Title
An occupant behavior modeling tool for co-simulation:

Permalink
https://escholarship.org/uc/item/38p241sg

Authors
Hong, Tianzhen
Sun, Hongsan
Chen, Yixing
et al.

Publication Date
2015-10-01

ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

An Occupant behavior modeling tool for co-simulation

Tianzhen Hong, Hongsan Sun, Yixing Chen,
Sarah Taylor-Lange, Da Yan

Energy Technologies Area
October,2015

Energy and Buildings 117 (2016) 272–281

Contents lists available at ScienceDirect

Energy and Buildings

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

An occupant behavior modeling tool for co-simulation

Tianzhen Hong[a,*], Hongsan Sun[b], Yixing Chen[a], Sarah C. Taylor-Lange[a], Da Yan[b]

[a] Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA
[b] Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 26 June 2015
Received in revised form 5 September 2015
Accepted 15 October 2015
Available online 10 November 2015

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

---

* Corresponding author.
E-mail address: thong@lbl.gov (T. Hong).

http://dx.doi.org/10.1016/j.enbuild.2015.10.033
0378-7788/© 2015 Elsevier B.V. All rights reserved.

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

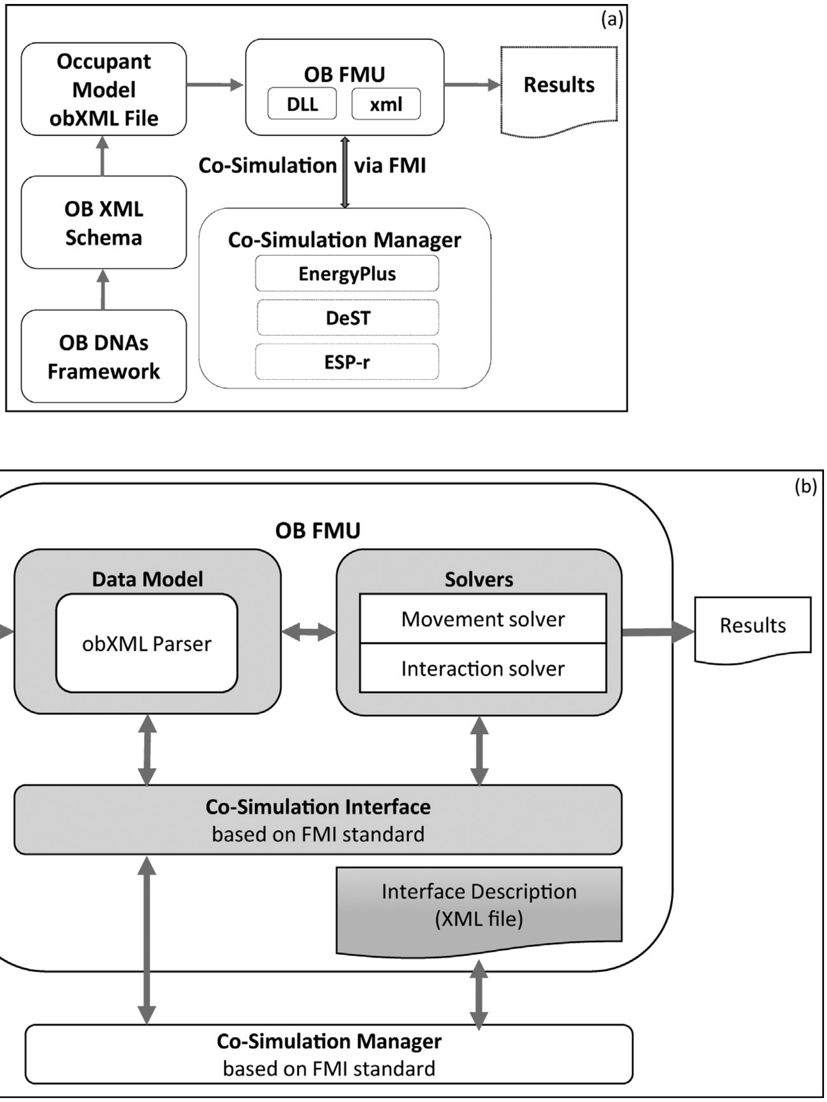


Fig. 1. (a) An overview schematic of the OB modeling tool and (b) a detailed structure of the obFMU structure with obXML file inputs and co-simulation manager components.

standard [44], the ASHRAE adaptive comfort standard [45] or a user defined comfort envelope. The *actions* element has 2 child elements of *interaction* and *movement*. *Interaction* element includes the input option of mathematical models (i.e. constant value, linear 1D, 2D, 3D, quadratic 1D, logit1D, 2D, 3D and Weibull 1D) used to calculate the probability of an action occurring. The *systems* element represents the building equipment or components that the occupant physically interacts with and has the child elements of *windows*, *lights*, and *HVAC*.

The obXML schema contains the definition and description of all variables for the FMU and provides a basis for the xml output file. This xml output file is a key piece in the obFMU development and is used as part of the overall OB modeling tool process.

2.2. *The co-simulation interface based on the FMI standard*

FMI is a tool independent standard developed by the Information Technology for European Advancement (ITEA2) project called MODELISAR [38]. The FMI supports model exchange and co-simulation using XML, C-code and C-header files [37]. Fig. 3 shows the schematic diagram of the obFMU co-simulation interface which follows the FMI standard. The co-simulation manager initializes each obFMU through two FMI functions: *fmiInstantiateSlave* and *fmiInitializeSlave*. The *fmiInstantiateSlave* allocates the required memory for each obFMU instance, while the *fmiInitializeSlave* sets the default values for the instance. Then, the co-simulation manager performs time step simulations by calling the *fmiGetReal*, *fmiSetReal*, and *fmiDoStep* functions. The *fmiGetReal* passes data from the obFMU to the co-simulation manager, and the *fmiSetReal* provides data from the co-simulation manager to the obFMU. After each time step simulation, the co-simulation manager checks whether it is at the end of the simulation or not. If yes, then the *fmiFreeSlaveInstance* function is called to release the memory of the obFMU instance.

2.3. *FMU interface description file in xml format*

Following the FMI standard, the relevant information for communication in the co-simulation environment is provided by the XML-file. Fig. 4 shows the description of the input and output variables for obFMU v1.0 in XML format. The obFMU v1.0 requires 4 input variables (zone dry-bulb air temperature, zone daylighting illumination level, zone CO_2 concentration, and zone lighting power) and generates 4 output variables (zone HVAC operation schedule, zone lighting operation schedule, zone infiltration schedule, and zone occupancy schedule).

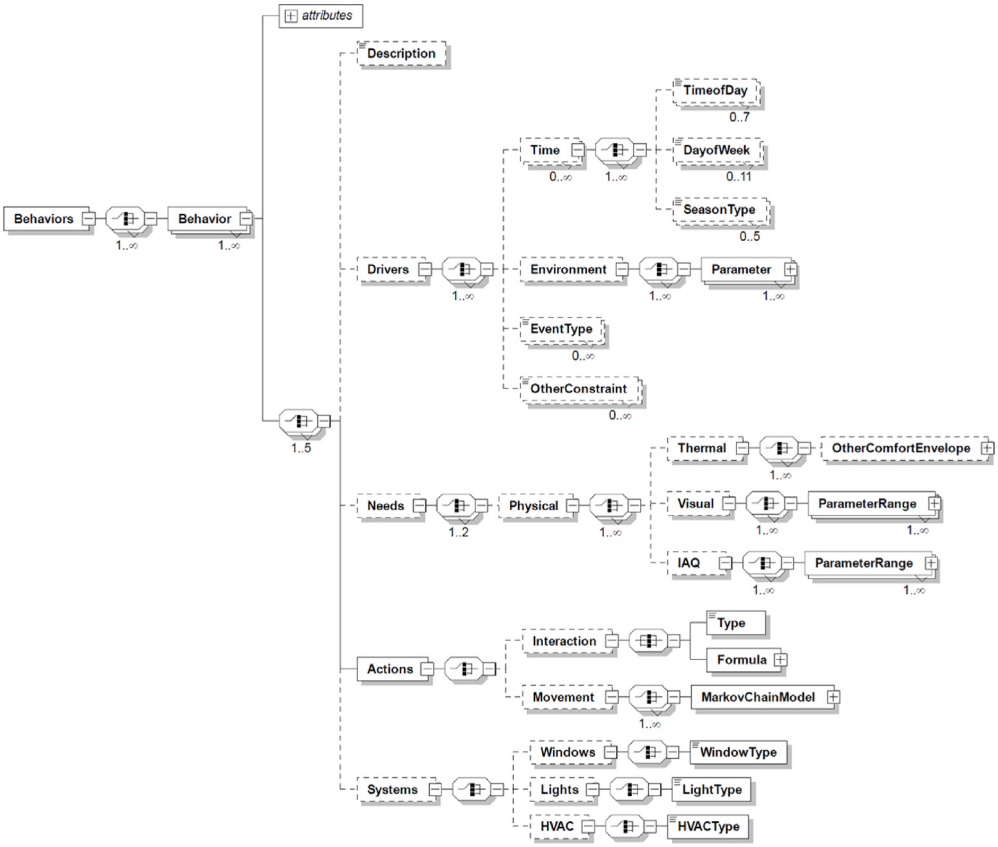


Fig. 2. The tree diagram from the xsd file showing the general characteristics of the behaviors root element, with behavior parent element and children elements of drivers, needs, actions and systems (DNAS).

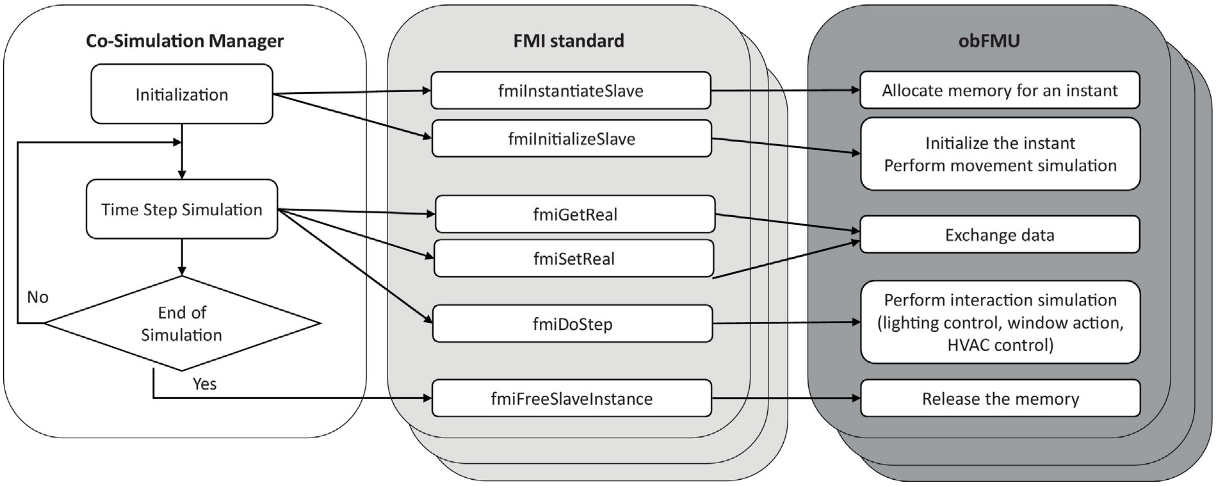


Fig. 3. Schematic diagram of the obFMU co-simulation interface.

2.4. Data model and solvers

The obFMU data model is developed based on the obXML schema v1.0. Each obFMU instance handles the occupant behavior simulation for one zone. The co-simulation manager can create multiple obFMU instances for multi-zoned buildings. The data model requires the zone level information, such as zone floor area, zone type, zone meeting events, and so on, to be defined. This is followed by information about the occupant including their behavior description. In obFMU v1.0, the lighting system, windows system, air conditioning system, and heating system are considered (Fig. 5). An obXML parser is developed to obtain the occupant behavior description from the obXML file.

There are two types of solvers in obFMU v1.0 the movement solver and interaction solver. The movement solver is called once per co-simulation to determine the location of each occupant at each time step. The occupant movement model uses Markov chain movement [46] with a transition probability matrix that determines the probability of an occupant moving from location to location based on the previous location. The interaction solver is called at each time step in each obFMU instance to simulate the occupants' behavior in the associated zone. Such behaviors consist of turning on and off the lights, opening or closing the windows, or controlling the HVAC. The obFMU can be used by other BEM programs with the FMU management feature, such as EnergyPlus. Fig. 5 shows the data exchange between EnergyPlus and obFMU during

```
<?xml version="1.0" encoding="ISO-8859-1"?>
<!-- GUID generated at http://guid.us -->
<fmiModelDescription fmiVersion="1.0"  modelName="obFMU"  modelIdentifier="obFMU"
  numberOfContinuousStates="42"  numberOfEventIndicators="42"  version="1.0"
  guid="{7b2d6d3f-ac4d-4aa8-93eb-d53357dc58ec}">
<ModelVariables>
  <ScalarVariable name="Zone_Temperature"  valueReference="201" causality="input"><Real/></ScalarVariable>
  <ScalarVariable name="Zone_illum"        valueReference="202" causality="input"><Real/></ScalarVariable>
  <ScalarVariable name="Zone_co2"          valueReference="203" causality="input"><Real/></ScalarVariable>
  <ScalarVariable name="Zone_Light_Power"  valueReference="204" causality="input"><Real/></ScalarVariable>
  <ScalarVariable name="OutdoorAir_Drybulb_Temperature" valueReference="205" causality="input">
    <Real/>
  </ScalarVariable>

  <ScalarVariable name="Zone_HVAC_SCH"   valueReference="101" causality="output"><Real/></ScalarVariable>
  <ScalarVariable name="Zone_light_SCH"  valueReference="102" causality="output"><Real/></ScalarVariable>
  <ScalarVariable name="Zone_infil_SCH"  valueReference="103" causality="output"><Real/></ScalarVariable>
  <ScalarVariable name="Zone_occ_SCH"    valueReference="104" causality="output"><Real/></ScalarVariable>
  </ModelVariables>
<Implementation>
  <CoSimulation_StandAlone>
    <Capabilities canHandleVariableCommunicationStepSize="true" canHandleEvents="true"/>
  </CoSimulation_StandAlone>
</Implementation>
</fmiModelDescription>
```

Fig. 4. FMU interface description file for the obFMU v1.0.

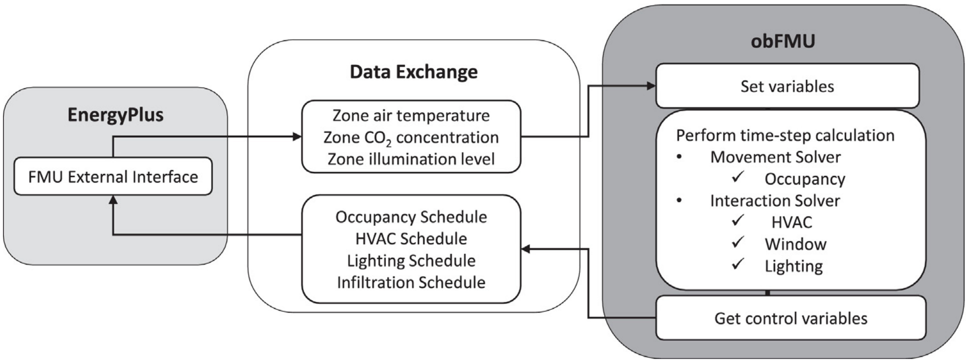


Fig. 5. Data exchange between EnergyPlus and the obFMU.

each time step. The EnergyPlus is the co-simulation manager, while the obFMU is the slave.

3. Applications

To show how obFMU can be used, three examples are presented. The obFMU co-simulates with EnergyPlus to simulate occupant behavioral actions, specific to (1) turning on and off the lights, (2) opening or closing the windows, and (3) operating the HVAC control. For all examples, a simple single story building with the geometry of 44 m × 20 m × 3.5 m located in Miami, Florida, was considered. The single-story office building had a central corridor and with single office rooms on either side of the central hallway. Each office had one operable window and on/off lighting control (i.e. no dimming or occupancy sensors). The HVAC system used in the building was a packaged single zone heat-pump system. A total number of 16 occupants were work in the building. In the simulations, both the movement solver and the interaction solver were used.

3.1. Coupling the obFMU with EnergyPlus to model occupant behavior lighting control

Office lighting can reach 20–60% of an office building's total electrical consumption [47,48]. In this example, the occupant action of lighting control (turning on and off the lights) is simulated using the OB modeling tool. For turning the lights on, two contingencies are considered: (1) turning on the lights when occupants first entering the room or (2) turning on the lights when occupants feel the room is dark. For turning the lights off, the two scenarios are considered: (1) turning off the lights when occupants leaving the room or (2) turning off the lights when it is bright outside. In the XML schema, the child element *interaction*, from the parent element *action*, includes different mathematical methods that define the probability of the action occurring. In this case, Weibull functions were used to determine the probability of turning the light on or off as a function of the illuminance level. Fig. A.1(a) shows a code snippet of the xml code describing the action of turning the lights on and Fig. A.1(b) displays the cumulative distribution function with the probability of turning the lights on as a function of the illuminance.

The simulation results for the lighting control in an office and spanning a 3-day period are shown in Fig. 6. The results indicate that as the illuminance level increases due to natural daylighting, there is enough work plane illuminance in the office to satisfy the occupants' visual comfort, without turning on the lights. As the outside lighting level decreases (around 6:00 pm) the lighting is switched on and off for a period of time to satisfy occupant comfort. Additionally, on days 1 and 2 a single occupant remains in the office slightly past 6:00 pm, perhaps working after hours, and during this brief period the lights are turned on and off. The lighting schedule indicated from this simulation captures the integrated nature of the occupant's activity on a daily basis.

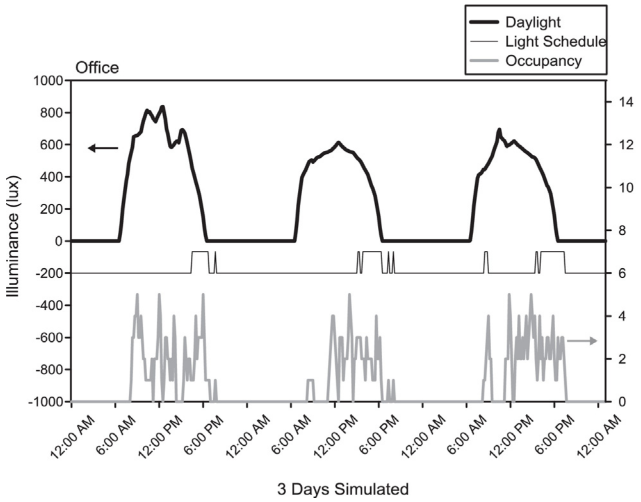


Fig. 6. The simulation results for lighting over a 3-day period, showing the occupancy, lighting schedule and the outdoor daylight level.

3.2. Coupling the obFMU with EnergyPlus to model occupant behavior window action

One of the most important issues in the built environment is regulating the indoor and outdoor thermal and air quality interaction [49], with the window being one of the most widely used systems to manipulate the IEQ [50]. Indoor and outdoor temperatures are some of the most relevant parameters affecting window opening and closing behavior [51,52]. Andersen et al. [53] also suggested that indoor stuffiness, monitored by the carbon dioxide (CO_2) concentration levels, was an important driver for window opening behavior. In this example, the occupant action of window control (opening and closing the window in the office) is simulated. For the window open model, two contingencies are considered: (1) opening the window when the occupant feels hot or (2) opening the window when feeling stuffy. For the window closing model, the two scenarios are considered: (1) closing the window when leaving the room or (2) closing the window when feeling cold. The Weibull model of the window opening or closing can be described as a function of temperature (when feeling hot), occupant movement (leaving the room) or CO_2 concentration (when feeling stuffy). Fig. A.2(a) shows a code snippet of the xml code describing the action of opening the window. For this case the drivers are environmental, specifically the indoor temperature, the needs are thermal comfort, the actions include opening the window and the system is the window. Fig. A.2(b) displays the Weibull function with the probability of opening the window as a function of the temperature.

The simulation results for the window control in an office and spanning a 3-day period are shown in Fig. 7. Schedules including occupant presence (number of people), the window opening and closing action indicated by infiltration, the indoor CO_2 concentration and the indoor air temperature. For reference the CO_2 concentrations in outdoor air typically range from 300 to 500 ppm [54]. The results indicate that as the CO_2 concentration increases (from roughly 500 ppm to 1000 ppm), the indoor temperature also slightly increases (from 25 °C to 32 °C), resulting in stuffy or stale office conditions. This discomfort drives the occupant to take action and open the window. Upon window opening, almost instantaneously the CO_2 concentration drops to about 500 ppm accompanied with a drop in the indoor temperature (to 25 °C). The closing of the window correlates with the occupant's satisfaction with their indoor environment or the occupant vacating the office.

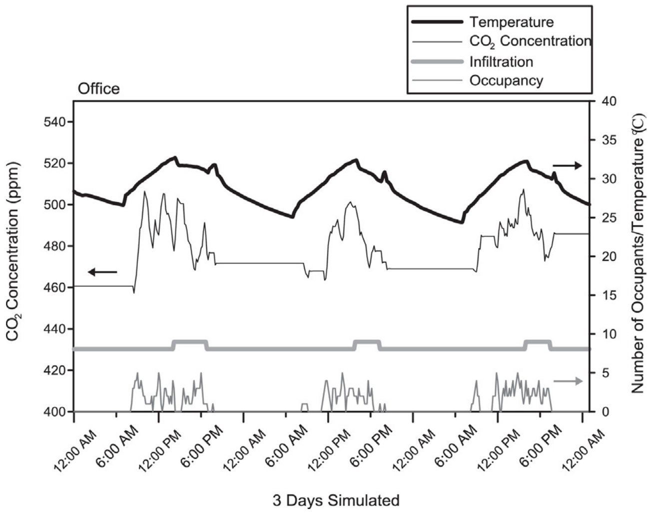


Fig. 7. The results for window operation simulated over a 3-day period, showing the occupancy, the window open/close action indicated by the infiltration, the CO_2 concentration and the indoor temperature.

3.3. Coupling the obFMU with EnergyPlus to model HVAC control

In general, the energy consumption used for heating and cooling in developed countries accounts for 50% of the building energy use and roughly 20% of the total national energy [55]. The common practice among building simulation programs is to fix the heating set-point temperature at 20 °C [49], which is often unrepresentative of actual conditions. In this example, the occupant action of air conditioning (AC) control (turning on and off the air conditioner) is simulated. For turning on the AC, two contingencies are considered: (1) turning on the AC when occupants enter the room or (2) turning on the AC when occupants are feeling hot. For turning off the AC, the two scenarios are considered: (1) turning off the AC when leaving the room or (2) turning off the AC when feeling cold. The Weibull model of turning on the AC when feeling hot can be described as a function of temperature [11]. Fig. A.3(a) shows a code snippet of the xml code describing the action of turning on the AC. For this case the *drivers* are environmental, specifically the indoor temperature, the *needs* are thermal comfort, the *actions* include turning on the AC system and the *system* is the HVAC system. Fig. A.3(b) displays the Weibull function with the probability of turning on the AC as a function of the temperature.

The simulation results for the AC control in an office and in a meeting room, spanning a 3-day period, are presented in Fig. 8. The simulation takes into effect the cumulative distribution frequency of the probability of the AC being turned on or off, based on the temperature. The occupant presence, the real-time simulation results of the air conditioning schedule derived from the contingency scenarios, and the indoor temperature are presented (Fig. 8). The results indicate that as the room occupancy or the indoor temperature increases the AC turns on. If the occupants vacate the office (or the meeting room) or the temperature set point is achieved, the AC turns off. In general, the resulting AC schedule is unique for each day.

4. Discussion

The modernity of co-simulation enables researchers and practitioners to generate less pre-defined schedules that reflect key drivers that motivate an occupant's behavior. The obFMU provides an environment for co-simulation, utilizing the capabilities of domain-specific simulation and providing the flexibility to be integrated with an array of building modeling programs, extending beyond EnergyPlus. This allows users the ability to select

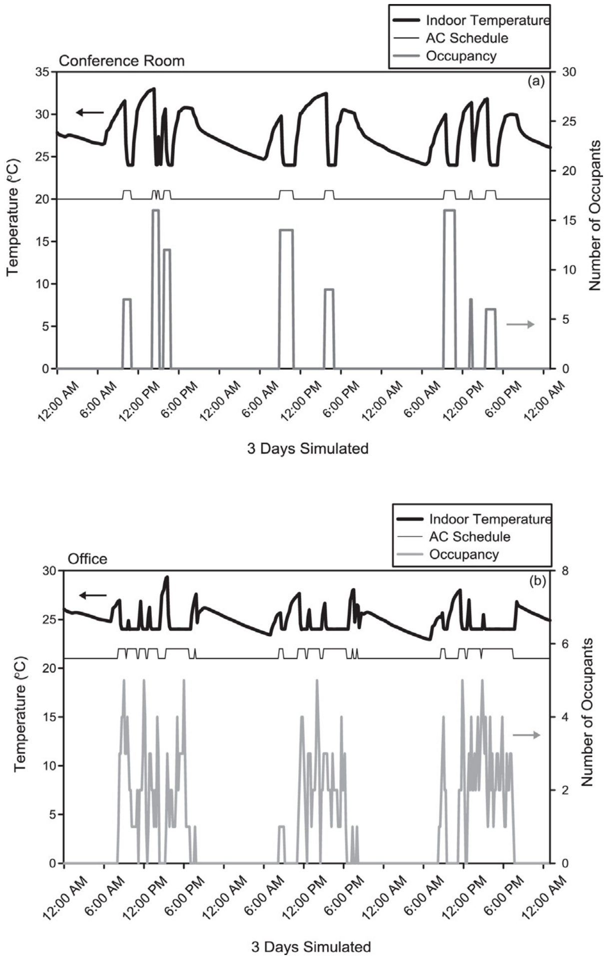


Fig. 8. The results for air conditioning operation simulated over a 3-day period, showing the indoor temperature, occupant presence, and air conditioning operation for (a) conference room and (b) office.

preferred simulation programs. The obFMU is self-integrating with the co-simulation manager to perform the numerical integration, promoting the interoperability of the tool.

The current version (v1.0) of the obFMU enables the co-simulation of the two interaction types: turn on (open) or turn off (close) the system; three systems: lights, windows, and HVAC system; three event types and their combinations (totally 7 types): stay, entering, or leaving the room; two other constraints: have or have no other occupants in the room; and nine probability models. In addition to the example scenarios introduced in Sections 3.1–3.3, the obFMU allows the combination of the interaction types, systems, event types, other constraints and probability models, which can provides up to $(2 \times 3 \times 7 \times 2 \times 9 =)$ 756 different behavior scenarios. The obFMU v1.0 can be used to perform co-simulation of the above mentioned behaviors in any buildings without coding and rebuilding the FMU, by specifying the occupant behaviors using the obXML schema. It also provides a platform for other researchers to contribute their own occupant behavior models by writing new code and rebuilding the FMU. The current version focuses on window action, lighting and HVAC control. Future behaviors that can be easily implemented include shade/blind action, plug load operation and thermostat action.

Despite significant advancements, limitations arose including the current inability to pass simulation flags to the obFMU including *WarmUp*, *SizingCalc*, *WatherPeriodSim*. In addition, EnergyPlus iterations lag one time step behind the obFMU. Currently, during each iteration the existing schedules are overwritten. Moreover, additional areas of improvement include reconsidering the constraints associated with: (1) systems partially open or partially closed, (2) groups versus individual behavior, (3) the occurrence of simultaneous multiple-actions and the sequence of occupant actions and, (4) accounting for culturally motivated actions. Currently, the occupant behavior model considers individual actions on a first come basis and that groups of occupants perform one-time actions in agreement. Capturing these diverse aspects of behavior in simulation and co-simulation with BEM programs (e.g. EnergyPlus, DeST, ESP-r) proves challenging. Future work will also include organizational decision making considering an interdisciplinary collaboration with experts from social and behavioral sciences.

The main aim in the creation of the OB modeling tool was to provide a new approach to enhancing OB modeling in current BEM programs, which captures diversity and stochastic nature of occupant activities in buildings rather than using homogeneous user schedules [56]. The objectives of this paper were to describe how the OB modeling tool works and provide a few examples of how it can be used. Future work will compare and contrast the OB modeling tool with traditional methods or directly with EnergyPlus inputs, to assess building performance. More testing of the modeling tool including improvements to the obXML schema and updating the obFMU will occur resulting in a second version released and made available to the public at http://behavior.lbl.gov.

5. Conclusions

Presented was the development of an occupant behavior modeling tool, obFMU. The obFMU reads occupant behavior representation using an XML file based on an obXML schema following the DNAS (drivers-needs-actions-systems) ontology. The obFMU enables co-simulation of occupant behavior with building energy modeling programs based on the FMI standard. The Weibull function characterized in the obXML schema was able to describe lighting, window and HVAC actions based on environmental parameters such as illuminance, outdoor air temperature, indoor CO_2 concentration or indoor air temperature. The results demonstrate how the co-simulation module works, providing occupant actions based on drivers and probability functions. The significant advancements from this work include:

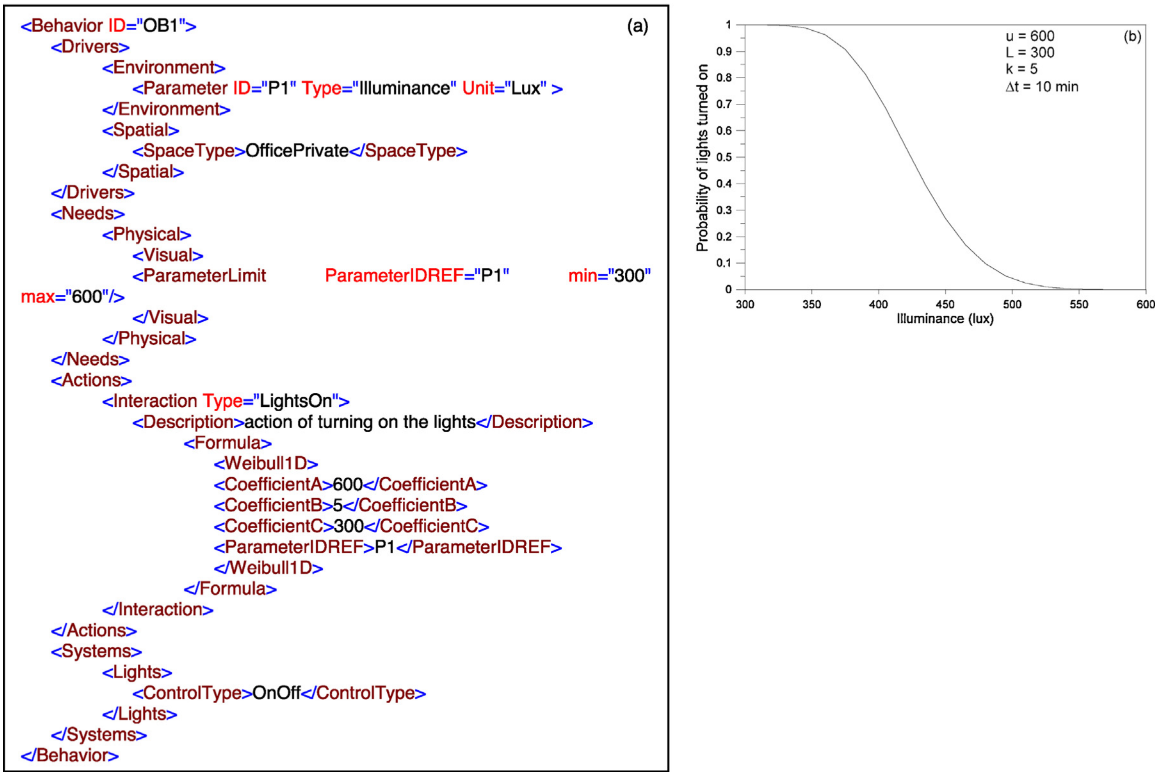
(1) The development and applications of a new occupant behavior tool, the obFMU, for co-simulation with all building energy modeling programs implementing the FMI, which does not limit users to a particular simulation program.
(2) The obXML and obFMU enables and implements interoperability of occupant behavior models.

The behavior modeling tool provides a new approach to simulating occupant actions, with the aim of eventually improving occupant information modeling. The model provides a diverse set of options, proving flexible and promoting interoperability between occupant behavior models and existing building energy modeling programs. Broadly, this work and future versions of the obFMU will aid in accounting for some of the discrepancies that arise between simulated and actual building energy use.

Acknowledgement

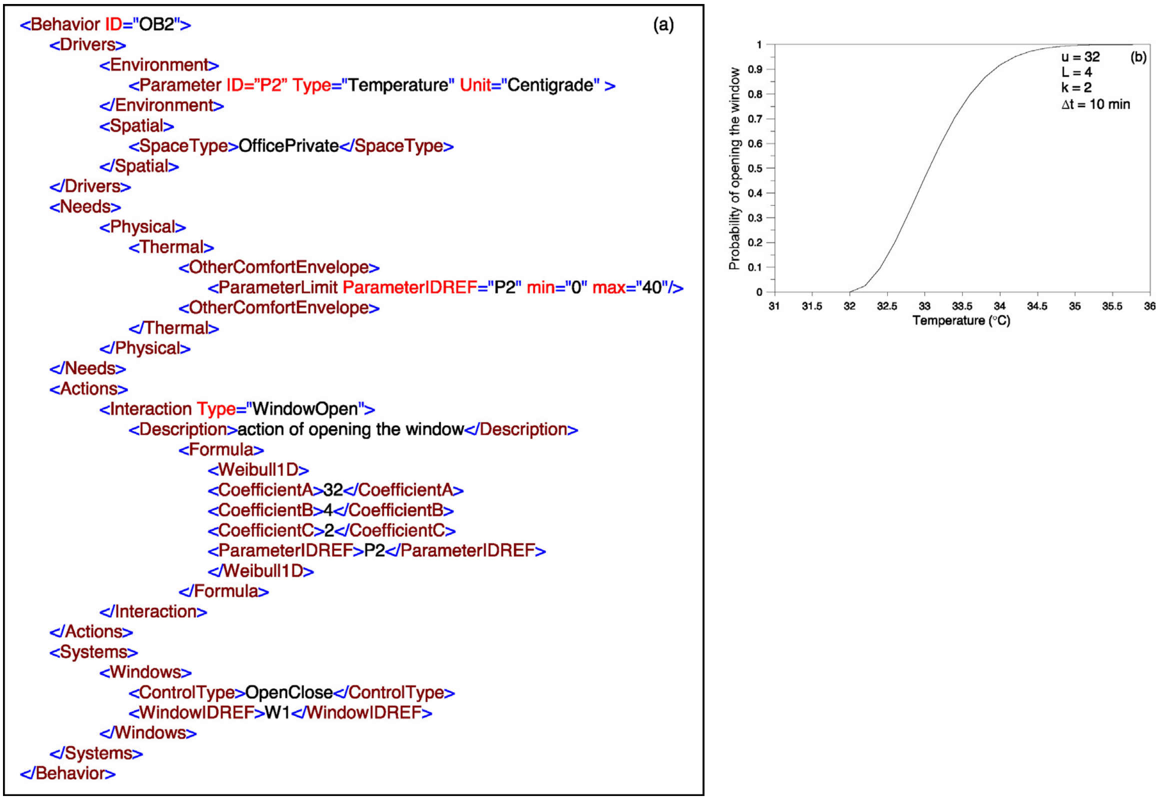
This work was sponsored by the United States Department of Energy (Contract No. DE-AC02-05CH11231) under the U.S.-China Clean energy Research Center for Building Energy Efficiency. The work is also part of the research activities of the International Energy Agency Energy in Buildings and Communities Program Annex 66, Definition and Simulation of Occupant Behavior in Buildings.

Appendix.



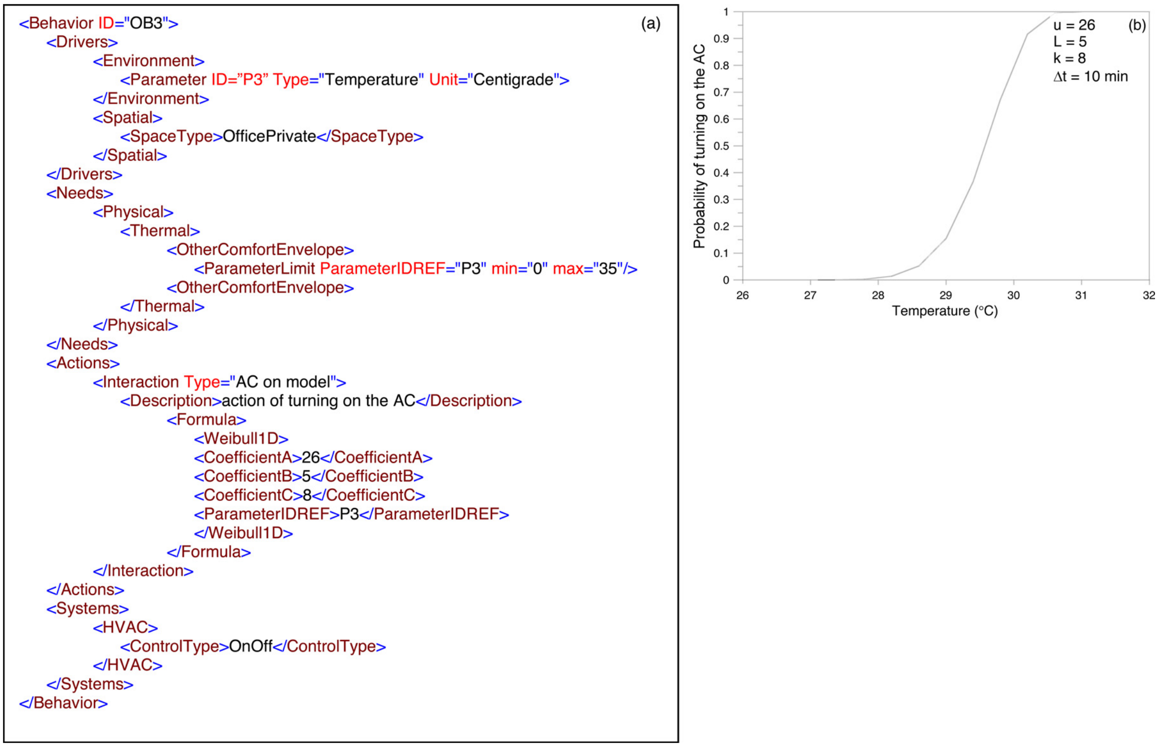
```
<Behavior ID="OB1">                                                    (a)
    <Drivers>
            <Environment>
                <Parameter ID="P1" Type="Illuminance" Unit="Lux" >
            </Environment>
            <Spatial>
                <SpaceType>OfficePrivate</SpaceType>
            </Spatial>
    </Drivers>
    <Needs>
            <Physical>
                <Visual>
                <ParameterLimit          ParameterIDREF="P1"          min="300"
max="600"/>
                </Visual>
            </Physical>
    </Needs>
    <Actions>
            <Interaction Type="LightsOn">
                <Description>action of turning on the lights</Description>
                        <Formula>
                            <Weibull1D>
                            <CoefficientA>600</CoefficientA>
                            <CoefficientB>5</CoefficientB>
                            <CoefficientC>300</CoefficientC>
                            <ParameterIDREF>P1</ParameterIDREF>
                            </Weibull1D>
                        </Formula>
            </Interaction>
    </Actions>
    <Systems>
            <Lights>
                <ControlType>OnOff</ControlType>
            </Lights>
    </Systems>
</Behavior>
```

Fig. A.1. (a) An .xml code snippet describing the Weibull function for turning the lights on and (b) the cumulative distribution function with coefficient parameters.



```
<Behavior ID="OB2">                                                         (a)
    <Drivers>
            <Environment>
                <Parameter ID=”P2” Type="Temperature" Unit="Centigrade" >
            </Environment>
            <Spatial>
                <SpaceType>OfficePrivate</SpaceType>
            </Spatial>
    </Drivers>
    <Needs>
            <Physical>
                <Thermal>
                        <OtherComfortEnvelope>
                            <ParameterLimit ParameterIDREF="P2" min="0" max="40"/>
                        <OtherComfortEnvelope>
                </Thermal>
            </Physical>
    </Needs>
    <Actions>
            <Interaction Type="WindowOpen">
                <Description>action of opening the window</Description>
                        <Formula>
                            <Weibull1D>
                            <CoefficientA>32</CoefficientA>
                            <CoefficientB>4</CoefficientB>
                            <CoefficientC>2</CoefficientC>
                            <ParameterIDREF>P2</ParameterIDREF>
                            </Weibull1D>
                        </Formula>
            </Interaction>
    </Actions>
    <Systems>
            <Windows>
                <ControlType>OpenClose</ControlType>
                <WindowIDREF>W1</WindowIDREF>
            </Windows>
    </Systems>
</Behavior>
```

Fig. A.2. (a) An .xml code snippet describing the Weibull function for opening the window when feeling hot and (b) the cumulative distribution as a function of temperature with coefficient parameters.



```
<Behavior ID="OB3">
    <Drivers>
        <Environment>
            <Parameter ID="P3" Type="Temperature" Unit="Centigrade">
        </Environment>
        <Spatial>
            <SpaceType>OfficePrivate</SpaceType>
        </Spatial>
    </Drivers>
    <Needs>
        <Physical>
            <Thermal>
                <OtherComfortEnvelope>
                    <ParameterLimit ParameterIDREF="P3" min="0" max="35"/>
                <OtherComfortEnvelope>
            </Thermal>
        </Physical>
    </Needs>
    <Actions>
        <Interaction Type="AC on model">
            <Description>action of turning on the AC</Description>
                <Formula>
                    <Weibull1D>
                    <CoefficientA>26</CoefficientA>
                    <CoefficientB>5</CoefficientB>
                    <CoefficientC>8</CoefficientC>
                    <ParameterIDREF>P3</ParameterIDREF>
                    </Weibull1D>
                </Formula>
        </Interaction>
    </Actions>
    <Systems>
        <HVAC>
            <ControlType>OnOff</ControlType>
        </HVAC>
    </Systems>
</Behavior>
```

Fig. A.3. (a) An .xml code snippet describing the Weibull function for turning on the AC when feeling hot and (b) the cumulative distribution as a function of temperature with coefficient parameters.

References

[1] U.S. Energy Information Administration, Annual Energy Outlook 2014 with Projections to 2040. DOE/EIA-0383(2014), U.S. Department of Energy, Washington, DC, 2014.

[2] K. Schakib-Ekbatan, F.Z. Çakıcı, M. Schweiker, A. Wagner, Does the occupant behavior match the energy concept of the building? Analysis of a German naturally ventilated office building, Build. Environ. 84 (2015) 142–150.

[3] K. Sun, D. Yan, T. Hong, S. Guo, Stochastic modeling of overtime occupancy and its application in building energy simulation and calibration, Build. Environ. 79 (2014) 1–12.

[4] W. O'Brien, K. Kapsis, A.K. Athienitis, Manually-operated window shade patterns in office buildings: a critical review, Build. Environ. 60 (2013) 319–338.

[5] T. Hong, H.-W. Lin, Occupant behavior: impact on energy use of private offices, in: First Asia Building Simulation Conference ASim, Shanghai, China, 2013.

[6] Final Report IEA Annex 53 Total Energy Use in Buildings, Analysis and Evaluation Methods, IEA, 2013.

[7] , IEA, 2013.

[8] R.C. Sonderegger, Movers and stayers: the resident's contribution to variation across houses in energy consumption for space heating, Energy Build. 41 (2009) 337–353.

[9] J. Zhao, B. Lasternas, K.P. Lam, R. Yun, V. Loftness, Occupant behavior and schedule modeling for building energy simulation through office appliance power consumption data mining, Energy Build. 82 (2014) 341–355.

[10] A. Mahdavi, F. Tahmasebi, Predicting people's presence in buildings: an empirically based model performance analysis, Energy Build. 86 (2015) 349–355.

[11] X. Ren, D. Yan, C. Wang, Air-conditioning usage conditional probability model for residential buildings, Build. Environ. 81 (2014) 172–182.

[12] J. Langevin, J. Wen, P.L. Gurian, Modeling thermal comfort holistically: Bayesian estimation of thermal sensation, acceptability and preference distributions for office building occupants, Build. Environ. 69 (2013) 206–226.

[13] H.B. Gunay, W. O'Brien, I. Beausoleil-Morrison, A critical review of observation studies, modeling, and simulation of adaptive occupant behaviors in offices, Build. Environ. 70 (2013) 31–47.

[14] D. Aerts, J. Minnen, I. Glorieux, I. Wouters, F. Descamps, A method for the identification and modelling of realistic domestic occupancy sequences for building energy demand simulations and peer comparison, Build. Environ. 75 (2014) 67–78.

[15] H.B. Gunay, W. O'Brien, I. Beausoleil-Morrison, R. Goldstein, S. Breslav, A. Khan, Coupling stochastic occupant models to building performance simulation using the discrete event system specification formalism, J. Build. Perform. Simul. 7 (2014) 457–478.

[16] P.D. Andersen, A. Iversen, H. Madsen, C. Rode, Dynamic modeling of presence of occupants using inhomogeneous Markov chains, Energy Build. 69 (2014) 213–223.

[17] Y.S. Lee, A.M. Malkawi, Simulating multiple occupant behaviors in buildings: An agent-based modeling approach, Energy Build. 69 (2014) 407–416.

[18] J. Langevin, J. Wen, P.L. Gurian, Simulating the human-building interaction: Development and validation of an agent-based model of office occupant behaviors, Build. Environ. 88 (2015) 27–45.

[19] F. Haldi, D. Robinson, The impact of occupant's behaviour on building energy demand, J. Build. Perform. Simul. 4 (2011) 323–338.

[20] D. Yan, W. O'Brien, T. Hong, X. Feng, H.B. Gunay, F. Tahmasebi, A. Mahdavi, Occupant behavior modeling for building performance simulation: current state and future challenges, Energy Build. 107 (2015) 264–278.

[21] T. Hong, S.C. Taylor-Lange, S. D'Oca, D. Yan, S.P. Corgnati, Advances in research and applications of energy-related occupant behavior in buildings, Eng. Adv. (2015) (accepted for publication).

[22] X. Feng, D. Yan, T. Hong, Simulation of occupancy in buildings, Energy Build. 87 (2015) 348–359.

[23] S. D'Oca, T. Hong, Occupancy schedules learning process through a data mining framework, Energy Build. 88 (2015) 395–408.

[24] International Energy Agency, Energy in Buildings And Communities Program. Annex 66: Definition and Simulation of Occupant Behavior in Buildings, 2013–2017, http://www.annex66.org/.

[25] T. Nouidui, M. Wetter, W. Zou, Functional mock-up unit for co-simulation import in EnergyPlus, J. Build. Perform. Simul. 7 (2014) 192–202.

[26] D.B. Crawley, L.K. Lawrie, F.C. Winkelmann, W.F. Buhl, Y.J. Huang, C.O. Pedersen, R.K. Strand, R.J. Liesen, D.E. Fisher, M.J. Witte, J. Glazer, EnergyPlus: creating a new-generation building energy simulation program, Energy Build. 33 (2001) 319–331.

[27] Y. Chen, L. Gu, J.S. Zhang, EnergyPlus and CHAMPS-Multizone co-simulation for energy and indoor air quality analysis, Build. Simul. (2015), http://dx.doi.org/10.1007/s12273-015-0211-1.

[28] Z. Zhai, Q. Chen, Performance of coupled building energy and CFD simulations, Energy Build. 37 (2005) 333–344.

[29] Z. Zhai, Q. Chen, P. Haves, J. Klems, On approaches to couple energy simulation and computational fluid dynamics programs, Build. Environ. 37 (2002) 857–864.

[30] M. Wetter, Co-simulation of building energy and control systems with the building controls virtual test bed, J. Build. Perform. Simul. (2011) 185–203.

[31] Dassault Systemes AB, Dymola Dynamic Modeling Laboratory, 1991–2012, http://www.3ds.com/products/catia/portfolio/dymola (accessed 22.06.15).

[32] G.W. Larson, R.A. Shakespeare, Radiance, 1988–2012, http://radsite.lbl.gov/radiance/ (accessed 22.06.15).

[33] J. Clarke, ESP-r, 1974–2012, http://www.esru.strath.ac.uk/Programs/ESP-r.htm (accessed 22.06.15).

[34] W. Bernal, M. Behl, T.X. Nghiem, R. Mangharam, MLE+: A Tool for Integrated Design and Deployment of Energy Efficient Building Controls, Buildsys'12, Canada, 2012.

[35] C.J. Andrews, D. Yi, U. Krogmann, J.A. Senick, R.E. Wener, Designing buildings for real occupants: an agent-based approach, IEEE Trans. Syst. Man Cybern. A: Syst. Hum. 41 (2011) 1077–1091.
[36] F.H. Abanda, L.F. Cabeza, Exploring building occupants' behaviour using emerging building information modelling, in: 5th International/11th Construction Specialty Conference, British Columbia, 2015.
[37] T. Blochwitz, M. Otter, M. Arnold, C. Bausch, C. Clauß, H. Elmqvist, A. Junghanns, J. Mauss, M. Monteiro, T. Neidhold, D. Neumerkel, H. Olsson, J.-V. Peetz, S. Wolf, The functional mock-up interface for tool independent exchange of simulation models, in: Proceedings of the 8th Modelica Conference, Dresden, Germany, 2011, March, pp. 105–114.
[38] MODELISAR Consortium, Functional Mock-up Interface, 2008–2012a, https://fmi-standard.org/ (accessed 22.06.15).
[39] MODELISAR Consortium, Functional Mock-up Interface for Co-simulation, 2010, https://svn.modelica.org/fmi/branches/public/specifications/FMI_for_CoSimulation_v1.0.pdf (accessed 22.06.15).
[40] D. Broman, C. Brooks, L. Greenberg, E.A. Lee, M. Masin, S. Tripakis, M. Wetter, Determinate composition of FMUs for co-simulation, in: International Conference on Embedded Software, Montreal, Canada, 2013.
[41] T. Hong, S. D'Oca, S.C. Taylor-Lange, W.J.N. Turner, Y. Chen, S.P. Corgnati, An ontology to represent energy-related occupant behavior in buildings. Part II: implementation of the DNAs Framework using an XML schema, Build. Environ. 94 (2015) 196–205.
[42] T. Hong, S. D'Oca, W.J.N. Turner, S.C. Taylor-Lange, An ontology to represent energy-related occupant behavior in buildings. Part I: introduction to the DNAs Framework, Build. Environ. 92 (2015) 764–777.
[43] S. Roth, Open Green Building XML Schema: A Building Information Modeling Solution for Our Green World, gbXML Schema (5.12), 2014, www.gbxml.org.
[44] ISO, International Standard 7730, Moderate Thermal Environments – Determination of the PMV and PPD Indices and Specification of the Conditions of Thermal Comfort, 2nd ed., International Standards Organization, Geneva, 2004.
[45] ASHRAE/ANSI Standard 55-2010 Thermal Environmental Conditions for Human Occupancy, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA, 2010.
[46] J. Page, D. Robinson, N. Morel, J.-L. Scartezzini, A generalized stochastic model for the simulation of occupant presence, Energy Build. 40 (2008) 83–98.
[47] I.P. Knight, Measured energy savings due to photocell control of individual luminaries, Light. Res. Technol. 31 (1999) 19–22.
[48] M. Bodart, A. De Herde, Global energy savings in office buildings by the use of daylighting, Energy Build. 34 (2002) 421–429.
[49] V. Fabi, R.V. Andersen, S.P. Corgnati, Influence of occupant's heating set-point preferences on indoor environmental quality and heating demand in residential buildings, HVAC&R Res. 19 (2013) 635–645.
[50] S. D'Oca, T. Hong, A data-mining approach to discover patterns of window opening and closing behavior in offices, Build. Environ. 82 (2014) 726–739.
[51] H.B. Rijal, P. Tuohy, M.A. Humphreys, J.F. Nicol, Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings, Energy Build. 39 (2007) 823–836.
[52] F. Haldi, D. Robinson, Interactions with window openings by office occupants, Build. Environ. 44 (2009) 2378–2395.
[53] R.V. Andersen, B.W. Olesen, J. Toftum, Modelling window opening behavior in Danish dwellings, in: Proceedings of Indoor Air, 2011, 12th International Conference on Indoor Air Quality and Climate, Austin, TX, 2011.
[54] ASHRAE, ANSI, Standard 62.1-2013 Ventilation for Acceptable Indoor Air Quality, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, 2013.
[55] L. Perez-Lombard, J. Ortiz, C. Pout, A review on buildings energy consumption information, Energy Build. 40 (2008) 394–398.
[56] ASHRA/ANSI Standard, 90.1-2013, Energy Standard for Buildings Except Low-Rise Residential Buildings, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA, 2013.

Glossary

ABM: agent based model
AC: air conditioning
ASHRAE: American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BCVTB: building controls virtual test bed
BEM: building energy modeling
CFD: computational fluid dynamics
DNAS: drivers, needs, actions, systems
EBC: Energy in Buildings and Communities Programme
FMI: functional mock-up interface
FMU: functional mock-up unit
HVAC: heating, ventilating, and air conditioning
IAQ: indoor air quality
IEA: International Energy Agency
IEQ: indoor environmental quality
ISO: International Organization for Standardization
OB: occupant behavior
XML: eXtensible Markup Language