Journal of Building Engineering 15 (2018) 137–155

Contents lists available at ScienceDirect

Journal of Building Engineering

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

Development and performance comparison of low-order black-box models for a residential HVAC system

Abdul Afram[a,*], Alan S. Fung[a], Farrokh Janabi-Sharifi[a], Kaamran Raahemifar[b]

[a] Department of Mechanical and Industrial Engineering, Ryerson University, 350 Victoria Street, Toronto, ON, Canada M5B 2K3
[b] Department of Electrical and Computer Engineering, Ryerson University, 350 Victoria Street, Toronto, ON, Canada M5B 2K3

ARTICLE INFO

Keywords:
Black-box modeling
Grey-box modeling
Residential HVAC system modeling
Modeling and validation
Parameter estimation
Artificial neural network (ANN)
Transfer function models
Process models
State-space models
Auto-regressive exogenous (ARX) models

ABSTRACT

In this paper black-box models of residential HVAC systems commonly found in many Canadian households are developed. The models are useful for performance evaluation, operating point optimization, energy and cost optimization, and new control system design. The HVAC system under investigation is installed at House A of Toronto and Region Conservation Authority's (TRCA) Archetype Sustainable House (ASH) in Vaughan, Ontario, Canada. The system is comprised of four major subsystems, i.e., heat recovery ventilator (HRV), air handling unit (AHU), air source heat pump (ASHP) and the building envelope (zone). Data measured during the winter and summer of 2015 was used to develop black-box models of the system during both seasons for each subsystem. The developed models include artificial neural network (ANN) model, transfer function model (TF), process model, state-space model and auto-regressive exogenous (ARX) model. The performance of these models was compared both visually and analytically. Though visual comparison indicated that all models performed well, the analytical comparison revealed the true differences between them. It was found that state-space models outperformed all other models, the ANN and transfer function models were second best, which were followed by process models and ARX models. Grey-box models developed in a previous paper were also added for comparison, but all black-box models outperformed the grey-box models.

1. Introduction

HVAC systems consume a significant amount of energy in a household and in cold climates such as Canada, the heating could result in even higher energy consumption due to sub-zero temperature throughout the winter season. Therefore, it is of paramount importance to study the operating characteristics of HVAC systems and optimize these systems for lower energy consumption and reduced operating cost. For new installations, more advanced HVAC systems can be installed which comply to the modern building codes and standards and have higher efficiency. Unfortunately, older buildings and HVAC systems cannot be replaced on a cost-effective basis. Therefore, it is best to optimize the existing HVAC systems through appropriate selection of operating points and development of new controllers which can integrate the energy saving strategies such as peak load shifting, set-point temperature reset during night, appropriate start and stop times, economizer cycle control and thermal energy storage in their design. One such approach is to develop a hierarchical control system which has supervisory control layer for scheduling and timing of the operating points based on the optimization objectives (e.g., reduction in energy consumption, operating cost reduction based on a variable electricity price etc.). Supervisory control layer can either employ a simple rule-based control or more advanced control systems such as model predictive control and fuzzy logic control etc. The lower level functions (e.g., regulation of set-points at desired positions) can be performed by local level control layer which can employ classical controllers (e.g., on/off, PID etc.).

In order to analyze the existing control systems, performance of the HVAC systems and to develop new control systems, the models are required to replicate the dynamics of the system. Models are used to develop the new control system as they form the mathematical foundation of the calculations performed in the controller and are also used to simulate the system behaviour when the new control input is applied to the system. An accurate model can replicate the response of the actual system to a high degree of accuracy resulting in highly accurate control system development. Several approaches are used in the literature to model the HVAC systems which are catagorized under three broad classes known as white-box, black-box and grey-box approaches [1,2]. White-box (also known as physics-based, forward or first principle) models are developed by writing the energy balance equations of

* Corresponding author.
E-mail addresses: abdul.afram@ryerson.ca (A. Afram), alanfung@ryerson.ca (A.S. Fung), fsharifi@ryerson.ca (F. Janabi-Sharifi), kraahemi@ryerson.ca (K. Raahemifar).

https://doi.org/10.1016/j.jobe.2017.11.021
Received 15 May 2017; Received in revised form 25 November 2017; Accepted 25 November 2017

the system and require the comprehensive knowledge of the system physics and engineering principles involved during the operation of the system. The parameters of these models are taken from the manufacturer supplied data or estimated using the material properties of the system. On the other hand, black-box models do not require the understanding of the system at all and can solely be developed by observing the inputs and outputs of the system and fitting the data to a mathematical function. Therefore, they are easier to develop and have high accuracy compared to white-box models but their performance degrades as the operating conditions vary from the training data resulting in poor generalization capabilities compared to white-box models. The grey-box approach uses both the system knowledge and measured input/output data for model development. The white-box model is used as the mathematical structure of the grey-box model whose parameters are estimated from the measured data using the optimization based parameter estimation approaches. This results in models which are both accurate and have good generalization capabilities but are the hardest to develop.

The HVAC performance can be analyzed using the dedicated energy simulation tools such as TRNSYS [3–5] and Energy-Plus [6,7], or more generic programming environments such as MATLAB® Simulink® [7–14]. Usually, TRNSYS and Energy-Plus help to build the models quickly with their built in component libraries and block diagram based graphical user interfaces. User has to supply the parameters of the white-box models used in these programs. Due to their limited support for advanced controller development, and integration of energy conservation strategies (such as thermal energy storage [6,7,15,16], temperature reset [17], precooling during off-peak and set-point changes during peak hours [18,19], optimum start-stop times, ventilation control [17,20], and economizer cycle control [17,21,22]), as well as difficult integration of black-box and grey-box models, these programs restrict the ability for innovative solutions and are only suitable for existing system's performance simulation. In contrast, MATLAB® and Simulink® are generic programming environments and are well known among HVAC researchers for their versatility and ease of integration with the advanced controller designs and energy conservation strategies. More advanced, e.g., hybrid models comprising of a mix of white-box, black-box and grey-box models can be developed in MATLAB® and Simulink®. Several HVAC systems toolboxes have been developed for MATLAB® Simulink® such as International Building Physics Toolbox (IBPT) [23], SIMBAD toolbox [24], conventional and renewable energy optimization toolbox (CARNOT) [25], heat, air and moisture modeling toolkit (HAM-tools) [26] and ASTECCA toolkit [10,27]. These toolboxes provide a similar functionality to the TRNSYS and Energy-Plus as they use physics-based models whose parameters are to be supplied by the user. But, since these toolboxes are developed in MATLAB® Simulink®, they can be easily integrated into control system design. A co-simulator for HVAC was developed in [28] comprising of TRNSYS and MATLAB® where scheduling and control task was performed in MATLAB® whereas, the system dynamics simulation was carried out in TRNSYS.

This paper compares the grey-box models and black-box models in order to determine the best performing models of the residential HVAC system during both summer and winter seasons. Grey-box models were developed in a previous paper by the researchers and therefore, the details are omitted for their development from this paper.

The rest of the paper is structured as follow. The system description is provided in Section 2. The Section 2 also describes the inputs and outputs of several subsystems of residential HVAC system under investigation followed by a description of the modeling and validation datasets, and developed grey-box and black-box models in Section 3. Visual and analytical comparison of the models is carried out in Section 4. Conclusions, Acknowledgments, Appendix and References are presented in Sections 5, 6, 7 and 8 respectively.

Fig. 1. Two semi-detached houses known as TRCA Archetype Sustainable House (ASH) located in Vaughan, Ontario, Canada.

2. System description

Residential HVAC system is installed at the House A of Toronto and Region Conservation Authority's (TRCA) Archetype Sustainable House (ASH) located in Kortright Centre for Conservation, Vaughan, Ontario, Canada. There are two semi-detached houses on the site called House A and House B as shown in Fig. 1. House B comprises of a future focused more advanced HVAC system geared towards the high efficiency and reduced operating cost comprising of energy recovery ventilator, ground source heat pump, and multi-zone air handling unit (AHU). In contrast, House A comprises of HVAC system found in most canadian households comprising of heat recovery ventilator (HRV), air source heat pump (ASHP) and a single-zone AHU. The grey-box and black-box models of House B were developed in [8,29,30]. In [31], the grey-box models were used to optimize the parameters of the existing control system. Black-box models of House A HVAC system are developed in this paper. The brief system description is provided below. A more comprehensive description of the system can be found in the works of previous researchers in [4,5,28,32–38].

The block diagram is given in Fig. 2. The symbols are defined in Table 1. HRV supplies fresh air to the house and helps to conserve energy by preheating or precooling the incoming fresh air depending on the season. Outside fresh air and exhaust air from the zone enter the HRV where heat transfer occurs between the two streams. During winter, exhaust air input from the zone is at a higher temperature than the outside air therefore, the heat is transferred from the exhaust air to the fresh air thus preheating it. During the summer season opposite is true where exhaust air is at a lower temperature compared to the outside air and therefore, the heat is transferred from the fresh air to the exhaust air thus precooling it. During both seasons, the temperature of fresh air at the outlet of HRV is close to the zone temperature.

Zone temperature is continuously monitored by the zone temperature controller. The zone temperature set-point is manually set to 22 °C during both seasons. The zone controller has a dead-band of ± 1.5 °C. During winter season, when the zone temperature falls below the lower threshold of 20.5 °C, the zone temperature controller generates control signal to turn the ASHP on. The direct expansion heating/cooling coil of the ASHP is placed inside the AHU. When ASHP turns on during winter, it supplies heat to the AHU where it is transferred to the supply air and thus the zone receives the hot supply air above 30 °C which brings the zone temperatue within the desired range. When the zone temperature hits the upper threshold level of 23.5 °C, the ASHP is turned off.

During summer season, when the zone temperature goes above the upper threshold limit of 23.5 °C, ASHP turns on and supplies cooling. The heat is extracted from the supply air cooling it below 15 °C. When the cold supply air enters the zone, the zone temperature starts to drop. The controller turns the ASHP off when the zone temperature reaches lower threshold limit of 20.5 °C. Zone temperature controller continuously monitors the zone temperature during both heating and