Multistep Approach for Optimizing Design and Operation of the C-Town Pipe Network Model

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Abstract: A multiobjective approach is used here to optimize design and operation of the C-Town pipe network, searching for trade-off solutions between (1) installation cost, (2) operational cost, and (3) cost of the pressure-reducing valves. Due to the large number of decisional variables and to the complexity of the constraints considered, the optimization problem was tackled in five steps: (1) identification of some feasible (on the basis of the many constraints) first attempt solutions; (2) application of a multiobjective genetic algorithm to the 2D optimization problem with objective functions 1 and 2, in order to obtain optimal trade-off solutions between the installation cost and operational cost, without considering the installation of pressure-reducing valves; (3) application of the multiobjective genetic algorithm to the optimization problem with objective functions 2 and 3 for each of the solution selected at the end of Step 2, in order to assess how the operational cost can decrease thanks to the installation and operation of pressure-reducing valves; (4) derivation of the 3D Pareto surface by grouping the solutions found at the end of Steps (2) and (3). A solution was extracted from the 3D Pareto surface of optimal solutions following some specific criteria. This solution was then further refined (Step 5) in order to allow for variable settings of the pressure-reducing valves installed and to make it compliant with the battle guidelines concerning leakage modeling. **DOI:** 10.1061/(ASCE)WR.1943-5452.0000585.

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Introduction

Water distribution systems require frequent upgrades and interventions during their useful life in order to keep up with urban extension and population growth. Other upgrades are also needed to reduce the occurrence of pipe bursts and the amount of leakage. Overall, the interventions in a network can be grouped into three categories:

1. Design, related to network construction or expansion;
2. Maintenance, aimed at attenuating pipe breaks and leakage; and
3. Actuator regulation, aimed at searching for the most suitable settings of the regulators (such as pumps and valves) installed in the network, in order to dynamically adjust the network itself to spatial and temporal demand variations.

These three categories of interventions should be carried out simultaneously in order to guarantee maximization of the overall network operational efficiency.

Optimization techniques proposed in the scientific literature can be used to assist water-utility managers in selecting and prioritizing the interventions to be made (Alperovits and Shamir 1977; Jowitt and Xu 1990; Quimpo and Shamsi 1991; Ormsbee and Lansey 1994; Simpson et al. 1994; Arulraj and Rao 1995; Alvisi and Franchini 2006; Alvisi and Franchini 2009; Campisano et al. 2010; and Creaco and Franchini 2012; Alvisi and Franchini 2013; Creaco and Franchini 2013; Alvisi and Franchini 2014; Creaco et al. 2014b). These listed papers do represent valid contributions to the field but have the drawback of focusing only on one category of interventions at a time: i.e., design (Alperovits and Shamir 1977; Simpson et al. 1994; Creaco and Franchini 2012; Alvisi and Franchini 2014; Creaco et al. 2014), maintenance (Quimpo and Shamsi 1991; Arulraj and Rao 1995, Alvisi and Franchini 2006; Alvisi and Franchini 2009; Alvisi and Franchini 2013), or actuator regulation (Jowitt and Xu 1990; Quimpo and Shamsi 1991; Campisano et al. 2010; Creaco and Franchini 2013).

Unlike the simpler case studies usually dealt with in the scientific literature, the optimization problem proposed in the context of BBLAWN is closer to water utility managers' reality, since it involves design, maintenance, and actuator-regulation aspects at the same time. A new methodology was then developed to tackle the multiple facets of this optimization problem.

BBLAWN Optimization Problem and Its Simplification

The case study of the BBLAWN is the C-Town network, made up of

- $n_0 = 1$ reservoir;
- $n_t = 7$ tanks;
- $n = 388$ nodes with unknown heads;
- $n_p = 432$ pipes;
- $n_{pu} = 11$ pumps grouped in 5 pumping stations; and
- 1 throttle valve.

The network is subdivided into $n_{\mathrm{dis}} = 5$ districts, each of which featuring a pumping system and a system of tanks (actually a single tank for all the districts except for Districts 1 and 5 where two tanks are present). The operation of each district can be summed up in two loading conditions: (1) district and associated tank fed by the district pumping system, and (2) pumping system off and district

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fed by its system of tanks. District pumping stations are numbered like the districts. As benchmark of the network operation, a series of 7 days (168 h), scanned with a 1-h-long time step, was considered. An accurate description of the optimization problem of the BBLAWN is present in the work of Giustolisi et al. (2015).

The objective space of the optimization is made up of three functions: (1) installation cost C_i, related to the laying of new pipes plus the widening of the tanks plus the insertion of new pumps; (2) operational cost C_o, obtained as the sum of the yearly pumping cost and the monetized value of the yearly leakage volume; (3) cost C_v of the pressure-reducing valves (PRVs) installed in the network in order to lower the service pressure and then attenuate leakage.

The decisional variables can be grouped as follows:

- Subgroup (1): Diameters of the new pipes that can be installed at the various pipe sites to replace the old leaky pipes or in parallel to the latter (size $2n_p$);
- Subgroup (2): Tank-widening volumes (size n_t);
- Subgroup (3): Pumps that can be used to replace the old pumps of low efficiency, or can be laid in parallel to them (size $n_{pu} + n_{\text{dis}}$);
- Subgroup (4): Positions of the isolation valves that can be closed in the network in order to create, inside each district, subdistricts whose service pressure can be easily regulated by means of pressure-reducing valves (size $2n_p$ because, theoretically, an isolation valve could be inserted in each pipe and in its parallel pipe);
- Subgroup (5): Positions and settings (initially assumed as fixed) of the PRVs to be installed in the network (size ~~2~~n_p because, theoretically, a PRV could be installed in each pipe and in its parallel pipe);
- Subgroup (6): Switch on and off settings of the various pumps, and open and closed setting of the throttle valve [size $2 \times (n_{pu} + n_{\text{dis}} + 1)$].

According to this classification, the total number of decisional variables is then equal to ~~6~~$n_p + n_t + 3n_{pu} + 3n_{\text{dis}} + 2 =$ ~~2,649~~.

In order to simplify the research space, some assumptions were made:

- Simplification 1: No parallel pipes were allowed, since laying parallel pipes has the drawback of increasing network length and then leakage;
- Simplification 2: Following engineering judgment, laying pumps in parallel was allowed for only in Pumping Stations 1 and 5 (Fig. 1);
- Simplification 3: The potential positions of the isolation valves to be closed and of the PRVs to be installed were identified a priori thanks to the algorithm proposed by Creaco and Pezzinga (2014, 2015) and on the basis of engineering judgment. Overall, 64 potentially closed isolation valves and 51 potentially installed PRVs were identified (Fig. 1).

Simplification 1 makes the size of Subgroup 1 equal to $n_p = 432$.

Simplification 2 makes the size of Subgroup 3 equal to $n_{pu} + 2 = 13$ and the size of Subgroup 6 equal to 28.

As far as Simplification 3 is concerned, some comments deserve to be made about the algorithm proposed by Creaco and Pezzinga (2014, 2015) and its application to the C-Town network. This algorithm is hybrid, being based on the coupling of a multiobjective genetic algorithm [NSGAII (Deb et al. 2002)] and of an algorithm based on the iterated linear programming [upgraded version of that presented by Jowitt and Xu (1990)]. The genetic algorithm enables optimal location of the control valves as well as identification of the isolation valves that have to be closed, with the objective to simultaneously minimize leakage volumes and control valve costs. The algorithm based on iterated linear programming is embedded in the genetic algorithm and searches for the optimal settings of the control valves for each solution proposed by the genetic algorithm, made up of a set of isolation valves closed and control valves installed in the network. The algorithm of Creaco and Pezzinga (2014, 2015) was applied to each of the $n_{\text{dis}} = 5$ districts of the BBLAWN network at a time, considering the two different loading conditions previously described.

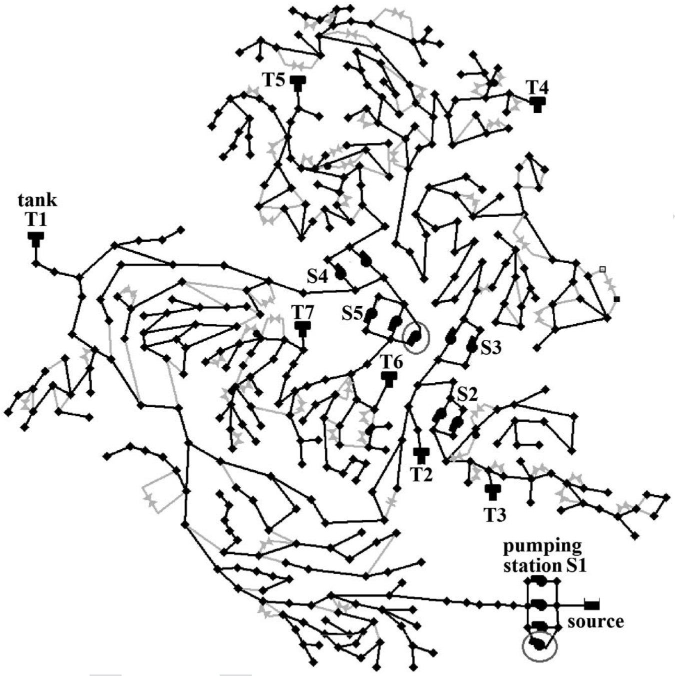


Fig. 1. C-Town network; in grey the pipes where an isolation valve can be closed and the potential location of PRVs (these valves are here shown in parallel to their location with an attempt to be better identified); grey circles show the two locations where new pumps can be installed in parallel in Stations 1 and 5

Overall, Simplification 3 makes the sizes of Subgroups 4 and 5 equal to 64 and 102, respectively.

Thanks to the previous simplifying assumptions, the total number of decisional variables was then reduced to 646.

The constraints of the optimization include

- Constraint 1: Continuity equations for network nodes and tanks;
- Constraint 2: Momentum equations for network pipes, pumps, and valves;
- Constraint 3: Minimum pressure head requirements for the various network nodes (see the BBLAWN guidelines); and
- Constraint 4: Tank levels at the end of the operational period, which have to be larger than or equal to their respective initial levels.

Whereas Constraints 1 and 2 were automatically respected in the present study thanks to the use of the hydraulic simulator *EPANET2* (Rossman 2000), the respect of Constraints 3 and 4 was obtained through adoption of penalties in the objective functions.

In the following sections, first the optimization algorithm used to explore the 3D research space is described and applied. Then, the choice and refinement of the final solution taken out from the 3D Pareto surface are explained.

Optimization Algorithm

As shown in the previous section, the optimization problem of BBLAWN is very complex since it simultaneously concerns pipe replacements, pump replacements and additions, pump settings, tank upgrades, isolation valve closures and, finally, PRV installations and regulations. A decoupling strategy (Creaco et al. 2014a) was then adopted in this study, in a bid to simplify the problem. In particular, this strategy consisted in splitting the problem in various stages. In particular, the following steps were then carried out using the software *EPANET2* (Rossman 2000) for network simulation:

1. Identification of some feasible first attempt solutions;
2. Optimization with Objective Functions 1 (installation cost) and 2 (operational cost: energy cost plus water-loss cost);
3. Optimization with Objective Functions 2 (operational cost) and 3 (cost of the pressure-reducing valves);
4. Approximation of the 3D Pareto surface; and
5. Refinement of a final solution selected within the 3D Pareto surface obtained in Step 4.

In the following subsections, these steps are thoroughly described.

Step 1

In this step, engineering judgment was used to implement some variations in the network asset and in pump settings in order to obtain some first-attempt solutions with no PRVs (and then with $C_v = 0$) in the trade-off between Objective Function 1 (C_i) and Objective Function 2 (C_o). In particular, seven first-attempt solutions were obtained in this step:

- Two solutions with very low values of C_i (around 5×10^4 Euro) and quite high values of C_o (slightly lower than 2×10^6 Euro). In these solutions, very small variations were made from the initial layout, which enabled the network to respect the pressure constraints, including replacement of some pipes in the original layout and variations in pump settings;
- Four solutions with intermediate values of C_i and C_o, close to 3×10^5 and 1.6×10^6 Euro, respectively. These solutions were obtained by replacing pipes mainly in the lines which interconnect pumps and tanks, enlarging tanks T4 and T5, closing some network pipes in order to create some districts, and manually fixing the pump settings; and
- One solution with a very high value of C_i (around 7.2×10^5 Euro) and quite low value of C_o (around 5.2×105 Euro). This solution was obtained by replacing pipes in the whole network, enlarging tanks T4 and T5, closing a large number of pipes in order to create many districts, and manually fixing the pump settings.

These solutions, whose values of C_i and C_o are reported in the graph in Fig. 2, made it possible to get an initial idea of the range of values taken by the first two objective functions.

Step 2

The objective of this step was to explore the trade-off between Objective Function 1 (C_i) and objective Function 2 (C_o), while neglecting the effects of the installation of PRVs. To this end, a 2D optimization was performed using the multiobjective genetic algorithm NSGAII (Deb et al. 2002) and considering a population of 200 individuals and a total number of 400 generations. The first attempt solutions detected in Step 1 were inserted in the initial population in order to accelerate the convergence of the NSGAII towards feasible solutions. The decisional variables considered in Step 2 were those belonging to the Subgroups 1, 2, 3, 4, and 6 presented in the section entitled "BBLAWN optimization problem and its simplification."

At the end of the 400 generations, a 2D Pareto front of optimal solutions featuring $C_v = 0$ was obtained. Then, 10 solutions well scattered over the whole range of values of the objective function values were taken out from this front and reported in the graph in Fig. 2. As an example, one of these solutions is Solution 19 featuring values $C_i = 531{,}126$ Euro and $C_o = 736{,}699$ Euro. The efficiency and effectiveness of the Step 2 optimization is proven by the fact that the solutions of the 2D Pareto front dominate by far the first attempt solutions assumed in Step 1.

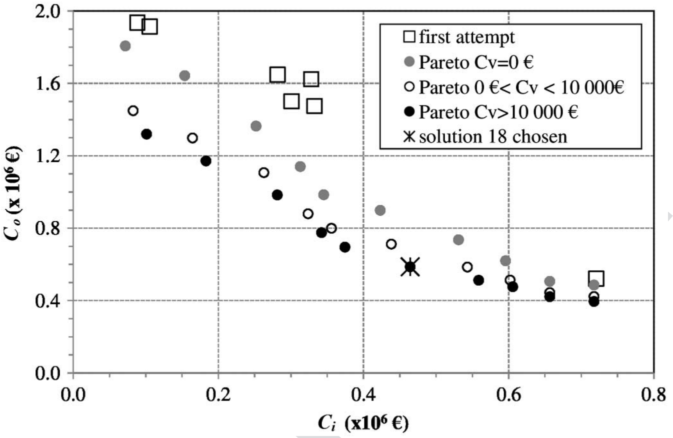


Fig. 2. First-attempt solutions and solutions of the 3D Pareto surface; ~~end~~ solution chosen

Step 3

This step was aimed at exploring the trade-off between Objective Function 3 (C_v) and Objective Function 2 (C_o) starting from the asset of each of the 10 solutions selected at the end of Step 2. To this end, other 2D optimizations (one for each of the 10 solutions) were performed using the multiobjective genetic algorithm NSGAII (Deb et al. 2002) and considering a population of 50 individuals and a total number of 100 generations. The decisional variables considered in Step 3 were those belonging to the Subgroups 4, 5, and 6 presented in ~~section 2~~. During each optimization, an artifice was adopted to enable reduction in the total cost C_v of installed PRVs. This artifice consisted in replacing the generic pipe where PRV installation is encoded with a new pipe featuring the smallest diameter and, then, the lowest PRV cost.

At the end of the generic Step 3 optimization, a Pareto front of optimal solution in the space C_v-C_o was obtained for the generic of the 10 asset solutions selected at the end of Step 2. In each Step 3 Pareto front, the solution with the lowest C_v value (i.e., $C_v = 0$) coincided with the starting Step 2 solution. From each Step 3 Pareto front, two solutions were taken out:

- Solution 1: Solution with an intermediate C_v value, corresponding to an intermediate number of valves installed in the network;
- Solution 2: Solution with the highest C_v value, corresponding to the highest number of valves installed in the network.

As example of the extracted solutions from the 2D Pareto fronts of Step 3, there are Solutions 20 and 21, which were obtained from the optimization carried out starting from Solution 19 of Step 2. These solutions feature C_v equal to 6,783 and 14,418 Euro, respectively.

Step iv

The objective functions values of the two solutions selected from each of the Step 3 Pareto fronts in Step 3 were reported in the graph in Fig. 2 along with those obtained at the end of Step 2. Three different colors were used in the figure to differentiate the solutions on the basis of the C_v value. As a result of this, an approximation of the Pareto surface, which is made up of 30 solutions and represents the trade-off between the three objective functions, was obtained. For each of these solutions, the objective function values are also reported in the following Table 1, along with the partial rank in terms of each of the objective functions and the total rank obtained as the sum of the solution partial ranks. Finally, Table 1 reports, for each solution, the total yearly cost C_{tot}, obtained as the sum of the three objective functions, which are all expressed as yearly costs.

For the selection of the final solution in the 3D Pareto surface, two different criteria, related to the minimum rank and to the minimum cost respectively, could be applied. The first criterion would lead to selection of either Solution 27 or Solution 30, which have the lowest rank equal to 30. The second would lead, instead, to selection of Solution 18, which features the lowest value of the total cost C_{tot}. In the end, Solution 18 was chosen as ~~end~~ solution because Solutions 27 and 30 were deemed to be exceedingly extreme, and then unacceptable to water utility managers, since they would require replacement of all network pipes. Furthermore, Solution 18 is not much worse than Solutions 27 and 30 in terms of total rank (32 instead of 30).

As shown in Fig. 3(a), Solution 18 encodes replacement of all the pipes in District 1 (fed by pumping station 1). In the other districts, pipe replacements concern the paths that link the pumping stations to the tanks and the PRV sites. As shown in Fig. 3(b), Solution 18 also encodes the closure of the isolation valves in some network pipes and the permanent switch-off of some pumps. No pump replacements and additions are encoded in Solution 18 and tank extension only concerns tank T5.

A proof of the effectiveness of the optimization is provided in the graphs in Fig. 4, which report the flow supplied by pumping station S2 and the water level in tank T3 fed by S2, respectively. These graphs, selected as representative and illustrative of the operation of pumping stations and network tanks, show that the optimization process was able to create a daily cyclic profile for pumped flows and water-tank levels. This profile was achieved through the search for proper pump settings, which causes pumps to operate mainly at night time, when energy costs are lower.

Step v

Solution 18 selected at the end of Step 4 was refined in Step 5. In particular, this process included two different refinements:

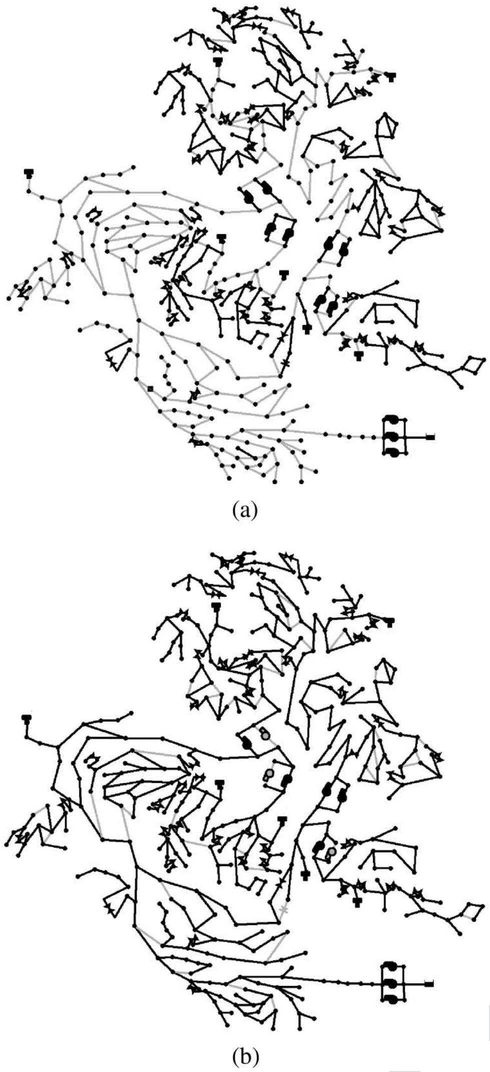
- Refinement 1: Determination of time-varying settings for the pressure head to be imposed downstream of PRVs;
- Refinement 2: Transformation of leakage modeling from the Tucciarelli et al. (1999) formulation, easily obtained in *EPANET2* by means of the nodal emitters, to the Germanopoulos (1985) formulation, which is compliant with the BBLAWN guidelines (Giustolisi et al. 2015).

Both refinements determine no variations in the network asset of Solution 18, and then in the values of C_i and C_v. In fact, they are only expected to change leakage and, then, C_o.

In order to accomplish Refinement 1, the critical node (i.e., the node with the lowest pressure head) was identified downstream of each PRV installed in the network. The *EPANET2* results relative to this node enabled calculation of the excess of pressure head compared to the minimum requirement at each time instant of operation. At each time instant, the downstream target pressure head of

Table 1. For Each Solution of the 3D Pareto Surface, ID, Values of the Objective Functions C_i, C_o, and C_v and of Total Cost C_{tot} Rank~~ed~~ in Terms of Each Objective Function and Total Rank

Identifier solution	C_i (Euro)	C_o (Euro)	C_v (Euro)	C_{tot} (Euro)	C_i rank	C_o rank	C_v rank	Total rank
1	72 (177)	1,806 (742)	0	1,878 (918)	1	30	1	32
2	82 (979)	1,449 (744)	6 (783)	1,539 (506)	2	28	2	32
3	101 (470)	1,319 (473)	14 (668)	1,435 (611)	3	26	4	33
4	153 (885)	1,643 (264)	0	1,797 (149)	4	29	1	34
5	164 (687)	1,297 (958)	6 (783)	1,469 (428)	5	25	2	32
6	183 (178)	1,171 (792)	14 (668)	1,369 (637)	6	24	4	34
7	252 (278)	1,364 (167)	0	1,616 (445)	7	27	1	35
8	263 (080)	1,107 (292)	6 (783)	1,377 (155)	8	22	2	32
9	281 (571)	983 (825)	14 (668)	1,280 (064)	9	20	4	33
10	313 (079)	1,140 (553)	0	1,453 (632)	10	23	1	34
11	323 (881)	879 (923)	6 (783)	1,210 (587)	11	18	2	31
12	342 (372)	775 (156)	14 (668)	1,132 (196)	12	16	4	32
13	345 (320)	985 (540)	0	1,330 (861)	13	21	1	35
14	356 (123)	799 (591)	6 (783)	1,162 (497)	14	17	2	33
15	374 (613)	695 (880)	14 (668)	1,085 (161)	15	13	4	32
16	423 (459)	898 (393)	0	1,321 (852)	16	19	1	36
17	438 (690)	711 (645)	6 (783)	1,157 (118)	17	14	2	33
18	464 (520)	586 (898)	14 (418)	1,065 (836)	18	11	3	32
19	531 (126)	736 (699)	0	1,267 (825)	19	15	1	35
20	543 (514)	585 (412)	6 (783)	1,135 (709)	20	10	2	32
21	558 (844)	512 (451)	14 (418)	1,085 (713)	21	9	3	33
22	595 (870)	620 (012)	0	1,215 (883)	22	12	1	35
23	602 (320)	513 (736)	6 (783)	1,122 (840)	23	8	2	33
24	605 (881)	476 (541)	14 (418)	1,096 (840)	24	5	3	32
25	657 (014)	506 (471)	0	1,163 (485)	25	7	1	33
26	657 (014)	444 (426)	6 (783)	1,108 (223)	25	4	2	31
27	657 (014)	421 (396)	14 (418)	1,092 (828	25	2	3	30
28	717 (786)	486 (171)	0	1,203 (957)	26	6	1	33
29	717 (786)	422 (714)	6 (783)	1,147 (283)	26	3	2	31
30	717 (786)	395 (452)	14 (418)	1,127 (657)	26	1	3	30
18 refined	464 (520)	580 (842)	14 (418)	1,059 (780)	—	—	—	—


(a)

(b)

Fig. 3. Solution 18: (a) in grey, pipes replaced in the network; (b) in grey, pipes where the isolation valve is closed and permanently-switched-off pumps

each PRV was then reduced in order to lead the critical-node pressure head excess to 0. This refinement virtually enables a far control node to be considered for each PRV, instead of the node placed immediately downstream. As a result of this refinement, a slight reduction in C_o from 586,898 to 583,670 Euro was obtained.

Refinement 2 was carried out in order to express leakage through the Germanopoulos (1985) formulation, which assumes the generic pipe leakage to be calculated as a function of the average pressure head at the pipe's end nodes and then to be allocated to the pipe end-nodes themselves.

In order to obtain the Germanopoulos (1985) formulation for Solution 18, *EPANET2* was run iteratively according to the following stages, which refer to the generic network operation time instant:

- Stage 0: A starting distribution of network nodal pressures is considered (a good first attempt distribution is represented by the distribution obtained through the *EPANET2* run with the emitters). The application of a suitably set up *MATLAB* subroutine enables evaluation of pipe leakages on the basis of the Germanopoulos (1985) formulation;
- Stage 1: Pipe leakages evaluated in the previous phase are stored in memory;

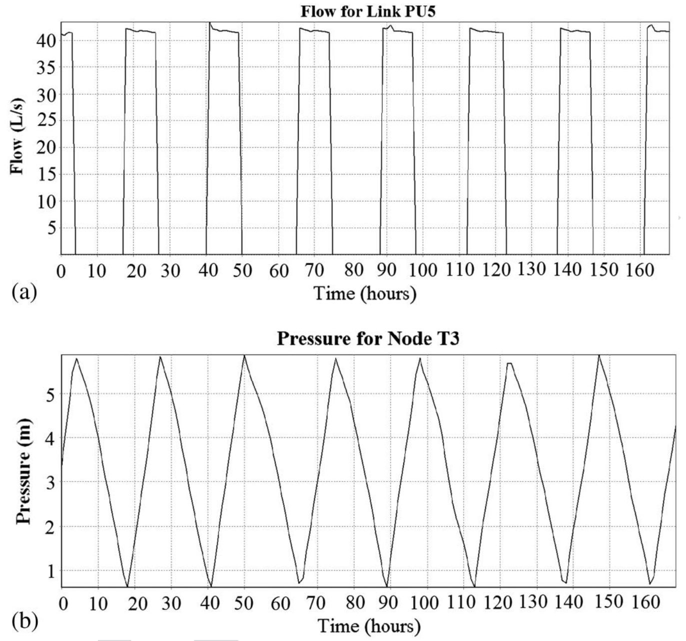


Fig. 4. Solution 18; (a) ~~water discharge~~ pumped by pump PU5; (b) water level in Tank T3

- Stage 2: Pipe leakages are allocated to the network nodes;
- Stage 3: An *EPANET2* input file of the network is constructed where, for each node, a variation in the total demand (users' demand + allocated leakage) is allowed (by means of patterns);
- Stage 4: *EPANET2* is run; a distribution of network nodal pressures is obtained. The application of the *MATLAB* subroutine enables evaluation of pipe leakages on the basis of Germanopoulos (1985) formulation;
- Stage 5: The absolute differences between pipe leakages in Stage 4 and those of Stage 2 are calculated. If the maximum absolute difference is below a certain tolerance threshold, convergence on pipe leakages evaluated on the basis of the Germanopoulos (1985) formulation has been reached. Otherwise the procedure continues from Stage 1.

The application of Refinement 2 only slightly changed the operational cost C_o from 583,670 to 580,842 Euro. This small variation proves that the Tucciarelli et al. (1999) formulation, used throughout the optimizations, approximates very well the Germanopoulos (1985) formulation required by the BBLAWN guidelines. As a result of this, the overall methodology adopted in this work, based on the adoption of the Tucciarelli et al. (1999) formulation for the representation of leakage, is legitimated.

Conclusions

This work showed how the design and operation of a real and complex network can be optimized using a multistep approach that combines engineering judgment and optimizations. In particular, following the search for first-attempt solutions obtained through application of engineering judgment, an optimization process with three objective functions [(1) installation cost, (2) operational cost, and (3) cost of the pressure-reducing valves] was carried out. For the sake of simplification, this process was split into subsequent 2D optimizations, where the trade-off between installation cost and operational cost was first explored, followed by that between cost of pressure-reducing valves and operational cost. After an approximated 3D Pareto surface was obtained, a criterion based on the minimum total cost, obtained as the sum of installation, operational, and valve costs, was conveniently used for selecting the ~~ultimate~~ solution. At the end of the applications, the benefits derived from adopting, for each pressure-reducing valve, a far control node instead of the node placed immediately downstream, were investigated. Since this variation was made available by the organizers of the battle without extra installation costs, it was profitably implemented in the ~~end~~ solution, in light of the subsequent slight decrease in the operational cost. However, in real case studies, the implementation of this option could require extra costs related to the installation of real time control devices, which then need to be compromised with the benefits in an ad hoc financial analysis.

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