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Development of regression equations for predicting energy and hygrothermal performance of buildings

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Abstract

Regression equations can be used for predicting indoor air temperature, relative humidity and energy consumption in an easier and more rapid way than building energy simulation tools. The independent variables, that is, the input data, are heating, ventilation and air conditioning (HVAC) power, outdoor temperature, relative humidity and total solar radiation. The present methodology for obtaining the regression equations is based on defining a couple of linear Multiple-Input/Single-Output (MISO) models, since two main outputs are involved, that is, indoor temperature and relative humidity. The methodology has been tested for the low- and high-thermal mass cases of the BESTest model (cases 600 and 900) and the output data is generated by using a building hygrothermal simulation tool. Validation procedures have shown very good agreement between the regression equations and the simulation tool for both winter and summer periods.

Keywords: Regression equations; Building model; System identification

1. Introduction

Since the world-wide energy crisis in the 70s, building energy simulation programs have been developed in USA and Europe in order to reduce the energy consumption especially of heating, ventilation and air conditioning (HVAC) systems. In general, the main objectives of obtaining models for thermal analysis in commercial and residential buildings are the improvement of indoor climate conditions for occupants and the prevention of energy waste to decrease the HVAC equipment operating cost.

Usually, models are obtained via the physics (white-box) or via an identification process (black-box) or in between both (grey-box). White-box models are preferably used in situations where there is a need to evaluate influences on the building hygrothermal behaviour due to changes in the structure materials or in a specific variable or where there are energy performance enhancements and variations in the internal gains. These models are obtained based on the conservation equations for energy and mass balances. Simulation programs, such as EnergyPlus [1], ESP-r [2], TRNSYS [3], PowerDomus [4] and ASTECCA [5], as well as other tools described in detail in [6] use physical models.

Black-box models are counterparts of the white-box ones and regression equations are common structures of those models. In the case of a whole-building system, a linear regression can be used on the identification process to correlate output and input data [7,8].

Accurate regression models are adequate to a great variety of purposes such as prediction of indoor air conditions and energy consumption/demand, control of HVAC equipment, reliability aspects and systems management. For instance, performance analysis of control strategies applied to HVAC systems has been revealed by most building practitioners that the use of building energy analysis programs is still complicated, time-consuming and costly [9]. In this way, there is a need for some simplified approaches to simulate the building coupled to HVAC

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equipment, particularly during the initial conceptual design stage, when different building design schemes can be considered.

Over the last decades, some approaches based on black-box modeling have been developed in order to understand building behaviour submitted to different climate conditions. Based on Givoni's method [10], Krüger and Givoni [11] presented an application of a set of formulae to predict daily indoor temperatures in three monitored low-cost houses, while a thermal performance analysis also based on Givoni's regression model was presented by Papst and Lamberts [12]. Another application of this kind of model is presented in [13] where predictive regression equations to evaluate the maximum, average and minimum indoor air temperature have been elaborated. However, the models presented in [10–14] do not consider solar radiation and are limited to cases where the air change rate is high and building thermal mass is low.

Virk and Loveday [14] presented a model in which a multivariable stochastic identification technique is applied to a full-scale test room with a dedicated heating, ventilating and air conditioning plant. This model could predict indoor temperature of a test-zone in cold climates. In their model, as well as in the models previously mentioned in [10–13], no solar radiation was taken into account either.

Moreover, advanced control algorithms need a process model to be implemented. Combining the HVAC and building envelope study, several detailed analysis can be performed as shown in [15,16].

Additionally by using simplified building models, closed-loop control systems can be implemented and tested in an easier way. The need of new control strategies for the building automation is presented in [17], where one of the causes for the occupants' dissatisfaction is attributed to the poor quality of HVAC systems controls. Levermore [18] estimated that the avoidable energy waste in buildings is in the range of 20–50% and that 15% of the energy waste can be avoided by good control of the systems.

Regression equation models can be as accurate as the original data, regardless if obtained by experimental or numerical means. When regression equations are obtained from a complete and accurate set of experimental data, they can provide precise results, but in a faster and easier way than using building simulation tools.

Considering all those benefits, simplified and accurate regression models, which are able to predict the indoor climate variations, are discussed in this work. In this way, this paper describes a methodology for obtaining linear regression equations for two building models. The models are constructed from observed data. In the black-box system identification approach, a set of input/output data is collected from the actual system and, by means of a least-square optimization procedure, the model that best fits the collected data is computed. The aim is obtaining a model that describes the HVAC system and building behaviour in a structure that is useful for building hygrothermal and energy analysis and also for advanced control law synthesis.

In the next section, the simulation tool used to generate data for the identification process is presented. Then, in Section 3, the building identification method is described followed by the model estimation and validation. Finally, an application example using this methodology is provided and conclusions about this research are addressed.

2. Simulation tool and environment

In order to derive a model based on a system identification procedure, both input and output data collected from experiments or simulations are necessary. In the present study, data used on the identification procedure was obtained by running simulations in the PowerDomus software [19].

2.1. PowerDomus

PowerDomus is an object-oriented program that has been developed to predict the hygrothermal performance of multi-zone buildings considering both vapor diffusion and capillary migration. A lumped formulation for temperature as well as for water vapor is adopted in each building zone. Eq. (1) describes the energy balance for a zone subjected to loads by conduction, convection, short-wave solar radiation, inter-surface long-wave radiation, infiltration and HVAC system related loads. The software interface is presented in Fig. 1.

$$\dot{E}_{\mathrm{t}} + \dot{E}_{\mathrm{g}} = \rho_{\mathrm{air}} c_{\mathrm{air}} V_{\mathrm{air}} \frac{\mathrm{d}T_{\mathrm{int}}}{\mathrm{d}t} \tag{1}$$

where $\dot{E}_{\mathrm{t}}$ is the thermal energy that crosses the building envelop (in W), $\dot{E}_{\mathrm{g}}$ is the internal energy generation rate (W), ρ_{air} is the density of air (kg/m^3), c_{air} is the specific heat of air (J/(kg K)), V_{air} is the room volume (m^3), T_{int} is the room air temperature (K) and t is the time (s).

The term $\dot{E}_{\mathrm{t}}$, in Eq. (1), includes loads associated with the building envelope (sensible and latent conduction heat transfer), furniture (sensible and latent), fenestration (conduction and solar radiation), openings (ventilation and infiltration) and HVAC systems.

The total conduction heat flux that crosses the control surface of each zone is calculated as

$$Q_{\mathrm{walls,s}}(t) = \sum_{i=1}^{m} h_{\mathrm{c},i} A_i [T_{i,x=L}(t) - T_{\mathrm{int}}(t)] \tag{2}$$

for the sensible conduction load and as

$$Q_{\mathrm{walls,s}}(t) = \sum_{i=1}^{m} L(T_{i,x=L}(t)) h_{m,i} A_i [\rho_{\mathrm{v,n},i}(t) - \rho_{\mathrm{v,int}}(t)] \tag{3}$$

for the latent load.

In Eqs. (2) and (4), the following definition is provided: A_i represents the area of the ith surface (in m^2), h are the convection coefficients for heat (h_{c}, W/(m^2 K)) and mass (h_m, m/s), $T_{\mathrm{n},i}(t)$ is the temperature at the i'th internal surface of the considered zone (K), L is the vaporization latent heat (J/(kg K)) and ρ_{v} is the water vapor density (kg/m^3).

The temperature and vapor density within the envelop are calculated by the combined heat and moisture transfer model based on the theory by Philip and DeVries [20] quoted by