Applied Energy 164 (2016) 303–311

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Modeling and optimization of a wastewater pumping system with data-mining methods

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HIGHLIGHTS

- Data-mining methods are applied to wastewater pumping system modeling and optimization.
- Neural networks are used to model pump energy consumption and wastewater flow rate.
- An artificial immune network algorithm is employed to solve the bi-objective optimization problem.
- Six to fourteen percent of energy could be saved when balancing the energy cost and wastewater flow rate.

ARTICLE INFO

Article history:
Received 8 August 2015
Received in revised form 9 November 2015
Accepted 28 November 2015

Keywords:
Neural network
Pumping system
Energy saving
Artificial immune network algorithm
Bi-objective optimization
Data mining

ABSTRACT

In this paper, a data-driven framework for improving the performance of wastewater pumping systems has been developed by fusing knowledge including the data mining, mathematical modeling, and computational intelligence. Modeling pump system performance in terms of the energy consumption and pumped wastewater flow rate based on industrial data with neural networks is examined. A bi-objective optimization model incorporating data-driven components is formulated to minimize the energy consumption and maximize the pumped wastewater flow rate. An adaptive mechanism is developed to automatically determine weights associated with two objectives by considering the wet well level and influent flow rate. The optimization model is solved by an artificial immune network algorithm. A comparative analysis between the optimization results and the observed data is performed to demonstrate the improvement of the pumping system performance. Results indicate that saving energy while maintaining the pumping performance is potentially achievable with the proposed data-driven framework.

1. Introduction

Water supply and treatment processes are energy-intensive. Studies reported that their energy usage accounts for 4% of the national electricity in U.S. [1,2] and 7% of the electrical energy worldwide [3]. Pumps and aeration systems are major energy consumers in a wastewater treatment process. Singh et al. [4] studied the energy auditing of a wastewater treatment process and concluded that pumps consumed a significant share of 79% of the used electrical energy in wastewater treatments. Therefore, it is valuable to investigate the energy saving of wastewater pumps and generate emerging techniques to enhance the sustainable wastewater management.

The improvement of the sustainability in wastewater treatments has been mainly studied from two perspectives including the advancement of the sludge management and the development of the low-energy treatment technology [5]. In studies of the sludge management, applications of novel technologies for digesting sludge and producing biogas have been widely discussed [6–8]. Two categories of studies, the innovation of the wastewater treatment method [9] and the improvement of the wastewater treatment operation [10], have been conducted to achieve a low-energy wastewater treatment. In [9], the potential of energy saving in the nutrient removal process with the utilization of algal reactors was investigated. In [10], a fuzzy logic control was applied to reduce the energy consumption of the wastewater treatment process. Compared with studies in [6–9], the energy saving through improving treatment operations including pump operations does not require additional investments and thus is more beneficial.

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http://dx.doi.org/10.1016/j.apenergy.2015.11.061
0306-2619/

The previous literature majorly studied the operation of single pumps. Raggl et al. [11] presented a sensorless control approach of a permanent-magnet synchronous machine bearingless pump. DeWinter and Kedrosky [12] introduced a 3500-hp adjustable speed drive to control the oil pipeline pump. Himavathi and Umamaheswari [13] developed a fuzzy model to control a three-phase induction motor driving a submergible pump. These studies [11–13] addressed the improvement of the single pump performance through the installation of new hardware. However, the wastewater is moved by the collaboration of multiple pumps in treatment processes. Thus, operations of multi-pumping systems in the wastewater treatment need to be investigated. The previous literature studied multi-pumping systems from the scheduling rather than the control perspective. Wang et al. [14] discussed a bi-objective optimization model of an urban water distribution system. Cost minimization while preventing land subsidence was achieved by optimal scheduling of the water supplying pumps. Barán et al. [15] developed a pump scheduling model with multiple objectives and presented a comparative study of different evolutionary algorithms applied to solving the scheduling model. Zhang et al. [16] proposed a mixed integer nonlinear programming model for optimizing the operational schedule of the wastewater pump system. Scheduling the operations of pumping systems typically investigates the optimal working configurations of pumps each hour while the optimal speed settings for variable speed pumps are not adequately studied.

The development of information technology enables the collection of a large volume of real time pump operational data in wastewater treatment facilities. Measured parameters include the pump operational status (on/off), pump speed, power consumption, head, etc. Through mining collected data, useful knowledge could be discovered to optimize the performance of pumping systems. Compared with traditional pump researches [17–19] and energy saving research [20] conducted with physics-based models, this paper proposes a data-driven framework for modeling the wastewater pumping system and optimizing its performance. A neural network algorithm [21,22] is applied to develop models for predicting the pump energy consumption and the wastewater flow rate after pumping. The modeling capability of neural network has been demonstrated in previous studies including a pump study [23] and a study of modeling a hydro plant [24]. Two objectives, minimizing the energy consumption of the pumping system and maximizing the flow rate of wastewater after pumping (which benefits the safe control of the wet well level), are considered in the model. An adaptive mechanism for assigning weights to two objectives is designed. An artificial immune network algorithm [25,26] is introduced to solve the bi-objective optimization model. A computational study is conducted to analyze the potential of energy saving in the wastewater treatment through optimizing control settings of pump speeds.

2. Description of the pumping system and its data

2.1. Pump configuration

A wastewater treatment plant with the following design specifications is considered in this research. The daily minimum, average, and maximum of raw wastewater flows in design are 113,652 m^3/day, 227,304 m^3/day, and 672,820 m^3/day respectively. The daily minimum, average, and maximum of the biochemical oxygen demand (BOD) in design are 9140 kg/day, 45,722 kg/day, and 127,958 kg/day. The pumping system in the preliminary treatment area of the wastewater treatment plant includes six 55-MGD class variable speed pumps, indexed 1 through 6. Although the six pumps were supplied by the same manufacturer, they were not identical due to the maintenance induced changes. The maximum number of operating pumps is five because one pump is always considered as a backup unit. The pumping system in the preliminary treatment is depicted as Fig. 1.

As shown in Fig. 1, the wastewater is first gathered by sewers and flows into the wastewater treatment plant. A bar screen is employed to strain the solids contained in the influent, and the screened influent is retained in the wet well. The pumping system connects the wet well with the aerated grit chamber. Its main responsibility is to lift the influent from the wet well to the aerated grit chamber.

Due to the change in system dynamics and the ‘‘head influence” phenomenon, the pump curve can no longer offer accurate information for its control. The research reported in this paper sheds light on the control of the pumping system from a data-driven perspective. Pumps in the pumping system are operated in five parallel configurations due to various flow rates of the influent in the wastewater preliminary treatment. Each configuration of pumps includes all combinations of operating pumps. Since the number of combinations present in the dataset available in this research is limited and the number of data points across different configurations varies, the pump configurations with the most data points are selected for analysis. Table 1 presents information on pump configurations.

In this study, four configurations shown in Table 1 are considered. The configuration of five pumps working together is arbitrarily controlled by the plant operator and therefore is not considered in this study. Parameter C is used to describe the configurations of pumps, $C \in \{C_1, C_2, C_3, C_4\}$. The binary value of C (0 and 1) describes the on/off status of the configuration of pumps.

2.2. Wastewater treatment plant data

The data used in this research were collected at a wastewater treatment plant with about 1400 monitored parameters and stored in an SQL server. Four parameters related to the pumping system (e.g., the pump speed, energy consumed by the pumping system, water flow rate after pumping, and wet well level) were selected as a dataset for the study. The length of the dataset is from July 20, 2010 to December 31, 2010.

Values for the four parameters were collected at different sampling intervals. The pump speed and the energy consumed by the pumping system were sampled at 5 min intervals. The water flow rate after pumping was collected every 15 s. The sampling interval of the wet well level was 1 min. Since it is not feasible to analyze the dataset includes parameters with different sampling intervals, the sampling interval of each of the four parameters was synchronized at 5 min. In this study, each configuration of pumps represents a system. Therefore, the pumping system needs to be analyzed based on pump configurations. The processed dataset is separated to four sub-datasets according to the configurations of pumps. Table 2 presents the information of the four sub-datasets. More than half of the data points correspond to the single pump configuration because the influent flow rate is significantly impacted by the rainfall. The dataset contains the data points at the end of summer and fall and at the beginning of winter. In the wastewater processing plant area, rainfall significantly diminishes in late fall and early winter. Each sub-dataset is further split into training and test data sets for data analysis (Section 3).

2.3. Estimated influent flow rate

The influent flow rate is a significant factor impacting the selection of pump configurations and their speed settings as it indicates the workload for pumps. However, such data are not available in the database for several reasons. First, sensors are not mounted