Energy and Buildings xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Energy and Buildings

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

An occupant behavior modeling tool for co-simulation

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ARTICLE INFO

Article history:
Received 26 June 2015
Received in revised form 5 September 2015
Accepted 15 October 2015
Available online xxx

Keywords:
Behavior modeling
Co-simulation
Energy modeling
Occupant behavior
Building simulation
EnergyPlus

ABSTRACT

Traditionally, in building energy modeling (BEM) programs, occupant behavior (OB) inputs are deterministic and less indicative of real world scenarios, contributing to discrepancies between simulated and actual energy use in buildings. This paper presents a new OB modeling tool, with an occupant behavior functional mock-up unit (obFMU) that enables co-simulation with BEM programs implementing functional mock-up interface (FMI). The components detailed in the development of the obFMU include an overview of the DNAS (drivers-needs-actions-systems) ontology and the occupant behavior eXtensible Markup Language (obXML) schema, in addition to details on the creation of the obFMU that contains the co-simulation interface, the data model and solvers. To demonstrate functionality of the tool, three examples of occupant behaviors were simulated, including: (1) turning on and off lights, (2) opening and closing windows, and (3) turning on and off the air conditioners. The obFMU can be used via co-simulation with all building simulation programs that implement the FMI, thus users are not limited to a particular tool. Another advantage is the use of obXML schema to represent occupant behavior, standardize the description of occupant behavior enabling information exchange.

1. Introduction

In 2013, residential and commercial buildings consumed more than 40% of the United States total energy and more than 70% of the electrical energy, resulting in a national energy bill of $410 billion [1]. Additionally, low energy buildings often fail to meet expected performance, with occupant behavior (OB) contributing decidedly toward building energy consumption and indoor environmental quality (IEQ) [2]. Occupants are not passive participants in buildings, they interact with building systems such as opening and closing windows, operating shades or blinds, controlling lights, adjusting the thermostat and operating electrical equipment, all of which influence the energy consumption of the building [3–5]. The International Energy Agency (IEA), Energy in Buildings and Communities Programme (EBC) Annex 53 defined energy-related occupant behavior, as “observable actions or reactions of a person to adapt to ambient environmental conditions such as temperature, indoor air quality or sunlight” [6,7]. It is suggested that up to 71% of energy demand variation in buildings is due to occupant behavior [8].

One tool to help combat the rising energy demand in buildings is the use of occupant behavior modeling. Traditionally, two categories of behavioral models are used, implicit and explicit. Implicit models deal with rules associated with physical systems (e.g. windows and lights) rather than the occupant directly and include: (i) linear and logistic regression [9], (ii) probability equations [10,11], (iii) statistical analysis of measured occupancy data [3], (iv) sub-hourly occupancy-based control models and, (v) Bayesian estimations [12]. Explicit models deal with rules and logic associated directly with the occupant and include: (i) Markov chain [13–16] and agent-based modeling [17,18], (ii) the Bernoulli process [19] and, (iii) survival analysis. Yan et al. [20] and Hong et al. [21] provide a comprehensive literature review of the current state of occupant behavior simulation and modeling. Solutions are needed which go beyond the traditional behavioral inputs used in building energy modeling (BEM) programs, e.g. deterministic occupancy schedules, thermostat settings, lighting use, plug-loads and HVAC schedules, to account for the stochastic nature of occupant decision making [22,23]. The IEA EBC Annex 66 “Definition and Simulation of Occupant Behavior in Buildings” is working to advance the field forward by developing new data, methodologies and tools to simulate occupant behavior in buildings, assisting in building design, operation, and energy technology evaluation [24].

Some of the more sophisticated approaches in BEM include customized code, customized tools, and co-simulation; with co-simulation allowing a more realistic and robust representation of occupant behavior. The intention of co-simulation is to couple two or more simulation tools together, providing a data exchange environment between subsystems. Commonly, this technique

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http://dx.doi.org/10.1016/j.enbuild.2015.10.033

enhances individual components of BEM programs, by describing separate, discrete, algebraic equations that concurrently simulate with the primary BEM, such as EnergyPlus [25]. EnergyPlus, is one of the most widely used BEM programs, simulating heating, cooling, lighting, ventilation and water use in buildings [26]. To enhance EnergyPlus capabilities, co-simulation programs have been written for indoor air quality [27], advanced lighting and daylighting, computational fluid dynamics (CFD), multi-zone airflow networks, and HVAC systems and controls [25]. This paper presents a co-simulation software tool providing another approach to enhancing occupant behavior modeling with existing BEM programs such as EnergyPlus.

Co-simulation in EnergyPlus can be performed in three distinct ways. First, one-to-one coupling is where a specific interface is implemented such as coupling EnergyPlus with a CFD tool to improve the accuracy of convective heat transfer coefficients [28,29]. Secondly, middleware coupling is where a co-simulation master orchestrates the exchange of data [27]. The building controls virtual test bed (BCVTB) [30] allows users to link modules with MATLAB, Simulink, Dymola [31], Radiance [32], and ESP-r [33]. Thirdly, the standardization of co-simulation using functional mock-up interface (FMI), the technique used in this paper, allows for the direct coupling with various programs.

Few researchers have integrated a separate occupant behavior software module with a BEM program, using co-simulation. Gunay et al. [15] considered 3 domains, the building, HVAC and occupant and coupled these using a discrete event system specification (DEVS) building energy model. Langevin et al. [18] developed an agent-based model (ABM) of office occupant behaviors coupling the ABM in MATLAB with the building energy simulation EnergyPlus via the BCVTB. Similarly, Lee and Malkawi [17] coupled an ABM programmed in MATLAB with EnergyPlus, with the assistance of BCVTB and MLE+ architecture. MLE+ provides integrated support for control design and optimization, by assisting communication between integrated building simulations and controller formulation [34]. Andrews et al. [35] developed a framework using an agent-based approach to test how well buildings are likely to perform, given realistic occupants. Abanda and Cabeza [36] suggested that one of the most important criterion when exploring building occupants' behavior in emerging building information modeling (BIM) is the ability for interoperability and flexibility between different packages. Co-simulation allows for interoperability between OB models and existing BEM programs providing flexibility to new users and potential use in BIM.

This paper describes the development of an OB modeling tool which includes the creation of the occupant behavior FMU (obFMU) v1.0 and its co-simulation abilities with EnergyPlus v8.3.0. The interface follows the FMI, an independent standard that allows for component development and tool coupling using a combination of eXtensible Markup Language (XML) and compiled C-code [37–40]. The standard contains two main parts, (1) an explanation of how a modeling environment can generate C-code and be utilized and, (2) the interface standard for coupling in a co-simulation environment [25]. The component or simulation model that implements the FMI framework is called the functional mock-up unit (FMU).

The development of the OB modeling tool aims to provide researchers with a new methodology to simulate occupant behaviors within the context of building energy modeling. New contributions to the field include the creation of the obFMU enabling co-simulation of occupant behavior with BEM programs. Three occupant behavior examples in lighting control, window operation and HVAC control, in a Florida office building, are provided to demonstrate some of the modeling tool's simulation capabilities. The resulting occupant schedule outputs from these examples can be used in building energy simulation. Finally, the advancements and limitations of this work are discussed.

2. Methodology

An obFMU was developed for co-simulation, requiring an XML file to be generated based on an obXML (occupant behavior eXtensible Markup Language) schema [41] and configuration with EnergyPlus. Fig. 1(a) shows the architecture of the obFMU which contains four main components, including the co-simulation interface, the interface description file in XML format, the data model, and solvers. The obXML schema describes the occupant behavior by implementing a DNAS (drivers-needs-actions-systems) framework [42]. The obFMU is the engine of the occupant behavior simulation and co-simulates via the FMI with the simulation tools, e.g. EnergyPlus. To show how the new tool can be used, examples of different occupant behaviors (i.e. lights switching, window opening, and HVAC control) are presented. The objective of the obFMU is to simulate the occupants' behaviors at each time step based on the occupant behavior description file defined in the XML format and the environmental conditions obtained through the co-simulation interface (Fig. 1(b)). A further detailed description of each component is introduced in Sections 2.1–2.4.

2.1. Overview of the DNAS ontology and obXML schema

The objective of this section is to provide a high-level overview of the DNAS ontology and resulting occupant behavior obXML schema. Specific details about the development of the ontology and implementation of the obXML schema can be found in Hong et al. [41,42].

To systematically describe the impact of occupant behaviors on building energy consumption, a human-building interaction framework was created [41]. The ontology was based on four key elements, drivers, needs, actions and systems (DNAS). Within this DNAS ontology the *drivers* represent the stimulating factors that provoke occupants to desire a change or need to perform an action or in-action with the building environment. The *needs* represent the physical or non-physical criteria that must be met to ensure occupant comfort with their surroundings. The *actions* are the interactions of the occupant with the building systems. The *systems* refer to the equipment or mechanisms within the building that the occupant alters to achieve comfort. An example of applying the DNAS concept is as follows: An occupant enters his/her office space and it is dark. So the *driver* is darkness or the lack of work plane illuminance. The *need* is to obtain visual comfort. The *action* is switching on the lights and the *system* is the lighting system in the office.

The DNAS framework was implemented into an obXML schema [42]. The obXML schema v1.0 for obFMU v1.0 is a subset of obXML schema presented in [42]. It is styled with one main root element *OccupantBehavior* and three parent elements *buildings*, *occupants* and *behaviors*. The parent *building* element is tailored specifically to the inputs required to detail occupant behavior and is not intended to replicate other schemas, such as the Green Building XML schema (gbXML) [43] nor duplicate the building input files already established in EnergyPlus. The parent *occupants* element describes all of the occupants in the building using a unique occupant ID attribute, coupling the occupant with a behavioral action. The parent *behaviors* element, shown in Fig. 2, has child elements that follow the DNAS framework. The *drivers* element is divided into four sub-child elements of (1) *time* (time of day, day of week, season), (2) *environment* (describing the major categories of temperature, IAQ, daylight factor, illuminance, glare, relative humidity, solar irradiance, raining and noise parameters), (3) *eventtype* (detail occupants' circumstance), and (4) *otherconstraints*. The *needs* element is categorized into *physical* comprised of 3 sub-child elements of *thermal*, *visual* and *IAQ*. For example, a thermal driver (e.g. indoor temperature) can signal occupant discomfort and be characterized under the needs comfort criteria using the ISO adaptive comfort

Please cite this article in press as: T. Hong, et al., An occupant behavior modeling tool for co-simulation, Energy Buildings (2015), http://dx.doi.org/10.1016/j.enbuild.2015.10.033