Energy and Buildings 84 (2014) 193–202

Contents lists available at ScienceDirect

Energy and Buildings

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

Urban energy simulation: Simplification and reduction of building envelope models

Eui-Jong Kim[a,*], Gilles Plessis[b], Jean-Luc Hubert[b], Jean-Jacques Roux[a]

[a] *Université de Lyon, CNRS, INSA-Lyon, CETHIL, UMR5008, F-69621 Villeurbanne, France*
[b] *Research and Development Division, Electricité de France (EDF), Les Renardières, 77818 Moret sur Loing, France*

ARTICLE INFO

Article history:
Received 18 February 2014
Received in revised form 30 April 2014
Accepted 26 July 2014
Available online 7 August 2014

Keywords:
Urban simulation
Building energy model
Simplified model
Balanced realization
Model order reduction
Modelica

ABSTRACT

This paper describes a building model designed for an urban energy simulation tool. In this context, trade-off between computing time and result precision is particularly important. Our methodology involves physical simplifications and model order reduction. The physical simplications are achieved by using equivalent envelopes, linearization scheme and pre-processing, so that a Modelica detailed model can be derived into a linear and time-invariant system using fewer component models. Balanced realization reduction can then be applied on such systems leading finally to a 6-order model. Effects of the simplification and reduction on heating and cooling loads are evaluated using typical building envelope cases. Results show that the simplifications and reduction induce errors under 1% in annual energy consumption and a maximum of 3% in instantaneous values but are accurate enough to reproduce dynamics of the detailed model. Additionally, the final reduced model uses a simple numerical solver and runs in less than 1 s without compromising precision for hourly annual simulations being 700 times faster than the detailed model, which is promising for use in urban energy simulation.

1. Introduction

Design of sustainable cities through simulation tools has become one of the hot topics during the last decade [1]. It is regarded as a solution to reduce the greenhouse effect and handle resource scarcity in complex ecosystems such as urban areas. This paper is focused on building envelopes, one of the key components in urban modelling. Existing building models are usually either too complex and computationally expensive or too simple to adequately predict a precise urban load profile.

With developments in building energy tools such as Trnsys [2] and Energy+ [3], detailed building models have been directly used for urban energy simulations [4,5]. Since the simulations of such models are time-consuming, the number of buildings to simulate is limited.

To simulate a large number of buildings, some statistical models [6] and steady-state models [7] have been used, but only annual or monthly energy consumption predictions are available with these approaches.

Some city-oriented simulation tools have been developed that directly describe building envelopes with different levels of simplification to run hourly building simulations. Solene, originally an architectural and urban radiance tool, integrates a building thermal model to carry out urban energy analyses [8]. The model is derived from a nodal network model representing a multizone building [9]. The physical formulation is based on representing building envelope elements (windows, walls, roof, floor...) by means of an electrical analogy. Therefore, a building is composed of thermal zones, and each zone is described by thermal resistances and capacitances (RC model). More recently, the urban simulation tool CITYSIM [10] adopted a similar RC model. In this case, a zone is represented by 2 capacitances describing the indoor air node and the building envelope node. A comparison [11] with a reference model in ESP-r [12] showed that the model error in annual energy is around 10% and discrepancies on indoor temperatures and hourly loads can be significant (e.g. 5 °C for some wall types).

Another urban simulation tool SUNtool [13] integrates "grey-box" models defined for a specific building typology. The grey-box model is based on a model reduction technique that reduces the model order of a full-knowledge physical model [14]. Although this kind of model is capable of reproducing thermal dynamics of buildings, the procedure to generate the grey-box models requires test simulations, and therefore the model relevance is highly sensitive to the typology used and the number of simulations [15].

---

* Corresponding author. Tel.: +33 472 437 488; fax: +33 472 438 522.
E-mail addresses: eui-jong.kim@insa-lyon.fr, euijong.a.kim@gmail.com (E.-J. Kim).

http://dx.doi.org/10.1016/j.enbuild.2014.07.066
0378-7788/

Nomenclature

A, B, C, J, D	initial state model matrices
Ω, Π, H	transformed-basis matrices using balanced realization method
M	state-transforming matrix
Wc	controllability Gramian
Wo	observability Gramian
T	temperature vector (°C)
U	solicitation vector
X	transformed-basis state vector
Y	output vector
$\tilde{\mathbf{Y}}$	approximated output vector
F	view factor
n	number of state variables
S	surface area (m^2)
t	time (s)

Greek symbols

α	absorptivity coefficient
Φ	solar heat flux (W/m^2)
σ	Stefan-Boltzmann constant (W/m^{2}K^4)
ε	body emissivity
γ	linearized part
τ	variable transmittance rate
ω	Hankel singular value

Subscripts

abs	absorbed solar flux
dif	diffuse solar irradiance
dir	direct solar irradiance
i	i_{th}-orientation
n	complete order (model)
r	reduced order (model)
ref.	reference model
sky	sky temperature
s	surface
Si	final matrices for ith sub-zone
test	test model
trans	transmitted solar flux
win	windows
wall	walls

The work presented in this paper aims to develop efficient and accurate building models suitable for urban simulation tools. The work presented here aims at providing the same level of detail as in advanced building energy simulation tools. The methodology to decrease the number of equations of the initial detailed model (DM) is based consecutively on physical simplifications, producing a simplified model (SM), and model order reduction, leading to a final reduced model (RM). The methodology proposed to derive the RM from the DM is almost the same for most building types. Accordingly, once the DM is well defined for a specific typology, the corresponding RM can be easily obtained using the proposed methodology and with given building parameters. However, other existing reduced models [13–15] are stand-alone versions and subject to a pre-defined typology, and thus they may result in error when used for a different building typology.

The proposed model takes into account the most significant sollicitations (input variables) and physical phenomena: outdoor temperature, solar radiation, surrounding longwave radiation, thermal inertia and heat transfers through the building envelope. Computation of boundary conditions is not discussed in this article, so they are regarded as known. In the following sections, the three models: DM, SM, and RM will be described with used methodologies. Then, detailed model comparisons and some sensitivity tests are presented.

2. Detailed model

2.1. Modelica-based model

Modelica®, an acausal modeling language, is used in this work using Dymola® [16]. Amongst other advantages, an acausal modeling language allows to modify easily pre-defined component models for our own purpose as the numerical algorithm for resolution is separated from the modeling part. Impact of physical phenomena on observed variables can be evaluated by including or excluding them into the model composition.

This section presents the DM from which the SM and RM models are derived. The DM is used as a reference model for comparison. It is modelled thanks to elements of BuildSysPro, the EDF's library of Modelica models for buildings and energy systems [17]. This library contains a large number of models which have been validated experimentally and by software inter-comparison [17,18].

The SM model presented in the next section is the resulting model from our preliminary sensitivity analysis [19]. In addition, whole-building matrices in a state-space representation that are required for the reduction can be easily exported using a Modelica function.

2.2. Description of the DM model

The current DM presented hereafter is defined with typical hypotheses used in common simulation tools. The model uses one-dimensional component models of walls and windows. In this DM, wall layers, corresponding meshes, and insulation position (inside or outside) are fully specified. The components account for conductive heat transfers between inner computation nodes, convective heat transfers with the ambient air and radiant heat transfers for both the short- and long-wave radiation. As commonly used, the conductive and convective heat transfer coefficients are assumed constant, but the long-wave heat transfer coefficient is variable in function of temperatures of concerned bodies. The window model includes the solar transmittance calculation using variable transmittance rates (τ) as a function of the solar incident angle. The solar radiation transmitted through windows is assumed entirely absorbed on the floor. In addition, the DM model considers heat loss through ventilation using a constant air change rate.

The DM model is composed of several components of walls or windows depending on the building morphology. For a building of n wall-orientations, 3n solar radiation information (Φ_{dir}—direct, Φ_{dif}—diffuse, cos$i$—cosine of the incident angle) should be given to the model as seen in Fig. 1.

For example, if a parallelepipedic building is simulated with a single southern window, 7 component models (5 walls, 1 floor,

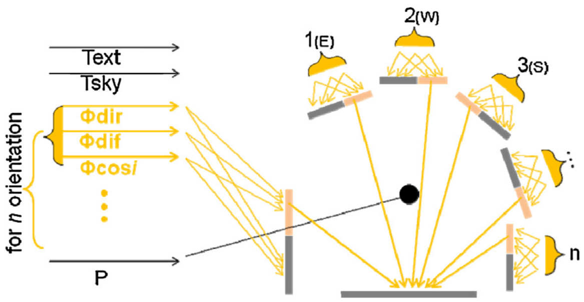

Fig. 1. Inputs to the DM model (n-orientation single zone case).