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Minimization of water pumps' electricity usage: A hybrid approach of regression models with optimization

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ABSTRACT

Due to pervasive deployment of electricity-propelled water-pumps, water distribution systems (WDSs) are energy-intensive technologies which are largely operated and controlled by engineers based on their judgments and discretions. Hence energy efficiency in the water sector is a serious concern. To this end, this study is dedicated to the optimal operation of the WDS which is articulated as minimization of the pumps' energy consumption while maintaining flow, pressure, and tank water levels at a minimum level, also known as pump scheduling problem (PSP). This problem is proved to be NP-hard (i.e. a difficult problem computationally). We therefore develop a hybrid methodology incorporating machine-learning techniques as well as optimization methods to address real-life and large-sized WDSs. Other main contributions of this research are (i) in addition to fixed-speed pumps, the variable-speed pumps are optimally controlled, (ii) and operational rules such as water allocation rules can also be explicitly considered in the methodology. This methodology is tested using a large dataset in which the results are found to be highly promising. This methodology has been coded as a user-friendly software composed of MS-Excel (as a user interface), MS-Access (a database), MATLAB (for machine-learning), GAMS (with CPLEX solver for solving optimization problem) and EPANET (to solve hydraulic models).

1. Introduction

Demand for water is projected to significantly increase in the upcoming years and decades. In hindsight, the worldwide water consumption has quadrupled in the last fifty years (see Coelho and Andrade-Campos (2014)). According to the International Energy Agency (IEA), water needs for energy production are set to grow at twice the rate of energy demand (IEA, 2012). The largest strain of increased water consumption is attributed to soaring coal-fueled electricity and biofuel production (see OECD (2013)). To put that into perspective, the water distribution systems (WDSs) and wastewater treatment in the United States are responsible for around four percent of all electricity usages (Denig-Chakroff, 2008; Pasha & Lansey, 2014) and account for about five percent of national greenhouse gas emissions per annum (Griffiths-Sattenspiel & Wilson, 2009). As another example, the water distribution in Toronto consumes five times the energy consumed by all the city's traffic signals and streetlights (Maas, McClenaghan, & Pleasance, 2010).

Operation costs of water pumps are blamed for a large share of the electricity bill associated with running a water distribution system (Bohórquez, Saldarriaga, & Vallejo, 2015; Jowitt & Germanopoulos, 1992; Mala-Jetmarova, Sultanova, & Savic, 2017; Sarbu, 2016). In some studies, around three percent of the worldwide electricity consumption goes to pumping, out of which around ninety percent is exhausted by the motor-pumps (Liu, Ouedraogo, Manghee, & Danilenko, 2012; Moreira & Ramos, 2013). In the city of Milan, Italy, the billing cost of pumping water to 50,000 customers was around 16 M€/year which warranted an investigation to reduce the cost through optimization of the operations of the pumps and that resulted in 26% reduction (Castro-Gama, Pan, Lanfranchi, Jonoski, & Solomatine, 2017). A similar observation has also been reported by other researchers (Boulos et al., 2001).

On the one hand, water pumps of a WDS are largely electricity-intensive and on the other hand, they are poorly and inefficiently being operated. Inefficient pump stations can be caused by an inefficient control of the pumps, or even by an oversized system. Most existing pump systems are oversized (many of them by more than 20%), that in itself highlights a great opportunity to address and rectify such a rampant and large-scale energy ineffi-

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ciency and wastage (Coelho & Andrade-Campos, 2014). Moreover, growing environmental awareness also calls for energy efficiency and hence optimal pump control (Ashok & Banerjee, 2000; Bonvin et al., 2017; Ghaddar, Naoum-Sawaya, Kishimoto, Taheri, & Eck, 2015; Marchi, Simpson, & Ertugrul, 2012; Pulido-Calvo & Gutiérrez-Estrada, 2011). Consequently, there exists an ample space and great economic opportunity to optimize the operations of a WDS.

The improvements of energy efficiency in WDS can be passed through actions such as monitoring operations for leakages control, water demand prediction, pump systems optimization, storage/production reservoir systems optimization and real-time operations (Coelho & Andrade-Campos, 2014). More precisely, the main improvements in energy efficiency can be obtained with: (1) pumping stations and system design improvement; (2) installation of variable-speed pumps (VSPs); (3) efficient operation of pumps; and (4) minimization of water losses through pressure control (Feldman, 2009). The saving potential of the VSPs has been widely investigated and acknowledged in the literature and industry. Vogelesang (2009) quantitatively indicated a potential energy reduction of 27% with only a 10% of pump speed decrease. VSPs have been proven to be an effective way to reduce the pumping energy (Coelho & Andrade-Campos, 2014; Pemberton, 2005). Furthermore, in comparison with conventional pumps, the VSPs reduce the number of switches (on/off) by the pumps which result in a reduction of pipe breaks (Feldman, 2009) and hence a higher efficiency. The number of switches (on/off) is the root cause of high maintenance cost associated with the conventional pumps (Boulos et al., 2001; Wanjiru, Zhang, & Xia, 2016).

Given the above-mentioned efficiency gap embedded in the existing infrastructure and advantages of the variable-speed pumps, authors in this study are motivated to address variable-speed pump scheduling problem (PSP) tailored to real-life WDSs. Therefore, a mathematical programing structure is set up in which the cost of electricity usage pertaining to the VSPs' operation (as an objective function) is minimized subject to a hydraulic model formulated as constraints, that is to meet customers' water demand at an adequate pressure (note that the proposed method can also address fixed-speed pumps). As a solution method, we employ a hybrid method consisting of state-of-the-art techniques in machine-learning and large-scale optimization algorithms (Bagloee, Asadi, Sarvi, & Patriksson, 2018). For the former, we employ supervised learning and curve-fitting methods, and for the latter, we transfer the original problem into an integer (binary) problem to be solved easily. Given the complexity associated with the pumps' scheduling in real world and our conviction to tailor a practical and versatile method, several computing packages and software are interwoven and synthesized in a unifying platform as follows: (i) the methodology is coded using Visual Basic programing language, (ii) MS-Excel is used as a user-friendly interface to communicate input/output with a user, (iii) MS-Access is used as a database to efficiently save and retrieve data during the computations, (iv) for the machine-learning parts (i.e. supervised-learning as well as curve-fitting) we employ MATLAB (MathWorks, 2016), (v) we have encoded the binary problem separately in GAMS (Brooke, Kendrick, & Meeraus, 1996) a highly efficient and capable optimization software and call "express", an efficient solver and (vi) to solve for mathematical equations of the hydraulic model we employ EPANET 2.0 (Rossman, 2000) a computationally efficient and widely used software among researchers and practitioners (Coelho & Andrade-Campos, 2014). Since the primary aim of this study is to address efficiency gap in electricity consumption in real-life water distribution systems, we use a large WDS known as BWSN as a case-study consisting of 14,822 pipes and 12,523 nodes (Ostfeld et al., 2008). Furthermore, we have also tested the proposed methodology to the Richmond benchmark to compare it to three methods developed by some researchers in the literature (Giacomello, Kapelan, & Nicolini, 2012).

The rest of the paper is organized as follows. In the next section, we first present an overview of how a water distribution system works and is modeled which leads to a research question for this study. In Section 3, a review of the relevant studies is provided. In Section 4, the mathematical setup of the methodology is presented. Section 5 is dedicated to the machine-learning followed by numerical tests in Section 6. We conclude the paper in Section 7.

2. Research question: pump scheduling problem

Water distribution system (WDS) is a set of interconnected hydraulics components (pipes, reservoirs, wells, tanks, pumps and valves as well as nodes or junction representing water consumers such as houses, buildings, plants etc.) to convey water from sources to customers with appropriate quality, quantity and pressure (Balekelayi & Tesfamariam, 2017). The WDSs are complex in terms of both size and topology (Abdul Gaffoor, 2017) and they are topologically represented as graph networks. First, one needs to create a mathematical model describing the hydraulic relationship of the WDSs for which a steady-state behavior of water circulation is often assumed that is the hydraulic behavior is presumed to remain constant within a predefined discrete time-step (say an hour). The steady-state formulation governing flow, pressure, and energy loss in the WDSs is based on two general laws which result in a system of nonlinear equations: mass and energy conservation laws (we call them hydraulic equations or hydraulic model). To this end, the U.S. EPA (Environmental Protection Agency) has developed an open-source computer program, EPANET to perform dynamic simulation and water quality analysis over an extended period of time (Rossman, 2000) which is widely used in the industry and academia. Given physical characteristics of a WDS including topography, pumps, sizes and types of pipes, as well as an operation scenario (i.e. when to switch on/off pumps and valves, operations rules etc.), the EPANET computes flowrates in the pipes and hydraulic grade lines at the nodes (Ingeduld, 2003).

In addition to the amount of water demand to be supplied to the customers, represented by nodes (also called junctions), a WDS must also provide water at a minimum pressure (say 18 psi). Price and Ostfeld (2015) employ EPANET 2.0 to solve a hydraulic problem to arrive at an intuitive setup for the pumps operations. If a hydraulic node is found not meeting minimum service pressure, the node is queried in the operational graph to find the shortest (cheapest) path to the node from a water source via a pump (or a series of pumps) using the Dijkstra algorithm. The pump(s) is(are) switched on (or set to operate with a higher speed, in case of a variable-speed pump). Accordingly, the hydraulic solver is then reinitialized and solved with the updated pump operation pattern to search again for nodes not meeting minimum service constraints. The Achilles-hill factor here is the lack of assurance of maintaining demand/pressure constraints satisfied for all the nodes in the subsequent iterations when pumps' setup is subject to change, hence applications of the proposed method to real WDS are yet to be investigated.

On the one hand, arriving at a right operation setup or scenario is a highly complicated task, to the extent, even to this day, in some advanced country, WDSs are controlled manually by municipal operational staff based on their engineering judgment (Abdul Gaffoor, 2017). On the other hand, electricity-driven centrifugal pumps which are widely used in the WDS, as noted above, are operationally expensive, that in turn is a worthy motivation to develop an efficient and systematic control method.

The use of electric pumps in the WDS started in the first half of the 20th century (Bene, 2013). In many cases, pumps operate