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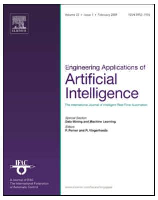

Data-driven minimization of pump operating and maintenance cost

Zijun Zhang [a,*], Xiaofei He [b], Andrew Kusiak [b]

[a] *Department of Systems Engineering & Engineering Management, City University of Hong Kong, Hong Kong*
[b] *Department of Mechanical and Industrial Engineering, 3131 Seamans Center, The University of Iowa, Iowa City, IA 52242-1527, USA*

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ABSTRACT

A data-driven model for scheduling pumps in a wastewater treatment process is proposed. The objective is to minimize the cost of pump operations and maintenance. A neural network algorithm is applied to model performance of the pumps using the data collected at a municipal wastewater treatment plant. The discrete-state Markov process is utilized to develop a model of maintenance decisions. The developed pump performance and maintenance models are integrated into a scheduling model. A hierarchical particle swarm optimization algorithm is designed to solve the proposed scheduling model. The concepts developed in this paper are illustrated with two case studies.

1. Introduction

Producing environmentally safe effluent is the focus of wastewater treatment process (Dalmacija et al., 1996; Chu et al., 2012; Ho and Ho, 2012). Minimizing operational expenses of wastewater treatment processes, including energy consumption, is often used as another objective (Spellman, 2008). Recent reports (Goldstein and Smith, 2002; Bunn and Reynolds, 2009) point out that wastewater treatment processes are energy intensive, particularly due to the use of pumps. Thus, reducing the energy consumption as well as other costs incurred by pumps in wastewater processing is of interest to the industry.

The interest in energy savings for pumps is growing. Ma and Wang (2009) studied the control of variable speed pumps to optimize energy efficiency of air-conditioning systems. Zhuan and Xia (2013) applied model predictive control to reduce electricity cost of running a water pumping station. Golcu et al. (2006) investigated improvement of pump energy efficiency through mechanical design perspective. Wang et al. (2009) discussed energy saving of water supply pumps through the optimal scheduling of the pump operations. Zhuan and Xia (2013) applied dynamic programming to schedule pumps with the objective of minimizing the total cost including energy cost.

Although large-scale solids, e.g., paper and solid objects, are removed by bar screens before processing, the wastewater pumps degrade faster than clean water pumps. Korving et al. (2006) reported that the failure of sewage pumps is highly dependent on the composition of the sewage and discontinuous operation of pumps. In order to guarantee the serviceability of wastewater pumps, appropriate maintenance scheduling which minimizes the maintenance cost and impacts on pump operations becomes extremely important. Several studies of pump overhaul scheduling have been reported (Richardson and Hodkiewicz, 2011). However, the past research seldom considered the interaction between the operation and maintenance scheduling as well as the electricity consumption and maintenance cost.

Integrated scheduling of operations and maintenance has been widely discussed in manufacturing systems. Chung et al. (2009) investigated the production and maintenance scheduling of machines and proposed a modified genetic algorithm to solve the model established in their research. Ruiz et al. (2007) discussed the impact of scheduling and preventative maintenance to flowshop sequencing in manufacturing. Berrichi et al. (2009) proposed a bi-objective optimization model for scheduling production and maintenance of the parallel machines. As presented in Chung et al. (2009), Ruiz et al. (2007), and Berrichi et al. (2009), the integrated scheduling research was mostly conducted in a manufacturing context. Scheduling operations of pumps is different from manufacturing scheduling due to nonlinearity of the pump performance. Thus, a more suitable integrated scheduling model needs to be introduced to schedule operations and maintenance of pumps.

This research presents a pioneering study on scheduling operations and maintenance of pumps in a wastewater treatment process. The objective is to minimize the energy consumption and maintenance cost while maintaining the desired hydraulic workload of wastewater pumps. In wastewater processing, a group of pumps

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[*] Corresponding author.
E-mail addresses: zijzhang@city.edu.hk (Z. Zhang), xiaofei-he@uiowa.edu (X. He), andrew-kusiak@uiowa.edu (A. Kusiak).

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Nomenclature

C_i	ith pump configuration
$\mathbf{y}_{i,t}$	an output vector describing the performance of the ith pump configuration at time window t
$y^1_{i,t}$	the energy consumption of the ith pump configuration at time window t
$y^2_{i,t}$	the wastewater outflow rate of the ith pump configuration at time window t
$f_i(\cdot)$	the multi-input and multi-output (MIMO) model of the ith pump configuration
E_t	the energy consumption of the pump system at time window t
$\mathbf{E}(\bullet)$	the function for estimating total energy consumption when operating the pump system over a maintenance period
F_t	the wastewater outflow rate of the pump system at time window t
l_t	the raw wastewater junction chamber level at time window t
N_C	the total number of pump configurations
N_T	the total number of operational time windows
$\mathbf{x}_{i,t}$	the input vector of the model of the ith pump configuration at time window t
$x^j_{i,t}$	the speed setting of pump j in the ith pump configuration at time window t
s^j_t	the on/off status of pump j at time window t, $s^j_t \in \{0,1\}$
$\mathbf{s}_t$	the vector of s^j_t
$g_{i,j}$	$g_{i,j}=1$, if pump j is operated in the ith pump configuration; otherwise $g_{i,j}=0$
x_{lb}	the lower bound of the pump speed setting
x_{ub}	the upper bound of the pump speed setting
$u_i(\mathbf{s}_t)$	$u_i(\mathbf{s}_t)=1$, if the ith pump configuration is selected according to $\mathbf{s}_t$; otherwise $u_i(\mathbf{s}_t)=0$
e	the measured value of output parameter
$\hat{e}$	the estimated value of output parameter
n_d	the total number of data points
k	the index of data points
d_j	$d_j=1$, if pump j is selected for maintenance; otherwise $d_j=0$
$\mathbf{d}$	the vector of d_j
a	the maintenance action, $a=1$, 2
$\mathbf{P}_a$	the transition matrix of the pump condition states under maintenance action a
R_a	the cost of implementing maintenance action a
r_1	the cost if the pump is healthy after maintenance, usually 0
r_2	the cost if the pump is not fixed after maintenance
$L(\cdot)$	the cost model of the pump operations loss due to the lack of maintenance
$C(\bullet)$	the cost model of maintenance
p^a_{nm}	the transition probability of a pump condition switching from state n to state m under maintenance action a
δ_o	the length of one time window of the pump operation
δ_m	the length of one time window of the pump maintenance
n_w	an integer parameter describes the number of operational time window covered by a maintenance time window
λ_1	the frequency of a pump with condition in state n' at t and in state m' at $t+\delta_m$
λ_2	the frequency of a pump with condition in state n' at t.
A	the area of a wet well
Q_t	the influent flow rate at time t
$\mathbf{v}_1$	a vector for obtaining the energy consumption from the output of MIMO model
$\mathbf{v}_2$	a vector for obtaining the wastewater outflow rate from the output of MIMO model
V	the total cost of operating and maintaining the pump system
$V_{\mathbf{d},a}$	the total cost of operating and maintaining the pump system given $\mathbf{d}$ and a
t_m	the time window of starting pump maintenance
N^p, M^p	the particle sizes in the 1st and 2nd layer search of the Hierarchical Particle Swarm Optimization (HPSO)
G	the termination criteria of the 1st and 2nd layer search of HPSO
fit_1	the best fitness of the 1st layer search of HPSO
fit_2	the best fitness of the 2nd layer search of HPSO
$\mathbf{vs}'$	the vector of candidate solutions in the 1st layer search of HPSO
$\mathbf{vx}'$	the vector of candidate solutions in the 2nd layer search of HPSO
υ	the particle velocity in HPSO
ps	the particle position in HPSO
lbest	the local best position of particles in HPSO
gbest	the global best position of the swarm in HPSO
ω	the inertia parameter of flight()
h,q	the velocity control parameter of particles in flight()

operate collaboratively. Due to the head effect, the dynamics of pumps working in parallel configuration is not simply a linear combination of the dynamics of individual pumps. Thus, the traditional pump efficiency curves restrict the potential space for further enhancement of the pump performance. In this research, a data-driven approach rather than physics-based one (van Zyl et al., 2004; Hajji et al., 2010; Lopez-Ibanez et al., 2008) is applied to model pumps working at various configurations and predict energy consumption. The modeling power of data-mining algorithms has been demonstrated in numerous studies (Kusiak and Zhang, 2012; Verma et al., 2013). Moreover, the data-driven models are adaptive to the variation of pump system dynamics over time based on continuous updates. Such modeling approach saves the cost of tuning pumps efficiency curves. The maintenance decision-making is formulated as a Markov decision process (MDP) (Bellman, 1957). The feasibility of using a Markov decision process in studying machine maintenance scheduling was demonstrated in Abeygunawardane et al. (2013) and Wu and Zhao (2010). The optimization model includes the data-driven pump performance model and MDP maintenance decision-making model. Due to the model complexity, an extended particle swarm optimization algorithm is applied to solve it. Two case studies, Case 1 and 2, are presented to demonstrate the capability of proposed model in generating high quality operations and maintenance schedules.

Besides application to pumps, the proposed framework is potentially applicable to schedule operations and maintenance of other energy consumption and production systems involving multiple units, e.g., wind turbines.

2. Pump performance model

A pump system including six heterogeneous pumps in a wastewater treatment process is investigated. This system delivers wastewater from