A Simulation Framework for Quantifying the Influence of Occupant Behavior on Savings of Energy Efficiency Measures

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Abstract

The performance of energy conservation measures (ECMs) is influenced by uncertainties such as climate change, operation modes and occupant behavior in buildings. Occupant behavior has a significant impact on building energy use and is one of the biggest uncertainties that affect the effectiveness of building retrofits. This study introduces a simulation framework to quantify the impact of occupant behavior on energy savings of ECMs. Three types of occupant behavior style, austerity, normal and wasteful, were defined to represent different levels of energy consciousness in terms of the control of HVAC, window, lights and plug-in equipment. A case study was performed in a real building to demonstrate the application of the framework. Based on the simulation results, the impact of occupant behavior on ECM savings vary with the type of ECM: for occupant-independent ECMs, which are purely technology-driven and have little interaction with the occupants, such as reducing LPD, reducing EPD, improving envelope properties, improving system efficiency and daylighting control, the energy saving percentage is barely affected by occupant behavior style; while for occupant-dependent ECMs, which have strong interaction with the occupants, such as VRF system and natural ventilation, the energy saving percentage is significantly affected by occupant behavior style. Although ECM savings with different occupant behavior styles would vary depending upon many factors, the presented simulation framework is robust and can be adopted to quantify the impact on ECM savings of other uncertainty factors such as climate change and building operation mode.

Introduction

The building industry is facing critical challenges of aggressively reducing energy use. Energy retrofits and the implementation of energy conservation measures (ECMs) can be cost-effective means of reducing energy consumption in buildings. Nowadays, more high-efficiency equipment and ECMs are developed and applied to buildings in order to improve the building performance and reduce energy use. However, building energy retrofits have many uncertainties, such as climate change (Hong, Chang, and Lin 2013)(Blyth et al. 2007), building operations (Wang, Mathew, and Pang 2012)(Menassa 2011), human behavior change (Yohanis 2012; Owens and Wilhite 1988; Guerra Santin, Itard, and Visscher 2009), government policy change (Baek and Park 2012)(Tobias 2009), all of which directly affect the selection of retrofit technologies and hence the success of a retrofit project. Dealing with these uncertainties is a considerable technical challenge in any sustainable building retrofit project (Ma et al. 2012).

Occupant behavior has a significant impact on building energy use and is one of the biggest uncertainties that affect the effectiveness of building retrofits (Sun et al. 2014). According to the investigation of the householders' energy behavior performed by Yohanis (Yohanis 2012), significant energy-saving could be achieved by improving the energy awareness of the occupants. Santin et al. (Guerra Santin, Itard, and Visscher 2009) studied the importance of household characteristics and occupant behavior on energy use for space and water heating in the Netherlands, and concluded that occupant characteristics and behavior significantly affect building energy use. Virote and Neves-Silva (Virote and Neves-Silva 2014) stated that the expected return of energy efficient technologies could be weakened by the occupants' behavior within the building. To more precisely predict the energy savings, they implemented occupant behavior models in a building energy consumption model based on stochastic Markov chains. Li examined the impact of actual building occupancy on the assessment of ECMs and observed big differences in energy savings (Li et al. 2015). Marshall investigated the effectiveness of ECMs for different occupancy patterns in residential buildings of UK. The savings have been shown to vary depending on the occupancy pattern of the household (Marshall et al. 2016). These studies showed that occupant behavior could significantly affect the energy use in buildings as well as the saving potentials of building retrofits. However, the previous studies are mostly based on survey results, and few studies were conducted to quantify the effects of occupant behaviors on the energy saving potentials of ECMs.

This study proposes a framework to quantify the impact of occupant behavior on ECMs savings. The framework is illustrated in the Methodology Section. A case study, which adopts the framework in a real building to quantify the influence of different occupant behaviors on ECM savings, is presented in the Case Study Section. We define three types of occupant behavior styles: austerity, normal and wasteful. Each style represents different levels of energy consciousness in terms of the control of HVAC, window, lights and plug-in equipment. For example, occupants with austerity style tend to save energy by setting higher cooling temperature, turning off HVAC, lights, and electric equipment when leaving; while occupants with wasteful style behave the opposite way. By defining two extremes of occupant behavior as in the austerity and wasteful styles, this study would identify the possible occupant-related risks on energy saving potential of ECMs in the retrofit analysis. Several ECMs are investigated in the case study, including lighting power density, equipment power density, envelope, system efficiency, lighting control, Variable Refrigerant Flow Heat Recovery (VRF-HR) system, VRF-HR coupled with natural ventilation, and the all integrated measure package.

Methodology

Overview

A framework was developed in this study to quantify the impact of occupant behavior on the performance of Energy Conservation Measures (ECMs) by simulation, shown in Figure 1. The traditional method to evaluate the energy saving potential of an ECM consists of the following steps: (1) developing a baseline model with a standard set of deterministic inputs including weather data, internal heat gains, system efficiencies, and occupant behavior; (2) calculating the energy use of the baseline model; (3) applying the ECMs to the baseline model and calculate the energy use afterwards. The estimated ECM saving results via the traditional method is a single deterministic value. However, the ECM savings are influenced by many factors, such as building type, weather data, operation, and occupant behavior. For example, a high efficient chiller can save very limited energy in cold climate due to little cooling load; a well-designed natural ventilation building wouldn't work if the occupants don't like opening the windows. Therefore, a single result is not able to reflect the uncertainties of the ECM savings. To address that limitation, a framework was proposed in this study to evaluate ECM savings considering the variations of the inputs and its influence on the ECM saving potentials, including the following steps: (1) developing a set of baseline models based on variable inputs; (2) calculating the energy use of the baseline models; (3) applying the ECMs to each baseline model and calculate the energy use of each model. The estimated ECM saving results via the proposed framework will be a range instead of a single value. In this study, we focus on the influence of the occupant behavior.

Estimating the uncertainties of the ECM savings is critical especially for the risk analysis and decision making of ECM investment (Heo, Augenbroe, and Choudhary 2011). A decision maker should estimate the comprehensive risk while considering investing an ECM. The traditional ECM evaluation method adopts deterministic inputs, which ignores uncertainties. On the other hand, the proposed framework can address the uncertainties of the ECM savings brought by different occupant behaviors, which helps decision makers assess the potential risk of investing the ECMs in buildings with different occupant behaviors.

The whole building simulation with EnergyPlus was used to evaluate the impact of occupant behavior on the energy saving potentials of ECMs. Based on the investigated office building, baseline models were developed in EnergyPlus version 8.5. EnergyPlus is an open source program that models heating, ventilation, cooling, lighting, water use, renewable energy generation, and other building energy flows (Crawley et al. 2001) and is the flagship building simulation engine supported by the United States Department of Energy (DOE). It includes many innovative simulation capabilities including sub-hourly time-steps, natural ventilation, thermal comfort, co-simulation with external interfaces, renewable energy systems, and user customizable energy management systems (EMSs). Some of the innovative capabilities such as natural ventilation, daylighting, external schedules and EMS were used in this case study.

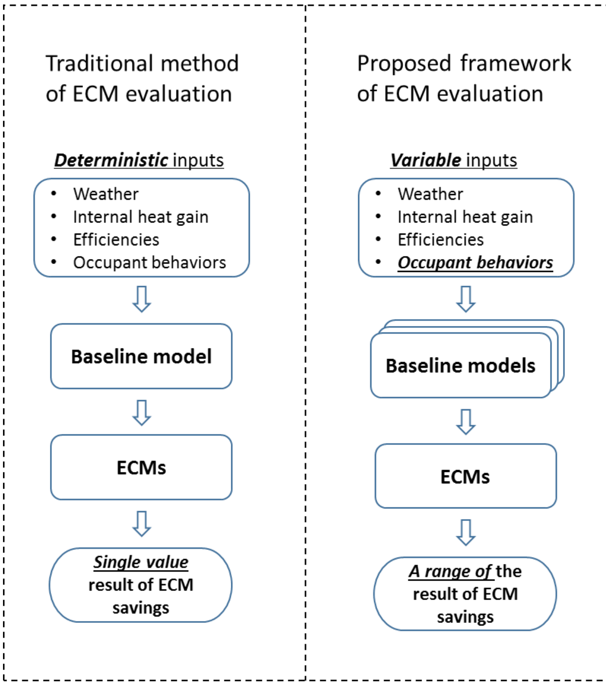

Figure 1 A framework to quantify the impact of occupant behavior on ECMs by simulation

In previous studies, some occupant actions were distinguished based on the user types. Parys et al. (Parys, Saelens, and Hens 2009) and Reinhart (Reinhart 2010) used four user types in terms of their active and passive attitudes on lighting and blind controls, and Santin (Santin 2011) defined behavioral patterns as spenders, affluent-cool, conscious-warm, comfort, and convenience-cool based on behavior factors such as use of appliances, energy-intensive, and ventilation in housing. In our study, three occupant behavior styles are based on the three office workstyles defined in Hong (Hong and Lin 2013). To represent the diversity of occupants and their behavior in building energy simulation, first we categorize the occupant style into three distinguished attitudes in regards of their consciousness to energy consumption: Austerity, Normal, and Wasteful, and determine their behavior respectively. The normal behavior generally represents the design condition of a building, the austerity behavior represents the extreme condition of energy savers, while the wasteful behavior represents the extreme condition of energy spenders. This is to simplify the complexity of the occupant behavior. This method would not necessarily aim to represent the realistic occupant behavior in buildings, rather represent the boundary of either extreme as in energy savers and spenders. As described in Table 1, the occupant behaviors considered in this study includes temperature setpoints for heating and cooling, lighting control, plug-load control, HVAC control and window operation. For each occupant behavior, the three behavior styles represent proactive energy savers, average (representative) occupants, and energy spenders. The defined three occupant behavior styles are an example for the purpose of demonstration. They could vary for different cases under different circumstances.

Table 1 Description of three occupant behavior styles

Occupant Behavior	Austerity	Normal	Wasteful
Cooling Setpoint (°C)	26	24	22
Heating Setpoint (°C)	18	21	22
Control of lights	Dim lights if unoccupied	Follow standard schedule	Always on during working hours
Control of plug-loads	turn 30% off if unoccupied	Follow standard schedule	Always on during working hours
HVAC occupancy control (For VRF ECM only)	Off if unoccupied	Off if unoccupied	Always on
HVAC startup control (For VRF ECM only)	Turn on HVAC only when occupants feel hot, based on a probabilistic model of HVAC operation	None	None
Window operation (For natural ventilation ECM only)	Concurrent HVAC and natural ventilation	Either HVAC or natural ventilation	HVAC and natural ventilation both on all the time

Occupant behavior styles

The settings of the normal behavior are either the designed setpoints or consistent with the actual setpoints of the case building. The settings of the austerity behavior have wider ranges: higher cooling setpoint and lower heating setpoint, but they are both within the comfort range of ASHRAE Standard 55-2010 (ASHRAE 2010). The settings of the wasteful behavior have an extreme narrow range: same cooling and heating setpoints.

The control logic of lights and plug-loads are similar. The standard lighting and plug-load schedules, or the average schedules of a real building were used as the normal behavior. For the wasteful behavior, both lights and plug-loads were always on during working hours of the building. For the austerity behavior, the lights will be dimmed and the plug-load will be reduced by 30% when the zone is unoccupied. This is based on previous research on occupancy-based control of plug loads, which shows savings of 5-32% of the electricity use (Metzger, Sheppy, and Cutler 2013; Mahdavi, Tahmasebi, and Kayalar 2016; Leviton 2014).

For HVAC systems that have zonal control, occupants are allowed to turn on/off the HVAC in their zone without affecting others; for the centralized controlled HVAC systems, occupants are not able to control their HVAC operation individually. For the baseline models, the HVAC system is PVAV (packaged variable air volume), which doesn't allow zonal control, so the PVAV system is centralized controlled with a fixed schedule throughout the working hours. Therefore, the occupant-based controls of HVAC are not applicable for baseline models. For the ECMs that are using VRF systems, which allows zonal control, the occupant-based controls of HVAC are applied with the following logic: (1) For the austerity and normal behaviors, the HVAC will be turned off when the occupants leave the room (HVAC occupancy control), and (2) the austerity occupants would not turn on the HVAC unless they feel hot/cold (HVAC startup control).

The probability of turning on the HVAC system relates to the current conditioning mode (cooling or heating) and the indoor air temperature. Ren (Ren, Yan, and Wang 2014) investigated the indoor temperature and HVAC usage of 34 families in six Chinese cities and used a three-parameter Weibull distribution function to describe different air conditioning usage patterns. As the residents have independent control of their HVAC systems, which applies to the condition of our study, Ren's model was adopted to estimate the time-step HVAC control status in our models.

In the baseline model, the window operation is not applicable as the PVAV system is centralized controlled with a fixed schedule throughout the working hours. The window operation is only applicable for the ECMs that are using VRF system, which allows zonal control. In this study, three ventilation modes in Wang's research (Wang and Greenberg 2015) were adopted for the three occupant behavior styles: (1) concurrent mix-mode ventilation for austerity behavior, where natural ventilation is taken as the priority to provide cooling for perimeter zones, and mechanical systems provide supplementary cooling when natural ventilation alone is not enough to meet cooling setpoints, (2) change-over mix-mode ventilation for normal behavior, where the VRF indoor unit of this zone will be turned off whenever a window in the perimeter zone is open, and (3) HVAC and windows both on all the time for the wasteful behavior.

Occupancy schedules

Occupancy has a significant impact on the energy saving potentials of ECMs (Li et al. 2015). The occupancy schedules adopted in the simulation are supposed to reflect the realistic occupant movement in buildings. The Occupancy Simulator was adopted to simulate the realistic occupant movement in each zone, with inputs from the site survey of real buildings. The Occupancy Simulator, developed by Lawrence Berkeley National Laboratory (LBNL), is a user-friendly web app that uses the stochastic Markov chain model to simulate occupancy in buildings (Chen, Luo, and Hong 2016). The method to generate realistic occupancy schedules is similar to the method used in our previous research on estimating the energy saving potentials of occupant behavior measures (Sun and Hong 2016).

The generated schedules can reflect the variation, diversity, and stochastic characteristics of the realistic occupant movements. These generated schedules are more reasonable than the normalized occupancy schedules and can help improve the simulation accuracy. To make it consistent with all the studied ECMs, the same set of generated schedules is applied to both the baseline models and the ECMs.

Case Study

A case study was performed in a real building to quantify the influence of different occupant behaviors on ECM savings, in order to demonstrate the application of the framework. A real office building was field investigated, including the geometry, zoning, zone occupancy and occupancy schedules. The impact of occupant behavior on ECMs savings was evaluated in four climate zones: Chicago, Fairbanks, Miami, and San Francisco. These selected cities represent the four typical climate types in the U.S.: humid continental, subarctic, tropical (subtropical), and Mediterranean (mild).

The three occupant behavior styles defined in the Methodology Section were adopted to represent different levels of energy consciousness and the boundary of either extreme as in energy savers and spenders. The occupant behavior style is assumed to be consistent before and after the ECMs are implemented, so the three types of occupant behavior style were applied to generate three levels of baselines for the ECM evaluation in each climate type. Besides, the authors used the Occupancy Simulator to simulate the realistic occupant movement in each zone, with inputs from the site survey of the case building. Therefore, three baseline models implementing the three occupant behavior styles with realistic occupancy schedules were developed for the ECM evaluation in each climate type.

The effective useful life of the equipment in commercial buildings varies from 5 to 25 years (Skumatz, Economic, and Hickman 1994)(Pacific Northwest National Laboratory 2011). We assume to apply the ECMs in a 15-year-old building. Therefore, the efficiencies of the baseline models should comply with ASHRAE Standard 90.1-2001. On the other hand, more recent ASHRAE Standard 90.1-2013, considered as a representative of the new building technologies, was adopted as the efficiencies of the ECMs in the case study.

Case building model

The field investigated office building has two above-ground stories with a total conditioned floor area of 1,723 m^2. Main room functions include office, conference room, classroom, and lounge. The perimeter zones have operable windows, which allow the occupants to open windows for cooling or ventilation. The total number of occupants in the case building is 63.

Based on the realistic geometry and zoning of the case building, the three defined occupant behavior styles, and the generated realistic occupancy schedules, the three baseline models were developed in EnergyPlus Version 8.5 for each climate type, as shown in Figure 2. The efficiency inputs of the baseline models are based on ASHRAE Standard 90.1-2001. The thermal properties of the envelope are shown in Table 2. The Occupancy Simulator was used to generate stochastic occupancy schedules based on the survey results of the case building.

The baseline model is equipped with Packaged Variable Air Volume (PVAV) systems, which uses direct expansion (DX) cooling coil to supply cooling and gas heating coil for reheat. As the baseline models are based on ASHRAE 90.1-2001, economizers are not required for small capacity PVAV systems, so the minimum requirement of outdoor air is supplied. The sizing of the HVAC equipment for each baseline model was kept the same through all the ECM calculations since HVAC equipment will stay the same unless replaced or removed during the retrofit. The sizing information was first obtained by autosizing the equipment of the baseline model.

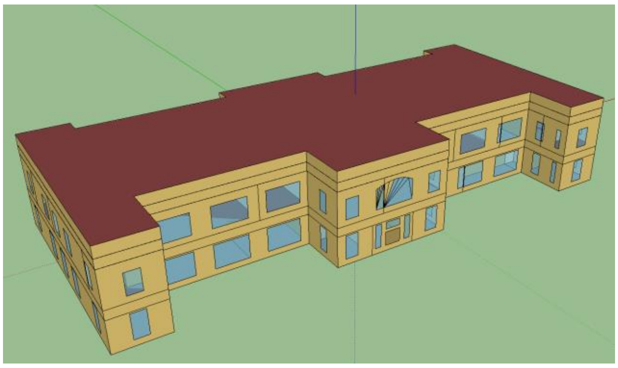

Figure 2 The 3D view of the baseline model

Table 2 Envelope thermal properties based on ASHRAE Standard 90.1-2001

	Chicago	San Francisco	Miami	Fairbanks
Wall U-factor W/(m^2.K)	0.701	0.857	3.293	0.453
Roof U-factor W/(m^2.K)	0.36	0.527	0.36	0.273
Window U-factor W/(m^2.K)	3.24	6.93	6.93	2.61
Window SHGC	0.39	0.61	0.25	0.45

Energy conservation measures (ECMs)

To investigate the impact of occupant behavior on energy savings of ECMs, seven individual ECMs, and one integrated ECM were evaluated in this study. We applied the ECMs in a 15-year-old building. The efficiency requirements of ASHRAE Standard 90.1-2001 were used in the baseline models to represent the case building. The ASHRAE Standard 90.1-2013 was adopted as the efficiencies of the ECMs. The details of the ECMs are illustrated as follows:

(1) Reducing lighting power density (LPD)

LPD is reduced from 14 W/m^2 to 8.83 W/m^2.

(2) Reducing electric equipment power density (EPD)

Average EPD is reduced from 14 W/m^2 to 10.5 W/m^2.

(3) Improving envelope properties

This ECM improves the thermal properties of the building envelope from ASHRAE 90.1-2001 (Table 2) to ASHRAE 90.1-2013 (Table 3).

Table 3 Envelope thermal properties based on ASHRAE Standard 90.1-2013

	Chicago	San Francisco	Miami	Fairbanks
Wall U-factor W/(m^2.K)	0.513	0.701	3.293	0.273
Roof U-factor W/(m^2.K)	0.184	0.220	0.273	0.158
Window U-factor W/(m^2.K)	2.38	2.84	3.24	2.16
Window SHGC	0.4	0.25	0.25	0.45

(4) Improving system efficiency.

This ECM improves the cooling system efficiency from ASHRAE Standard 90.1-2001 to the 2013 edition, as shown in Table 4. The gas burner efficiency remains the same.

Table 4 Improvement of the HVAC system efficiencies

Capacity	ASHRAE 90.1-2001	ASHRAE 90.1-2013
<65000 BTU	9.7 SEER	14 SEER
65000-135000 BTU	9.9 EER	12 IEER
135000-240000 BTU	9.1 EER	11.4 IEER
>=240000 BTU	8.8 EER	10.4 IEER

(5) Daylighting control

Daylight sensors are installed in perimeter zones to allow daylighting control. The lights will automatically dim continuously from maximum electric power to minimum electric power as the daylight illuminance increases. The lights stay on at the minimum point with further increase in the daylight illuminance.

(6) Variable refrigerant flow heat recovery (VRF-HR) system

Variable refrigerant flow (VRF) systems vary the refrigerant flow to meet the dynamic zone thermal loads. They can provide flexible controls, better thermal comfort capabilities, and less energy consumption (Hong et al. 2016; Yu et al. 2016). VRF-HR systems can deliver simultaneous heating and cooling to different zones by transferring heat between the cooling and heating indoor units.

This ECM replaces the original PVAV systems with the VRF-HR systems to enable flexible zonal control and achieve more efficient operation. The heat recovery feature allows further energy saving potentials. It should be noted that the VRF-HR system generally does not have an airside economizer due to small air ducts providing the only minimal amount of outdoor air directly to zones. Therefore, the amount of supplied outdoor air is the same between the PVAV systems and the VRF-HR systems. The efficiency curves of the VRF-HR systems were obtained from VRF manufacturers.

(7) Natural ventilation coupled with the VRF-HR system

The ECM of natural ventilation is implemented together with the VRF-HR system as the occupant-based control of HVAC system. Window operation is only applicable for the VRF-HR system, which allows zonal control. As discussed in the Methodology Section, three ventilation modes were adopted for the three occupant behavior styles in this ECM: (1) concurrent mix-mode ventilation for the austerity behavior, (2) change-over mix-mode ventilation for the normal behavior, and (3) HVAC and windows both on all the time for the wasteful behavior.

(8) The integrated ECM

All the ECMs are integrated as a new ECM, except that the ECM of improving system efficiency is excluded because the HVAC system has switched to the VRF-HR system with new efficiency curves and the improvement of cooling system efficiencies does not apply.

Simulation results

The energy performance of the baseline models and the models implemented with the ECMs were simulated using EnergyPlus Version 8.5. Site energy is used as the energy metric. The results are elaborated as follows.

(1) Impact of occupant behavior on baseline energy use

Before evaluating the impact of occupant behavior style on ECM savings, the author first analyzed their impact on the energy consumption of the baseline models. Figure 3 shows the total energy use intensity of the baseline models with the three occupant behavior styles in four climate zones. Compared with the normal behavior style, the model with austerity behavior style consumes 17.8-32.1% less energy, while the model with wasteful behavior style consumes 27.8-47.8% more energy. When comparing wasteful behavior style with austerity behavior style, the energy use differences are greater than 55.6% for Fairbanks where is cold and as high as 117.6% for San Francisco where is mild climate.

The occupant behavior style has a significant influence on building energy use. Even though the buildings are physically identical, they consume quite different energy when occupied by different types of energy users. The energy spenders could consume more than twice the energy of the energy savers.

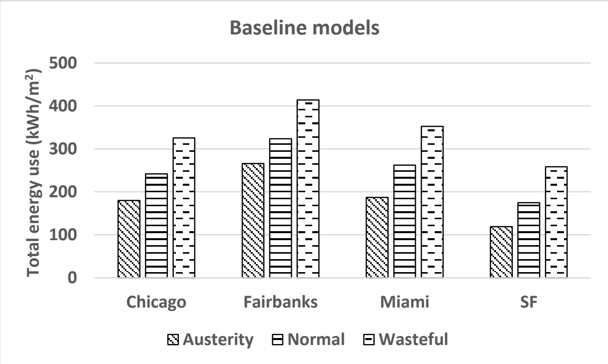

Figure 3 Total site energy use of the baseline models

(2) Impact of occupant behavior style on ECM savings

Each ECM was implemented in the three baseline models with different occupant behavior styles in each climate type. The energy performance of each ECM was then simulated and compared with the baseline models. Figure 4 to Figure 7 illustrate the ECM saving percentages compared to the baseline models under the three behavior styles in each climate type. The simulation results indicate that the ECM saving percentages of LPD, EPD, envelope, system efficiency, and daylighting control are barely affected by the occupant behavior style. This is because they are purely technology-driven ECMs, which don't rely on the interactions with the occupants to save energy. For example, the ECM of reducing lighting power density doesn't require any actions from the occupants, in other words, no choices need to be made by the occupants. Its saving percentage barely varies with behavior style.

On the other hand, the ECM saving percentages of VRF-HR system, natural ventilation, and the integrated ECM are significantly affected by the occupant behavior style. Their energy performance is closely related to how the occupants interact with the ECM. For example, when the VRF-HR system is installed, it allows zonal control. The occupants have decisions to make on how to control their indoor units: austerity occupants only turn on the indoor units when they feel hot, normal occupants turn on the indoor units as long as they are in the room, while wasteful occupants keep the AC on during entire working hours. Also, the cooling and heating setpoints are different among the behavior styles. Therefore, the energy performance of such ECMs heavily depends on how the occupants behave. Even though the same VRF-HR system is installed, the distinct amount of energy is consumed due to different occupant operation mode. Likewise, the saving potentials of natural ventilation also heavily depend on how the occupants control the windows and the HVAC system. The integrated ECM involves a VRF-HR system and natural ventilation, so it is also largely affected by behavior style.

In summary, for ECMs that are purely technology-driven and have little interaction with the occupants, or occupant-independent ECMs, such as reducing LPD, reducing EPD, improving envelope properties, improving system efficiency and daylighting control, the energy saving percentage is barely affected by occupant behavior style. For ECMs that have a strong interaction with the occupants, or occupant-dependent ECMs, such as VRF system and natural ventilation, the energy saving percentage is significantly affected by occupant behavior style.

Climate also has impact on the ECM savings of different occupant behavior styles. For example, the VRF heat recovery system has the greatest savings with wasteful behavior style in San Francisco, while it is the opposite to other three climates. This is because in mild climate like San Francisco, the close or even equal cooling and heating setpoints of the wasteful behavior style generate a significant simultaneous cooling and heating load. In the baseline model with PVAV systems, this can only be satisfied by cooling coupled with reheat. However, the VRF heat recovery system can easily handle a simultaneous cooling and heating load by recovering heat from cooling zones to heating zones—significantly improving system efficiency and reducing energy consumption. Therefore, VRF has the greatest saving potential for the wasteful behavior and the least saving potential for the austerity behavior in San Francisco. On the other hand, in climates with distinct cooling and heating seasons such as Chicago, Miami, and Fairbanks, a simultaneous cooling and heating load is much less frequent than that in mild climates, so the saving percentages for the wasteful behavior are less than those of the normal and austerity behaviors.

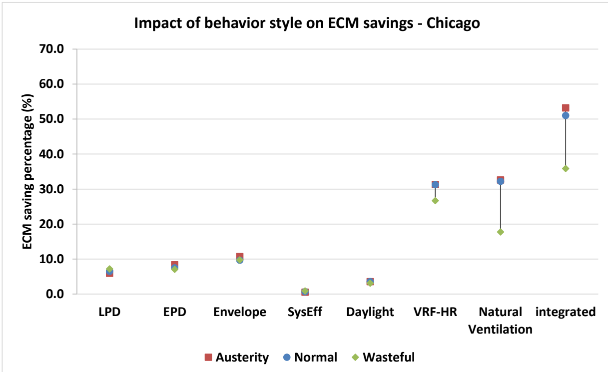

Figure 4 ECM saving percentages compared to the baseline models with different behavior styles in Chicago

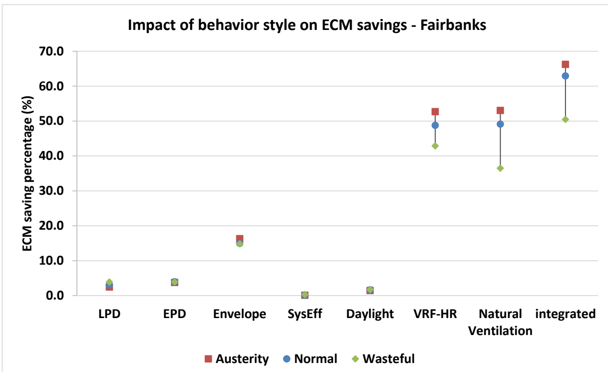

Figure 5 ECM saving percentages compared to the baseline models with different behavior styles in Fairbanks

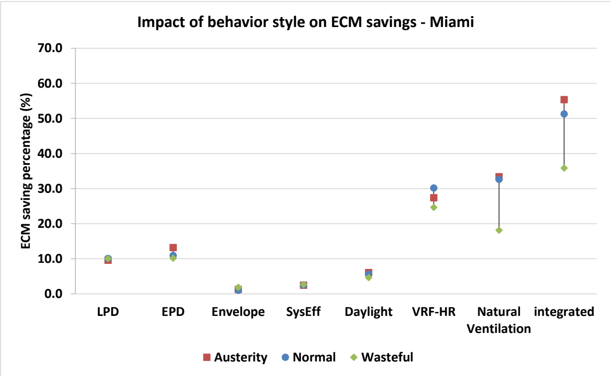

Figure 6 ECM saving percentages compared to the baseline models with different behavior styles in Miami

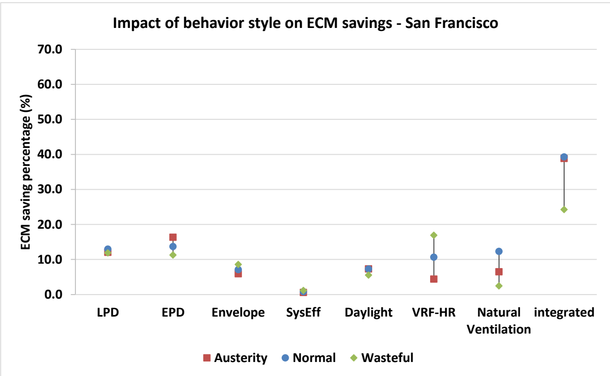

Figure 7 ECM saving percentages compared to the baseline models with different behavior styles in San Francisco

Discussion

The simulated results using the proposed framework indicate a range of ECM savings with different occupant behaviors in buildings. How the results are interpreted and adopted would vary by application purposes.

When the framework is applied to the retrofit analysis of existing buildings, the ECM savings range can be significantly reduced as the buildings are occupied and the types of occupant behaviors are recognized. In this case, the decision makers can minimize the investment risks by selecting the ECMs that benefit the most from the current occupant behavior style. On the other hand, when the framework is applied to the design of new buildings, the simulated range of ECM savings informs decision makers of the potential risk of technology choices due to variation and uncertainty of occupant behaviors. As the tenants are usually uncertain at the design stage, it is less risky to choose occupant-independent ECMs, such as reducing lighting power density, improving envelope properties, and improving HVAC system efficiencies. If occupant-dependent ECMs are considered as well, it would help to largely reduce the risk by educating and training occupants to understand the design intent of the building systems or by implementing automatic/intelligent controls, such as automatic shading, lighting, and HVAC controls coupled with occupancy sensors

Conclusions

This study introduced a simulation framework to quantify the impact of occupant behavior on ECM savings. Three types of occupant behavior style, austerity, normal and wasteful, were defined to represent different levels of energy consciousness in terms of the control of HVAC, window, lights and plug-in equipment. These behavior styles don't necessarily represent the realistic occupant behavior in buildings, but rather represent the boundary of either extreme as in energy savers and spenders. The framework was applied to a case study to evaluate the ECM energy saving variations among different behavior styles. The Occupancy Simulator was used to simulate the occupant movement in each zone with inputs from the site survey of the case building. The main findings from this study include: (1) The occupant behavior style has a significant influence on building energy use. Buildings occupied by energy spenders could consume more than twice the energy of the energy savers, (2) For occupant-independent ECMs, which are purely technology-driven and have little interaction with the occupants, such as reducing LPD, reducing EPD, improving envelope properties, improving system efficiency and daylighting control, the energy saving percentage is barely affected by occupant behavior style. For occupant-dependent ECMs, which have a strong interaction with the occupants, such as VRF system and natural ventilation, the energy saving percentage is significantly affected by occupant behavior style.

The simulation results may vary due to different climate types, building types, ECM types, occupant behavior, and occupancy schedules. However, the developed framework is generic and can be used to quantify the impact on ECM savings of other uncertainty factors such as climate change and building operation mode. Future studies can collect and use more realistic data of occupant behavior as input.

Acknowledgment

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