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Data-driven modeling approach for performance analysis and optimal operation of a cooling tower

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ABSTRACT

This paper proposes a data-driven adaptive modeling approach to investigate the performance and optimal operation of a cooling tower for energy conservation. To achieve this aim, the cooling tower process was first characterized by an adaptive model with nonnegative garrote (NNG) variable selection procedure, which ensured a compact and robust input–output relation. Owing to the high accuracy of the obtained model, implementing the optimal operation strategy for energy saving became readily practicable. Subsequently, on the basis of the statistical results of NNG variable selection, the effects of ambient air temperature and humidity on the cooling capacity of the tower were investigated by principal component analysis (PCA). Finally, the optimal strategy of fan operation was proposed and its implementation was virtually studied based on data from the actual operation of a cooling tower, which showed that there was considerable room for energy conservation. This is the first attempt to use the NNG variable selection method for developing model for cooling tower and to propose a model-based control scheme for operating a cooling tower.

1. Introduction

Mathematical model and/or empirical model, that predict output variables, are essential in process system analyses. These models are useful if they contain important information regarding the relationships between the output variables and adjustable input variables, because the process quality can then be improved by changing these input variables. Various modeling methods and applications have been studied in different fields [1].

Many challenging issues in model development remain unresolved. For example, input–output relations may be nonlinear and change with time as the operating conditions of a process change. Adaptive models or just-in-time models are often used to deal with the time-varying characteristics of industrial processes [2,3]. Although non-parametric models such as neural networks or multiple local model networks are often used to handle nonlinearity [4,5], such black-box models inevitably suffer from potential overfitting and vague interpretability. Moreover, although linear multivariate statistical analyses such as principal component regression (PCR), partial least squares (PLS), and canonical variable analysis (CVA) can compress the sensor variables into a few key latent variables [6–8], they may still include contributions from a large number of predictor variables. This is highly undesirable because operators would fail to understand the physical meanings of the input–output relations and focus on a manageable number of key factors.

Proper variable selection is important for the transparency and robustness of a model [9]. Recently, shrinkage methods that perform variable selection by shrinking or setting some coefficients of a "greedy" model to zero are receiving much attention. A popular form of these methods is the nonnegative garrote (NNG) [10], which has not been widely used for modeling process systems.

Cooling towers are a very important part of many processes, such as power generation systems, chemical or petrochemical plants, and refrigeration or air-condition systems. They dissipate waste heat from hot process streams into the environment by virtue of mass and heat transfer between the cooling water and ambient air. Investigating whether there is substantial room for energy conservation by improving the operation of cooling towers is of significant importance because they consume enormous amounts of electrical energy.

Theoretical analyses of cooling towers can be traced back to the work of Merkel [11], who first developed a theory for thermal evaluation of a cooling tower by making some simplifying assumptions. Subsequently, revisions of Merkel's approximations,

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Nomenclature

$T_{cw,in}$	inlet water temperature of cooling tower (°C)
$T_{cw,out}$	outlet water temperature of cooling tower(°C)
F_{cw}	water mass flow rate of cooling tower (kg/h)
P_{air}	atmospheric pressure (hPa)
V_{wind}	wind speed (m/s)
$T^D_{air,in}$	dry bulb temperature of inlet air to the cooling tower (°C)
$E_{air,in}$	enthalpy of inlet air to the cooling tower (kJ/kg)
$E_{air,out}$	enthalpy of outlet air from the cooling tower (kJ/kg)
m^D_{air}	mass flow rate of dry air (kg/h)
$H_{air,in}$	relative humidity of inlet air to the cooling tower (%)
W_{fan}	cooling tower fan power (mW)
F_{air}	flow rate of dry air (calculated from the fan power consumption)
n_{fan}	fan rotate speed (n/min)
γ_{cw}	cooling tower effect index (°C kg/h kW)

such as the effectiveness-NTU method [12] and Poppe method [13], were proposed; these methods have been comprehensively reviewed by Kloppers and Kröger [14].

Some studies focused on cooling water design problem via software simulation and experimental data [15–17]. Some researchers investigated the effects of special fill materials and fill styles on cooling performance [18–21]. Based on the Merkel's method and the Poppe model, Serna-González *et al.* presented mixed-integer nonlinear programming (MINLP) algorithms to obtain the optimal design of mechanical draft counter flow cooling towers [22,23]. Performance assessment is another important issue. Besides CTI (cooling tower institute) standard specification [24], some performance assessment methods were presented, namely, effectiveness-NTU based analysis [25], exergy analysis [26], software simulation [27,28], or fouling model development [29].

As noted above, an important issue is whether there is considerable room for energy conservation by improving the operation of cooling towers [30–32]. Here, by using actual process data, the NNG variable selection method was employed to develop an adaptive modeling method for cooling towers, and the optimal operation conditions for energy saving were investigated. Principal component analysis (PCA) was adopted to analyze the effect of environment temperature and humidity on the cooling capacity of the cooling tower. The optimal strategy of fan operation was proposed and virtually studied with actual process data obtained from operating a cooling tower. The formulation of the model does not take pumping power of cooling water into account, because it is almost constant in this study.

The rest of the paper is organized as follows. In the next section, a description of the system and the problem statement are introduced. In Section 3, an adaptive modeling method based on NNG variable selection is developed for a cooling tower. A model-based optimal strategy is proposed and implemented to improve the actual operation of a cooling tower in Section 4. A summary with some concluding remarks is presented in Section 5.

2. System background description

A pump draws water and sends it to the top of the cooling tower fill. The water is then evenly sprayed over the fill while ambient air is pulled into the tower from opposite sides by a cooling fan at a rate determined by the operator. After absorbing heat from the hot water stream, the air stream is expelled through the top of the cooling tower. As a result of rejecting heat to the air stream, the temperature of the water steam drops; the steam then flows into the water basin, after which its temperature rises when the waste heat is removed from the hot process.

The general variables used to represent a cross-flow induced draft tower can be grouped into two types: (1) the cooling water-related variables of inlet water temperature $T_{cw,in}$, outlet water temperature $T_{cw,out}$, and water mass flow rate F_{cw}; and (2) the ambient air-related variables of the dry bulb temperature of inlet air $T^D_{air,in}$, relative humidity of inlet air $H_{air,in}$, mass flow rate of dry air m^D_{air}, atmospheric pressure of inlet air P_{air} and wind speed V_{wind}.

The object of study is a cooling tower in a large iron and steel plant in Taiwan, which supplies cooling water for hot processes such as tandem cold mills (TCMs) and continuous annealing lines (CALs). The cooling tower unit in this plant has three fans, each of which operates in one of 3 modes: close, low speed, and high speed. Owing to the restriction of the turn-down ratio, the fan set usually operates in one of the following seven modes ordered from low to high levels: three closed (C3_L0_H0), two closed and one low speed (C2_L1_H0), one closed and two low speed (C1_L2_H0), three low speed (C0_L3_H0), two low speed and one high speed (C0_L2_H1), one low speed and two high speed (C0_L1_H2), and three high speed (C0_L0_H3).

The 60,250 samples used in this study were collected from the cooling tower within five months, *i.e.*, from March 2011 and between December 2011 and May 2012. The data on cooling tower operation were obtained every 5 min. After removing the abnormal samples when the hot processes were out of production, 60,000 samples remained.

Owing to frequent variation in production processes, the cooling fan is often manipulated by the field operator at high operation modes to ensure that the outlet water temperature is lower than the required level. This inevitably results in unnecessary consumption of electricity energy. The objective of this study is to investigate how to operate the cooling tower with minimum energy consumption and meet the temperature requirements for cooling water.

3. Adaptive modeling for cooling tower

3.1. NNG variable selection

The NNG method can be generalized to a two-stage shrinkage method. In the first stage the sign for each variable is determined using the ordinary least squares (OLS) procedure. In the second stage, the corresponding magnitudes are computed by solving a series of constrained quadratic programming problems.

Assume being given a set of observation data {**X**, **y**}, where $\mathbf{X} \in \mathrm{R}^{n\times px}$ is an input matrix whose columns represent the measured candidate variables, and $\mathbf{y} \in \mathrm{R}^{n\times 1}$ is the corresponding vector of response data. Suppose that **X** and **y** have been normalized to zero-mean and unit standard deviation. Let $\hat{\boldsymbol{\beta}} \in R^{p_x\times 1}$ be a set of the ordinary least square estimates of the coefficients for the following linear model

$$\boldsymbol{y} = \boldsymbol{X\beta} + \in \tag{1}$$

The second stage shrinkage can be formulated as the following optimization problem:

$$J = \min_{c_j} \sum_{i=1}^{n} (y_i - \boldsymbol{X_i c}. \times \hat{\boldsymbol{\beta}})^2 \quad \text{subject to} \quad c_j \geq 0, \quad \sum_{j=1}^{p_x} c_j \leq s \tag{2}$$