Occupant modelling for building design and energy codes: roadmap, feasibility study, best practices guidebook, and tested case study

Date: Sunday, February 02, 2020

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Executive Summary

The objective of this research and development project was to develop methods and recommendations to advance the state-of-the-art in building occupant modelling practice from a primarily research-oriented status to common building simulation-supported design practice and building codes. The work was divided into four interrelated phases:

1. Technology roadmap to advance standardized occupant modelling in simulation-based design practice and building code;
2. Technical feasibility study to evaluate the practical and theoretical implementation of occupant modelling into BPS tools and codes;
3. Best practices design guidebook for occupant modelling for building design; and,
4. Simulation and documentation of a case study building for which the work from the first three phases is demonstrated.

The work was completed, as proposed, in approximately two years. Key highlights include:

- A workshop with all partners and additional industry and government stakeholders was hosted. The workshop ultimately led to a 60-page roadmap document with detailed recommendations for timelines and priorities of occupant modelling for building design and building codes. The finds included recommendations for updating the current occupant-related schedules and densities in the building code as well as a comprehensive investigation of the code requirements that are founded on current standard occupant assumptions.
- For phase 2, simulation tools were assessed for their occupant modelling capabilities. In general, tools were found to use only simplistic occupant modelling methods. Following that, a journal article was written to summarize these findings and make recommendations. Given the limitations of current models, a novel intermediate approach was proposed and developed whereby detailed occupant models are pre-simulated to yield design-specific occupant-related schedules. It was shown that probabilistic design, whereby the risk of extreme occupancy scenarios is quantified, can reveal significant cost savings while managing risk.
- For phase 3, comprehensive sensitivity analyses were performed, which ultimately led to the best practices design guideline. It was found that assumptions about occupants and lighting are particularly significant compared to current standard practice. Moreover, the impact of occupants across different Canadian climate zones is not straightforward. For example, window opening behavior is most impactful in Canada's more moderate climates, but less impactful in the extreme climates. The guidebook was disseminated widely via workshops and online step-by-step videos.
- Phase 4 involved a case study (a mid-rise office building in Toronto). All key stakeholders were interviewed to understand the design process regarding occupant assumptions. It was found that assumptions between professionals varied by as much as a factor of two and that these differences lead to profoundly different design recommendations. Extensive simulation studies were performed to assess the sensitivity of occupant related assumptions. From these studies, a recommended workflow to

investigate the impact of occupant-related assumptions was developed. Among other findings, this phase showed that practitioners do not necessarily need to use advanced occupant models to quantify the potential impact of occupants.

All work was documented and disseminated via conference and journal articles, online videos, magazine articles, and webinars/presentations. After the project term, significant work continued, including the formation of the 100-researcher, 5-year International Energy Agency/Energy in Buildings and Communities Annex 79; plans to publish a book on occupant-centric design (which will include the case study of the current project); and, a project on informing the occupant-related aspects National Building Code with new knowledge and data. Meanwhile, the principal investigator and his team continues to widely disseminate findings (e.g. via webinars and workshops). Moreover, collaborative research with the project partners has continued.

Acknowledgements

The proponents of this work are grateful for the generous funding and in-kind support from project partners, including Natural Resources Canada, Rowan Williams Davies & Irwin (RWDI), and Autodesk. The project was funded by Natural Resources Canada's Energy Innovation Program – Clean Energy Innovation Project #812. This work would not have been possible without the input, ideas, and inspiration of the above partners. We also thank National Research Council for ongoing support and feedback regarding building code-related aspects of the work.

We thank the participants of the stakeholders' workshop for devoting over a day of their time to travel to Ottawa to provide valuable input to workshop. Participants were: Afaf Azzouz, Andrew Hicks, Azam Khan, Andrea Pietila, Daniel Heffner, Daniel Knapp, Gabriel Wainer, Guy Newsham, Ian Beausoleil-Morrison, Meli Stylianou, Phylroy Lopez, Rhys Goldstein, Ruth Urban, Sam Yip, Sebastián Carrizo, and Umberto Berardi.

The content of this report does not necessarily reflect the views of any of the above parties.

Contents

1 Background

A large body of scientific literature indicates that occupants impact building energy use in profound ways and that physically identical buildings have measured energy use varying by factors of two to three (e.g., Gram-Hanssen 2010, Haldi and Robinson 2011). Building performance simulation (BPS), which is a powerful tool aimed at accurately and cost-effectively predicting building performance to support all phases of the building life cycle (from early design to operation) and also code and program development (e.g. for incentives), normally involves very simplistic modelling assumptions about occupants with little grounding in reality. Moreover, current occupant modelling methods are unsuitable for evaluating many technologies (e.g., demand controlled ventilation and occupancy-controlled lighting) that are important for designing net-zero energy and other high-performance buildings (O'Brien and Gunay 2019). In contrast to building materials and systems, occupant modelling – particularly outside of research – is in its infancy. But the increasing role of occupants on building performance as a result of lower overall energy use, more reliance on passive systems, growing interest in net-zero energy means that the importance of accurately modelling occupants is only going to increase with time [74]. Without accurate representation of occupant's interactions with electric lighting, blinds, windows, and equipment in building simulation, two risks emerge:

1. Energy and other predicted performance results can be inaccurate, and,
2. Inaccurate simulation predictions will mislead designers to make sub-optimal design decisions and government to develop inappropriate codes and incentives programs. Sub-optimal design decisions will leave building owners, operators and society at large with a long-term liability.

The risks and rewards of improve occupant modelling are further tabulated in Table 1.

Table 1: List of risks and rewards associated with advanced occupant modelling

Risks	**Rewards**
1. Undersized equipment as a result of underestimating occupant-related heating, cooling, or ventilation loads and corresponding discomfort. 2. Undersized spaces as a result of underpredicting occupancy o If occupancy modelling is relied on for sizing spaces (i.e., architectural programming), there is a risk that unsuitable occupancy modelling assumptions could lead to undersized spaces. 3. Poor design decisions because occupant modelling assumptions were not appropriate. For instance:	1. Reduced equipment sizing as a result of realistic occupant modelling assumptions 2. Reduced energy use and greenhouse gas emissions as a result of right-sized equipment running in its near-optimal operating range 3. Improved architectural design (e.g., window to wall area ratio, shade materials, building massing, interior finishes, etc.) based on modelling occupants' potentially energy-adverse adaptive behaviours 4. Greater acknowledgement of the benefit of adaptive comfort-related opportunities for occupants

○ Designing a building with multiple adaptive opportunities based on model, but then occupants misuse them in energy-adverse ways. ○ Key design decisions, such as building massing, interior finishes, window size, and window shade fabric are inappropriate because occupants use spaces or systems differently than expected.	5. Identified opportunities to use systems that adapt to occupancy (e.g., demand-controlled ventilation, motion-activated lighting) 6. Improved occupant comfort and health in and usability of buildings as a result of appropriate design decisions 7. Robust design from stochastic occupant models (e.g., architectural features that inherently reduce the frequency of discomfort-triggering occupant responses) 8. Assessment of building resilience and potential to improve it through adaptive comfort opportunities 9. Smaller buildings to reflect lower real occupancy

While the long-term objective of the project –to have occupant modelling integrated into common design practice and required by building codes– is challenging, a recent survey (O'Brien, Gaetani et al. 2016) indicates that 73% of practicing building simulation users agree or strongly agree that better occupants' interactions with building systems should be represented more accurately.

The objective of the proposed was to develop methods and recommendations to advance the state-of-the-art in occupant modelling practice from a primarily research-oriented status to common building simulation-supported design and code compliance. The Carleton University researchers, in close collaboration with leading private and public partners, completed the following tasks.

1. Develop a comprehensive roadmap between the current state-of-the-art and formalized inclusion of occupant modelling into BPS design practice and building codes.
2. Perform a technical feasibility study to evaluate the practical implementation of occupant modelling into BPS tools and codes. Stemming from the first phase, this will involve detailed simulation studies and critical assessment of technical and non-technical barriers.
3. Develop a best practices guidebook for occupant modelling, based upon a comprehensive review of current practice, simulation findings, and conclusions from the first two phases.
4. Develop a real worked example of a new office building, involving the researchers, consultants, and the client, to demonstrate, test, and document modelling procedures and best practices.

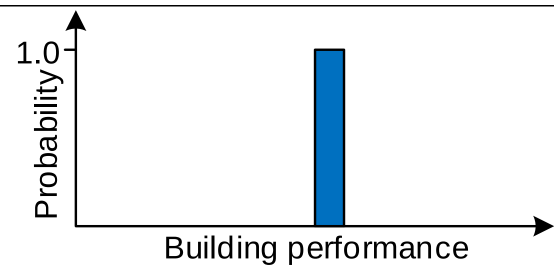
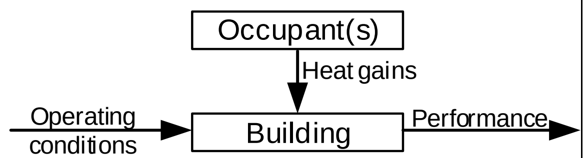
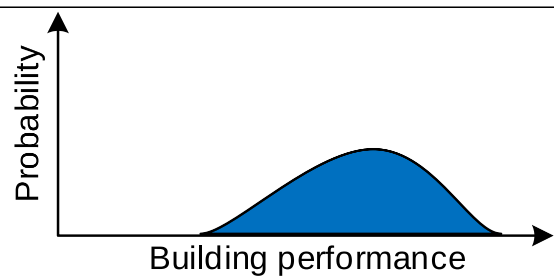
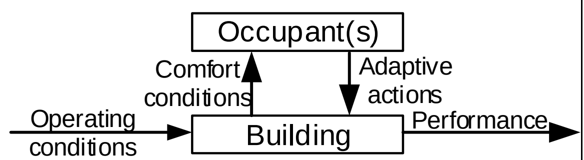
This background section provides context and fundamental knowledge on the topic, while the sections that follow provide greater detail about the project methods, findings, and outcomes.

1.1 Occupant modelling strategies

Occupant modelling approach is a critical aspect of capturing the influence of occupants in BPS predictions. On the basis of the previously-defined characteristics of occupant model, such models be placed in four categories, as outlined in Table 2 and Table 3. *Deterministic* models perform exactly the same for every simulation run; whereas *probabilistic* (also known as *stochastic*) models are associated with randomness – either at the outset of a simulation or during a simulation (e.g., at each timestep or at each month). *Static* occupant models do not respond to specific predicted building conditions, whereas *dynamic* models incorporate the two-way interaction between the occupants and the building.

By far the most prevalent occupant modelling practice is to use static deterministic models in the form of fixed schedules (e.g., those in ASHRAE Standard 90.1 and NECB). Fixed schedules offer the advantage of repeatability, simplicity, and transparency, all of which are attractive for mainstream building simulation for applications such as code compliance. However, there are two limitations of static deterministic models.

Table 2: Properties of current and potential future occupant modelling approaches in practice

	Stochasticity	**Dynamic/static**
Conventional		
Advanced		

First, fixed schedules neglect the two-way interactions between occupants and building. This means that benefits or consequences of certain design features are not properly characterized. For instance, fixed exterior shading can reduce the frequency of daylight glare that triggers occupants to close blinds and turn on lights to compensate (O'Brien and Gunay 2015). However, NECB states that blinds should be modelled as open unless they are motorized and automated. Second, static deterministic models to not provide insight into uncertainty and risk. For instance, the potential for robust design (whereby a building is designed to be more robust against uncertainty of occupant behaviour) and the potential to take calculated risks (e.g., size HVAC such that it will be adequate for 99% of expected occupancy levels (O'Brien, Abdelalim et al. 2018)). A subtler limitation of static deterministic models is that when a single set of occupant assumptions is chosen, it tends to be chosen as conservative. For instance, the NECB occupancy schedules for offices assume 90% occupancy midday during weekdays, whereas offices tend to peak at 50 to 80% occupancy (Duarte, Van Den Wymelenberg et al. 2013).

Table 3: Four categories of occupant models and examples

	Deterministic	**Stochastic**
Static	A fixed model that does not respond to conditions during simulation (e.g., a schedule corresponding to the number of occupants in a room over a day) **Examples of model in practice:** NECB and ASHRAE Std. 90.1 standard schedules for lighting, plug loads, and occupancy **Most suitable applications of model:** building codes and standards primarily at the whole-building level; early design stages	A model that is not the same for every simulation or timestep but that does not specifically change during a simulation due to conditions (e.g., an occupancy schedule that can be multiplied by a random number to scale it upwards or downwards) **Example in practice:** None known **Most suitable applications of model:** HVAC and renewable energy system equipment sizing
Dynamic	A model that represents the occupant in a consistent way but captures the two-way interaction between occupants and buildings (e.g., a model that defines whether or not an occupant will turn on a light based on a fixed illuminance threshold). **Example in practice:** IES LM 83 daylight metrics for LEED uses a fixed illuminance threshold to determine whether shades are open or closed **Most suitable applications of model:** codes and standards at the room and zone scales, particularly related to adaptive comfort systems	A model that responds to conditions (e.g. time of day, indoor temperature) with a degree of randomness (e.g., a model used to predict the probability that occupants will turn on the lights) **Example in practice:** None known; this is primarily research stage, for which it is very common **Most suitable applications of model:** detailed architectural design and equipment sizing at the room and zone levels

Though there are no known examples in common use, an approach to introduce stochasticity to occupant modelling, while relying on convention is stochastic schedules (i.e., **stochastic static models**) (O'Brien, Abdelalim et al. 2018). Such schedules would be parametric and have randomized parameters that are selected at the beginning of the simulation year, day, or some other frequency. Such schedules can provide insight about performance uncertainty, though would typically not be able to characterize the two-way interaction between buildings and their occupants. However, this limitation is generally acceptable for non-adaptive occupant-related domains, such as plug loads and occupancy.

Deterministic dynamic models, for where there are several established examples in use, allow the two-way interactions between buildings and their occupants to be characterized but do so consistently. This means that the model outputs depend on building-specific inputs (e.g., indoor environmental quality (IEQ) that the design that defines the IEQ). Models that only depend on time or occupied state as an input are not considered dynamic in the current context. An example of a deterministic dynamic model is in Illuminating Engineering Society (IES) of North America Standard LM 83 imposes a modelling requirement that shades are closed whenever 2% of workplane analysis points receive greater than 1000 lux of direct sunlight (IESNA 2012). This means the building designer can use this model to help inform window size, placement, and type to minimize the amount of time that the shade is closed.

Finally, the state-of-the-art in occupant modelling in the current literature (Yan, O'Brien et al. 2015, Yan, Hong et al. 2017) is focused on **dynamic stochastic models**. These models both characterize two-way interactions and do so stochastically, such that every simulation yields a different result. Such models have primarily been applied to the single room or small building scale and have spanned domains of light use, thermostat adjustment, operable window use, window shade/blind use, beverage consumption, clothing level selection, and desk fan use (Gunay, O'Brien et al. 2013).

Another distinction between the state-of-the-art in occupant modelling and typical approach is that the new ones are often **agent-based models**. Agent-based models treat occupants as individuals, who experience the indoor environment, have objectives, make decisions and take actions, and interact with each other. The leading models in the literature are quite simple, but can still be considered agent-based because they represent individual occupants how interact with the building (Gunay, O'Brien et al. 2013).

Stochastic models, in turn, can take on numerous forms (Gunay, O'Brien et al. 2013, Gunay, O'Brien et al. 2015). The common ones are described here. **Markov Chain models** predict whether an action will occur (e.g., the occupant turns on the light) on the basis of the current state (e.g., the light is off) and as a function of one or more variables (e.g., workplane daylight illuminance). Markov Chain models are among the more common and have the advantage of not only predicting resulting state (e.g., whether the light is on or off) but also the event. The number of events can be used as a proxy of discomfort (Gunay, O'Brien et al. 2018). The underlying function of Markov Chain models is commonly logistic regression. Another common form of dynamic stochastic models is **Bernoulli models**. Bernoulli models predict the state of a particular system (e.g., light state or window position) rather than actions. While Bernoulli models are conceptually straightforward and somewhat easier than Markov Chain models to implement, they are not suitable for predicting the number of occupant actions. The main remaining model form described here is **survival models**. Rather than predicting state change or state in a given simulation time step, survival models predict how long a system will stay in a certain state. It has been used to predict whether occupants will turn off lights or office equipment as a function of how long they are absent.

Figure 1 shows four illustrative examples for lighting for the four occupant behaviour modelling approaches.

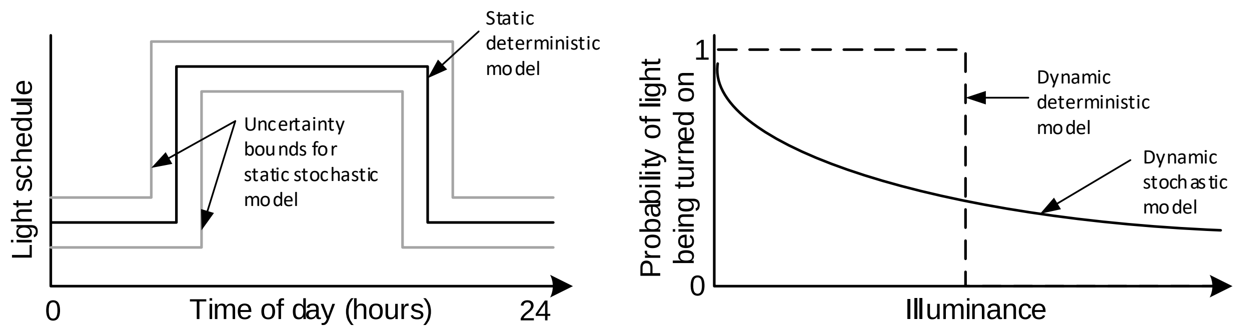


Figure 1: deterministic and stochastic models: schedule-based (static) models (left) and dynamic models (right)

On the basis that the current project is focused on occupants, we proceed with only that type of building agent. However, future research is needed to understand and potentially model the impact of all agents (i.e., owners, operators, tenants, etc.). Individual people from the other groups could have orders of magnitude more impact than occupants. Owners could make major lighting upgrades and janitors may turn on and leave on lights from the time they perform a cleaning until the next morning (Brown, LaRue et al. 2016, Gilani and O'Brien 2019). Table 4 provides a list of major occupant-related domains of interest and some corresponding characteristics. These domains are then shown graphically in Figure 2.

Table 4: Office occupant-related modelling domains of interest

Domain	**Definition**	**Key indicators**	**Known predictors**	**Impact(s) of interest**
Occupancy	Presence of occupants in building	• Occupant density • Absolute number of occupants • Occupancy diversity schedule	• Time of day • Day of week • Holidays	• A necessary condition for occupant actions (except for remotely controlled systems) • Metabolic heat and moisture gains; CO_2 and odour generation
Manual lighting control	Adjustment of lighting state or dimmable level	• Power • State/dimmed level • Lighting power density and	• Occupancy (arrival, departure, intermediate periods) • Indoor illuminance	• Electricity use • Heat gains • Illuminance

		diversity schedule	from electric lights or daylight	
Office plug-in equipment	Use (duration, power consumption) of plug-in office equipment, such as computers and printers and kitchenette equipment	• Power • Power density and diversity schedule	• Time of day/week • Anticipated occupant absence duration • Office type	• Electricity use • Heat gains
Window shades/blinds	Action on or position of window shades and blinds	• Mean state • Number of opening and closing actions per day	• Outdoor and outdoor illuminance • Indoor luminance • Views to outside	• Indoor illuminance • Solar gains • Heat loss
Operable windows	Action on or state of operable windows	• Mean state • Number of opening and closing actions per day	• Indoor and outdoor temperature • Noise • Indoor air quality	• Sensible and latent heat gains/losses • Contaminant transport • Resulting draughts and airflow
Thermostats	Thermostat adjustment patterns and resulting setpoints	• Mean occupied and unoccupied setpoints • Frequency of adjustments and conditions leading to them	• Indoor temperature • Indoor relative humidity	• Heating and cooling energy • Resulting indoor temperature
Personal fans	Adjustment of and state of fan (e.g., on, off, modes)	• Mean fan state • Number of fan state/speed adjustments per day • Fan power	• Indoor air or operative temperature	• Fan electricity and heat gains • Thermal comfort and implications of air movement

Clothing level	Clothing level of occupants	• Clo level and schedule	• Indoor and outdoor air temperature (with significant time lag)	• Thermal comfort implications
Metabolic rate	Indoor heat gains of occupants and internal heat generation	• Met • Heat per occupant (W/occupant) • Heat per floor area (W/m^2)	• Occupant presence and activity type	• Heat, moisture and CO_2 gains of occupants

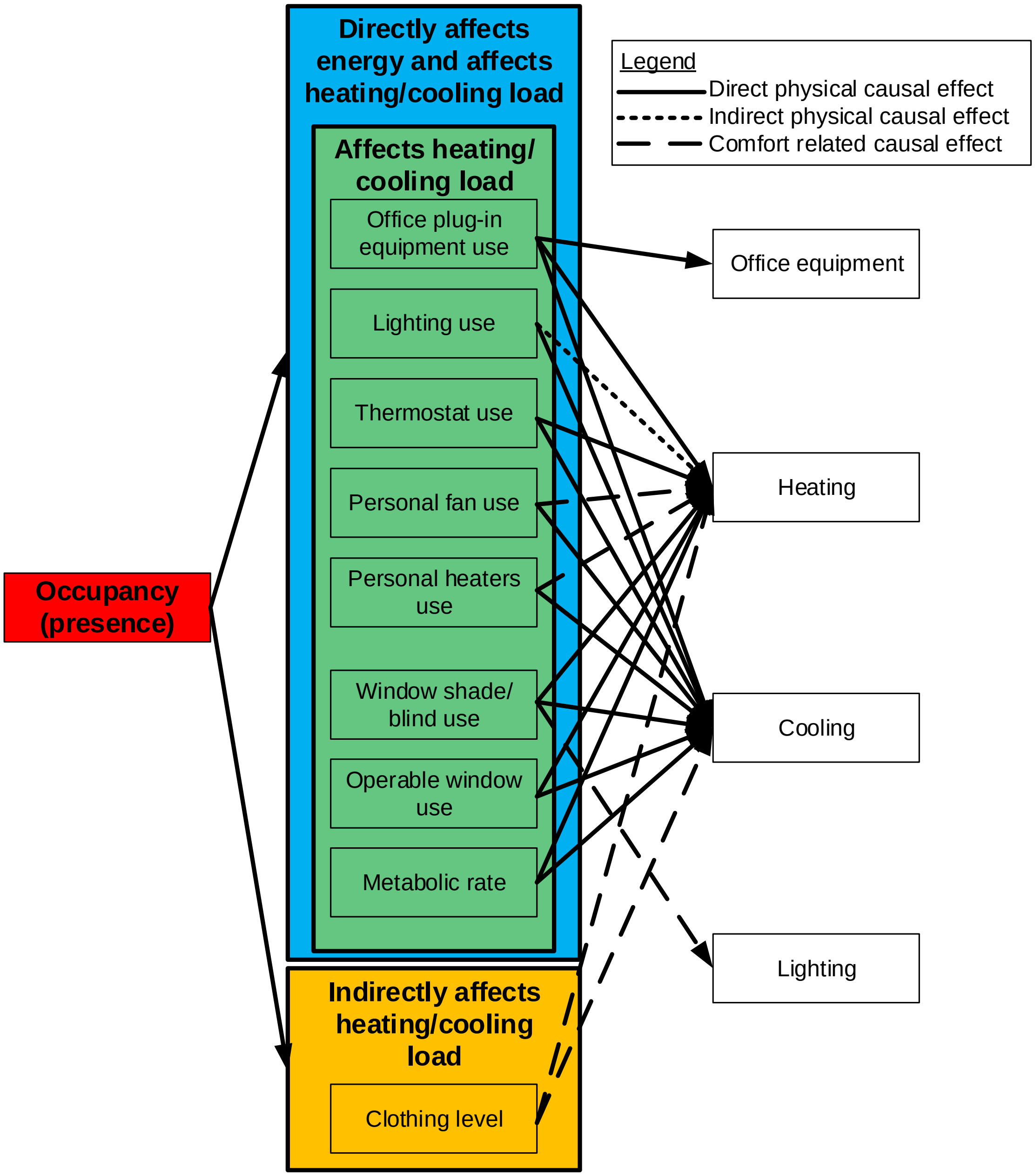


Figure 2: Map of key occupant behaviours, organized by how they impact building performance

A growing body of building performance simulation (BPS) researchers view occupants as a leading cause of discrepancies between BPS predictions and reality. As such, hundreds of researchers (e.g., members of IEA EBC Annex 66) are working on occupant modelling and simulation to "close the gap" between predicted and measured building performance (Sun, Yan et al. 2014). However, another camp of BPS researchers and users has argued that the role of BPS is to predict relative performance (Hensen and Lamberts 2012, Burton 2014).

The performance-based compliance path of the current National Energy Code of Canada for Buildings (NECB) (herein "the Code"), similarly to most building energy codes and standards, relies on annual building simulations to demonstrate that the proposed building achieves equal or better energy performance than a reference building (Sentence 8.4.1.2.(2)) (National Research Council Canada (NRC) 2015). See Figure 3 for summary of three code compliance paths that are typical of most building energy codes and standards. The performance compliance path implies that relative performance predictions are adequate for the Code. For instance, the Code allows great flexibility on occupant modelling assumptions, so long as they are the same for the reference and design building. For internal loads, Sentence A-8.4.2.7.(1) states "While any internal load values are permitted to be used, those default values should be used in the absence of better information." Reasonably applied deviations from the defaults values are difficult to disprove for the modeller and code official alike. Standard 90.1-2016 (ASHRAE, 2016) takes the stricter stance that the local code authority must approve all deviations from standards; personal communication with modellers in many jurisdictions suggest that strictness varies widely in different locales.

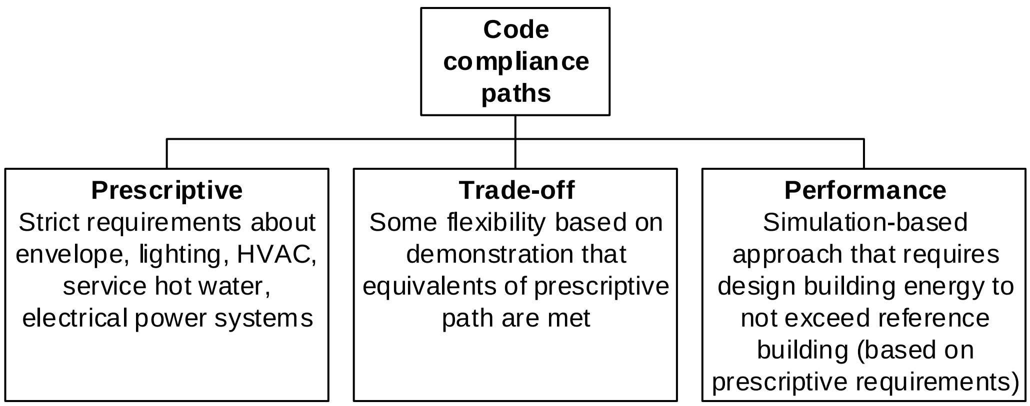


Figure 3: Typical building energy code compliance paths

In contrast to the practice focusing on relative performance between the proposed and reference cases, a recent survey of international BPS tool users and developers (O'Brien, Gaetani et al. 2016) suggested that just over half of modeller participants do not agree with the statement "It does not matter if assumptions about occupants in BPS tools fully represent real occupants as long as occupants are represented the same way in all design variants." Ouf and O'Brien (2018) demonstrated the consequence of allowing modellers to use customized occupant-related schedules: predicted energy savings from various energy efficiency measures could be greatly manipulated by adjusting occupant-related schedules. For instance, energy efficient lighting is more beneficial to annual lighting electricity use reductions if lights are assumed to be on for more hours each day. Thus, the current occupant modelling approaches can have unintended consequences, such as leading design teams towards unwise decisions or operating conditions that *increase* absolute energy use. Gilani, O'Brien et al. (2016) further showed that simple occupant modelling assumptions may lead to significantly different optimal building designs than if occupants are more accurately characterized. Thus, absolute accuracy –rather than merely relative accuracy—is important, as is becoming evident by detailed studies (such as those above). Accuracy in this roadmap is defined as absolute (not relative) unless otherwise stated. However, it must be acknowledged that occupants and their behaviours are associated with a certain degree of uncertainty – particularly for unbuilt buildings. Of course, there are many other sources of uncertainty as well, such as weather, construction quality, and material properties.

Meanwhile, occupant modelling is critical for simulation-based building design approaches because occupants are playing an increasingly important role in building energy performance. Current occupant modelling methods are unsuitable for evaluating many technologies (e.g., demand-controlled ventilation and occupancy-controlled lighting) and supporting design decisions (e.g., how many offices to put in the same control zone) that are important for designing high-performance buildings. The results of such evaluations are also critical for improving building codes, incentives, and other policy-related issues.

1.2 Building modelling objectives, design phase, and spatial scale

Before discussing occupant modelling strategies, current and potential applications for building performance simulation in the new building design process must be considered. This can be represented by three axes, as shown in Figure 4. **Model objective** refers to the role of the BPS model to support the design process. **Design phase** refers to the model purpose within the design process – from conception to construction. **Model spatial scale** refers to the physical scale of the model – from room-level to community or larger.

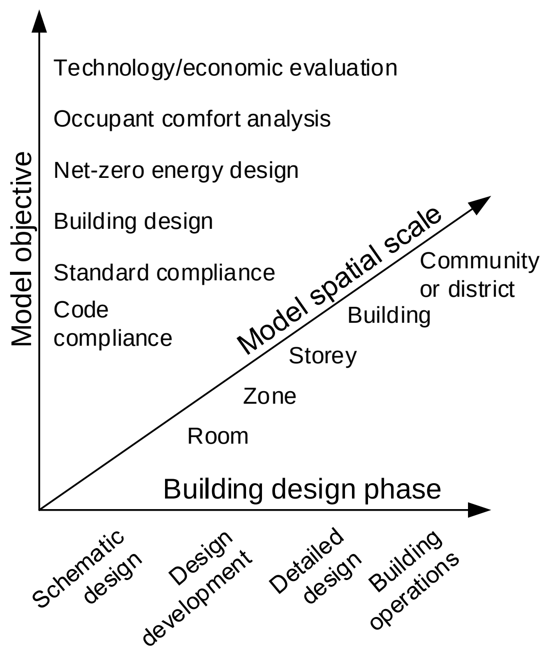


__Figure 4: Three-dimensional space of building simulation applications for design__

The three axes are not necessarily independent, in that the ultimate solution for best occupant modelling practice does not likely populate the entire 3D matrix. For instance, code compliance and net-zero energy building design nearly always focus on building scale models because the performance metrics focus on whole-building annual energy. In contrast, occupant comfort analysis would likely focus on the room or zone scale, where the occupants are located. Similarly, early phases of design are likely to focus on larger scale considerations (building massing and overall design strategy), whereas detailed design also focuses on the room and zone scale. The next three sections explore the three axes of Figure 4 in much greater detail.

1.2.1 Building model objectives

As reiterated by workshop participants, there are numerous objectives for creating and using BPS models for new buildings. The modelling approach for all building aspects –not only occupants— can be greatly impacted by the modelling objective and thus this is a central theme for this document. Key modelling objectives and their implications are summarized in Table 5. Other uses for BPS models that are outside of the current scope include: retrofit analysis and model predictive control.

Table 5: Summary of primary applications of BPS for new building construction.

Model objective	**Description/ purpose**	**Imposed occupant modelling constraints**	**Possible modeller bias**	**Typical desired model outputs**		
				Annual energy/GHG emissions	**Peak loads**	**Comfort**
Code and compliance	Demonstrate that proposed building model performs better than code minimum; often additional requirements for IEQ	Occupant assumptions in design are same as reference building and often use standard schedules and density values	Demonstrate code compliance by making assumptions about occupants that exaggerate energy savings from energy efficiency measures	X		X
Standard design process	Show impact of various design decisions to support the design process	None, though likely reliance on standard schedules to model occupants if no better information is available	Depending on liability, incentives, and client desires, modellers may make optimistic or conservative occupant modelling assumptions	X	X	X

Absolute target-based design (net-zero energy and contractual performance requirements)	Examine an integrated set of building design features (both EEMs and renewable energy systems) to achieve a predicted, and possibly measured, net-zero energy	None	Depending on expectations, modellers may be incentivized to make conservative assumptions about occupants to mitigate liability or optimistic assumptions to achieve energy target cost-effectively	X		X
HVAC sizing	Using design conditions (climate, occupancy), assess the minimum permissible heating, cooling and ventilation equipment size.	Often use standardized conservative schedules and densities	Mechanical engineering consultants are likely to be risk-adverse to avoid under-sizing equipment		ASHRAE suggests monthly peaks	

1.3 Project scope and objectives

The objective of this R&D project was to develop methods and recommendations to advance the state-of-the-art in building occupant modelling practice from a primarily research-oriented status to common building simulation-supported design practice and building codes. The focus is on commercial and institutional buildings, though the findings can be mostly generalized to residential buildings. The ultimate long-term objective is to support the Canadian (and indirectly international) construction industry to design buildings that: (1) are more comfortable and productive environments, (2) use less energy and emit lower greenhouse gas emissions as a result of better informed decision-making, and (3) have higher performance certainty with regards to occupants, particularly in the context of net-zero energy buildings and other buildings with absolute energy targets. The impacts of better building design are widespread and cover the triple bottom line of environmental, economic, and social benefits.

With close intense collaboration with leading public and private sector partners with complementary skills, knowledge, and assets, to ensure that the research is both advanced and grounded in practicality, we sought to deliver concrete recommendations for how building performance simulation tool developers, policy makers, and building code developers can properly integrate appropriate occupant modelling in order for developers and their consultants to demonstrate that buildings have been designed with occupants in mind.

This project was comprised of four phases.

1. Roadmap to advance standardized occupant modelling in simulation-based design practice and the building code
2. Technical feasibility study to evaluate the practical and theoretical implementation of occupant modelling into building performance simulation tools and building codes
3. Occupant modelling for building design – best practices guidebook for Canada
4. Case study to demonstrate advanced occupant modelling in a practical industry-oriented setting

2 Summary of research work

This section is structured by phase and by key activities that were performed. The papers and reports are summarized. Links to the full versions are provided.

2.1 PHASE 1: Technology roadmap to reach advance standardized occupant modelling in simulation-based design practice and building code

This phase was centred around a comprehensive technology roadmap towards advanced occupant modelling in building simulation to support design and building codes. Before the roadmap was researched and written, a stakeholders’ workshop was held to gather diverse views from key stakeholders (e.g., industry, researchers, government). On May 1, 2017, Carleton University hosted the workshop. In all, approximately 30 participants including academics, government researchers, consultants, and software developers participated. The format of the workshop was such that each of the four themes included a brief background presentation by one of the organizers, a small diverse group discussion on the listed question, and then the groups presented their key findings to the other participants.

Table 6: Photos from workshop

Following the workshop, the roadmap was written (O'Brien, Ouf et al. 2018), and a conference paper (Abuimara, O'Brien et al. 2018) and public webinar were given. In summary, the roadmap first provides a detailed background information is provided on code compliance paths and design processes, in the context of occupant modelling. The state-of-the-art in occupant modelling methods and formalisms is introduced, with many definitions provided. Four traits of advanced occupant models are described, including dynamic, stochastic, data-drive, and agent-based. The numerous actors that influence building energy performance are described, including owners, managers, operators, janitorial staff, tenants, and finally the focus of this roadmap, occupants. Finally, the primarily occupant-related phenomena that affect building energy performance are summarized, including: occupancy (presence), lighting, office equipment, window shading devices, operable windows, thermostats, personal fans, clothing level, and metabolic rate.

The International Energy Agency guide for technology roadmaps was followed closely to develop the roadmap towards advanced occupant modelling. It includes five stages: 1) goals and scope, 2) milestones, 3) gaps and barriers, 4) action items, 5) priorities and timelines. The overarching **goal** is to increase the accuracy of occupant modelling for improved occupant comfort, health, and productivity, and improved building performance, including energy, usability, and robustness. The **scope** of the roadmap was set to be limited to Canadian office buildings, with occupants as the actors. The **milestones** were divided into four categories, including: occupant modelling research, building energy codes, building design practice and modeller education, and building simulation tools. Seven **gaps** were identified, on the topics of: critical occupant-related domains, simplicity of current occupant modelling methods, outdated occupant schedules, contextual factors affecting behaviour, current building code requirements, occupant modelling in design practice, BPS tools. Key identified **barriers** include: unquantified value of detailed occupant modelling, challenges in communicating occupant assumptions, building codes and associated limitations, modelling complexity, and modeller education. The stages of the roadmap are summarized in Figure 5.

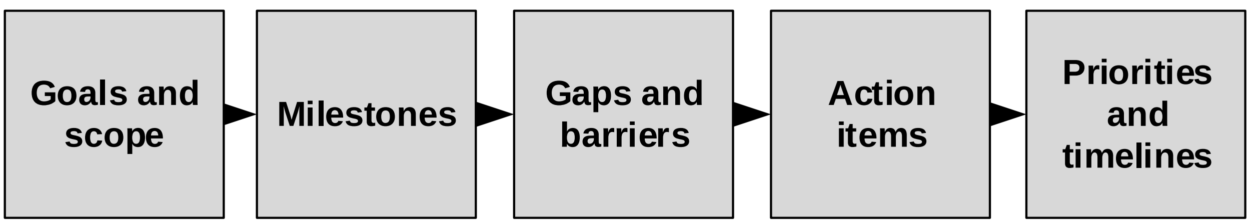


Figure 5: Roadmap outline

In the context of the gaps and barriers that were identified, **action items** to address the milestones were established. Concrete recommendations for applied research, advancing building codes and design processes, and modeller education were made. Finally, **priorities and timelines** were established. Specifically, action items that are seen is particularly critical and could be achieved in the short term were identified. These include: systematically assessing the most critical and sensitive behaviours for all climate zones (and eventually all building types); making recommendations for the most appropriate occupant modelling approach as a function of building size, occupant domain, and building model objective; critically assessing the National Energy Code of Canada for Buildings (NECB) to identify weaknesses and opportunities; establishing systematic method and corresponding repository to collect occupancy, plug load, and lighting data for the purpose of updating NECB schedules; developing, demonstrating, and documenting new design workflows that use advanced occupant models; and finally, pursuing outreach and dissemination activities to communicate to industry that advanced occupant modelling is important, worthwhile, and economically justifiable. Further details can be found in (O’Brien, Ouf et al. 2018); the roadmap can be directly downloaded from the link provided in Section 4.

2.2 PHASE 2: Technical feasibility study to evaluate the practical and theoretical implementation of occupant modelling into BPS tools and codes

The second phase focused on the technical aspects of occupant modelling, including current building performance simulation (BPS) tool capabilities and future needs, reporting of probabilistic performance predictions, and assessment of the accuracy of current occupant models used in building codes and practice.

Ouf, O'Brien et al. (2018) systematically assessed the occupant-related features and capabilities in the existing commonly used BPS tools, as summarized in Table 7. In general, the review concluded that while all review tools had some occupant-related features, they are generally several decades behind the literature. For example, most tools still rely on schedules to define occupants, whereas the most advanced models discussed for Phase 1 have seldom been implemented into existing BPS tools.

Table 7: Summary of occupant-related features in common BPS tools

Available direct inputs			**Energy Plus V8.8**	**Open Studio V2.3**	**Design Builder V5.0**	**IES VE V20 17**	**e QUE ST V3.65**
Schedules		Hourly inputs	✓	✓	✓	✓	✓
		Sub-hourly or interval-based inputs	✓	✓	✓	✓	
		Schedule inputs from file	✓			✓	
		Change simulation timestep	✓	✓	✓	✓	
		Optional interpolation to the simulation time-step	✓	✓	✓		
		Graphically represent schedules		✓	✓	✓	
		Specify functions / rules within schedules				✓	
Densities and other characteristics	Occupants	Occupant density	✓	✓	✓	✓	✓
		Occupant radiant heat fraction	✓	✓			
		Occupant sensible heat gain / fraction	✓	✓	✓	✓	✓
		Occupant metabolic Rate	✓	✓	✓	✓	
		Occupant CO_2 generation rate	✓	✓	✓		
		Explicit positioning and orientation of occupants	✓				
		Occupant clothing level schedule	✓	✓	✓	✓	
		Dynamic model for occupant clothing level	✓				
Rul	Day	Linear / continuous control	✓	✓	✓	✓	✓

		Stepped control	✓	✓	✓	✓	✓
		Sensor positioning available	✓	✓	✓	✓	✓
		Based on glare discomfort index	✓	✓	✓	✓	
		Probabilistic input for manual daylighting control	✓	✓			
	Window opening controls	Based on schedule	✓		✓	✓	✓
		Based on indoor temperature	✓		✓	✓	✓
		Based on outdoor temperature	✓		✓	✓	✓
		Based on thermal comfort	✓				
		Minimum opening duration	✓				
		Minimum closing duration	✓				
		Fraction of window open	✓		✓	✓	✓
		Maximum wind speed threshold	✓		✓	✓	✓
		Probabilistic input for opening or closing if conditions are met	✓				✓
		Occupancy check (i.e. check occupants' presence)	✓				
		Close windows when raining			✓		
	Blind controls	Based on schedules	✓	✓	✓	✓	✓
		Based on solar irradiance	✓	✓	✓	✓	✓
		Based on outdoor temperature	✓		✓	✓	✓
		Based on indoor temperature	✓		✓	✓	✓
		Based on cooling load	✓		✓		
		Based on heating load	✓		✓		
		Based on glare discomfort index	✓	✓	✓		✓

On the basis of the review, the following recommendations were made.

1. Increase occupant-related inputs into BPS tools.
2. Automate the process of running multiple simulations with varying occupant-related scenarios.
3. Have a library of occupant scenarios that can be evaluated.
4. Add occupant-centric outputs, such as energy use per occupant.
5. Streamline the user experience such as occupant-related inputs can be automatically generated based on room types.

The recommendations were summarized as a mock-up graphical user interface, from which select features could be incorporated into BPS tools.

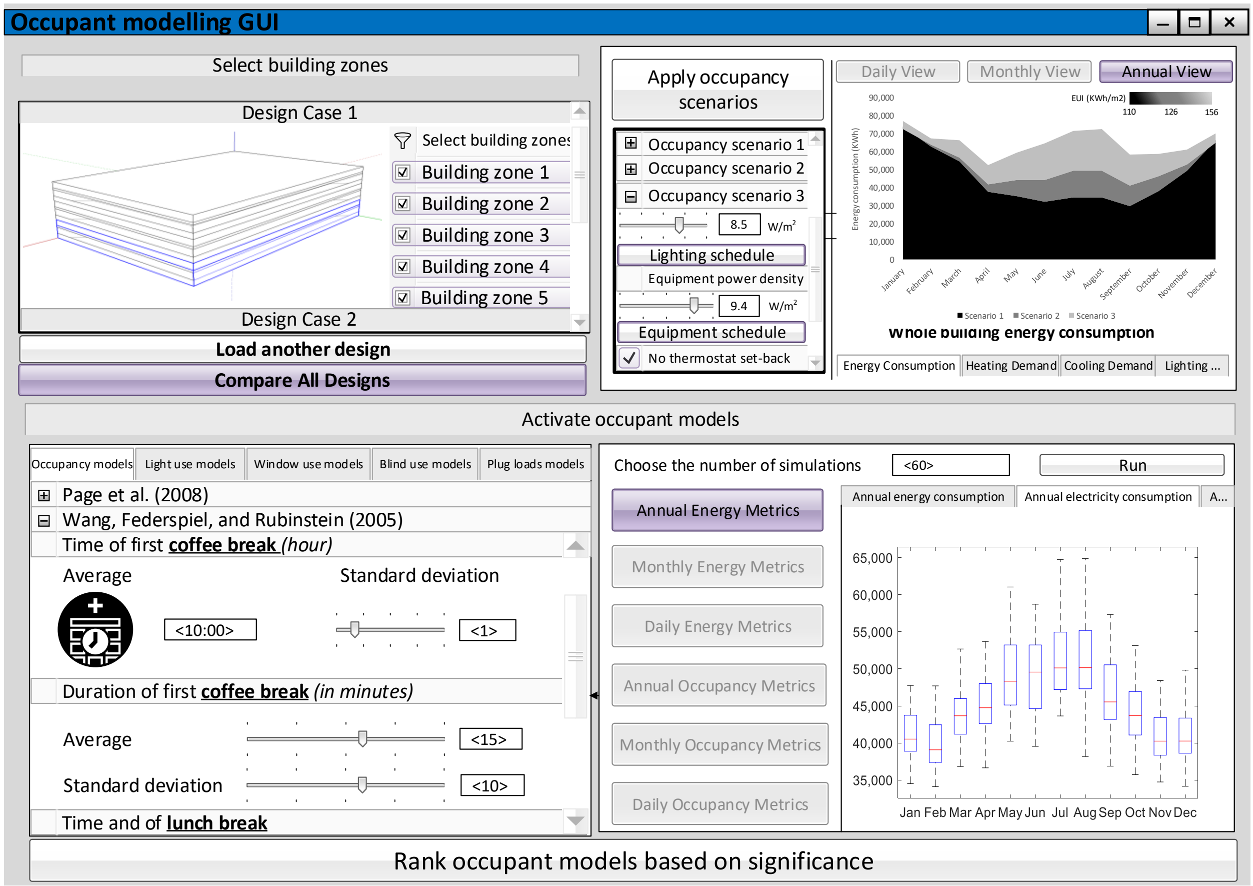


Figure 6: Example non-functional mock-up graphical user interface showing key occupant-related features for BPS tools

Following the review of BPS tools, a method to generate design-specific occupant-related schedules was developed. Rather than use advanced models, schedules are widely used by practitioners. Thus, this method could achieve the mutual benefits of simplicity, yet be somewhat specific to the building that is being modelled. This work was published as a journal (Ouf, O'Brien et al. 2019) and also a conference paper in the International Building Physics Conference in 2018 (Ouf, O'Brien et al. 2018), where it won best paper award. In this work, the focus was on lighting and how it is impacted by building orientation, window size, and shade use. Part of the novelty of the work is that the parametric simulations were summarized using decision trees such that the user chooses the most appropriate schedule based on the aforementioned variables. An example is shown in Figure 3.

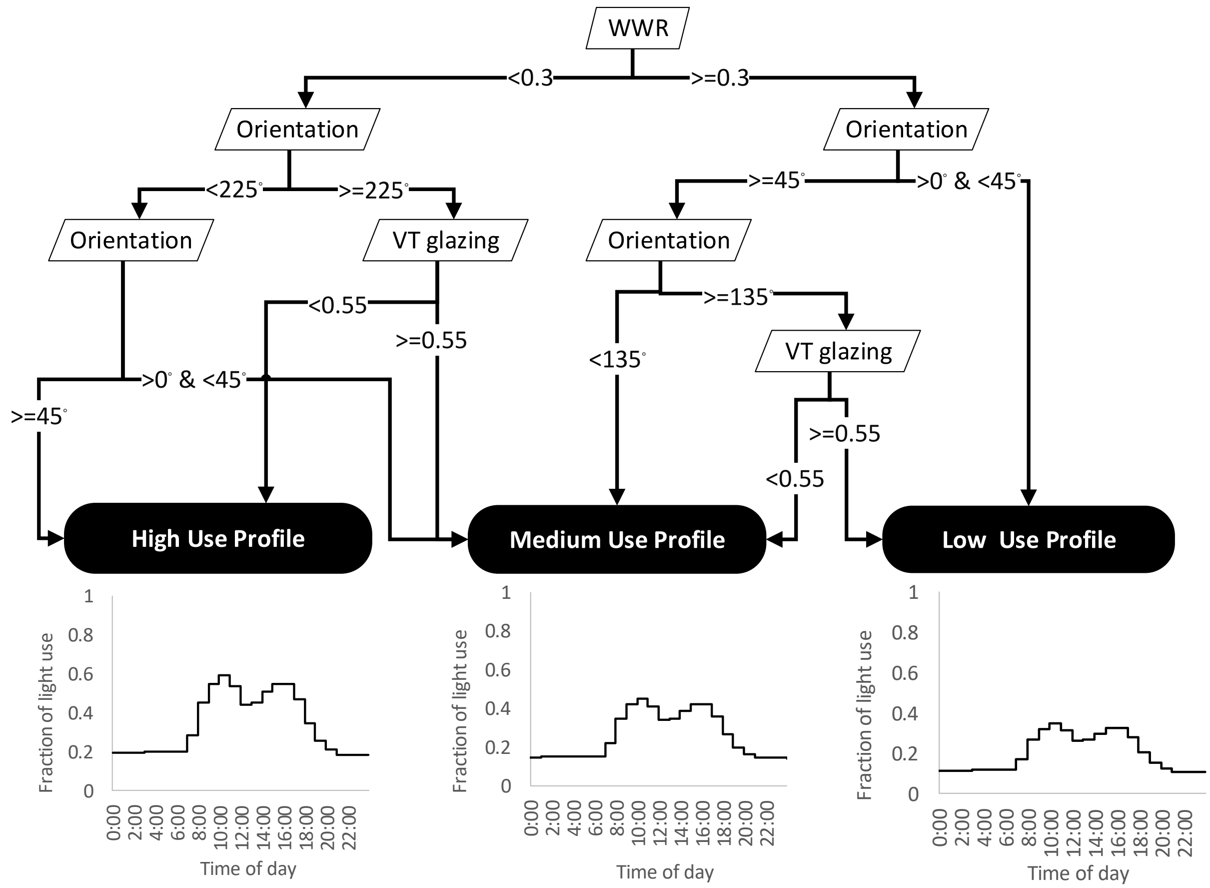


Figure 7: Example decision tree to guide building simulation users to choose the most appropriate lighting schedule based on various building parameters.

The final part of Phase 2 was a series of papers that proposed probabilistic design of HVAC systems (O'Brien, Abdelalim et al. 2019) and PV systems for net-zero energy buildings (Abdelalim, O'Brien et al. 2019). These papers argued that designing for extreme/worst-case occupancy scenarios is very costly, despite the unlikeliness of such cases occurring.

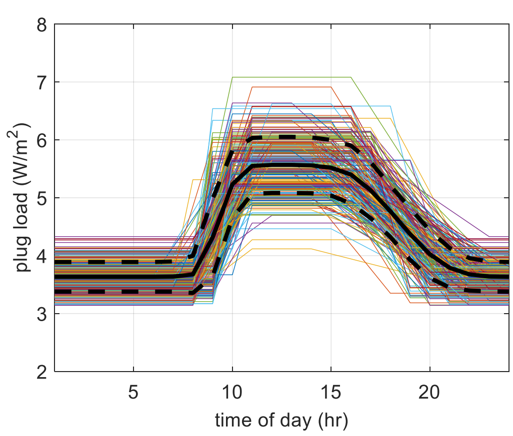


Figure 8: Example of plug load model with measured data fit to the linear piecewise model

First, a probabilistic schedule-based model for plug loads, lighting, and occupancy were developed from measured data of an office tower in Ottawa. Then the model was implemented in an EnergyPlus model (Figure 9) and run hundreds of times to derive a probability distribution for peak HVAC equipment and PV array sizes. The results of those distributions are shown in Figure 10 and Figure 11. In both cases, they show that each incremental point of confidence that the system is adequately sized for all scenarios is increasingly expensive.

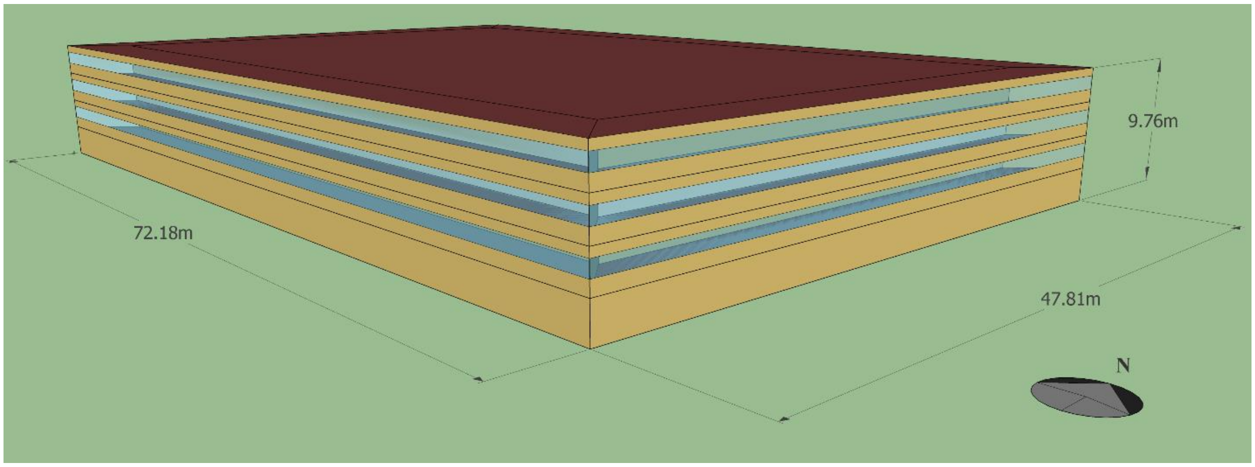


Figure 9: Archetype office model in EnergyPlus

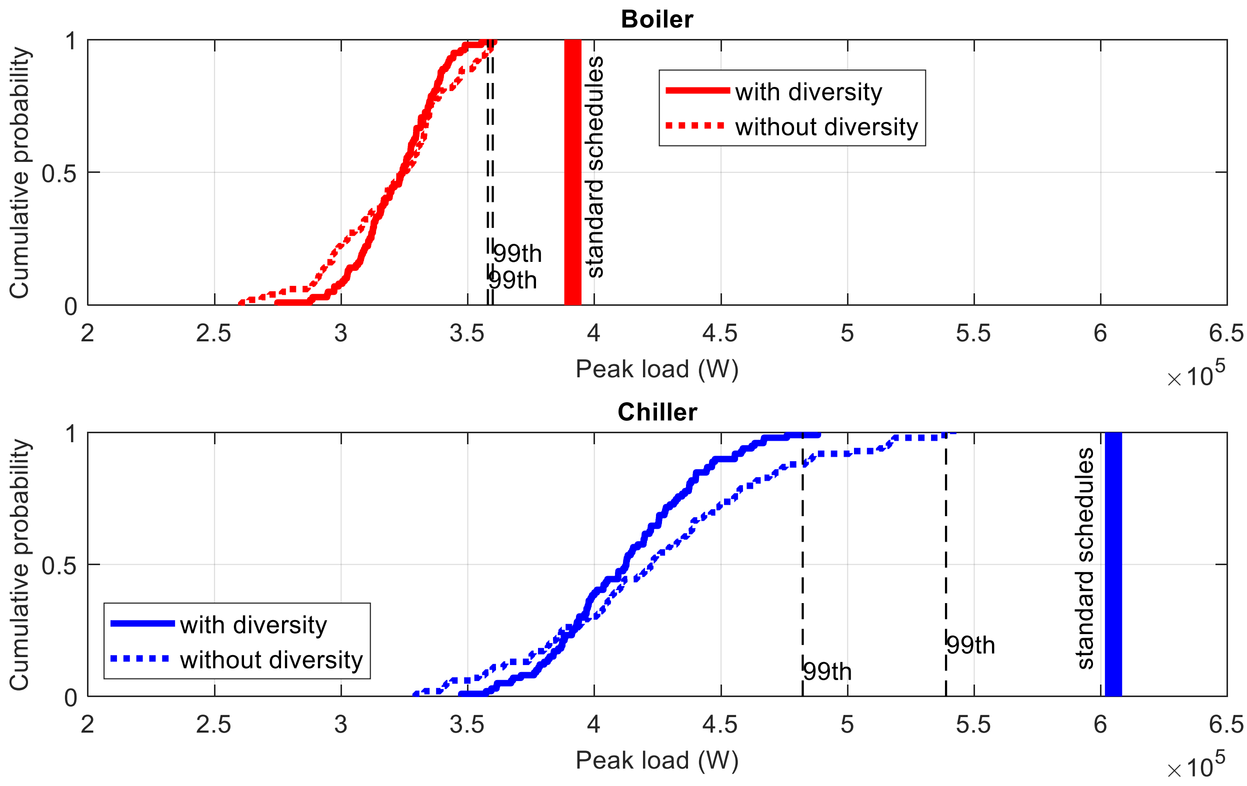


Figure 10: Cumulative probability of peak loads obtained from the stochastic occupancy schedules

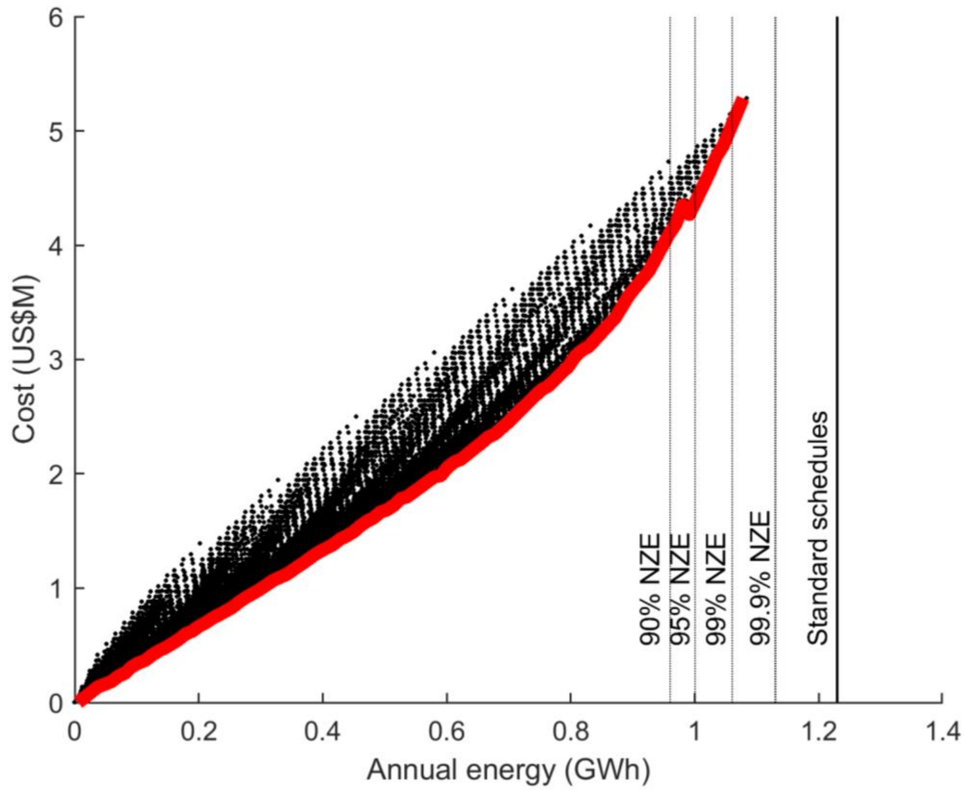


Figure 11: Relationship between confidence to achieve net-zero energy and the cost of the PV array

2.3 PHASE 3: Occupant modelling for building design best practices guidebook for Canada.

This phase was primarily devoted to educating early adopters of advanced occupant modelling in practice. It served the purposes of improving the state-of-the-art, removing barriers for consultants, improving industry receptiveness, and serve as a training tool. The central deliverable was a guidebook on best practices for occupant modelling. This was supported by several workshops, online videos, and example models. These are all provided on the HBI Lab website as well as Section 4 of this report.

Additionally, a series of systematic simulation-based investigations was performed to support selecting the most appropriate occupant modelling strategies. The two most profound are summarized here. First, the impact of spatial scale (i.e., single office up to large buildings) was investigated regarding uncertainty from occupants (Gilani, O'Brien et al. 2018). Second, the occupant domains were systematically modelled using standard and advanced methods for the major climate zones across Canada (Gilani and O'Brien 2019).

To explore the impact of uncertainty at different spatial scales, a building with a variable number of offices was modelled and occupancy, window use, and light use models were examined (Figure 12).

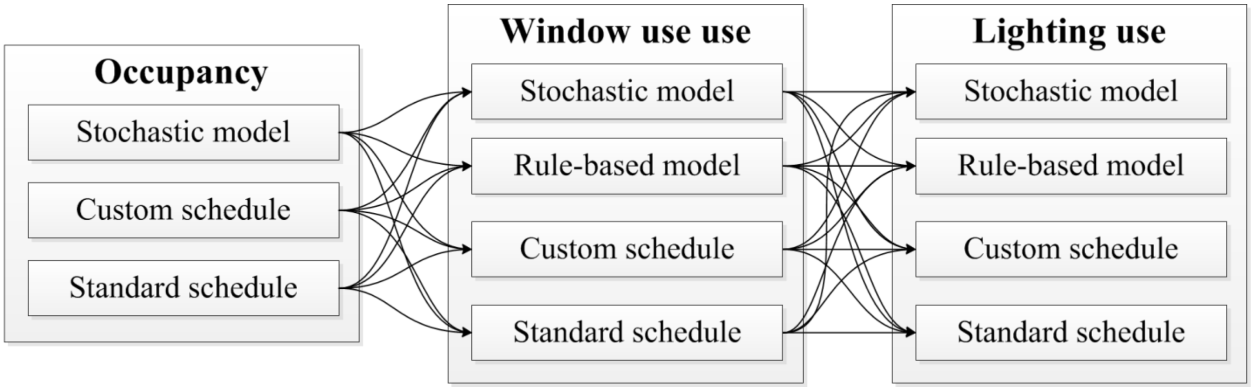


Figure 12. Combinations of various occupant model forms that were considered: occupancy, window shade use, and lighting domains.

Using a Monte Carlo approach, it was found that results converge at buildings with approximately 100 offices or more (see Figure 6). That is, above buildings of this size, the individual occupants – even if relatively extreme in their behaviour – do not cause the building-scale performance to deviate significantly from the mean. This result suggests that for larger office buildings, simpler occupant models can normally be used in place of advanced stochastic occupants, without concern of mischaracterization.

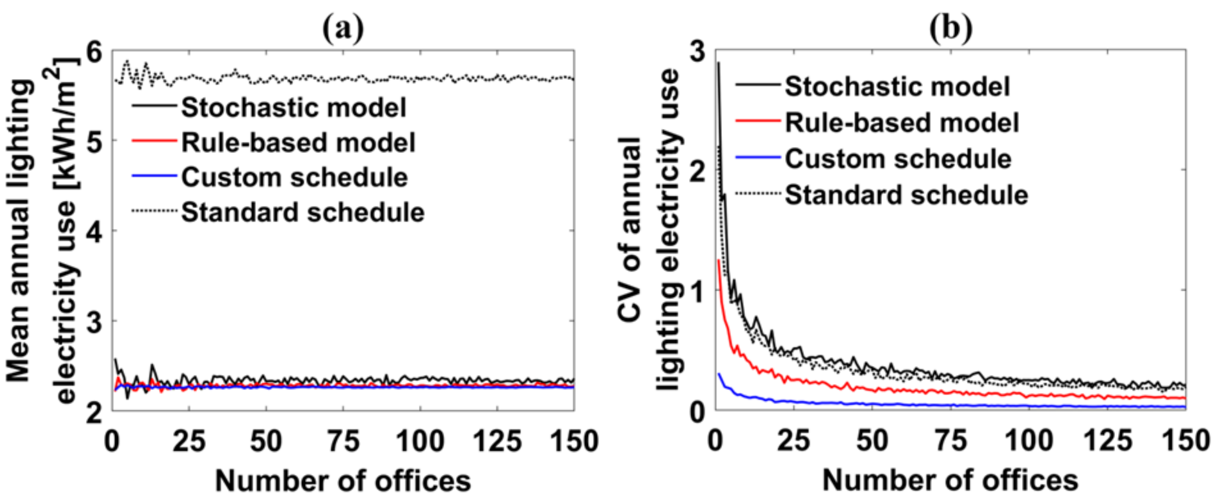


Figure 13. Annual lighting electricity use (kWh/m²) of samples with different sizes based on the simulation results of 150 annual run periods when the stochastic models were implemented for occupancy and window shade use, while four models (i.e. stochastic and rule-based models and custom and standard schedules) were implemented for light switch-on actions: (a) mean, (b) and coefficient of variation.

The second key study systematically compared the results of standard and advanced occupant models for occupancy, lighting, blinds, windows, plug loads, and thermostats – and all possible combinations of these. These were run in a building across climate zone 4 (e.g. Vancouver) to climate zone 8 (e.g., Yellowknife). The results are summarized in Figure 14, where the deviation between the standard occupant modelling approach and advanced approach is quantified for natural gas use and electricity. The results indicate that the energy use is particularly sensitive to lighting and occupancy, though it is quite dependent on the combination of advanced models that are used. It is also notable that certain domains are particularly sensitive to climate. For example, there is relatively little risk of energy-adverse window opening behaviour in the coldest climate zones (e.g. 7 and 8) because the frequency of warm days but cold nights is lower than in the milder climates.

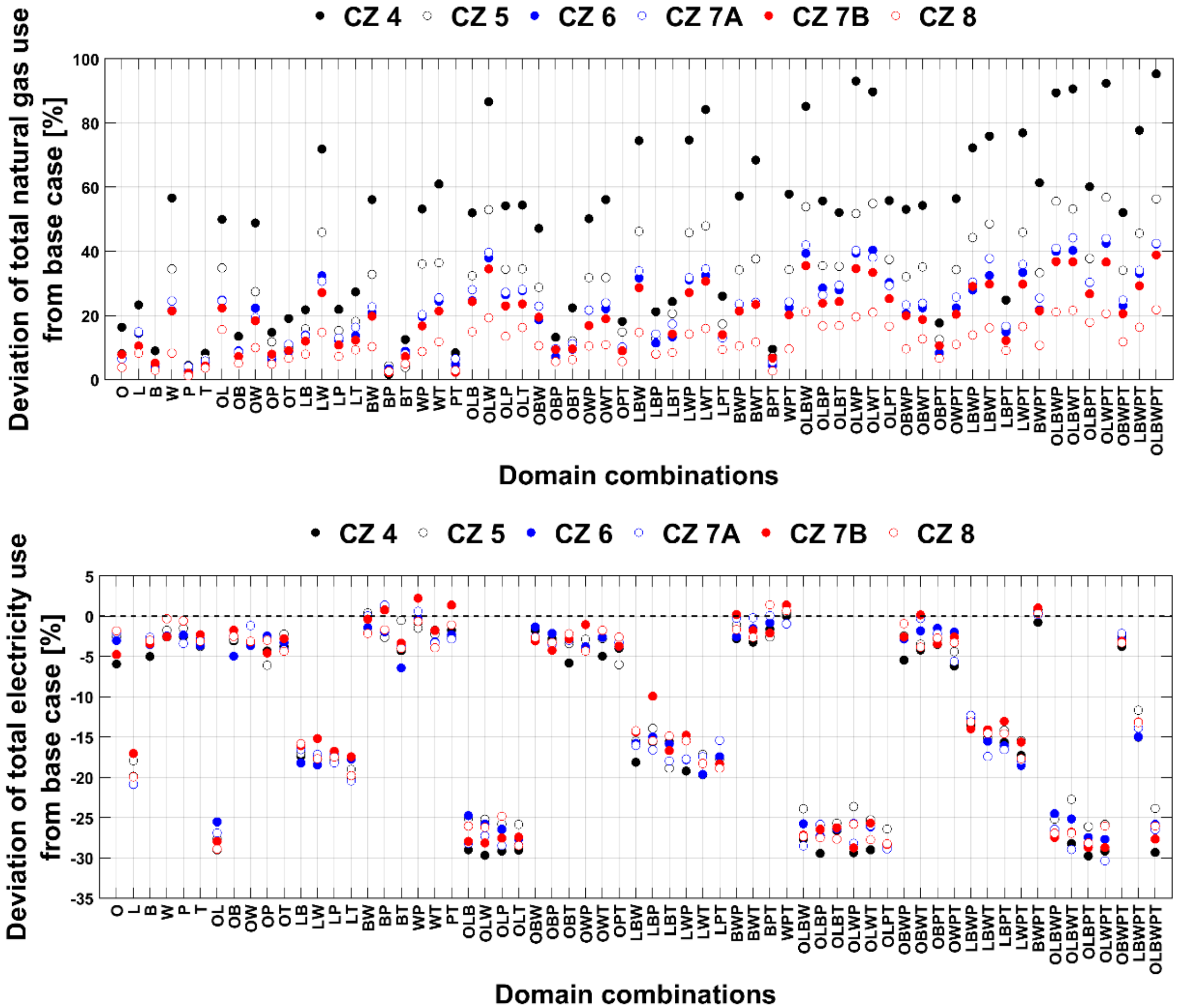


Figure 14. Comparing impact of modeling approaches of various occupant-related domain combinations on the deviation of the predicted annual energy use in six Canadian climate zones: (top) natural gas energy use, and (bottom) electricity energy use.

Figure 15 shows the sensitivity of individual domains against climates for annual natural gas and electricity use, using a main effects plot. As above, occupancy and lighting were found to be the most sensitive models regarding annual energy use.

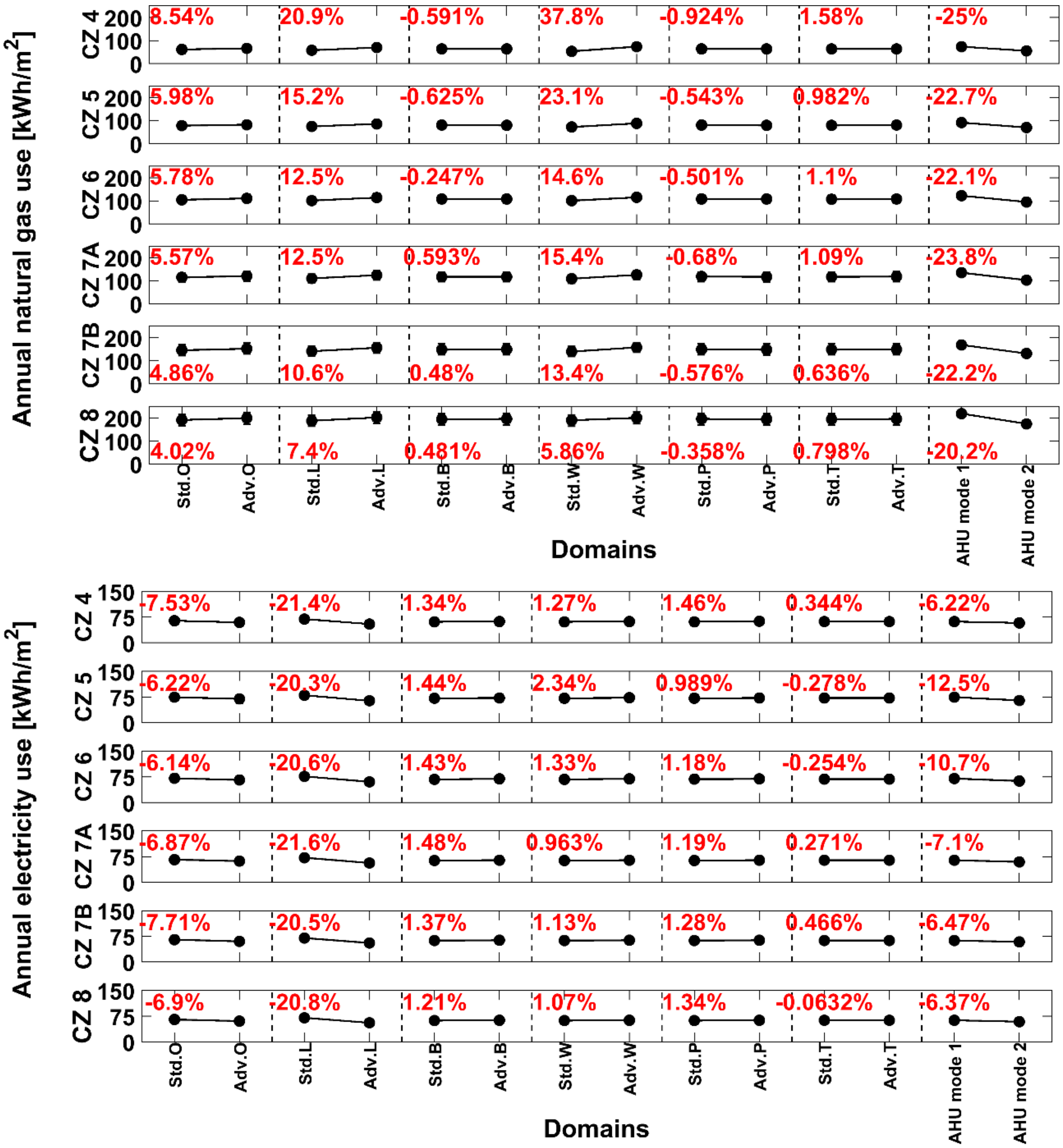


Figure 15. Comparing main effect of modeling approaches of each occupant-related domain using standard assumptions ("Std.") and advanced models ("Adv.") and two AHU modes in six Canadian climate zones: (top) natural gas energy use, and (bottom) electricity energy use.

2.4 PHASE 4: Real worked case study of occupant modelling

Phase 4 is the capstone of the project, as it heavily involved collaboration with the partners to apply project findings to a real case study. The case study was one of RWDI's office building projects in Toronto (Figure 16 and Figure 17).

The case study involved several major aspects: interviews with all key stakeholders about occupant-related aspects of the design process, a sensitivity analysis using modelling, and design optimization. Highlights are briefly summarized here. The work has also been widely disseminated (Abuimara, O'Brien et al. 2018, Abuimara, O'Brien et al. 2019, Abuimara, O'Brien et al. 2020) (refer to Section 4 for details).

Figure 16: Rendering of case study at 80 Atlantic Avenue, Toronto. (source: RJC Engineers)

Figure 17: Construction of case study at 80 Atlantic Avenue, Toronto in 2019. (source: RJC Engineers)

Early in the project, the architect, owner, energy modeller, and mechanical engineer were interviewed. In brief, the assumptions about occupants tended to be quite simplistic and also varied widely. A striking result is the major differences in assumptions of the three companies that modelled the building (Figure 18). One of the challenges of these parties was that the tenants were largely unknown during design.

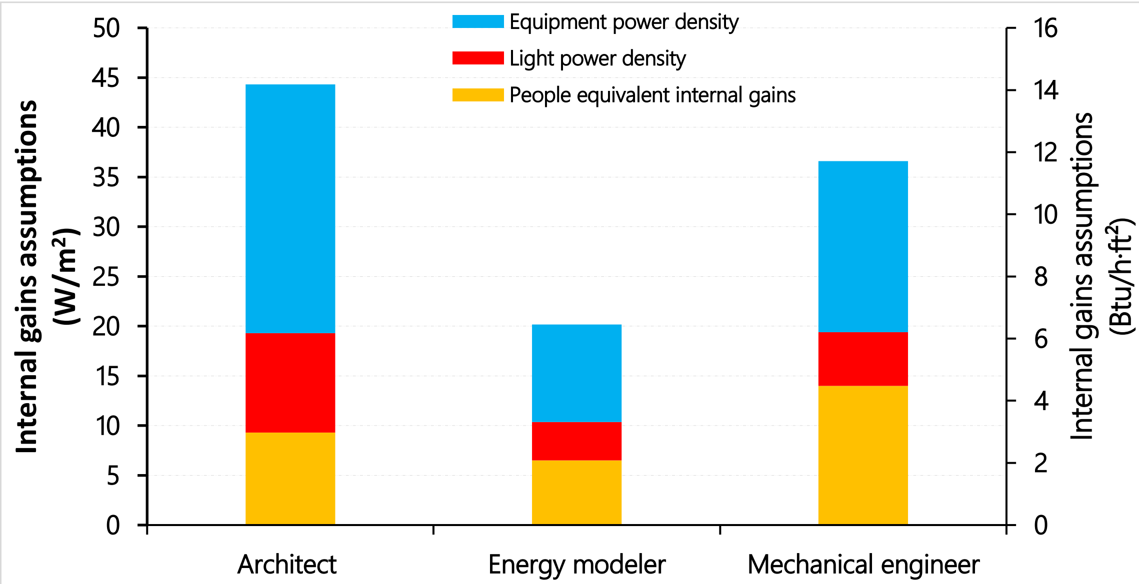


Figure 18: Modeling assumptions about heat gains from occupants, lighting, and equipment made by the architect, energy modeller, and mechanical engineer for the case study project.

Next, the study quantified the energy impact of design upgrades according to the energy modelling and architect assumptions. As shown in Figure 19, some improvements (e.g., better windows, higher roof insulation, and demand-controlled ventilation) were significantly affected by the assumptions that were used.

	Modeler assumptions	Architect assumptions
USI=1.467, SHGC=0.245	3.02%	1.87%
USI=2.036, SHGC=0.584	4.15%	0.41%
WWR = 30%	-0.16%	0.55%
USI=1.62, SHGC=0.388	4.64%	1.86%
Roof_RSI = 7 m²·K/W	2.95%	1.13%
Roof_RSI = 9 m²·K/W	5.28%	2.02%
Roof_RSI = 11 m²·K/W	6.75%	2.47%
Wall_RSI= 4 m²·K/W	0.79%	0.36%
Wall_RSI= 5 m²·K/W	1.44%	0.65%
Wall_RSI= 7 m²·K/W	2.12%	0.97%
Infl = 0.15 ach	2.23%	0.65%
COP = 4	1.26%	1.30%
COP = 5	3.03%	3.13%
Boiler eff. = 0.95	2.22%	0.99%
Pump eff. = 0.95	0.17%	0.08%
ERV eff. [0.88, 0.78]	1.06%	0.44%
DCV	2.33%	4.94%

More savings

Less savings

Figure 19: Ranking of design alternatives with different occupant-related assumptions made by the energy modeler and the architect.

Building on the results of Phases 2 and 3, which relied on advanced occupant models (e.g. agent-based, stochastic), Phase 4 explored simpler methods to evaluate the impact of occupants on different energy-related design options. Using an energy model for the case study (Figure 20), the research showed how parametric and uncertainty analysis could be paired to distinguish design features that are particularly sensitivity to occupants from those that are robust against occupants. A workflow (Figure 21) was developed and results for the case study building presented as a heat map (Figure 22).

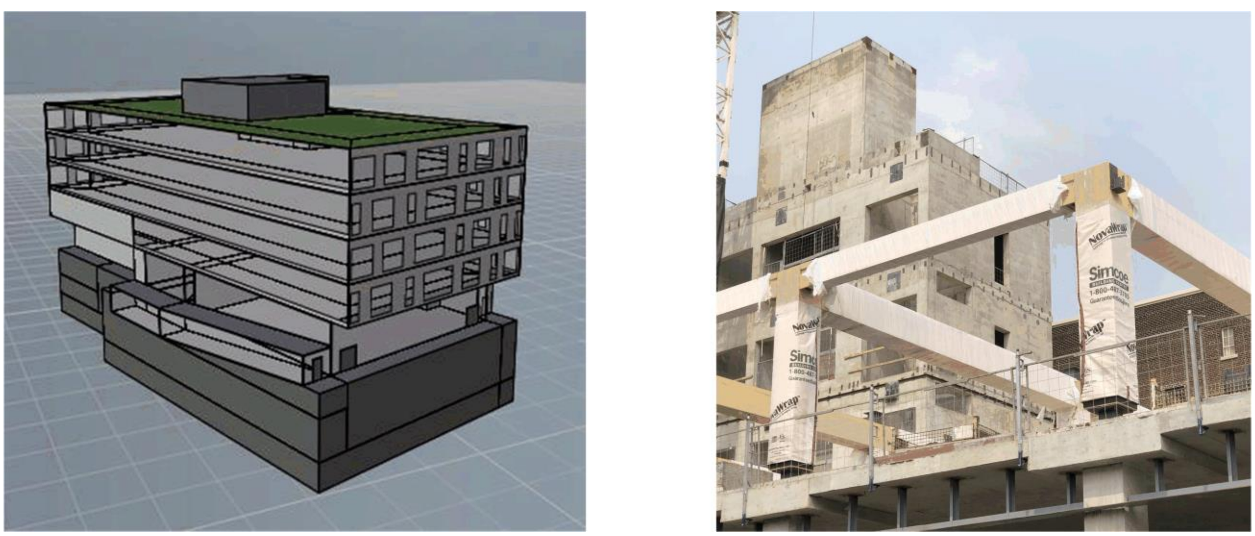


Figure 20: The case study: An office building in Toronto, Canada

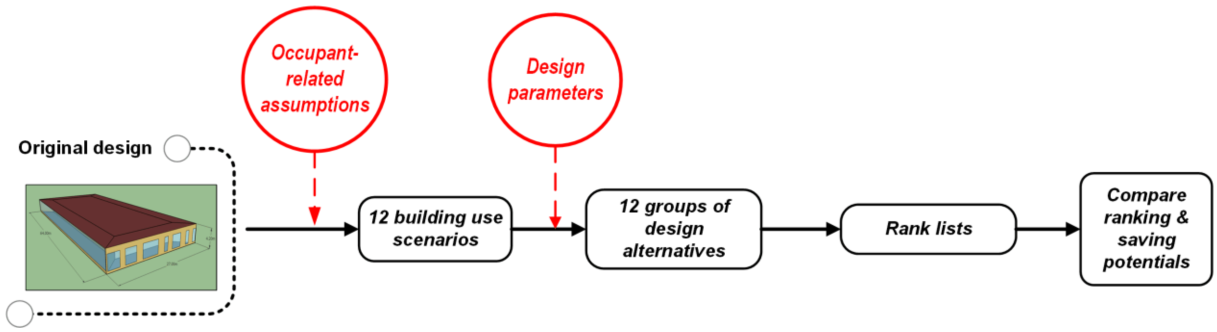


Figure 21: The simulation-based investigation workflow

Occupant scenarios

Design parameters	Original design scenario	Schedules x (0.4)	Schedules x (0.6)	Schedules x (0.8)	Schedules x (1.2)	Setpoints [clg 26.7, 22℃],[htg 15.6,22℃]	Setpoints [Always 22℃]	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 $m^2 \cdot K/W$	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%
Roof_RSI = 9 $m^2 \cdot K/W$	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 $m^2 \cdot K/W$	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 $m^2 \cdot K/W$	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 $m^2 \cdot K/W$	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 $m^2 \cdot K/W$	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%
[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%
Infl = 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%
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%

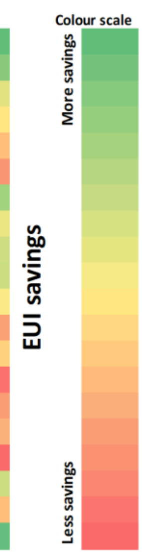


Figure 22: Ranking of design alternatives for various occupant-related scenarios

While Phase 4 was focused on a single case study building, in a single context, it adds to a growing body of evidence that: 1) occupants are treated in simple ways in the design process, and 2) that occupant-related assumptions can profoundly affect optimal design strategies. We hope that this case study provides tangible evidence to the design community.

3 Project benefits, outcomes, and ongoing work

The planned benefits and deliverables of this project were achieved or exceeded as per the original plan. The direct and immediate benefits from this project include: 1) project partners developed greater know-how that is influencing their work and service offerings, and 2) significant advancement of the state-of-the-art in occupant modelling, which was widely disseminated to the research community and government via a significant number of peer-reviewed publications.

The project was heavily influenced by the National Energy Code of Canada for Buildings (NECB) and used the requirements of that code for most of the discussion and simulation studies. Much like other codes internationally, NECB uses simplified and dubious assumptions about occupants. Thus, much of the project focused on developing better occupant modelling practice and making recommendations for NECB. For example, O'Brien and Gunay (2019) showed that the NECB does not reward buildings with finer resolution of lighting control zones (Figure 23 and Figure 24). This work showed that lighting energy use could be halved with finer lighting control zone resolution and that the assumption of near-full occupancy in offices may cause decision-makers to underestimate this benefit.

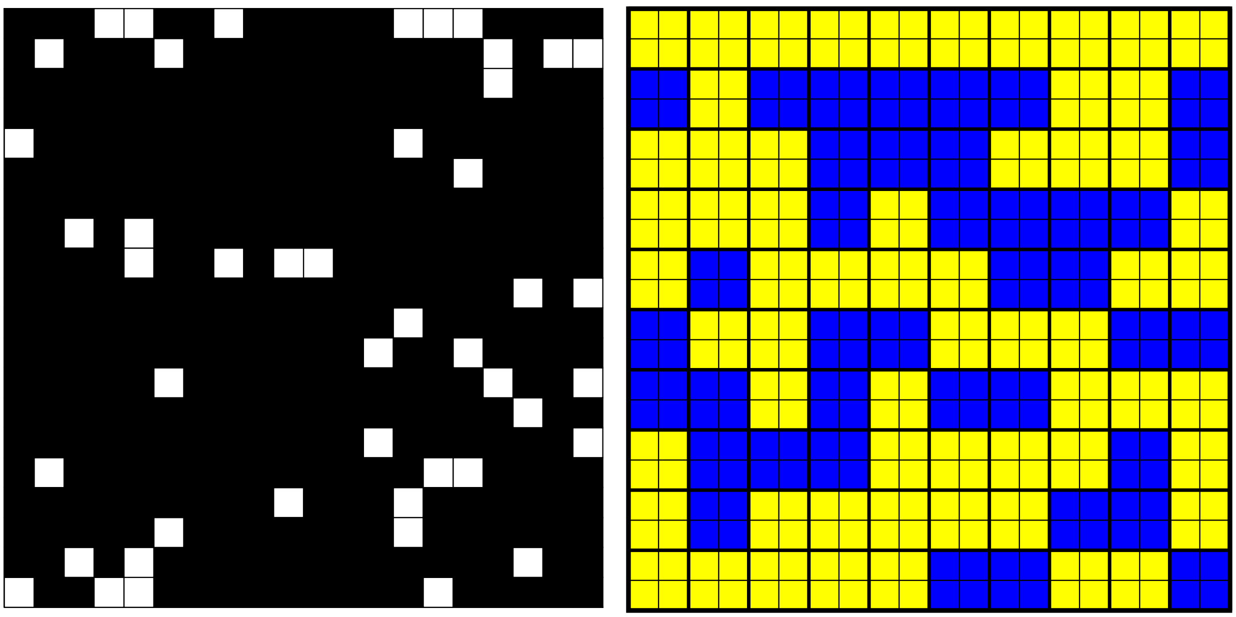


Figure 23: Layout of the open office space showing simulation results for one point in time: occupancy (left) and lighting state (right).

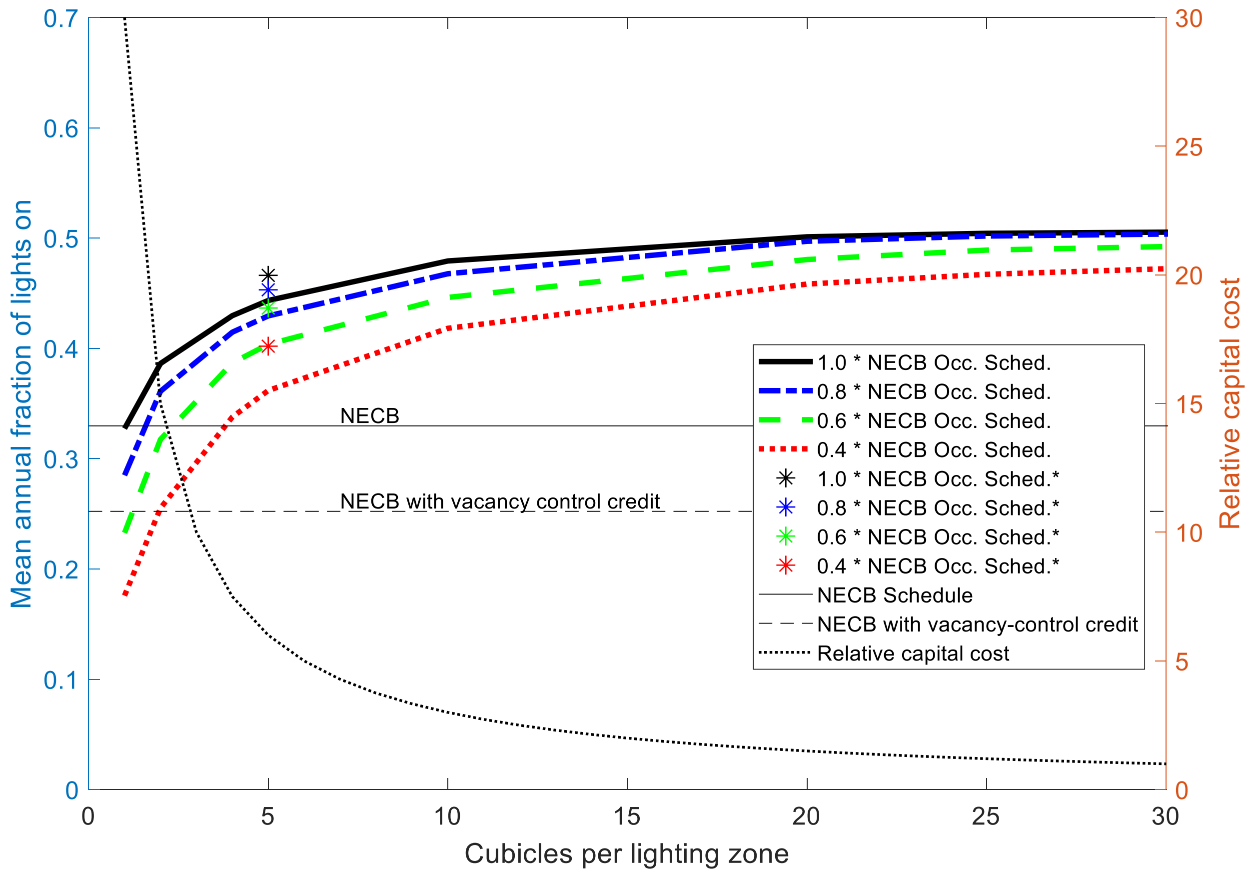


Figure 24: Simulation results showing the fraction of total time that lights are on for lighting control zone sizes from one to 30 cubicles per lighting zone and four different occupancy scenarios. The four points represent the NECB lighting control zone requirements and are shown just for context.

Moreover, this project demonstrated how more advanced occupant modelling could be used to more accurately evaluate code requirements. The research team met with NRC (who administrate the committee for NECB) to provide recommendations and get feedback on the research. Moreover, this project spurred a longer-term collaboration with NRC which is expected to direct lead to changes in the National Building Code.

The researchers' leadership in this area propelled them to start a five-year international collaboration under the International Energy Agency - Energy in Buildings and Communities Programme. Specifically, Prof. Liam O'Brien is one of two Operating Agents for IEA EBC Annex 79. Annex 79 is largely a continuation of this EIP. Also, as a result of the project, Canada has high representation on Annex 79 (approximately 15 researchers out of 100 from 16 countries). Some key areas of future work that Annex 79 will pursue are: code recommendations and occupant-centric design guidelines. Addressing the gaps of the current project, Annex 79 will take a global view of occupant-related code requirements. To date, 23 regions’ codes have been reviewed and compared in order to learn best practices. Some notable findings are that assumptions vary by a factor of five or more between countries and that several codes require occupant user manuals. The next step is to make concrete recommendations for advancing the way occupants are treated in building codes. To solidify the findings of this project and bring an international and multidisciplinary perspective, and occupant-centric building design book is planned to be published. Complementing the current case study in Phase 4, the book will include approximately six additional case studies from a variety of climates (e.g. Quebec City and Melbourne) and building types (e.g. university building, multi-unit residential building).

The project also led to the PI of this project being invited as co-authors on a new chapter on occupant modelling in the ASHRAE Fundamentals Handbook. The Handbook is seen as the leading reference for building design professionals and students. The chapter introduces the practitioner and research community to the state-of-the-art in occupant modelling.

This project revealed that while there are needed advances in occupant modelling fundamentals, one of the biggest barriers is adoption and the necessary training and outreach. Given the wide variety of forms of dissemination (refer to Section 4), one of the biggest benefits of this project to Canada and society has been the level of information and education that was shared by the research team and partners.

The researchers have continued advocating for changes to the building code via continued work (and a two-year contract) with the National Research Council. This work involves identifying all aspects of the NBC that relate to occupants, comparing these aspects to the latest knowledge and data, performing batch simulations to demonstrate the impact of these aspects, and finally making recommendations for code changes where applicable.

The trained student and post-doctoral fellows have had great success as a result of this project. Two of them are now assistant professors, one is a researcher at Natural Resources Canada, and the PhD student is within a year of completing his PhD. The PhD student has also been awarded several prestigious awards (ASHRAE Grant-in-aid and NSERC PGS), which are largely due to this project. One of the post-doctoral fellows also won a best paper award at the International Building Physics Conference in 2018.

4 List of publications and other dissemination

Knowledge dissemination was a major component of this project. In total, 32 documents were publicly disseminated, including journal articles, conference papers, technical reports, and magazine articles. Some of these items reached 10s of thousands of professionals. For example, three articles were published in ASHRAE Journal that summarize the problems and our recommendations for occupant modelling. Results were also disseminated through educational workshops. For instance, the team delivered an all-day workshop at the eSim conference in Montreal. The workshop was attended by researchers, government, and industry professionals. During her visit to Autodesk, Dr. Sara Gilani (one of the post-docs) gave a half-day workshop to Autodesk employees. The team presented their work, particularly that with building code implications, to a large group of National Research Council researchers and managers. The best practices guidebook has been posted online and promoted widely. To accompany this written document, a set of step-by-step instructional videos for occupant modelling was developed and also posted online. The following list summarizes the key elements of dissemination of the project, starting with the most recent. Links are provided where available.

4.1 Journal articles

Abuimara, T., O'Brien, W., Gunay, B. (in press) Quantifying the Impact of Occupants During the Simulation-Aided Design Process: A Case Study. Building Research and Information. 47(8):866-882. https://doi.org/10.1080/09613218.2019.1652550

Ouf, M., O'Brien. W., Gunay, B. (2020) Optimization of electricity use in office buildings under occupant uncertainty. Journal of Building Performance Simulation. 13(1): 13-25. https://doi.org/10.1080/19401493.2019.1680733

Gilani, S., O'Brien, W. (2019) Exploring the impact of office building occupant modeling approaches on energy use across Canadian climates. Energy and Buildings. 132:327-337. https://doi.org/10.1016/j.enbuild.2019.05.042

Ouf, M., O'Brien. W., Gunay, B. (2019) On quantifying building performance adaptability to variable occupancy. Building and Environment. 155:257-267. https://doi.org/10.1016/j.buildenv.2019.03.048

O'Brien, W., Gunay, B. (2019) Do building energy codes adequately reward buildings that adapt to partial occupancy? Science and Technology for the Built Environment. 25(6):678-691. https://doi.org/10.1080/23744731.2019.1581015

Abdelalim, A., O'Brien, W., Gilani, S. (2019) A probabilistic approach towards achieving net-zero energy buildings using stochastic tenant models. Science and Technology for the Built Environment. 25(6):743-752. https://doi.org/10.1080/23744731.2019.1598137

Ouf, M., O'Brien. W., Gunay, B. (2019) A method to derive design-sensitive schedules for light use in buildings. Building and Environment. 25(2):221-232. https://doi.org/10.1080/23744731.2018.1514855

O'Brien, W., Abdelalim, A., Gunay, B. (2019) Development of an office tenant electricity use model and its application for right-sizing HVAC equipment. Journal of Building Performance Simulation. 12(1):37-55. https://doi.org/10.1080/19401493.2018.1463394

D'Oca, S., Gunay H.B., Gilani S., O'Brien W. (2019) A review of the occupant modeling approaches in offices with illustrative examples. Building Services Engineering Research and Technology. https://doi.org/10.1177%2F0143624419827468

Ouf, M., O'Brien. W., Gunay, B. (2018) Improving occupant-related features in building performance simulation tools. Building Simulation. 11(4):803–817. https://doi.org/10.1007/s12273-018-0443-y

Gilani, S., O'Brien, W., Gunay, B. (2018) Simulation of occupants' impact at different spatial scales. Building and Environment. 132:327-337. https://doi.org/10.1016/j.buildenv.2018.01.040

4.2 Conference papers

Gilani, S., Goldstein, R., Breslav, S., Tessier, A., O'Brien, W. (2019) Building Performance Implications of Occupant Mobility. Building Simulation 2019. Sept. 2-4. Rome, Italy.

O'Brien, W., Gunay, B., Ouf, M. (2019) Simulation-based Approach to Assess Occupant-adaptability Of Buildings. Building Simulation 2019. Sept. 2-4. Rome, Italy.

Abuimara., T., O'Brien, W., O'Brien, W. (2019) Simulating the Impact of Occupants on Office Building Design Process: A Case Study. Building Simulation 2019. Sept. 2-4. Rome, Italy. https://www.dropbox.com/s/ti94pb83plfsdq2/BS2019%20-%20Simulating%20the%20Impact%20of%20Occupants%20on%20Office%20Building%20Design%20A%20Case%20Study.pdf?dl=0

Ouf, M., O'Brien, W., Gunay, B. (2019) Quantifying Occupancy-adaptive Building Operations. Building Simulation 2019. Sept. 2-4. Rome, Italy.

Ouf, M., O'Brien, W., Gunay, B. (2019) Optimizing Building Performance using Stochastic Occupant Models. ASHRAE Winter Conference. Jan. 12-16. Atlanta, GA

Gilani, S., O'Brien, W. (2018) Quantification of building energy performance uncertainty associated with building occupants and operators. International Building Physics Conference 2018. Sept. 24-26 Syracuse, NY. https://www.dropbox.com/s/efd2km92tq2v4ay/IBPC2018-Quantificationofbuildingenergyperformanceuncertainty.pdf?dl=0

Gilani, S., O'Brien, W., Gunay, B. (2018) Exploring occupants' impact at different spatial scales. International Building Physics Conference 2018. Sept. 24-26 Syracuse, NY https://www.dropbox.com/s/xqhd5z1n8773kqb/IBPC2018-Spatialscalepaper.pdf?dl=0

Ouf, M., O'Brien, W., Gunay, B. (2018) Generating design-sensitive occupant-related schedules for building performance simulations. International Building Physics Conference 2018. Sept. 24-26 Syracuse, NY (Best paper award)

Abuimara, T., O'Brien, W., Gunay, B., Burpee, H., Day, J. (2018) Designing for Occupants: A Review of the Integrated Design Practice. ACEEE Summer Study. Aug. 12-17, 2018 Pacific Grove, California. https://www.dropbox.com/s/mkh2jw0k3kbflsv/ACEEE-Designing%20for%20Occupants%20A%20Review%20of%20the%20Integrated%20Design%20Practice.pdf?dl=0

Gilani, S., O'Brien, W. On the appropriateness of occupancy models for various temporal and spatial scales. eSim 2018. May 9-10, Montreal, QC

Abdelalim, A., O'Brien, W. An approach towards achieving net-zero energy buildings based on a stochastic tenant model. eSim 2018. May 9-10, Montreal, QC. https://www.dropbox.com/s/vu9kfec2hrb31ih/eSim2018_An%20Approach%20Towards%20Achieving%20Net-Zero%20Energy%20Buildings%20Based%20on%20a%20Stochastic%20Tenant%20Model.pdf?dl=0

Gunay, B., O'Brien, W. Implementation of occupant models in EnergyPlus through an OpenStudio measure. eSim 2018. May 9-10, Montreal, QC. https://www.dropbox.com/s/zg6fmddq0jcx0yg/eSim2018_Implementation%20of%20occupant%20models%20in%20EnergyPlus%20through%20an%20OpenStudio%20measure.pdf?dl=0

Ouf, M., O'Brien, W., Gunay, B. A Framework to Improve Occupant Modeling Capabilities in Building Simulation Tools. eSim 2018. May 9-10, Montreal, QC. https://www.dropbox.com/s/skwlfk05y50gy2n/eSim%202018_A%20Framework%20to%20Improve%20Occupant%20Modeling%20Capabilities%20in%20Building%20Simulation%20Tools.pdf?dl=0

Abuimara, T., O'Brien, W., Gunay, B., Carrizo, S. Assessing the impact of occupants on building design decision making. eSim 2018. May 9-10, Montreal, QC. https://www.dropbox.com/s/j81tav543xghj5b/eSim2018_Assessing%20the%20impact%20of%20occupants%20on%20design%20decision%20making.pdf?dl=0

Abuimara, T., O'Brien, W., Gunay, B., Abdelalim, A., Ouf, M., Gilani, S. Modelling occupants in buildings: Stakeholders' workshop on current barriers, challenges, and needs. eSim 2018. May 9-10, Montreal, QC. https://www.dropbox.com/s/plfyfc4k6r5q4ss/eSim2018_Tareq%20Abuimara_1110_Modelling%20occupants%20in%20buildings.pdf?dl=0

O'Brien, W., Gunay, B., Beausoleil-Morrison, I., Kesik, T. Carrizo, S., Danks, R., Ouf, M., Gilani, S., Abdelalim, A., Roadmap for Occupant Modelling for Building Codes and Standards. eSim 2018. May 9-10, Montreal, QC. https://www.dropbox.com/s/3c32nkbbscc47u5/eSim_2018_Roadmap%20for%20Occupant%20Modelling%20in%20Building%20Codes%20and%20Standards%20Final.pdf?dl=0

4.3 Technical reports and guidebooks

O'Brien, W., Ouf, M., Gunay, B., Gilani, S., Abuimara, T., Abdelalim, A. (2018). Roadmap for the advancement of occupant modelling for building codes, standards, and design practice. https://www.dropbox.com/s/ajhtplmrzr3zxa6/Roadmap%20for%20the%20advancement%20of%20occupant%20modelling.pdf?dl=0

Gilani, S., O'Brien, W. Best practices guidebook on advanced occupant modelling. https://www.dropbox.com/s/kkx7e1eqqt6urvj/Best%20Practices%20Guidebook%20on%20Advanced%20Occupant%20Modelling.pdf?dl=0. Instructional videos: https://carleton.ca/hbilab/projects/nrcan-occupant-modelling-project/

Review of current schedules used in building performance simulations. https://www.dropbox.com/s/g1qz31thcubo99j/Review%20of%20current%20schedules%20used%20in%20building%20performance%20simulations.pdf?dl=0

4.4 Magazine articles

Abuimara, T., O'Brien, W., Gunay, B. (2020) How can assumptions about occupants misinform building design? ASHRAE Journal. https://www.dropbox.com/s/n5h6roavbdcc37p/ASHRAE%20Journal%20Jan%202020%20-%20How%20can%20assumptions%20about%20occupants%20misinform%20building%20design.pdf?dl=0

O'Brien, W., Gilani, S., Ouf, M. (2019) Occupant modeling for building design and code compliance – Part 1. ASHRAE Journal. February. https://www.dropbox.com/s/dtmnulsxiul00kn/ASHRAE%20Journal%20-%20February%202019%20Part%201.pdf?dl=0

Ouf, M., Gilani, S., O'Brien, W. (2019) Occupant modeling for building design and code compliance – Part 2. ASHRAE Journal. March. https://www.dropbox.com/s/qgvsijtovq1ur7o/ASHRAE%20Journal%20-%20March%202019%20Part%202.pdf?dl=0

Gilani, S., O'Brien, W., Ouf, M. (2019) Occupant modeling for building design and code compliance – Part 3. ASHRAE Journal. April.

https://www.dropbox.com/s/qgvsijtovq1ur7o/ASHRAE%20Journal%20-%20March%202019%20Part%202.pdf?dl=0

Ouf, M., O'Brien, W. (2018). Can we game code compliance through occupant modeling? ASHRAE Journal. February. https://www.dropbox.com/s/wtom9nq45aq9d1u/ASHRAE%20Journal_Occupant%20Modeling%20for%20Code%20Compliance%20and%20Incentive%20Programs.pdf?dl=0

4.5 Presentations and webinars

Occupant modelling roadmap webinar; Slides: https://www.dropbox.com/s/qrni02vux6lbovh/Occupant%20modelling%20roadmap%20webinar.pdf?dl=0 Video: https://www.screencast.com/users/PatGilbert/folders/Liam.Obrien/media/d58d9759-f4d5-440e-bc1a-9c9d68b87ed7/embed?theme=dusk

O'Brien, W. eSim 2018 keynote talk: Humanizing building simulation: Current state and future outlook of modelling occupants. https://www.dropbox.com/s/ggeqr41mbjpw53r/Keynote%20eSim%202018%20O%27Brien.pdf?dl=0.

O'Brien, W., Gilani, S., Ouf, M. eSim 2018 occupant modelling workshop. https://www.dropbox.com/s/yq7q681h0zpjhwi/eSim2018_Workshop_SimulatingOccupantsInBuildings.pdf?dl=0

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Abuimara, T., W. O'Brien, B. Gunay, J. Day and H. Burpee (2018). Designing for Occupants: A Review of the Integrated Design Practice. CEEE 2018 Summer Study on Energy Efficiency in Buildings. Pacific Grove, CA.
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Gunay, H. B., W. O'Brien, I. Beausoleil-Morrison and J. Bursill (2018). "Development and implementation of a thermostat learning algorithm." Science and Technology for the Built Environment **24**(1): 43-56.
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O'Brien, W. and H. B. Gunay (2019). "Do building energy codes adequately reward buildings that adapt to partial occupancy?" Science and Technology for the Built Environment: 1-14.
O'Brien, W., A. Abdelalim and H. B. Gunay (2018). "Development of an office tenant electricity use model and its application for right-sizing HVAC equipment." Journal of Building Performance Simulation: 1-19.
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