy et al. 1993; Simpson et al. 1994; Dandy et al. 1996; Savic and Walters 1997; Walters et al. 1999; Fanni et al. 2000; Babayan et al. 2007).

Meta-heuristic algorithms can afford several benefits compared with classical mathematical programming techniques, since they can be implemented without heavy a-priori model requirements, such as convexity or differentiability in the objective function and constraints. Thanks to their ability to manage discrete variables, meta-heuristic optimization procedures can deal directly with the alternatives available (e.g., commercial diameters, cleaning and duplication alternatives) when applied in pipe network design optimization. Each alternative normally consists of a set of discrete organized strings that are coded using predefined rules. Recently, meta-heuristic approaches have also been used with the aim of optimizing the location and calibration of valves in the networks. When writing about the optimization problem, we are also searching to strategically place the valves in order to achieve leakage reduction by utilizing pressure control in the network.

The optimal valve insertion problem has already been extensively investigated with more classical approaches by several authors, who used optimization techniques to obtain linear objective functions and linear constraints; for example, in Sterling and Bargiela (1984) an optimizing function is determined by the sum of total pressures in the network, without including the terms relating to losses among constraints. Subsequently, in Germanopoulos and Jowitt (1989), a method is proposed while maintaining the objective function as a sum of pressures in the network nodes; it included terms pertaining to losses in the set of constraints. An approximate method that applies the decomposition technique in quadratic sub-problems (sequence of quadratic programming) is presented in Vairavamoorthy and Lumbers (1998); in order to formulate the objective function, a target pressure value is chosen to minimize deviations from referenced pressure at the nodes.

The use of meta-heuristic techniques to tackle this problem is more recent: Savic and Walters (1995), Reis and Chaudhry (1999) and Reis et al. (1997) developed models to locate valves in water distribution systems. Araujo et al. (2006) developed a methodology comprising two phases: (1) repeated evaluations of network performance obtained by simulating the system configuration using EPANET routines (Rossman 2000); (2) adjustment of the valve openings in order to optimize pressures through the evaluation of another aptitude function. The first stage consists of the optimization of the number and possible location of "pseudo-valves" in the network pipe branches, simulating an additional roughness that minimizes pressure in the nodes. In Araujo et al. (2006), the location scenarios of these pseudo-valves and their respective head losses (i.e., opening degree) are randomly generated, so that the procedure achieves the minimum pressures with an optimum number of valve locations. In real cases, this procedure can produce an increase in the amount of valves placed in the network.

This paper presents a pressure reducing valve location and calibration procedure based on analysis of the piezometric level at nodes in order to guide the meta-heuristic optimization, which then establishes a limited set of possible locations for valve insertion. Moreover, to enable valve location optimization taking into account different demand and flow capacity patterns (which in some branches can cause flow reversal), we insert variations in the topological network description. Thus, the optimization procedure will not impose constant direction to the flow in the pipes, and it will be possible to implement the optimization process considering different demand patterns.

2 Pressure Reducing Valves (PRV) Insertion and Calibration Methods

In general terms, identification of optimal location and calibration of pressure reducing valves (PRV) could be obtained considering a simple *random search method* in which a pre-defined number of valves are randomly inserted in the network and the optimization procedure then yields an optimum calibration of them. This procedure belongs to enumerative methods, which will eventually produce an optimum global solution, but only after significant computational effort. It is certainly the most simplistic approach, though it can also be used in association with some meta-heuristics techniques to improve the search when updating the candidate locations in the procedure. However, there are difficulties in prioritizing the number of valves. Thus, in general terms, this method is difficult to apply to real networks.

Following the topological structure of the network, the *district method*, as applied by Alonso et al. (2000), involves inserting valves on all district supply pipes. This method is based on the assumption that the distribution network is organized in urban districts, so it is not always suitable for existing urban networks that are grown without partitions. This case typically occurs in historical cities where pipe networks in old neighborhoods are strictly connected to new urbanized areas. Often, these distribution systems had no efficient maintenance program, and they require pressure control for leakage reduction. A sample scheme for valve insertion using the district method is reported in Fig. 1.

Procedures in which the valve location problem is a phase of an optimization process that, initially, foresees one valve on each pipe-branch (*dummy valves*), belonging to the *calculus-based* class of methods. The *dummy valves* technique amplifies the size of the problem because the number of project variables is minimally equal to the number of pipe-branches analyzed in the network.

Combining meta-heuristic optimization with hydraulic analysis of the network, Araujo et al. (2006) approach the problem of valve location and calibration by considering two separate phases: in the first, a Genetic Algorithm (GA) procedure determines a parameter for each pipe expressing a dummy-roughness in order to respect the pressure constraint at the nodes (pseudo-valves); in the second phase, the meta-heuristic determines the optimum calibration value of the valve. This approach is, in some respects, similar to that applied by Alperovits and Shamir (1977) and by Jowitt and Xu (1990), where a deterministic optimization procedure uses the

Fig. 1 Valve insertion according to the network district method (Alonso et al. 2000)

Hazen-Williams equation with one parameter representing calibration of the dummy valve inserted on each pipe branch.

Nevertheless, these calculus-based methods do not consider problems related to real world network applications in an appropriate manner, especially regarding the number of unknown variables, extension of the solution arena and the computational effort required. Often in papers, very small application problems are proposed as test cases to operate selection of pipes where the insertion of valves is assumed to occur but no robust method is reported for large dimension networks. In Alperovits and Shamir (1977) and in Araujo et al. (2006), the method considers a pseudo-valve for each pipe, and, consequently, computational effort grows considerably if real networks are considered.

On the basis of previous considerations, a method to locate valves is illustrated in the following, and it is based on piezometric analysis of the network to define candidate configurations when setting the alternatives considered in the meta-heuristic procedure. Essentially, it aims at reducing the sets of alternative valve locations and calibration parameters to be examined using meta-heuristic procedures in the search for optimum.

3 The Pressure Reference Method (PRM)

To ensure the optimal use of valves in distribution networks, two different problems must be solved: (1) choosing the number and location of valves and (2) establishing their calibration in order to optimize the pressure (Liberatore and Sechi 2005). These aspects, together with the techniques used in the PRM method to achieve an optimal solution, are discussed below.

While we are dealing with the case of pressure reducing valves (PRV), the optimization procedure can be used in largely the same manner for flow regulation valves as well.

In the PRM method, candidate valve locations are restricted to a set of pipes defined on the basis of hydraulic analysis using EPANET routines (Rossman 2000). To analyze the valve location problem we consider a reference pressure value, H_{PRM}. We also define N as the complete set of nodes in the water distribution network, G. To consider the flow variability, various demand patterns $d = 1, \ldots K$ are defined as different sets of requests at the nodes. On the basis of hydraulic analysis and using the demand pattern d, we define a sub-set $N_{1,d}$ of nodes in which pressures exceed the reference pressure H_{PRM}. In addition, we define $N_{2,d} = N - N_{1,d}$. Then, in network G, we examine the subset G_v of pipes with (i, j) candidates for valve location, for which we have: G_v: $(i, j) \in G; i \in N_{1,d}; j \in N_{2,d}$.

Therefore, in G_v, we grouped those pipes for which one of the extremity nodes belongs to $N_{1,d}$ (i.e., the node is located in an area where pressure exceeds the reference value), while the other node has pressure within the allowed range (so it belongs to set $N_{2,d}$). We also refer to n_v as the number of pipes in the set G_v. In this manner, we can indicate to the meta-heuristic the favorite pipe set candidates for valve location as those that "cross" the ideal boundary of a reference pressure, which can be visualized by means of an iso-piezometric line $H = H_{\mathrm{PRM}}$. An example of the G_v set definition is given in Fig. 2, where the right sketch is given the favorite set where the meta-heuristic procedure operates to locate the PRV valves.

As previously stated, in the first phase of PRM, the pipe set used to locate valves refers to a defined H_{PRM} : reference pressure value at nodes. The valve pressure setting parameters H^* are optimized in the second phase of PRM. Calibration of H^* is realized using a discrete set of values managed by meta-heuristic optimization.

Therefore, in the second phase of the PRM approach, the EPANET routines must be iterated and linked to the optimization procedure, and the results make it possible to assess valve calibration to meet pressure targets at nodes. Moreover, hydraulic simulations of the same valve configuration for different demand patterns ($d = 1, \ldots K$) obviously stem from different valve pressure parameters. The pressure head upstream and downstream of the valve are referred as H_m and H_v. Therefore, to accomplish the limitation of pressure in the network, if $H_m > H^*$, then the valve is

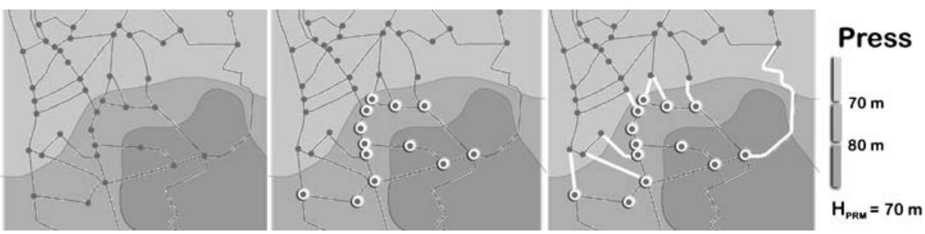

Fig. 2 Location of pipe-set for valve insertion: the pipe-set is identified using a prefixed H_{PRM} reference pressure

partially closed (active), while, if $H_m < H^*$, the valve is inactive (completely open), and, in the event of flow inversion ($H_v > H_m$), the valve is completely closed.

As mentioned before, by fixing the first phase of the H_{PRM} reference pressure, the set of candidate valve locations is restricted to a set of pipes defined on the basis of hydraulic analysis in the PRM second phase. The objective function (OF) of the model is expressed as a weighted multi-objective function that considers the cost of inserting valves and the penalty when the pressure exceeds the maximum allowable value:

$$\min \ \mathrm{OF} = \gamma_1 \mathrm{OF}_1 + \gamma_2 \mathrm{OF}_2 \tag{1}$$

where:

$$\mathrm{OF}_1 = \sum_{d=1,K} \sum_{i=1,N} \left| c_i \left(H_{i,d} - H_{\max} \right)^2 \right|_{H_{i,d} > H_{\max}} \tag{2}$$

$$\mathrm{OF}_2 = \sum_{j=1,nv} f\left(H_j^*, D_j \right) \tag{3}$$

$H_{i,d}$ is the pressure head at node i with demand pattern d; $H_{\max}$ indicates the maximum permitted head at the nodes; H_j* indicates the calibration pressure of the valve, where $j = (1, ..., n_v)$, and the valve is placed in the pipe with diameter D_j. The weights γ_j are non-negative and sum to 1, and c_i are the penalty coefficients associated with node i for head violation.

Hydraulic simulation of the network in the current configuration makes it possible to evaluate the overall penalty function, OF_1, of failed compliance with pressure constraints in the demand patterns. In some situations, it can also be necessary to insert in OF_1 terms considering penalties due to pressures falling under the admitted value, due to valve settings. We also observed that the correct calibration of penalty values c_i associated with head violation is strategically important to reduce computation time and to reach optimality in a limited number of iterations. In OF_2, the economic cost of valves is essentially linked to the number of valves and the diameter D_j of the pipes in which they are placed, while the valve setting parameter H_j* also influences penalties on the heads which appear in OF_1.

Penalty coefficients, c_i, as well as weights, γ_j, in the OF have to be set considering specific situations. In PRM applications, we preferred to minimize penalties resulting from incorrect hydraulic head assessment in the network, rather than minimizing the economic cost of valves. Moreover, sensitivity analysis varying, H_{PRM} and relating it to $H_{\max}$, is significant because these values operate on the G_v set (candidate valve locations) and on n_v (number of pipes in G_v), in addition to the influence on the OF. The dependency of G_v, n_v and OF on H_{PRM} and $H_{\max}$ is unknown *a priori* and will be analyzed in the following application cases.

Using EPANET routines, pressure reducing valves must be defined by assigning them a working direction so that they close if flow in the pipe reverses. In the valve location scheme, this can produce problems when sub-nets become disconnected from supply nodes. When searching for valve location, the PRM procedure inserts, in parallel, an additional small-length pipe equipped with a check valve that blocks by-pass flow side-by-side with the PRV. Figure 3 shows the scheme with the insertion of the check valve in a generic pipe, and arrows indicate the allowed flow directions.

Therefore, the PRM method does not explicitly fix flow direction, but it assumes the initial conditions while leaving open the possibility for the flow to be reversed.

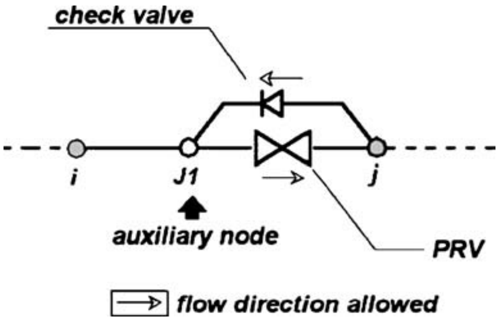

Fig. 3 Scheme of valve insertion on pipe allowing flow reversal

4 PRM Development Using the Scatter Search Meta-heuristic

In previous papers, different meta-heuristic optimization approaches were applied to water distribution system design and rehabilitation problems. In particular, in Liberatore et al. (2003), genetic algorithms (GA), tabù search (TS) and scatter search (SS), as illustrated in Glover and Laguna (1997), were applied to the well-known test problem given by Gessler (1985), while introducing some extensions. The results showed good performance of the GA in terms of objective function values, but high computation time was needed. More promising approaches to combinatorial optimization problems are the SS and TS meta-heuristics, which showed flexibility and effectiveness in the applications.

Similar to other meta-heuristics methods, SS uses a set of points in the research space as data for generating the candidate solution population; thanks to the adoption of search and selection techniques, the population is much smaller than using a GA. While TS keeps only one solution, and applies a mechanism for updating solutions from one iteration to the next, Scatter-Search metaheuristic (like the GA) was designed to operate on a set of solutions that change between iterations. The success in application of a meta-heuristic procedure in a specific optimization problem can be influenced by specific aspects; nevertheless, the population set solution approach in the considered optimization task generally seems more efficient than methods where only one solution is treated at a time. Scatter Search reaches more efficient results by integrating advanced techniques that "combine" more promising solutions to create different new ones. A major difference between classic GA implementation and SS is that, while the former relies heavily on randomization, the second uses memory and other strategic choices to create new solutions, e.g., the combination of already explored solutions.

Among the algorithms reviewed in Liberatore et al. (2003), SS afforded the most efficient evolution of the examined meta-heuristic techniques, since it integrates many aspects of them while adding several improvements. The optimization path is guided by the gradual input of data on the admissible solutions level and in its neighborhoods. Indeed, SS can acquire information both from the points "visited" and from those generated separately through flexible management of the problem's constraints. Moreover, auxiliary heuristic techniques make it flexible and able to provide excellent quality solutions, as shown by the broad range of problems on which it was tested (Glover 1999; Glover and Laguna 1999).

The PRM has been developed by implementing the SS routines present in the OptQuest Library in the C programming language (Laguna and Martì 2000), in order to optimize water distribution networks. The PRM approach integrates the SS optimization module of OptQuest with the hydraulic analysis module for verifying urban distribution networks using EPANET routines. The method is implemented in computer code that manages the interaction between processes related to hydraulic simulation and the OptQuest Library optimization module. The role of the PRM computational interface is to organize the path search for optimal configuration harmonization using the computational tools. The code is developed in the Fortran90 language for interface processing and in ANSI C language for the hydraulic check and metaheuristic routines. The current development platform is Microsoft Windows.

In this work, we only illustrate optimization procedures for allocating and calibrating valves, even if this mixed approach using SS metaheuristic optimization and EPANET simulation modules has also been used for more general design and rehabilitation problems in water distribution systems (Liberatore et al. 2003).

5 Applications of the PRM Method

5.1 Reference Network

The PRM was first applied to a reference network already used by other authors (Bargiela 1984; Germanopoulos and Jowitt 1989; Araujo et al. 2006), which is shown in Fig. 4. The network consists of 37 pipes and 22 nodes.

Network characteristics were taken from the literature, and all supply nodes are considered to have a fixed elevation level at 56 m. Most significant demand patterns

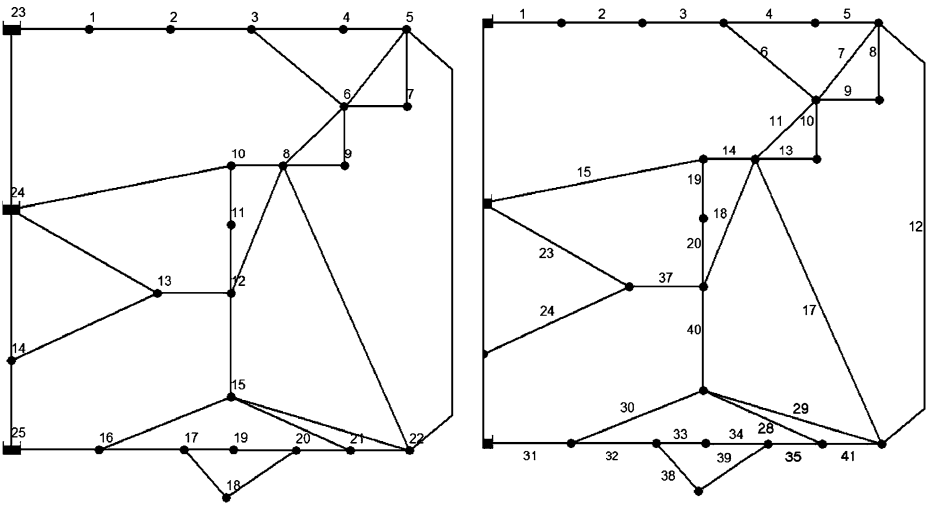

Fig. 4 The reference network: on the *left* is shown the node numbering, and on the *right*, the pipe numbering

Table 1 Reference network: daily change in demand pattern coefficients

Demand pattern	Daily time	Coefficient
DP1	4 a.m.	0.61
DP2	9 a.m.	1.41
DP3	2 p.m.	1.13
DP4	5 p.m.	1.23
DP5	9 p.m.	0.92
DP6	12 a.m.	0.81

were selected from the daily change diagram, as in Jowitt and Xu (1990), and are reported in Table 1. The hydraulic analysis produces the piezometric surfaces showed in Fig. 5, where the dark color highlights areas with pressure head $H > 40$ m in the six demand patterns scenarios.

The figure shows that pressure fields are related to daily demand patterns and interactions with network topology. A sensitivity analysis of the first phase of the procedure is provided considering the mean demand pattern (i.e., coefficient equal 1.0) and varying the H_{PRM} reference pressure to determine candidate locations of the valves (G_v) and number (n_v). For H_{PRM} in the range from 30 to 45 m, the procedure gives different G_v and n_v. The behavior of n_v related to H_{PRM} is shown in Fig. 6. It can be observed that the minimum n_v equals 4 for H_{PRM} in the range of 36–37 m; by moving out from this range, the number of candidate pipes for valve location increases.

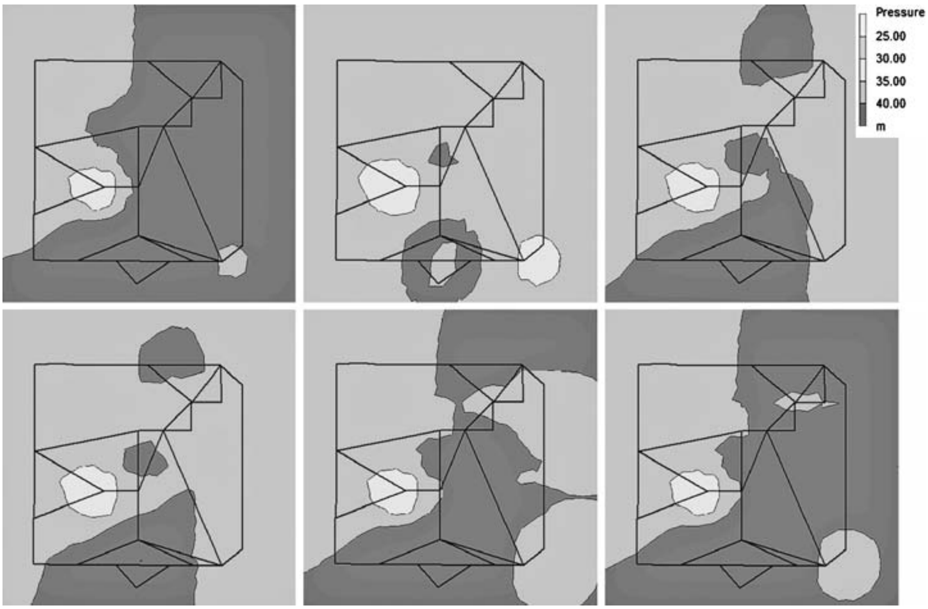

Fig. 5 Pressure fields for the six demand patterns, associated with 4 a.m., 9 a.m., 2 p.m., 5 p.m., 9 p.m. and 12 a.m. *Dark color* zones have $H > 40$ m

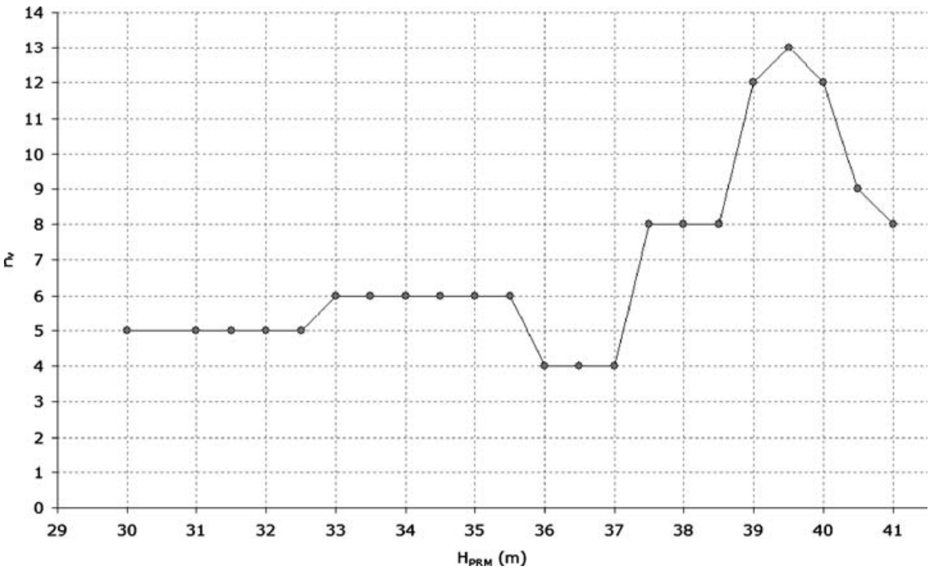

Fig. 6 *Number* of candidate pipes n_v for valve location related to the reference pressure H_{PRM}

It is clear that, to minimize costs related to the number and location of valves, it is necessary to verify the adaptability of candidate location sets to pressure control under different demand conditions so that penalties for overheads are acceptable.

In the second phase, we operate the meta-heuristic optimization to minimize the objective function (1), considering a valve location candidate set obtained for the

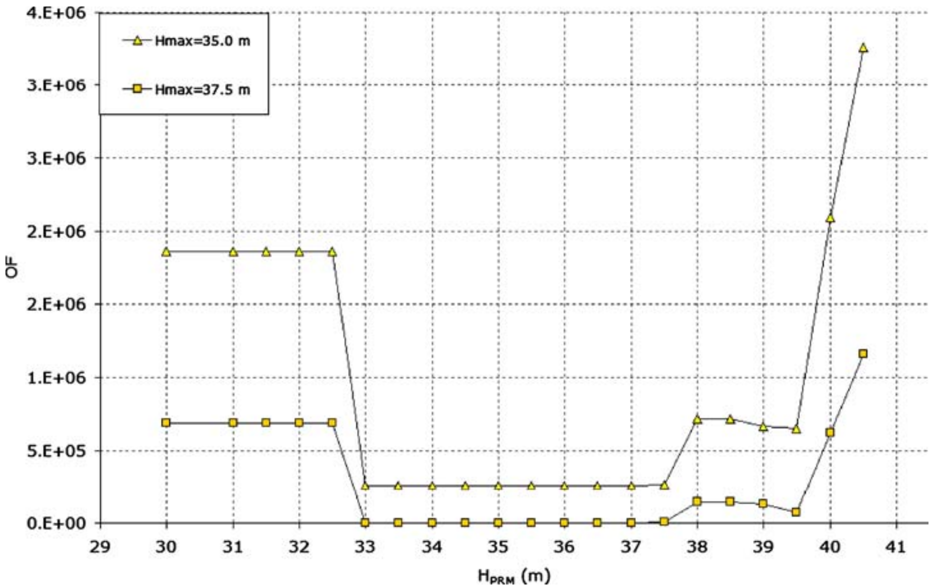

Fig. 7 OF behavior related to reference pressure H_{PRM} and maximum allowed pressure at nodes $H_{\max}$

Table 2 Optimal valve locations and calibrations reached by the PRM procedure

Pipe	DP1	DP2	DP3	DP4	DP5	DP6
	H^* (m)					
P1	35.4	35.4	33.1	31.1	34.1	34.7
P15	34.5	34.5	34.1	40.5	34.6	37.7
P31	33.4	33.4	32.7	30.5	31.8	30.2
P37	22.3	22.3	33.6	34.4	32.1	31.4
Min H_i (m)	29.6	29.6	30.4	30.4	30.1	30.0
Max H_i (m)	37.0	37.0	36.8	36.8	36.9	37.0

mean demand pattern in the first phase and calibrating H_j* so that pressure heads do not exceed the maximum allowed $H_{\max}$ in each considered demand pattern.

Further sensitivity analysis results from varying both $H_{\max}$ and H_{PRM}. Even if the correct valve location needs to consider $H_{\text{PRM}} < H_{\max}$, so that nodes where pressure exceeds the maximum are not allowed, we also consider results in a more extended field. In Fig. 7, OF values are shown when setting candidate sets (phase 1) using H_{PRM} in the range from 30 to 40.5 m and considering maximum allowed pressure $H_{\max}$ equal to 35 and 37.5 m. In the range of H_{PRM} from 33 to 37 m, variation of H_{PRM} does not increase the OF, and pressure control in this range can be achieved with 4 optimally calibrated valves.

The fact that considering $H_{\max} = 35$ m we obtain a flat progress in the OF up to $H_{\text{PRM}} = 37$ m is related to the indifference in defining the subset G_v of candidates for valve location on the basis of piezometric level. Finally, considering $H_{\text{PRM}} = 37$ m, the PRM procedure located and calibrated the four valves in the network (Table 2). Figure 8 shows a comparison with results obtained by Araujo et al. (2006).

Due to the substantial adherence to the problem defined in Araujo et al. (2006), it is possible compare the results: the PRM procedure generated similar results, as

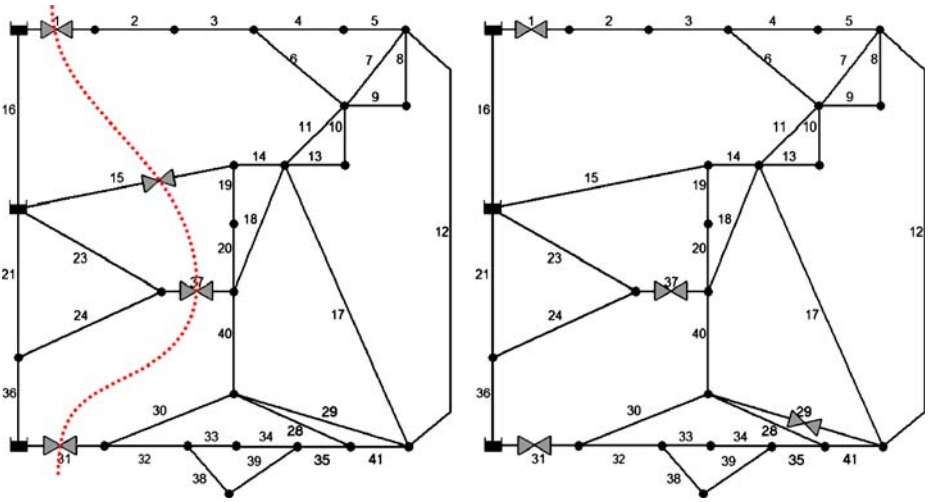

Fig. 8 Valve locations obtained with PRM (*left*) compared with results obtained by Araujo et al. (2006) (*right*)

shown in Fig. 8, even if some differences can be noted in the assumptions (i.e., in Araujo et al. (2006), a small reservoir excursion levels were also introduced). The PRM places a valve on pipe 15 rather than 29; this is justified by the behavior of the piezometric head in the network at different demand patterns.

By adopting the PRM method configuration, we obtained pressure at all nodes in the range 29.5–36.98 m. The time spent in the entire procedure is insignificant (less than 5 s of CPU in a standard PC).

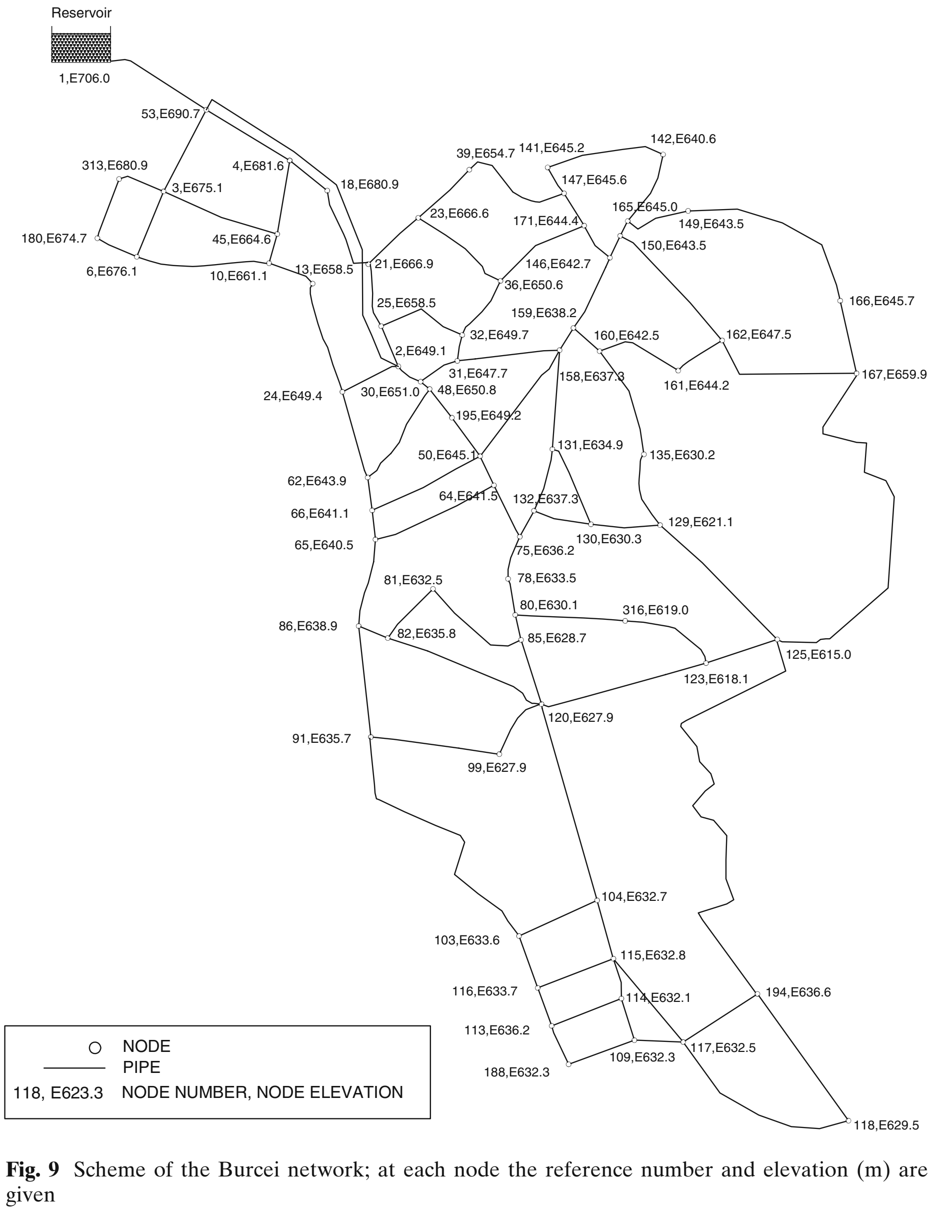

Fig. 9 Scheme of the Burcei network; at each node the reference number and elevation (m) are given

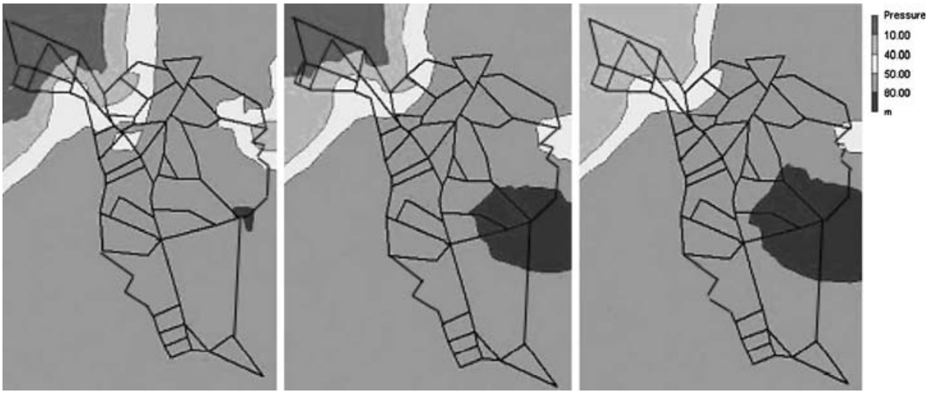

Fig. 10 Pressure fields for maximum (*left*), mean (*center*) and minimum demand patterns

5.2 Real Network

The PRM procedure was also applied to a real network, the distribution network of the town of Burcei in Sardinia (Italy) that was investigated in 1999 during a metering campaign for leak detection and water loss control. This network serves a population of nearly 3,000 inhabitants. The network consists of 98 pipes and 72 nodes and is shown in Fig. 9. The elevation at each node varies, and the maximum difference in network elevation is about 100 m. Demand is concentrated at the nodes, and we examined three demand patterns: d_1, maximum daytime demand; d_2, minimum night-time demand; and d_3, which is related to the mean demand distribution.

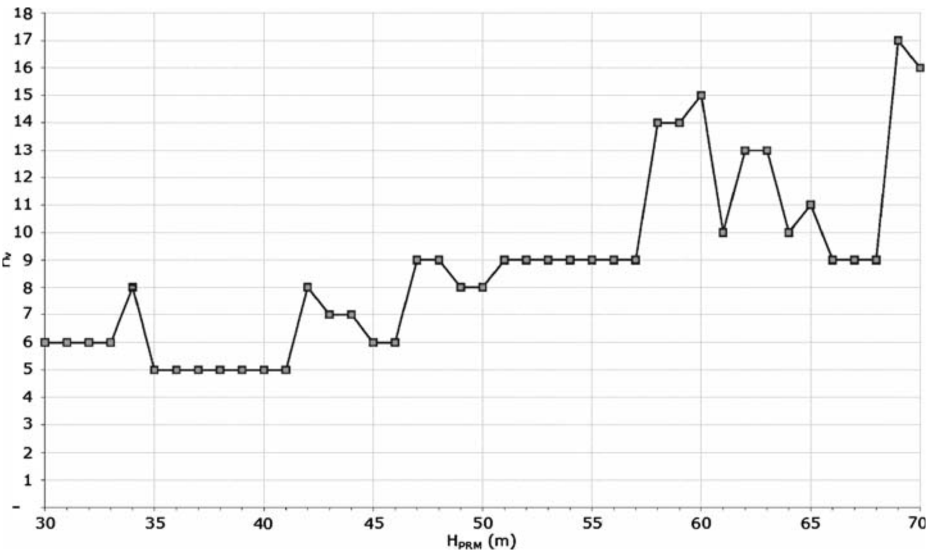

Fig. 11 Number of candidate pipes n_v for valve location related to H_{PRM}

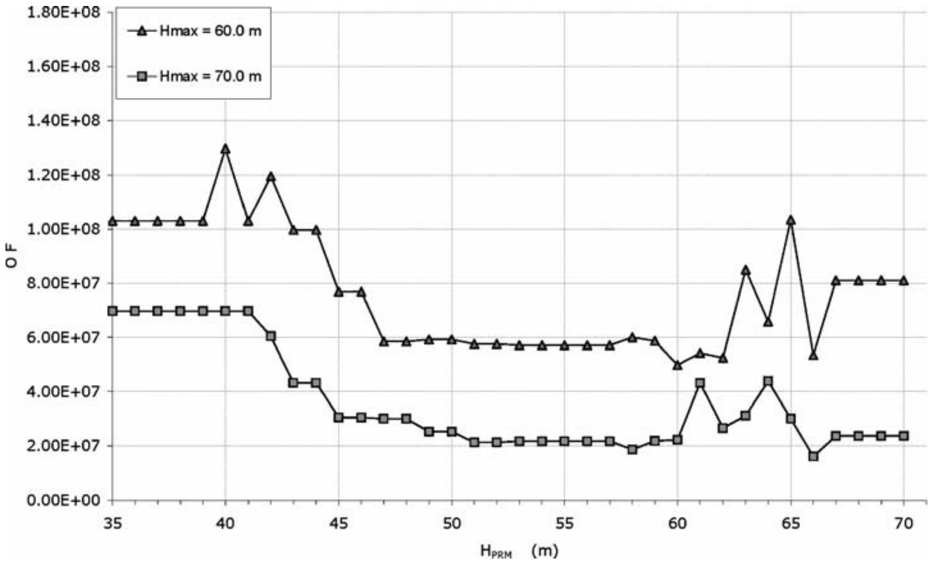

Fig. 12 OF behavior related to reference pressure H_{PRM} and maximum allowed pressure $H_{\max}$

Roughness and other hydraulic characteristics were attributed on the basis of pipe material and years of service. Using calibration values, it is possible to obtain a good comparison between pressures measured at control points and those obtained in the hydraulic verification model. Hydraulic simulation highlighted that, without pressure control, there are extensive urban areas with extremely high pressures (even exceeding 80 m). Figure 10 shows pressure fields considering the different demand patterns.

The PRM first phase provides the number of candidate pipes (n_v) given in Fig. 11 using demand pattern d_3 and varying the H_{PRM} reference pressure in the range between 30 and 70 m.

The graphs in Fig. 12 show the behavior of the OF in the second phase of the PRM. The traces referred to $H_{\max}$ are given considering maximum allowed pressure equal to 60 and 70 m. Varying H_{PRM} (and, consequently, G_v and n_v), we can observe a generalized decreasing behavior of the OF up to $H_{\mathrm{PRM}} = 60$ m.

Table 3 Location and setting of valves in the network

Valve	Pipe	From node	To node	Valve setting		
				d_1	d_2	d_3
1	P24	31	158	51.1	53.9	36.9
2	P31	50	158	35.1	49.0	32.3
3	P34	64	75	25.7	46.6	42.0
4	P47	86	82	38.3	42.9	38.2
5	P48	86	91	40.4	43.3	44.0
6	P82	146	159	25.2	47.2	26.5
7	P83	159	160	43.4	45.6	44.4
8	P84	160	135	28.7	40.7	36.0
9	P100	167	125	52.8	46.0	45.8

Setting final results, we consider $H_{\max} = 70$ m and $H_{\mathrm{PRM}} = 66$ m, corresponding to the minimum value of the OF. The PRM gives a final result of nine pipes for the insertion of valves. In Table 3 and Fig. 13, valves are identified and settled for each demand pattern. At the end of the PRM procedure, no nodes violate the assigned

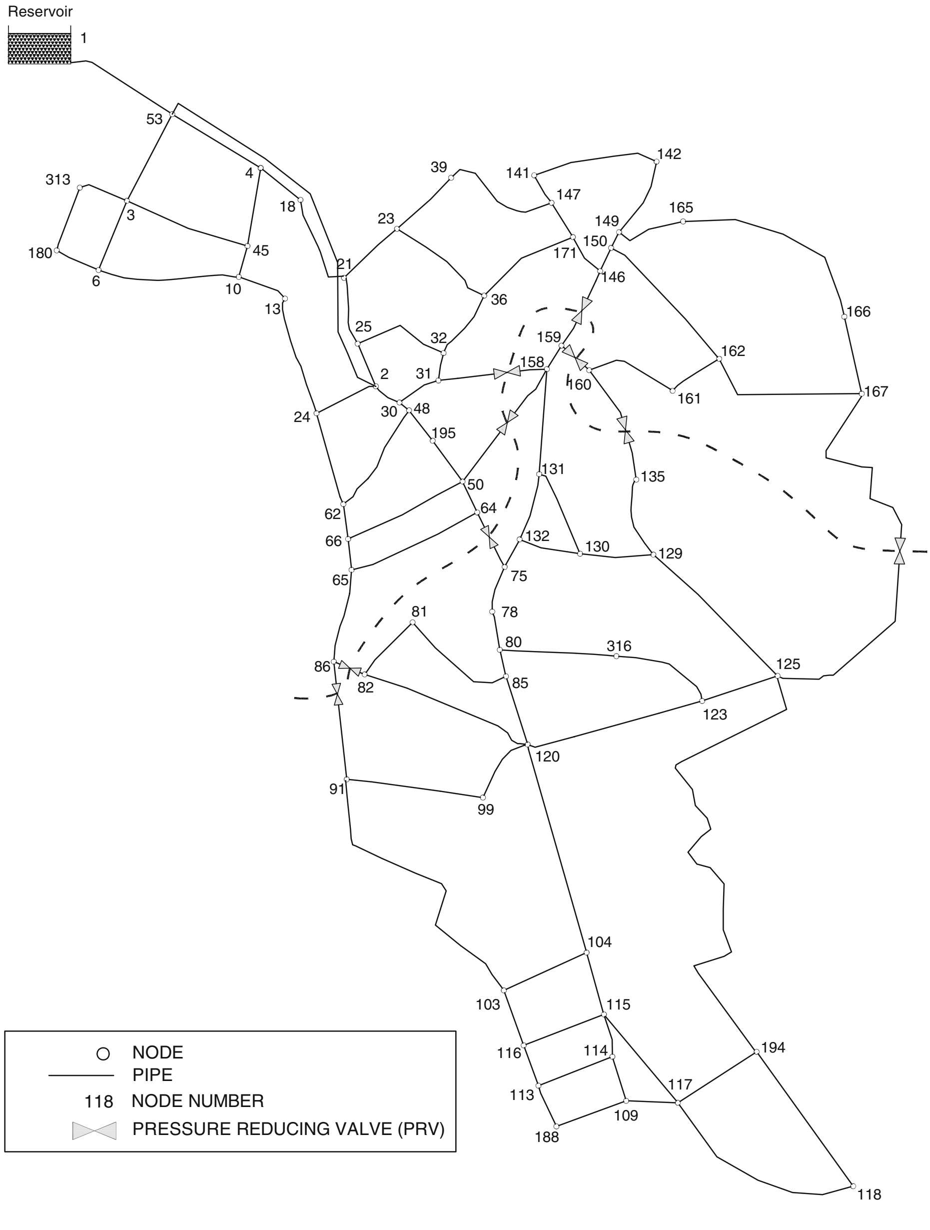

Fig. 13 Valve locations in the network provided by the PRM procedure. *Dashed line* symbolizes the iso-piezometric line corresponding to H_{PRM}

maximum allowed pressure, H_{max}, in the entire network. The time spent in the entire procedure is about 400 s of CPU in a standard PC.

6 Conclusions

In the PRM method, combined procedures are used for optimal location and calibration of valves in water distribution networks. In the first phase, candidate sets for the location of valves are restricted to pipes defined on the basis of hydraulic analysis considering the reference pressure value H_{PRM}. The meta-heuristic Scatter Search routines were used in the second phase to identify the best solution in the location and calibration problems by optimizing a weighted multi-objective function that considers the cost of inserting valves and the penalty for node pressures that exceed the maximum allowable value H_{max}.

Among methods for valve insertion in existing and unstructured networks, the PRM system allows rapid identification with modest computational burdens and controls the network pressure with a limited number of valves. The application of PRM to a reference network and to a real case confirms the potential of the PRM. Furthermore, varying the H_{PRM} reference pressure to determine the candidate pipes location set for valves, easily allows a sensitivity analysis. The OF behavior, when modifying the allowable maximum pressure at nodes, is also compared setting final valve locations.

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