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WaterNetGen HELPS C-Town

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Abstract

The methodology proposed to solve the C-Town water distribution network problem (BBLAWN) comprises two optimization models: a least cost design model to identify the pipes to be replaced and size them; and an optimal operation model to define the pump controls and the PRV settings. Both models are solved by linking a hydraulic simulation model (WaterNetGen, a pressure driven EPANET extension) with a simulated annealing algorithm. This methodology, supported by some additional engineering expertise, provided a set of good solutions in terms of capital cost, and a good commitment with the environmental and financial damage caused by water losses.

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1. Introduction

This paper presents the procedure used to solve the C-Town water distribution network (WDN) problem, from the Battle of Background Leakage Assessment for Water Networks (BBLAWN). The goal of this challenge is to design a methodology for reducing water losses due to background leakage and apply it to a real water distribution system. Solutions may include new pipes (replacing or placed in parallel to existing pipes), tanks (adjacent to the existing tanks), PRVs and pumps.

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The methodology proposed here comprises two optimization models: 1) a least cost design model to identify the pipes to be replaced and size them; and 2) an optimal operation model to define the pump controls and the PRV settings. Both these models are solved by linking a hydraulic simulation model with a simulated annealing algorithm. The hydraulic simulation model is used to estimate the network hydraulic behaviour, and assess the electricity costs and water losses. These hydraulic calculations are performed by WaterNetGen [1, 2], an EPANET [3] extension with a pressure-driven hydraulic model that allows the assessment of burst and background leakages. The simulated annealing algorithm was developed by Sousa [4] to solve the optimal design and operation of WDN problem. The least cost design model is an adaptation of the model used by Sousa *et al.* [5] to solve the Anytown problem. The optimal operation model was adapted from Sousa *et al.* [6]. The pressure management was inspired in the work by Gomes *et al.* [7] to implement pressure management in District Metered Areas for water loss reduction. In these optimization models, the objective function is the minimization of the total cost: capital (pipes, tanks, PRVs and pumps) and operational (electricity and water losses), and the constraints are the energy and mass conservation laws and the operational limits (minimum pressure and tank water levels). The decision variables of the least cost design model are the new pipe diameters (it was decided not to include new tanks or pumps), and the optimal operation model includes new PRV settings, and pump controls (defined by tank water levels).

This approach, supported by some additional engineering expertise, provided a set of good solutions in terms of capital cost, and a good commitment with the environmental and financial damage caused by water losses. It also provided the opportunity to look for short term strategies with low investment and high income (installation of PRVs) and medium/long term strategies implying higher investment (replacement of existing pipes).

2. Methodology description

As previously mentioned, the methodology is based on the use of two optimization models (least cost design model and optimal operation model), supported by engineering expertise to help in choosing the best strategies to follow. Although these decisions were taken empirically without any guarantee of global optimality, the apparent good quality of the results obtained somehow gives confidence on the methodology.

The application of the optimal operation model to the C-Town WDN confirmed that it was possible to obtain an admissible solution with the existing infrastructure, by only optimizing the pumping stations operation. Since the system has already enough storage capacity to assure an adequate operation, the option to include additional tanks was discarded. The same happened with pumps, and it was also decided to exclude additional pumps (in most of the solutions obtained, one pump in each pumping station was almost always OFF). Although new pumps have better maximum efficiency than existing ones (80% against 70%), taking in consideration the annual electricity cost (around 250,000€/year), this 10% efficiency increase is not enough to justify the replacement of the existing pumps.

The first solution obtained with the optimal operation model implies an annual operating cost of about 4,000,000€. As leakage represents about 93% of the operating cost and electricity only 7%, it was clear that the main goal should be reducing leakage instead of reducing the electricity cost, and this could be attained by introducing PRVs and new pipes, and simultaneously optimizing the pumping stations operation to reduce pressure as much as possible.

PRVs are a quick and cheap solution and, due to the high pressure levels in the C-Town WDN, seem to be a very promising strategy. On the other hand, the introduction of new pipes placed in parallel to existing ones would increase water losses (water losses from existing pipes would remain almost unchanged) and therefore this solution was discarded. The strategy adopted consisted in replacing the existing pipes with new ones (this solution is cheaper and produces a considerable leakage reduction).

2.1. Least cost design model

The least cost design model is used to identify the best set of pipe diameters for the pipes to be replaced in order to reduce their cost. However, in this particular case, the objective function must take into consideration not only the pipe costs but also the leakage and electricity costs (these are influenced by the set of diameters chosen). The decision variables are the binary variables that identify the diameters of the pipes to be replaced, and the constraints are the

usual energy and mass conservation laws and the operational limits (node minimum pressures and minimum and maximum tank water levels). The optimization model is the following:

$$\text{Minimize } \sum_{j=1}^{NPi} C_{pipe,j}(D_j) \cdot L_j + C_{Leakage} + C_{Electricity} \quad (1)$$

subject to:

$$D_j = \sum_{i=1}^{ND_j} YD_{j,i} \cdot DC_{j,i} \quad \text{with} \quad \sum_{i=1}^{ND_j} YD_{j,i} = 1 \quad j = 1, 2, \dots, NPi \quad (2)$$

$$\sum_{j=1}^{NPi} I_{ij} \cdot Q_{j,t} = Q_{c,i,t} \quad i = 1, 2, \dots, N \quad t = 1, 2, \dots, NTS \quad (3)$$

$$\Delta H_{j,t} = \frac{10.674 L_j}{C_{HWj}^{1.852} \cdot D_j^{4.87}} \cdot Q_{j,t}^{1.852} \quad j = 1, 2, \dots, NPi \quad t = 1, 2, \dots, NTS \quad (4)$$

$$H_{i,t} \geq H_{i,min} \quad i = 1, 2, \dots, N \quad t = 1, 2, \dots, NTS \quad (5)$$

$$H_{t,max} \geq H_{t,i} \geq H_{t,min} \quad i = 1, 2, \dots, NTA \quad t = 1, 2, \dots, NTS \quad (6)$$

where NPi - number of pipes in the network; $C_{pipe,j}(D_j)$ - unit cost of pipe j as a function of its diameter (€/year/m); D_j - diameter of pipe j (m); L_j - length of pipe j (m); $C_{Leakage}$ - cost of leakage (€/year); $C_{Electricity}$ - cost of electricity (€/year); ND_j - number of commercial diameters for pipe j ; $YD_{j,i}$ - binary variables that identify the optimal commercial diameter for pipe j ; $DC_{j,1}, DC_{j,2}, \dots, DC_{j,ND}$ - set of commercial diameters for pipe j (m); I - network incidence matrix ($N \times NPi$); $Q_{j,t}$ - discharge in pipe j at time step t (m³/s); $Q_{c,i,t}$ - water demand at junction node i at time step t , node consumption and pipe leakage (m³/s); N - number of junction nodes in the network; NTS - number of time steps during the simulation period; $\Delta H_{j,t}$ - headloss in pipe j at time step t (m); C_{HWj} - Hazen-Williams coefficient of pipe j ; $H_{i,t}$ - piezometric head at junction node i at time step t (m); $H_{i,min}$ - minimum piezometric head for junction node i (m); $H_{t,i}$ - piezometric head at tank i at time step t (m); $H_{t,max}$ - maximum piezometric head for tank t (m); $H_{t,min}$ - minimum piezometric head for tank t (m); NTA - number of tanks in the network.

The leakage cost was calculated with the volume of water lost (leakage) during the simulation period (one week) multiplied by 52 (number of weeks in a year) and by the environmental penalty:

$$C_{Leakage} = EP \cdot 52 \cdot \sum_{t=1}^{NTS} \Delta T_t \cdot \sum_{j=1}^{NPi} \beta_j \cdot L_j \cdot P_{mean,j,t}^{\alpha_j} \quad \text{with} \quad P_{mean,j,t} = \frac{(H_{1,j,t} - Z_{1,j}) + (H_{2,j,t} - Z_{2,j})}{2} \quad (7)$$

where EP - environmental penalty (2€/m³); ΔT_t - duration of time step t (h); β_j and α_j - leakage parameters of pipe j ; $P_{mean,j,t}$ - mean pressure along pipe j at time step t (m); $H_{1,j,t}$ and $H_{2,j,t}$ - piezometric head at the end nodes of pipe j at time step t (m); $Z_{1,j}$ and $Z_{2,j}$ - elevation at the end nodes of pipe j (m).

The electricity cost is calculated taking into consideration the pump power (flow multiplied by the head and divided by the efficiency) and the electricity tariff along the simulation period (one week), multiplied by 52 weeks:

$$C_{Electricity} = 52 \cdot \sum_{t=1}^{NTS} CE_t \cdot \Delta T_t \cdot \sum_{p=1}^{NPu} \frac{\gamma \cdot PQ_{p,t} \cdot PH_{p,t}}{\eta_{p,t}} \quad (8)$$

where CE_t - cost of electricity at time step t (€/kWh); NPu - number of pumps in the network; γ - water specific weight (kN/m³); $PQ_{p,t}$ - flow of pump p at time step t (m³/s); $PH_{p,t}$ - head of pump p at time step t (m); $\eta_{p,t}$ - efficiency of pump p at time step t . $PH_{p,t}$ and $\eta_{p,t}$ depend on $PQ_{p,t}$ (head and efficiency curves, respectively).

2.2. Optimal operation model

The optimal operation model defines the best pump controls in order to reduce the operating cost, and so its objective function is the minimization of the leakage and electricity costs. The decision variables are the pump controls – ON and OFF (defined by tank water levels), and the constraints are the usual energy and mass conservation laws and the operational limits (node minimum pressures and minimum and maximum tank water levels). The optimization model is similar to the least cost design model, except the objective function (does not include the pipe cost) and the decision variables.

2.3. Methodology implemented to solve the optimization models

The optimization models are solved in WaterNetGen [2] by linking a Simulated Annealing algorithm (optimizer) with WaterNetGen, an extension of EPANET to perform Pressure Driven Analysis - PDA [3] (hydraulic simulator), as depicted in Fig. 1.

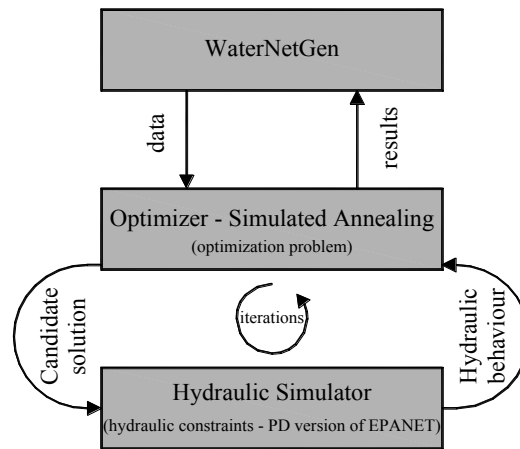


Fig. 1. Flowchart explaining the methodology implemented to solve the optimization models.

The optimization procedure is as follows: throughout the search the optimizer generates candidate solutions (least cost design – pipe diameters, optimal operation – pump controls) and calls the hydraulic simulator to perform PDA, estimating the hydraulic behaviour of the network, and evaluate the objective function. This cycle is repeated until the convergence criterion is met. The final result is the set of pipe diameters or pump controls that minimize the objective function value.

2.4. Hydraulic simulator - WaterNetGen

WaterNetGen [2] is an EPANET extension for automatic generation and sizing of synthetic water distribution network models [1]. It also allows evaluating technical performance [8] and the analysis of critical scenarios, like firefighting or pipe bursts. WaterNetGen uses a Simulated Annealing algorithm that solves a least cost design model for pipe design purposes. As the pressure-driven hydraulic model included in WaterNetGen allows the assessment of background and bursts leakages, it was now adapted to also solve an optimal operation model (minimization of leakage and electricity costs). A deeper explanation of WaterNetGen structure and functionalities can be found in another communication in this conference [9].

3. Strategy used

The first attempt was to produce a solution that could be implemented immediately, by only optimizing the pump controls in order to reduce the operating cost (leakage and electricity). This was accomplished by using the optimal operation model alone and it produced an annual cost of 3,993,937€ (3,734,958€ of leakage and 258,979€ of electricity). Even with this optimized operation the system presents a high level of leakage (25.4%).

The second attempt intended to reduce the leakage cost as quickly as possible, and it was decided that the best strategy to attain this goal should be the installation of PRVs. The places to install PRVs were chosen by studying the network topology and its hydraulic behaviour (flow and pressure). To help in identifying the best locations a sort of cost/benefit analysis was performed, resulting in tables indicating, for each PRV diameter (D), amount of pressure reduction (ΔH_{PRV}), and the β value (leakage parameter), the length of pipes necessary so that the leakage cost reduction equals the PRV cost (Table 1 presents an example).

Table 1. Cost/benefit analysis for PRV installation (example for D = 102mm, PRV cost = 323€/year)

ΔH_{PRV} (m)	Pipe length (m)		
	$\beta = 1E-8$	$\beta = 2E-8$	$\beta = 4E-8$
5	103	51	26
10	51	26	13
15	34	17	9
20	26	13	6
25	21	10	5
30	17	9	4
35	15	7	4
40	13	6	3
45	11	6	3
50	10	5	3
55	9	5	2
60	9	4	2

With this simple criterion, Table 1 leads to the conclusion that most of the pipes could have a PRV, but it was decided not to do that because it is not a reasonable solution (although for the present challenge it was in fact an economic solution). The first locations chosen were sets of branched pipes due to its low impact on the network hydraulic behaviour. Afterwards, it was observed that this initial solution could be highly improved if some additional PRVs could be installed in looped pipes, but this could complicate the network operation. So, it was decided to branch some looped parts by closing some pipes (it is assumed that all pipes have valves) and then install the PRVs. To accomplish this, some care has to be taken due to the fact that leakage occurs along the pipes, but modelling assigns half of the pipe leakage to each of its ending nodes. By just changing the pipe status to CLOSED, half of the pipe leakage is assigned to each end node but now they are not connected anymore. To avoid this problem, new junctions were added to assure that the pipe is really disconnected and its leakage is correctly assigned (this is only for modelling purposes, the pipe can still be physically connected with a valve closed). This is explained in Fig. 2: (a) - model with pipe P32 CLOSED (half of the leakage from pipe P32 is incorrectly assigned to junction J186) and (b) - model with pipe P32 disconnected from junction J186 (leakage from pipe P32 is assigned to junctions J2 and 102). In pipes connected to reservoirs or tanks the pipe leakage is totally assigned to the other end node. The installation of PRVs also implied the introduction of new junction nodes (upstream or downstream the PRV, depending on its location). Fig. 2.(c) illustrates this procedure for the case of PRV 23.

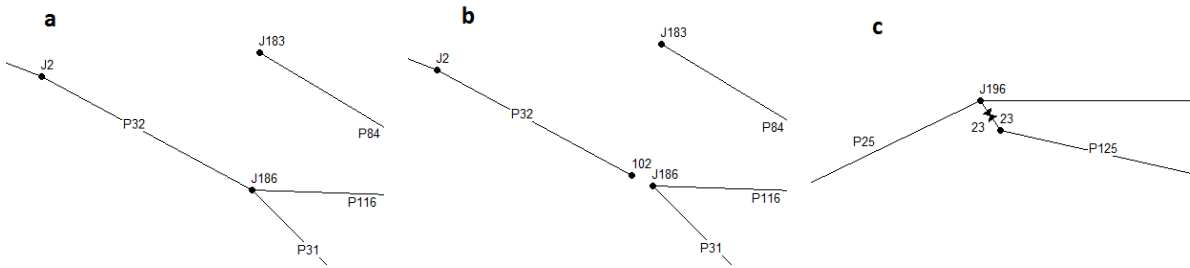


Fig. 2. (a) model with pipe P32 CLOSED; (b) model with pipe P32 disconnected from junction J186; (c) model after introducing PRV 23.

The result of this procedure was the installation of 41 PRVs (although many more could be installed with economic benefit). This strategy implied an annual cost of 2,772,084€ (2,495,367€ of leakage, 241,051€ of electricity and 35,666€ for the PRVs). By comparing this with the previous solution, it was concluded that a small investment in PRVs (35,666€/year) produced a reduction of 1,239,591€/year in leakage and an additional reduction of 17,928€/year in electricity. For this solution, the benefit/investment ratio is 35.3 proving that this is indeed a very interesting strategy, and the leakage level reduces to 18.5%. Fig. 3 shows the difference in the pressure distribution along the network before and after the installation of the PRVs (red junctions are practically located along the transmission mains between the source and the tanks and the remaining junctions are mostly green).

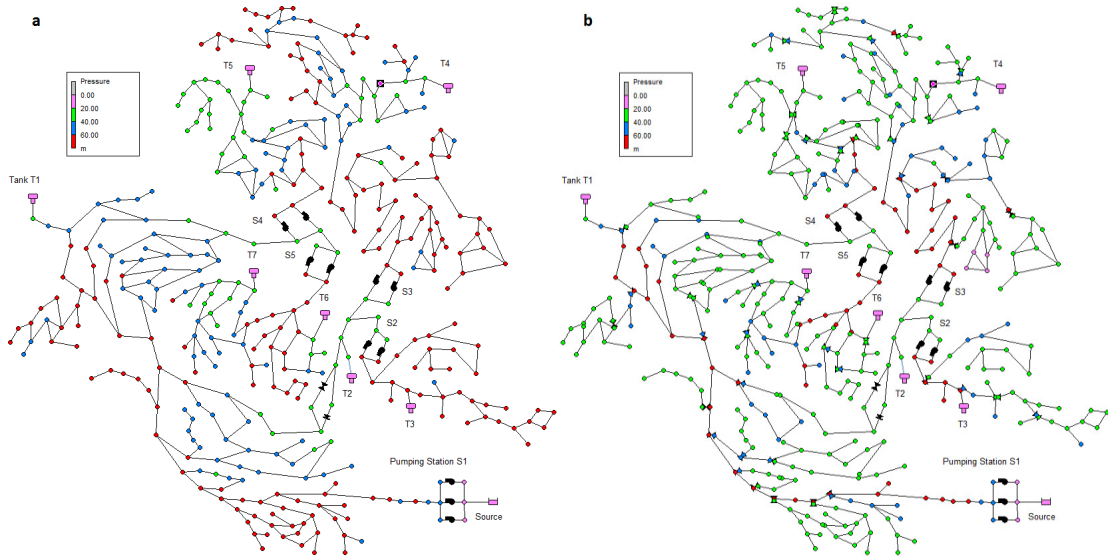


Fig. 3. (a) pressure before PRVs; (b) pressure after PRVs.

The last strategy implemented can be considered as a mid/long term one and concerns pipe replacement. The pipes to be replaced were chosen by estimating the benefit their replacement produce in terms of leakage reduction. To do that, after obtaining the solution with PRVs, a cost/benefit analysis was performed by calculating the difference between existing pipes and replaced pipes leakage costs (Leakage before and Leakage after, respectively) plus the replacement cost. This was done merely in terms of economic benefit, no matter the location of the pipes (in a real world situation care should be taken in choosing pipes close to each other, but here, due to the BBLAWN contest evaluation criteria, that was not done). After ordering the pipes by the benefit their replacement produce, it was easy to identify the most promising ones (Table 2).

Table 2. Cost/benefit analysis for pipe replacement (€/year).

Link ID	Length (m)	Diameter (mm)	Leakage before	Pipe replacement	Leakage after	Benefit
Pipe P102	1 280.30	508	138 323	31 572	27 665	79 086
Pipe P19	750.87	508	83 155	18 516	16 631	48 008
Pipe P20	579.67	508	64 025	14 295	12 805	36 926
Pipe P22	567.30	406	59 815	11 011	11 963	36 841
Pipe P110	425.83	508	47 619	10 501	9 524	27 594
Pipe P99	452.37	508	47 761	11 155	9 552	27 053
...

Table 3. Summary of the solutions proposed.

Solution	Pipes (€/year)	PRVs (€/year)	Leakage (€/year)	Electricity (€/year)	Total (€/year)	Investment (€/year)	Benefit (€/year)	Ben./Inv. ratio	Leakage level
Optimize controls			3 734 958	258 979	3 993 937				25.4%
PRVs (41)		35 666	2 495 367	241 051	2 772 084	35 666	1 257 519	35.3	18.5%
PRVs+10%Pipes	115 963	35 666	2 024 014	226 956	2 402 599	151 629	1 742 967	11.5	15.6%
PRVs+20%Pipes	171 422	35 666	1 774 420	221 327	2 202 835	207 088	1 998 190	9.6	14.0%
PRVs+30%Pipes	210 847	35 666	1 536 791	231 104	2 014 408	246 513	2 226 042	9.0	12.3%
PRVs+40%Pipes	277 521	35 666	1 294 782	232 951	1 840 920	313 187	2 466 204	7.9	10.6%
PRVs+50%Pipes	331 624	35 666	1 083 017	226 718	1 677 025	367 290	2 684 202	7.3	9.0%
PRVs+100%Pipes	579 826	35 666	520 461	235 268	1 371 221	615 492	3 238 208	5.3	4.4%

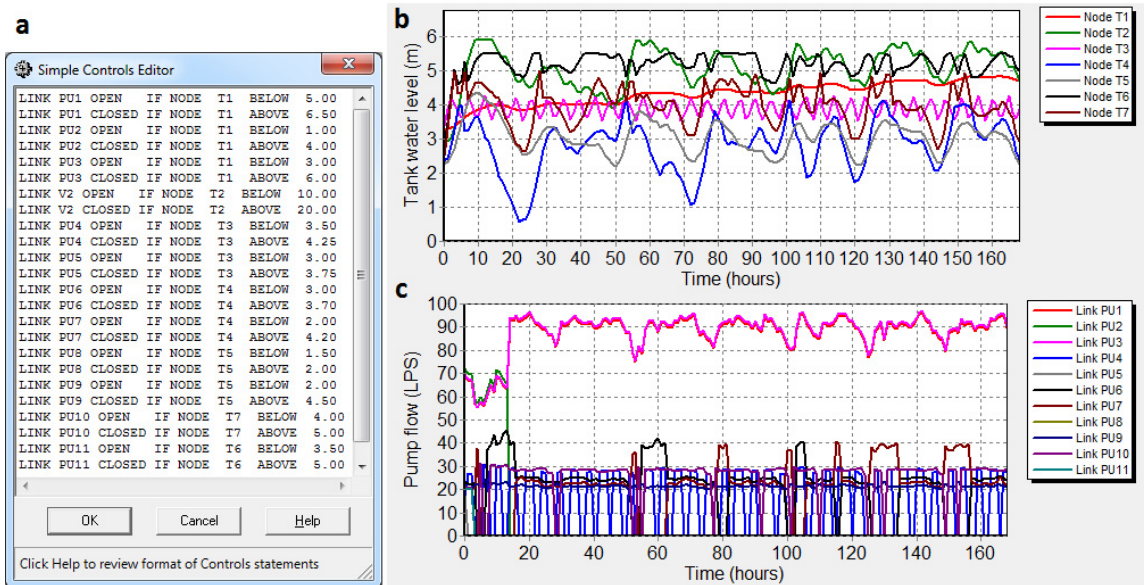


Fig. 4. Solution PRVs+100%Pipes (a) pump controls (valve V2 was intentionally always OPEN); (b) tank water levels; (c) pump flows.

It was decided to propose different levels of pipe replacement, defined as a function of the WDN total length: 10%, 20%, 30%, 40%, 50% and 100%. Thus, the water company can decide what to do looking at the investment necessary for the replacement and the estimated benefit in terms of leakage and electricity costs reduction (see a summary of the results in Table 3). The solutions obtained implied investments from 115,963€/year (10%) to 579,826€/year (100%) and produced leakage costs from 2,024,014€/year to 520,461€/year, respectively. With these results, the water company can plan the actions to be taken according to its annual budget, prioritizing the most efficient ones. For these solutions, the benefit/investment ratios ranged from 11.5 (10%) to 5.3 (100%), and the leakage levels reduced to 15.6% (10%) or 4.4% (100%). Fig. 4 illustrates some of the results from solution PRVs+100%Pipes (installation of 41 PRVs and replacement of all the pipes in the network).

4. Conclusions

This paper presents the procedure used to solve the C-Town water distribution network (WDN) problem, from the BBLAWN. The goal of this challenge is to design a methodology for reducing water losses due to background leakage and apply it to a real water distribution system. The methodology here presented is based on the use of two optimization models (least cost design model and optimal operation model), supported by engineering expertise to help in choosing the best strategies to follow, starting with the optimization of the pump controls, followed by the installation of PRVs and the replacement of existing pipes.

After optimizing the pump controls, 41 PRVs were installed in strategic locations (in originally branched pipes and in looped pipes that also became branched by closing some pipes). Although many more PRVs could be installed with economic benefit, it was decided not to do that because it would be impracticable in real world situations. This first strategy could be implemented immediately and the results showed that the small investment in PRVs (35,666€/year) could produce a reduction of 1,239,591€/year in leakage and an additional reduction of 17,928€/year in electricity.

The pipe replacement strategy can be considered as a mid/long term one. It was decided to propose different levels of pipe replacement (10%, 20%, 30%, 40%, 50% and 100%, defined as a function of the WDN total length) so that the water company can decide what to do looking at the investment necessary for the replacement and the estimated benefit in terms of leakage and electricity costs reduction. The solutions obtained implied investments from 115,963€/year (10%) to 579,826€/year (100%) and produced leakage costs from 2,024,014€/year to 520,461€/year, respectively. With these results, the water company can plan the actions to be taken according to its annual budget, prioritizing the most efficient ones. For these solutions, the benefit/investment ratios ranged from 35.3 (41VRPs) to 5.3 (PRVs+100%Pipes), and the leakage levels reduced from 25.4% (3,734,958€/year) to 4.4% (520,461€/year).

Although some of the decisions were taken empirically without any guarantee of global optimality, the apparent good quality of the results obtained somehow gives confidence on the methodology designed.

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