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On optimization of thermal sensation satisfaction rate and energy efficiency of public rooms: A case study

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ABSTRACT

For sustainability, many studies have been conducted on energy saving for HVAC (heating, ventilation, and air-conditioning) systems. In a public place, different persons may have different thermal comfort requirements. Few studies are done so far for energy saving in a public place with HVAC systems that can accommodate many persons with thermal sensation differences for different persons being taken into account. In this work, during the summer from May to September in 2016, an investigation for energy saving is done in a large library room at Macau University of Science and Technology, Macau, China. In such a large room, the temperature in different areas is different and many students with different thermal sensations study in the room at the same time. Under such an environment, to save energy as well as maximize the total thermal satisfactory rate, a large number of experiments are carried out. Based on the collected data, methods are given to predict the indoor temperature for each reading area and thermal satisfactory rate under the current indoor temperature. Then, an efficient algorithm is developed to maximize the thermal satisfactory rate for the entire room by optimizing the input temperature of the ACC (air-conditioning control) system such that energy can be saved. Results show that, under the worst situation, by comparing with the manual control, the daily electricity saving is about 93 kWh and the electricity saving during the period from May to September is about 13,950 kWh.

1. Introduction

Environmental issues, such as climate change and global warming, attract more and more attention for sustainable development. For this purpose, it is vitally important to save resources, reduce energy consumption and pollution. Traditionally, in operating production systems, there are various objectives to be optimized, such as productivity maximization [Bai et al., 2016; Wu and Zhou, 2012a; and Wu et al., 2013], cost minimization [Hou et al., 2017], minimization of the usage of critical resources [Zhang et al., 2017], and constraint satisfaction [Yang et al., 2017; and Wu and Zhou, 2012b]. However, no significant attention was paid for the energy issue. Recently, with sustainable development as a vitally important issue, energy saving is an important objective in operating a production system and great attention has been paid for it [Wang et al., 2016; Wu et al., 2016, 2017].

It is known that energy consumption in buildings contributes a significant part of the total energy consumption in both developed and developing countries [Jia et al., 2015]. Thus, in recent years, besides the energy issue in operating production systems, great attention has been paid to find energy-saving solutions for buildings. In a building, heating, ventilation, and air-conditioning (HVAC) systems are responsible for the largest share in energy consumption of all building energy consumers [U.S. Dept. Energy, 2012]. Therefore, it is critical to find efficient and effective ways to manage HVAC systems for improving the energy efficiency and reducing the energy cost of buildings.

As the simplest way for HVAC control, thermostats are used to provide temperature feedback for what is known bang-bang control [Kwadzogah et al., 2013]. Specifically, by such a method, if the current temperature is below/above the set-point, a heating/cooling unit would be turned on until the temperature returns to the set-point. Although it is a straightforward and inexpensive control method, it is ineffective in accurately tracking the set-point temperature and wasteful in terms of energy. By replacing bang-bang control with a simple and relatively inexpensive PID (proportional, integral and derivative) controller, tracking error can be

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overcome. However, such a control method is still energy-consuming [Guo and Zhou, 2012].

In order to save energy in HVAC systems, MPC (model predictive control) approaches can be used to predict its future evolution and obtain its optimal control in a moving horizon basis. MPC is usually adopted as a supervisory controller at a hierarchically higher level, while PID is used to control individual thermal zones at a lower level [Maasoumy and Sangiovanni-Vincentelli, 2012]. As a class of control methods, MPC is used to control a rolling process that runs an embedded optimization model repeatedly to obtain a sequence of decision variable adjustments based on updated forecasts of uncertain variables [Chen et al., 2013]. Therefore, MPC is the only control methodology that takes the prediction of future system behaviors into consideration [Kwadzogah et al., 2013].

Great efforts have been made in energy saving for buildings by using MPC. In [Kelman et al., 2011], an MPC approach is proposed to minimize energy use in HVAC systems. Then, the phenomenon of a local optima of the MPC model for HVAC systems is investigated in order to develop tailored branch and bound algorithms with guarantees of convergence to the global optimality. In [Siroky et al., 2011], MPC is applied for energy savings in a building heating system and the results from real implementation show that the energy saving potential are between 15% and 28%. In [Ma et al., 2012], an MPC approach is presented for building cooling systems with thermal energy storage in order to minimize energy consumption while satisfying the cooling demand of the campus and operational constraints. In [Deng et al., 2015], an MPC strategy is proposed to optimally schedule a campus central plant and a heuristic algorithm is developed to obtain suboptimal solutions for the MPC problem.

Although the aforementioned results show that energy consumption can be minimized by applying an MPC approach, its performance depends on the accuracy of a model. It means that the simplification of building models and unpredicted external disturbance make it difficult to put MPC approaches into practice. A public place can accommodate many persons at the same time, while different persons may have different thermal comfort requirements. Such differences of thermal comfort requirements are not considered in above mentioned studies.

The ASHRAE (American Society of Heating, Refrigerating and Air-conditioning Engineers) defined thermal comfort as “the condition of the mind in which satisfaction is expressed with the thermal environment” [ANSI/ASHRAE Standard 55]. Since a large number of factors affect the perception of human beings, persons who have a common culture and stay in very similar spaces may have very different opinions on thermal comfort. Even in the same environment, thermal sensations are different among people [Djongyang et al., 2010]. Thermal sensation is strongly affected by the following six factors: four physical variables (air temperature, air velocity, relative humidity, mean radiant temperature) and two personal variables (clothing insulation and activity level, i.e., metabolic rate) [Lin and Deng, 2008].

In a building's environmental system, the cooling or heating control system is adjusted according to the thermal comfort standards which determine the energy consumption. Therefore, the thermal comfort standards play a significant role in building sustainability [Yao et al., 2009]. There are two different approaches to evaluate the thermal comfort: the rational or heat-balance approach and the adaptive approach [Doherty and Arens, 1988]. Each of them has its potentialities and limits. The rational approach uses data from climate chamber studies to support its theory [Kwok and Rajkovich, 2010]. A well-known work by using such an approach is the Predicted Mean Vote – Predicted Percent Dissatisfied model (PMV-PPD) [Fanger, 1970]. It presents a uniform description of how the thermal sensations are related to the environment parameters and the personal factors.

By following Fanger's work, a series of studies are conducted as stated in the follows. In [Oseland, 1995], a two-phase method is proposed for analyzing the thermal comfort of 30 employees in their home, office and a climate chamber. By the study in [Humphreys and Nical, 2002], it indicates that PMV often differs markedly and systematically from the actual mean vote, both for naturally ventilated and air-conditioned spaces and efforts are made to explore the scope for improving PMV. A one-objective optimization algorithm is presented by Djuric et al. [2007] to minimize the total costs under the condition that the thermal comfort represented by PPD is satisfied. A novel two-stage regression of the ASHRAE empirical PMV model is built by Wu and Sun [2012], which incorporates architectural parameters and control variables as predictors. In [Langevin et al., 2013], probability distributions are developed for each of comfort variables by using Bayesian probit analysis. With the distributions, revised PMV-PPD curves for field offices are presented.

Different from the rational or heat-balance approach, the adaptive approach uses data from field studies of people in building [Kwok and Rajkovich, 2010]. With the adaptive approach, thermal comfort models and techniques are presented. An indirect method for determining the midpoint of the thermal comfort temperature is presented in [Zingano, 2001]. An enthalpy estimation is proposed by Chu and Jong [2008] for thermal comfort control and energy saving. A theoretically adaptive model of thermal comfort is developed in [Yao et al., 2009] based on the “Black Box” theory by considering culture, climate, social, psychological and behavioral adaptations. An overview of the tools for predicting ventilation performance in buildings can be found in [Chen, 2009]. A field study of thermal comfort is conducted by Wang [2006] with regard to sex (male, female) in residential buildings in Harbin, northeast of China. It is found that males are less sensitive to temperature variations than females. With the adaptive approach, the studies of thermal comfort in classrooms are reported in [Corgnati et al., 2009; and Buratti and Ricciardi, 2009]. They present the relationship between the thermal comfort and the environment during different seasons. With the application of information technology in an office environment, a data-driven learning method is proposed for the personalized thermal comfort [Zhao et al., 2014a] and individual thermal complaint by using the feedback data from information acquisition system [Zhao et al., 2014b]. Besides, studies on thermal comfort of patients in hospitals and people in outdoor spaces are conducted in [Hwang et al., 2007] and [Zambrano et al., 2006], respectively. Recently, field studies are encouraged to obtain more reliable information about the actual workplace comfort and the relevant parameters.

In many cases, there are a large number of people in a large room where the temperatures of different areas are different. Also, in the same environment, thermal sensations are different among people as well [Djongyang et al., 2010]. As far as the authors know, such differences are not considered in the existing studies for maximizing the thermal sensations of the people in the whole room, and at the same time, minimizing the energy consumption by controlling the HVAC system. This motivates us to conduct this study.

In this work, an experimental investigation is done in a large indoor room that is at the third floor of the library of Macau University of Science and Technology, Macau, China. From May to September in Macau, the ACC (air-conditioning control) system in the university is always running during the day since the average outside temperature of each month is over 25 °C. The investigation is carried out in such days in 2016. By considering that there are a large number of people in a large room and thermal sensations among different individuals are different, the main objective of this