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Performance optimization of HVAC systems with computational intelligence algorithms

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ABSTRACT

A model for minimization of HVAC energy consumption and room temperature ramp rate is presented. A data-driven approach is employed to construct the relationship between input and output parameters using data collected from a commercial building. Computational intelligence algorithms are applied to solve the non-parametric model. Experiments are conducted to analyze performance of the three computational intelligence algorithms. The experiment results indicate that particle swarm optimization and harmony search algorithms are suitable for solving the proposed optimization model. Three case studies of HVAC performance optimization based on simulation are presented. The computational results demonstrate that simultaneous minimization of energy and room temperature ramp rate is more beneficial than minimization of energy only. The proposed approach is implemented to demonstrate its capability of saving energy.

1. Introduction

Minimizing the energy consumption of heating, ventilation, and air conditioning (HVAC) systems is of concern as it constitutes over 50% of the building energy consumed in the US [1]. Studies of saving energy in HVAC systems have been addressed using two main approaches, updating hardware [2,3] and improving control strategies [4–6]. Research of updating hardware focuses on introducing novel technologies to improve the functionality of the HVAC sub-systems and its conditioning environments. In [2], Niu et al. examined the possibility of energy saving by replacing traditional all-air systems with water-panel type cooled-ceiling systems in a building. In [3], Cordoba et al. studied reduction of energy consumption of HVAC system by using coated glazing for office buildings.

Improved HVAC control may reduce its energy consumption without additional costs. The supervisory control has been widely applied to improve the efficiency of HVAC systems [7]. The model-based HVAC supervisory control has been vigorously investigated to achieve more advanced performance. In such studies, an accurate model for predicting HVAC energy consumption by optimizing control settings is critical. Typically, physics-based models, such as Stoecker's model [8], were mainly considered in studying HVAC control. Fong et al. [4] studied energy management of HVAC system by computing optimal settings based on Physics-based models. Lu et al. [9,10] formulated a global energy optimization model for a HVAC system by integrating mathematical models of its major components and conducted simulation studies. Wang and Jin [11] studied the optimal control of an air-conditioning system using physics models. Alcala et al. [12] applied fuzzy logic approach to determine the control settings of HVAC for minimizing its energy consumption. Physical models offer general mathematical form for accurately depicting major components of HVAC systems. They are applicable to conduct simulations of various HVAC systems. However, most of physical-based models, particularly detailed models, are complicated. Solving these models commonly requires iterative processes which may result in instability and divergence as well as high computational cost and memory demand [13]. Studies of simplified HVAC control problems with physics-based models have also been addressed. The main goal of such research is to discover effective control insights with much lower computational cost. Nassif and Moujaes [14] investigated three combinations of controller setting points for saving energy of HVAC system based on physics models.

Recently, data-driven models rather than physics-based models have been applied to investigate HVAC systems. Teeter and Chow [15] presented an early work of using neural network to

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Nomenclature

d	time interval, 15 min in this study
$g()$	the energy consumption model
$f_i()$	the model of room i's temperature
$\mathbf{E}$	a vector of observed energy consumption, kWh
y	the observed value of the output parameter of the data-driven model
$\hat{y}$	the predicted value of the output parameter of the data-driven model
n	the total number of data points
m	the total number of rooms
$\mathbf{x}_{t+d}$	a vector of controlled parameters at time $t+d$
$\mathbf{x}_t$	a vector of controlled parameters at time t
$\mathbf{u}_t$	a vector of uncontrolled parameters at time t
E_{t+d}	computed energy consumption from time t to time $t+d$, kWh
E_t	computed energy consumption from time $t-d$ to time t, kWh
$T_{t,i}$	computed temperature of room i at t, °F
$T_{t+d,i}$	computed temperature of room i at $t+d$, °F
$R_{t,i}$	standardized ramp of room i's temperature at t
$U_{T,i}$	the upper boundary of T of room i, °F
$L_{T,i}$	the lower boundary of T of room i, °F
$\mathbf{x}_l$	a vector of the lower boundaries of controllable parameters
$\mathbf{x}_u$	a vector of the upper boundaries of controllable parameters
O	the objective considered in the optimization
w	the coefficients assigned to the objectives in the objective function
ξ	the allowable maximum increment of room temperature at each update
a_1^i	the size of the initial population in algorithm i, $i\in$\{EA, PSO, HS\}
a_i^{EA}	the size of the offspring population for $i=2$, mutation parameters for $i=3$ and 4, and size of tournament selection for $i=5$
a_i^{PSO}	parameter controlling the velocity of flight in PSO, $i=2, 3, 4$
a_i^{HS}	the size of the harmony memory for $i=2$, harmony memory consideration rate (HMCR) for $i=3$, pitch adjusting rate (PAR) for $i=4$, and band width for $i=5$
ε_1	the average frequency of convergence in 200 iterations
ε_2	the average computational time of convergence, s
fit	the value of O computed based on solution candidates

model HVAC systems. Lee et al. [16] applied neural networks to study fault diagnosis of the air-handling units in HVAC systems. Kusiak et al. [17] applied a data-driven approach to optimize the energy consumption of air-handling units. Data-driven approaches are promising in modeling complicated systems and numerous applications have been reported [18–20]. Such approaches are powerful to extract accurate models customized for targeted systems through fitting data. The supervisory control systems are able to collect data of HVAC system conditions, which offers a solid platform for applying data-driven approaches.

The objectives of HVAC control majorly include the reduction of energy consumption and improvement of comfort level. In this research, a rarely considered important objective, minimization of the average of room temperature ramp rate (TRR), is considered in HVAC control besides minimization of energy consumption. A TRR expresses the change of room temperature over a sampling time interval, e.g., 15 min. The average TRR is the mean TRR of five considered rooms. The minimization of the energy consumption only at a given time interval may result in significant fluctuations of the room temperature, reduce the energy saving space, and even increase the future energy consumption. The minimization of TRR is beneficial to smooth the settings of the controlled set points and stabilize the energy saving. Moreover, this study considers the minimization of total energy consumption of an HVAC system rather than the energy consumption of its components in several previous studies [17]. The total energy consumption consists of energy consumed by air handling units (AHU), chillers, pumps, and fans. A data-driven approach is applied to build predictive models of energy consumption and average TRR. The accuracy of the predictive models is validated. In the control, two set points are optimized, the discharged air temperature set point (DAT-SP) and the supply air static pressure set point (SP-SP), in order to discover the more suitable balance between air flow rate and inlet temperature in five rooms, reduce the total energy consumption, and ensure comfort. The variable air volume (VAV) boxes are controlled by the default proportional integral derivative (PID) controller.

A performance optimization model is introduced by incorporating the data-driven predictive models and constraints. Solving the proposed optimization model with traditional solution algorithms is challenging because of the complexity and nonlinearity. Thus, three computational intelligence (CI) algorithms are considered for the model solving: an evolutionary algorithm [21,22], a particle swarm optimization [23], and a harmony search algorithm [24,25]. The performance of these algorithms depends on their parameter settings. The design and analysis of computer experiments (DACE) [26,27] is introduced to generate 300 samples of parameter settings for each algorithm to compare three CI algorithms. Five instances are considered in the evaluation. The best performing CI algorithm is selected to optimize the HVAC system's performance. Three cases are investigated in this study to demonstrate the improvement in the HVAC system's performance. The computational results are assessed by comparing with the baseline strategies. Significant energy savings are demonstrated in this simulation. The benefit of TRR as a factor in energy optimization for a long-time horizon is validated. The implementation of proposed methodology has also been conducted and the results prove that the energy saving can be achieved.

2. Predictive models of HVAC system

2.1. System description

This study was conducted in a commercial building, the University Service Building (USB) at the University of Iowa. In the USB, one air handling unit (AHU), controlled by a direct digital controller (DDC), is utilized to serve the heating, air conditioning, and ventilation of a three-floor building with a gross floor area of 71,123 ft^2 (6607 m^2). The schematic drawing of AHU for USB is shown in Fig. 1. Supply and return fans are used for circulate the air in the considered building. Pumps are applied to circulate water of heat exchangers. The variable air volume (VAV) box is mounted and controlled in each room.

The AHU of USB was operated by constantly fixing the values of the temperature set point (DAT-SP) and the static pressure set point (SP-SP) at 55 °F (12.78 °C) and 2.3 in. WG (0.57 kPa), respectively. This constant setting aims to guarantee sufficient capacity for most of the peak loads. However, in the summer period with exceptionally high outside air temperature, the air conditioning of the considered HVAC is insufficient to several zones and extra