Building and Environment 56 (2012) 69–77

Contents lists available at SciVerse ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Multi-stage regression linear parametric models of room temperature in office buildings

Siyu Wu, Jian-Qiao Sun*

School of Engineering, University of California, 5200 North Lake Road, Merced, CA 95343, USA

ARTICLE INFO

Article history:
Received 25 October 2011
Received in revised form
3 January 2012
Accepted 22 February 2012

Keywords:
HVAC system
Temperature model
Multi-stage regression
Autoregressive model

ABSTRACT

Mathematical models of the heating, ventilation, and air conditioning (HVAC) components play an important role in control design and fault detection of the system. The work in this paper incorporates architectural parameters in linear parametric models of room temperature in office buildings. Specifically, we allow the physics-based autoregression moving average (pbARMAX) model to have a multi-stage structure in order to explicitly include the architectural parameters of the room in the model. Extensive measurements of the room temperature are used to develop and validate the multi-stage model. The resulting model can predict the temperature in different rooms accurately in both short-term and long-term. Over a period of four weeks, the predictions have a root mean squared error less than 0.10 with a coefficient of determination larger than 0.99.

1. Introduction

The significant energy consumed by heating, ventilation, and air conditioning (HVAC) systems [1–3] leads to a worldwide increase in relevant research over the past decades. According to the National Institute of Standards and Technology, various system faults, inefficient control strategies, and poor commissioning contribute 10%–40% share of the energy consumed by HVAC systems [4]. Mathematical models of HVAC units provide bases for detecting faults, upgrading control strategies, and improving commissioning, and thus have a potential to reduce energy consumption of HVAC systems by 20%–30% [5]. An important part of modeling HVAC systems is to develop accurate, robust, and yet simple models of the room temperature. The aim of this study is to develop such models to predict the room temperature in office buildings. Specifically, we present a modeling approach that allows the pbARMAX model to have a multi-stage structure in order to explicitly include the architectural parameters of the room in the model.

The indoor temperature characterizes the thermal condition of a room, as is the case in the predicted mean vote (PMV) model [6,7], the ASHRAE Standard 55 [8] and the ISO Standard 7730 [9]. Ascione et al. need precise room temperature estimation to evaluate the strict thermo-hygrometric environment in museums [10]. Balaras et al. require the accurate knowledge of the room temperature to examine the indoor environment in hospitals [11]. The room temperature is also required for the analysis of thermal performance, indoor air quality [12], and for the evaluation of the indoor environment in naturally ventilated buildings [13]. Furthermore, a robust model that accurately predicts the room temperature is important for control design. Engdahl and Johansson have studied optimal supply air temperature in a variable air volume (VAV) system [14]. Yang and Kim predict the time of room temperature variations [15]. Orosa has investigated the thermal comfort based control strategy [16]. Tanimoto and Hagishima have developed a Markov model for the on-off cooling schedule control [17].

There are two types of room temperature models, i.e., analytical models and numerical models. The analytical models widely implemented in popular simulation tools such as EnergyPlus [18], DOE-2, TRANSYS, Modelica [19], etc. incorporate architectural parameters, and provide the most comprehensive description of the thermal process in the building with accurate estimation of various system outputs. The analytical models allow parametric studies of influence of the building envelope on indoor thermal behavior. This is very important because architectural and material parameters of a building greatly influence its thermal performance. Extensive parametric studies will help us optimize the design of and the material selection for buildings. However, various simplifying assumptions to deal with complexity of thermal interactions, unmeasured disturbances, uncertainty in thermal properties of structural elements and other parameters make it quite a challenge to obtain reliable analytical models [20].

---

* Corresponding author. Tel.: +1 209 228 4540.
E-mail addresses: swu8@ucmerced.edu (S. Wu), jqsun@ucmerced.edu (J.Q. Sun).

0360-1323/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.buildenv.2012.02.026

Nomenclature

$\Delta E_{\mathrm{h,d}}$	internal heat generated by human and devices (W)
ρ	air density (kg m^{-3})
θ	solar flux angle on windows (°)
ζ	window-to-wall ratio (%)
ϕ	heat gain from solar flux (W)
ψ	solar heat flux density (W m^{-2})
e	prediction error
h	heat convection coefficient (Wm^{-2} K^{-1})
k	thermal conductivity coefficient (Wm^{-1} K^{-1})
m	number of measurements
$\dot{m}$	mass flow rate (kg s^{-1})
n	time sequence of measurements
q	delay operator
t	time
x	distance from inside surface (m)
A, B, C	polynomials in the transfer functions for the ARMAX model
AHU	air handling unit
C_{v}	volumetric heat capacity of air (kJ kg^{-1} K^{-1})
C_{p}	heat capacity of air at constant pressure (kJ kg^{-1} K^{-1})
D	damper position (%)
H	specific enthalpy of humid air (kJ kg^{-1})
L	thickness of wall or window (m)
P	parameter group
R	residual of temperature simulation (K)
S	surface area exposed to sun (m^2)
T	temperature (K)
V	volume of room (m^3)
X	an attribute
RH	relative humidity of air (%)
VAV	variable air volume unit

Subscripts

i	inside
o	outside
oa	outside air
rm	room
wa	wall
wd	window
clg	cooling water
htg	heating water
surf	surface
disch	discharge

Superscript

$\tilde{}$	measurements
$\hat{}$	estimated values

On the contrary, data-driven, fully numerical modeling approaches establish models by using only input and output measurements. Many researchers have developed numerical models of the room temperature under various conditions. Ríos-Moreno et al. have demonstrated that the linear autoregression model with external input (ARX) model can be adopted to predict classroom indoor air temperature with very high accuracy [21]. Lowry and Lee have investigated the response of internal temperature in an office building and discovered that the output-error (OE) model provides reliable predictions [20]. Peitsman and Bakker have developed a multiple input single output ARX model to evaluate the performance of a VAV unit [22]. Yiu and Wang have studied the optimal order of a multiple input multiple output autogregressive moving average (ARMAX) model to forecast the performance of an air conditioning system of an office building in Hong Kong [23]. Mustafaraj et al. have compared different linear parametric models of the room temperature in an office, and find that the Box-Jenkins (BJ) model outperforms the ARX model and the ARMAX model under certain environmental conditions [24]. Although these numerical models are computationally efficient due to their simple structures, they are heavily dependent on the measurements, which implies poor generalization of the model in some parameter space.

To help optimize the model selection, and to improve the generalization ability of fully numerical models, researchers have turned to semi-physical or gray-box modeling approach. The gray-box models are constructed based on both the underlying physical laws and experimental data. Déqué and colleagues have implemented the gray-box technique to simulate the temperature variation in a ground floor flat [25]. Ghiaus et al. have conducted the gray-box identification of some temperature properties within the constant air AHU units [26]. Based on the physical laws, Wen and Smith have applied the gray-box approach to model the room temperature in VAVs [27]. Leephakpreeda has combined the gray prediction model and the adaptive comfort theory model to estimate the indoor comfort temperature [28]. Nevertheless, the gray-box models are numerical and therefore don't include architectural parameters.

It is thus natural to consider combining the strength of the analytical model and the data-driven numerical approach. Tsilingiris has studied the influence of structural parameters of a wall on the heat loss [29]. Devgan et al. [30] and Aste et al. [31] have investigated the influence of external wall and window construction parameters on the building overall heat transfer and energy performance of well insulated buildings. By exploring the optimal dimensions of walls and glasses, Hwang and Shu [32], and Sozer [33] have tried to improve the thermal comfort, and the energy efficiency of buildings. Korolija et al. has concluded that it is not possible to form a reliable judgment about the building energy performance without considering the architectural parameters [34]. Numerical models without including the building parameters do not reveal the relationship between the building thermal performance and the parameters. We propose two new multi-stage regression, physics-based linear parametric (mpbARMAX) models of the room temperature to take the advantages of both analytical and numerical modeling approaches [35,36]. In other words, we build a two-stage regression structure into the mpbARMAX model to explicitly include building geometries.

The rest of the paper is organized as follows. In Section 2, we review the pbARMAX model and introduce the two-stage regression structure. In Section 3, we develop the two-stage mpbARMAX models and validate them with extensive data from a building on the campus of University of California at Merced. The models are compared with a representative ARMAX model in both short-term and long-term predictions. Finally, Section 4 discusses and summarizes the findings.

2. Methodology

We first review the two pbARMAX models of the room temperature. We then introduce linear regression representations of the coefficients in the pbARMAX models as a function of