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Reduced order modeling and parameter identification of a building energy system model through an optimization routine

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HIGHLIGHTS

- A BES model based on 1st principles is developed and solved numerically.
- Parameters of lumped capacitance model are fitted using the proposed optimization routine.
- Validations are showed for different types of building construction elements.
- Step response excitations for outdoor air temperature and relative humidity are analyzed.

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ABSTRACT

Different control techniques together with intelligent building technology (Building Automation Systems) are used to improve energy efficiency of buildings. In almost all control projects, it is crucial to have building energy models with high computational efficiency in order to design and tune the controllers and simulate their performance. In this paper, a set of partial differential equations are formulated accounting for energy flow within the building space. These equations are then solved as conventional finite difference equations using Crank–Nicholson scheme. Such a model of a higher order is regarded as a benchmark model. An optimization algorithm has been developed, depicted through a flowchart, which minimizes the sum squared error between the step responses of the numerical and the optimal model. Optimal model of the construction element is nothing but a RC-network model with the values of Rs and Cs estimated using the non-linear time invariant constrained optimization routine. The model is validated with comparing the step responses with other two RC-network models whose parameter values are selected based on a certain criteria. Validations are showed for different types of building construction elements viz., low, medium and heavy thermal capacity elements. Simulation results show that the optimal model closely follow the step responses of the numerical model as compared to the responses of other two models.

1. Introduction

A number of methods have been developed to construct load models or energy consumption models that simulate a building/plant system for load prediction or cost saving estimates. Such models vary in magnitude from modeling of a single slab (or a wall) [1] to modeling of a complete building through modeling of rooms subjected to temperature variations. A three stage process for model formulation was illustrated in [2]. In the first step, the building system is converted from continuous state to a discrete state. This involves selection of nodes at the points under study, representing the homogeneous or non-homogeneous control volumes like that of internal air mass, boundary surfaces, building fabric elements, renewable energy systems, equipment of the room, etc. Equations satisfying mass, momentum and energy conservation principles are developed in the second step for each node which is in thermodynamic contact with its surrounding nodes. Last step involves solving the equations derived in the second step for successive time steps to obtain state variables of the node for future time periods as a function of present time state variables with the boundary conditions prevailing at both times.

Models developed to simulate the building energy systems can be divided into many types. Basically, models are classified as physical, symbolic and mental models. Symbolic models are comparatively less complex and are thus frequently used. Models can be mathematical and non-mathematical models. Development of mathematical model of a system involves mapping of the physical

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Nomenclature

BES	building energy systems
BEMS	Building Energy Management Systems
BAS	Building Automation Systems
BESPs	Building Energy Simulation Programs
FiD Method	(Finite difference) method
3R-2C network	lumped capacitance network with three series resistances and two parallel capacitors
ANN	Artificial Neural Network
CN	Crank–Nicholson
PDE	partial differential equation
'N'	number of layers in a multi layered wall
'R_T'	Total Thermal Resistance (K/W)
'r_{si}'	internal surface resistance of a wall (K/W)
'r_{so}'	external surface resistance of a wall (K/W)
'd_i'	thickness of *i*th layer of a multi layered wall (m)
'R_1'	outer thermal resistance (K/W)
'C_1'	outer capacitance (J/K)
'R_2'	wall thermal capacitance (K/W)
HVAC	heating, ventilation and air-conditioning
ρ_a	density of air in the building space (kg/m^3)
Q_{casual}	casual heat (due to occupants) gain (W)
T_{cs}	temperature of the building space to be conditioned by hvac system (°C)
U_{win}	window *U*-value (W/m^2 K)
't'	time (s)
'α'	thermal diffusivity of the material (m^3/s)
'ω'	weighing factor
'Fo'	Fourier's number
'$u(t)$'	time step response function
'f_{SSE} (T)'	sum-squared error function
'A'	cross-sectional area of multi-layer construction element (m^2)
'Q'/'q'	rate of heat transfer (kW/m^3)
'L'	length of a multi-layer construction element (m)
'T'	temperature values (K)/temperature vector
'ρ'	density of *i*th layer of a multi layered wall (kg/m^3)
C_{pi}	specific heat capacity of *i*th layer of a multi layered wall (kJ/kg K)
'C_T'	total thermal capacitance (J/K)
'k_i'	thermal conductivity of *i*th layer of a multi layered wall (kW/m K)
'R_3'	inner thermal resistance (K/W)
'C_2'	inner capacitance (J/K)
'B_i'	Biot number
LTI	linear-time invariant
C_{pa}	specific heat capacity (J/kg K) of air in the building space
Q_{hvac}	heat output from hvac system. +ve if heating and −ve if cooling (W)
N	no. of air changes per hour from the hvac system (per hour)

laws governing the dynamics of the system's process into mathematical relations using variables and constants. Due to ease in evaluation and manipulation mathematical models are the most suitable and the most widely used category of models [3]. Mathematical models can be of theoretical and experimental type. As name suggest, theoretical models involve breaking down of a larger system under study into a number of smaller and simpler subsystems. Mathematical equations constrained through physical laws are then used to relate the different subsystems. On the other hand, experimental models are developed through empirical relations i.e., through measurement of input and output signals of the system and then, evaluating the system's response. Such models don't provide any information about the mechanics or behavior of the system. Differential or difference equations along with the use of soft computing techniques like fuzzy are made use of in experimental modeling.

Models are also classified as White box, Grey box or Black box models. White box modeling of buildings involve a detailed description of the heat transfer processes occurring in the building. A thorough understanding of the system and all influential sub processes is required to efficiently describe the dynamics of a building energy system [4]. Also called as semi-physical models, Grey box models are inherited from the white box models [5] but the parameters of the model defining the system are not measured directly but estimated through various identification processes [6]. Models which do not normally contain any physical knowledge regarding the system (majorly due to lack of knowledge about the physical structure of the system) are called as black box models. Statistical methods are used to formulate the model [7] and the physical parameters are partly hidden in the discrete time parameterization. Constructing an accurate and a generic model to interpret the thermal dynamics of a building involves solving heat transfer equations of conduction, convection and radiation and mass transfer equations.

Building Energy Management Systems (BEMS)/Building Automation Systems (BAS) are employed for achieving energy efficient targets of the owners thereby, reducing operating costs through better supervisory controls. A number of previous studies have shown potential savings for optimized controls in the range of 10–40% of costs to provide heating, cooling & ventilation [8,9]. The primary objective of the building energy managers is ensuring occupant comfort at minimum operational cost. Considerable adaptive and predictive control strategies, based on accurate energy modeling & monitoring, are developed. Building Energy Simulation Programs (BESPs) such as TRNSYS, Energy Plus, and Design Builder, are utilized for such purposes. However, in order to achieve cost-effective implementations, the associated control design and implementation must be automated for deployment in a scalable manner.

Such BESPs are high fidelity tools as they involve solving a large number of energy balance equations for every time step to evaluate the performance of the BES under study. Moreover, direct usage of BESPs for evaluating the energy performance indices for a BES under study is complex and can sometimes; lead to an over or under estimation of building energy consumption. In order to investigate developed control strategies to BES, a sufficiently accurate energy model with reduced order is necessary.

Literature articles [7,10–13] are available which have developed model order reduction techniques in state space domain using optimization techniques of genetic algorithms, solving Kuhn–Tucker equations using sequential quadratic programming, etc. Such works involve either empirical modeling [5,7,14,15] of the building space under study through the use of sensors and energy monitoring software or using a BESP to develop a benchmark model and then, adopting an order reduction technique.

Each BES is unique in terms of its application, operation, occupancy pattern and environmental/location aspects and thus, require different engineered solutions for enhancing the energy performance of the building. Constructing an accurate and a generic model to interpret the thermal dynamics of a building involves solving the heat transfer equations of conduction, convection and radiation, mass transfer equations and energy balance equations. In this paper a generalized BES model is developed with the parameters estimated through an optimization routine.