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Integrated optimal cost and pressure management for water distribution systems

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Abstract

The economic crisis of recent years has refocused interest in minimizing energy consumption in WDS management. An integrated methodology is presented which seeks to fulfill three broad energy-conservation aims: conventional pump-scheduling is considered to minimize direct electricity consumption; concurrently, the optimization considers the production of energy by strategically locating in the network Pumps operating As Turbines (PATs) which can act in an analogous fashion to conventional Pressure Reducing Valves, whilst additionally recovering electricity. Results, obtained on a real WDS, demonstrate a clear economic benefit to installing PATs for energy recovery in conjunction with a pump-scheduling and pressure management regime.

Keywords: Water distribution systems; Energy production; Pump As Turbine (PAT); Pressure Reducing Valve (PRV);

1. Introduction

Owing to the economic and energy crises of recent years, the possibility of promoting alternative energy sources has become of greater interest in many fields. The necessity of satisfying the energy requirements at low cost is leading towards the application of strategies which could simultaneously permit a reduction in consumption and

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allow the production of energy from novel sources. Recently, this objective has been of increasing interest with reference to the operational management of Water Distribution Systems (WDS) which are energy-intensive by their very nature. Hitherto, the reduction of energy consumption in WDS has been usually concerned with developing strategies for reducing pumping costs (e.g. Lansey and Awumah, 1994; Ramos et al., 2012); reducing leakages, i.e. through limiting pressure within the network (e.g. AbdelMeguid and Ulanicki, 2011; Araujo et al., 2006; Germanopoulos and Jowitt, 1989) or taking into consideration both of the above aspects in the optimization process in order to detect the optimal Pareto Front (e.g. Giustolisi et al., 2013; Morley et al., 2013).

The need of reducing overall energy costs required in the operation of a hydraulic system coupled with the necessity of reducing pressures to minimize leakage has spawned the concept of using the pressure dissipation for energy production by inserting turbines in the network (e.g. Artina et al., 2008; Carravetta et al., 2013; Fontana et al., 2012). Owing to the high cost of turbines employed in micro-hydropower stations, an alternative, more economic possibility, is that of using a pump operating in reverse which can act as a turbine: Pump As Turbines (PATs) (e.g. Agarwal, 2012). However, the use of PATs is nowadays limited mainly due to the difficulty of predicting the efficiency of a pump operating in this fashion. This information is not yet disseminated by the device manufacturers and this has led to several studies that tackle this issue based on experimental data or through computational fluid dynamics analysis in order to estimate the PAT performance (e.g. Carravetta et al., 2012; Fecarotta et al., 2011; Derakhshan and Nourbakhsh, 2008; Nautiyal et al., 2010; Williams, 1995). Nevertheless, these investigations do not cover the entire speed range which could be of interest and thus are limiting the applications of PATs in real systems. Naturally, if a PAT is installed where a reduction of pressures was already considered necessary, in order to use that head for energy production, it is required to establish the limitations of PAT mode operation - at the same time guaranteeing in the pressure reduction required in the network for appropriate operation. The principal aim of the optimization problem formulated herein is to suggest a novel methodology which reduces the energy consumption in a WDS by minimizing the pumping costs and considering both the placement of the PATs and the equivalent pressure setting necessary to minimize leakage within the network and to maximize the economic benefit derived from energy recovery. The optimization procedure is undertaken by means of a highly parallelized evolution algorithm employing a pressure-driven analysis in order to evaluate the hydraulic constraints (Morley et al., 2013). A more appropriate analysis has, furthermore, to consider the water demand by means of a probabilistic approach. Under this assumption, the water requirements has been here modelled by means of a normal distribution with a value of the variation coefficient (CV) equal to 0.1 (e.g. Tricarico et al., 2007). The methodology presented has been applied to a real water system which demonstrates a clear economic benefit to installing PATs for energy recovery in conjunction with a pump-scheduling and pressure management regime.

2. Problem formulation

A multiobjective problem has been formulated by considering:

$$\textit{Minimize:} \qquad \textit{pump cost} = \sum_{t=1}^{T} \sum_{k=1}^{N_P} P_k^t \cdot c_k^t \tag{1}$$

$$\textit{Minimize:} \qquad \sum_{t=1}^{T} \sum_{i=1}^{n} \left(P_{i,t} - P_{\min} \right) \tag{2}$$

$$\textit{Maximize:} \qquad \textit{Annual PAT income} \tag{3}$$

where: T - the number of time steps in the extended period simulation; N_p - the number of pumps in the network; P_k - the power consumption of the k^{th} pump [kw/h]; c_k - energy cost tariff for the k^{th} pump [€/kw/h]; $P_{i,t}$ - pressure calculated at node i in the interval time t; P_{min} - minimum pressure requirements for fully satisfy the water demand;

The optimization is thus subject to the hydraulic equation constraints, for each time step:

$$\sum_{j=1}^{N_{j,i}} Q_j - Q_{DEL_i} = 0 \qquad i = 1,\dots,N_n \tag{4}$$

$$H_{j,u} - H_{j,d} = r_j \cdot q_j^{\varepsilon} \qquad j = 1,\dots,N_l \tag{5}$$

where: Q_j is the flow in the j^{th} pipe; Q_{DELi} is the delivered flow at the i^{th} network node; $H_{j,u}$ - head at upstream node of the j^{th} pipe; $H_{j,d}$ - head at downstream node of the j^{th} pipe; r_j - coefficient of the j^{th} pipe (headloss formula, function of pipe length, diameter and roughness coefficient); ε is the flow exponent function of the headloss formula used; $N_{j,i}$ is the number of pipes connected to the i^{th} network node; N_l is the number of network links; N_n the number of network nodes.

Firstly, a solution must be hydraulically feasible – that is to say that there are no nodes in the network experiencing negative pressures and that all of the demands on the system should be met in full. The latter is achieved by specifying a minimum pressure constraint that all nodes in the network with a demand must satisfy in order for a solution to be considered valid.

To produce a sustainable system operation, i.e. operation that is repeatable over successive days, a further constraint is implemented such that the levels of any tanks/reservoirs in the system should be at least as high as they were at the beginning of the scheduling horizon. Additionally, the user may specify a time for each tank at which it must meet a specified level to meet any regulatory requirements to this end.

$$P_i^t \geq P_{\min} \;\; if \;\; Q_{DEL_i}^t > 0 \qquad i = 1,\dots,N_n \;;\; t = 1,\dots,T \tag{6}$$

$$\left(L_{i,0} - L_{i,T}\right) \geq 0 \qquad i = 1,\dots,N_s \tag{7}$$

where: N_s - the number of network tanks P_i – the pressure at the i^{th} network node; $L_{i,0}$ – the level of the i^{th} tank at the initial timestep, $L_{i,T}$– the level of the i^{th} tank at the final timestep.

The minimum pressure requirement has been set equal to 10m for all nodes with an associated demand and the extended period simulation has been considered of a single day with interval times of 1 hour. For each interval time the flow has been considered as a random variable and has been modelled by means of the Normal Distribution in which the mean value is the base demand at network nodes and the CV is set equal to 0.1, the case study considered being a large network which supplies a number of users greater than 1,000 (Tricarico et al., 2007).

For the purposes of pump scheduling, pump decision variables are defined as the unknown status of each pump (1 - working, 0 - not working) for each hour of the scheduling horizon (smaller time intervals can be used too, if appropriate). In addition, prior to the optimization, each pump may have its status fixed to “Always on”, “Always off” or to respect the existing pump control as defined in the hydraulic model – i.e. to exclude it from the optimization process altogether.

The selection of PATs can either be done globally in which any PAT defined in the EPANET model can be installed with any of the PAT types defined or a restricted subset of the PATs can be replaced up to a user-specified quantity. In addition, the initial water levels of each of the tanks in the system can be considered as decision variables.

The above problem has been constrained by considering all of the possible PAT allocations in the network by considering different PAT curves which could be chosen as a function of the flow and pressures available at the point of installation. A wide set of PAT characteristic curves have been considered by varying the number of stages and impeller diameters in order to cover almost all the entire range of flow-pressures that might be encountered. In particular, for this case study, 33 different pumps of the KSB brand (www.ksb.com) has been modelled which could be employed as PATs in reverse mode. The rotational speed of the pump has been considered nominally 1450rpm while operating in turbine mode, rotational speed has been considered as 1500rpm.

The Best Efficiency Point (BEP) has been calculated accordingly with the formulation of Willliams (1995) in which is possible to determine Q_{tb} and H_{tb} of the PAT from the BEP of the pump:

$$Q_{tb} = \frac{N_t}{N_p} \cdot \frac{Q_{pb}}{\eta_{pb}^{0.8}} \qquad H_{tb} = \left(\frac{N_t}{N_p}\right)^2 \cdot \frac{H_{pb}}{\eta_{pb}^{1.2}} \tag{8}$$

where Q is the flow rate; H is the head; N is the rotational speed; η is the efficiency and with the subscripts p, t and b refers to pump, PAT, and BEP, respectively. According to the experimentation undertaken by Derakhshan and Nourbakhsh (2008), the BEP of the PAT was supposed to coincide with pump BEP.

The PAT power (kW) at its BEP can consequently be calculated by:

$$P_{tb} = \rho\, g\, Q_{tb} H_{tb} \eta_{tb} \tag{9}$$

where: ρ and g are the fluid density and gravitational acceleration respectively.

Because water demand varies in a water distribution network, it is necessary to study the characteristic curves away from the BEP, too. The estimation of the PAT characteristic curves on the basis of the BEP has been done by reference to the same experimental study described above (Derakhshan and Nourbakhsh, 2008) which are valid for a pump rotational speed of 1450 rpm, a PAT Nt = 1550 rpm and for centrifugal pumps with specific speed Ns<60 (m,m^3/s):

$$\frac{H_t}{H_{tb}} = 1.0283\left(\frac{Q_t}{Q_{tb}}\right)^2 - 0.5468\left(\frac{Q_t}{Q_{tb}}\right) + 0.5314 \tag{10}$$

$$\frac{P_t}{P_{tb}} = -0.3092\left(\frac{Q_t}{Q_{tb}}\right)^3 + 2.1472\left(\frac{Q_t}{Q_{tb}}\right)^2 - 0.8865\left(\frac{Q_t}{Q_{tb}}\right) + 0.0452 \tag{11}$$

The PAT power, P_t, can be calculated for each time interval in which the day has been segregated and for each PAT. The product of it for the time interval (Δt) in which the PAT is working in a year is the Energy (kWh):

(12)

$$E = \sum_{PAT=1}^{NPAT} \sum_{t=1}^{24} \rho\, g\, Q_t\, H_t\, \eta_t\, \Delta t$$

The PAT Annual Revenue can be thus estimated by multiplying the result of Eq, (12) by the tariff of energy purchase. The cost of energy selling varies as a function of the total power (MWh) produced. For example, according to Italian Financial law, an energy price of 220 €/MWh could be considered for power generation lower than 1 MW.

The annual PAT income that needs to be maximized in the optimization problem is thus obtained by subtracting the PAT maintenance from the annual revenue. As a preliminary study, maintenance cost can be considered to be 15% of the total turbine installation costs, a function of the PAT installation costs and of the civil works required for its installation, which could be approximated as being 30% of the PAT installation costs (Fontana et al., 2012). The latter can be estimated on the basis of the installed power as being of the order of 545 €/kW, considering the sum of the costs of the PAT, the generator and the inverter required to connect the installation to the electrical distribution network (Carravetta et al., 2013). The ratio between the total installation costs and the annual income determines the number of years before a return on investment can be expected.

Given the extended runtimes that can be necessary with evolution algorithms, integrated into the software is the deEPANET (Distributed Evaluation for EPANET) system for parallelizing the computation associated with hydraulic simulation (Morley et al., 2006). This implements a parallel-processing system which can distribute a pool of hydraulic networks awaiting simulation to local processors or remotely to computers on a LAN. Because of the relatively trivial data transfer speeds relative to computational effort required for an extended period hydraulic simulation, near linear improvements in GA runtimes are achieved with the addition of processing cores.

3. Case study

The case study analyzed has been the trunk mains model of the Sorrento Peninsula, Italy, managed by G.O.R.I. S.p.a.. It is located in the Campania region, between the Gulfs of Napoli and Salerno. It supplies eight urban areas totaling around 90,000 users and an additional 70,000 seasonal users during the summer period. In particular the eight water distribution systems supplied by the system are: Vico Equense, Meta, Piano di Sorrento, S. Agnello, Sorrento, Massa Lubrense, Capri and Anacapri, as shown in Fig. 1. Two sources are responsible for supplying the entire system: the well field of Gragnano and the Fontana Grande source.

The trunk mains system is located on a peninsula characterized by the Lattari mountain chain and supplies mountainside communities as well as WDS along the coastal areas. Because of the highly varying elevations of the systems, pumping stations are employed which supply the higher zones present in the network and correspondingly high pressures are established throughout the network that are reduced by means of Pressure Reducing Valves (PRVs), already present in the system. The entire system consists of two reservoirs, 68 tanks and 13 pumps.

The proposed case study is of particular interest for the aims suggested in this paper, being a system in which high and low pressure zones coexist. This leads to the need to pump the water to the higher levels - and thus the necessity of minimizing pumping costs by scheduling the pump operation in accordance with the lowest-priced tariff - whilst simultaneously requiring the significant reduction of pressures in the coastal zones of the network - which is of interest for determining the trade-off between power-generation revenue and operational costs that can be obtained through the use of PATs.

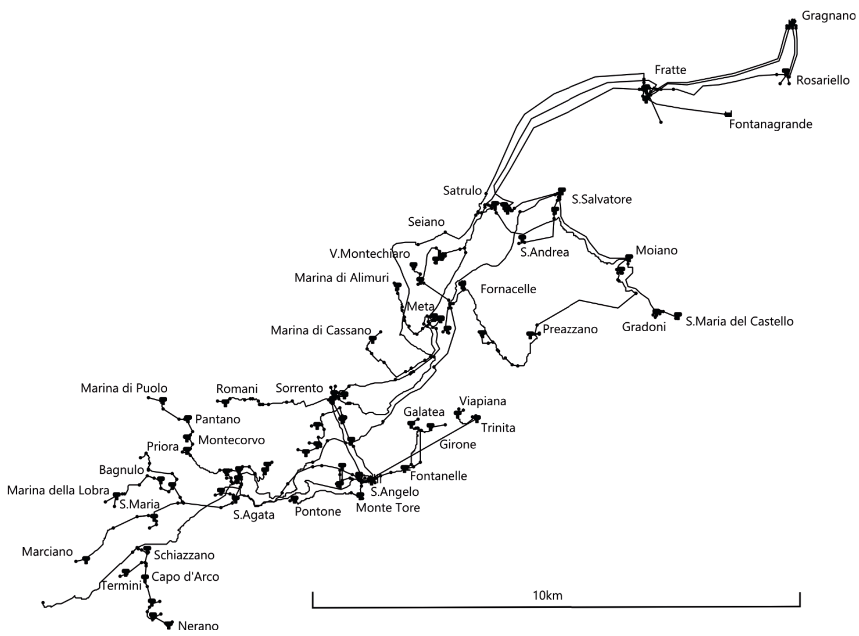

Fig. 1. Plan of the case study area

The problem has been solved by considering the possibility of allocating PATs to replace the existing PRVs in the network. In order to constrain the search space, the total number of PATs to be installed has been limited to maximums of 5, 10 and 15, even if for this case study, as it will be shown in the results, a limited number of 10 PAT is generating a greater income respect to higher pumps number. As well as the 33 available PAT characteristic curves, an "install nothing" option is also available which, if selected, restores the original PRV arrangement.

Furthermore, simulations have been undertaken by considering the water demand required by users firstly as deterministic and subsequently as probabilistic, letting water demands vary following the Normal distribution with a mean value equal to the base demand and a CV equal to 0.1.

Simulations have been undertaken considering the 24 hours of simulation with a time step of 1 hour.

4. Results

Results obtained by applying the approach above described has produced the following Pareto Fronts reported respectively for the deterministic and probabilistic simulations by considering the possibility of allocating in the system a number of installations ranging between 5, 10 and 15 PATs.

By minimizing the surplus pressure and the pumping costs, coupled with the maximization of the PATs income leads to a Pareto Front of solutions which have to take into consideration all these objectives collectively. The choice of a solutions to be adopted, therefore, has to be made among those which are considering the minimum cost energy for pumping, the minimum pressure surplus and at the same time the maximum PAT income (i.e. circled solutions of Fig.2).

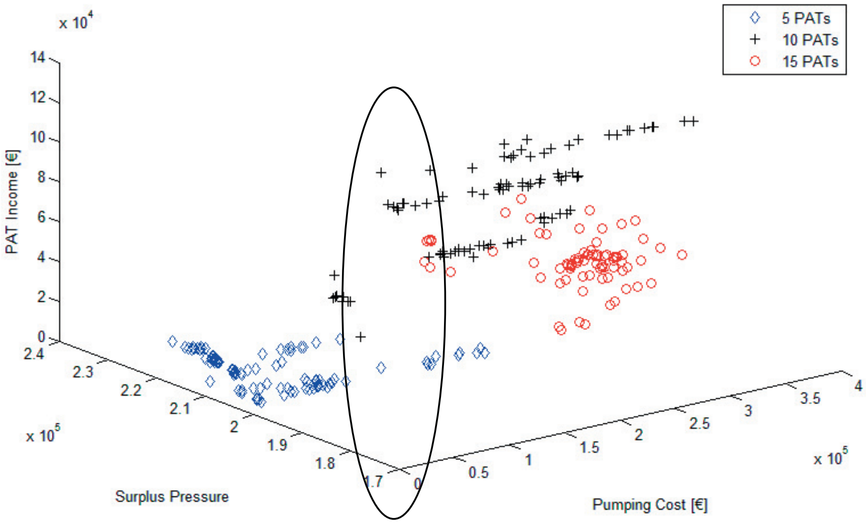

Fig. 2. Pareto Front for deterministic simulations at varying the number of PATs installed

As shown, increasing the number of PATs allocated in the system, also increase the PAT income, although generally these solutions are also associated with a greater pumping cost. In the case of the 15 PAT installations, it can be seen that the income from the PATs is considerably reduced than that seen for the 10 PAT installations – despite an increase in the overall pumping costs for the solutions. It is postulated that this is because the available head in the system is being divided between the greater number of turbines making their installation less economical. Under this assumption is like to considering the 10 as threshold value for PATs installation in this case study.

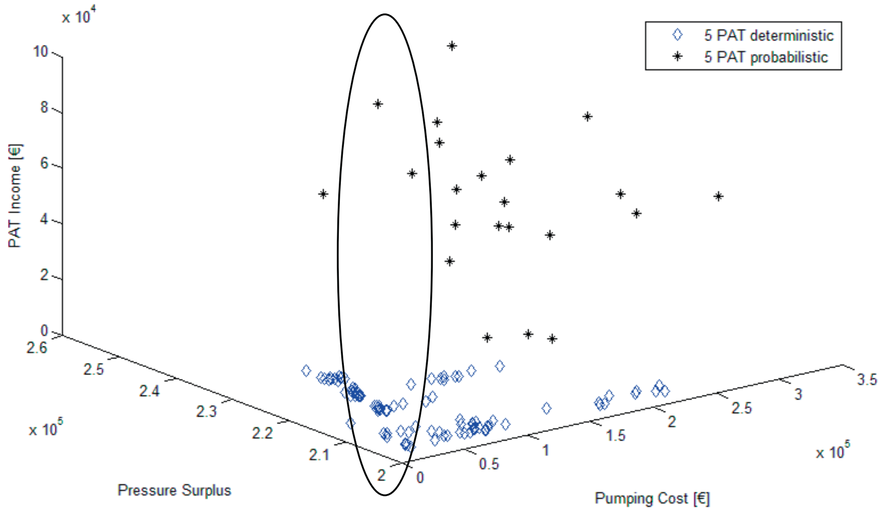

Fig. 3. Comparison of the Pareto Fronts for probabilistic and deterministic simulations with 5 PATs installed

Stochastic solutions, however, for the same number of installed PATs produce solutions with higher pumping costs and greater PAT income with respect to the deterministic solutions (Fig. 3). The latter, indeed, prove sensitive to even small variations in demand. This is demonstrated by the appreciably higher pumping costs associated with the stochastic solutions. These solutions maintain higher pressures within the system and maintain the tanks across the system at a higher level – resulting in more robust solutions. A commensurate increase in the income from the PAT generators is revealed as a side-effect of this higher system-wide pressure.

Almost all of the solutions obtained present a PAT income comparable with respect to the pumping costs which allows one to suggest that if the actual PRVs present in the system where replaced by PATs, the income generated could cover almost all the costs for the operation of the pumps – subject to the existence of a preferential feed-in tariff such as the one in place at the present time. In a few cases solutions have been identified in which the PAT income has been demonstrated to be greater with respect to the pumping costs, as for instance in the solution shown in Fig. 4 which has a pumping costs of €13,840.70 with a PAT income of €14,262.40.

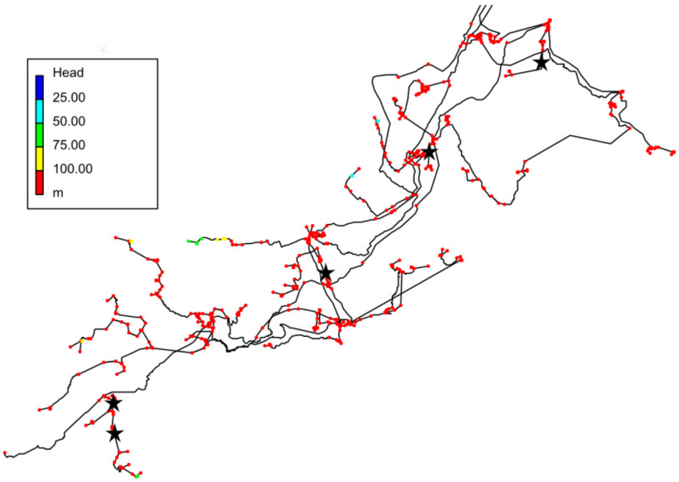

Figure 4. One of the Pareto Front configuration for 5 PATs installed.

This results could allow thus to cover all the energy costs necessary for the pumping but at the same also the possibility to have a revenue from the energy production. Of course, the preliminary results herein proposed should be further analyzed. By comparing all the solutions obtained for 5PATs with the deterministic and probabilistic approaches it is possible to note that they can be placed in the network in different positions in function of the different configurations obtained and that just few of them are overlapping among the two methods (Fig. 5).

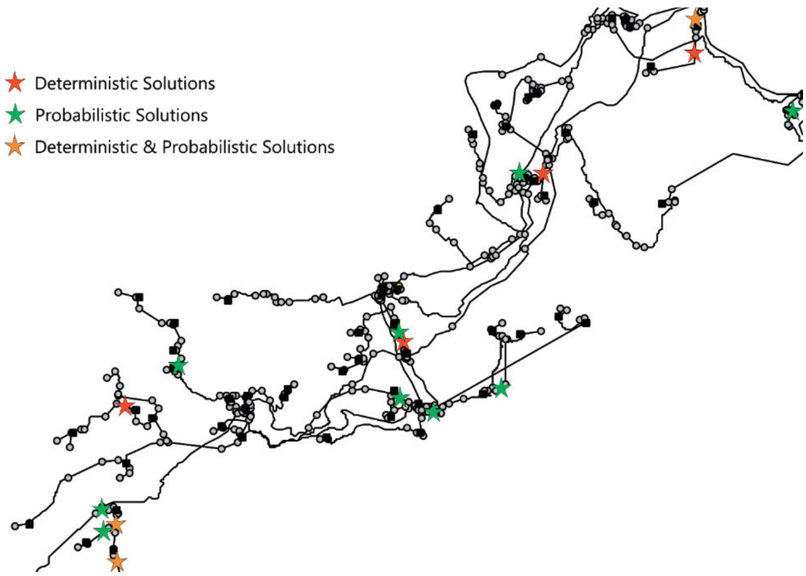

Fig. 5. All possible allocation for 5 PATs in both approaches, deterministic and probabilistic

5. Conclusions

A novel methodology for the WDS pressure management has been suggested in this work which are accomplishing three objectives simultaneously. In particular the minimization of the pumping costs with the minimization of the surplus pressures in order to contain them at the minimum required and at the same time the maximization of the PAT income which can be allocated along the trunk mains instead of the installed PRVs. The problem has been optimized by means of evolutionary algorithms and the results have been compared by considering the approach both as deterministic and probabilistic in the water demanded by users. The possibility of inserting PATs along the mains for energy recovery has shown a clear economic benefit in conjunction with a pump-scheduling and pressure management regime. PAT income has a value almost of the same order of magnitude of the pumping costs, thus allowing a significant reduction of the operating costs for the case study examined. Stochastic solutions are, moreover, presenting which illustrate a higher pumping costs respect to the deterministic ones due to the necessity of maintaining higher pressures within the system and higher level of the tanks across the network, and thus could be considered more robust configurations. As a side effect of this higher system- wide pressure is increased income from the PAT generators for configurations in which water demand has been considered to vary probabilistically. Furthermore, for this case study it has been seen that a threshold values in the number of PATs exists in order to maximize the power generation income.

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