Simulating the Impact of Occupants on Office Building Design: A Case Study

Tareq Abuimara¹, Burak Gunay¹, William O'Brien¹

¹ Carleton University, Ottawa, Canada

Abstract

Emerging evidence suggests that occupants play a significant role and contribute uncertainty to building energy performance, yet they are modelled using simple schedules that may not reflect reality. This paper examines the impact of occupant-related assumptions on the building simulation-based design process. Thirteen variants of the model of a real office building model were generated representing 13 occupant scenarios. Each occupant scenario was simulated with 32 different design alternatives. The design alternatives were ranked based on their energy performance. The results indicate that the ranking of about one-third of the 32 design features is significantly affected by occupant-related assumptions. The design decisions regarding window materials and ventilation mode are the most sensitive to occupant-related assumptions.

Introduction

The use of building performance simulation (BPS) is increasingly fundamental for the building design process to predict the performance (Attia, Gratia, De Herde, & Hensen, 2012; Attia, Hensen, Beltrán, & De Herde, 2012). BPS is used for a number of purposes such as code compliance, building certification (e.g., LEED), net-zero or high performing building design, measurement and validation and sometimes for HVAC design (Ouf, O'Brien, & Gunay, 2018). However, uncertainty is a major challenge facing the BPS-aided building design process. Occupants are recognized as a major source of uncertainty due to their random and diverse nature (Gaetani, Hoes, & Hensen, 2016; Hoes, Hensen, Loomans, De Vries, & Bourgeois, 2009). Occupants are active agents who interact with building components and influence energy use in buildings. They can increase energy use in some cases by a factor of two or even more (Haldi & Robinson, 2011). Occupant behaviour can cause a significant gap between the actual and the simulated performance (de Wilde, 2014).

Therefore, studying occupant behaviour has garnered a surge of attention by researchers over the last few decades (IEA-EBC, 2014, 2018). Many efforts have been dedicated to study occupancy and occupant interactions with different building components such as lights, windows, blinds and thermostats. Statistical models were developed based on the data collected through sensors located in buildings. These models are

designed to predict occupants' actions based on specified predictors. For example, using the occupancy state and the availability of daylight to predict the likelihood of switching the lights on/off (Gunay, O'Brien, & Beausoleil-Morrison, 2013; Reinhart, 2004).

In general, practitioners in the architecture, engineering and construction (AEC) industry tend to follow the occupancy, lighting, and plug loads-related densities (e.g., number of people per m², lighting power per m²) and schedules prescribed in building energy codes and standards (O'Brien et al., 2016). The schedules are diversity factors which account for the steady-periodic variations in occupancy, lighting, and plug loads during the week by multiplying the densities with values between zero and one. Building energy codes and standards, such as ASHRAE Standard 90.1, treat occupants as passive recipient of the indoor conditions and not as an active agents who interact with building components and systems (Ouf & O'Brien, 2018). Hence, this method of modelling occupants is recognized even by practitioners as an outdated and incomprehensive, and can lead to inaccurate predictions and design decisions (Gilani, O'Brien, Gunay, & Carrizo, 2016). Although the inaccuracy of the current method is widely recognized, the AEC industry is yet to uptake the results of research into practice due to a number of reasons. First and foremost, the industry is hesitant to adopt approaches that are not required by the codes. In addition, practitioners often have limited time and budget allocation for a given project which does not always allow for detailed modelling of occupants. Further, some practitioners are still uncertain about how sensitive the design process to the occupant-related assumptions (Abuimara et al., 2018; O'Brien et al., 2018; Ouf et al., 2018).

To this end, this paper aims at demonstrating the potential implications of occupant-related assumptions during the design process through a BPS-based investigation conducted on a real case study building. The sensitivity of design parameters to occupant-related assumptions during the design process is studied. This paper first presents a description of the office building case study. Second, a description of the modelling and simulation tools is provided. Third, occupant-related assumptions and design parameters considered in the investigation are listed. Then, the simulation workflow

and the results are presented. Finally, the results are discussed, and future work recommendations are developed.

Methods

This section describes the methods followed to conduct the BPS-based investigation of the case study. The case study model, the modelling tools, the occupant related assumptions, the design parameters and the simulation workflow are described. The proposed methodology relies on the sensitivity of energy use intensity (EUI) reductions to the occupant-related assumptions. We did not consider the sensitivity of EUI savings to other sources of uncertainty, as this was outside the scope of this paper.

The case study model

An office building in Toronto, Canada which is currently under construction was chosen to be the base model for the investigation. The building comprises of two floors of underground parking, a floor of retail space, and four floors of office space. For simplicity, one of the of the four office levels was modelled for the simulation-based investigation. Each office level has a floor area of 1728 m² (see Figure 1). Table 1 provides an overview of the case study envelope and systems – as extracted from the engineering drawings and design specifications.

Simulation tools

The simulation-based investigation was conducted by using several modelling software. EnergyPlus 8.9.0 was used for the whole building simulation. The building geometry was created using SketchUp Make 2017, while OpenStudio 2.5.0 was used to configure the HVAC systems. MATLAB 2017a was used to automate the simulations.

Figure 1: Office building typical floor.

Occupant-related assumptions

Thirteen (13) occupant-related assumptions were made to create a wide variety of scenarios for the simulation runs. The occupant related-assumptions include alternative schedules (occupancy, lights, equipment), temperature setpoints, equipment loads, and window blinds use scenarios. Table 2 presents an overview of these occupant-related assumptions. The assumptions included alternative people, lighting, and plug-in equipment schedules. It also included alternative people densities and plug-in equipment densities. The major difference between these assumptions is that densities are used by the software to size the HVAC equipment in the sizing run. While changes in schedules influence only the operational energy uses.

Design parameters

To generate design alternatives, several design parameters were applied to the model for each occupant scenario. The design parameters included envelope-related parameters (e.g. wall insulation) and HVAC system-related parameters (e.g. boiler efficiency, cooling COP). Further, some of these parameters were early design parameters such as window to wall ratio (WWR), whereas some others were design development parameters such as the solar heat gain coefficient (SHGC) of the windows. Table 3 provides a list of the design parameters used in this study.

Table 1: An overview of the energy model of the original design.

Category	Item	Specification
Floor area	Floor	1728 m ²
Envelope	Walls	RSI= 4.6 K·m ² /W
	Roof	RSI = 5.3 K·m ² /W
	Glazing	USI = 1.9 W/m ² K, SHGC = 0.33
	Window to wall ratio (WWR)	Gross WWR = 46.5% (South = 85%, North = 12%, East = 41%, West = 41%)
	Air leakage	0.19 ach @ 5 Pa
HVAC	Packaged roof top unit	Underfloor air distribution and zone reheat coils
	Airside heat recovery effectiveness	85% sensible, 70% latent
	Space heating	Hydronic baseboard, reheat coils at zone level
	Economizer	Enabled (controlled by differential enthalpy)
	Ventilation rate	0.54 L/s.m ²
Boilers	Heating efficiency (natural gas)	90%
	DHW boiler efficiency (natural gas)	90%

Internal loads	Plug-in equipment power density	9.9 W/m ²
	Lighting power density	3.9 W/m ²

The simulation workflow

The design parameters provided in Table 3 were applied to the models of the thirteen occupant scenarios (original design + 12 occupant scenarios). 32 design alternatives were generated for each occupant scenario and

simulated. Thereafter, the rank lists were created for each base model's alternatives. Finally, the rank lists were compared against the original design rank list. Figure 2 shows a summary of the simulation set-up and workflow.

Table 2: Occupant-related assumptions.

No.	Type of assumptions	Values of assumptions
1.	Schedules (people, lights, equipment)	Multipliers 0.4, 0.6, 0.8, 1.0 (original design), 1.2
2.	Plug-in loads	9.9 (original design), 14.8, 7.4 W/m ²
3.	Number of people	20.0 m ² /person (default), 13.3 m ² /person, 40.0 m ² /person
4.	Setpoint / Setback	Original design (cooling 24°C / 32°C, heating 15.6°C / 22°C) Option 1 (cooling 22°C / 26.7°C, heating 22°C / 15.6°C) Option 2 (cooling 22°C, heating 22°C)
5.	Blind use	Default (always open), always closed, solar radiation-triggered control

Table 3: Design parameters.

Design Parameters	Base model value	Alternatives		
South window to wall ratio (WWR)	85%	30%	50%	70%
Window properties - U-factor - Solar heat gain coefficient (SHGC)	U = 1.90 W/m ² K, SHGC = 0.33	U = 1.47 W/m ² K, SHGC = 0.25	U = 2.04 W/m ² K, SHGC = 0.58	U = 1.62 W/m ² K, SHGC = 0.39
Exterior window overhang	NA	Projection factor: South = 0.7 (2.5 m deep) West = 0.85 (2.5 m deep)		
Window shading: Blinds Blind properties	*Blinds open Reflectance = 0.7 Emissivity = 0.9	Reflectance = 0.55 Emissivity = 0.9	Reflectance = 0.5 Emissivity = 0.55	
Wall insulation	RSI = 3.1 m ² ·K/W	RSI = 4 m ² ·K/W	RSI = 5 m ² ·K/W	RSI = 7 m ² ·K/W
Roof insulation	RSI = 5.3 m ² ·K/W	RSI = 7 m ² ·K/W	RSI = 9 m ² ·K/W	RSI = 11 m ² ·K/W
Air infiltration	0.19 ach	0.15 ach	0.2 ach	0.25 ach
Demand controlled ventilation	Disabled	Enabled		
COP	3.5	4	5	
Boiler efficiency	0.9	0.85	0.95	
Energy recovery ventilator (ERV) effectiveness	At 100% = 0.85 At 75% = 0.70	At 100% = 0.88 At 75% = 0.78	At 100% = 0.80 At 75% = 0.70	At 100% = 0.75 At 75% = 0.65
Pump motor efficiency	0.9	0.95		
Light power density	3.9 W/m ²	5.8 W/m ²	7.8 W/m ²

Figure 2: The simulation-based investigation workflow.

Results

The results of simulating the design alternatives of the 13 occupant scenarios (12 + the base case) are shown in Figure 3 and Figure 4. The results of the design alternatives that did not demonstrate sensitivity to occupant scenarios and did not achieve energy savings were excluded for the ease of interpretation.

The results in Figure 3.a and Figure 4 show clearly the changes happening in saving potentials and design alternatives ranking. For instance, the demand-controlled ventilation (DCV) became more effective with lower occupancy (0.4 schedules) – generating a greater energy savings potential. In contrast, the DCV became less effective when the building is over-occupied (1.2 schedules). The way the DCV functions allows the supply of ventilation based on the number of occupants. In other words, the more occupancy was associated with more ventilation and subsequently an increase of energy use (Lawrence, 2004). Another example is the design alternatives with higher SHGC. Windows with higher SHGC had more impact with lower occupancy rates (i.e. 0.4 and 0.6 schedules). The increase in solar heat gains helped compensate the decreased internal heat gains from occupants, lights and plug-in equipment.

The results for the two scenarios of the indoor temperature setpoints and overnight setback are shown in Figure 3.b and Figure 4. The results showed that the cooling COP became more effective as a design parameter as the associated alternatives improved in ranking. The increased demand on cooling to meet the lower setpoint and setback required an upgraded cooling system that can meet the additional loads efficiently. In addition, the improved envelope properties (window U-factor, SHGC, and wall RSI) increased in significance because it minimized heat gains and losses through the building envelope and assisted maintain the setpoints. In contrast, the boiler less efficient in saving energy as result of the increased heating setpoint. Besides, DCV is less influential as the HVAC system needs to operate for

longer times to deliver the ventilation rates required to maintain the new setpoints. The results of the second setpoint scenario, in which a constant setpoint (22°C) was used year-around, showed that the boiler efficiency, COP, the envelope insulation and the improved window properties became more influential as design parameters. The constant setpoint forced more demand on the HVAC systems which made more efficient HVAC equipment attain priority in ranking and achieve higher energy savings.

In Figure 3.c and Figure 4, varying the number of people, unlike altering occupancy, lighting and equipment schedules affected not only energy use but also the sizing of the HVAC equipment. The BPS tool multiplies the input occupant densities with the design day schedule in perform sizing. This approach led to a different impact on the effectiveness of the design parameters. For example, in Figure 3.c and Figure 4 where the number of people were 50% of the original design, the DCV was less efficient as a design parameter. Contrary to that, when the number of people was 150% of the original design number, the DCV became more effective as a design parameter. The improved COP of the cooling system has also gained more impact when the number of people was increased (150% of original design). The increase in the number of people is associated with additional internal gains which added burdens on the cooling system and a more efficient cooling system will be prioritized as a design parameter. Figure 3.d and Figure 4 shows two window blind use scenarios. The first scenario assumes that the internal window blinds are closed all the time, which is not a typical modelling assumption but can be plausible in practice. In other words, some studies have observed that some occupant will close the blinds as a reaction to discomfort (e.g. glare) and leave them closed for an extended period (days or even weeks) (O'Brien, Kapsis, & Athienitis, 2013). For instance, a study by Kapsis et al. (2013) on blind use in a high-rise building using time-lapse photography, found that the mean shading occlusions

Figure 3: The impact of changes in (a) schedules, (b) number of people, (c) blind use, (d) setpoints, and (e) equipment loads on the ranking and energy saving of design alternatives.

Occupant scenarios															
Design parameters	Original design scenario	Occupant scenarios													
		Schedules x (0.4)	Schedules x (0.6)	Schedules x (0.8)	Schedules x (1.2)	Setpoints [c]g 26.7, 22.2°C][r]mg 15.6,22°C]	Setpoints [Always 22°C]	50% of People density [40 m²/person]	150% of People density [13.3 m²/person]	Original design [Blinds always on]	Blinds triggered by solar radiation	75% of Plug-in load [7.4 W/m²]	150% of Plug-in load [14.8 W/m²]		
Roof_RSI = 11 m²·K/W	6.98%	7.92%	7.99%	7.60%	5.97%	6.59%	5.84%	7.96%	6.24%	6.68%	7.00%	7.52%	5.31%	More savings	Color scale
Roof_RSI = 9 m²·K/W	5.77%	6.41%	6.50%	6.17%	4.87%	5.37%	4.54%	6.60%	5.04%	5.49%	5.53%	6.08%	4.54%		
Roof_RSI = 7 m²·K/W	3.09%	3.45%	3.56%	3.41%	2.75%	2.90%	2.75%	3.52%	2.71%	3.11%	3.07%	3.36%	2.71%		
Wall_RSI= 7 m²·K/W	2.38%	2.63%	2.72%	2.57%	2.17%	2.38%	2.45%	2.65%	2.19%	2.42%	2.39%	2.54%	1.97%		
Wall_RSI= 5 m²·K/W	1.60%	1.90%	1.86%	1.74%	1.51%	1.63%	1.68%	1.80%	1.48%	1.62%	1.63%	1.71%	1.33%		
Wall_RSI= 4 m²·K/W	0.87%	1.03%	1.03%	0.96%	0.81%	0.92%	0.93%	1.00%	0.80%	0.91%	0.88%	0.96%	0.72%	EUI savings	
[U=1.62, SHGC=0.388]	4.98%	6.57%	6.07%	5.57%	4.42%	4.86%	4.85%	5.41%	4.44%	4.61%	4.78%	5.48%	4.01%		
[U=2.036, SHGC=0.584]	4.03%	7.41%	6.32%	5.15%	3.15%	3.67%	2.90%	4.19%	3.51%	0.93%	1.84%	4.93%	2.54%		
[U=1.467, SHGC=0.245]	3.43%	3.72%	3.93%	3.87%	3.31%	3.65%	4.09%	3.94%	3.33%	5.28%	5.23%	3.87%	3.12%		
WWR = 30%	3.17%	2.28%	2.95%	3.15%	3.42%	3.77%	4.84%	3.76%	3.29%	6.17%	5.16%	3.27%	3.21%		
WWR = 50%	2.16%	1.63%	2.10%	2.23%	2.21%	2.49%	3.16%	2.65%	2.20%	1.17%	3.30%	2.29%	2.17%		
WWR = 70%	1.03%	0.71%	1.04%	1.15%	1.04%	1.05%	1.42%	1.31%	1.04%	1.50%	1.58%	1.16%	0.94%		
Boiler eff. = 0.95	2.17%	3.40%	2.95%	2.54%	1.85%	2.29%	2.59%	2.05%	2.38%	2.36%	2.36%	2.49%	1.65%		
Pump eff. = 0.95	0.17%	0.22%	0.20%	0.18%	0.15%	0.19%	0.14%	0.17%	0.15%	0.17%	0.17%	0.18%	0.13%		
ERV eff. [0.88, 0.78]	1.11%	1.34%	1.29%	1.24%	0.98%	1.09%	1.15%	1.15%	1.05%	1.10%	1.10%	1.22%	0.86%		
Infil = 0.15 ach	1.35%	1.54%	1.52%	1.48%	1.23%	1.37%	1.49%	1.53%	1.25%	1.31%	1.38%	1.49%	1.16%	Less savings	
Blinds (Solar Ref.=0.6, Solar Trans= 0.15)	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1.36%	1.44%	0.00%	0.00%		
COP = 5	3.07%	2.66%	2.83%	2.95%	3.20%	3.34%	3.09%	3.00%	3.02%	2.69%	2.67%	3.02%	3.18%		
COP = 4	1.28%	1.11%	1.18%	1.23%	1.33%	1.39%	1.29%	1.25%	1.26%	1.12%	1.11%	1.26%	1.32%		
DCV	5.85%	8.58%	8.39%	7.44%	4.15%	4.84%	2.54%	1.20%	11.72%	6.54%	5.59%	6.10%	5.25%	Default scenario & Scenarios bases	
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%		

Figure 4: Design alternatives ranking.

ranged between 84% on south façade and 60% on the north façade. In addition, the study reported that 72% of the window shades never adjusted throughout the study period. The second scenario was the case where blinds are triggered by the solar radiation on windows. Design alternatives in both scenarios experienced a recognizable number of ranking changes in different ways. When the blinds were assumed to be always closed, windows with a high SHGC and the reduced WWR became less effective design parameters as the design alternatives have dropped down in ranking. The increase in window SHGC and the decrease of WWR on south façade became ineffective when the windows were always shaded.

When blinds were triggered by solar radiation, decreased WWR yielded less solar gains during times of overheating. They also allowed the useful daylight while blocking unwanted glare and consequently, reduced demand on cooling. In addition, they allowed the useful solar gains during heating season which contributes to heating the building and daylight utilization.

Two window blinds materials were used as design parameters in the two window blinds use scenarios. A change in energy use and ranking was observed with the use of alternative shade material.

Reducing the equipment loads to 75% of the original design value, as shown in Figure 3.e and Figure 4 resulted in minimal ranking change. The improvement of roof insulation becomes more influential as a design parameter and moved up on the ranking. On the other hand, the increased equipment loads (150% of the original design) led the cooling COP and the reduced WWR to gain significance and move up in ranking. The increased internal gains from equipment imposed a sizable load on the cooling system and an upgraded system (high COP) becomes more influential as a design parameter.

Discussion

The results of the simulated 13 occupant scenarios indicated different energy use pattern, savings potential and ranking of design alternatives. The design process sensitivity to the occupant-related assumptions point toward the fact that designers should produce a case-specific set of assumptions that recognize the different aspects of the intended building use. Codes and standards should also recognize the sensitivity of energy performance to occupant-related assumptions and consider the accompanying variation of saving potential.

Some technologies, such as DCV, become more beneficial when non-standard occupant assumptions were used. This provides an opportunity to utilize such technologies to achieve energy savings when designing or upgrading buildings. Codes and standards should also incentivize the use of adaptive technologies such as DCV to promote more adoption of these technologies.

Wall and roof insulation have showed robustness to the different occupant scenarios, in terms of ranking. This makes them ideal for the design of buildings with unknown building use characteristics. In contrast, using window assembly alternatives showed sensitivity to the different occupant scenarios as they experienced ranking changes in most of the cases. Generally, the study results underlined the notion that designers should devote more efforts in selecting occupant-related assumptions. Building operation and control strategies also need to be investigated in order to make the appropriate design decisions.

Conclusions and future work

The findings of this paper demonstrated the sensitivity of building design decisions to occupant related assumptions. The energy savings potential and the ranking of some of the design parameters were observed to be highly sensitive to occupant-related assumptions. The results also indicated that high occupancy in buildings can reduce the energy savings potential from design upgrades. In addition, it demonstrated the benefit of some of the HVAC technologies in certain occupancy scenarios. In contrast, low occupancy showed a trend of greater energy use savings with all explored design parameters.

The findings of this study are specific to the case study and its context. Other limitations of this study are: (1) the occupant-related assumptions were used one at a time not combinations, (2) design parameters were also applied one at a time and no combinations were considered, and (3) the study is limited to the consider occupant-related assumptions or design parameters. Future research should consider: (1) applying combinations of design parameters and occupant-related assumptions, (2) conducting a similar investigation for different building archetypes and climatic conditions, and (3) conducting an optimization study to quantify the implications of occupant related-assumptions on the building design optimization.

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