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Nowadays, the implementation of pressure management in District Metered Areas (DMAs) is considered one of the most effective tools for leakage control, particularly in large networks and in systems with deteriorated infrastructures and with high pressure. The goal of the methodology proposed in this paper is to identify the optimal entry points at DMAs, determine the network needs in terms of reinforcement/replacement, and fix both the location and settings of different types of Pressure Reduction Valves (PRVs) for leakage control. This methodology is based on an optimisation model, which is solved by a Simulated Annealing algorithm, and the solutions obtained always fulfil the minimum pressure requirements for the network. The objective function comprises the total cost of the DMAs implementation and the economic benefits that can be achieved by pressure management. Finally, the results for two case studies are presented and discussed.

Keywords: District Metered Areas (DMAs); pressure management; simulated annealing; water loss management

1. Introduction

In the context of Water Distribution System (WDS) operation and management, the leakage control is an important goal, because high rates of leakage can represent significant economic losses (Marques *et al.* 2005, Gomes *et al.* 2011). This evidence has been raised internationally, and in Portugal it is present in a national strategic plan for the water sector, which fixes an upper limit of 20% for the water loss in WDS (PEAASAR II 2007). With the sectorisation of large networks (division in District Metered Areas - DMAs) and the evaluation of the leakage level in each DMA, the leakage location activities can be directed to the worst parts of the system, increasing its efficiency. This concept, first introduced in UK in the early 1980s (WRc 1994), has been applied in many water companies worldwide. However, the identification of the DMAs boundaries and the optimal DMAs entry points is not always easy, and can affect significantly the cost of the DMAs implementation. Furthermore, as this process involves closing the boundary valves, the hydraulic behaviour of the network can change considerably and cause operational problems.

The size of each DMA and the optimal DMA entry points vary from system to system, and depend on the network configuration, the infrastructure condition, the water quality and the financial resources of the water companies. The experience demonstrates that in urban areas the adequate size for a DMA should be between 500 and 3000 service connections, but it can be reduced to 500 to 1000 in deteriorated infrastructures. By no means should it be advisable to have a DMA containing more than 5000 service connections, because it gets too difficult to control water losses (location of new bursts can become extremely demanding). Alternatively, in areas with low density of service connections, the size of a DMA should be fixed in terms of pipe length, because the difficulty to find bursts is more related to the pipe length than to the number of service connections (WRc 1994, MacDonald and Yates 2005, Morrison *et al.* 2007). Each DMA should be supplied by a limited number of pipes in which flow meters are installed (entry points), to measure water imports (if a DMA supplies other DMAs, they also measure water exports), and these are not necessarily definitive because changes in the operating conditions might require a modification to the boundaries. There are many examples of success worldwide on implementation of DMAs (Farley and Trow 2003, MacDonald and Yates 2005, Naveh *et al.*

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2005, Anuvongnukroh *et al*. 2007, Morrison *et al*. 2007, Pilcher *et al*. 2007). Furthermore, several models have been developed to illustrate the cost and economic benefit of DMAs management in practice (WRc 1994, Andersen and Powell 2000, Mckenzie and Langenhoven 2001, Walski *et al*. 2003, Jankovic *et al*. 2004, Loveday and Dixon 2005, Girard and Stewart 2007, Gomes *et al*. 2011).

The specialised literature presents very little work about the optimisation of DMAs design. Tzatchkov *et al*. (2006) present a methodology based on graph theory to obtain the number of independent sectors in WDS, the set of nodes belonging to each sector, the set of disconnected nodes, and the source to node contribution. The algorithms are implemented in a computer AutoCAD-based system. Sempewo *et al*. (2008) proposed a methodology to define zoning schemes for WDS based on the analogy of graph theoretic and graph partitioning principles used in distributed computing to distribute workloads among processors. The zoning schemes can be obtained by balancing length, demand or flow within zones, with the objective of monitoring of unaccounted for water. Although it proved to be an efficient and effective approach for the optimal demarcation of complicated WDS, it was observed that the tool is sensitive to the number of partitions, the topology of the WDS and the partitioning algorithms used. Awad *et al*. (2008, 2009) presented a methodology that can be used to DMAs design and install Pressure Reducing Valves (PVRs) to reduce excessive outlet hydraulic pressure at certain times of the day. This methodology uses Genetic Algorithms to identify the optimal DMAs boundaries and to determine the most advantageous type, location and settings of the PRV. The objective function includes the benefits from pressure reduction on water leakage, pipe burst frequency, pressure-sensitive water consumption, active leakage control effort, energy consumption and customer contacts. More recently, Di Nardo and Di Natale (2011) proposed a design support methodology which helps to identify the flow meters locations and the boundary valves needed to define permanent DMAs. The methodology is based on graph theory, and uses performance indices (energetic, statistical and hydraulic) to compare the level of service from different district layouts. Perelman and Ostfeld (2011) present a tool to divide WDS based on graph theory. The algorithm divides the system into independent sectors according to the flow directions in pipes. According to the authors, the resulted sectoring is generic but can be utilised for different purposes such as water security enhancements by sensor placements at sectors, or efficient isolation of a contaminant intrusion.

Presently, hydraulic models are very important tools to help water companies in defining a strategic plan to WDS management. Considering the needs of the water industry, an innovative methodology is proposed in this paper to help in the network sectorisation and implementation of pressure reduction, for water loss management. The main advantage of this methodology, when compared with others from the literature, is that it simultaneously include in the same study: 1) definition of the most appropriate number of metering stations (DMAs entry points) and their locations, the boundary valves and the pipes to reinforce/replace in order to ensure the maximum velocity and meet the minimum service pressure requirements, 2) adjustment of the service pressure in each DMA according to the pressure at its critical node (within the DMA or downstream DMAs entry points), and 3) planning the investment needed at different times during the project plan. In this context, the implementation of pressure reduction in certain districts of the network can be very important, especially during the night (aimed at reducing water losses through the network). As mentioned, this methodology can also be used to plan the investment needed at different times during the project plan and the total investment can thus be adjusted according to the actual needs and the financial resources of the water company. The economic analysis has been commonly used in the design/rehabilitation of WDS (Alvisi and Franchini 2006, Dandy and Engelhardt 2006, Tricarico *et al*. 2006, Jung *et al*. 2009, Saldarriaga *et al*. 2010).

2. Methodology

Taking into consideration all the pipes from the DMAs boundaries and the hydraulic operation of the WDS, the methodology proposed in this paper uses a hydraulic simulator, written in FORTRAN and previously developed by Sousa (Cunha and Sousa 1999, 2010), and a Simulated Annealing algorithm to identify the most appropriate number of metering stations (DMAs entry points) and their location, the boundary valves, the pipes to reinforce/replace in order to ensure the maximum velocity and meet the minimum service pressure requirements and most appropriated number, location and settings of different types of PRVs for water loss reduction (it was implemented as a computational tool written in FORTRAN and its flowchart can be seen in Figure 1). This methodology assumes that the DMAs boundaries are known (this topic plays an important role in this context, and it depends on the infrastructure condition, different sources of water supply, water quality problems and the financial resources of the water companies), an issue that many times in common practice is solved with the technicians empirical knowledge. Moreover, the water quality problems that can arise from the DMAs

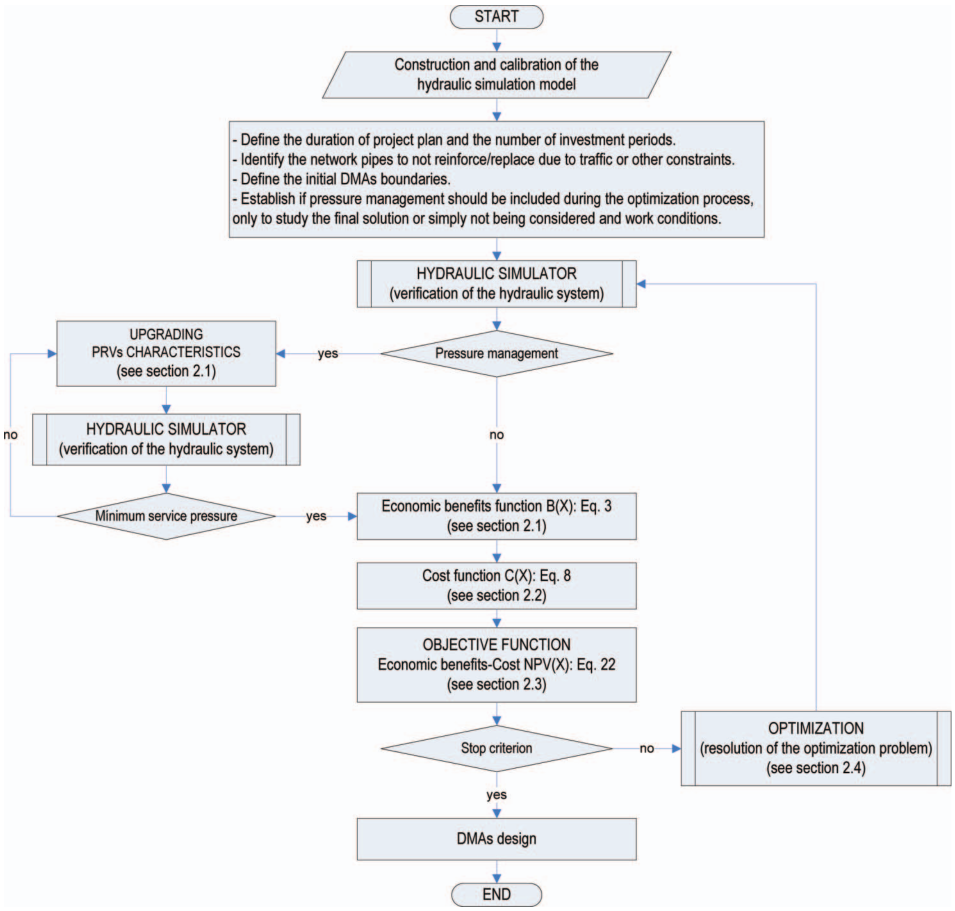

Figure 1. Methodology flowchart.

implementation were not considered and it is assumed that the indirect and operational costs are similar for different solutions and thus can be ignored.

The following steps must be performed before starting the optimisation process (DMAs design):

- Define the duration of the project plan (years) and the number of investment periods.
- Identify the network pipes which are not to reinforce/replace due to traffic or other constraints.
- Identify the initial DMAs boundaries, and, if necessary, the set of permanent DMAs entry points that must be included in the final solution of the problem.
- Establish if pressure management should be included during the entire optimisation process, only for the final solution or simply not being considered. Select the type of PRV to use (fixed-outlet PRV, time-modulated PRV and/or pressure-modulated PRV) and the minimum piezometric head adjustment required so that the PRVs work properly. Finally, define if the type of PRV to be considered during the optimisation process is initially decided by the user or selected automatically according to any initial specific adjustment required for each type of PRV (maximum adjustment of the piezometric head downstream of the PRV for each working period).

During the optimisation process, while the locations of the flow metering stations correspond to DMAs entry points (for any flow direction), the locations and adjustments of the piezometric head downstream of the PRVs are based on two criteria (the location and adjustment of the PRVs occurs from downstream DMAs to upstream DMAs). PRVs should only be located in DMAs entry points where the flow direction is always the same during the project plan (if the flow direction changes during the project plan, these entry points should not have PRV and both DMAs will belong to the same pressure zone). The adjustment of the piezometric head downstream of any type of PRV equals the minimum difference between the service pressure and the minimum pressure required, evaluated at the critical node for all the simulation time steps of that working period. In this context, a critical node corresponds to the node with the lowest pressure located within the DMA or the minimum pressure required at the downstream DMAs entry points.

2.1. *Economic benefits function and pressure management*

This section describes the economic benefits arising from DMAs implementation, including the pressure management at the DMAs entry points, which can produce considerable benefits in terms of water loss reduction throughout the project plan. The present methodology employs a procedure, previously proposed by the authors (Gomes *et al.* 2011), to estimate the economic benefits from pressure management at DMAs entry points – reduction of water production minus the reduction of billed water. However, other economic benefits, like the reduction in pipe burst frequency, active leakage control effort, energy consumption and customer contacts, can also be used as proposed by Awad *et al.* (2009). As a result from the DMAs implementation, the total reduction of water loss volume at the WDS (ΔVL) is given by the difference between the current water loss volume (VL^{Phase1}) and the estimated water loss volume after the DMAs implementation (VL^{Phase2}):

$$\Delta VL = \left(VL^{Phase1} - VL^{Phase2}\right) \tag{1}$$

As pressure is known to influence consumption, it is expected that the total billed water will decrease with the pressure reduction (ΔVR), and this decrease can be estimated by the difference between the actual billed water (VR^{Phase1}) and the estimated billed water after the DMAs implementation (VR^{Phase2}):

$$\Delta VR = \left(VR^{Phase1} - VR^{Phase2}\right) \tag{2}$$

Knowing the duration of each investment period (ny), the annual interest rate (intR), the cost of water production per m^3 (C_p) and the water selling price per m^3 (C_v), it is possible to estimate the direct economic benefits that can be achieved with the DMAs implementation, Equation (3) – economic benefits function B(X):

$$B(X) = \left[C_p \times \Delta VL - \left(C_v - C_p\right) \times \Delta VR\right] \times \left[365 \times \frac{(1 + intR)^{ny} - 1}{intR \times (1 + intR)^{ny}}\right] \tag{3}$$

It is important to be aware that the computed value of B(X) can be negative, representing a cost rather than a net benefit.

For this computational application, it is assumed that the customers' water consumption can be divided into three parts (admitting that the whole consumption is authorised and billed): the pressure-independent consumption, QRC_{indep} (e.g. toilet flushing, roof tanks, washing machines, dishwashers), the pressure-dependent consumption, QRC_{dep} (e.g. shower use, hand washing, watering gardens) and the real losses downstream of the customer meter are also considered as pressure-dependent, QRL_{dep} (important for systems with a high density of metered properties). Moreover, real losses upstream of the customer's meter are not billed and they are regarded as pressure-dependent, $QNRL_{dep}$.

For each instant of the simulation period, the total outflow in each network node (Q_1), after the DMAs implementation, can be estimated by Equation (4) – adjustment of Phase 1 revenue water and non-revenue water to the Phase 2 pressure conditions:

Q varies with P^N :

$$\begin{cases} Q_1 = \left(QRL_{dep,0} + QNRL_{dep,0}\right) \times \left(\frac{P_1}{P_0}\right)^{N1} + QRC_{dep,0} \times \left(\frac{P_1}{P_0}\right)^{N2} + QRC_{indep,0} & \text{if} \quad P_1 > 0 \\ 0 & \text{if} \quad P_1 \leq 0 \end{cases} \tag{4}$$

where: P_0 and P1 are, respectively, the service pressures before and after the DMAs implementation; the exponent N1 expresses the pressure/leakage relationship and the exponent N2 expresses the pressure/consumption relationship (applied solely to the pressure-dependent consumption). Some reference studies concluded that for N1 a value of 1.0 will usually be reasonable (combination of fixed and variable area leaks). Assuming that pressure-dependent consumption varies with pressure in accordance with a square root relationship, the value of N2 should be taken as 0.5 (Lambert 2000, Mckenzie and Langenhoven 2001, Fantozzi and Lambert 2007, Giustolisi *et al.* 2008, Gomes *et al.* 2011).

The pressure reduction after the DMAs implementation can be affected by three factors: 1 – reduction of the number of DMAs entry points; 2 – inevitable degradation of the infrastructure (increasing head loss); and 3 – pressure management by the introduction of PRVs. To reduce the excess of pressure after the DMAs implementation, three types of PRVs are proposed at each DMA entry point: fixed-outlet PRV; time-modulated PRV and pressure-modulated PRV. The type of PRV should be previously decided by the user or selected automatically according to any initial specific adjustment required and the working condition for each type of PRV (see Section 2). For a fixed-outlet PRV there is a single working condition (the head downstream of the PRV is always the same). For a time-modulated PRV there can be several working conditions (for instance, one during the night period – from 0–6 am, and another during the rest of the day). The pressure-modulated PRV is certainly the most efficient system because it constantly adjusts the working conditions to reach the minimum pressure required at the monitoring node (usually the critical node). To summarise, no matter what type of PRV is used, it is necessary to define the most suitable working conditions for that PRV at each DMA entry point. The procedure adopted here determines the adjustment of the piezometric head downstream of the PRV (ΔH_{PRV}), that is, the increase of head loss the PRV must produce to reach the desired working conditions. For each working period of the PRV and each DMA, the adjustment equals the minimum difference between the service pressure (initially the Phase 1 pressure and afterwards the consecutive estimated pressures for Phase 2) and the minimum pressure required, evaluated at the critical node for all the simulation time steps of that working period, Equations (5) to (7).

$$P^{\text{Phase2}}_{\text{service}} \geq P^{\min}_{\text{critical node,s}} \quad \text{for} \quad s = 1, \ldots, S \tag{5}$$

$$\Delta H_{PRV,s} = \min\left(P^{\text{Phase2}}_{\text{critical node,s}} - P^{\min}_{\text{critical node,s}}\right) \text{ for } \quad s = 1, \ldots, S \tag{6}$$

$$\text{If} \begin{cases} H^{\text{upstream}}_{PRV,s} - \left(H^{\text{setting}}_{PRV,s} - \Delta H_{PRV,s}\right) \geq \Delta H_{\min} \\ \quad \text{then } H^{\text{setting}}_{PRV,s} = H^{\text{setting}}_{PRV,s} - \Delta H_{PRV,s} \\ H^{\text{upstream}}_{PRV,s} - \left(H^{\text{setting}}_{PRV,s} - \Delta H_{PRV,s}\right) < \Delta H_{\min} \\ \quad \text{then without PRV} \\ \qquad \text{for } s = 1, \ldots, S \end{cases} \tag{7}$$

where:

$P^{\text{Phase2}}_{\text{service}}$ - Service pressure (m) after the DMAs implementation and pressure management (Phase 2);

$P^{\min}_{\text{critical node,s}}$ - Minimum pressure required (m);

$\Delta H_{PRV,s}$ - Adjustments of the piezometric head downstream of the PRV (m) for each working period s;

$P^{\text{Phase2}}_{\text{critical node,s}}$ - Minimum pressure at critical node (Phase 2), for each working period s;

S - Number of the PRV working periods during the simulation period;

$H^{\text{upstream}}_{PRV,s}$ - Piezometric head upstream of the PRV, for each working period s;

$H^{\text{setting}}_{PRV,s}$ - Piezometric head downstream of the PRV, for each working period s;

$\Delta H_{\min}$ - Minimum adjustment required for the piezometric head downstream of the PRV (m), to work properly.

2.2. *Cost function*

This section describes the total cost of pipe reinforcement/replacement, metering stations (flow meter and chamber), PRVs and penalties for constraint violations, Equation (8) – cost function C(X). The pipe reinforcement/replacement is related to the installation of new pipes parallel to the existing ones or the substitution of existing pipes by new ones with greater capacities, and has two objectives: ensure that the maximum velocity allowed in each pipe of the network is not exceeded; and increase the transport capacity of the network to satisfy the minimum pressure requirements. These costs are computed by multiplying the pipe length by the unit cost for the pipe reinforcement/replacement, which depends on the diameter of the new pipe. The global cost of the metering stations and the PRVs depends on the diameter of the flow meter and the PRV, which in turn was set assuming a maximum velocity of 1.0m/s. The cost of the boundary valves is not considered, because it is supposed that they already exist:

$$\begin{aligned} C(X) = \sum_{p=1}^{NP} \left[C_{\text{pipe},p}(D_p) \times L_p\right] \\ + \sum_{m=1}^{NM} \left[C_{\text{inlet},m}(DF_m) + C_{\text{inlet},m}(DPRV_m)\right] \\ + \sum_{v=1}^{NV} (\text{viol}_v \times \beta_v) \end{aligned} \tag{8}$$

where: NP is the number of pipes; $C_{\text{pipe},p}(D_p)$ is the unit cost for the pipes reinforcement/replacement (€/m); D_p is the diameter of the new pipe (mm); L_p is the pipe length (m); NM is the number of DMAs entry points; $C_{\text{inlet},m}(DF_m)$ is the global cost of each DMA entry point with flow meter and chamber (€/unit); DF_m is the flow meter diameter (mm); $C_{\text{inlet},m}(DPRV_m)$ is the global cost of PRV at each DMA entry point (€/unit); $DPRV_m$ is the PRV diameter (mm); NV is the number of constraints violations; viol_v is the maximum violation for the constraint v; β_v is the unit cost of penalty for violation v (between 1E + 06 and 1E + 08).

This problem includes two types of constraints, commonly used in the design of WDS (Cunha and Sousa 2010):

(i) Hydraulic constraints

Concerning mass conservation law at each junction node in the network (9), nonlinear head-flow relationship describing the flow through the pipe (10), reservoirs water level during the simulation period (11), water level at the end of the simulation period (12), and update of reservoirs levels between successive simulation time steps (13).

$$\sum_{p=1}^{NP} I_t \times Q_{p,t} = QC_{i,t} \quad \forall\, i \in NN \quad \text{and} \quad \forall\, t \in T \tag{9}$$

$$\Delta H_{p,t} = K_p \times Q_{p,t}^{n} \quad \forall\, p \in NP \quad \text{and} \quad \forall\, t \in T \tag{10}$$

$$HR_{max} \geq HR_{r,t} \geq HR_{min} \quad \forall\, r \in NR \quad \text{and} \quad \forall\, t \in T \tag{11}$$

$$HR_{r,24} \geq HR_{r,0} \quad \forall\, r \in NR \tag{12}$$

$$HR_{r,(t+\Delta t)} \geq HR_{r,t} - 3600 \times \frac{QR_{r,t}}{AR_r} \times \Delta t \quad \forall\, r \in NR \quad \text{and} \quad \forall\, t \in T \tag{13}$$

where: I_t is the incidence matrix of the network at instant t; $Q_{p,t}$ is the flow in pipe p at instant t (m^3/s); $QC_{i,t}$ is the demand in the node i at instant t (m^3/s); NN is the number of nodes; T is the simulation period (usually 24 hours, with time step of 1 hour); $\Delta H_{p,t}$ is the head loss in pipe p at instant t (m); K_p and n are the resistance law coefficients (head-flow relationship); HR_{max} and HR_{min} are the maximum and minimum reservoirs water level (m); $HR_{r,t}$ is the water level in reservoir r at instant t (m); $HR_{r,24}$ and $HR_{r,0}$ are the water level in reservoir r, at the end and at the beginning of the simulation period (m); $HR_{r,(t+\Delta t)}$ and $HR_{r,t}$ are the water level in reservoir r in two successive simulation time steps (m); $QR_{r,t}$ is the flow from reservoir r at instant t (m^3/s); AR_r is the reservoir r cross-section (m^2); Δt is the time step (if flows in m^3/s, Δt in hours).

Project constraints

These constraints concern the pressures in the junction nodes (14) and (15), velocities in the pipes (16), minimum diameter in the pipes (17), optimal pipe diameter to reinforcement/replacement (18), the total number of DMA entry points (19), optimal flow meter diameter in the DMA entry point (20), optimal PRV diameter in the DMA entry point (21).

$$P_{max} \geq P_{i,t} \geq P_{min} \quad \forall\, i \in NN \quad \text{and} \quad \forall\, t \in T \tag{14}$$

$$\max(P_{i,t}) - \min(P_{i,t}) \leq FP_{max} \quad \forall\, i \in NN \quad \text{and} \quad \forall\, t \in T \tag{15}$$

$$V_{p,t} \leq V_{max} \quad \forall\, p \in NP \quad \text{and} \quad \forall\, t \in T \tag{16}$$

$$D_p \geq D_{p,min} \quad \forall\, p \in NP \tag{17}$$

$$D_p = \sum_{j=1}^{ND_p} YD_{p,j} \times DC_{p,j} \text{ with } \sum_{j=1}^{ND_p} YD_{p,j} = 1 \quad \forall\, p \in NP \tag{18}$$

$$\text{DMA entry points}_{maximum} \geq \text{DMA entry points} \geq \text{DMA entry points}_{minimum} \tag{19}$$

$$DF_m = \sum_{j=1}^{NDF_m} YDF_{m,j} \times DCF_{m,j} \quad \text{with} \quad \sum_{j=1}^{NDF_m} YDF_{m,j} = 1 \quad \forall\, m \in NM \tag{20}$$

$$DPRV_m = \sum_{j=1}^{NDPRV_m} YDPRV_{m,j} \times DCPRV_{m,j} \quad \text{with} \quad \sum_{j=1}^{NDPRV_m} YDPRV_{m,j} = 1\ \forall\, m \in NM \tag{21}$$

where: P_{max} and P_{min} are the maximum and minimum pressure requirements (m); $P_{i,t}$ is the service pressure in node i at instant t (m); FP_{max} is the maximum pressure variation allowed during the simulation period (m); $V_{p,t}$ is the velocity in the pipe p at instant t (m/s); V_{max} is the maximum velocity allowed (m/s); D_p is the diameter of the new pipe (mm); $D_{p,min}$ is the minimum diameter requirement (mm); ND_p is the number of commercial diameters assigned to pipe p; $YD_{p,j}$ is the binary variables representing the use of a given diameter in pipe p; $DC_{p,1}, DC_{p,2}, \ldots, DC_{p,NDp}$ is the set of commercial diameter for pipe p (mm); DF_m is the flow meter diameter (mm); NDF_m is the number of commercial flow meter diameters assigned to entry point m; $YDF_{m,j}$ is the binary variables representing the use of a given flow meter diameter in entry point m; $DCF_{m,1}, DCF_{m,2}, \ldots, DCF_{m,NDFm}$ is the set of commercial flow meter diameters for entry point m (mm); $DPRV_m$ is the PRV diameter (mm); $NDPRV_m$ is the number of commercial PRV diameters assigned to entry point m; $YDPRV_{m,j}$ is the binary variables representing the use of a given PRV diameter in entry point m; $DCPRV_{m,1}, DCPRV_{m,2}, \ldots, DCPRV_{m,NDPRVm}$ is the set of commercial PRV diameters for entry point m (mm).

2.3. *Objective function or net present value of the project*

When dealing with the DMAs design and/or the pressure management, it is advisable to considerer the degradation of the WDS infrastructures. On the other hand, if the water consumption is expected to increase with time (most common in practice), it may become appropriate to plan the investment to be performed in different moments along the project plan, adjusting the total investment according to the actual needs and the financial resources of the water companies. The DMAs design can be formulated as an optimisation problem. This NP-hard problem is related to the number of DMAs and the total number of DMAs entry points, the pipes to reinforce/replace and the most advantageous type, location and settings for the PRVs. The objective function NPV(X) maximises the net present value of the differences between the economic benefits from pressure management (reduction of water production minus the reduction of billed water) and the total implementation costs (flow meters and chambers, PRVs and pipes reinforcement/replacement), along the duration of the project plan, Equation (22):

$$\text{maximum NPV(X)} = \sum_{i=1}^{n} \frac{B(X)_i - C(X)_i}{(1+\text{intR})^{\pi_i}} \qquad (22)$$

where NPV(X) is the objective function or net present value of the project (€), X is the solution of the Simulated Annealing algorithm (see section 2.4), n is the number of investment periods along the duration of the project plan, $B(X)_i$ is the total economic benefits during the investment period i and updated to the beginning of this investment period (€) (Section 2.1), $C(X)_i$ is the total investment costs at the beginning of the investment period i (€) (Section 2.2), π_i is the time from the beginning of the project to the investment period i (years), and intR is the annual interest rate (%).

2.4. *Simulated Annealing algorithm*

Simulated Annealing is an optimisation method based on the analogy with the physical annealing process (Metropolis *et al.* 1953), and has been applied, quite successfully, in many engineering optimisation problems (Cunha and Sousa 1999, Varela and Ribeiro 2001, Blum and Roli 2003). In the annealing process the temperature is increased to give mobility to the molecules, and, after a slow cooling, it is expected that those molecules will form a crystalline structure. In each step of the algorithm, a change of configuration is produced, and then its energy is evaluated. The new configuration is chosen at random in the neighbourhood of the current configuration and it is accepted or not, according to the Metropolis criterion. If it is accepted, this new configuration will be used as the current configuration for the next step. If not, the original current configuration will continue to play this role. If the system is properly cooled, molecules will reach the minimum energy state, which corresponds to an ordered crystalline configuration.

The implementation of the Simulated Annealing algorithm can be described as follows:

Step 1: At the initial temperature (T_0), the algorithm starts by generating an initial solution (X_0) – all the pipes of the DMAs boundaries are replaced and all the other pipes in the network are reinforced at the beginning of the project plan (the biggest diameter is assigned to every new pipe in the network). Moreover, every pipe entering a DMA is an entry point (there are no boundary valves). The location and adjustment of different PRVs will be defined later, when the hydraulic behaviour is analysed.

Step 2: At temperature T_{k+1} the number of solutions generated is L_{k+1}, which varies according to the percentage of solutions accepted at the last temperature (Pa_k). Each new solution (X_z) is generated from the current solution (X_{z-1}) by randomly applying one of the following procedures (the connection between all the network nodes is always guaranteed): 1) select a DMA and reduce/increase its number of entry points; 2) select a DMA and change one of its entry points; or 3) select one of the investment periods and change a pipe diameter (in 60% of the cases the diameter is reduced – this procedure allows to improve the performance of the algorithm and accelerates its convergence). When a pipe diameter is reduced below the minimum diameter required, this pipe is no longer considered during the project plan. Conversely, when a pipe diameter is greater than or equal to the minimum required, for a certain investment period, it is assumed that it will remain until the end of the project plan. Whenever a DMA boundary is selected to close (to reduce the number of DMAs entry points), the DMA boundary pipes will be sequentially analyzed until one connection between both DMAs is accepted (to obtain similar hydraulic behaviour and/or to assure the connection between all the network nodes). On the other hand, when a DMA boundary pipe is selected to open (add a new metering station), another DMA boundary pipe is selected to close, preserving the same number of the DMAs entry points.

Step 3: The hydraulic simulator evaluates the hydraulic performance of the system and defines the location and adjustment of the PRVs (using the conditions defined in section 2 and the procedures describe in Section 2.1). Afterwards, using Equations (3) and (8), the total economic benefits and costs for each investment period are estimated, and Equation (22) evaluates the net present value of the project (NPV) for the new solution. The new solution is accepted or not, according to the Metropolis criterion. If it is accepted, this solution will be used as the starting point for the next step. If not, the original current solution will be used.

Step 4: After five temperatures without accepting any modification between DMAs entry points, the search is focused only on applying procedure 3) for the last accepted solution, because the probability to accept another configuration for the DMAs entry points gets too low.

Step 5: The algorithm ends if the stop criterion is reached, that is: for two successive temperatures the number of solutions accepted (Pa_k) remains lower than 5% and the difference between the averages of the project net present value between two successive temperatures is 1.0% (ε) or lower. Table 1 shows the cooling scheme adopted for the Simulated Annealing algorithm.

To test the robustness of this cooling scheme two procedures were used for several case studies: 1) using different initial solutions; 2) take final solutions obtained from procedure 1 and use them as initial solutions for the DMAs design. Although the results have been satisfactory, it is not possible to ensure that the best solution corresponds to the global optimal solution for each problem (this problem belongs to the class NP-hard).

3. Case study

3.1. *Case study I (small network)*

The effort of analysis and monitoring of the WDS can be effectively reduced when the network is divided in permanent or temporary DMAs. The methodology proposed in this paper was used to estimate the net present value of the DMAs implementation and to define a strategic plan to WDS management along a project plan, for a hypothetical case study (see Figure 2). The network is gravity fed by one single reservoir (the reservoir elevation is 85 m) and has 25 km of pipes. The network average flow is 300 m^3/h and the consumption daily pattern used to perform dynamic simulations is shown in Figure 2. At the beginning of the project plan, the minimum and maximum service pressures were 34.41 m (node 8) and 59.66 m (node 16), respectively. However, the minimum pressure required for whole life of the project plan is 18.37 m. Tables 2 and 3 show the physical characteristics of the network and the average total outflow (consumption and losses), number of inhabitants and service connections assigned to each node of the network (non-domestic customers were not considered). Table 4 shows the suitable DMAs boundaries for the WDS. The Hazen-Williams (HW) formula was used to evaluate the head losses.

For the present case study, it is intended to identify the optimal single inlet at each DMA, the network needs in terms of reinforcement/replacement and/or most advantageous type, location and setting of PRVs, for the duration of the project plan. This study considered 20 years for the project life period, divided in two equal investment periods. Moreover, it was assumed that the consumption increases 1.25% per year and the infrastructure decay rate is 1.0% per year (reduction of the Hazen-Williams coefficients). To estimate the net present value of the project for different solutions, an annual interest rate of 5% was used.

It was assumed that any pipe of the DMAs boundaries could be replaced or closed and all the other pipes in the network could be reinforced. Two materials were used to reinforce/replace the pipes: high density polyethylene (HDPE) for diameters below 315 mm and ductile iron (DI) for larger diameters. The costs of the network reinforcement and

Table 1. Cooling scheme for the Simulated Annealing algorithm.

Initial configuration	$X_0 = \{D_1, D_2, \ldots, D_{NP}\} = D_{max}$;where: NP number of network pipes
Initial temperature	$T_0 = -\left(\frac{0.10 \times NPV(X_0)}{\ln(Pa_0)}\right)$; where : $Pa_0 = 80\%$
Number of transitions at each temperature	if $Pa_k > 80\%$ then $T_{k+1} = 0.50 \times T_k$ and $L_{k+1} = 20 \times NP$
	if $50\% < Pa_k \leq 80\%$ then $T_{k+1} = 0.75 \times T_k$ and $L_{k+1} = 50 \times NP$
	if $20\% < Pa_k \leq 50\%$ then $T_{k+1} = 0.90 \times T_k$ and $L_{k+1} = 75 \times NP$
	if $Pa_k \leq 20\%$ then $T_{k+1} = 0.95 \times T_k$ and $L_{k+1} = 75 \times NP$
Stop criterion	$Pa_k < 5\%$
	$\varepsilon \leq 1.0\%$
	with: $\varepsilon = \frac{\lvert NPV_{average,k} - NPV_{average,k+1}\rvert}{NPV_{average,k+1}}$

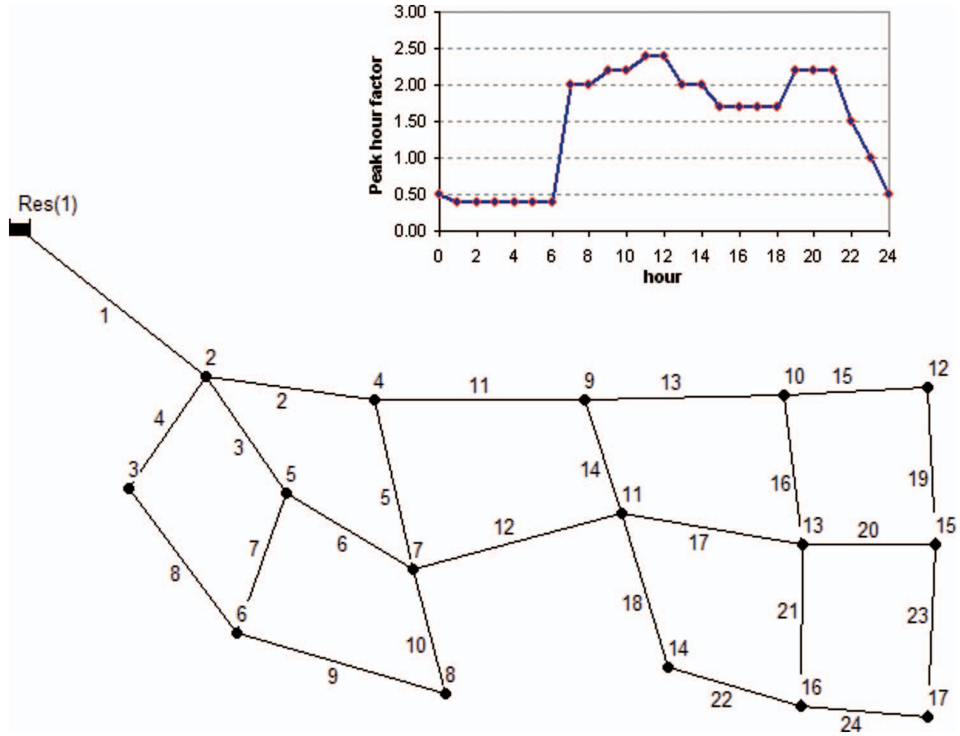

Figure 2. Network scheme and consumption daily pattern.

replacement are related to the pipe diameter and, in this study, were considered equal (see Table 5).

The cost of the DMAs entry points and PRV are given by the diameter of the flow meter (one flow meter and one PRV at each DMA entry point), which are fixed assuming a 1.0 m/s velocity for the maximum flow (see Table 5). The minimum and maximum pressure requirements were 18.37 m and 60.0 m, respectively, and the maximum pressure fluctuation was 30.0 m. In each pipe, according to the Portuguese legislation, the maximum velocity is obtained by Equation (23), where D is the internal diameter of the pipe (mm):

$$V_{max} = 0.127 \times D^{0.4} (m/s) \qquad (23)$$

The benefits were estimated by using reference data reported in the literature (see Table 6) (WRc 1994). The production cost and selling price of water were taken as 0.50 €/m^3 and 1.75 €/m^3, respectively.

Nowadays, water loss management techniques require the installation of flow meters and, if advantageous, PRVs in strategic points of the WDS. Considering the DMAs boundaries for the WDS (see Table 4), the study intends to identify the most suitable entry point for each DMA and the most advantageous type, location and setting of the PRVs. Five scenarios were considered using fixed-outlet PRV (see Table 7) – the minimum adjustment required for the piezometric head downstream of the PRV was set equal to 3.0m: at scenarios 1 and 2, a single DMA entry point was fixed without active PRV (boundary pipes 11 and 12, respectively); in scenarios 3 and 4, the installation of fixed-outlet PRV was considered after the DMAs implementation (using the final solution from scenarios 1 and 2, respectively); to conclude, in scenario 5, the most suitable DMAs entry points were identified, and a fixed-outlet PRV was installed at each DMA entry point. Table 8 and Figure 3 show the network topology for scenario 5.

By solving scenarios 1 and 2, it was possible to conclude that the pipe boundary 12 is better than the pipe boundary 11 to establish the connection between both DMA. While in scenario 1 the network reinforcement was necessary to ensure the minimum pressure requirement at the critical node, in scenario 2 it was no longer necessary. These results show that the network reinforcement is quite related with the DMAs design and the cost of the flow meters depends on the flow increase along the duration of the project plan. The benefits are related with the magnitude of the pressure reduction, after the DMAs implementation. For scenarios 3 and 4, the benefits from pressure management were estimated after the DMAs implementation, and, as expected, for the whole duration of the project plan, when pressure management is implemented the

Table 2. Pipes characteristics (at beginning of the project plan).

ID Pipes	Upstream node	Downstream node	Length (m)	Diameter (mm)	Flow distribution coefficient	HW
1	Res(1)	2	2,000	500.0	0	125
2	2	4	1,000	350.0	1	125
3	2	5	1,000	350.0	1	125
4	2	3	1,000	213.2	1	130
5	4	7	1,000	350.0	1	125
6	5	7	1,000	268.6	1	130
7	5	6	1,000	170.6	1	130
8	3	6	1,000	170.6	1	130
9	6	8	1,000	170.6	1	130
10	7	8	1,000	93.8	1	130
11	4	9	1,000	268.6	0	130
12	7	11	1,000	350.0	1	125
13	9	10	1,000	170.6	1	130
14	9	11	1,000	213.2	1	130
15	10	12	1,000	119.4	1	130
16	10	13	1,000	136.4	1	130
17	11	13	1,000	268.6	1	130
18	11	14	1,000	213.2	1	130
19	12	15	1,000	119.4	1	130
20	13	15	1,000	213.2	1	130
21	13	16	1,000	136.4	1	130
22	14	16	1,000	170.6	1	130
23	15	17	1,000	119.4	1	130
24	16	17	1,000	119.4	1	130

Table 3. Nodes characteristics (during the project plan).

ID Nodes	Elevation (m)	Average outflow (l/s)	Inhabitants	Service connections
Res(1)	85	–	–	–
2	42	5.682	2,455	409
3	41	3.788	1,636	273
4	35	3.788	1,636	273
5	38	5.682	2,455	409
6	39	5.682	2,455	409
7	35	7.576	3,272	545
8	45	3.788	1,636	273
9	30	3.788	1,636	273
10	27	5.682	2,455	409
11	30	7.576	3,272	545
12	30	3.788	1,636	273
13	28	7.576	3,274	545
14	28	3.788	1,636	273
15	31	5.682	2,455	409
16	25	5.682	2,455	409
17	35	3.788	1,636	273

Table 4. DMAs boundaries.

Network topology	DMAs boundaries (pipes)	Total service connections (unit)	Total inhabitants
DMA1	11 - 12	3,409	20,455
DMA2	1 - 11 - 12	2,591	15,545

benefits increase. Finally, in scenario 5, a combination of scenarios 1 to 4 was considered, and the net present value of the project was estimated. Through scenario 5 it was possible to observe that a minor reinforcement of the network can produce a considerable increase of the economic benefit.

For the second investment period, in scenarios 3 to 5, there is no PRV in pipe boundary 12. This results from a PRV operation constraint that implies a minimum head loss, and in this case the adjustment for the piezometric head downstream of that PRV would be lower than the value considered (3.0 m).

The algorithm performance for scenario 5 is shown in Table 9. First, the initial solution was changed and then the number of the DMAs entry points was reduced. Still at high temperatures, the number of exchanges between DMAs entry points was intensified. Along the search, for each new solution, the net present value of the project is estimated and used to direct the search to the next solution. When the temperature "drops", the number of DMAs entry points exchanges was reduced, and then the search is restricted to the network reinforcement/replacement and the PRVs settings. Using the initial net present value of the project as reference (total cost and benefit), in each solution the economic benefit from pressure management does not observe significant changes. On the other hand, the total cost was significantly reduced, because the initial solution has the maximum cost (reinforce/replace all the pipes in

Table 5. Unit cost of the pipes to reinforce/replace, DMAs entry points and PRVs.

Pipe material	Commercial diameter (mm)	HW	Unit cost (€/m)	Commercial diameter (mm)	Unit cost (€) DMAs entry points (flow meter and chamber)	Unit cost (€) PRVs (different types)
Unit cost of the pipes to reinforce/replace						
HDPE	63	130	30.24	50	3,983.69	1,888.06
	75	130	31.03	65	4,181.66	1,964.66
	90	130	33.25	80	4,218.44	2,156.11
	110	130	36.79	100	4,557.29	2,253.31
	125	130	39.77	125	5,057.35	2,709.86
	140	130	43.25	150	5,616.78	2,851.26
	160	130	49.04	200	7,521.79	3,891.03
	200	130	62.38	250	10,741.18	5,702.51
	250	130	82.55	300	15,032.65	8,191.46
	315	130	114.30	350	20,281.64	10,014.71
DI	350	125	174.01	400	27,589.12	15,413.86
	400	125	200.37	450	33,820.41	15,413.86
	500	125	260.82	500	40,828.75	26,120.77
	600	125	347.11	600	53,610.90	31,346.09
	700	125	447.44	700	66,497.40	55,885.11

the network with the maximum diameter). Table 10 shows the optimal solution, which corresponds to the lowest cost solution (last solution), and the greatest benefit solution (initial solution). It is worth to note that, in this particular case, the best solution obtained by the cost-benefit analysis was the lowest cost solution.

After the DMAs implementation (due to the reduced number of DMAs entry points, network reinforcement/replacement, pressure management, consumption increase and infrastructural decay), the minimum service pressure may not be the same as before, and the critical node can also change. On the other hand, the maximum service pressure may also change during the minimum night flow period. Table 8 shows the critical nodes and the minimum and maximum service pressures for scenario 5 (in this case, the critical node remained the same during the day and night periods and along the project plan).

To check the robustness of the methodology in terms of the solutions produced, three procedures were used: 1 – start with the same initial solution for different searches; 2 – use different initial solutions; and 3 – take as initial solutions parts of the final solutions obtained with procedures 1 or 2. As previously mentioned, this optimisation problem is NP-hard, but the results showed that the methodology here presented produces high quality solutions. However, it is not possible to ensure that it produced the global optimal solution. In most of the solutions obtained (50 solutions for each of the different procedures presented), the differences are not significant and are related to minor adjustments in the network reinforcement/replacement.

Table 6. Reference parameters (WRc 1994).

Losses downstream of the delivery point at 50m	0.5	l/service connection/h
Minimum domestic night flow pressure-independent	8	l/inhabitant/h
Minimum domestic night flow pressure-dependent	2	l/inhabitant/h
Percentage of active population	6	%
Exponent of the losses-pressure relationship: N1	1.0	–
Exponent of the consumption-pressure relationship: N2	0.5	–

It is widely known that the total economic benefit is related to pressure management, and that different types of PRVs can be used. Tables 11 to 13 show the total costs and economic benefits from the DMAs implementation using different types of PRV at the DMAs entry points: fixed-outlet PRV, time-modulated PRV and pressure-modulated PRV. For a fixed-outlet PRV, the adjustment to the piezometric head downstream of the PRV is obtained as the difference between the service pressure at the critical node and its minimum pressure required, evaluated during the period of maximum consumption (one single working condition). For a time-modulated PRV, the adjustments to the piezometric head downstream of the PRV

Table 7. A single DMA entry point (FM - flow meter; PRV - fixed-outlet PRV).

Investment period		DMA entry point	Total cost of reinforce/replace	Total cost of flow meter and PRV	Total economic benefit	Net present value of the project
scenario 1	0–10	1 (FM) and 11 (FM)	−288,310€	−54,102€	56,905€	–230,797€
	10–20	1 (FM) and 11 (FM)	0	−7,008€	96,126€	
scenario 2	0–10	1 (FM) and 12 (FM)	0	−54,102€	53,338€	50,494€
	10–20	1 (FM) and 12 (FM)	0	−7,008€	90,502€	
scenario 3	0–10	1 (FM + PRV) and 11 (FM)	−288,310€	−69,516€	722,616€	419,501€
	10–20	1 (FM) and 11 (FM)	0	−7,008€	96,126€	
scenario 4	0–10	1 (FM + PRV) and 12 (FM)	0	−69,516€	781,942€	763,684€
	10–20	1 (FM) and 12 (FM)	0	−7,008€	90,502€	
scenario 5	0–10	1 (FM + PRV) and 12 (FM + PRV)	−259,230€	−79,531€	961,913€	1,055,141€
	10–20	1 (FM + PRV) and 12 (FM)	0	0	703,664€	

Table 8. Network topology after the DMAs implementation (scenario 5).

	0 − 10		10 − 20	
Scenario 5	PRV (pipe 1)	PRV (pipe 12)	PRV (pipe 1)	PRV (pipe 12)
Network reinforcement		17 (250mm)		
Network reinforcement		20 (315mm)		
Network reinforcement		23 (200mm)		
DMA entry point	1 (450mm)	12 (350mm)		
Total cost of reinforce/replace[a]	−259,230 €		0	
Total cost of flow meter and PRV[b]	−79,531 €		0	
Total economic benefit[c]	961,913 €		703,664 €	
Net present value of the project[d]	1,055,141 €			
Minimum adjustment of the PRV (m)	13.26	3.64	8.59	
Minimum service pressure (m)	18.37	18.37	18.37	18.41
Critical node	8	17	8	17
Maximum service pressure (m)	32.88	30.89	35.36	45.05
Critical node	4	16	4	16

[a]First term from equation (8);
[b]Second term from equation (8);
[c]Obtained from equation (3);
[d]Obtained from equation (22).

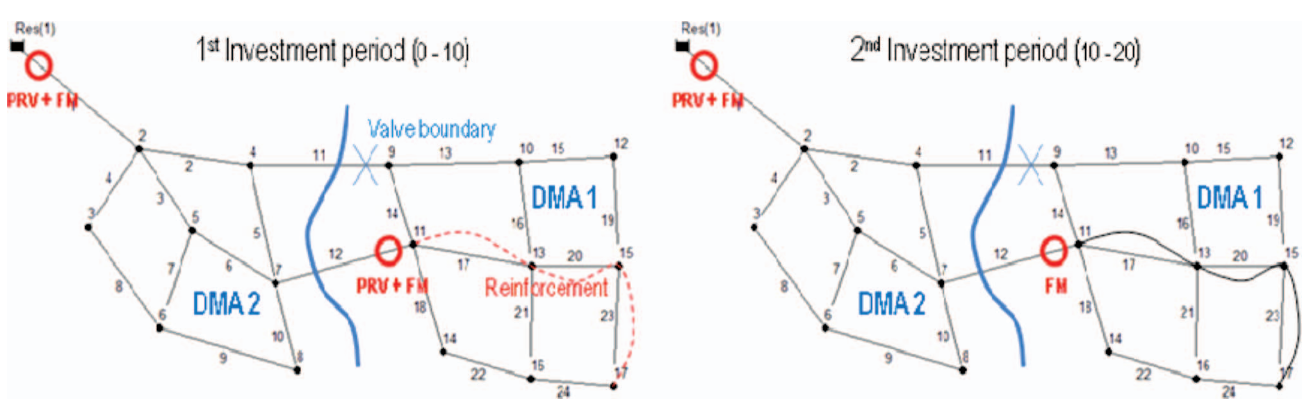

Figure 3. DMAs implementation, for the duration of the project plan (scenario 5).

are determined in such a way that, for each working period (there are two working conditions, one during the night period – from 0–6 am, and another during the rest of the day), the pressure at the critical node just fulfils its minimum pressure required. The procedure is similar for the pressure-modulated PRV. The main

Table 9. Algorithm performance for scenario 5 (Runtime: 3h 56min).

				New solutions				
					Exchange pipe diameter		Exchange DMA entry points	
Step	Temperature	NPV average	NPV optimal	Total	Accepted	Rejected	Accepted	Rejected
1	76,390,228	−8,439,467	−7,979,669	12	12	0	0	0
2	26,736,579	−7,202,651	−1,294,711	480	473	0	7	0
3	9,357,803	−3,234,501	−210,689	480	450	18	12	0
4	3,275,231	−1,439,299	191,400	480	455	15	8	2
5	1,146,331	−173,221	630,789	480	461	10	1	8
6	401,216	268,660	630,789	480	451	18	0	11
7	140,426	328,637	630,789	480	440	33	0	7
8	49,149	653,464	894,006	480	322	140	0	18
9	36,862	758,288	979,783	1,200	733	430	0	37
10	27,646	710,646	979,783	1,200	729	471	0	0
11	20,735	794,867	979,783	1,200	601	599	0	0
12	15,551	829,373	1,010,492	1,200	430	770	0	0
13	13,996	853,765	1,010,492	1,800	597	1,203	0	0
14	12,596	917,958	1,016,919	1,800	481	1,319	0	0
...	...	...	...	...	...	...	...	...
23	7,125	973,357	1,055,141	1,800	146	1,654	0	0
24	6,769	991,453	1,055,141	1,800	98	1,702	0	0

difference is that the adjustments to the piezometric head downstream of the PRV must be calculated for all the time steps of the simulation period. The simulation period considered here was 24 hours with an 1 hour time step, and so there can be 24 different working conditions. As the pressure-modulated system exploits the pressure to its limit (for each time step, there is always one node reaching its minimum pressure required), the benefits get maximised.

Table 10. Comparative analysis (scenario 5).

Option	Total costs	Benefit	Net present value of the project
Lowest cost	− **338,761€**	1,393,902€	1,055,141€
Greatest benefit	−10,717,761€	**1,749,511€**	−8,968,250€
Cost-benefits analysis	−338,761€	1,393,902€	**1,055,141€**

3.2. Case study II (large network)

The adaptation of the WDS described by Arulraj and Rao (1995) was used to evaluate the performance of the proposed methodology. The system can be described as follows: 1) the average flow at the network entry point is 383.40 m^3/h (using the consumption daily pattern presented in case study I); 2) the network is approximately 26.5 km long and is gravity-fed from one reservoir (node 81); 3) the minimum and maximum service pressures are 26.23 m (node 79) and 52.69 m (node 1), respectively; and 4) the minimum and maximum service pressures required are 18.37 m and 60.00 m, respectively. Using the initial DMAs boundaries and a single entry point DMAs, the purpose of this study is to identify the most advantageous location of the DMAs entry points, boundary valves and the network needs in terms of pipe reinforcement/replacement, for the duration of the project plan. In addition, two options are made: without PRVs and including the pressure management during the optimisation process. This study considered a 20 years project plan (two investment periods of 10 years each) and the minimum adjustment required for the piezometric head downstream of the PRV was set equal to 3.0 m (fixed-outlet PRV is proposed). Moreover, it was assumed that the consumption increases 1.25% per year and the infrastructure decay rate is 1.0% per year (reduction of the Hazen-Williams coefficients). To estimate the net present value of the project for different solutions, an annual interest rate of 5% was used.

For this case study, the location of metering station and boundary valves established three DMAs (see Figure 4), that correspond to three different pressure zones when pressure management is included in the optimisation process (see Figure 5). The DMA1 and DMA2 are connected to DMA3, and the DMA3 is connected to the reservoir. In the 1st investment period, the minimum adjustments for the piezometric head downstream of the fixed-outlet PRV at the DMA entry points are: 7.240 m (DMA1), 3.085 m (DMA2) and 7.828 m (DMA3); and in the 2nd investment period

Table 11. Influence of different types of PRV on the project net present value.

Type of PRV		DMA entry point	Reduction		Total cost of reinforce and replace	Total cost of flow meter and PRV	Total benefit	Net present value of the project
			VL + VR	VR				
Without	0–10	1 (FM) 12 (FM)	0.43%	0.02%	0	−54,102€	53,338€	50,494€
	10–20	1 (FM) 12 (FM)	0.65%	0.03%	0	−7,008€	90,502€	
Fixed-outlet	0–10	1 (FM + PRV) 12 (FM + PRV)	8.43%	0.69%	−259,230€	−79,531€	961,913€	1,055,141€
	10–20	1 (FM + PRV) 12 (FM)	5.35%	0.35%	0	0	703,664€	
Time-modulated	0–10	1 (FM + PRV) 12 (FM + PRV)	8.88%	0.81%	−259,230€	−79,531€	991,107€	1,133,117€
	10–20	1 (FM + PRV) 12 (FM)	6.20%	0.51%	0	0	783,124€	
Pressure-modulated	0–10	1 (FM + PRV) 12 (FM + PRV)	9.27%	0.81%	−259,230€	−79,531€	1,044,102€	1,257,567€
	10–20	1 (FM + PRV) 12 (FM)	6.99%	0.53%	0	0	899,517€	

FM: flow meter; PRV: fixed-outlet PRV; VL: daily water losses; VR: daily billed water

Table 12. Adjustment of the piezometric head downstream of the PRVs (investment period 0 − 10).

	Investment period (0 − 10)											
	Fixed-outlet PRV				Time-modulated PRV				Pressure-modulated PRV			
	VRP (pipe 1)		VRP (pipe 12)		VRP (pipe 1)		VRP (pipe 12)		VRP (pipe 1)		VRP (pipe 12)	
Hours	Upstream (m)	Setting (m)	Upstream (m)	Setting (m)	Upstream (m)	Setting (m)	Upstream (m)	Setting (m)	Upstream (m)	Setting (m)	Upstream (m)	Setting (m)
1	84.937	67.915	67.790	55.920	84.947	**63.435**	63.326	**53.403**	84.947	**63.435**	63.326	**53.403**
2	84.937	67.915	67.790	55.920	84.947	**63.435**	63.326	**53.403**	84.947	**63.435**	63.326	**53.403**
3	84.937	67.915	67.790	55.920	84.947	**63.435**	63.326	**53.403**	84.947	**63.435**	63.326	**53.403**
4	84.937	67.915	67.790	55.920	84.947	**63.435**	63.326	**53.403**	84.947	**63.435**	63.326	**53.403**
5	84.937	67.915	67.790	55.920	84.947	**63.435**	63.326	**53.403**	84.947	**63.435**	63.326	**53.403**
6	84.937	67.915	67.790	55.920	84.947	**63.435**	63.326	**53.403**	84.947	**63.435**	63.326	**53.403**
7	82.354	67.915	62.150	55.920	82.357	67.910	62.151	55.918	82.375	**66.491**	60.761	**55.115**
8	82.354	67.915	62.150	55.920	82.357	67.910	62.151	55.918	82.375	**66.491**	60.761	**55.115**
9	81.791	67.915	60.911	55.920	81.795	67.910	60.913	55.918	81.805	**67.169**	60.188	**55.498**
10	81.791	67.915	60.911	55.920	81.795	67.910	60.913	55.918	81.805	**67.169**	60.188	**55.498**
11	81.178	**67.915**	59.558	**55.920**	81.182	**67.910**	59.561	**55.918**	81.182	**67.910**	59.561	**55.918**
12	81.178	**67.915**	59.558	**55.920**	81.182	**67.910**	59.561	**55.918**	81.182	**67.910**	59.561	**55.918**
13	82.354	67.915	62.150	55.920	82.357	67.910	62.151	55.918	82.375	**66.491**	60.761	**55.115**
14	82.354	67.915	62.150	55.920	82.357	67.910	62.151	55.918	82.375	**66.491**	60.761	**55.115**
15	83.101	67.915	63.792	55.920	83.104	67.910	63.792	55.918	83.128	**65.594**	61.517	**54.619**
16	83.101	67.915	63.792	55.920	83.104	67.910	63.792	55.918	83.128	**65.594**	61.517	**54.619**
17	83.101	67.915	63.792	55.920	83.104	67.910	63.792	55.918	83.128	**65.594**	61.517	**54.619**
18	83.101	67.915	63.792	55.920	83.104	67.910	63.792	55.918	83.128	**65.594**	61.517	**54.619**
19	81.791	67.915	60.911	55.920	81.795	67.910	60.913	55.918	81.805	**67.169**	60.188	**55.498**
20	81.791	67.915	60.911	55.920	81.795	67.910	60.913	55.918	81.805	**67.169**	60.188	**55.498**
21	81.791	67.915	60.911	55.920	81.795	67.910	60.913	55.918	81.805	**67.169**	60.188	**55.498**
22	83.534	67.915	64.741	55.920	83.536	67.910	64.741	55.918	83.563	**65.077**	61.953	**54.326**
23	84.382	67.915	66.595	55.920	84.384	67.910	66.593	55.918	84.408	**64.082**	62.805	**53.760**
24	84.882	67.915	67.674	55.920	84.883	67.910	67.671	55.918	84.895	**63.497**	63.278	**53.437**

Table 13. Adjustment of the piezometric head downstream of the PRVs (investment period 10 − 20).

	Investment period (10 − 20)											
	Fixed-outlet PRV				Time-modulated PRV				Pressure-modulated PRV			
	VRP (pipe 1)		VRP (pipe 12)		VRP (pipe 1)		VRP (pipe 12)		VRP (pipe 1)		VRP (pipe 12)	
Hours	Upstream (m)	Setting (m)	Upstream (m)	Setting (m)	Upstream (m)	Setting (m)	Upstream (m)	Setting (m)	Upstream (m)	Setting (m)	Upstream (m)	Setting (m)
1	84.862	70.457	—	—	84.898	**63.487**	—	—	84.898	**63.487**	—	—
2	84.862	70.457	—	—	84.898	**63.487**	—	—	84.898	**63.487**	—	—
3	84.862	70.457	—	—	84.898	**63.487**	—	—	84.898	**63.487**	—	—
4	84.862	70.457	—	—	84.898	**63.487**	—	—	84.898	**63.487**	—	—
5	84.862	70.457	—	—	84.898	**63.487**	—	—	84.898	**63.487**	—	—
6	84.862	70.457	—	—	84.898	**63.487**	—	—	84.898	**63.487**	—	—
7	80.831	70.457	—	—	80.837	70.439	—	—	80.891	**68.252**	—	—
8	80.831	70.457	—	—	80.837	70.439	—	—	80.891	**68.252**	—	—
9	79.977	70.457	—	—	79.983	70.439	—	—	80.013	**69.297**	—	—
10	79.977	70.457	—	—	79.983	70.439	—	—	80.013	**69.297**	—	—
11	79.048	**70.457**	—	—	79.055	**70.439**	—	—	79.055	**70.439**	—	—
12	79.048	**70.457**	—	—	79.055	**70.439**	—	—	79.055	**70.439**	—	—
13	80.831	70.457	—	—	80.837	70.439	—	—	80.891	**68.252**	—	—
14	80.831	70.457	—	—	80.837	70.439	—	—	80.891	**68.252**	—	—
15	81.972	70.457	—	—	81.977	70.439	—	—	82.053	**66.867**	—	—
16	81.972	70.457	—	—	81.977	70.439	—	—	82.053	**66.867**	—	—
17	81.972	70.457	—	—	81.977	70.439	—	—	82.053	**66.867**	—	—
18	81.972	70.457	—	—	81.977	70.439	—	—	82.053	**66.867**	—	—
19	79.977	70.457	—	—	79.983	70.439	—	—	80.013	**69.297**	—	—
20	79.977	70.457	—	—	79.983	70.439	—	—	80.013	**69.297**	—	—
21	79.977	70.457	—	—	79.983	70.439	—	—	80.013	**69.297**	—	—
22	82.637	70.457	—	—	82.642	70.439	—	—	82.725	**66.066**	—	—
23	83.959	70.457	—	—	83.963	70.439	—	—	84.040	**64.501**	—	—
24	84.767	70.457	—	—	84.769	70.439	—	—	84.813	**63.590**	—	—

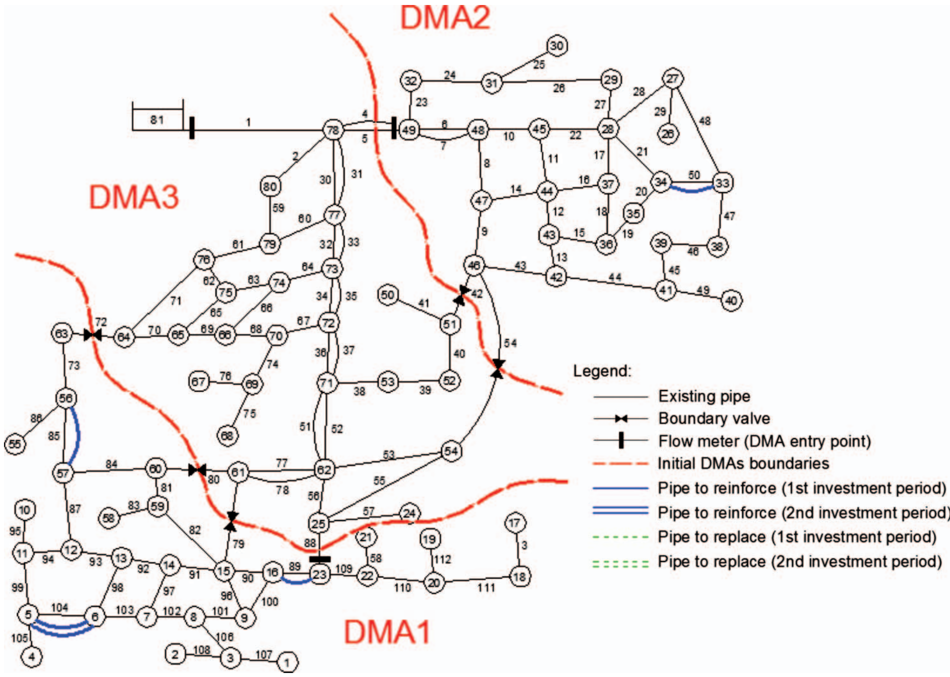

Figure 4. DMAs implementation, for the duration of the project plan (without PRVs).

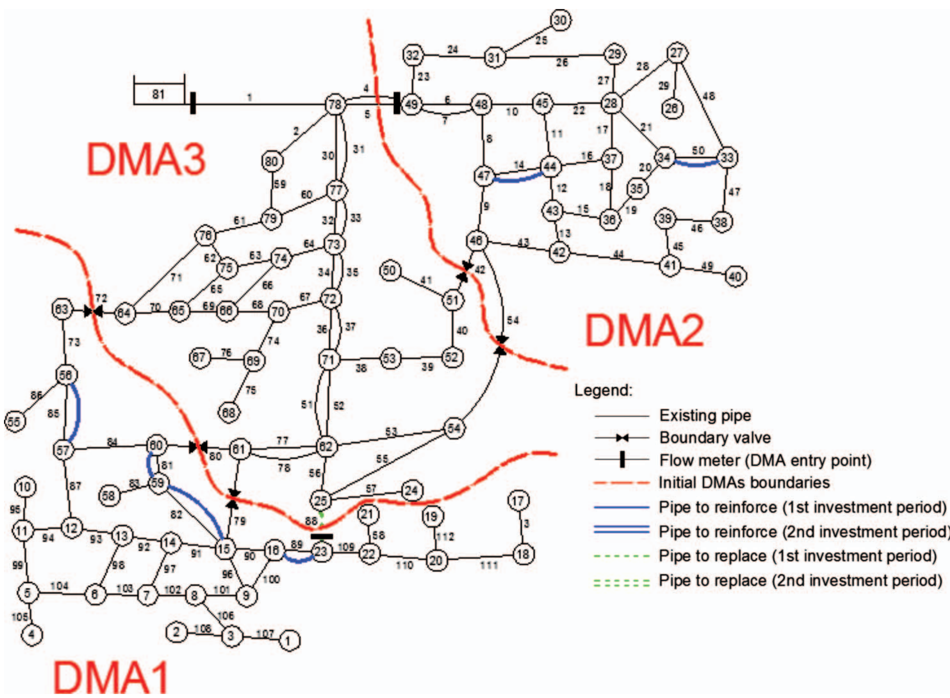

Figure 5. DMAs implementation, for the duration of the project plan (with active PRVs).

are: 6.309 m (DMA1), 3.064 m (DMA2) and 7.738 m (DMA3). Considering the hydraulic behaviour, before and after the DMAs implementation, it is possible to observe that the locations of the metering stations correspond to the DMAs entry points with higher flows (pipes 4/5 and 88).

The results show also that the locations of the metering stations, boundary valves and pressure management along the network will influence the service pressure, and, consequently, the total flow to the system input. The net present value of the project and the hydraulic behaviour of the system, after the

DMAs implementation, can be seen in Table 14 and Table 15 presents the description of the network pressure zones when pressure management is included in the optimisation process. The benefits arise from the average pressure reduction in the system due to the reduced number of DMAs entry points, network reinforcement/replacement, pressure management and consumption increase and infrastructure decay. It can be seen that a minor reinforcement of the network pipes, to adjust the maximum velocity and the pressure at the critical node, may increase the global benefits and even be sufficient to make the DMAs implementation self-sustainable.

4. Conclusions

Water loss management is of fundamental importance to improve the efficiency of many systems worldwide, and to ensure long-term environmental and social sustainability. On the other hand, reducing water loss to zero is practically impossible and would be extremely expensive. Considering the needs of the water companies, an innovative methodology is proposed in this paper to implement water loss management, through network sectorisation and pressure reduction. Furthermore, this methodology can be used to plan the investment needs in different moments along the project plan, adjusting the total investment according to the actual needs and the financial resources of the water companies. In this context, the implementation of pressure management in certain subsystems of the network proved to be an interesting measure, especially during the night period.

The methodology proposed in this paper follows the ‘‘water losses management international best practices’’ and evaluates the costs and the benefits that can be achieved with the DMAs implementation, along the duration of the project plan. It is based on the pressure pattern control and on the water flows

Table 14. Net present value of the project.

A single entry point DMAs			Cost/benefit analysis (without PRVs)	Cost/benefit analysis (with active PRVs)
Reduction (%)	VL + VR	0–10	0,36	7,09
	VR		0,02	0,46
	VL		0,27	5,62
	VL + VR	10–20	0,50	7,00
	VR		0,02	0,40
	VL		0,38	5,58
Total cost of reinforce and replace (€)		0–10	−24,928	−356,451
		10–20	−19,482	0
Total cost of flow meter and PRV (€)		0–10	−94,174	−127,542
		10–20	−7,307	−30,714
Total benefit (€)		0–10	73,877	1,431,348
		10–20	114,735	1,587,307
Net present value of the project (€)		0–20	8,765	1,902,968

VL: daily water losses; VR: daily billed water

Table 15. Description of the network pressure zones (end of each investment period).

Cost/benefit analysis (investment period)		DMA1 0–10	DMA1 10–20	DMA2 0–10	DMA2 10–20	DMA3 0–10	DMA3 10–20
With active PRVs	DMA entry points	88 (FM + PRV)		4/5 (FM + PRV)		1 (FM + PRV)	
	Boundary valves	72 − 79–80		42–54		42 − 54 − 72 − 79–80	
	Maximum flow (l/s)	115.112	128.348	104.631	116.164	275.194	306.147
	Minimum flow (l/s)	13.784	15.369	13.623	15.053	34.837	38.657
	Minimum pressure (m)	18.372 (node 60)	18.373 (node 60)	18.370 (node 49)	18.370 (node 49)	18.380 (node 79)	18.370 (node 79)
	Maximum pressure (m)	36.410 (node 1)	36.743 (node 1)	33.016 (node 26)	32.990 (node 26)	29.958 (node 24)	29.990 (node 24)

FM: flow meter; PRV: fixed-outlet PRV

monitoring, in order to reduce water loss and to optimise the WDS efficiency. Moreover, this approach can be used to monitor the level of water loss in each DMA and to direct the activities of leak location in the worst parts of the system.

The methodology presented uses a Simulated Annealing algorithm to identify the optimal DMAs entry points, the network needs in terms of reinforcement/replacement and the most advantageous type, location and settings for the PRV, along the duration of the project plan. The results for two case studies demonstrate the effectiveness of this new methodology, and they would lead to an interesting benefit for the water company. Furthermore, it was showed that, after the DMAs implementation, a minor reinforcement of the network pipes, to adjust the pressure at the critical node, may increase the global benefits and, sometimes, be sufficient to make pressure management an economically feasible option. In future works a detailed study of these effects will be explored.

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