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MODEL-BASED SECTORIZATION OF WATER DISTRIBUTION NETWORKS FOR INCREASED ENERGY EFFICIENCY

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This Efficient management of water supply systems is nowadays one of the most important challenges for water utilities. Common efficiency gains in such systems can be achieved by reducing the leakages and by reducing the energy consumption. For the case of minimization of energy consumption a new technique for sectorization and efficient pressure management is presented, based on water distribution modeling and optimization. The technique is applicable to situations when energy consumption reduction can be achieved by dividing a large Pressure Management Zone (PMZ) in smaller, but more efficient PMZs, or sectors. It consists of two steps: 1) An initial selection of areas of influence of existing water sources (e.g pumping stations) is obtained through tracer analysis; this analysis identifies a set of potential valves that can be used for creating sectors; 2a) the PMZ are determined through a multi-objective optimization using AMGA2, by operation of isolation valves that lead to sectors in a configuration that minimizes energy consumption; 2b) creating the sectors involves an inherent pressure management in each sector, which will be dealt as a pump scheduling optimization problem. The methodology proposed will be applied to the case study of Milano water distribution network under the framework of the on-going EU-FP7 project, ICeWater.

1. INTRODUCTION

A water distribution network (WDN) is the potable water system that most inhabitants in developed and underdeveloped countries use in a constant basis. With the constant growth of populations water utilities become prone to increase their efficiency and reduce their operational losses [10]. When WDN grow too big to control centrally, the systems are then split into subsectors. Division into smaller systems is a necessary methodology in current water distribution systems (WDS) and two approaches can be applied for this task [7].

First, is water network partitioning (WNP), which consists of dividing a network into separate district metered areas (DMA). To perform this, the operation of existing (or new) valves and flow meters, which can be opened or closed at any moment (e.g. manual operation, SCADA) is used to establish new path circulation in the network [8]. DMA are used also to simplify the water balance calculation, water audit and monitoring of water volumes into a certain part of the WDN [1].

Second, is water network sectorization (WNS) and similar to the case of WNP, new split areas are operated, named pressure management zones (PMZ). The main difference with WNP is that in WNS each zone is supplied by its own source (or sources). In this regard, WNS implies a real isolation and operation of the subsystems individually. A second difference between WNS and WNP is that the former requires an additional pressure management. In general, the use of PMZ reduces hydraulic head and water leakage [29]. Other benefits of WNS are availability to perform continuous monitoring of leakages for the utility, increase in reliability, reduction of water shortage [10] and improved network protection against malicious or accidental contamination [9].

1.1 Optimal district creation

Historically the methods for creation of WNP into DMA or WNS into PMZ were based in empirical analysis using variables such as number of connections, properties, number of customers, number of pipes and area of length in a sector [16][33][34]. Only a few researchers have developed optimization approaches for the creation of sectors in a WDN.

First, some authors have denominated this field as decomposition of WDN [24], meaning to separate parts of the network with a single supply source. This approach has been presented using a design problem (minimum cost of deployment of a new network) rather than with the operation of an existing system. Other authors, used graph theory to perform decomposition of the WDN [7][8][35], but yet again only from the design problem perspective. A third approach in the optimal creation of sectors is the use of artificial intelligence and data mining techniques to classify pipes, via graphical and vector information [15] techniques. However, these methods lack of physical characterization given by a hydraulic simulator due to their data driven origins.

Similar to graph theoretical approaches, other authors proposed a fourth approach identifying topological clustering [1][24] or topological changes [14] in WDN. These contributions are useful for decision support of operation and management of WDN, although are not intended for DMA creation. These approaches resemble more the idea of WNP rather than WNS. A recent approach taking concepts both from graph theory and complex systems decomposition theory [10] was used as an alternative for automated DMA development [5]. In this case, the methodology was compared to a hand-made DMA creation in a large WDN (more than 12,000 pipes), nonetheless results were not compared to other methodologies.

In order to perform isolation, either for DMA or PMZ, it is required to estimate optimal location of valves which maximizes or minimizes an objective. Some authors have developed techniques for such purpose [2][10][13][21][25]. Such techniques, are presented as multi-objective optimization problems in which the objective function is measured based on the flows and pressures of a simulation of the WDN, mainly using EPANET2.0 [24]. In all cases the algorithm used for optimization is meta-heuristic, being a genetic algorithm the most common selection (e.g. NSGA-II, [3]).

Decision variables are the set of valves to be opened or closed in the network, and are usually set as binary type variables. This research proposes a similar approach, but instead a new meta-heuristic algorithm, named AMGA2 [31], is selected. AMGA2, stands for Archive based Micro-Genetic Algorithm and uses a reduced number of objective function evaluations while showing better convergence to the real Pareto set in multi-objective optimization benchmark problems. Although to our knowledge (to date) it has not been applied in water resources problems.

1.2 Optimal pressure management

In the case where PMZ sectors have been created, it is required to perform a proper pressure management (PM) to improve energy efficiency use at each individual subsystem. Pressure management is a technique used not only for energy use reduction, but also it is used to reduce pipe bursts and water leakage [12][29]. The economic implications of pressure management are obvious, resulting in lower annual operational costs for utilities due to the connection of pressure and water leakage [19]. To perform optimal pressure management some authors have dealt with the problem in a similar way than for the case of optimal valve location [10][17][27] by operating a set of valves in the network.

Other approach, takes into account the use of pressure regulating valves (PRV). PRV can be classified into three categories: fixed outlet, time modulated and flow modulated. Fixed outlet PRV allow for a fixed rate of flow at every moment of the day, and lack of significance for the case study presented. Time modulation PRV, requires set-up of a time pattern for operation of the valve. This feature is not common in most real systems. As an advantage, time modulation requires a reduced cost of operation and maintenance. Flow modulation in PRV, could be set sensitive to more variables and is able to updates a schedule with a resolution of 1s. For example, the flow modulated PRV can adapt their opening ratio to the current pressure in a critical point of the PMZ [22][25] or they can operate changing the total flow entering the PMZ. The disadvantages of flow modulation are that require installation of additional equipment for control and second that their energy consumption is higher and more expensive to operate. It is impossible to operate the proposed case study without including new elements that are not already installed in the WDN.

In this case the problem of PM will be dealt with a pump scheduling (PS inside every PMZ. In this case the goal is to select which pump operates during a day and which ones are set off, while at the same time maintaining a minimum pressure in each PMZ.

Several authors have dealt with PS, and in most of the cases the decision variable is set to operate or turn off the pump during a time step. Two different approaches can be applied for optimization of pump schedules. First, Implicit Pump Schedule Optimization formulation (IPSO) where the flows and pressures are treated as the decision variables together with the tanks levels [23]. Second, Explicit Pump Schedule Optimization formulation (EPSO) where the actual operation of the pump stations are set as pump switches [20]. This research follows an EPSO approach.

2. CASE STUDY: MILANO WDN

Since October 2012, the EU-FP7, ICeWater project started. ICeWater stands for ICT solutions for Efficient Water Resources Management. The project runs until the end of 2015. One of the project partners is Metropolitana Milanese S.p.A (MM), which is responsible for the operation of the WDN of Milano from source extraction, water treatment, distribution and customer commercialization. MM has provided the data of their WDN for future analysis.

The system supplies potable water to around 1.3 million inhabitants. It is conceived as two connected systems, the transmission network and the distribution network. The transmission network takes groundwater from around 642 wells. The wells accumulate water in 31 tanks distributed along the city. Water is distributed using a network with a total of 29 pump stations with a total of 101 booster pumps. Each pump station varies in the number of tanks and pumps for supply. It can be mentioned as well that each pump station can be operated independently of the others if required. The current research is applied only to the distribution network.

The WDN currently operates as one large PMZ. Around 27,000 valves are located inside the distribution network and its operation can be used to perform a WNS.

The main challenges, from the hydraulic point of view, for operation of the WDN of Milano are: (1) The population has decreased in the city during the last 30 years, and the installed capacity exceeds the required demand. (2) Given the reduced demand the city also operates currently with a higher pressure. This behavior drastically increases, as pointed by operatives of MM, during the summer holiday season when the city becomes largely a "ghost town". (3) The topography of the city varies between 105 and 145 m.a.s.l. The operation of the system as a fully connected PMZ, creates non-efficient energy management of the 101 booster pumps. High pressure in lower parts of the city and low pressure in the higher ground (Figure 1). (4) Excess of pressure in the lower parts of the city has originated, in addition, an increase in pipe bursts in the last 15 years (e.g. near Abbiategrasso pump station).

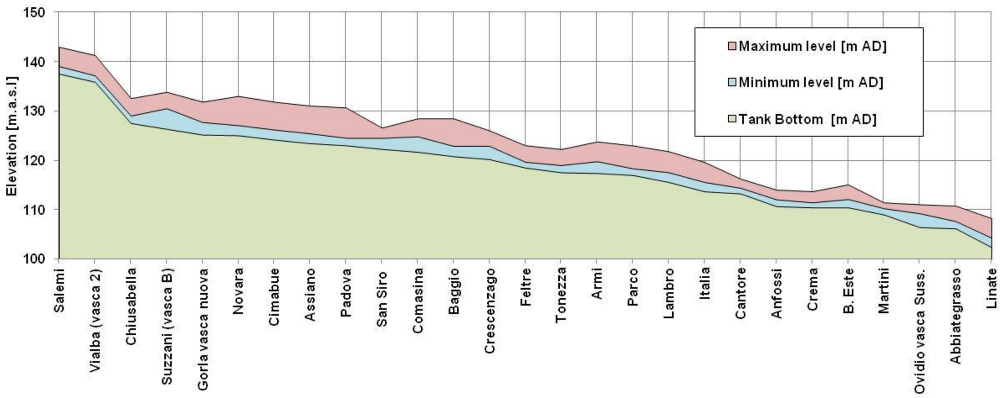

Figure 1. Vertical profile of pump stations at Milano

For all this reasons, the suggested methodology for sectorization will be applied together with the implementation of PM in each PMZ. It is expected that a solution which may decrease energy use, will be achieved at the end of ICeWater project, for the city of Milano.

3. PROPOSED METHODOLOGY

There are 2 steps that are required for the development of a proper sectorization of the system of Milano. First, a reduction in the number of feasible isolation valves used in the optimization process must be performed using tracer analysis. Second, an optimization algorithm is run to select which parts of the city will have its own supply sources. Together with this a PS applied to the system to obtain the minimum energy consumption and maintaining a desired level of reliability in each PMZ. In the following subsections each of the steps will be explained broadly. The methodology proposed here is new, because most of the development of algorithmic WNP and WNS has been applied for design problems and not for planning purposes of real and large WDN.

3.1 Tracer analysis

Although, as presented in section 1.1 most of the research is based on topological and graph theoretical approaches they have surfacing flaws. First, a subjacent assumption that the flows in a pipe can be directed in only one direction at all times is wrong. In a large system water can be brought from different sources changing the flow direction during the day. Second, most of the graph theoretical approaches take into account an initial condition of the system. The usual measure is the major energy loss in pipes, however this initial condition means that you may need to run a simulation beforehand. If you know how the system operates beforehand and where water comes from and where is used, there is no need to make a topological analysis of the system. Third, when estimating the topological distance between nodes, the most frequently used metric used is the pipe loss. Given that the algorithm of calculation for network connectivity is Dijkstra's minimum distance [6], a theoretical issue arises if the first condition is violated. It results in negative metrics (e.g. negative pipe losses) which the algorithm is unable to take into account for calculation.

A tracer analysis is proposed as an initial indicator of the area of influence of each pump station working individually in the network. First, it allows for extended period simulation, allowing pipes to flow in both directions if necessary. Second, the energy losses are computed based on a hydraulic simulation for each pump station independently, isolating its impact on the WDN during operation. Third, the maximum extent of supply for each pump station gives an idea of the possible number of pipes and customer nodes which each pump station can supply in the most critical scenario. Fourth, the tracer analysis hints on a reduced number of valves to be operated from the large number present at Milano, in the boundaries between maximum extents.

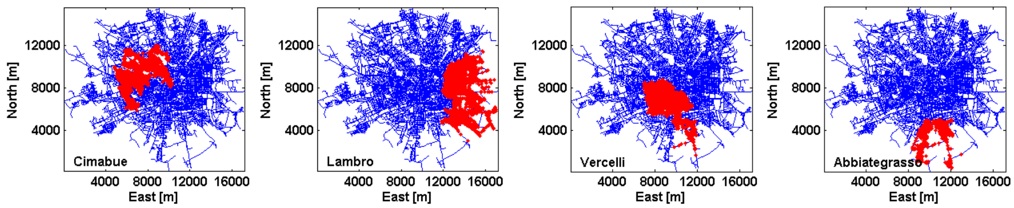

Figure 2. Maximum extent of tracer analysis for sectorization in Milano.

The hydraulic simulation for tracer analysis is performed with the use of EPANET2.0. A model of the WDN was implemented using the most recent data from the GIS system of MM. A source is set from each pump station individually. Initial concentration of the tracer is set to 100 units in each case. Simulations are performed in an extended period simulation for 24 hours. The time resolution of computation is of one hour. The time pattern of demands in the system was set based on a statistical analysis of the demands for ~50,000 customers in the city. For these simulations, all valves are set as open to allow maximum coverage of supply by each pump station. Figure 2, shows the maximum extent of tracer influence (red area) for four different sources in Milano WDN. The selected sources are Cimabue, Lambro, Vercelli and Abbiategrasso pump stations. Similar results can be found for each pump station of the system, covering the whole domain of the city.

3.2 Proposed water network sectorization optimization

The juxtaposition of coverage areas generates subareas in the intersections where groups of valves can be operated to isolate the system as individual PMZ. Being that the case an idealization of the network can be made in which all pump stations can supply one PMZ, and around it between 2 and 4 sets of valves can be opened or closed (Figure 3A). Set of valves means that the valves along the interface between two pump stations will be operated simultaneously. There is also the possibility that two, three or four pump stations can supply water to a specific PMZ.

The problem now becomes to estimate which combination of closure of valves (as a group) guarantees a minimization of energy consumption for each pump station. In the idealization of the problem as presented in Figure 3A there are 47 sets of valves. This is significant reduction in the number of decision variables of the problem from the original set of 27,000 valves.

The decision space is big enough (e.g. 47 sets of valves, 2 states on/off; a total of 2^47 combinations) to adopt the use of a meta-heuristic optimization algorithm. The first set of decision variables (x_v) will be a binary vector (0/1) for each set of valves. In case that the value becomes 0 the valves are closed and reciprocally a value of 1 means that the valves of that set remain open:

$$x_v = \{v_1, v_2, v_3, ..., v_{47}\} \qquad (1a)$$

As a sample Figure 3B and Figure 3C, shows two different combinations of sectorization obtained for the idealization of the Milano network. In general, different numbers of PMZ can be created. Many pump stations that are contiguous work as a single PMZ and also it is possible find isolated PMZ supplied by only one pump station.

A second set of decision variables (x_p) is originated by the fact that after closing the sets of valves, groups of pumps will operate together to supply a single PMZ. To guarantee a reduction of the number of decision variables each pump is considered individually as on or off during the whole simulation. This set of decision variables (x_p) replicates the behavior of x_v :

$$x_p = \{\delta_1, \delta_2, \delta_3, ..., \delta_{101}\} \quad (1b)$$

In this way the total number of decision variables (x) to be optimized will be equal to 148 binary values. During a daily operation the head and discharge of the pumps will be updated by the hydraulic model according to the required demand. The problem will be treated as a multi-objective optimization. Two objective functions will be used during optimization: (a) minimization of energy use in the system, and (b) maximization of resilience of the WDN [32].

The total cost of pumping (2) will be calculated as follows:

$$C = \Delta t \sum_{t=1}^{nt} c_{st} \sum_{k=1}^{npump} \gamma \delta_k Q_{kt} H_{kt} / \eta_k \quad (2)$$

Where, $C =$ Total cost of pumping in the system [eur], $H_{kt} =$ Head of pump k in station at time [m], $Q_{kt} =$ Discharge of pump k at time t [m^3/s], Efficiency of pump k [adim], $\delta_k =$ Binary number of pump operation of pump k (Pump ON =1; Pump OFF = 0) [adim], cost of energy at time t [eur/kW-h], $\Delta t =$ time interval [hr], $\gamma =$ Specific weight of water [kN/m^3]. The goal is to minimize the pumping cost.

If during a time step the pressures fall below the required pressure (20m) in the city, there is a need to estimate how reliable the system is. The reliability metric used is the resilience index (3).

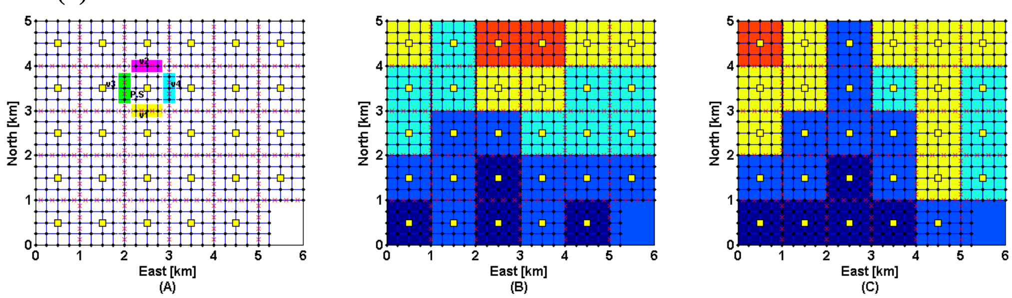

Figure 3. Idealization of the WDN Milano (A) and examples of sectorization (B, C).

The resilience index measures the efficiency of the energy use of the system. It is estimated as the ratio between the excess of energy in the WDN, and the total amount of energy put into the system at any time. A mathematical formulation of resilience index is presented in (3), where, $I_r =$ Resilience Index [between 0 and 1], $h_{ava,i} =$ total head available at node i [m], $h_{req,i} =$ required pressure of node i [m], $q_i =$ Demand of node i [m^3/s], $Q_j =$ Total discharge supplied by source j (tank or reservoir) [m^3/s], $H_j =$ Total head supplied by source j (tank or reservoir) [m], $P_k =$ Total power supplied by pump k [kW], $\gamma =$ specific weight of water [kN/m^3]. In the system of Milano the only energy is supplied by pumping and the tank levels are frown.

$$I_r = \frac{\sum_{i=1}^{nnodes} q_i \left(h_{ava,i} - h_{req,i} \right)}{\left(\sum_{j=1}^{nres} Q_j H_j + \sum_{k=1}^{npumps} \frac{P_k}{\gamma} \right) - \sum_{i=1}^{nnodes} q_i h_{req,i}} \quad (3)$$

As mentioned before AMGA2 is proposed as the optimization algorithm to select the proper combination of set valves. It requires setting a population of decision variables. Figure 4, presents the iterative procedure for optimal WNS and PM. First a set of random decision variables is created, then evaluation of the hydraulic model of the WDN will be performed using EPANET2.0. After that he objective functions are evaluated. Due to the multi-objective nature of the problem a Pareto Non-Dominated selection is implemented in AMGA2 for evolution of the solutions. The iteration continues until a maximum number of generations (*MaxGen*) is completed.

4. EXPECTED RESULTS & CONCLUSIONS

This research is an on-going work in progress. Results of the application of the methodology will be available during the presentation at the conference.

An initial analysis, of tracers in the system of Milano, indicates that there is room for energy consumption reduction applying the proposed methodology for sectorization. It is expected that the reduced energy use in the system can also provide major flexibility in the operation of the system when maintenance of large sectors of the city are planned.

The proposed methodology is intended for the specific case of Milano and its specific characteristics (e.g. topography, pump stations, limited tank storage). Its application to other environments can change drastically and new variables may be taken into account.

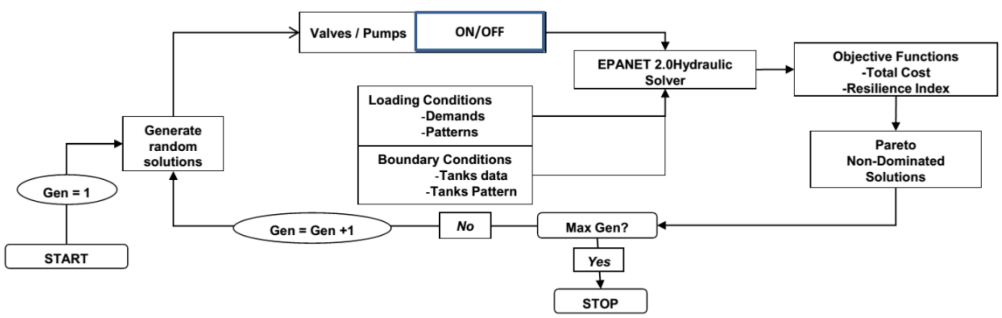

Figure 4. Iterative procedure for WNS and PM using a meta-heuristic algorithm.

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