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Minimizing energy consumption of an air handling unit with a computational intelligence approach

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ABSTRACT

A data-mining approach is applied to optimize the energy consumption of an air handling unit. A multi-perceptron ensemble algorithm is used to model a chiller, a pump, and the supply and return fans. A non-linear model is developed to minimize the total energy consumption of the air-handling unit while maintaining the temperature of the supply air and the static pressure in a predetermined range. A dynamic, penalty-based, electromagnetism-like algorithm is designed to solve the proposed model. In all, 200 test data points are used to validate the proposed algorithm. The computational results show that the energy consumed by the air-handling unit is reduced by almost 23%.

1. Introduction

The world's consumption of energy has increased over the years. Heating, ventilation, and air-conditioning (HVAC) systems use as much as 60% of the energy consumed in buildings [1], and they account for approximately 30% of the total energy consumption in the United States [2]. The energy efficiency of HVAC systems is being considered as a vehicle for accomplishing energy savings.

Many research efforts related to the modeling and optimization of HVAC systems have been reported in the literature. Lu et al. [3,4] formulated a mixed-integer, non-linearly constrained model for minimizing the energy consumption of HVAC systems. Engdahl and Johansson [5] minimized the energy use of a system with variable air volumes by setting the supply air temperature optimally in response to load, fan power, coefficient of performance of the chiller, outdoor temperature, and outdoor relative humidity. They showed that the recommended control strategy was more energy-efficient than requiring a constant temperature for the supply air. Numerous studies involving multi-objective optimization of HVAC systems have been performed to determine the most effective trade-offs between total energy cost and indoor thermal comfort [6–9]. Nassif et al. [6,9] proposed a supervisory control strategy for online optimization of energy use and thermal comfort by adjusting set points of local-loop controllers in a multi-zone HVAC system. Wright et al. [8] applied a genetic algorithm to seek optimal settings for the temperature and flow rate of the supply air for a single-zone HVAC system.

The air handling unit (AHU) in an HVAC system impacts its overall performance. The goal of our research was to minimize the total energy consumption of an AHU system while maintaining the temperature and static pressure of the supply air at an acceptable level. Four controllable variables, i.e., the flow rate of the chilled water supply, the position of the chilled-water coil valve, the temperature of the chilled water supply, and the speed of the supply fan speed were taken into consideration for optimal control. It is challenging to solve HVAC models because of their multi-dimensional and non-linear nature. Thus, in this paper, a data-mining approach was used to develop dynamic energy-consumption models of an AHU system. Data-mining algorithms can identify operating patterns using large datasets even when there is limited insight into the underlying operations and physical processes. Applications of data mining in the manufacturing, marketing, and energy industries [10–13] have proven its effectiveness in decision making and optimization. To obtain optimal settings for the AHU system, a novel, intelligent algorithm, i.e., the electromagnetism-like algorithm (EM) [14], was proposed. A dynamic, penalty-based approach was embedded into the EM to address the non-linear constraints. The approach proposed in this paper has been validated with datasets collected in an industrial AHU system.

2. Model formulation

A typical air handling unit (AHU) of an HVAC system supplies conditioned air to building zones. Fig. 1 illustrates the schematic diagram of such an AHU system. The supply air is at a specific

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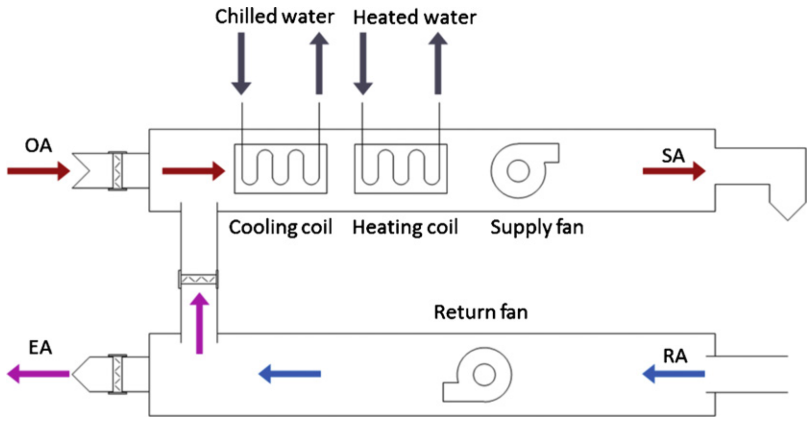

Fig. 1. Schematic diagram of a typical AHU system.

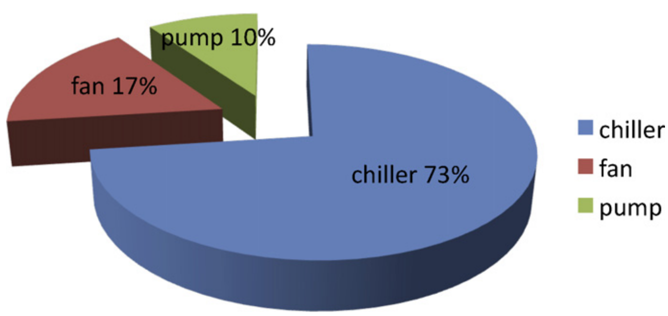

Fig. 2. Energy consumption of different components in a sample cooling session.

temperature and flows at a specific rate to meet the heating or cooling load and ensure thermal comfort. Outdoor air mixes with the return air, and the mixed air passes through cooling coils, heating coils, and the supply fan. Chilled water in the cooling coils cools the mixed air, and hot water or steam in the heating coils heats the mixed air to maintain the desired temperature of the supply.

The supply and return fans assist in moving the air for heat exchange as well as circulating it in the HVAC system at the required flow rate. Several components, i.e., the chiller, the boiler, the supply and return fans, and the water pump, consume energy. Since the experiment for this research was conducted between June 22, 2011 and July 5, 2011, the energy used for heating was insignificant and, thus, was not taken into consideration.

Fig. 2 shows the energy consumption of different components of the HVAC system. Because our two-week experiment was performed in the summer, the chiller accounted for most of the energy consumed by the AHU system. The amount of energy consumed by a chiller is highly dependent on the heat transfer efficiency of the cooling coils. The greater the efficiency is, the less the energy consumption is. Turbulent air and water flows result in greater heat transfer efficiency than laminar flows [15]. This suggests that instead of keeping the air and water flows moderate or steady, keeping them turbulent or being changed frequently and dramatically would make the heat transfer more efficient. A trade-off of the energy consumption between the chiller, the pump, and the fans can be accomplished by controlling the temperature of the chilled water supply, the flow rate of the water, and the flow rate of the air flow at optimal conditions. Thus, four controllable variables, i.e., the flow rate of the chilled water, the temperature of the chilled water, the position of the valve on the chilled water coil, and the speed of the supply fan, were considered to optimize the total energy consumed by the chiller, the pump, and the fans while maintaining the temperature and static pressure of the supply air at the required levels.

A data-mining approach was used to establish dynamic predictive models of the energy consumption of different components of the AHU system. Based on large datasets, the data-mining algorithms captured the dynamic operating patterns of the system. After the learning process, data-driven predictive models were developed. Once the current values of the inputs are determined, the output of the system at some chosen future time can be predicted by the models. Eq. (1), below, is a typical, multi-input, single-output predictive model derived by the data-mining algorithms:

$$y(t+d) = f(x(t), x(t-1), \cdots, u(t), u(t-1), \cdots,) \tag{1}$$

where $x \in R^m$ is a vector of m controllable variables, $u \in R^n$ is a vector of n uncontrollable variables, and $y(t+d)$ is the predicted values of the outputs at time stamp $(t+d)$.

Note that the terms $y_1(t+d)$, $y_2(t+d)$, $y_3(t+d)$ are the energy consumed by the chiller, the fans, and the pump, respectively.

The AHU energy optimization model is presented in (2).

$$\begin{aligned}
&\min\ E_{total} \\
&E_{total} = E_{fans} + E_{pump} + E_{chiller} \\
&E_{fans}(t+d) = f(\vec{x}_1(t+d), \cdots, \vec{x}_1(t), \vec{x}_1(t-1), \cdots, \vec{u}_1(t), \vec{u}_1(t-1), \cdots) \\
&E_{pump}(t+d) = f(\vec{x}_2(t+d), \cdots, \vec{x}_2(t), \vec{x}_2(t-1), \cdots, \vec{u}_2(t), \vec{u}_2(t-1), \cdots) \\
&E_{chiller}(t+d) = f(\vec{x}_3(t+d), \cdots, \vec{x}_3(t), \vec{x}_3(t-1), \cdots, \vec{u}_3(t), \vec{u}_3(t-1), \cdots) \\
&T(t+d) = f(\vec{x}_4(t+d), \cdots, \vec{x}_4(t), \vec{x}_4(t-1), \cdots, \vec{u}_4(t), \vec{u}_4(t-1), \cdots) \\
&P(t+d) = f(\vec{x}_5(t+d), \cdots, \vec{x}_5(t), \vec{x}_5(t-1), \cdots, \vec{u}_5(t), \vec{u}_5(t-1), \cdots)
\end{aligned} \tag{2}$$

$$\begin{aligned}
&\text{Subject to :} \\
&\vec{x}_i \in S_i (i = 1, 2, \cdots, 5) \\
&T \in S_T \\
&P \in S_P
\end{aligned}$$

where each $\vec{x}_i$ and $\vec{u}_i (i = 1, 2, \cdots, 5)$ represent the controllable and uncontrollable variables used for each predictive model, respectively. $T(t+d)$ and $P(t+d)$ are the temperature and static pressure of the supply air, respectively, at time stamp $(t+d)$ after passing through the AHU system. S refers to the constraints imposed by each variable.

3. Model development and validation

3.1. Description of the experiment and preprocessing of the data

The HVAC system discussed in this paper is operated by the Energy Resource Station (ERS) of the Iowa Energy Center in Ankeny,