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Quantification of building energy performance uncertainty associated with building occupants and operators

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ABSTRACT

Occupants play an important role in building energy performance, while building operators are the other side of the coin. This research quantifies the relative impact of probabilistic versus standard occupant models on building energy use. Energy performance of a high-performance reference small office building in Ottawa, Canada, is investigated using a simulation-based analysis. The impact of building users is studied by systematically altering occupant and operator-related domains, including occupants' presence and use of lights, window shades, operable windows, plug-in appliances, and thermostats. The results showed that the predicted natural gas energy use increased by a factor of about two compared to the reference occupant models. The predicted electricity energy use decreased about 49% compared to the reference occupant models. This deviation for the gas use resulted from modeling all six domains and for the electricity use resulted from simulating all six domains except for the window shade and operable window use using probabilistic models and operators' adjusted thermostat setpoints with the air handling unit scheduling to be on all day. The maximum deviation of the predicted electricity energy use with occupants' adjusted thermostat setpoints caused by the simultaneous probabilistic modeling of the four domains of occupants' presence and use of lighting, plug-in appliances, and thermostat. The lighting use domain showed the highest main effect on the energy use. The findings of the examination of occupant and operator-related modeling assumptions emphasizes the necessity to consider both operators' and occupants' impact on the predicted energy performance of the small building-scale model.

KEYWORDS
Building occupants and operators; Uncertainty; Building energy performance; Simulation-based analysis; Probabilistic models.

INTRODUCTION

Building engineers are required to design buildings that comply with building standards in the design phase of new constructions. However, constructed buildings which were designed to be energy-efficient may not meet building engineers' expectations due to the uncertainties associated with the predicted energy performance in a simulation-aided design process (Macdonald and Clarke, 2007). One of the widely-recognized sources of uncertainty in the predicted energy performance of buildings is how buildings are used in reality (Menezes et al., 2012; de Wilde, 2014). Occupants are perceived as the main users of buildings; however, operators are the hidden users who may divert real energy performance of buildings from what were expected. Consequently, the degree of uncertainty associated with buildings' operators may rival the uncertainty caused by buildings' occupants. The great degree of uncertainty from buildings' users on building energy performance and the corresponding importance of improving modeling practice have been repeatedly emphasized by the occupant behavior research community. For instance, Clevenger and Haymaker (2006) quantified

occupants' impact on the energy use of two typical buildings in the USA by changing different ranges for the occupant-related schedules, loads, and densities, individually and in a combination of all the considered occupant behaviours. Similarly, Hopfe and Hensen (2011) performed an uncertainty analysis of various occupant-related loads and densities. In contrast to Clevenger and Haymaker's (2006) approach of implementing discrete ranges, Hopfe and Hensen (2011) used the Monte Carlo analysis within a continuous distribution of the considered parameters (Macdonald, 2002). Furthermore, Hong and Lin (2013) incorporated a similar approach to Clevenger and Haymaker's (2006) study and compared the energy use of a typical office room for the two extreme ranges of using energy to a standard energy usage. While the aforementioned studies evaluated the impact of different building users' behaviours on the energy use of a room or building-scale model, there is still the gap in the literature with respect to the relative impact of occupants and operators on the energy use of buildings.

To address this gap, the current research performed an assessment of uncertainty associated with occupants and operators on the annual energy use of a building-scale model. The main objective of this paper is to quantify the relative impact of buildings' occupants and operators on the energy performance of buildings. Occupant and operator-related domains which were studied in this paper include: occupants' presence and use of lights, window shades, operable windows, plug-in appliances, and thermostats. Probabilistic models for each of these domains were applied systematically one at a time as well as with different numbers of domain combinations to quantify the impact of each domain and differently sized groups of domains with two sets of air handling unit (AHU) schedules and two thermostat adjustment models. The main research questions of the current study are: (1) What is the relative effect of different occupant and operator-related domains on the energy performance of buildings? (2) Among the considered domains in the current research, which domain causes the highest main effect on the energy use? (3) Relevant to the previous question, the interaction of which domains causes the highest effect on the energy use?

METHODOLOGY
This section describes the building model, occupant and operator models which were implemented in simulation, and the simulation process.

Building model description
The office building was modeled in SketchUp and OpenStudio on the basis of ANSI/ASHRAE/USGBC/IES Standard 189.1 (2014) for a high-performance small office building in climate zone 6A (Figure 1). Thermal energy demand of each office was delivered by independently controlled variable air volume boxes with reheat coil. Independently controlled hot water baseboard heaters delivered supplementary heating to each office. Each perimeter office had an operable window with the opening area of 0.1 m^2. The heating demand of the simulated model, which was located in a heating-dominated climate, was delivered by a gas boiler.
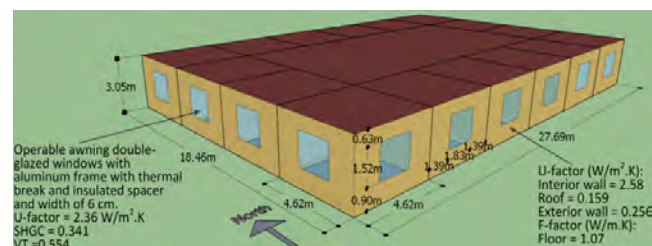

Figure 1. Geometry and envelope specifications of the office building model.

Occupant and operator models

A one-storey office building model was simulated in this study. The building consisted of one core open-plan office and 16 perimeter private offices. Standard schedule-based and probabilistic occupant models were incorporated in simulation (Table 1). Probabilistic models were implemented in the EMS application of EnergyPlus. The case study building was assumed vacant on weekends. Lights were assumed to be turned off automatically with 30-minute time delay after occupants left their offices. A daylight sensor to serve as an input to the occupant's manual light and shade adjustments was located at a height of 0.8 m in the center of each perimeter office. For the corner offices, it was assumed that once occupants took action to use operable windows and/or shades, they adjusted both operable windows and/or shades.

To perform a relative comparison between occupants and operators' impact, based on an informal study of numerous Canadian commercial buildings energy audits, two AHU modes were implemented to represent one major aspect of operator behavior: (1) always on, and (2) from 6am to 6pm on. To investigate the operators and occupants' impact, two thermostat adjustment models were implemented: (1) occupant agent, and (2) operator agent. Heating and cooling setpoints were set 21 and 24ºC from 6am to midnight and were set back to 15.6 and 26.7ºC the rest of the day. This setpoint adjustment was set when Gunay et al.'s (2018) model of occupant-agent thermostat adjustment was implemented. Heating and cooling setpoints were set to 21 and 24ºC at the beginning of each annual run time for when Gunay et al.'s (2018) model of operator-agent thermostat adjustment was implemented. This thermostat setpoint setting follows Gunay et al.'s (2018) study, as once an operator changed thermostat setpoints, changes were kept fixed unless occupants requested another adjustment. The upper cooling setpoint was confined to 30ºC. It was assumed that operators only adjusted thermostats between 7am and 4pm.

Table 1. Occupant and operator models.

Domain	Models		
	Probabilistic models		Standard-based schedule
	Private offices	Open-plan office	
Occupancy	Page et al.'s (2008) occupancy algorithm	O'Brien et al.'s (2018) model	ANSI/ASHRAE/USGBC/IES Standard 189.1 (2014)
Lighting use	Reinhart's (2004) light switch-on model		
Window shade use	Haldi et al.'s (2016) model	-	Always open
Operable window use	Haldi and Robinson's (2009) model	-	Always closed
Electric equipment use	Gunay et al.'s (2016) model	O'Brien et al.'s model (2018)	
Thermostat adjustment	Gunay et al.'s (2018) model of occupant or operator thermostat adjustment	Gunay et al.'s (2018) model of operator thermostat adjustment	ANSI/ASHRAE/USGBC/IES Standard 189.1 (2014)

Simulation

The timestep was set as five minutes. To quantify the impact of the occupant and operator-related domains, probabilistic models for each domain were used: (1) one at a time, and (2) different numbers of domain combinations. The domain(s) that was (were) not chosen to be simulated using the probabilistic model, was (were) simulated using the standard-based schedules. The results of a study involving 100 annual simulations showed that 20 annual

simulation runs was adequate that the difference between the minimum and maximum standard deviation to the average gas and electricity energy use fell below 10%. Since incorporating probabilistic occupant models for all the domains resulted in the highest uncertainty compared to when all the domains are not simulated using the probabilistic models, the required simulations for each domain combination was determined as 20.

RESULTS AND DISCUSSION
The reference small office building using the default occupant and operator-related values (i.e. base case) was simulated for one annual run period. The energy performance of the simulated building model was compared to the reference occupant models based on two performance measures: (1) total natural gas use for heating demands, and (2) total electricity use for cooling demands, lights, electric equipment, the fan, and pumps. To present results in this section, occupants' presence and use of lights, blinds, operable windows, plug-in appliances, and thermostats are hereafter referred to as: "O", "L", "B", "W", "P", and "T".

Figure 2 shows the results of implementing probabilistic models for the considered domain(s) on the energy use. Note that occupants' thermostat adjustment model was implemented in these cases. This figure shows that, generally, the interaction between a larger numbers of domains which were simulated using probabilistic models caused the predicted energy use to deviate from the base case more than those using probabilistic models for only a portion of the considered domains. The maximum effect on the electricity use was when the probabilistic models for the domains of occupants' presence and use of lights and plug-in appliances were incorporated in simulation. Figure 2 indicates that generally, AHU mode 1 caused higher deviation of the predicted natural gas energy use from the base case (with AHU mode 1) compared to AHU mode 2, while AHU mode 2 caused higher deviation of the predicted electricity energy use from the base case (with AHU mode 1). For example, the gas energy use increased by 70% with AHU mode 1, while it increased by 41% with AHU mode 2 when all considered domains were simulated using probabilistic models. On the other hand, the electricity energy use decreased by 40% with AHU mode 1, while it decreased by 52% with AHU mode 2 when all considered domains were simulated using probabilistic models.
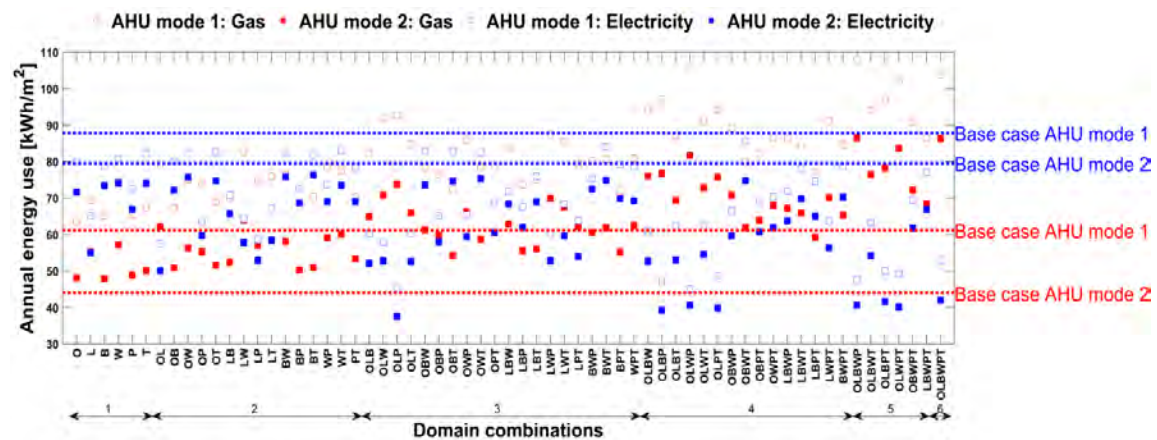

Figure 2. Comparing impact of various domain combinations with two AHU schedules.

Figure 3 compares the energy use when operators or occupants adjusted thermostat setpoints. This figure shows that adjustment of temperature setpoint by operators resulted in higher deviations in the predicted energy use from the base case compared to when occupants adjusted thermostat setpoints. Figure 3 indicates that generally the maximum deviation of the predicted electricity energy use from the base case was when occupants' presence and use of

lights, plug-in appliances, and thermostat adjustment were implemented. The three most influential domains whose modeling assumptions significantly affected the natural gas energy use were lighting, operable windows, and thermostat adjustment.
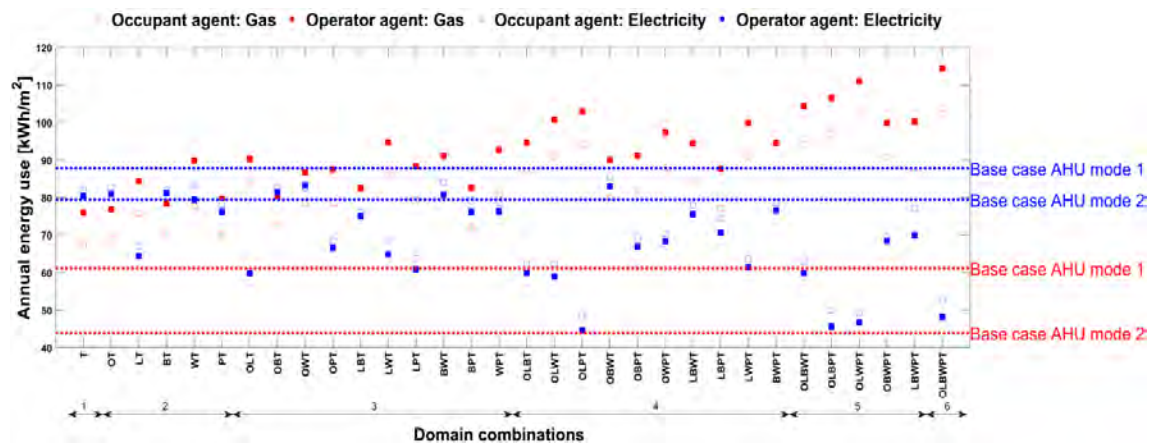

Figure 3. Comparing impact of various domain combinations with two models for thermostat adjustment and AHU mode 1.

To quantify the impact of simulating each domain using the corresponding probabilistic model on the energy use, the main effect of simulating each domain using the probabilistic model was investigated (Figure 4). To this end, the average and standard deviation of the energy use of all the possible domain combinations with either AHU mode 1 or 2 (see Figure 2) were calculated when each of the six domains was simulated using: (1) standard-based schedule, and (2) probabilistic model, whereas all the other domains were simulated using either standard-based schedules or probabilistic models. Figure 4 indicates that modeling assumptions of all the six domains had a main effect on the predicted energy use. Among the considered domains, lights had the highest effect on the total energy use. Blinds and operable windows had the lowest impact on the gas and electricity energy use, respectively. Additionally, Figure 4 shows the main effect of the two considered AHU modes. The results indicate that the AHU mode had a main effect on the energy use.
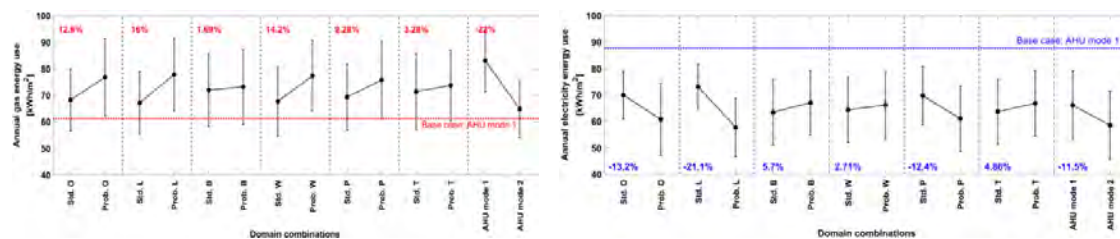

Figure 4. Comparing main effect of each domain using standard-based schedule ("Std.") and probabilistic model ("Prob.") and AHU modes.

CONCLUSION AND FUTURE WORK
The findings of this research showed that modeling assumptions of occupants' use of lights had the highest main effect on the total energy use. In general, the larger the number of the occupant and operator-related domains whose modeling assumptions were altered, the larger the impact of the interaction between the domains. The maximum deviation of the predicted electricity use resulted from the simultaneous probabilistic modeling of occupants' presence and use of lights and plug-in appliances. This study indicated that considering operators' role in building energy performance is imperative. This research was focused on a building-scale

model in a heating-dominated climate zone. The relationship between the current results and different climates is necessary future work.

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