MULTI-OBJECTIVE OPTIMIZATION OF ISOLATION VALVE CLOSURES AND CONTROL VALVE INSTALLATIONS IN WATER DISTRIBUTION NETWORKS

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KEY POINTS

- *Hybrid multi-objective algorithm is proposed, which simultaneously minimizes the number of installed control valves and leakage in water distribution networks*
- *Better numerical effectiveness than traditional multi-objective genetic algorithms*
- *Optimizing isolation valve closures and control valve installations at the same time leads to better leakage reduction than optimizing control valve installations alone*

1 INTRODUCTION

Leakage from water distribution systems represents a serious problem, especially in periods of water scarcity, because it results in loss of purified drinking water. Furthermore, it entails economic losses, related to the waste energy and material resources used in abstraction, transportation, and treatment (*Farley & Trow*, 2003). Among the various techniques that can be adopted for leakage reduction, there is active pressure management, which can be performed by installing control valves (*Puust et al.*, 2010). The problem of the optimal location and regulation of control valves for leakage reduction in water distribution systems has been much investigated over the last three decades. A good literature review of the methods proposed to tackle this problem was carried out by *Vicente et al.* (2016).

A drawback of most of the methods lies in the fact that they did not consider that isolation valves are present in many pipes of the water distribution networks and can contribute to leakage attenuation (*Walski et al.*, 2003). In fact, although the operation of isolation valves is generally analyzed within the framework of other problems — such as segment disconnection (*Creaco et al.*, 2010) or district formation (*Di Nardo et al.*, 2013) — the closure of some isolation valves suitably identified in the network can

- enable lowering of nodal pressure heads by itself, and
- eliminate paths for water to bypass the installed control valves, and then make the operation of control valves more effective.

In this paper, an algorithm for the optimal control valve location and regulation, which also identifies the isolation valves that have to be closed in the network in order to improve control valve regulation, was developed. The algorithm is multi-objective and hybrid, being based on the coupling of a multi-objective genetic algorithm GA and of the linear programming LP.

Hereinafter, first the algorithm is described; then, the study applications are shown, reporting the comparison of the new hybrid algorithm with the NSGAII (*Deb et al.*, 2002) in terms of numerical performance and showing the extent to which the closure of isolation valves can contribute to leakage reduction.

2 METHODS

The algorithm use in this work is the result of the coupling of a multiobjective GA and of an algorithm based on the iterated LP.

The multiobjective GA is the NSGAII (*Deb et al.*, 2002), whereas the iterated LP is an upgraded version of that presented by *Jowitt & Xu* (1990); the upgrades in the iterated LP consist of

- adoption of the matrix form, which lends itself to be used with various pipe resistance formulas, whereas the iterated LP of *Jowitt & Xu* (1990) is only valid when the Hazen-Williams formula is used to express pipe resistance; and
- insertion of a relaxation method to enhance the computational efficiency.

In particular, the GA enables optimal location of the control valves, as well as identification of the isolation valves that have to be closed, with the objective of simultaneously minimizing leakage, which is evaluated through the Germanopoulos (1988) formulation, and installation costs. The algorithm based on the iterated LP is embedded in the GA and searches for the optimal settings of the control valves for each solution proposed by the GA, made up of a set of valves in the network.

Being based on the coupling of different algorithms, the algorithm proposed in this work belongs to the category of hybrid algorithms (*Talbi*, 2002). Generally, a hybrid algorithm is built with the objective to combine the desired features of each component algorithm, so that the overall algorithm is better than the individual components. According to the *Talbi* (2002) classification, the algorithm proposed in this work can be considered a low-level hybrid algorithm because one of the two component algorithms (i.e., the iterated LP) is embedded in the other (i.e., the GA) as a functional part.

More details of the algorithm can be found in the work of *Creaco & Pezzinga* (2015a; 2015b).

3 APPLICATIONS

3.1 Case-study

The applications of this work concerned the network in Figure 1a, which is modified from the work of *Jowitt & Xu* (1990), made up of 25 nodes (of which 22 with unknown head and 3 source nodes with fixed head, i.e., nodes 23, 24, and 25) and 37 pipes. Details about the features of nodes and pipes can be found in the work of *Creaco & Pezzinga* (2015a).

Three loading conditions, relative to low, intermediate, and high nodal demands, respectively, were adopted to reproduce the network daily operation as to source heads and nodal demands (see *Creaco & Pezzinga*, 2015a). Each of the operation conditions was assumed to be representative of a 8-h-long time interval in the day.

As to leakage, values of the leakage coefficient and exponent were assumed for all the pipes of the network, leading to a daily leakage volume of 2,575 m^3 without control valves being installed and isolation valves being closed.

In the applications, the optimal location of control valves in the network and the identification of the isolation valves that have to be closed were searched for. One isolation valve was assumed to be already present at each network pipe. The objective functions used within the optimization application were the total number N_{tot} of control valves (as a surrogate for the installation valve cost) and the daily leakage volume W_L.

The minimum desired pressure head was set at 25 m for all network nodes, unlike the work of *Jowitt & Xu* (1990) where a value of 30 m was considered. The different choice is due to the fact that a lower minimum desired pressure head value makes it possible to better investigate the service pressure lowering effects of isolation valve closure.

A population of 50 individuals and a total number of 100 generations, corresponding to a total number of 5×10^3 objective function evaluations, were used for the GA of the hybrid algorithm.

3.2 Results

The Pareto front of optimal solutions obtained after 100 generations by means of the new hybrid algorithm is reported in Figure 1b. The front, which presents solutions up to a number of installed control valves $N_{tot} = 7$, has an asymptotic trend as the number of installed control valves grows. The first solution with $N_{tot} = 0$ (0 control valves installed) features a value of $W_L = 2{,}055$ m^3, which is much lower than the value of 2,575 m^3 obtained when no control valves are installed and no isolation valves are closed. This leakage reduction effect is due to the closure of some isolation valves in the network. In particular, a significant leakage volume reduction is noticed until the number of installed valves equals 4. For larger number of valves, the decrease in the leakage volume becomes insignificant. The final Pareto front obtained with the hybrid algorithm is also compared with the Pareto front after 30 generations in the graph in Figure 1b. The closeness of the two fronts entails that the new algorithm converges rapidly in terms of number of iterations. The quick convergence is ascribed to the very simple encoding of individual genes (see *Creaco & Pezzinga*, 2015a; 2015b for further details).

Figure 1b also shows the Pareto front obtained in a benchmark optimization, performed using the traditional NSGAII, where the iterated LP is not embedded, and which then features additional genes with respect to the hybrid algorithm to characterize control valve regulation. In this benchmark optimization, 500 population individuals, and 1,000 generations (both larger than in the optimization performed with the hybrid algorithm), which lead to a total number of objective function evaluations equal to 5×10^5, were used in order to have the same overall computation time as the hybrid algorithm, where a significant computation burden is required by the iterated LP. Figure 1b shows that the Pareto front obtained by means of the new hybrid algorithm dominates that obtained by means of the traditional NSGAII, which also has the drawback of not presenting solutions featuring a number of control valves larger than 2. The worse effectiveness of the traditional NSGAII is due to the bad numerical performance of the fully GA in searching for the optimal control-valve settings besides valve locations. In the hybrid algorithm, the large computation burden associated with the iterated LP is paid back by the subsequent improvement in the overall algorithm performance.

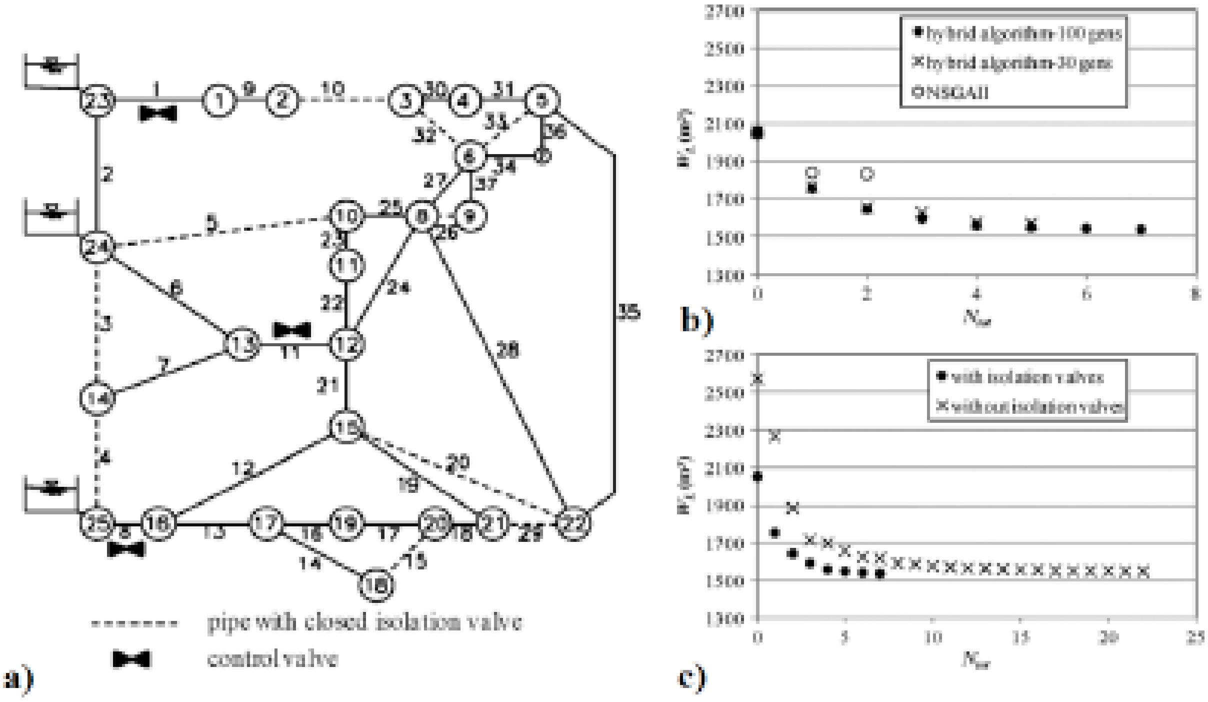

Figure 1. Network of Jowitt & Xu (1990): solution obtained with N_{aw} =3 control valves installed and considering closure of isolation valves (b) Pareto front of optimal solutions in the trade-off between daily leakage volume W_L and number N_{aw} of control valves installed, obtained by applying the hybrid algorithm described in this work; comparison with the Pareto front obtained applying the NSGAII (c) comparison of Pareto fronts obtained while considering or neglecting the possibility of closing the present isolation valves within the hybrid algorithm.

Once the good numerical performance of the new hybrid algorithm has been highlighted, the evaluation of the correctness of the basic assumption of the new methodology, i.e., that related to taking the presence of isolation valves into account, is now focused on. To this end, Figure 1c reports the comparison of the final Pareto front of the optimization performed by using the hybrid algorithm (as in Figure 1b) and the final Pareto front of an optimization performed by using the hybrid algorithm without allowing for the identification of the isolation valves that have to be closed during the optimization process.

In the optimization without isolation valves, the algorithm yields solutions that have objective function values close to those obtainable by the algorithms proposed by previous authors, such as *Nicolini & Zovatto* (2009), up to a number of installed valves $N_{tot} = 5$. The new algorithm has the advantage of also yielding solutions for $N_{tot} > 5$. The analysis of Figure 1c shows that the Pareto front obtained considering the closure of isolation valves dominates the other front (obtained without taking account of the presence of the isolation valves). In other words, in order to obtain a certain daily leakage volume reduction, a larger number of control valves has to be installed if isolation valves are not used to contribute to pressure head lowering as well as to facilitate the control valve regulation.

For example, Figure 1c shows the graphical representation of the Pareto front solution derived from the optimization taking account of the presence of the isolation valves and featuring a number of control valves $N_{tot} = 3$. This solution entails closing the isolation valves present in pipes 3, 4, 5, 10, 15, 20, 26, 29, 32, and 33 and installation of control valves in pipes 1, 8, and 11.

4 CONCLUSIONS

In this paper, a multi-objective algorithm for the combined optimization of pipes and control valves for leakage reduction in water distribution networks was presented. The algorithm makes it possible to explore the trade-off between installation costs (or a surrogate for them) and daily leakage volume. With respect to other algorithms in the scientific literature, the applications pointed out the main advantage of the new algorithm, which lies in the fact that it considers the presence of isolation valves in the network, which can be closed in order to contribute to leakage attenuation and to eliminate water paths around the control valves, thus facilitating control-valve regulation. Another interesting aspect of the algorithm is its hybrid nature, which makes it possible to split the research space between two inner algorithms: a GA, useful to search for the suitable control valve installations and isolation valve closures, and the LP, aimed at searching for the optimal settings of the control valves installed. This hybrid nature makes the algorithm very efficient in comparison to traditional GAs in facing the optimization problem considered in this paper.

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