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Impacts of Occupant Behavior on Building Energy Consumption and Energy Savings Analysis of Upgrading ASHRAE 90.1 Energy Efficiency Standards

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Abstract: Commercial prototype building models were developed by the United States Department of Energy (DOE) to analyze the energy savings of the ASHRAE 90.1 standard. However, in the DOE models, occupant behavior inputs were deterministic and the stochasticity of occupant behavior was not fully characterized. This study evaluated the impacts of stochastic occupant behavior on building energy consumption and energy savings analysis from upgrading the ASHRAE 90.1-2016 to 2019 in sixteen climate zones in the United States (U.S.). Three occupant behavior styles (austerity, normal, and wasteful) were defined to represent the different levels of energy consciousness. The DOE medium office prototype models were used as the baseline (normal behavior style). The occupant behavior functional mock-up unit (obFMU) was used to model the stochastic occupant behavior models (austerity and wasteful). The EnergyPlus medium office prototype models were modified to co-simulate with the obFMU models. The results of 16 climate zones were aggregated by the relative construction volume of each climate zone. The results showed that the weighted national annual source energy use intensity (EUI) of the austerity, normal, and wasteful behavior styles were 203.81 kWh/m^2, 287.15 kWh/m^2, and 388.33 kWh/m^2 for ASHRAE 90.1-2016, and 192.43 kWh/m^2, 273.48 kWh/m^2, and 371.28 kWh/m^2 for ASHRAE 90.1-2019, respectively. Compared to the normal behavior style, the austerity behavior style consumed 29% less source energy, while the wasteful behavior style consumed 36% more source energy. From upgrading the ASHRAE 90.1-2016 to 2019, the energy saving percentages based on the austerity, normal, and wasteful behavior styles were 5.59%, 4.78%, and 4.42%, respectively. The stochastic occupant behavior significantly impacted the building energy consumption, and their impacts on the energy savings analysis of upgrading ASHRAE 90.1 were also not negligible.

Keywords: building energy performance; ASHARE 90.1; occupant behavior; EnergyPlus; obFMU

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1. Introduction

With the rapid development of the global economy, building energy consumption has increased and is responsible for approximately 30% of global energy usage [1,2]. Building energy efficiency regulations have been developed for energy conservation and emission reduction in buildings [1]. For example, in 1975, the United States (U.S.) published and implemented the building energy efficiency standard, ASHRAE 90.1. As energy prices and technology began to evolve rapidly, the ASHRAE Board of Directors voted in 1999 to place the standard on continuous maintenance. As of the 2001 edition, the standard is published in its entirety during the fall of every third year, continuing to the 2019 edition. The standard parameters are revised every three years, presenting minimum performance characteristic values for all of the parameters related to the building envelope, air conditioning system requirements, lighting power density, and similar considerations [3].

As ASHRAE 90.1 evolved, the Pacific Northwest National Laboratory (PNNL) modified the suite of commercial prototype building models [4]. The suite of commercial prototype buildings covers 75% of the commercial building floor area in the U.S. for new construction including both commercial buildings and mid-to high-rise residential buildings, and across all U.S. climate zones. These commercial prototype building models derived from the commercial reference building models developed by the Department of Energy (DOE) [5]. The input parameters for the DOE commercial prototype building models were determined from the ASHRAE Standard 90.1, ASHRAE Standard 62.1, and as well as some studies of the data and standard practices. These models represent reasonably realistic building characteristics and construction practices [6]. They were used to determine the energy-saving potential of the different versions of the ASHRAE 90.1 standards.

People spend most of their time indoors [7]. Occupants and their behaviors (movement behavior and interaction behavior) are one of the driving factors of building energy consumption [8–13]. However, in many building performance simulation (BPS) studies (including DOE prototype building models), the occupant behavior inputs were deterministic [5,14,15] and lacked dynamic, stochasticity, and diversity. For example, the occupancy schedule of each thermal zone and the switching state of the lighting, equipment, and heating, ventilating, and air conditioning (HVAC) systems were consistent.

Occupancy information could determine the heating, ventilation, and lighting requirements [16]. The deterministic occupancy cannot reflect the load demand caused by the dynamic change in the number of people. Ahmed et al. [17] developed a new occupant hourly schedule for an office building and evaluated the impact of occupant behavior on the peak cooling load by energy simulation. The results illustrated that the peak cooling load in an office room was increased by a factor of 1.1–1.3 compared to the use of constant average value. Norouziasl et al. [18] investigated the performance of lighting occupancy sensors (represented the stochastic occupancy) in a simulated office. The results revealed that installing lighting occupancy sensors could reduce the annual lighting energy consumption by approximately 33%–55% compared to the sensor-free simulation.

Moreover, people have different energy-saving awareness, and the use habits of lighting, equipment, and HVAC systems differ from person to person. The deterministic occupant behavior inputs cannot depict this difference. Sun and Hong [19] employed BPS to evaluate the impact of three typical occupant behaviors (austerity, normal, and wasteful) on the energy use of an office building, and the simulation results demonstrated that compared to the normal workstyle, the austerity workstyle consumed up to 17.8–32.1% less energy, while the wasteful workstyle consumed up to 27.8–47.8% more energy. Jami et al. [20] identified the effect of occupant energy behavior scenarios (austerity, normal, energy spender) on the energy retrofit of a student dormitory via BPS. They found that energy conservation measures (ECMs) could improve energy efficiency by 32%, 56%, and 60% with the energy spender, normal, and austere occupant behavior models, respectively. He et al. [21] estimated the energy-saving potential of occupant behavior improvement by BPS based on a case study with a nationwide survey in Singapore and found that the building energy consumption could be reduced by up to 9.5% with moderate behavior improvement and up to 21.0% with aggressive behavior improvement. These studies all found that the stochastic behavior models had different impacts on the building energy consumption than the deterministic behavior models. Building prototypes (such as DOE commercial prototype building models) are regularly used in building performance analysis [22]. If stochastic occupant behavior models are integrated into DOE building models, it will be very helpful for researchers to evaluate the building energy performance by BPS tools (EnergyPlus, DeST 3.0 [23], etc.).

In terms of simulating the stochastic occupant movement behavior (e.g., arrival, departure, short-term leave, and from one office to another et al.) in an office building, Reinhart [24] used the cumulated probability statistics to simulate the status transition event (e.g., arrival, departure, and short-term leave). Wang et al. [25] used the Markov chain to simulate the random movement event (e.g., from one office to another).

Goldstein et al. [26] used the occupant activity simulation to simulate the chronological sequence of detailed activities with attributes of a task (e.g., meeting event). Chen et al. [27] developed a web-based stochastic occupancy simulator, Occupancy Simulator, which simulated the presence and movement of each occupant by three types of events including: (1) the random movement event with Wang's [25] homogeneous Markov chain model; (2) the status transition event with Reinhart's [24] cumulated probability statistics model; and (3) the meeting events with a new stochastic model. In terms of modeling the stochastic occupant interaction behaviors (e.g., the control of lighting, window, HVAC, and other building energy systems), the interaction behaviors between the occupants and energy systems have often been fitted to the probabilistic distribution function of indoor environmental parameters. Hunt [28], Reinhart [24], and Wang [29] all proposed a light-on probability model with work plane daylight illuminance as the independent variable. Nicol [30] proposed a heating-on probability model with outdoor dry bulb temperature as the independent variable. Haldi and Robinson [31], Yun and Steemers [32], and Zhang and Barrett [33] all proposed the window-open or window-close probability model with indoor or outdoor air temperature as the independent variable. The occupant behavior functional mock-up unit (obFMU) developed by Lawrence Berkeley National Laboratory can model both the occupant movement and interaction behaviors [34]. obFMU was selected in this study to co-simulate with EnergyPlus via the functional mock-up interface (FMI) to implement the occupant behavior models.

This study evaluated the impacts of stochastic occupant behavior on building energy consumption and energy savings analysis from upgrading the ASHRAE 90.1-2016 [35] to 2019 [36] based on the DOE medium office prototype models across sixteen U.S. climate zones. For the convenience of simulation, the DOE medium office building models grouped rooms on each floor into five zones, including one core zone and four perimeter zones. The five zones in each floor were served by a packaged rooftop air conditioner with a variable air volume (VAV) system. Each zone was occupied by more than 10 persons based on the occupancy density. Those zones, therefore, were defined as open-plan office spaces in this study. The HVAC systems were kept running during office hours all year round. Thus, the HVAC zonal on/off control behavior and window zonal open/close behavior were not considered in this study. This paper, therefore, focused on the stochastic light switch behavior, appliance use behavior, and thermostat setpoint behavior. Other occupant behavior inputs were the same as the DOE prototype models. The main components of this study were as follows:

1. Three occupant behavior styles (austerity, normal, and wasteful) were defined based on the energy consciousness levels of the occupants regarding their interactions with the lighting, equipment, and heating/cooling setpoint systems. The DOE medium office prototype models were used as the baseline case (with normal behavior style). The obFMU was used to model the stochastic occupant behaviors, including the occupant movement and two interaction behavior styles (austerity and wasteful).
2. The EnergyPlus medium office prototype models for the 2016 and 2019 editions across sixteen U.S. climate zones were modified to co-simulate with the obFMU models.
3. After verifying the effectiveness of the occupant behavior models, the impacts of the stochastic occupant behavior on the building energy consumption and the energy savings analysis from upgrading the ASHRAE 90.1-2016 to 2019 were analyzed.

2. Methodology

2.1. Framework Overview

Figure 1 shows the proposed framework with its three major steps. The first step was to define three occupant behavior styles (austerity, normal, and wasteful). The DOE medium office prototype models, where occupant behavior inputs were deterministic, were used as the baseline case (with normal behavior style). The obFMU was used to model the stochastic occupant behaviors, including movement and two interaction behaviors (austerity and wasteful behavior styles). An occupant behavior modeling program, occupant behavior eXtensible Markup Language-generator (obXML-generator), was developed to generate the occupant behavior model file, which was used as the input file for the obFMU model. The second step was to modify the EnergyPlus medium office prototype models (in EnergyPlus™ Version 9.0) for the 2016 and 2019 editions across sixteen U.S. climate zones to co-simulate with the obFMU models. Moreover, the normal behavior style was only simulated by EnergyPlus. The final step was to verify the effectiveness of the occupant behavior models and analyze the impacts of the stochastic occupant behavior on the building energy consumption and the energy savings analysis from upgrading the ASHRAE 90.1-2016 to 2019.

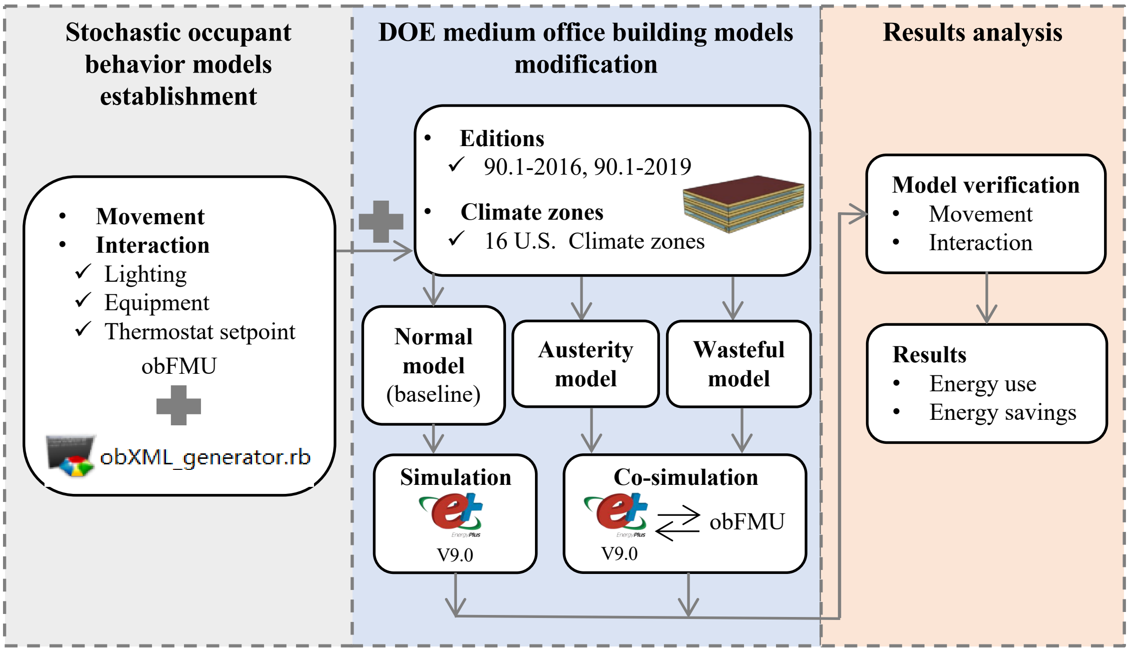


Figure 1. An overview of the framework.

2.2. DOE Medium Office Building Models

Commercial prototype building models [4] include 16 commercial building types in 19 climate zones (16 in the U.S.) for recent editions of ASHRAE 90.1. Figure 2 shows the basic situation of the DOE medium office building model. This building has three above-ground floors, a floor-to-floor height of 3.96 m, and a total floor area of 4983 m^2. Each floor has the same layout, consisting of one core zone and four perimeter zones, and each zone has a uniform space type, defined as the "office". The occupant density is 0.053 person/m^{2}, and the equipment power density is 8.07 W/m^2. The lighting power density was 8.50 W/m^2 in 2016 and 6.89 W/m^2 in 2019. Figure 2c shows the occupant behavior schedules in 15 zones, including the occupancy, interior lighting schedule, interior equipment schedule, and thermostat setpoint. These schedules were deterministic. This study focused on defining the stochastic occupant behavior models and analyzing the impacts of the stochastic occupant behaviors on building energy performance.

The Oak Ridge National Laboratory (ORNL) [37] updated the DOE medium office building model to include more space types such as open-plan office, enclosed office, corridor, etc. The ORNL's models are more detailed than the DOE's. However, this study wanted to briefly analyze the impacts of occupant behavior on the energy savings analysis of upgrading ASHRAE 90.1. The DOE's models have often been used to evaluate the energy saving potential of ASHRAE 90.1 [38,39], and no official statement has been made that the ORNL's models could replace the DOE's. This study still used the DOE's models. Table 1 lists the characteristics of the sixteen cities and climate zones in the U.S., which are described in ASHRAE Standard 169-2013 [40].

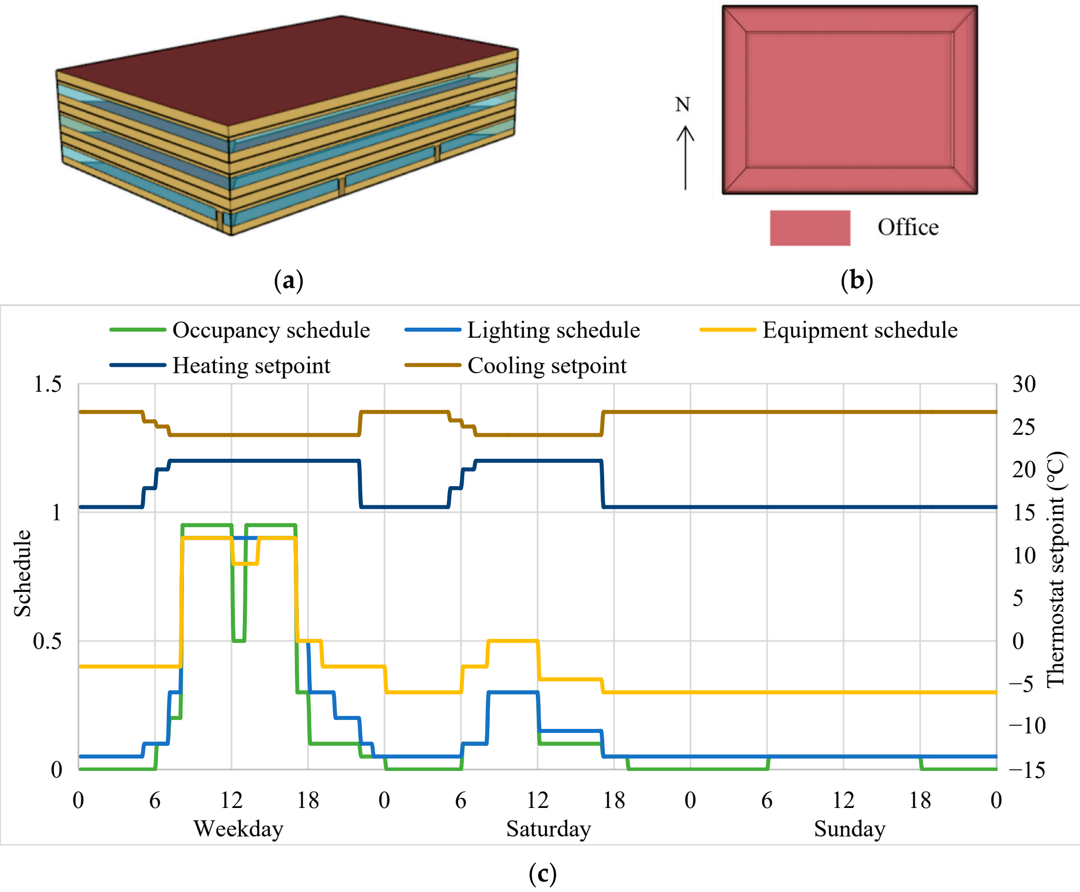


Figure 2. The basic situation of the DOE medium office building model: (**a**) 3D model; (**b**) thermal zones; (**c**) occupant behavior schedules.

Table 1. The characteristics of the sixteen cities and climate zones in the U.S.

Climate Zone	Thermal Climate Zone Name	Representative City
1A	Very Hot Humid	Honolulu, HI
2A	Hot Humid	Tampa, FL
2B	Hot Dry	Tucson, AZ
3A	Warm Humid	Atlanta, GA
3B	Warm Dry	El Paso, TX
3C	Warm Marine	San Diego, CA
4A	Mixed Humid	New York, NY
4B	Mixed Dry	Albuquerque, NM
4C	Mixed Marine	Seattle, WA
5A	Cool Humid	Buffalo, NY
5B	Cool Dry	Denver, CO
5C	Cool Marine	Port Angeles, WA
6A	Cold Humid	Rochester, MN
6B	Cold Dry	Great Falls, MO
7	Very Cold	International Falls, MN
8	Subarctic/Arctic	Fairbanks, AK

2.3. Occupant Behavior Models

2.3.1. obXML

To solve the problem of the existing data-driven behavior model's low standardization and consistency, Hong et al. [41] developed the obXML schema to describe the occupant behaviors quantitatively. The obXML is a key tool for defining the stochastic occupant behavior models in the obFMU. The algorithm and solver of the Occupancy Simulator were implemented in obFMU by Hong et al. Users can define the movement model of each occupant by three types of events [27]: (1) the random movement event; (2) the status transition event; and (3) the meeting events. The obXML schema describes the stochastic occupant interaction behavior by implementing a framework of the *Driver-Need-Action-System* (DNAS) [41]. *D* represents the environmental factors that stimulate the occupants to fulfill a physical, physiological, or psychological need. *N* represents the occupant's physical and non-physical requirements that must be met to ensure satisfaction with their environment. *A* represents the interactions with the energy systems that occupants can perform to achieve environmental comfort. *S* represents the equipment in the building.

2.3.2. Occupant Movement Model

For the convenience of simulation, the DOE medium office building models grouped rooms with the same setup parameters and set them to a unified thermal zone. The room type of each zone was defined as the "office". The lighting, equipment, and other energy systems in 15 zones were uniformly controlled. In this study, each thermal zone was split into some subspaces by obFMU, allowing the lighting and equipment system of each space to be under independent control. The control style of the thermostat setpoint was unchanged, and future studies would achieve independent control of the HVAC system. Each subspace was a four-person space, common in office buildings. Generally speaking, there are seven room types in the office building: office, corridor, meeting room, copy room, lobby, restrooms, and mechanical/electrical room [42]. Occupants mainly stay in the "office" for a long time and stay in the other six room types for a short time. Therefore, the room type was redefined as the office, meeting room, and other types, which took about 72%, 4%, and 24% of the total floor area, respectively. The area fraction of each room type defined in this study referred to the Database for Energy Efficient Resources (DEER) prototype building models [42]. The floor area of each subspace was approximately 66.5 m^2. The occupant density (0.053 person/m^2) did not change. Because there are no permanent occupants in the meeting room and other rooms, the number of people in these rooms was defined as 0. The original occupant type (only "staff") was redefined as staff, manager, and administrator types. See the details of each thermal zone in Figure 3 and its movement behavior in Tables 2–4. The definition of the random movement and status transition events in Table 3 referred to He's study [21] and the DOE's model (see Figure 2c). The definition of meeting events in Table 4 referred to Chen's study [27].

Table 2. The redefinition of the room type and movement behavior.

Zone	Area (m^2)	Room Type	Space Number	Occupant Number per Space	Total Occupant Number per Zone	Movement Behavior ID *
F1C	984.67	Office	16	4	64	S1
F2C	984.67	Other	5	0	0	S1
F3C	984.67	Office	16	4	64	S2; S2_Sat
F3N	207.58	Office	4	4	16	M
F3E	131.41	Office	3	4	12	S2; S2_Sat
F3S	207.58	Other	2	0	0	M
F3W	131.41	Office	3	4	12	S2; S2_Sat
F1N	207.58	Office	4	4	16	M
F1E	131.41	Office	3	4	12	M
F1S	207.58	Office	4	4	16	S3; S3_Sun
F1W	131.41	Office	3	4	12	A2
F2N	207.58	Office	4	4	16	A2
F2E	131.41	Office	3	4	12	A1
F2S	207.58	Meeting room	2	0	0	A1
F2W	131.41	Office	3	4	12	A1

* Note: S, M, and A are the first letter of staff, manager, and administrator, respectively.

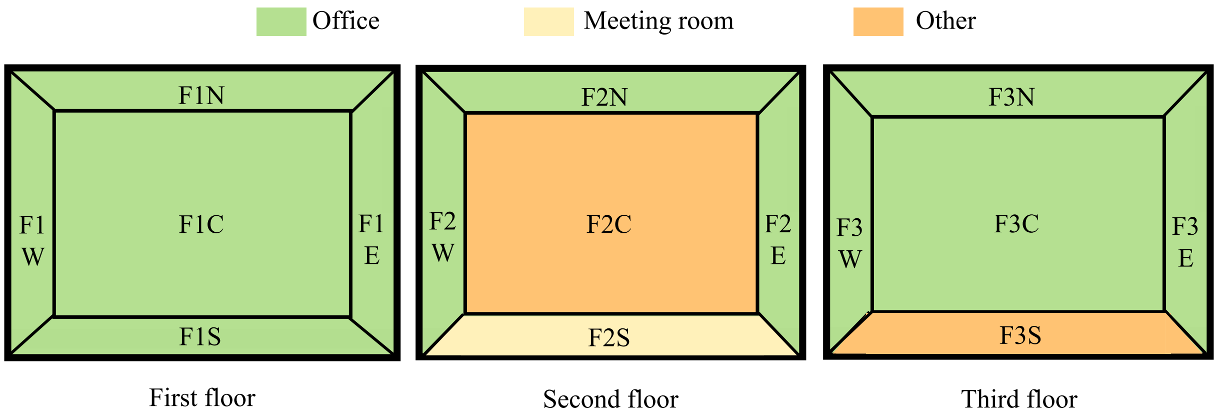


Figure 3. The redefinition of the room type of each thermal zone.

Table 3. The definition of the random movement event and status transition event.

Event Type	Space Category	Occupancy Schedule	Weekdays		Saturday	Sunday, Holiday, Other
			S1, S2, S3, M, A1	A2	S2_Sat	S3_Sun
Random movement event	Own office	Percent time presence Duration (min)	66% 90	66% 90	66% 90	55% 90
	Other office	Percent time presence Duration (min)	5% 30	5% 30	5% 30	5% 30
	Meeting room	Percent time presence Duration (min)	20% 60	20% 60	20% 60	20% 60
	Other rooms	Percent time presence Duration (min)	5% 20	5% 20	5% 20	5% 20
	Outdoor	Percent time presence Duration (min)	4% 10	4% 10	4% 10	15% 10
Status transition event	Arrival	Time	6:00–9:00	6:00–9:00	6:00–9:00	5:00–7:00
	Short-term leaving	Early occur time Typical occur time Typical duration (min) Minimum duration (min)	12:00 12:25 45 20	12:00 12:25 45 20		
	Departure	Time	16:30–18:30	22:30–23:30	11:00–20:00	17:00–19:00

Table 4. The definition of the meeting event.

Meeting Event	Day of Week	Number of Occupants per Meeting	Number of Meetings per Day	Meeting Duration (Hour)	Probability
1	Monday, Friday	2–21	2–5	0.5	0.12
				1	0.72
				1.5	0.12
				≥2	0.04
2	Tuesday, Wednesday, Thursday	2–21	3–7	0.5	0.12

2.3.3. Occupant Interaction Models

Table 5 shows the definition of three behavior styles. The normal behavior style indicates the average energy consciousness level, which refers to the deterministic occupant behavior in the DOE medium office building models. The austerity behavior style represents that the occupant actively saves energy. The wasteful behavior style means that the person did not care about energy consumption but cared about their own comfort. This study defined the occupant interaction models according to the main driving factors for their actions, divided into environmental factors (such as illuminance levels) and time-related stimuli (arrivals or departures et al.) [43]. After finishing the definition of the stochastic occupant behavior models (austerity and wasteful behavior styles), obXML was used to model the occupant behavior models.

Table 5. Occupant interaction models.

Occupant Behavior	Austerity	Normal	Wasteful
Control of lights	When people leave the room and it is empty, the lights are turned off. When people stay in the room, lights are turned off if sensed bright and turned on if sensed dark.	The standard schedule is followed.	When people leave the room for more than six hours and it is empty, the lights are turned off. The lights are always turned on during working hours.
Control of appliance	48% of the total plug loads are turned on during working hours, and 8% of the total plug loads are on standby after people leave work.	The standardschedule is followed.	100% of the total plug loads are turned on during working hours, and 61% of the total plug loads are on standby after people leave work.
Thermostat setpoint	19 °C Heating/26 °C Cooling	21 °C Heating/ 24 °C Cooling (The standard schedule is followed.)	22 °C Heating/23 °C Cooling

1. Interior lighting model

The interior lighting model implemented by the wasteful behavior style only related to the occupancy. The interior lighting model implemented by the austerity behavior style were affected by the occupancy and the work plane daylight illuminance. Sun's model [44], a three-parameter Weibull distribution, was used to describe the probability of turning on/off the lights when people stayed in the room in our austerity behavior model. The functions can be defined as Equations (1) and (2). The function shape is shown in Figure 4.

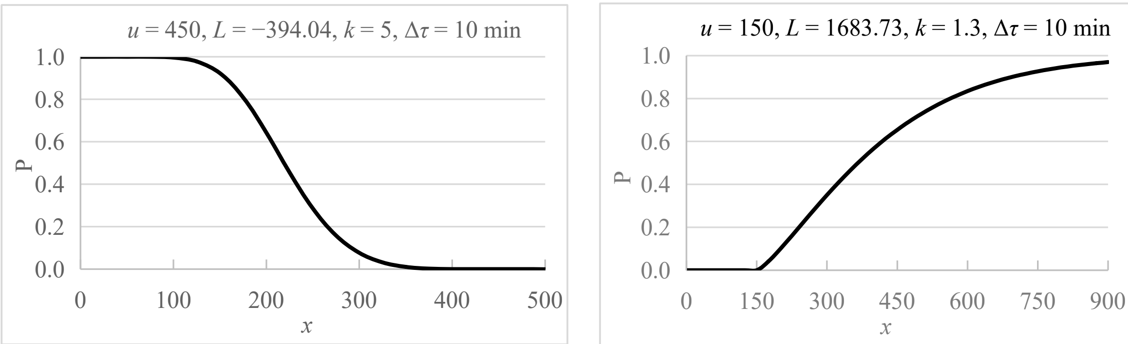
$$P = \begin{cases} 1 - e^{-\Delta\tau\left(\frac{x-u}{L}\right)^k}, & x \le u \\ 0, \ x > u \end{cases}, \ turn\ on\ when\ feeling\ dark; \tag{1}$$

$$P = \begin{cases} 1 - e^{-\Delta\tau\left(\frac{x-u}{L}\right)^k}, & x \ge u \\ 0, \ x < u \end{cases}, \ turn\ off\ when\ feeling\ bright\ enough. \tag{2}$$

where P is the probability of turning on/off the lights; $\Delta\tau$ is the time step, min; x is the work plane illumination, lux; u is the threshold for the uncomfortable domain that controls when the action will begin; L describes the range for the functional variable; and k describes the shape.

2. Interior equipment model

To define the interior equipment model for the austerity and wasteful behavior styles, this study made a measurement in a four-person office with the size of 4.2 m × 3.0 m × 3.9 m. The working hours were 9:00–17:00, and lunchtime was 12:00–13:00. Therefore, the total working time of the building was 8 h, and the total time people stayed in the building was 7 h (except for lunchtime). The on power and standby power of each type of equipment were measured separately for each behavior style, and the measurement duration was six hours. There were four computers, eight monitors (it was assumed that four monitors were used under the condition of austerity behavior style and eight monitors were used under the condition of wasteful behavior style), one water heater, and other equipment in the office. All equipment was turned on during working hours and on standby after people left work for the wasteful behavior style, and the computers were in high-performance mode. For the austerity behavior style, all equipment was turned on when people used it, on standby when people left for a short time, and turned off after they left work. The computers were on energy saving mode, and the monitors went dormant after 1 min if monitors were not used.



(**a**) (**b**)

Figure 4. The probability of turning on/off the lights. (**a**) Probability of turning on the lights; (**b**) Probability of turning off the lights.

Table 6 shows the mean power of all equipment calculated by the measurement results (see Figure 5). The equipment power density in the DOE medium office building models was 8.07 W/m^2, and the total design power was 536 W per subspace. Aside from the monitors, computers, and water heater, there were other types of equipment whose total power was assumed to be 92 W. The austerity workers would turn on 48% of the total plug loads during working hours and put 8% of the total plug loads on standby after leaving work; the 48% was calculated by Equation (3). Wasteful workers always turned on all equipment during working hours and put 61% of the total plug loads on standby after leaving work. The probability (0.9) of turning on plug loads and plug loads on standby referred to Wang's study [45].

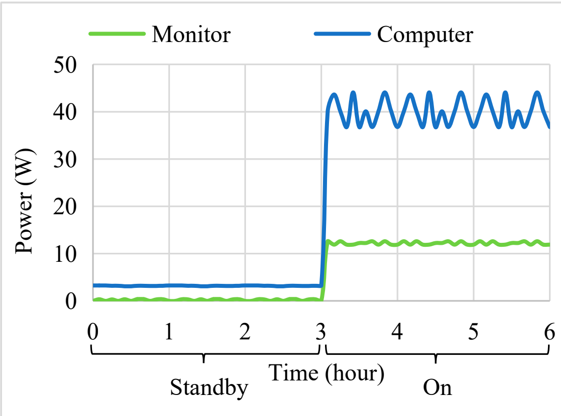
$$Percentage\ of\ turning\ on\ the\ plug\ load = (A_1B_1 + A_2B_2 + A_3B_3)/\tau \quad (3)$$

where A_1, A_2, and A_3 are the percentages of power for the austerity workers to stay in their own office, leave their own office for less than one hour, and leave their own office for more than one hour, respectively (see Table 6). B_1, B_2, and B_3 are the percentages of time for the austerity workers to stay in their own office, leave their own office for less than one hour, and leave their own office for more than one hour (including lunch event (1 h) and meeting event). The time percent that people stayed in their own office and conducted meetings was 66% and 20% (see Table 3) of the time they stayed in the building (7 h), respectively. Thus B_1, B_3, and B_2 were 4.62 h, 2.4 h, and 0.98 h, respectively. τ is the total working hours, 8 h.

Suppose the hot water consumption for each person was 1 L per day, the using power Q_w (38 W) could be calculated by Equation (4). The water heater was turned on only when people drank for the austerity behavior style. Hence, the mean power of the water heater for the austerity behavior style was 38 W, and there was no water heater line for the austerity behavior in Figure 5a. The mean power (98 W) of the water heater during working hours for the wasteful behavior style included standby power (60 W) and use power (38 W).

$$Q_w = n \cdot \frac{C_w m \Delta t}{\tau} \quad (4)$$

where n is the number of people, $n = 4$; C_w is the specific heat capacity of water, 4.2×10^3 J/(kg·°C); m is the water consumption, 1 kg; Δt is the temperature difference that water is boiled from normal temperature, 65 °C; τ is the total working hours, 8 h.



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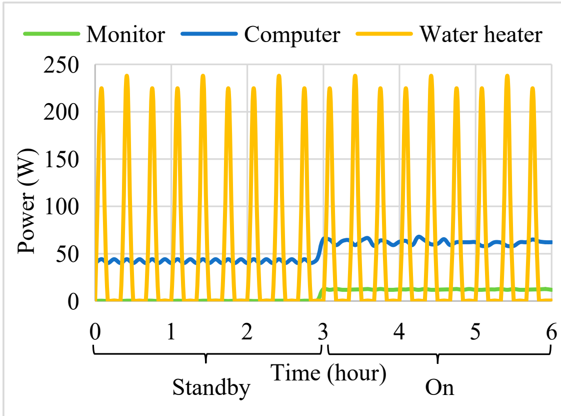


(**b**)

Figure 5. The power of each type of equipment for the austerity and wasteful behavior styles: (**a**) Austerity behavior style; (**b**) Wasteful behavior style.

Table 6. The mean power of all equipment.

Equipment Type	Austerity				Wasteful	
	Working Hours (on)	Leaving Less than 1 h (Standby)	Leaving More than 1 h (Standby)	Leaving Work (Off)	Getting off Work (Standby)	Working Hours (on)
Monitors (W)	48	0	0	0	0	96
Computers (W)	164	16	16	0	176	252
Water heater (W)	38	38	38	0	60	98
Others (W)	90	90	90	45	90	90
Total (W)	340	144	144	45	326	536
Percentage of total power	63%	27%	27%	8%	61%	100%

3. Thermostat setpoint model

The setpoints of the austerity behavior style mainly met the building energy saving requirements; thus, the temperature range was wider (a higher cooling setpoint and a lower heating setpoint), and the setpoints of the wasteful behavior style mainly met the occupant's comfort requirements. As a result, the temperature range was narrower (a lower cooling setpoint and a higher heating setpoint). As shown in Table 5, based on the heating/cooling temperature setpoint of the DOE medium office building models, the setpoint was adjusted by 2 °C for the austerity behavior style. If the setpoint was adjusted by 2 °C for the wasteful behavior style, the heating setpoint temperature (23 °C) was higher than the cooling setpoint temperature (22 °C), which was unsuitable. Therefore, the setpoint was adjusted by 1 °C for the wasteful behavior style. The temperature ranges of the austerity and the wasteful behavior in Sun's study [19] were referred to. The operation schedule of HVAC still followed the setup of the DOE medium office building models. The HVAC system was turned on from 7:00 a.m. to 10:00 p.m. on weekdays and from 7:00 a.m. to 6:00 p.m. on Saturdays. The HVAC system was turned off on Sundays and holidays.

2.4. The Development of the obXML-Generator

There were 264 occupants in the medium office building model. When establishing the stochastic occupant behavior model (such as the obXML.xml file), it was unrealistic to manually establish them one by one, as this process was time-consuming and error-prone. Therefore, this study used the Ruby language to develop a computer program, obXML-generator, that could quickly generate an obXML.xml file, as shown in Figure 6. First, based on the obXML schema (obxml_v1.4.xsd), the occupant behavior model parameters, including behaviors, holidays, meeting events, seasons, etc., were input in the "data" folder. Second, the building parameters, including basic information about each thermal zone, the building energy systems, behaviors, etc., were input into the "inputs.xlsx" file. Finally, the obXML-generator program was run to output the occupant behavior models.

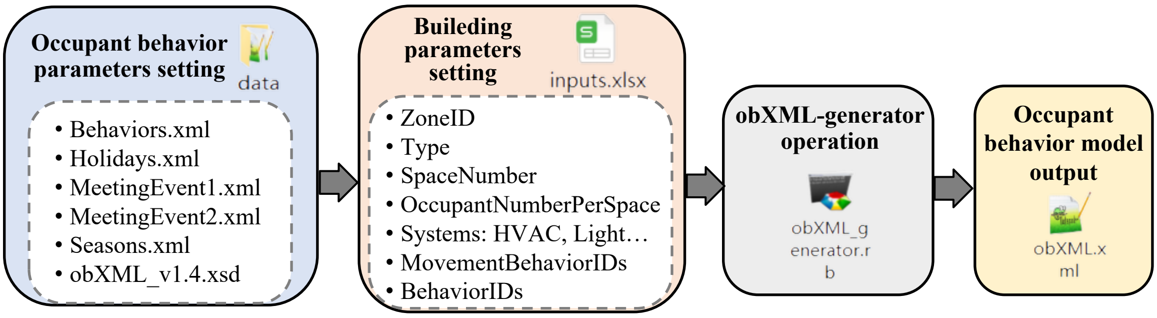


Figure 6. A guide to the use of obXML-generator.

2.5. The Co-Simulation between EnergyPlus and obFMU

After the stochastic occupant behavior models (austerity and wasteful behavior styles) were established, the co-simulation between obFMU and EnergyPlus could be run through the FMI. In Figure 7, obXML.xml and a co-simulation information file (obCoSim.xml) were used by obFMU as inputs. The building energy models, which were added to the co-simulation information, were used by EnergyPlus as inputs. EnergyPlus managed the co-simulation with the obFMU via FMI. The obFMU could simulate the occupant behaviors at each timestep based on the occupant behavior models and the environmental parameters obtained from EnergyPlus.

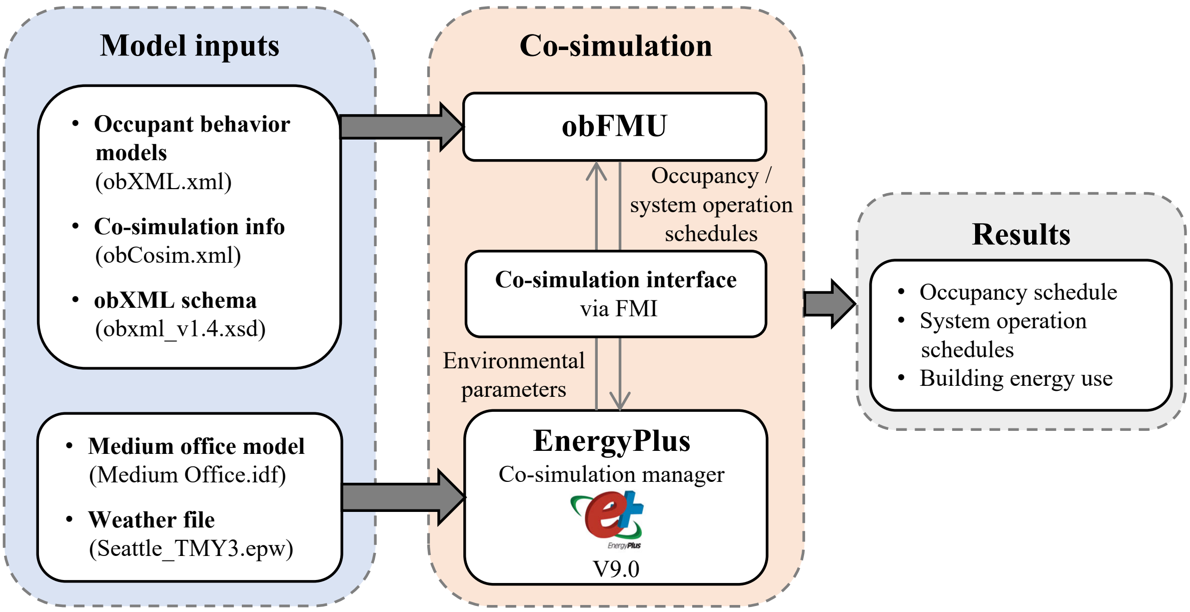


Figure 7. The data flow of the co-simulation between EnergyPlus and obFMU.

Moreover, the deterministic occupant behavior model (normal behavior style) was simulated only by EnergyPlus. The TMY3 weather data were used in the simulation. Finally, the operation schedules and building energy consumption in sixteen climate zones in the U.S. were outputted.

3. Results

3.1. Simulation Repetition

As the austerity and wasteful occupant behavior models were stochastic, the building energy consumption results of each simulation may be different. Thus, simulation repetition was required to calculate the mean value. Numerous studies showed that a repetition of ten times was adequate to determine the mean results [19,46]. There were few changes in the annual total source energy and total site energy among 20 times simulations for each occupant behavior model for the 2016 and 2019 editions across 16 climate zones. Therefore, a repetition of 20 times was adequate to determine the mean results.

3.2. Model Verification

The simulation results of a typical week for three occupant behavior models in Seattle in 2019 were analyzed. Because this study focused only on the impacts of stochastic occupant interaction behaviors on the ASHRAE 90.1 energy performance, the co-simulation model's occupancy should be consistent with that of the prototype model. Then, the energy use results of the three occupant interaction models were varied to ensure that the occupant interaction models were well-implemented.

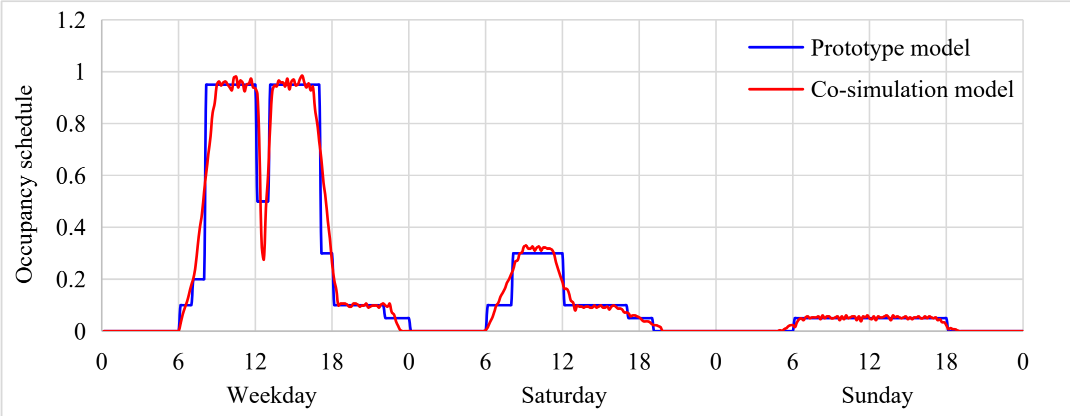
3.2.1. The Verification of the Occupant Movement Model

Figure 8 shows the occupancy of the co-simulation model and prototype model during a typical week in Seattle in 2019. In particular, the CVRMSE and the normalized mean bias error (NMBE) were used to evaluate the effectiveness of the occupant movement model. The CVRMSE (calculated using Equation (5)) measured the variation in the deviation between the co-simulation model's occupancy and the prototype model's occupancy. The NMBE (calculated using Equation (6)) measured the prediction error percentage between the co-simulation model's occupancy and the prototype model's occupancy. A smaller value of the CVRMSE indicated a smaller variation in deviations between the occupancy of two models and, consequently, a smaller prediction error. A smaller value of the NMBE (absolute value) indicated a higher prediction accuracy of the co-simulation model. According to ASHRAE Guideline 14-2014 [47], it can be considered acceptable when CVRMSE is less than or equal to 30% and NMBE is less than or equal to 10% for hourly intervals. The CVRMSE (26.51%) and NMBE (2.72%) of the occupancy of the co-simulation model at the building level were acceptable, which indicates that the occupancy of the co-simulation model was consistent with that of the prototype model at the building level (see Figure 8a), and the occupant movement model was suitable. From the comparison of the occupancy schedules in typical zones (see Figure 8b,c), unlike the occupancy schedule of the prototype model, the occupancy schedules of the co-simulation model in the two offices were different, so the defined occupant movement model could reflect the stochasticity, dynamics, and diversity of the occupancy.

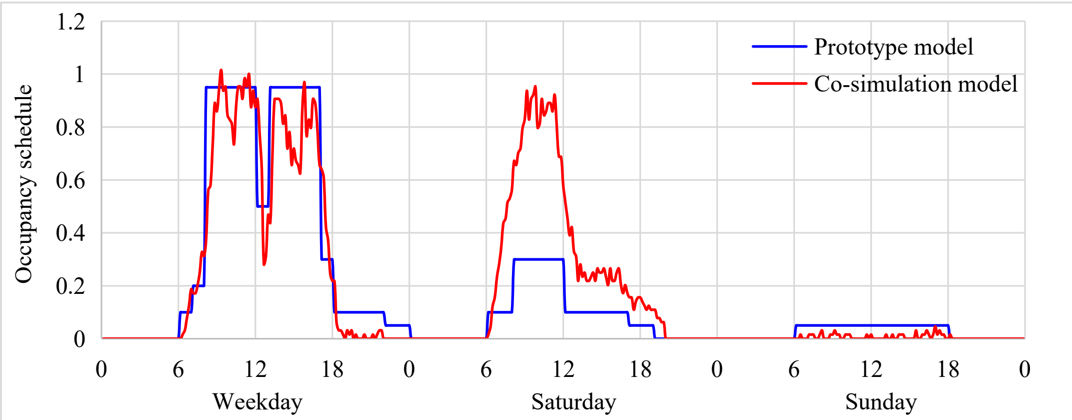
$$CVRMSE = 100 \times \frac{\left[\Sigma(y_i - \hat{y}_i)^2/(n-1)\right]^{\frac{1}{2}}}{\overline{y}} \tag{5}$$

$$NMBE = 100 \times \frac{\Sigma(y_i - \hat{y}_i)}{(n-1) \times \overline{y}} \tag{6}$$

where y_i is the hourly occupancy of the prototype model; $\overline{y}$ is the hourly occupancy average of the prototype model; $\hat{y}_i$ is the hourly occupancy of the co-simulation model; n is the total number of the data samples, which was 8760.



(**a**)



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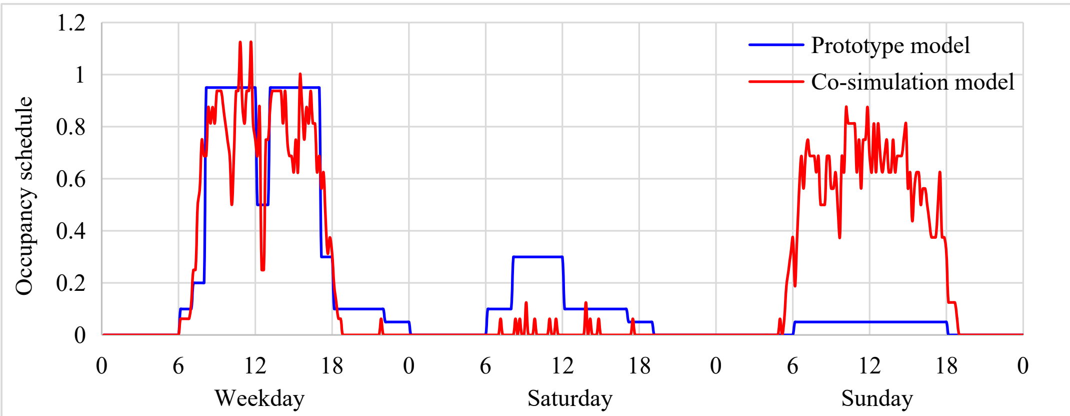


(**c**)

Figure 8. The verification of the occupant movement model: (**a**) Whole building; (**b**) F3C; (**c**) F1S.

3.2.2. The Verification of the Occupant Interaction Model

If the austerity behavior style consumes less energy use than the normal behavior style, and the normal behavior style consumes less energy use than the wasteful behavior style, the defined interaction models are suitable. The building energy use was reported after the simulation. The source energy was calculated as an indicator of the building energy consumption, including the source energy of electricity for the HVAC (heating, cooling, fans, and pumps), interior lighting, interior equipment, and the source energy of the natural gas for heating. The indicator is calculated as follows:

$$Source\ energy\ (\mathrm{GJ}) = 3.167 \times Electricity\ (\mathrm{GJ}) + 1.084 \times Natural\ gas\ (\mathrm{GJ}) \quad (7)$$

where 3.167 and 1.084 are the site-to-source energy conversion factors, referring to the standard value in the DOE commercial prototype building models. Site energy refers to the energy consumed at the building site, and source energy refers to the energy required to generate and deliver energy to the site [48].

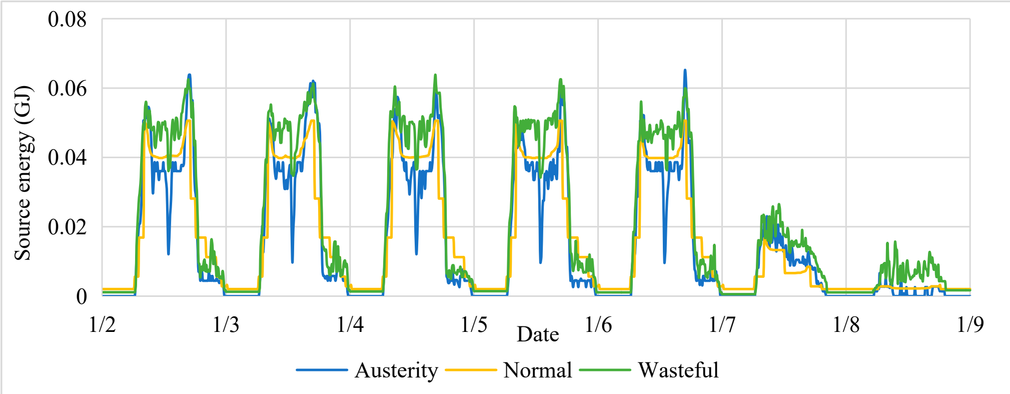
Figure 9 shows the energy use results of the three models during a week in Seattle in 2019. One may observe that the austerity behavior style consumed less energy than the normal behavior style for all energy systems. The wasteful behavior style consumed more energy than the normal behavior style for all energy systems. This indicates that the defined occupant interaction models met the requirements.

3.3. Results Analysis

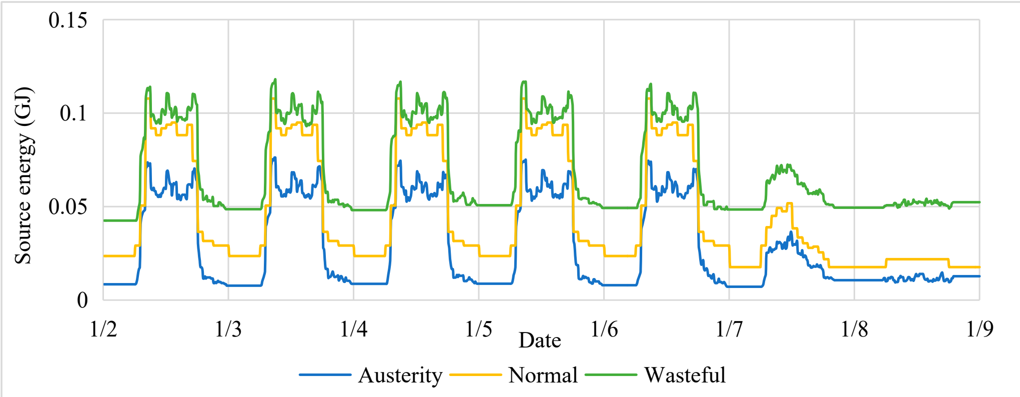
The quantitative energy saving analysis was built on the method of the weighted national annual energy use intensity (EUI) statistics, which were DOE developed to assess the energy performance of new editions of ASHRAE Standard 90.1 [48]. The weighting factors by 16 climate zones allowed for aggregation of the energy impact from each climate zone level to the national level. The construction volume for the medium office buildings in the 16 climate zones accounted for 0.21%, 0.85%, 0.29%, 0.83%, 0.72%, 0.14%, 1.16%, 0.04%, 0.19%, 1.00%, 0.35%, 0.01%, 0.21%, 0.03%, 0.02%, and 0.01% of the total construction volume for all buildings in the U.S., respectively. Therefore, the weighting factor of the medium office buildings for each climate zone can be calculated (see Tables 7–9).

Table 7. The EUI and energy savings for the normal behavior style.

Climate Zone	Weighting Factors (%)	EUI (kWh/m^2)				Energy Savings (%)	
		2016 Site	2016 Source	2019 Site	2019 Source	Site	Source
1A	3.47	108.22	335.82	103.76	321.70	4.12	4.20
2A	14.03	101.78	315.31	98.23	303.78	3.49	3.66
2B	4.79	96.75	298.88	92.84	285.92	4.04	4.34
3A	13.70	94.43	288.70	90.01	272.93	4.68	5.46
3B	11.88	90.23	275.93	87.04	264.27	3.54	4.23
3C	2.31	81.07	249.48	77.19	236.80	4.79	5.08
4A	19.14	94.59	278.71	91.46	264.89	3.31	4.96
4B	0.66	87.06	263.67	84.39	252.23	3.07	4.34
4C	3.14	81.09	243.04	78.07	229.97	3.72	5.38
5A	16.50	99.69	283.49	97.01	269.11	2.69	5.07
5B	5.78	90.74	267.15	87.81	253.73	3.23	5.02
5C	0.17	79.94	237.21	77.27	224.30	3.34	5.44
6A	3.47	112.35	309.50	108.24	291.97	3.66	5.66
6B	0.50	97.30	276.17	93.91	260.48	3.48	5.68
7	0.33	98.28	294.70	91.88	272.74	6.51	7.45
8	0.17	107.17	310.67	99.81	285.21	6.87	8.20
National average	100	96.11	287.15	92.67	273.48	3.58	4.78



(**a**)



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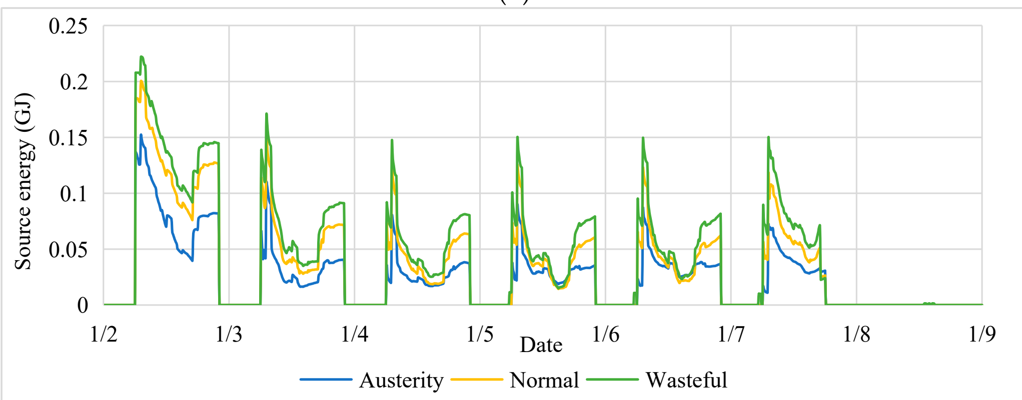

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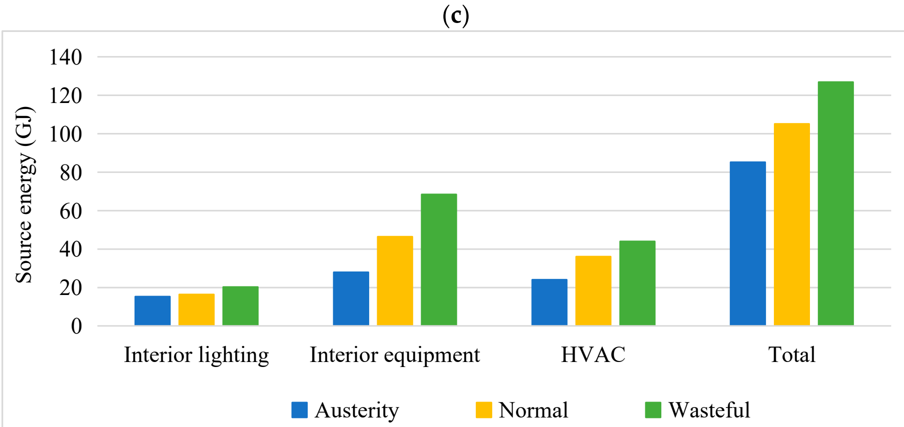


(**d**)

Figure 9. The weekly source energy for the three models in Seattle in 2019: (**a**) Interior lighting; (**b**) Interior equipment; (**c**) HVAC; (**d**) Weekly source energy.

Table 8. The EUI and energy savings for the austerity behavior style.

Climate Zone	Weighting Factors (%)	EUI (kWh/m^2)				Energy Savings (%)	
		2016 Site	2016 Source	2019 Site	2019 Source	Site	Source
1A	3.47	76.94	236.76	72.30	222.07	6.03	6.20
2A	14.03	72.45	222.12	69.43	211.65	4.17	4.71
2B	4.79	68.29	207.80	65.06	196.49	4.73	5.44
3A	13.70	68.31	202.51	65.07	190.28	4.73	6.04
3B	11.88	64.16	190.24	61.72	180.41	3.81	5.17
3C	2.31	56.13	169.49	53.03	158.53	5.53	6.47
4A	19.14	72.63	200.08	69.99	188.92	3.64	5.58
4B	0.66	63.20	181.95	61.42	173.21	2.82	4.80
4C	3.14	61.25	171.25	59.20	161.20	3.35	5.87
5A	16.50	79.01	206.97	76.36	195.02	3.35	5.78
5B	5.78	68.60	187.66	66.13	176.97	3.61	5.69
5C	0.17	61.89	168.41	60.36	159.12	2.48	5.52
6A	3.47	91.36	231.11	87.18	216.78	4.58	6.20
6B	0.50	77.11	200.45	74.11	188.47	3.88	5.98
7	0.33	76.26	217.91	70.65	199.40	7.35	8.50
8	0.17	87.59	237.82	81.28	217.96	7.21	8.35
National average	100	71.66	203.81	68.76	192.43	4.05	5.59

Table 9. The EUI and energy savings for the wasteful behavior style.

Climate Zone	Weighting Factors (%)	EUI (kWh/m^2)				Energy Savings (%)	
		2016 Site	2016 Source	2019 Site	2019 Source	Site	Source
1A	3.47	145.51	453.93	140.40	437.73	3.52	3.57
2A	14.03	137.59	428.79	133.32	415.18	3.10	3.17
2B	4.79	131.86	410.42	127.10	394.87	3.61	3.79
3A	13.70	126.36	391.61	120.47	371.69	4.66	5.09
3B	11.88	124.07	384.46	119.51	368.89	3.68	4.05
3C	2.31	114.30	354.97	109.09	338.26	4.56	4.71
4A	19.14	122.46	372.98	118.26	355.91	3.43	4.58
4B	0.66	118.87	367.11	114.74	352.03	3.47	4.11
4C	3.14	108.84	335.03	104.27	317.88	4.20	5.12
5A	16.50	125.63	374.27	121.84	356.20	3.02	4.83
5B	5.78	120.05	365.50	115.82	348.31	3.53	4.70
5C	0.17	106.85	327.77	102.49	310.61	4.08	5.24
6A	3.47	137.35	398.75	132.59	377.82	3.47	5.25
6B	0.50	123.68	367.81	119.08	347.92	3.72	5.41
7	0.33	126.17	385.43	118.20	358.90	6.31	6.88
8	0.17	132.22	394.72	123.34	364.27	6.71	7.71
National average	100	126.83	388.33	122.27	371.28	3.60	4.42

The EUI (kWh/m^2) can be calculated using Equation (8).

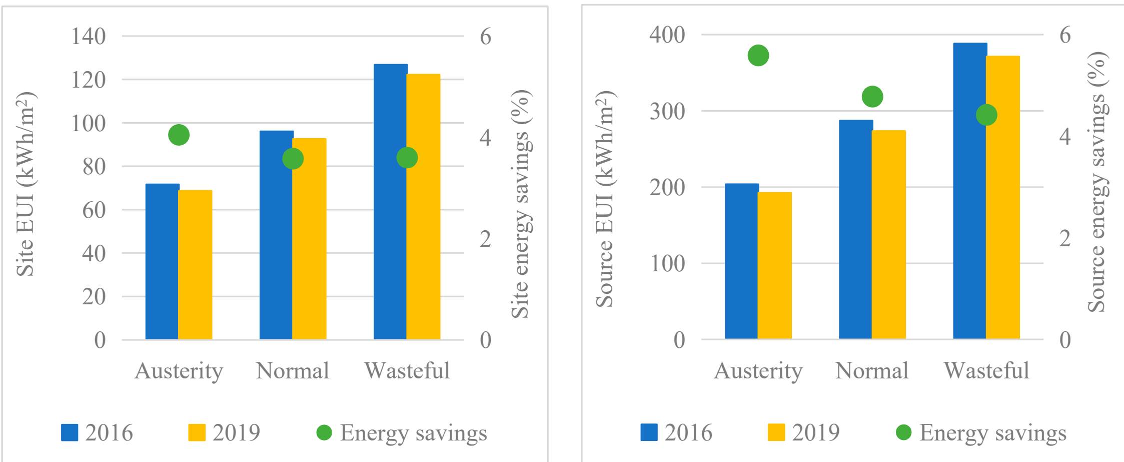
$$EUI = \frac{annual\ total\ source\ energy\ of\ building}{total\ floor\ area\ of\ building} \quad (8)$$

The energy saving percentage from upgrading the ASHRAE 90.1-2016 to 2019 is calculated in Equation (9).

$$Energy\ saving\ percentage\ (\%) = (E_1 - E_2)/E_1 \times 100\% \quad (9)$$

where E_1 is the EUI for each behavior style in 2016, kWh/m^2 and E_2 is the EUI for each behavior style in 2019, kWh/m^2.

Tables 7–9 and Figure 10 show the energy results for the three behavior styles in the 16 climate zones. The results were aggregated at a national level based on the weighting factors. The results indicated that the weighted national annual site EUI was 71.66 kWh/m^2, 96.11 kWh/m^2, and 126.83 kWh/m^2 for the austerity, normal, and wasteful behavior styles, respectively, in 2016. The weighted national annual site EUI was 68.76 kWh/m^2, , and 122.27 kWh/m^2 for the austerity, normal, and wasteful be92.67 kWh/m^{2}havior styles, respectively, in 2019. Compared to the normal behavior style, the austerity behavior style consumed 25% less site EUI, while the wasteful behavior style consumed 32% more site EUI. The weighted national annual source EUI was 203.81 kWh/m^2, 287.15 kWh/m^2, and 388.33 kWh/m^2 for the austerity, normal, and wasteful behavior styles, respectively, in 2016. The weighted national annual source EUI was 192.43 kWh/m^2, 273.48 kWh/m^2, and 371.28 kWh/m^2 for the austerity, normal, and wasteful behavior styles, respectively, in 2019. Compared to the normal behavior style, the austerity behavior style consumed 29% less source EUI, while the wasteful behavior style consumed 36% more source EUI. Compared to the normal behavior style, the site EUI and source EUI for the austerity behavior style had decreased, but the site EUI and source EUI for the wasteful behavior style had increased in each climate zone. In 2016 and 2019, the site EUI and source EUI for the wasteful behavior style were more than 1.5~2.1 times that for the austerity behavior style. From upgrading the ASHRAE 90.1-2016 to 2019, the site energy saving percentages for the austerity, normal, and wasteful behavior styles were 4.05%, 3.58%, and 3.60%, respectively. The source energy saving percentages for the austerity, normal, and wasteful behavior styles were 5.59%, 4.78%, and 4.42%, respectively. These findings show that the occupant behavior significantly impacted the building energy consumption, and their impacts on the energy savings analysis of upgrading ASHRAE 90.1 were also not negligible. Although the impacts of the stochastic occupant behaviors on the energy savings of DOE medium office models were slight, it will also be conducive to the energy conservation of high energy-consuming buildings to a certain extent.



(**a**) (**b**)

Figure 10. The national EUI and energy savings for the three occupant behavior styles: (**a**) Site EUI and energy savings; (**b**) Source EUI and energy savings.

4. Discussion

This study evaluated the impacts of stochastic occupant behaviors on the building energy performance from upgrading the ASHRAE 90.1-2016 to 2019. The novelty of the proposed methodology included two aspects. (1) The obFMU was updated to allow each thermal zone in the DOE medium office to be split into some subspaces by users. Users could also redefine the room type and the number of people in each room to achieve independent control of the lighting and equipment systems. (2) This study used the

Ruby language to develop a computer program, obXML-generator, that could quickly and accurately generate an occupant behavior model (obXML.xml file) based on the behavior and building parameter inputs. There are several aspects worth discussing or improving:

1. This study focused on the impacts of stochastic occupant behaviors on building energy performance. The stochastic occupant behavior models (austerity, normal, and wasteful) were defined, and the impacts of each occupant behavior model on the building energy performance were analyzed. However, there are many important parameters that significantly impact the building energy performance, such as the air infiltrations [49], the coefficient of performance (COP) of the VAV direct expansion (DX) cooling coil, and the conductance and the solar heat gain coefficient (SHGC) of windows [50], and so on. Many of these parameters were well-considered in the existing prototype building models in sixteen climate zones in the U.S. and thus were not discussed in this study. Table 10 presents the design parameters of the DOE medium office building models in Seattle for different editions of ASHRAE 90.1.
2. Occupancy and their behaviors all had significant impacts on the building energy consumption. However, it is very difficult to define the low-occupancy and high-occupancy cases, as it will bring more questions than the problem solved. Thus, this study focused only on the impacts of different occupant interaction behaviors with the stochastic and same occupancy.
3. This study only considered the occupant activities in the building operation stage. More comprehensive factors such as socio-economic characteristics, geographical location, subjective values, individual and collective adaptive action, and the optimization control of building energy systems [51] are needed to be integrated into occupant behavior models; therefore, more representative, synthetic occupants [52,53] can be generated.
4. This study only divided each thermal zone into four-person rooms to improve the DOE medium office building models. A field survey of room types in office buildings will be conducted to add more room types in the future study. Moreover, ORNL's building models have significant meaning in defining the space type of the DOE building models and occupant behavior models. We will refine our study if the ORNL's building models replace the DOE's.
5. The five zones in each floor in the DOE medium office building models were served by an air conditioner system. These zones, therefore, were defined as open-plan office spaces in this study. The HVAC systems were kept running during office hours all year round, so this study did not consider the HVAC zonal on/off control and window zonal open/close behaviors. Private offices will be considered in the prototype building models, and the occupant behavior models will be improved in the next work.
6. The use of shade systems can impact the use of artificial lighting, thus affecting the building energy consumption [54,55]. The shading control behaviors in the open-plan offices were more complex than in the private offices. There were more manually-operated shade behavior models that could be referred to in private offices than in open-plan offices [55–57]. Therefore, this study did not consider the stochastic shading control behaviors. We are collecting parameters such as the work plane illumination and occupancy schedule in the office buildings through measurement and expect to construct shade control behavior models in the future.

Table 10. Some of the design parameters of the DOE medium office building models in Seattle.

Building Design Parameters	90.1-2004	90.1-2010	90.1-2016	90.1-2019
Air infiltration flow per exterior surface area ($m^3/s)/m^2$	0.001024	0.000569	0.000569	0.000569
VAV DX cooling coil COP	3.23	3.40	3.40	3.40
Windows SHGC	0.39	0.40	0.36	0.36
Windows conductance ($W/m^2 \cdot K$)	3.24	2.90	2.16	2.05

5. Conclusions

This study evaluated the impacts of stochastic occupant behavior on building energy consumption and the energy savings analysis from upgrading the ASHRAE 90.1-2016 to 2019 in sixteen climate zones in the U.S. Three occupant behavior styles (austerity, normal, and wasteful) were defined to represent the different levels of energy consciousness of occupants regarding their interactions with the building energy systems (lighting, equipment, and heating/cooling setpoint). The DOE medium office prototype models for the 2016 and 2019 editions, where occupant behavior inputs were deterministic, were used as the baseline (with normal behavior style). The obFMU was used to model the stochastic occupant behaviors, including movement and two interaction behavior styles (austerity and wasteful). Then, the DOE medium office prototype models were modified to co-simulate with the obFMU models. Next, the impacts of the occupant behaviors on the building energy performance were analyzed. The main conclusions from this study were as follows:

1. The occupancy of the co-simulation model (with stochastic occupant movement behavior) was consistent with that of the DOE prototype model (with deterministic occupant movement behavior) at the building level.
2. The stochastic occupant behavior significantly impacted the building energy use. Compared with the normal behavior style in 2016 and 2019, the austerity behavior style consumed 25% less site energy and 29% less source energy, while the wasteful behavior style consumed 32% more site energy and 36% more source energy.
3. The impacts of the stochastic occupant behaviors on the energy savings from upgrading ASHRAE 90.1 were also not negligible. The different occupant behavior styles had different impacts on the ASHRAE 90.1 energy savings. From upgrading the ASHRAE 90.1-2016 to 2019, the source energy savings were 5.59%, 4.78%, and 4.42% for the austerity, normal, and wasteful behavior styles. Although the impacts of the stochastic occupant behaviors on the energy savings of the DOE medium office models were slight, it will also be conducive to the energy conservation of high energy-consuming buildings to a certain extent. In summary, it is necessary to consider the diversity, stochasticity, and dynamics of occupant behavior when updating the building energy efficiency standards.

This study also recommends some future work: (1) extending the study to other building types such as residential buildings and large office buildings; (2) evaluating the combined effect of stochastic occupancy and their behaviors on building energy performance; and (3) collecting data such as HVAC energy consumption, occupancy, and indoor and outdoor air temperature through large scale measurements to develop more open and realistic occupant behavior models.

Author Contributions: Data curation, Y.H. and Z.D.; Investigation, Z.C. and Y.Y.; Methodology, Z.D.; Project administration, Y.Y.; Resources, Z.C.; Software, Y.C. and Y.Y.; Supervision, Yixing Chen; Writing—original draft, Y.H.; Writing—review & editing, Y.C. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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