RE-DESIGN OF WATER DISTRIBUTION NETWORKS USING HYBRID OPTIMIZATION

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ABSTRACT

The objective considered in water distribution network design has usually been the minimization of construction and operational cost. Nevertheless other objectives should be contemplated; for instance water quality has lately become a crucial issue, because of the increased presence of polluting sources and consequently the more frequent contamination. Moreover a lot of literature exists about reliability of water supply systems: networks are often looped in order to face hydraulic and mechanical failure and many indexes has been developed to measure reliability of a water distribution system. Finally, leakage reduction is an important task: the introduction of District Metered Areas (DMAs) has been shown to prove effective for leakage monitoring and control. DMAs are discrete areas of a distribution network usually created by the closure of valves or complete disconnection of pipe work; meters are installed to measure the quantities of water entering and leaving and flow is analysed to quantify the level of leakage. Though guidance criteria exist, they are euristic and the development of a proper procedure to identify the most suitable configuration of DMAs from a previously looped network is still an open issue.

This study focuses on re-design of existing water distribution networks; the purpose is to develop an effective methodology for dividing a network into DMAs considering multiple objectives. Thus a hybrid approach, which incorporates graph partitioning technique into an optimization algorithm, is proposed: in other words the graph partitioning provides different DMAs configurations which are subsequently evaluated by the optimization algorithm. Finally a range of non-dominated solutions, that is the Pareto front, will be found.

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1. INTRODUCTION

Urban water distribution networks are typically designed in order to meet users' water demand and to perform supplying within acceptable pressure; pipe networks are usually made up by a series of interconnected closed loops, in order to ensure delivery of water to the users even if pipe failures occur. As a matter of fact, the optimal design process must consider as objective also the maximisation of the network performance in terms both of reliability and quality of water delivered. The 'minimum cost function' approach do not allow for correctly designing a looped water distribution network because the objective function does not incorporate the concept of reliability adequately, which is the main reason for avoiding a tree shaped network (Todini, 2000). The multiobjective nature of pipe sizing has been highlighted by Walski et al.(2001), and serious limitations of the optimisation based on cost minimization has been shown (Walski, 2001).

Existing water distribution network can require interventions, for instance in order to face changes in water demand, improve network management, reduce water losses; the need to cope with new issues has lead water practitioners to divide the system into districts. This paper focuses on the re-design of water distribution network aimed to partition the existing network into district metered areas (DMAs).

Experience has often shown the benefits brought to water distribution network by the creation of districts, such as leakage reduction, higher water security level and better real time flow monitoring and control (Charalambaus, 2005, Rogers, 2005, MacDonald, 2005). Nevertheless, division of water network division into DMAs has always been made following an empirical approach, based on field investigation and practical considerations without applying a proper methodology. Thus the development of a general and effective procedure able to partition a network and to evaluate the its goodness respect one or more objectives, is still an open issue. This study elaborates a hybrid procedure for optimal re-design of water distribution networks, in order to create district metered areas from a previously looped network.

As mentioned above, multiple objectives should be considered in the optimum search process: thus a Pareto front, which expresses the tradeoff between different objectives, will be found. Besides cost, in water distribution network re-design, reliability and water quality consideration are crucial for a good performance of the resulting network. Reliability is measured through Todini's resilience index, that expresses the surplus of energy per unit time provided respect than that required. Since water quality is associated with the age of water, travel and residence time is used in the procedure. In addition entropy is considered as further network performance indicator.

Thus by comparing the performances of DMAs configurations placed on the Pareto front, water distribution network managers can evaluate the benefits provided by a particular DMAs division rather than another one and make more conscious decisions in a long term overview.

2. WATER DISTRIBUTION NETWORK RE-DESIGN

The re-design of a water distribution network into DMAs is a tricky process, which if not undertaken with care can lead to supply problems, reduction of reliability and worsening water quality (Grayman et al., 2009). Murray et al. (2009) investigated the effects of DMA redesign respect to multiple criteria comparing the performance of two looped network and one DMA system with the corresponding DMAs versions and looped form respectively.

Creating DMAs from an originally looped network means primarily to determine the number of DMAs to be realized, which depends on the number of connections in each district. Secondly, following the criteria recommended by Baker (2009), water entering a DMA should be consumed within the DMA. In fact if DMAs were allowed to flow into downstream DMAs a reduction in the resilience index would be found. Moreover a decrease in water security would occur since in the event of a contamination incident, more district will be exposed to harmful contaminant (Murray et al., 2009). Therefore the pipe (or the pipe series) from which the DMAs will be fed, i.e. main transmission line, needs to be individuated. Finally DMAs boundary is defined. Since in the present study the boundaries are thought to be created by closing valves, the division into DMAs will not be definitive; thus it will be possible to modify the borders in order to manage changes in operating conditions, such that more flexibility to the network district can be provided.

District metering will change the hydraulic behaviour of the existing network and moving from a looped to a divided network may sensibly affect the redundancy; the design of districts has to be done with much attention, with the aid of simulation software, and should result from the comparison of different possible solutions (Di Nardo e Di Natale, 2009).

3. DISTRICT METERED AREAS IN WATER DISTRIBUTION NETWORKS

3.1 DEFINITION AND PURPOSE

District Metered Areas has originally been introduced in water distribution network in order to reduce leakage. A DMA is defined as a discrete area in a water distribution system that can be created by the closure of valves or complete disconnection of pipe work (Figure 1); the quantities of water entering and leaving the area are metered and the inlet and outlet flows can be analysed in order to estimate leakage level within the district (Morrison et al., 2007).

District metering, if implemented correctly, can considerably improve the management of existing water distribution network. Thus continuous flow measures within the districts allow the leakage identification and failure and burst location to be easier and less expensive and the addressing of maintenance interventions to be more effective.

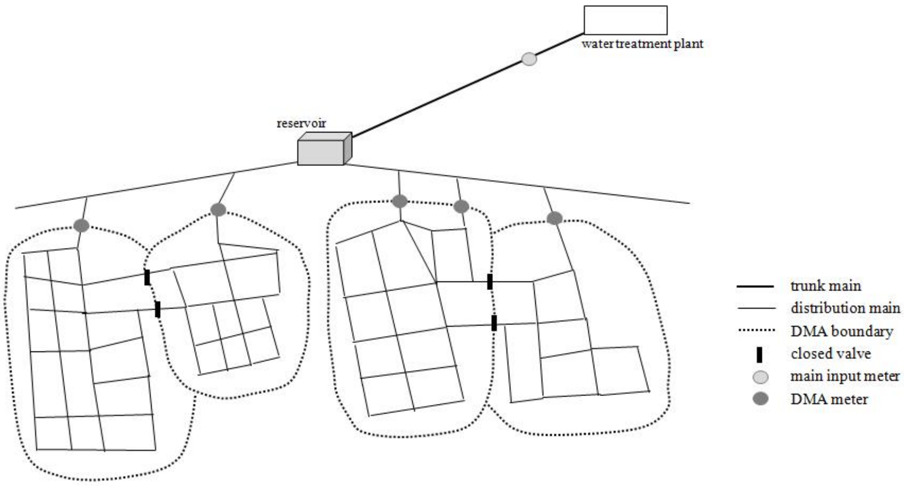

Figure 1 - Example of District Metered Areas configuration.

3.2 DMAS DESIGN CRITERIA

Very little work has been done in literature on developing a theoretical method for DMAs design. However some empirical criteria and general guide lines exist (Farley, 1985, Morrison et al., 2007, Baker, 2009).

In order to create DMAs without significantly affecting the quality of the service to the customers, a detailed and in-depth knowledge of the hydraulic operation of the existing network is required. Another preliminary advice is to separate as much as possible the DMAs from the trunk mains, improving the control of the former without affecting the flexibility of the latter. Furthermore some factors are regarding to be considered when designing a DMA, such as the size (area and number of connections), the economic level of leakage, the variation in ground level, water quality considerations, pressure requirements, fire fighting capacity, final leakage target, number of valves to be closed, number of meters to be installed and infrastructure conditions.

4. HYBRID PROCEDURE FOR OPTIMAL RE-DISIGN

As previously shown, the re-design of a water distribution network into DMAs is a complex issue and a variety of factors needs to be taken into account. Thus a hybrid procedure to find the optimal partition is proposed. It can be defined hybrid because combines the graph partitioning technique with an optimisation algorithm. The former creates the district configuration of the network, while the latter aims to find the optimal partitions set respect to multiple objectives (i. e. the range of solutions laying on the Pareto front).

Since water distribution networks are usually represented by a graph *G(E,V),* where vertices and edges correspond to junctions and pipes respectively, graph theory based methods has been applied in literature to divide the network into DMAs. Award et al. (2009) used Depth First Search to generate tree networks in order to be addressed in pressure reducing valves location. Di Nardo and Di Natale (2009) developed a decision support system for district metered water supply networks design which applied Shortest Path Search in DMAs boundary definition. Indeed they used Dijkstra algorithm in order to find a set of candidate pipes on which insert on/off valves, determining DMAs boundary this way.

Rather, a graph partitioning based method is here proposed. Depth First Search and Dijkstra algorithm are respectively a traversing graph method and a shortest path algorithm, both having a spanning tree as a result (Cormen, 2001). A spanning tree is a graph that includes all the vertices of the network and it is also a tree, i.e. it is connected and contains no cycles. The spanning tree resulting from the originally looped network will thus orient in determining the districts, whose boundaries will be defined according to the branch. By contrast, graph partitioning based method is a thoroughly different approach: given a graph *G(E,V)* where *V* and *E* denote respectively the set of vertices and edges, the balanced *k*-partitioning problem consists in partitioning the vertex set into *k* disjoint subsets approximately equally sized, such that the number of cutting edge is minimized. Hence the graph partitioning can be applied to district metering problem considering an appropriate function to minimized in the cut. Graph partitioning provides directly the partition of the network, a number *k* of clusters, that is DMAs boundary, whilst the former methods give spanning trees.

The whole procedure is showed in to Figure 2: a looped existing water distribution network, which is divided into DMAs applying the graph partitioning. Each edge has a cost of cut (*cce*, cost of cutting edge) defined by a function (Equation 1): thus pipes with bigger diameters will have bigger cutting cost. Varying coefficients α and β different partitions are found and a hydraulic simulation of the partitioned network is then performed using EPANET (Rossman, 2000), in order to verify that the requirement on hydraulic pressure is satisfied at each node and each time step.

$$cce = \alpha \cdot D^{\beta} \qquad (1)$$

Finally an optimisation algorithm will individuate the optimal solution among all the DMAs layouts found using graph partitioning. Four performance indicators are considered as objectives in the optimisation: total cost for the re-design, residence time as surrogate measure of water quality, Todini's resilience (Equation 2) index and entropy (Equation 3) for reliability (Coelho, 1997). Pareto optimal ranking will be found, so that water distribution network management practitioners can be assist in district metering process

$$I_r = \frac{\sum_{i=1}^{n\,nodes} q_i \cdot \left(h_{ava,i} - h_{req,i}\right)}{\sum_{j=1}^{n\,res} Q_j \cdot H_j + \sum_{k=1}^{n\,pumps} P_k/\gamma - \sum_{i=1}^{n\,nodes} q_i h_{req,i}} \quad (2)$$

$$S = -\frac{\sum_{ij \in IJ} \frac{q_{ij}}{Q_0} \ln q_{ij}}{Q_0} \quad \text{(Awumah et al., 1991)} \quad (3)$$

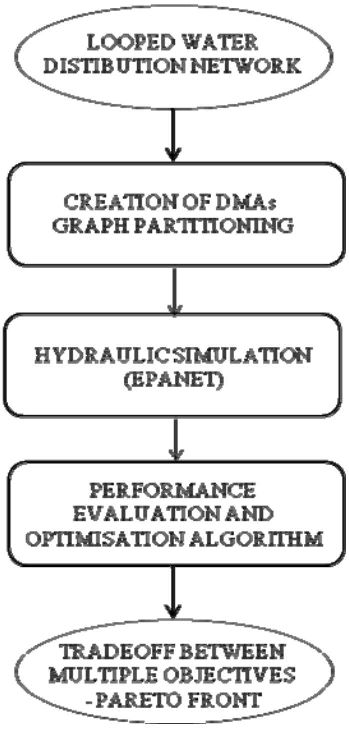

Figure 2 - Hybrid procedure for optimal redesign of water distribution network into DMAs.

5. APPLICATION

Graph partitioning has been applied to district the benchmark network 'Anytown' (Walski et al., 1989) and results are compared with Depth First Search and Dijkstra algorithms.

5.1.1 Depth First Search Based Method

Depth First Search is an algorithm to traverse a graph by visiting neighbour connected vertices, based on the principle of going forward (in depth) while there is such a possibility, otherwise to backtrack (Cormen et al., 2001); it build a spanning tree.

Water distribution network is considered as a directed graph where the orientation of edges are the flow directions corresponding to the peak of consumption. The spanning tree is grown up from the source node and DMAs boundary is defined allowing each district to be fed directly from the source (Figure 3).

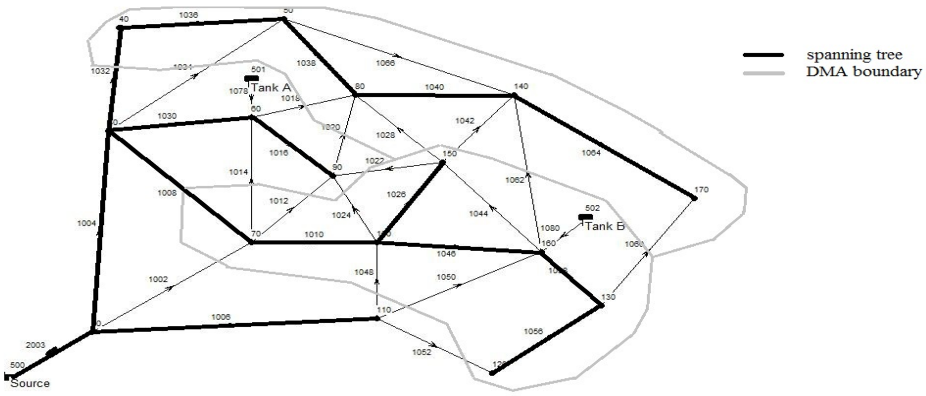

Figure 3 - Depth First Search based district metering.

5.1.2 Dijkstra Algorithm Based Method

Dijkstra algorithm solves the problem of finding the shortest path from a point in a graph to a destination (Dijkstra, 1959). Different results are obtained depending on weights assigned to links, Figure 4 illustrates the DMAs layout resulting from the shortest paths obtained considering directed and no weighted links. According with the previous method, boundaries are settled such that the DMAs are fed directly by the source in order to make them independent one to each other and provide higher water security.

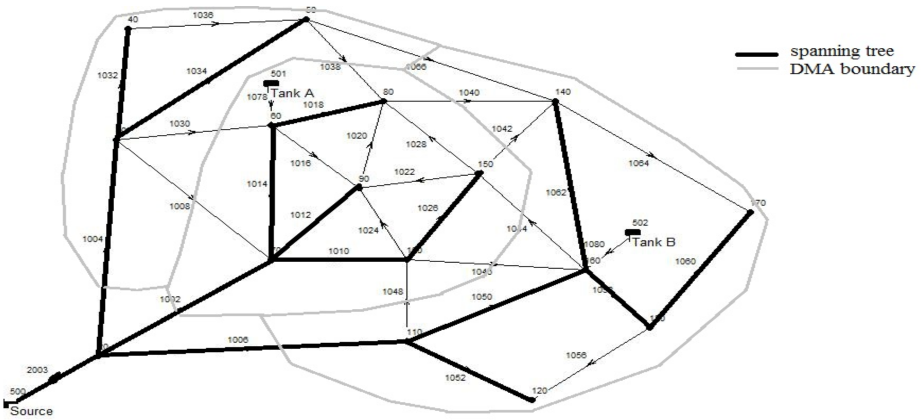

Figure 4 - Dijkstra algorithm based district metering

Path	Destination node
50	2
50 – 2	3
50 – 2 – 11	4
50 – 2 – 11	5
50 – 2 – 3	6
50 – 2	7
50 – 2 – 3 – 6	8
50 – 2 – 3	9

Path	Destination node
50 – 2 – 3	10
50 – 2	11
50 – 2 – 7	12
50 – 2 – 7 – 16	13
50 – 2 – 7 – 16	14
50 – 2 – 3 – 10	15
50 – 2 – 7	16
50 – 2 – 7 – 16 – 13	17

Table 1 - Shortest paths from source node (50).

5.1.3 Graph partitioning

The graph partitioning algorithm utilized for creating DMAs was developed by Hespanha (2004) and it is based on spectral factorization, that implies the formulation of the problem in matrix form. In addiction a symmetric and double stochastic adjacency matrix is required. Graph partitioning does not need the definition of DMAs boundary since the output of the algorithm is the membership subset of each node; as a consequence, boundaries are established by default.

Figure 5 and 6 show the obtained with $\alpha=1$, $\beta=1$ and $\alpha=1$, $\beta=0.4$ (Equation 1).

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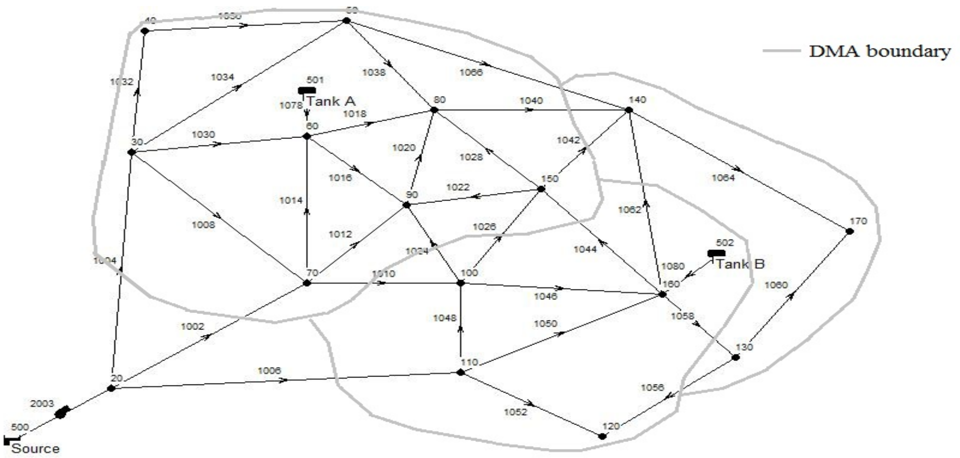

Figure 5 - Graph partitioning district metering (α=1, β=1).

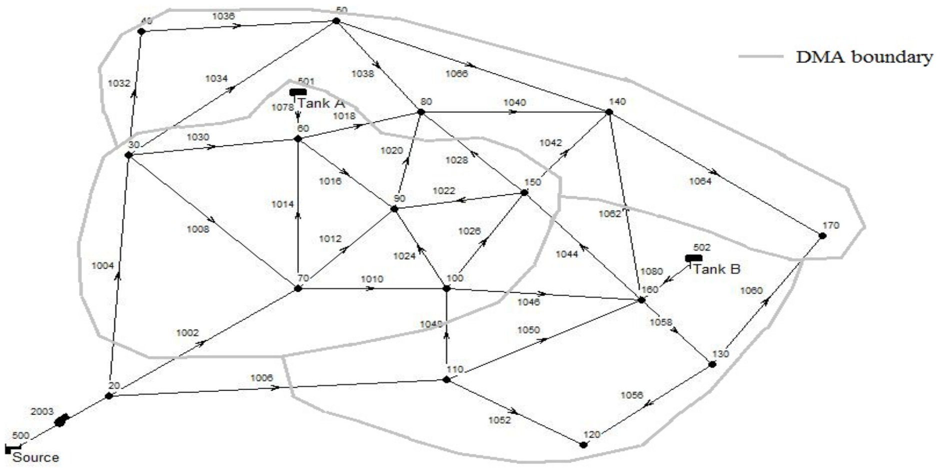

Figure 2 - Graph partitioning district metering (α=1, β=0.4).

6. CONCLUSIONS

A hybrid procedure for optimal DMAs design, based on optimisation of DMAs configuration deduced from graph partitioning, has been proposed. Two graph theory based methods for creating DMAs from a looped network have been compared with the graph partitioning approach. The two methodologies are deeply different because Depth First Search and Dijkstra algorithm generate directed spanning trees, whilst graph partitioning do not consider flow directions and forms clusters of nodes.

Results has shown that the graph partitioning yields more easily to a DMA layout in which some districts can be fed through another district and not directly from the source. Even if this can be accepted in DMA design, it has been proved to reduce water security performance (Award et al., 2009). Nevertheless, effectiveness of graph partitioning algorithm can be enhanced by improving the cost of cutting edge definition (Equation 1) or fixing appropriate constraints on the partition process.

In conclusion, graph partitioning seems to fit well to water network district metering problems, and if integrated into an optimisation algorithm seems to be an effective approach to define DMAs layout characterized by good performance. However, the methodology needs some improvements and the effects of the choice of the partitioning and optimisation algorithms have to be more deeply analyzed.

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