A HIGH LEVEL ARCHITECTURE FRAMEWORK FOR COUPLING BUILDING ENERGY PERFORMANCE MODELS

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ABSTRACT

In this paper, a framework that couples energy modeling with building information models (BIM), building automation systems and occupancy data is developed using a distributed computing environment based on the principles defined in the High-Level Architecture (HLA) proposed by the US Department of Defense (DOD). The premise is that building stakeholders typically overlook opportunities to influence occupancy behavior because it is hard to measure its impact on energy use. Coupling energy simulation models to occupancy agent based models allows them to efficiently analyze feedback and other intervention strategies prior to actual dissemination to building occupants. These distinct and standalone models are referred to as federates in the coupled HLA environment. A case study example illustrates how the model coordinates time and data synchronization and transfer between federates the different federates.

INTRODUCTION

Despite significant advances in energy simulation software (e.g., eQuest 2009; EnergyPlus 2009), energy management and control systems (EMCS) (EIA 2012; Goldman et al. 2010), and occupancy interventions (Abrahamse et al. 2005), buildings continue to be the number one consumers of energy in the world. In the United States (US), buildings use 40% of the nation's total primary energy and 70% of the generated electricity (EIA 2012; DOE 2010). The effects of this excessive energy use impact the economic well-being of the nation, contribute to reliance on foreign oil, and result in significant emissions of harmful greenhouse gases.

One important limitation of existing energy analysis and control tools is that they are highly de-coupled (i.e., developed for a specific purpose and phase of the building life-cycle), which prevents their individual benefits from being collectively exploited to accurately predict, monitor, and improve energy efficiency in buildings (Pang et al. 2012). These tools require specific expertise (e.g., facility managers might be proficient in the use of EMCS but consider simulation models to be too complex), are time consuming, and rely heavily on availability and quality of data. Thus, as parallel advances in energy simulation, EMCS, and occupancy intervention methods continue to evolve, it is critical to extend their capabilities to allow their collective use for decision-making across different phases of the building life-cycle to improve building energy performance and reduce any adverse impacts.

Whether it is energy simulation, management or occupancy interventions, building stakeholders can significantly benefit from coupling these resources under one simulation model where they can test strategies and analyze their impact on the building before their actual implementation. Such a simulation environment can reduce the facility manager's uncertainty in choosing technical and behavioral intervention strategies. This approach to coupling models by incorporating additional processes and representing more system parameters has been applied in several contexts. For example, the COMBINE project which aims to advance Earth system models for more accurate climate projections and for reduced uncertainty in the prediction of climate and climate change in the next decades couples advances in modeling from several fields such as: C- and N-cycle; aerosols coupled with clouds and chemistry; stratospheric dynamics and increased resolution, and ice sheets, sea ice and permafrost for the cryosphere (Combine 2013).

To overcome the limitations of the de-coupled approach to simulation, modeling and energy management, we propose an extensible simulation framework that allows for the coupling of distinct and spatially distributed models. The preliminary model presented in this paper focuses on coupling of energy and occupancy simulation models, and synchronization of their data exchange through the use of High-Level Architecture (HLA: IEEE 1516).

This paper describes the general framework of the model and case study. Additional information are provided in an extended version that is currently in review in the ASCE Journal of Computing in Civil Engineering - Special Issue on Computational Approaches to Understand and Reduce Energy Consumption in the Built Environment (Menassa et al. 2013).

OBJECTIVES

The objective of this paper is to describe the prototype of the extensible HLA framework that was developed to couple building energy analysis and occupancy models, and illustrate its functions through an application to a case study.

COUPLED BUILDING ENERGY SIMULATION

Several research efforts have been made to couple different building systems for control and testing. Direct coupling work includes: heat and air flow analysis in buildings (Hensen 1999), integration of multiple geographically distributed simulation applications within a building design tool (Lam et al. 2002), building energy simulation and Computational Fluid Dynamics (CFD) for prediction of energy and indoor environment (Zhai and Chen 2005), and component system packages for HVAC design (Trecka et al. 2006). A major limitation of these models is that they have been developed to address a specific application. As a result, the potential of these models to be reused and built upon by others is reduced.

On the other hand, the Building Controls Virtual Test Bed (BCVTB) developed at Lawrence Berkley National Laboratory (Pang et al. 2012; Wetter 2011) uses Ptolemy II (Brooks et al. 2007) as a modular middleware to couple simulation programs. Limitations of BCVTB are related to Ptolemy II since it only allows the modeling, simulation, and design of concurrent, real-time and embedded systems without great flexibility.

HIGH LEVEL ARCHITECTURE - HLA

In order to achieve the objectives, we applied the principles defined in the HLA proposed by the US Department of Defense (DOD) (Kuhl et al. 1999) to couple energy simulation with occupancy model developed as an agent based simulation model. The DOD HLA is a collection of general rules that manage the development of complex, interoperable simulations in a distributed network environment. The HLA guidelines have been standardized by IEEE (Institute of Electrical and Electronics Engineers), and specifically developed to enable scalability, extensibility, and interoperability. In addition, they allow for shared model development effort for complex multidisciplinary problems and the reuse and assembly of multiple (perhaps existing) models in different contexts as part of a larger, interdependent, complex simulation (Kuhl et al. 1999).

In any simulation framework that applies the HLA principles, the HLA rules must be enforced if a federate (i.e., single simulation model) or federation (i.e. collection of multiple running and interacting federates) is to be regarded as HLA compliant. The HLA interface specification defines the functional modes of interaction between multiple federates and the framework's Run-Time Infrastructure (RTI). The RTI is software that must conform to the HLA specifications and provide simulation facilitation services (e.g., coordinates the synchronization and transfer of data between federates). The Object Model Template (OMT) prescribes standards for defining HLA object modeling information, which includes the data to be handled by the RTI when a simulation federate executes.

The biggest motivation to apply the HLA principles is that no single simulation or model in any domain can satisfy all uses and users (Dahmann et al. 1998). However, with the HLA principles, different simulations models that have been developed or will be developed can be composed together and form a HLA-compliant federation. The important tasks in developing the HLA-compliant federation include: (1) investigating the requirements for creating a HLA-compliant energy simulation framework, and (2) establishing the necessary computing infrastructure to couple different models (i.e., middleware). In this research, CERTI HLA was selected and customized for the development of this federation. CERTI is open-sourced and has multiple language bindings (e.g. C++/JAVA/Matlab) whose flexibility is critical for scalability and extensibility.

One of the most important capabilities from HLA RTI is enabling seamless communication between processes. Each simulation model/process (i.e. federate) interacts locally with an RTI Ambassador process (RTIA) in a whole simulation system (i.e., federation). Specifically, the RTIA listens to both the federate and the RTI. When a RTIA receives a message, RTI delivers it to the other interested RTIAs. By enabling such communications throughout all the constituent federates (e.g., making them HLA-compliant), a larger coupled simulation system can be realized.

DESIGN OF ENERGY SIMULATION FEDERATION

Figure 1 (adapted from Menassa et al. 2013) illustrates how two federates, a building energy prediction federate (DOE2 Federate) and a building occupancy federate (Anylogic Federate), exchange an energy consumption parameter and a behavior level parameter. In general, the ability to encapsulate a software agent as a HLA federate depends on the presence of robust software API (application programming interface) offered by the implementation of the software agent. In addition, multiple language bindings (C++, Java, etc.) also facilitate the HLA federate encapsulation process around existing software tools. DOE 2 was selected since it is a widely used, accepted, and tested energy modeling engine (Crawley et al. 2008; Neymark and Judkoff 2004). For the purposes of this model, DOE 2 is chosen because it permits the timely generation and simulation of input files compared to more complex simulation engines. Anylogic is a tool that supports the most common simulation methodologies including Agent-Based modeling (ABM). Anylogic is a native Java environment that supports limitless extensibility such as custom Java codes, external libraries, and external data sources (XJ Technologies 2009; Borshchev and Filippov 2004). In addition to these characteristics, Anylogic was chosen because if was previously used by the authors to develop the computational agent-based model (ABM) (Azar and Menassa 2012). The ABM simulates occupancy as a variable element by assigning attributes and characteristics to building occupants such as energy consumption estimates that correspond to different and changing energy consumption behaviors of occupants over time. The DOE2 federate uses BIM (Building Information Modeling) to generate the initial DOE2 energy simulation federate input (Kim and Anderson 2012).

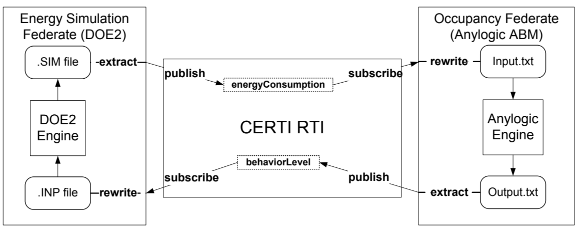

Figure 1: Data flow of energy simulation federation (adapted from Menassa et al. 2013)

Once this energy simulation is initiated, the DOE2 Federate will first read an initial input file (.INP file) generated by ifcXML (a neutral file format of BIM), in order to populate much of the information required for energy simulation in DOE2 from a building information model. The energy simulation federate invokes the DOE2 Engine from a command line to perform the initial energy estimate. Data from the estimate is then extracted from its output file (.SIM file) to compute the energy consumption parameter "energyConsumption" (see Figure 1). After it publishes this "energyConsumption" parameter through CERTI RTI, the DOE2 Federate will wait for CERTI RTI to update the behavior level parameter "behaviorLevel" from the Anylogic Federate for further simulation. When CERTI RTI receives the newly published "energyConsumption" parameter, it will immediately broadcast this value to those federates who are interested in (i.e., subscribe to) the value. In this case, the Anylogic Federate that has been waiting for the "energyConsumption" parameter, will rewrite the newly received value to an "Input.txt" file. This file serves as the input of the Anylogic Engine (see Figure 1). Since the Anylogic engine is not open-sourced and can't be invoked from command line, the authors circumvent the problem by designing an Anylogic model which runs endlessly. Whenever it finds out the "Input.txt" file has been rewritten, the Anylogic model will start a new building occupancy simulation based on the new value reflected from this new "Input.txt", and writes its output, i.e. "behaviorLevel", to "Output.txt". As long as Anylogic Federate detects that "Output.txt" is rewritten, it will: 1) extract its value; 2) publish to CERTI RTI as the new value of "behaviorLevel"; and 3) wait for the next update of "energyConsumption". Now similarly, CERTI RTI will broadcast the newly updated "behaviorLevel" to its audience, DOE2 Federate that will rewrite the INP file accordingly for the next simulation iteration (Figure 1) (Menassa et al 2013).

In order to achieve the above described inter-process data exchange, a data exchange description file (.FED file) is designed based on what data is going to be sent through the CERTI RTI. When each federate tries to initialize itself, this FED file has to be provided so that the federate can either create a new federation or join an existing federation. The invoking sequence of the CERTI HLA API is thus divided into three phases: 1) preparation, 2) main simulation loop, and 3) clean up.

Figure 2 shows the invoking sequence of the CERTI HLA API which is divided into three phases: 1) preparation, 2) main simulation loop and 3) clean up. Both the DOE2 Federate and Anylogic Federate take advantage of all these CERTI API features to achieve the high-level data flow shown in Figure 1.

CASE STUDY

A case study was conducted to test the proposed framework. A generic one-story office building in Ann Arbor, MI was chosen. The building has 20 occupants and the baseline building systems schedules are set to conform to ASHRAE 90.1-2007 and thermal set points to ASHRAE 55-2010 (ASHRAE 2010; ASHRAE 2007). This building is being tested to determine how changes in building occupancy energy consumption patterns due to feedback intervention will affect the energy use in the building. Occupancy interventions have been proven to be effective approaches in reducing building energy demand during operation phase of residential buildings (Peschiera and Taylor 2012; Abrahamse et al. 2005) and commercial buildings (Azar and Menassa 2012). In particular, feedback is an intervention technique that provides building occupants with their energy consumption levels, as well as target energy use levels. It is assumed that the energy consumption estimates provided by DOE2 are representative of the actual energy consumption levels of the building.

Description of the Federate and data exchange through CERTI RTI

Modeling an intervention (e.g., feedback), which occurs during building operation, requires a certain level of coupling and communication between the energy simulation software (e.g., DOE-2) and the occupancy behavior software (e.g., an agent based model). In addition, ArchiCAD was used to model the building under study and import the 3D model in DOE-2 to simulate the building energy performance.

In the study of feedback, real-time energy levels are critical for a realistic modeling of the feedback concept. Thus, actual energy consumption levels generated by DOE-2 were imported to Anylogic and communicated to agents, who adapt their behavior accordingly. More specifically, agents in the Anylogic model can be of two types: Green and non-Green. It was assumed that the 20 occupants of the building were initially evenly split between two categories. Every time step (i.e., one month), the number of Green and non-Green occupants is communicated to DOE-2, which generates an energy estimate that reflects the energy characteristics of these occupants. The difference between Green and non-Green occupants is expressed in DOE-2 through altering heating and cooling set points, and average kilowatt values per building square foot for lighting and equipment use. Then, feedback occurs at the end of each month, and the resulting influence to change behavior, can occur in two ways: Green occupants can convert their non-Green peers to the Green category and vice-versa. In the model, each category of occupants (i.e., Green and non-Green) has a Level of Influence (LI) parameter that defines the rate of convergence between the categories. For instance, a LI of 0.1 for Green occupants results in a 10 percent chance or probability that one Green occupant converts a non-Green peer every time step (See Azar and Menassa 2012 for additional details).

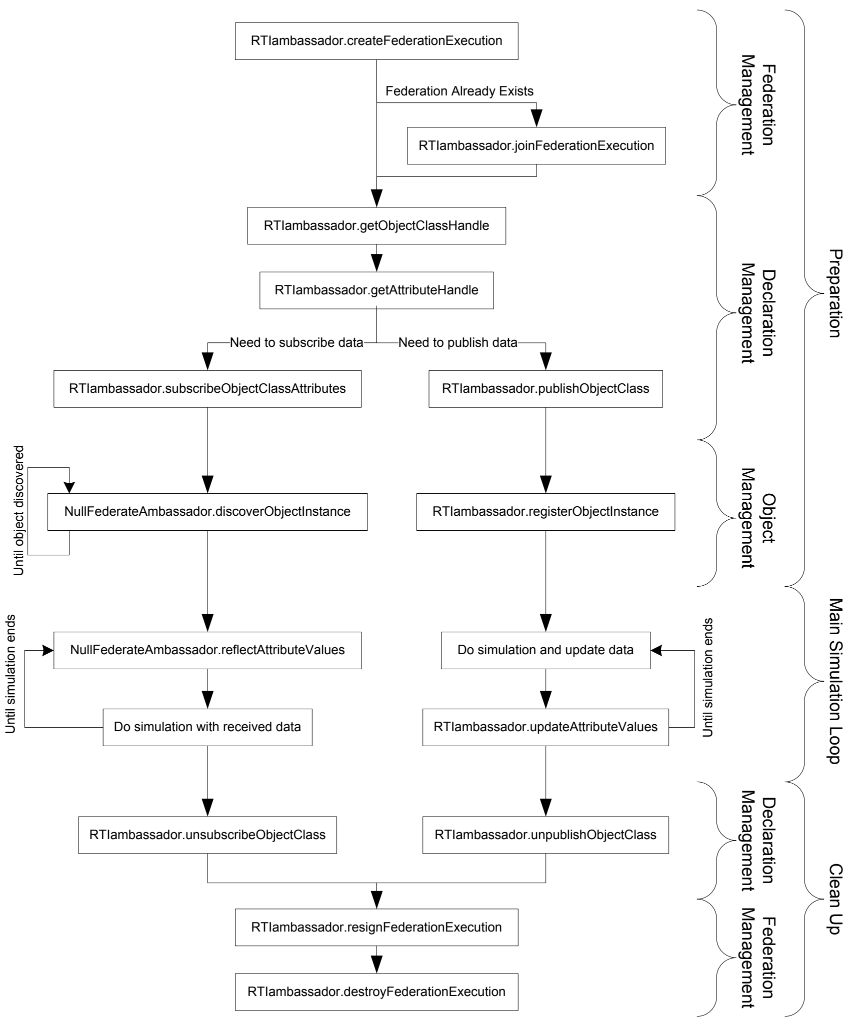

Figure 2: Invoking sequence of the CERTI HLA API

The LI of Green occupants was assumed to be proportional to how far away the actual building performance is from the target one. Overconsumption of energy is expected to increase the LI of the Green occupants leading to higher rates of convergence to the Green category. As for the influence of non-Green people, it was randomly generated using a uniform distribution between 0 and the LI of Green people. This particular function was chosen to generate, in a random manner, a lower influence for non-green people. The data exchange and time of engagement of the DOE2 and Anylogic models through the CERTI RTI federation are shown in Figure 3 (adapted from Menassa et al. 2013) and described here below:

Steps a-d in Figure 3:

a. A previously developed BIM of the building under analysis is manually loaded.
b. BIM is manually exported as an ifcXML file.
c. ifcXML file is transformed into an IMP file and imported in the DOE-2 model using the method described in Kim and Anderson (2012). The process is initiated manually.
d. DOE2 model is run for 12 months to generate the 'target' energy consumption levels and stored to be used in the DOE2 Federate for comparison with actual levels. Optimal occupancy behavior is assumed in this case. This whole process is automatically performed after launching the HLA model.

Steps 0-10 in Figure 3:

0. Anylogic is manually launched, which triggers the automated data exchange between DOE-2 and Anylogic through CERTI RTI Energy Simulation Federation.
1. Anylogic sends the initial number of Green and non-Green occupants to the HLA's ABM federate.
2. The ABM Federate communicates with the energy modeling Federate to translate the number of Green and non-Green to DOE-2 input parameters (INP file), which reflects the current behavior of building occupants. For instance, an increase in number of Green people results in lower lighting use schedules in DOE-2.
3. 3 and 9 - The energy modeling Federate launches the DOE-2 at t=0 or t-1, which predicts energy use for the first month (or second month).
4. 4 and 10- The energy consumption level for a given month is sent back to the energy modeling Federate which compares it to the 'target' energy level for this month that was generated in d.
5. The energy modeling Federate communicates the actual and target energy values to the ABM Federate.
6. The ABM Federate imports the values from Step 5 and launches a new run of the Anylogic model.
7. The updated values of Green and non-Green people resulting from changes in behavior due to Feedback are sent back to the ABM Federate. Changes in behavior resulted from the exposure of building occupants to their latest energy use levels (January) and their comparison to the desired levels (from d).
8. ABM Federate communicates the new numbers of Green and non-Green occupants to the energy modeling Federate in an INP file to be used as inputs in DOE2.

The steps keep repeating until the DOE-2 predictions correspond to the desired energy consumption levels, and the feedback intervention is considered successful. This provides the facility manager with an estimate of how long it will take for a certain level of feedback to influence occupants to reduce energy . The results of the simulation are presented in Figure 4 (Menassa et al. 2013), where the upper graph shows the behavior of occupants obtained from Anylogic and the lower graph illustrates the building energy performance obtained from DOE-2. The split in behavior led to an actual energy consumption level that is 14 percent higher than the desired one (Figure 4, lower graph). This overconsumption of energy resulted in a conversion of people towards the Green category over time. Convergence occurred at month 37 with all occupants becoming Green, resulting in maximum energy savings. The results confirmed the successful coupling of DOE-2 and Anylogic.

LIMITATIONS

The proposed model has several limitations that are currently being addressed through ongoing research by the authors.

First, the model described in this paper coupled only simulation software. However, the coupled simulation tools heavily rely on data input by the user, which increases sensitivity of the model results to changes in input parameters and limits the ability to use these models to simulate complex processes that are typically encountered during building operation phase.

Second, the model presented in this paper relied on manually transferring building data from an ArchiCAD v14 BIM to DOE 2 to simulate building energy performance. This presents several limitations related to the flexibility of using this model for decision making during building operation. A fully coupled BIM model will not only facilitate the data transfer to determine the base line building energy use, but will first provide an opportunity to visualize actual building performance especially when real time data is made available through a sensor/meter federate/federates as described above. In addition, having a fully coupled BIM will allow for changes in existing building components (e.g., increase outer skin insulation properties) to be evaluated in the emulated building environment prior to actual implementation in the building.

Third, the case study example illustrated the possibility to use the developed HLA federation to test the effect of feedback to occupants on reducing building energy consumption. In the absence of real time data about building energy consumption, the DOE 2 model was used to provide energy use data to the building occupants at each time step to initiate energy use behavior change in the building and the resulting change communicated back to the DOE 2 model where parameters (e.g., building schedule) were adjusted to reflect the energy use reduction/increase of the whole building. Although this approach is sufficient to verify the proposed model, the use of real time energy use and occupancy data as well as actual results of feedback effect will validate and increase the reliability of the model results to building operators and other decision makers.

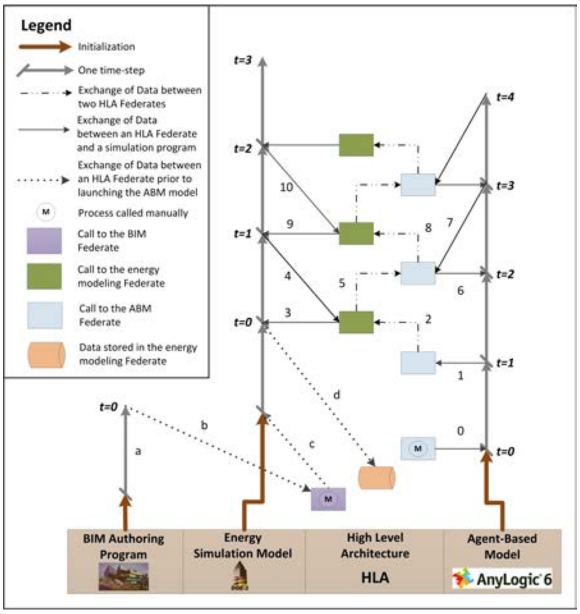

Figure 3: Data Synchronization and Function Call through HLA (Refer to Steps a-d and Steps 0-10 for detailed description of the different interactions)

CONCLUSIONS

The contributions of this research enable the coupling of building energy performance and operations for comprehensive and flexible energy simulation. The proposed framework will allow building stakeholders to use a simulation environment that models complexity as opposed to only approximating complexity. This is the case with most of other energy simulation frameworks discussed in this paper. Another important contribution lies in the HLA interface, which allows users to easily and effortlessly add additional software or hardware components depending on their intended applications and needs.

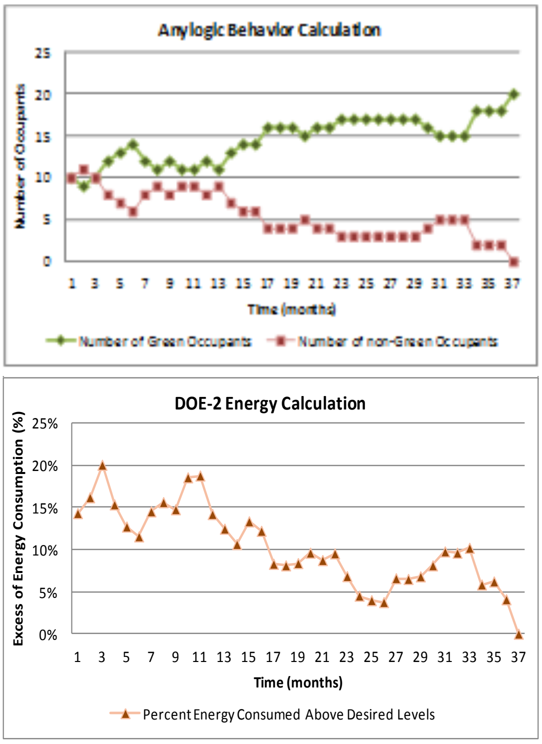

Figure 4: Model Results

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