Proceedings of the 2014 Winter Simulation Conference
A. Tolk, S. Y. Diallo, I. O. Ryzhov, L. Yilmaz, S. Buckley, and J. A. Miller, eds.

COUPLING OCCUPANCY INFORMATION WITH HVAC ENERGY SIMULATION: A SYSTEMATIC REVIEW OF SIMULATION PROGRAMS

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ABSTRACT

Adjusting for occupancy, when controlling an HVAC (Heating, Ventilation, and Air Conditioning) system, is an important way to realize demand-driven control and improve energy efficiency in buildings. Energy simulation is an efficient way to examine the effects of occupancy on a building's energy consumption and a cost-effective and non-intrusive solution to test occupancy-based HVAC control strategies. However, more than one hundred building energy simulation programs are used in research and practice, and large discrepancies exist in simulated results when different simulation programs are used to model the same building under same conditions. This paper evaluates different methods and sequences of coupling occupancy information with building HVAC energy simulation. A systematic review is conducted to analyze five energy simulation programs, including DOE-2, EnergyPlus, IES-VE, ESP-r, and TRNSYS, from the following five perspectives of heat transfer and balance, load calculation, occupancy-HVAC system connection, HVAC system modeling, and HVAC system simulation process.

1 INTRODUCTION

Buildings account for one-third of total global energy consumption (IEA 2013). In the United States, approximately 38% of the primary energy (e.g., oil or coal) (EIA 2012) and 70% of electricity are consumed by buildings (DOE 2011, USGBC 2010). In the commercial building sector, more than 80% of building energy consumption occurs during the operation phase (United Nations Environment Programme 2007) to maintain indoor environments and provide building-based functions. More than 40% of this energy is consumed by HVAC (Heating, Ventilation, and Air Conditioning) systems (EIA 2012). By analyzing the difference between actual energy consumed and energy required to satisfy heating/cooling loads, it is found that an average of 38% of HVAC-related energy could be saved if more efficient system-control technologies were to be adopted (DOE 2011). Although buildings' physical characteristics are known to have significant effects on energy consumption, these effects have decreased in recent years because governments worldwide have introduced regulations and policies aimed at improving energy performance of buildings (Guerra-Santin and Itard 2010). In this paper, it is assumed that energy can potentially be saved if HVAC systems are operated based on actual demands, and occupancy is a crucial factor in determining the effective demands for a building's HVAC controls (Tabak and de Vries 2010). Occupants affect a zone's thermal load and ventilation load (Zhang et al. 2012) and determine the conditioning requirements for HVAC control settings to maintain thermal comfort and air quality (Liao and Barooah 2010). Finding an HVAC control -based on occupancy- by providing personalized heat, cooling and ventilation to building spaces, only when they are required, can reduce energy consumption without sacrificing comfort or building functionality (Johnson Controls Inc. 2010).

In order to design occupancy-based HVAC control strategies, simulations are usually employed to explore the effects of occupancy on HVAC energy consumption, and HVAC system response to occupancy based control strategies. Compared to field experiments, simulation has several advantages: (1) It could control factors that cannot be controlled in a field experiment (e.g., outside weather conditions) to isolate the effects of occupancy; (2) sole consequences of a control strategy on energy consumption can be determined in simulation; (3) calculating energy consumed by an HVAC system might be difficult in a field experiment due to infeasibility of control or lack of metering; (4) simulation is less expensive and less time consuming; and (5) simulation is non-intrusive. In order to achieve maximum energy efficiency, an HVAC control strategy that accounts for occupancy must be designed on a case-by-case basis and in the context of specific physical and functional characteristics of a building, where simulation can play a pivotal role. Whole-building energy simulation programs, such as EnergyPlus, DOE-2, ESP-r, and TRNSYS, are promising tools for integrating heat and mass transfer, environmental data, and building-HVAC interaction processes. Furthermore, simulation models make it easier for users to interpret results (EIA 2012; Yan et al. 2008). Therefore, energy simulation could be potentially used as a tool to accurately and reliably calculate the energy consequences by incorporating occupancy into HVAC control strategies. Previous studies have compared energy simulation programs (Crawley et al. 2008; Zhu et al. 2012; Andolsun and Charles 2008), however to this date, there is no study, focusing on coupling occupancy with building HVAC energy simulation. A systematic review is conducted in this paper to identify which simulation program could accurately and reliably model the effects of occupancy on HVAC energy consumption, and HVAC system response to occupancy based control strategies.

The paper is structured as follows: Section 2 introduces the motivation for the study. Section 3 briefly discusses the importance of occupancy in building HVAC energy simulation, and presents the objectives of this paper. Section 4 analyzes different simulation programs by comparing their methods and sequences in coupling occupancy with building HVAC energy simulation, and discusses the applicability of each program. Section 5 summarizes each simulation program from five perspectives of heat transfer and balance, load calculation, occupancy-HVAC system connection, HVAC system modeling, and HVAC system simulation process. Finally, section 6 concludes the paper and introduces future work. This paper does not aim to compare the simulated results for a building using different simulation programs as different inputs are required and it is demanding and error-prone to develop an identical energy model for different programs. Different input requirements of different programs may cause additional deviations and uncertainties. The paper presents a systematic review for evaluating the applicability of each program in simulating the effects of occupancy on building HVAC energy consumption and HVAC system response for investigating energy-efficient HVAC control strategies based on occupancy. A qualified program should effectively react to occupancy, controls settings and boundary conditions, and calculate the accurate dynamic thermo physical states and flows of energy.

2 PROBLEM STATEMENT

In the last two decades, building energy simulation has begun to play a bigger role in selecting the most effective building energy conservation measures. However, because of the discrepancies between actual buildings and their virtual representations, the optimal and expected energy savings reported in simulations do not match those reported in actual buildings. Empirical studies have revealed noticeable differences between simulated and measured performances of energy conservation measures (Raftery, Keane, and Costa 2011; Zhu et al. 2013; Pan et al. 2006). More importantly, over one hundred building energy simulation programs are used in current research and practice, and large discrepancies also exist in simulated results when different simulation programs are used to model the same building under the same conditions. In order to provide an efficient way to examine the effects of occupancy on a building's HVAC energy consumption and a cost-effective and non-intrusive solution to test occupancy-based HVAC control strategies, simulation programs should be evaluated according to their methods and sequences for considering heat transfer and balance, load calculation, occupancy-HVAC system connection, HVAC system modeling, and HVAC system simulation process. Extensive research has been done to validate the accuracy and reliability of simulation results using different simulation programs (Yan et al. 2008; Henninger and Witte 2006; Witte et al. 2001) based on the requirements of the ASHRAE 140 (ANSI/ASHRAE 2007). However, these efforts focused on the differences in results, instead of systematically analyzing the coupling of occupancy information with building HVAC energy simulation. Several other studies have compared the advantages of different simulation programs (Andolsun and Charles 2008; Crawley et al. 2008; Zhu et al. 2012). However, to the authors' knowledge, no work to this date has specifically compared the principles in modeling the effects of occupancy on a building's HVAC energy consumption, and evaluating HVAC system responses to HVAC control strategies based on occupancy. Widely-used base case buildings and reference buildings for validation lack actual occupancy information and cannot reflect the actual HVAC energy consumption from the occupancy coupling perspective.

3 OCCUPANCY IN BUILDING ENERGY SIMULATION

All energy simulation programs are built on the first-principle mathematical modeling of heat balance within or around a building. An HVAC system is virtually run and energy is calculated to keep a constant and comfortable thermal environment under both exterior and interior impacts. Exterior impacts are the loads added to the building from the outside environment such as solar radiation. Buildings have envelopes, which are heat transfer surfaces. No matter how good the construction is, energy is conducted through envelope, if a temperature difference exists between a building's interior and exterior. There is also infiltration occurring in the intersection of surfaces such as windows and walls, as well as radiation through translucent surfaces by visible lights and invisible lights. Interior impacts result from the loads caused by equipment/appliances or users being present, which are closely related to occupancy. Generally, the importance of occupants in a building's HVAC energy consumption can be described from two perspectives. First, from occupancy and heat gain perspective. Here occupancy is used to define when occupants occupy a building and how many occupants there are in each zone. Occupants continuously generate heat into an environment due to their metabolisms and activities. They are associated with the use of other building systems such as lighting and appliances such as computers, which add heat to the environment. Second, from the occupancy and HVAC conditioning requirement perspectives. Occupants also determine active conditioning periods and conditioning effects of an HVAC system. When the space is occupied, an HVAC system is usually run to maintain a static and desirable thermal environment.

In general, energy simulation programs assume hourly frequencies to input occupancy and related internal gains, such as use of light in space while introducing heat to the space, and appliances, which constitute the main parts of the gained loads. Typically, there are two types of occupancy input: (1) diversity factors, numbers between zero and one representing the multipliers of nominal loads for occupant metabolic heat gains, such as the ones used in EnergyPlus; and (2) actual loads expressed in W or W/m2. ESP-r for instance, requires a measurement of the exact amount of heat given off by occupants. In an energy simulation program, exterior impact is set by hourly meteorological data from standard databases, such as the DOE (Department of Energy) database, while the interior impact is controlled by the settings related to occupants, lights, appliances, and schedules. The interactions between exterior impact and interior impact are represented by the thermal properties of an envelope. Since different simulation programs use different methods and sequences to model occupancy related heat gain and HVAC system response to exterior impact and interior impact, a comparison is necessary to evaluate which simulation programs are capable of coupling occupancy with building HVAC energy simulation. The objectives of this paper are: (1) to evaluate different programs for modeling the effects of occupancy on building HVAC energy consumption; and (2) to evaluate different programs for modeling HVAC system response to occupancy based HVAC control strategies (See Figure 1).

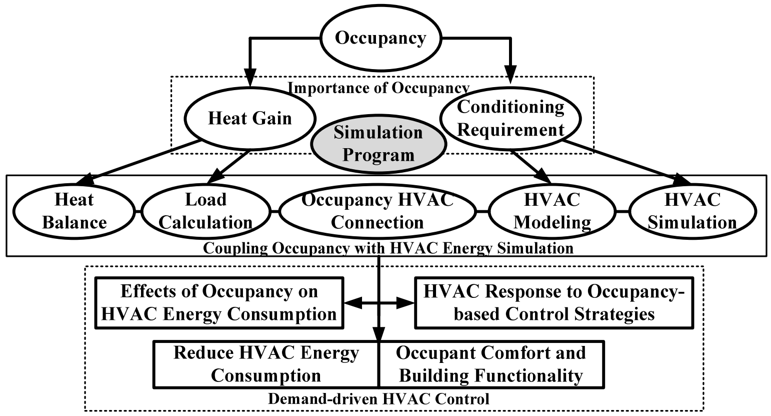

Figure 1. The relationship between occupancy and building HVAC energy simulation.

4 COMPARISON OF SIMULATION PROGRAMS

4.1 DOE-2

DOE-2 is a whole-building simulation program developed by the Department of Energy (DOE) to perform hourly energy simulation for conceptual determination of total building energy consumption. It has been widely used for more than 30 years to guide building design and simulation developments (Kim, Haberl, and Liu 2009). DOE-2 mainly consists of four subprograms of LOADS (sensible and latent heating/cooling loads), SYSTEMS (secondary air-side equipment), PLANT (primary water-side system) and ECONS (cost of energy) plus one BDL Processor (input translation) (Birdsall et al. 1990). LOADS, SYSTEMS, PLANTS and ECONS are sequentially simulated, with the output of the former one being the input of the next. There is no communication or interaction among the four subprograms. Considering the **heat transfer and balance**, DOE-2 assumes static space temperature and cannot achieve strict heat balance because it uses weighted coefficients based approximation instead of calculating convection and radiation separately (Hong et al. 2009). There are only four types of heat transfer surfaces: exterior wall, interior wall, window and underground wall.

Regarding the **load calculation**, DOE-2 loads are actually reported as HVAC system component loads without incorporating system issues into the load calculation. Loads are decided through transfer functions with customized weighting factors (Mitalas and Stephenson 1967). The **occupancy-HVAC connection** is achieved on an hourly basis by the sequence of occupancy heat gain, space load, secondary system load, and primary system load. Limited feedback from HVAC system operation is considered to update space load and temperatures. Regarding the **HVAC modeling**, a set of predesigned HVAC system types is available for selection. The PLANTS allows a part-load setting to calculate energy demand. **HVAC system simulation** follows the LSPE (load, system, plant, economic) sequence and is not able to simultaneously communicate with building envelope thermal dynamics. In LOADS, the DOE-2 first assumes a constant-temperature to estimate the loads then in SYSTEMS and PLANTS it reacts to interior impact and exterior impact for adjustment successively (see Figure 2a). There is no backward feedback. Conditions of adjacent spaces from the previous step are considered as conditions at the current time step to avoid solving simultaneous equations.

DOE-s considers a building HVAC system as a linear system related to space temperature and the coefficients for heat balance are kept constant during the entire simulation period. These significant limitations compared to other programs limit the application of DOE-2 for analyzing the effects of occupancy on HVAC energy consumption, and testing HVAC system responses to different occupancy based control strategies. In addition, DOE-2 has advanced requirements for modeling with limited sources and programming, however its computational efficiency is high and learning curve is small.

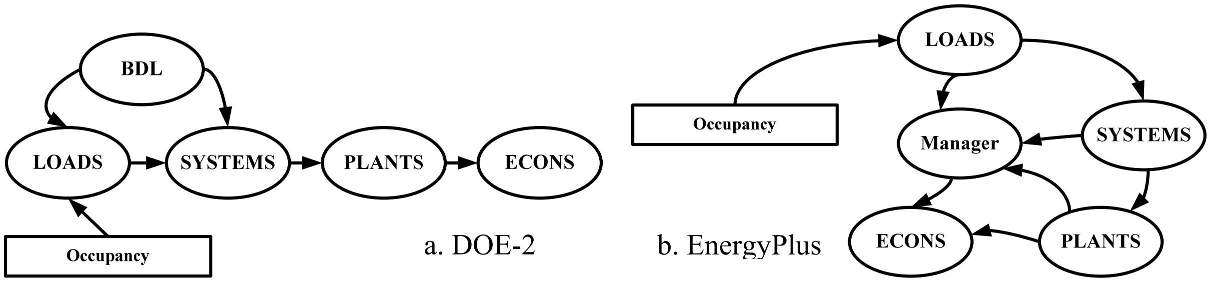

Figure 2. Energy simulation in DOE-2 (a) and EnergyPlus (b). Arrows show the flow of information.

4.2 EnergyPlus

EnergyPlus is developed with a heat/mass balance based on the DOE-2 and BLAST. To consider the **heat transfer and balance**, EnergyPlus uses a state space method for combined heat and mass transfer to ensure strict heat balances on each surface and space air (DOE 2010a). It is specialized in thermal **load calculation** by using predict-correct process with backward feedback for continuously updating the loads (Crawley et al. 2001). Applied heat transfer coefficients are based on the effects of interior and exterior impacts. Regarding **occupancy-HVAC connection**, at each time step, occupancy is incorporated by updating surface heat balance and air heat balance at the previous time-step.

Regarding the **HVAC modeling**, modularity is applied to provide a flexible and robust approach in specifying system characteristics. Loops define the movements of mass and energy, in which air loop simulation and water loop simulation are the main functional parts of an EnergyPlus simulation, both including the demand side and supply side. Within each loop the performance curves of equipment could be defined on a customized basis, however the convergence might not be achieved. To consider **HVAC simulation**, EnergyPlus also has four subprograms of LOADS, SYSTEMS, PLANTS and ECONS (See Figure 2-b). Different from the DOE-2, it provides an integrated simultaneous solution. The time steps of SYSTEMS and PLANTS could be automatically adjusted to meet the calculated LOADS (DOE 2010b). Although the conditions of adjacent spaces at the previous time step are still used to successively calculate current conditioning requirements, the short time step could effectively offset simulation deviations. After the loads are calculated for heat balance, the SYSTEMS then estimates the demands and the required responses of the PLANTS, as well as it sends feedback to update LOADS(Crawley et al. 2000). All of the connections are controlled by the building simulation manager. EnergyPlus can take real-time variations of heat balance into consideration and provide accurate space temperature estimates. Simultaneous HVAC simulation enables EnergyPlus to analyze the effects of occupancy on HVAC energy consumption, and to test HVAC system responses to different occupancy based control strategies. For example, EnergyPlus supports simulation of demand threshold controls (e.g. customized thermostats). In general, EnergyPlus has advanced requirements for managing simulation parameters and thermal-control dynamics; however its learning curve is small.

4.3 IES-Virtual Environment

IES-Virtual Environment (VE) is an integrated building simulation program for design aid and detailed assessment. Modeling in IES-VE is realized by different modules. The core of the IES-VE is to build an IDE (integrated development environment), shared by all of the analysis modules, to analyze building energy consumption and other building performance indicators, such as comfort and CO2 density. The model could be built directly using the ModelIT module or imported from other programs, such as Revit and SketchUp. This breakthrough eliminates the workload of building different models for different simulation programs and expedites the energy analysis cycle. Apache thermal analysis modules are used to analyze dynamic energy consumption and thermal conditions (Pollock and Gough 2007). There are four Apache modules used in IES-VE: ApacheCalc is for calculating heat loss and gain, while ApacheLoads is for calculating heating and cooling loads. ApacheSim is responsible for dynamic thermal simulation and ApacheHVAC is used to simulate HVAC plants (See Figure 3-a). The learning curve for IES-VE is small.

Regarding the **heat transfer and balance**, Apache modules use a finite-difference method to model the heat transfer process based on the CIBSE (Chartered Institution of Building Services Engineers) standards (ApacheCalc) (Naser 2006) and in accordance with the ANSI/ASHRAE Standard 140 (ApacheLoads). Conduction is assumed to be one-dimensional in each building element and thermal properties of surfaces are assumed to be uniform. In addition, heat balance is calculated based on a stirred tank model, which assumes the air temperature and humidity are the same in one space. Dynamic loads (ApacheSim) are integrated with fluid dynamics (Macroflo) by assigning air node to each space such that the mutual influences among spaces are considered in the **load calculation** (Figure 3-a). Regarding **occupancy-HVAC connection**, occupancy profiles are used to represent heat gain based on admittance techniques for conditioning requirements.

Regarding the **HVAC modeling**, ApacheHVAC provides pre-defined HVAC wizards and system prototypes autosizing, and also supports to create component based HVAC systems, which requires detailed and complicated system settings. The multiplexing features enable to assign HVAC data to very large, complex system models. In IES-VE, **HVAC simulation** could provide detailed system simulation with airflow analysis but has to be set with appropriate time steps, in which ApacheSim, ApacheHVAC and Macroflo are simultaneously taken in to account in thermal-control dynamics. The advantage of IES-VE is the fact that it uses an integrated model for performance analysis with high efficiency and does not require the user to have any prior knowledge of computer programming or of the mathematics and equations that govern building physics. IES-VE acts as more of a “off-the-shelf” program compared to others. However, the heat balance and load calculation in IES-VE are conducted by different modules, and the relationship between loads and HVAC settings cannot be customized, resulting in inaccurate calculations for occupancy-associated demands and loads (IES 2010). IES-VE has the extensive capability for modeling customized systems however is unable to specify settings for certain energy-efficient or sophisticated HVAC plants, such as GSHP (ground source heat pump), which also limits its applicability for analyzing the effects of occupancy on HVAC energy consumption, and testing HVAC system responses to different occupancy based control strategies.

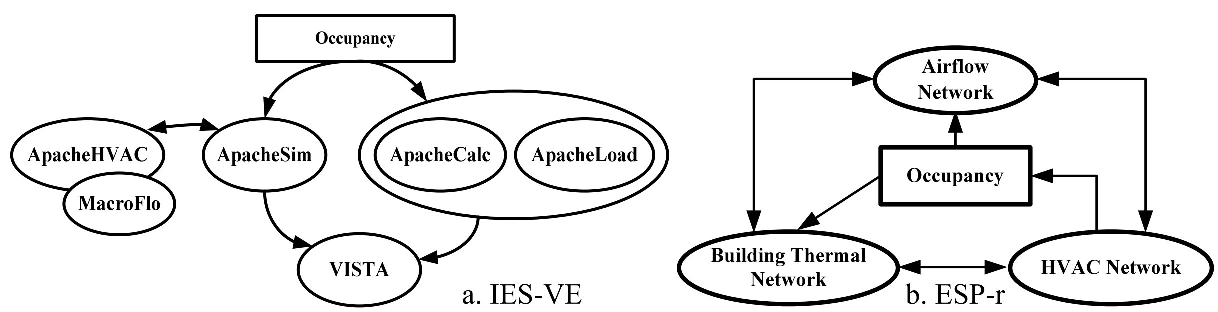

Figure 3. Energy simulation in IES-VE (a) and ESP-r (b). Arrows show the flow of information.

4.4 ESP-r

ESP-r is an open-source simulation program that can be run on several operating systems, such as Linux and Windows. It is a rigorous program in modeling building physics by using multi-sided polygons to define constructive elements and CFD (computational fluid dynamics) to combine mass flow and HVAC system simulation (Clarke et al. 1993). Regarding the **heat transfer and balance**, the ESP-r uses Crank-Nicholson difference formulation to simulate heat and mass transfer processes. Nodes are defined to represent air volumes of the building, geometrical components, connections or HVAC system components. Heat balance is achieved by equating the control volumes (CV) of energy flow from and to these finite difference nodes. The ESP-r has a unique optimization method for solving block-tridiagonal implicit matrix equations by only calculating non-zero components from thermal surfaces. This method could achieve high calculation accuracy and speed without iterations (ESRU 1999). For **load calculation**, all nodes are interconnected due to the interdependencies among thermal related components. The collection of equations then form an equation set (nodal network), describing the load state for the whole building. Regarding **occupancy-HVAC connection**, heat gain from occupants are added to the thermal network and integrated with air fluid dynamics. Data exchange is conducted with HVAC network at each time step. Regarding **HVAC modeling**, an assembly of components could be selected from a library to form the HVAC network, each node of which is connected to the data from other networks (Strachan, Kokogiannakis and Macdonald 2008). Once the data are prepared, the **simulator** begins to solve a set of conservation equations using the finite difference method until convergence is reached, and outputs the energy consequences. The process is discretized in to different networks and each network possesses its own solver (See Figure 3-b). In general, a global solution could be found simultaneously for each network and loose couplings are then established among networks.

ESP-r is a research-oriented tool. It is more flexible and holistic than other programs, allowing researchers to analyze the interconnections among occupancy, building thermal conditions and HVAC energy consumption. However, it lacks flexibility when testing HVAC system response to different occupancy based control strategies, and necessary autosized and default values for input parameters in more complicated and tentative tasks, such as occupancy based dynamic setpoint schedules. It does not support a trial-and-error process, and its steep learning curve requires analysts must have specific knowledge for thermal dynamics and physics modeling experiences to use this program.

4.5 TRNSYS

TRNSYS is an extensible program for transient building mechanical and electrical system simulation. The essence of TRNSYS is to simulate the performance of the entire system by breaking it down into individual components. It has a DLL (Dynamic Link Library) based structure and can be co-simulated with other programs such as ESP-r and Simulink. Regarding the **heat transfer and balance**, it sets multiple air nodes to the spaces and assumes the entire building and building systems are formed by a collection of “energy system components”, such as auxiliary heater and calculates the heat balance using algebraic and differential equation solvers (Klein et al. 2004). Through iteration within a component or a set of components, heat balance could be achieved. Utility components, building components and additional customized DLLs are used as load files for **load calculations**. An **HVAC system is connected with occupancy** by the input-output link of corresponding types (type is a category of components) such as connecting Type 56 (multizone building) with Type 516 and Type 520 (thermostat and heating/cooling behavior). Occupancy information could also be obtained through runtime calls from outside occupancy models during the simulation.

Regarding **HVAC modeling**, HVAC component and controller components could be selected from standard libraries or developed using programming languages (C, C++, PASCAL, FORTRAN, etc.). Each component or a group of components represents a process like piping hot water, requiring two types of information: input (time-dependent) and parameter (time-independent). Components are then connected to finish a task such as space cooling. In TRNSYS, **HVAC simulation** is equal to simulating the performance of individual HVAC related components. The output of one component could be used as the input of the next component (acyclic flow), or it integrates the loop within one set until nothing changes, and energy use of all components is dynamically added up to represent the entire building energy use. At each time step, the TRNSYS kernel checks whether the input exceeds the tolerance and chooses whether to run the related components or move to next time step (See Figure 4). Simulation is then converted to formulation of mathematical expressions and analysis of interconnections among components and groups (Beausoleil-Morrison et al. 2014).

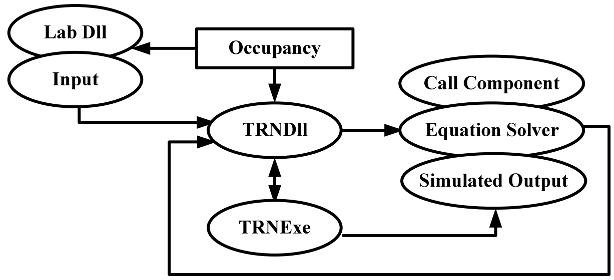

Figure 4. Energy simulation in TRNSYS (arrows show the flow of information).

TRNSYS has a steep learning curve and advanced requirements for mechanical system modeling and configuration. It models the input/output relationships of components by instantaneous or differential equations. The solver calls each component successively or using Powell method. The overall system iterations are performed until all components (and all sets of components) converge simultaneously. The most powerful feature of the TRNSYS -but also its main source of error- is that there is no assumption or range/default for components (Duffy et al. 2009). Any component related to heating, ventilation and air conditioning of a building has to be specified by analysts, which provide flexibility in modeling a non-conventional strategy, system configuration and specification. Compared to the other programs, TRNSYS can model complex systems that cannot be accurately modeled by other programs with high accuracy and precision. (e.g., simulation time step could be 0.1 second). Another key advantage for TRNSYS is its open source characteristic and modular structure, which could fit the investigation of different researches on occupant based and energy-efficient controls. Any customized systems can be tested by connecting different components. However, it is not applicable for analyzing effects of occupancy on HVAC energy consumption because differentiating the energy consequences caused by occupancy is difficult.

5 DISCUSSION

Based on the analysis provided above, there is a variety of building simulation programs specializing on different aspects related to building energy behavior . Each simulation program has its own method and sequence to couple occupancy information with building HVAC energy simulation, which are summarized in this section from the five perspectives of heat transfer and balance, load calculation, occupancy-HVAC system connection, HVAC system modeling, and HVAC system dynamic simulation. Regarding operability and practical use, the requirements of each program in terms of requisite knowledge, learning curve and computational complexity, are also considered as analysts may have different skills and experience levels (Table 1).

It can be concluded that EnergyPlus and IES-VE are both qualified to analyze the effects of occupancy on HVAC energy consumption, and to test HVAC system response to different occupancy based control strategies as they are both capable of connecting occupancy load with HVAC conditioning requirements and adjusting HVAC systems to respond to occupancy changes. However, EnergyPlus is more suitable since IES-VE requires complex system settings and could only roughly model the energy consequences of occupancy. In addition, it is unable to model certain energy-efficient or sophisticated HVAC plants. TRNSYS is an ideal tool to test different control strategies but cannot specify the effects of occupancy on energy consumption. On contrary, ESP-r doesn't have flexibility when testing HVAC system responses to different occupancy based control strategies; especially it lacks necessary autosized and default mechanisms for input parameters in more complicated and tentative tasks. The principles of sequential HVAC response and unbalanced space heat transfer exclude DOE-2 from any occupancy coupled building energy simulation.

Also, co-simulation by coupling different programs is recommended when a specific program reaches its limits. For example, at each time step EnergyPlus could be used to calculate occupancy related loads, then the results could be connected with the networks established in ESP-r, after which TRNSYS is called to control HVAC systems to respond to the network requirements. The performances of HVAC systems are finally returned to EnergyPlus and ESP-r for updating the balances of networks and space loads.

Table 1. Program comparisons for coupling occupancy information with HVAC energy simulation

	DOE-2	**EnergyPlus**	**IES-VE**	**ESP-r**	**TRNSYS**
Specialization	Conceptual energy simulation	Load Calculation	Integrated assessment and analysis	Physics Modelling	Mechanical and electrical system control
Heat transfer and balance	Weighted coefficients based method; Four types of heat transfer surfaces; No strict space heat balance	State space method; Strict heat balances on each surface and space air	Finite-difference method; Stirred tank model; Uniform surface thermal properties	Finite differences nodes; Equate the control volumes of energy flow	Set multiple air nodes to the spaces; Iteration among thermal related components
Load calculation	HVAC system component loads	Predict-correct process; Backward feedback and update	Dynamic loads; Assign air node to each space	Interconnected nodal networks to represent interdependencies among the thermal related components	Loads profiles consist of utility components, building components and additional customized DLLs;
Occupancy-HVAC system connection	Occupant heat gain- space load-secondary system load- primary system load; No feedback to space load and temperature	Occupant heat gain updates surface heat balance and air heat balance at previous time-step	Occupant heat gain is incorporated by admittance techniques; Interact with computational fluid dynamics	Occupant heat gain is connected with the thermal network and integrated with air fluid dynamics	Input-output connection of corresponding components; Interactive runtime calls
HVAC system modeling	Predesigned HVAC system types	Modularity; Mass and energy loops	Pre-defined wizards; System prototypes autosizing; Detailed component based HVAC systems	An assembly of components could be selected from library to form the HVAC network	Components and controllers are from standard libraries or developed using programming languages
HVAC system simulation	LSPE sequence (load, system, plant, economic); No backward feedback	Simultaneous LSPE (load, system, plant, economic)	Detailed system simulation with airflow analysis; Integrate ApacheSim, ApacheHVAC and Macroflo	A global solution for each network and loose couplings among networks	Simulating the performance of individual components; Perform overall system iterations until all components converge simultaneously

Requisite knowledge	High requirements for modeling with limited sources and programming	High requirements for managing simulation parameters and thermal-control dynamics	High requirements for detailed and complicated system settings	High requirements for thermal dynamics knowledge and physics modeling experience	High requirements for mechanical system modeling and configuration
Learning curve	Shallow	Shallow	Shallow	Steep	Steep
Computational complexity	High computational efficiency	Medium computation time and modeling complexity	Medium computation time; Multiplexing for large, complex system modeling	High computation time and system modeling complexity	High computation time and physics modeling complexity

6 CONCLUSIONS

It is estimated that the majority of building HVAC systems are operated inefficiently, and a large amount of HVAC related energy could be saved if more efficient system-control technologies are adopted. Adjusting for occupancy when controlling HVAC systems could realize demand-driven control and improve energy efficiency. Energy simulation is an effective tool to examine the effects of occupancy on a building's energy consumption and a cost-effective and non-intrusive solution to test occupancy-based HVAC controls. There are more than one hundred building energy simulation programs currently used in research and practice, and large discrepancies exist in simulated results when different building energy simulation programs are used to model the same building. Thus far, no study has specifically compared the methods and sequences in simulating the effects of occupancy on building HVAC energy consumption, as well as the HVAC system response to investigate energy-efficient HVAC control strategies based on occupancy. This paper analyzes the frequently used simulation programs, including DOE-2, EnergyPlus, IES-VE, ESP-r, and TRNSYS, to investigate their capabilities in coupling occupancy with building HVAC energy simulation. The methodology of this paper is based on a systematic review of five perspectives of heat transfer and balance, load calculation, occupancy-HVAC system connection, HVAC system modeling, and HVAC system simulation process. This paper does not use standard case buildings or reference buildings -such as models regulated by ANSI/ASHRAE Standard 140-2011- for validation, since it is difficult to get actual occupancy and energy related data for calibrating the standard cases. The authors plan to model a test bed building in different programs for comparing and validating the theoretical results summarized in this paper. Deviations and uncertainties caused by different input requirements of different programs will be studied. Occupancy is a broad concept including occupancy status, occupant number, presence-dependent activities and related behaviors, as well as occupancy based schedules, which all have significant impacts on the determination of effective demands for a building's HVAC controls. These subdivisions will be systematically studied in future work to compressively couple building HVAC energy simulation. In addition, a co-simulation environment will also be experimented to reduce run time, realize their complementary strengths for facilitating the coupling process.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Grant No. 1351701. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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