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Partial occupancy of commercial offices has become the norm in the wake of the COVID-19 pandemic. Given this, occupant-centric control (OCC), which adapt building systems based on occupants’ presence or preferences, offer an alternative to traditional control that assumes full occupancy. However, poor sequences of operation can degrade the benefits of OCC. This paper explores this interaction by examining energy data from two buildings – one with two control logic faults corrected and an occupancy-based ventilation OCC implemented in 2020, and one with traditional ventilation – from 2019 to 2020. Sequences that impacted implementation in the first building are discussed. Then, a calibrated energy model of the second building is developed to evaluate how occupancy-based ventilation alongside changes to the sequences of operation – namely supply air temperature (SAT) reset and economizer high limits – impacted energy use. The inclusion of OCC and improved sequences in the second building saved 30.6% and 9.6% of annual heating and cooling energy, respectively. Without an SAT reset, OCC saved 4.4% and 3.9% of heating and cooling, respectively, compared to 15.7% and 5.7% when an SAT was present. These results begin to characterize the relationship sequences of operation and OCC implementations have with one another in commercial offices.

1. Introduction

According to Statistics Canada, the proportion of the Canadian workforce working remotely full-time was 13% in 2018 [1], rising to 39% within one year of the COVID-19 pandemic [2]. Industries such as finances, technical and professional services, information technology, and the public service have been identified as having the highest potential remote work capacities, ranging from 58% to 85% [2]; as such, the distribution of the remote work has been disproportionately high in these industries, which typically operate out of commercial office spaces. Consequently, the occupancy of commercial office buildings has dropped during the pandemic; this trend will continue into the post-pandemic world. Indeed, return-to-work models in many workplaces are likely to take the form of hybrid workweeks whereby employees are only present in their offices for limited days of the week. As such, the occupancy in commercial office buildings moving forward will likely be partial and sporadic in nature, abandoning the historically rigid work schedules of traditional office environments.

Despite twenty-plus years [3,4] of transitioning away from these rigid schedules and the paradigm-shifting events of the COVID-19 pandemic, the operation of commercial office buildings’ heating, ventilation, and air conditioning (HVAC) systems – predominantly configured as multiple zone variable air volume (VAV) air handling units (AHUs) in North America [5] – has lagged considerably. Static start and stop times for equipment operating at near-full capacity throughout the workday regardless of occupancy levels are standard [6–8]. The current method of design for VAV AHU systems can itself be maladapted to operating buildings efficiently at partial occupancy, as the zoning of HVAC systems can be coarse compared to the spatial distribution and density of occupants (e.g., climate control of several single-occupant offices with a single VAV terminal unit). Additionally, these systems are typically sized and operated primarily to meet thermal loads, which may result in a disproportionate distribution of ventilation to zones with high thermal loads, regardless of occupancy [9]. In contrast to traditional building control is occupant-centric control (OCC), where building services are provided where and when they are needed and in the amount that they are needed [10]. While the use of OCC at a commercial scale has yet to be realized [11], OCC has the potential to improve both occupant comfort and building energy use given the type of occupancy that is likely to be seen in commercial office buildings in the post-pandemic world.
A recent review article by Park et al. [7] provides a window into the growing body of literature on field implementations of OCC. The authors note that one of the barriers to the adoption of these controls is that implementations have been limited in scope to one or a handful of zones; this allows for tightly controlled environments which are critical for measurement and verification of performance. However, these conditions do not reflect the challenges an OCC implementation might face in reality. A building automation system (BAS) is composed of complex hardware and software used by many parties over a building’s lifecycle. At any point from conception to decommissioning, faulty or inefficient control sequences can manifest; while OCC has the potential to improve building adaptability to partial occupancy, the implementation of these controls cannot be performed in a vacuum. Indeed, Chen et al. [12] and Shi et al. [13] note that simply upgrading or retrofitting buildings and their BASs without addressing underlying faults can forfeit any potential energy savings from controls interventions, including OCC. Markus et al. [14] elaborate on this point, noting that metadata must be cleaned, faults detected and addressed, and sequence of operation upgraded before any controls intervention can take place, as these interventions may not behave as expected otherwise. For example, Gunay et al. [15] analyzed 35 office buildings and found that as much as 46% of them did not have afterhours schedules or setbacks, while many of the same buildings did not have a supply air temperature (SAT) reset scheme. While the number and quality of fault detection and diagnostic (FDD) methods continues to increase [16], these studies typically focus on the methods and accuracy of the proposed algorithms; the number of studies which examine the energy and/or comfort implications of these faults is comparatively limited. Pairing these poor sequences of operation with OCC to evaluate their impact on implementation yields a gap in the literature which this study begins to address anecdotally.

The aim of this study is two-fold. First, energy use data from two office buildings before and after the COVID-19 pandemic are compared; one building had two sequences of operation corrected and an OCC introduced in the form of a system-level occupancy-based ventilation scheme at the beginning of 2020, while the other had ventilation systems operate traditionally both before and after the pandemic. Second, a simulation-based investigation of the building that operated without OCC during the pandemic is undertaken using a calibrated energy model. This simulation exercise is used to determine the potential energy savings and impact on indoor environmental quality (IEQ) the implementation of this OCC would have had on this building during the pandemic. Additionally, the calibrated energy model is leveraged to explore how two different changes to the sequences of operation, namely the addition or omission of an SAT reset and the inclusion or exclusion of a 21 °C economizer high limit, would impact the buildings’ energy use and IEQ with or without OCC.

The remainder of this paper is structured as follows. In the background section, the interactions between OCC and sequences of operation are explored within the literature. Then, the methodology section presents the two case study buildings, their associated data, and the calibration process and scenarios for the energy model, as well as the analysis approach taken for each respective aspect of the study. The results from this analysis and the limitations of the study are subsequently illustrated and discussed. Lastly, the conclusions and future work recommendations are developed and presented.

2. Background and previous work

OCC can be characterized as either occupant behaviour-centric control or occupancy-centric control [7]. Occupant behaviour-centric control adjusts the indoor environment based on occupants’ preferences that are learned either actively or passively. Active preferences learning is achieved with wearables (e.g., [17–19]) which allow occupants to provide feedback on their environment explicitly. Conversely, passive preference learning is achieved by monitoring occupants’ interactions with buildings’ environmental control systems and inferring their preferred environmental conditions. For example, occupants’ interactions with light switches (e.g., [20–22]) and thermostats (e.g., [23–26]) can be used to infer occupants’ preferred illumination and temperature setpoints, respectively. On the other hand, occupancy-centric control adjusts the indoor environment based on occupancy (i.e., presence/absence or occupant counts). For example, artificial lighting operation (e.g., [27–29]) and HVAC equipment schedules and airflow setpoints (e.g., [30–35]) can be altered based on the presence/absence of occupants or the number of occupants present, thus reducing lighting and conditioning loads if occupants are absent or the zones of interest are only partially occupied. Both types of OCC ultimately require a supervisory control program within the BAS to modulate dampers, valves, and/or other actuators to produce the desired equipment operation necessary to meet occupants’ needs as determined by OCC.

One such occupancy-centric control was introduced in the BAS of a case study building in a previous study [36] and will be the subject of further investigation. This OCC employed occupancy-based ventilation of the building at the AHU level. This involved reducing the outdoor air (OA) damper positions in the building’s AHUs based on the predicted building-level occupant count (i.e., as ventilation requirements are lowered due to fewer numbers of occupants, a smaller proportion of outdoor air can be used when economical, reducing the heating and cooling energy needed to condition the incoming outdoor air) via a new damper control program. However, this program is but one in a family of programs that ultimately govern how these dampers behave; errors or inefficiencies in the sequences of operation may inadvertently circumvent the programmed OCC, diminishing or even eliminating savings potential altogether. Given the nature of the OCC explored in this study (i.e., system-level occupancy-based ventilation), this study will focus primarily on how deficiencies in the sequences of operation of AHUs impact energy use and IEQ, and how the magnitude of this impact differs with or without this particular type of OCC.

Gunay et al. [37] provide an overview of the operation of VAV AHU systems. Briefly, the SAT in such systems is determined by a proportional-integral-derivative (PID) controller, which determines the appropriate heating/cooling coil valve and OA damper positions to achieve the desired SAT based on outdoor air enthalpy, dry-bulb temperature, or both. The result is a split-range sequencing scheme that determines the position of these equipment based on an operating state (OS) as defined in ASHRAE Guideline 36–2018 [38], namely heating (OS#1), economizing (OS#2), economizing and mechanical cooling (OS#3), and mechanical cooling (OS#4), see Fig. 1(a). When implementing this control scheme in an AHU based on dry-bulb temperature, the designer must define the outdoor air temperature (OAT) threshold between each operating state (i.e., the low and high temperature or enthalpy limits for OS#2 and the high limit for OS#3), as well as the SAT setpoints. An inappropriately high SAT setpoint limits the system’s ability to provide cooling to warm zones (e.g., core zones or zones with high thermal gains) as these zones require excessive volumes of air to meet cooling needs (i.e., as the temperature differential between the supply air and zone air decreases, the volume of air required increases). An inappropriately low SAT will also require excessive volumes of outdoor air, specifically during the heating season, which decreases the low limit for OS#2 and prolongs economizing into colder outdoor temperatures, resulting in higher loads on ter-
minal heating devices for larger portions of the year (i.e., perimeter heaters and VAV reheat coils). Due to this, SAT reset schemes are the best practice in such systems. An OAT-based SAT reset control scheme uses a stepwise function that specifies different SAT setpoints at different OATs; warmer SATs are used during the peak of the heating season ($T_{SA,h}$), which can still provide reasonable amount of cooling to overheated zones while reducing the load on terminal devices, while cooler temperatures are used at the peak of the cooling season ($T_{SA,c}$), to reduce the volume of air required for conditioning and the associated fan power. In between seasons or at interstitial OATs between a defined lower ($T_{OA,low}$) and upper ($T_{OA,high}$) limit, the SAT is interpolated, see Fig. 1(b). It should be noted that other SAT reset schemes can be used; SAT resets can be programmed to adjust the setpoints based on the fraction of zones that demand heating or cooling at a given timestep. Additionally, hybrid approaches of these two schemes can be created whereby the upper and lower bounds for the SAT reset are determined by OAT, and the SATs are adjusted between these ranges based on the fraction of heating and cooling demand by zones. However, this study will focus primarily on temperature-based SAT reset schemes.

Poor choices for the described temperature thresholds and control schemes which impact the AHU sequences of operation are not uncommon in practice. Some buildings forgo SAT setpoint reset schemes and utilize constant SATs year-round [39] despite the knowledge that this is poor practice [40]; for example, several case studies (e.g., [40–43]) have explicitly identified buildings where this is the case. The SATs in these case studies were typically lower than ideal to avoid the problem of overheating zones during the heating season, which resulted in an increased heating load due to prolonged use of the economizer state in the heating season; this can even cause damage to equipment due to operation outside intended conditions. For example, Abuimara et al. [44] describe an event where excessive volumes of outdoor air at low temperatures due to an erroneous free cooling low-limit resulted in the freezing of an AHUs heating coil.

In addition to SAT setpoints, the implementation of economizer high limits has been notoriously misunderstood [45]. For example, a study of 144 commercial buildings across the United States by Katipamula [46] found that approximately 19% of buildings had inappropriate economizer setpoints including high temperature limits; this is despite recommendations provided in ASHRAE 90.1–2019 [8] and ASHRAE Guideline 36–2018 [38] that specify economizer high limits based on the control method and climate zone (e.g., for OAT dry-bulb temperature-based economizers, the economizer high limit is the OAT threshold between OS#3 and OS#4 which triggers the economizing cycle to cease at excessively high OATs, recall Fig. 1(a)). The authors ranked the ratio of the savings to the level of effort for adding an economizer high limit as one of the highest amongst the AHU interventions studied. Economizer high limits serve to reduce the load on the cooling coils when mechanically cooling the return air becomes more economical than conditioning the outdoor air; this interaction is complex as the cooling coil often serves as a means for dehumidification for the supply air in tandem to its primary role of conditioning incoming air. However, Taylor and Cheng [45] determined that fixed dry bulb temperature-based economizers (i.e., economizers which use a static high limit based on the outdoor air dry bulb temperature, rather than the temperature differential between the SAT and outdoor air or air enthalpies) are most appropriate for ASHRAE Climate Zone 6A (i.e., the climate zone in which the case study buildings are located).

The impacts SAT schemes and economizer high limits have on system-level occupancy-based ventilation is due to the extension of the free cooling and economizing modes into the heating and mechanical cooling modes, respectively. This is because this OCC only functions when the OA damper of the AHU is operating at its minimum position [47]; at this minimum position, AHUs are designed to provide enough fresh outdoor air for the building at full occupancy. Therefore, if the actual number of occupants in the building can be estimated, the corresponding ventilation requirements for the actual number of occupants can be calculated, and the OA damper positions during OS#1 and OS#4 can be changed to reflect these new requirements.

The under-occupancy of commercial office buildings relative to their design intent is a well-documented phenomenon (e.g., [48–50]). When peak occupancies are below the design capacity, the minimum OA damper position can be lowered correspondingly. However, it should be noted that such system-level interventions are predicated on the assumption that the reduction in occupancy is homogenously observed across the floors of the building and may not be appropriate for all buildings or occupancy types. A reduction in the volume of outdoor air required to be heated or cooled can have a significant impact on sensible conditioning loads. In colder climates, these savings are more pronounced during the heating season, as the temperature differential between the OAT and the SAT is large. This interaction is the subject of the simulation-based investigation portion of this study.

3. Methodology

The aim of this study is to evaluate how changes to the sequences of operation impact the energy savings potential of OCC, specifically system-level occupancy-based ventilation strategies. This study can be broken down into two principal components; first, measured energy use data from two office buildings are compared between two years; the first year is 2019, where the buildings operated business-as-usual, while the second year is 2020, where buildings were vacated after March 15th due to the COVID-19 pandemic and remained unoccupied for the remainder of the year. One building operated using OCC during 2020, while another was operated with traditional ventilation strategies. Then, a simulation-based investigation is performed using the
characteristics of the traditional ventilation building to see how changes to the sequences of operation and OCC could have interacted and impacted energy use and IEQ had they been applied to the building before the onset of the COVID-19 pandemic.

3.1. Buildings and data set

Data from two office buildings were collected for the purpose of this study. Building A is an academic office building completed in 2010, whereas building B is an administrative office building completed in 1967. Both buildings have two main AHUs, with VAV terminal units and perimeter hydronic heaters at the zone level, and are located on the same campus in Ottawa, Canada (i.e., ASHRAE Climate Zone 6A). Building A is equipped with an enthalpy wheel, while building B has no heat recovery. Other general characteristics of the building are summarized in Table 1. The campus is served by a central steam plant during the heating season, while buildings provide cooling using their own on-site chillers in the cooling season. Hourly steam and chilled water energy use data (STM and CW, respectively, in tables and figures for brevity) for each building were collected for a two-year period spanning from midnight on January 1st, 2019, until midnight on January 1st, 2021. In addition, the number of Wi-Fi-enabled devices connected to the Wi-Fi access points in the two buildings studied were provided by IT services at concurrent hourly intervals for the period of midnight on April 23rd, 2019, until midnight on July 3rd, 2020. Note that these device counts were anonymized (i.e., no MAC or IP addresses were monitored or stored over the course of this study). While these Wi-Fi data were not available for the entire two-year period, these data could be used where available to establish baseline occupancy patterns in the buildings. This was based on a linear regression model that was trained using the number of Wi-Fi-enabled devices and ground truth occupancy data in building A from a previous study [49]. Briefly, this model discarded stagnant devices (e.g., wireless printers, computers left on overnight) and established an average of 1.2 Wi-Fi enabled devices per person in building A. For the purpose of this study, it is assumed that a similar relationship between the number of Wi-Fi enabled devices and occupants exists in building B due to the similarity between the buildings’ location, occupancy types, and demographics. Note that, while Wi-Fi data are not available past July 3rd, 2020, the occupancy of the buildings after this period was assumed to be negligible due to lockdowns. Additional data used for this study included actual meteorological year (AMY) weather files for 2019 and 2020 for Ottawa.

Building A and B both operated using traditional ventilation strategies during the 2019 data collection period, meaning the OSs outlined in ASHRAE Guideline 36–2018 [38] are followed at the appropriate OATs (recall Fig. 1(a)). Note that the minimum position of the OA dampers during traditional ventilation was 40% in building A and 30% in building B. While building B continued to operate using these OSs for the duration of 2020, the operating strategy for building A was altered to employ OCC of system-level ventilation when the OA dampers of the building’s AHUs were in the minimum position operating states (i.e., OS#1 and OS#4). While the focus of this study is not this intervention [36], it can be summarized briefly. This approach used the correlation between lighting/plug-in equipment load data and occupancy to categorize the building as either very sparsely, sparsely, moderately, or densely occupied. Lower OA damper positions corresponding to the expected occupancy during each day type were then employed to reduce the conditioning load during OS#1 and OS#4, see Fig. 2. Note that OS#2 and OS#3 were not affected by this intervention.

Critically, it should be noted that two errors in the sequencing logic of building A were corrected during the implementation of the described OCC. First, the enthalpy wheel in building A was not functioning during 2019 due to an error in the AHUs’ programming logic whereby the units were entering OS#2 during excessively cold OATs to address overheating in a single zone; this zone was an IT server room with an inappropriately sized VAV terminal unit which experience high indoor air temperatures year-round. The AHUs’ programming logic was altered to require a higher indoor air temperature to trigger cooling for this problematic zone. Lastly, an SAT reset error was discovered; the temperature differential-based SAT in building A erroneously compared average zone air temperatures (ZATs) and average ZAT setpoints. If the average ZAT was even a fraction of a degree warmer than the average ZAT setpoint in the winter (i.e., the majority of the heating season), the program assumed that the building was overheating and entered OS#2. A deadband was added to the control logic to correct this issue. Addressing these errors was critical as both caused economizing when the building should have been in OS#1 during the heating season or OS#4 during the cooling season; recall the OCC explored in this study can only operate when one of these two modes (see Fig. 2). Therefore, changes to these sequences of operation were necessary to enable this particular OCC; had these changes not been made, the OCC would have saved no energy if implemented exclusively. This serves as an extreme example of how the sequences of operation can impact the energy savings potential of OCC in unexpected ways when performing implementations in real buildings. However, it should be noted that because of this, it was not possible to attribute the proportion of energy savings attributable to the implementation of OCC or the correction of this erroneous control logic in building A between 2019 and 2020. This aspect of the interaction is explored in the simulation-based investigation portion of this study for the two more commonly poor sequences (i.e., lack of SAT reset and economizer high limit) identified in the literature. Note that the available OA damper data for building B was inspected to verify that no such undesirable economizing was occurring.

Table 1

| Characteristic          | Building A | Building B |
|-------------------------|------------|------------|
| Year completed          | 2010       | 1967       |
| Primary occupancy       | Office/Labs| Office     |
| Daily peak occupancy*   | 403        | 265        |
| Floors                  | 7          | 6          |
| Floor plan              | L-shaped   | Square     |
| Conditioned area (m2)   | 7310       | 8250       |
| Exterior above-grade area (m2) | 4280       | 3590       |
| Gross WWR (%)           | 35         | 50         |

*Based on 95th percentile weekday Wi-Fi device counts

Fig. 2. Operating states for AHU in building A after OCC intervention.
3.2. Measured energy use

The hourly steam and chilled water data were summed for 2019 and 2020 for the buildings to determine annual conditioning loads. These measured data were then compared to determine the change in the energy use for building’s A and B. The AMY weather data for each year were used to compute the heating degree days with a base temperature of 18 °C (HDD18°C) and cooling degree days with a base temperature of 10 °C (CDD10°C) for each year to help contextualize the differences in total energy use between 2019 and 2020.

The steam and chilled water data and the hourly temperature data from the AMY files were used to train three-parameter univariate changepoint models for each building in 2019 (i.e., when both buildings were operating using traditional ventilation and business-as-usual). These models were then used on the 2020 temperature data to estimate the expected temperature-adjusted energy use of each building had they continued to operate in a similar manner (i.e., how much energy would buildings A and B have used in 2020 if the buildings were not vacated due to the pandemic, and additionally in the case of building A, if OCC and the sequencing fixes had not been introduced). These data are then compared to the measured energy use data from 2020 and discussed.

3.3. Calibrated energy model

A calibrated EnergyPlus model for building B in 2020 was developed using the steam and chilled water data and genetic optimization to estimate unknown building parameters. This base case model was then simulated without an SAT setpoint reset and with an economizer high limit to evaluate the impact each change to the sequence of operation had on energy use. These simulations were repeated with a system-level occupancy-based ventilation scheme in place simultaneously to assess the impact this OCC had on energy use and IEQ given these changes. This section describes the base EnergyPlus model, the model parameters and optimization process, and each simulation scenario.

3.3.1. Base EnergyPlus model

Six 37-meter by 37-meter floors were used to approximate building B’s geometry, with window-to-wall ratios (WWRs) and floor heights in accordance with available measured drawings (i.e., 85% WWR on floors two through five, 50% WWR on floor six, 0% WWR on the basement floor, and 3.7-meter floor heights). Note that simplified geometry was used for the purpose of whole-building energy simulation; windows were grouped together on each floor along the length of the façade to simplify the geometry while still approximating the overall solar heat gains and distribution, and each floor was treated as five thermal zones (i.e., four perimeter zones with a depth of 8-meters each and one core zone per floor), see Fig. 3.

The HVAC system in the EnergyPlus model was configured to match building B based on the data available in the BAS. Two primary AHUs with variable speed supply and return fans were used; the fan efficiencies were assumed to be 70%. One AHU (AHU 1) served the core zones, while the second AHU (AHU 2) served the perimeter zones. The supply air pressure setpoints were 200 Pa and 250 Pa for AHU 1 and AHU 2, respectively, and the exhaust air pressure setpoints were 50 Pa for both AHUs. Seasonal switch-over between heating and cooling occurred on May 16th, 2020, while switch over back to heating occurred on September 8th, 2020. During the heating season, the heating coils in the AHUs, VAV terminal units, and perimeter hydronic units were available during operating hours. The operating hours are summarized in Table 2. The efficiency of the heating coils was assumed to be 80%. Similarly, during the cooling season, the cooling coils in the AHUs were available during operating hours. In both seasons, the ZAT setpoints were 22 °C during operating hours. Afterhours, setbacks to 17 °C and 27 °C were utilized in the heating and cooling seasons, respectively. The AHUs were allowed to turn on if the temperatures in a zone deviated 1 °C below or above the setback temperature during afterhours in the heating and cooling seasons, respectively. The maximum permissible discharge air temperature for the VAV terminal units during reheat was set to 35 °C. Notably, the temperature thresholds that govern the SAT reset scheme could not be determined from the available data; these unknown parameters were estimated using a genetic algorithm during the building energy model calibration process described in Section 3.3.2.

The whole-building occupancy profile for 2020 was determined using the relationship between the Wi-Fi device count data and occupancy previously discussed. Recall that the building was only regularly occupied from January through March 15th; occupancy after March was treated as zero due to the pandemic. The peak daily occupancy during weekdays for building B during the occupied period was determined to be 265 persons (recall Table 1). Occupants were assumed to be homogeneously distributed across the floorplate with a corresponding density of 30.83 m² per person at peak occupancy. A schedule file containing normalized hourly estimated occupancy was used, see Fig. 4. Note that the building’s AHUs had a total ventilation capacity of approximately 32 m³/s based on nameplate data and a minimum OA damper position of 30%; enough for 900 occupants as per ASHRAE 62.1–2019 [51].

3.3.2. Genetic algorithm and parameters

In order to develop an ASHRAE Guideline 14–2014 [52] compliant calibrated energy model, unknown envelope properties and operational parameters, see Table 3, were estimated using MATLAB’s ga (i.e., genetic algorithm) function. A custom script [37] searched the EnergyPlus input data file (IDF) and replaced parameters, ran the simulation, computed the cost function, and repeated iteratively until the termination criteria were met.

![Building B geometry used in the EnergyPlus model.](image)

**Table 2**

| Day type            | Start time (h) | Stop time (h) |
|---------------------|---------------|---------------|
| Weekdays            | 5             | 19            |
| Weekends            | 6             | 19            |
| Christmas break (Dec. 25 – Jan. 1) | 10 | 16 |
| Holidays (other)    | –             | –             |
The parameters \( U \) and \( \text{SHGC} \) represent the thermal transmittance and solar heat gain coefficient of the glazed portions of the envelope, respectively. \( R \) and \( \theta_{\text{def}} \) are the thermal resistance and air permeance of the opaque portions of the envelope, respectively. \( V_{\text{ba}} \) is the area normalized breathing zone outdoor air flow rate \([51]\), and \( q_{\text{inf}} \) are the thermal resistance and solar heat gain coefficient of the glazed portions of the envelope, respectively.

Occupancy was considered zero beyond these dates due to COVID lockdown.

Fig. 4. Hourly occupancy of building B from the beginning of January 2020 to the end of March 2020. Occupancy was considered zero beyond these dates due to COVID lockdown.

Table 3

| Parameter | Units | Lower bound | Upper bound |
|-----------|-------|-------------|-------------|
| \( U \)   | W m\(^{-2}\)K | 2           | 4           |
| \( \text{SHGC} \) | m\(^2\)K/W | 0.3         | 0.8         |
| \( R \)   | m\(^2\)K/W | 2           | 6           |
| \( \theta_{\text{def}} \) | m\(^2\)/s m\(^2\) | 0.0001     | 0.0025      |
| \( V_{\text{ba}} \) | m\(^3\)/s m\(^2\) | 0.0003     | 0.0025      |
| \( T_{\text{SA},1} \) | °C | 15          | 22          |
| \( T_{\text{SA},2} \) | °C | 10          | 15          |
| \( T_{\text{SA},3} \) | °C | 15          | 22          |
| \( T_{\text{SA},4} \) | °C | 10          | 15          |
| \( T_{\text{OA},\text{low},1} \) | °C | –10         | 2           |
| \( T_{\text{OA},\text{high},1} \) | °C | 5           | 12          |
| \( T_{\text{OA},\text{low},2} \) | °C | –10         | 2           |
| \( T_{\text{OA},\text{high},2} \) | °C | 5           | 12          |
| \( \max_{\nu_{\text{p},-}\nu_{\text{p}}} \) | W/m\(^2\) | 8           | 30          |
| \( \min_{\nu_{\text{p},-}\nu_{\text{p}}} \) | W/m\(^2\) | 1           | 20          |

The parameters \( U \) and \( \text{SHGC} \) represent the thermal transmittance and solar heat gain coefficient of the glazed portions of the envelope, respectively. \( R \) and \( \theta_{\text{def}} \) are the thermal resistance and air permeance of the opaque portions of the envelope, respectively. \( V_{\text{ba}} \) is the area normalized breathing zone outdoor air flow rate \([51]\) for the VAVs and their zones. \( T_{\text{SA},i} \) and \( T_{\text{OA},i} \) represent the SAT setpoints during the heating and cooling seasons, respectively. The low and high OATs that govern for the SAT reset are represented by \( T_{\text{OA},\text{low},i} \) and \( T_{\text{OA},\text{high},i} \), respectively. These four setpoints were parameterized for each of the two individual AHUs. Finally, the internal gains in the form of the combined plug-in equipment and lighting load were considered on a per-area basis. This combined electrical load was defined as a linear function of occupancy within an EMS script. The minimum plug-in equipment and lighting load was set as the y-intercept at zero occupancy (\( \min_{\nu_{\text{p},-}\nu_{\text{p}}} \)), while the maximum plug-in equipment and lighting load at maximum occupancy (\( \max_{\nu_{\text{p},-}\nu_{\text{p}}} \)) was used to calculate the slope of the linear function to determine the combined load at intermediate occupancies. In total, 15 parameters are used in the optimization process.

The value of the cost function \( F \) as computed after each simulation was the average of the coefficient of variation of the root mean squared error (CV(RMSE)) between the hourly measured and simulated steam and chilled water data. Note that the CV(RMSE) of the steam and chilled water energy data were calculated seasonally; the CV(RMSE) of the steam data was calculated for all hours (i.e., afterhours, work hours, weekends, and holidays) during the heating season, and the CV(RMSE) of the chilled water data was calculated for all hours during the cooling season. As the genetic algorithm seeks to minimize this cost function, this results in a lower average CV(RMSE) for heating and cooling as the optimization progresses between generations. Note that Guideline 14 requires a CV(RMSE) less than 30% and normalized mean bias error (NMBE) lower than 10% for calibration to be considered acceptable when using hourly data; the NMBE was verified to ensure it fell within this range after calibration.

Hyperparameters were selected to promote convergence, namely the number of generations for convergence (\( g_{\text{conv}} \)), the population size (\( n \)), cross-over fraction (\( f_{\text{crossover}} \)), and mutation rate (\( f_{\text{mutate}} \)). Vrajitoru et al. \([53]\) suggest that problems with more than ten parameters should have larger population sizes rather than numerous generations – approximately one-and-a-half to two times the number of parameters (referred to as the length (\( I \)) of the chromosomes). Based on this, the population size was set to 30 (i.e., double the 15 parameters). \( f_{\text{crossover}} \) was set to 50%, a popular option for \( f_{\text{crossover}} \) in problems with large solution spaces \([54]\). \( f_{\text{mutate}} \) was selected as 3.3% (i.e., a single chromosome per generation, and close to the \( 1/n \) relationship also described in Hassanat et al. \([54]\)) to ensure convergence is not delayed while still providing diversity. A relationship exists between \( I \) and \( g_{\text{conv}} \) as described by Thierens and Goldberg \([55]\) by the equation \( g_{\text{conv}} = (\pi/2) \times \sqrt{I} \). Based on this formula, a minimum of 11 generations would be required to reach convergence. It should be noted that Gibbs et al. \([56]\) state that this formula is only typically applied to binary or tournament solutions; however, their paper provides evidence that these principles extend over to other types of optimization problems so long as \( f_{\text{crossover}} \) is constant. Therefore, the genetic algorithm used in this study will have an \( n \) of 30, with a minimum of 11 generations, and an \( f_{\text{crossover}} \) and \( f_{\text{mutate}} \) of 50% and 3.3%, respectively. The ga function was terminated if the change in value between the cost function was less than \( 10^{-3} \) between iterations or if the number of generations exceeded \( g_{\text{conv}} \) by more than 25% (i.e., 14 generations), whichever came first.

3.3.3. Simulation scenarios

Once a Guideline 14 \([52]\) compliant baseline energy model was developed, six scenarios were simulated. The first three scenarios use traditional ventilation in the building, while the latter three scenarios employ the OCC described. These scenarios are summarized in Table 4.

In scenario A, the calibrated energy model was simulated using traditional ventilation (recall Fig. 3 (a)) and a constant SAT. The SATs were set to \( T_{\text{SA},1} \) and \( T_{\text{SA},2} \) for AHUs 1 and 2, respectively, as use of the heating season SATs would result in inadequate temperature differential between the SAT and ZAT setpoints during the cooling season. In scenario B, the calibrated energy model was simulated using traditional ventilation and \( T_{\text{OA},\text{low},1} \) and \( T_{\text{OA},\text{high},1} \) for AHU 1 and \( T_{\text{OA},\text{low},2} \) and \( T_{\text{OA},\text{high},2} \) for AHU 2 in the heating and cooling seasons, respectively. Scenario C used similar simulation parameters to scenario B, with the addition of a high limit which limited economizing to temperatures below 21 °C as specified in ASHRAE 90.1–2019 \([8]\).

Scenarios D, E, and F treated SATs and the economizer high limit in the same fashion as scenarios A, B, and C, respectively. However, OCC was implemented via an EMS script. This program calculated the person outdoor air flow rate at each timestep based on the

Table 4

| Scenario | Ventilation | SAT control | OCC high limit |
|----------|-------------|-------------|----------------|
| A        | Traditional | Constant    | –              |
| B        | Traditional | Reset       | –              |
| C        | Traditional | Reset       | 21 °C \([8]\)   |
| D        | OCC         | Constant    | –              |
| E        | OCC         | Reset       | –              |
| F        | OCC         | Reset       | 21 °C \([8]\)   |
building’s occupancy per ASHRAE 62.1–2019 [51]. Given the air distribution efficiency $E_z$ of 0.8, the building area of 8250 m², and a design occupancy of 900 persons, the area outdoor air flow rate $R_a$ (0.3 L/s·m² for office-type occupancy) and person outdoor air flow rate $R_p$ (2.5 L/s·person for office type occupancy) account for approximately 52% and 48% of the total outdoor air demand, respectively. As the peak daily occupancy of building B was 265 persons, only 29.4% of the person outdoor air flow fraction was required. Therefore, the new highest minimum outdoor air flow rate was 20% when 265 occupants were present, and the lowest minimum outdoor air flow rate was 16% when no occupants were present and when the building’s AHUs were in OS#1 or OS#4. Recall that the static minimum outdoor air flow fraction used in the building’s AHUs during traditional ventilation was 30%. For intermediate occupancy levels, the program interpolated the minimum outdoor air flow rate based on occupancy at each hourly timestep.

4. Results and discussion

The results from the two principal components of this study, namely the measured building energy use for building A and B and the results from the calibrated energy model and simulation scenarios, are discussed below. Measured and predicted energy use values for buildings A and B are first analyzed. Then, the results of the calibration process are analyzed and discussed. Finally, the results from the simulation scenario are examined and the underlying causes for the changes in energy use and IEQ are posited.

4.1. Measured energy use

The steam use in building A was reduced in the immediate aftermath of the lockdown, see Fig. 5(a). This reduction can be partially attributed to the reduced minimum outdoor air fraction required for building A during the end of the heating season due to low occupancy and the implemented OCC. As building A is equipped with an economizer and enthalpy wheel, the minimum outdoor air requirements from the occupancy-based ventilation enabled the building to passively cool with outdoor air during the shoulder seasons until the switch over to mechanical cooling. Recall that the enthalpy wheel in building A was not functioning during 2019 but was corrected during OCC implementation in 2020. Conversely, steam use in building B remained virtually unchanged before and during the lockdown, with significant heating required even during the shoulder season, see Fig. 5(b). Recall that building B does not contain an enthalpy wheel.

Cumulative steam and chilled water use for both buildings over the same period in 2019 and 2020 are provided for comparison. Overall, heating loads decreased by ~ 48% in building A and decreased by ~ 12% in building B between 2019 and 2020. Cooling loads decreased in building A by ~ 5% and increased in building B by 7% in the same timeframe. It is important to note that the values presented are not weather adjusted; changepoint models are subsequently used for this purpose.

The changepoint models for 2019 are presented for buildings A and B in Fig. 6(a) and Fig. 6(b), respectively. These models approximated the energy use of the buildings in the 2019 period as a function of the OAT. Note that this period had 4749 HDD$_{18}^{°C}$ and 1230 CDD$_{10}^{°C}$. Using the 2020 temperature data, the energy each building would have been expected to use (i.e., without any operational changes or changes to occupancy) in 2020 was estimated, see Table 6. Note that the same 2020 period had 3877 HDD$_{18}^{°C}$ and 1476 CDD$_{10}^{°C}$; heating requirements were lower during 2020; however, 2020 had significantly higher cooling demands associated with the increased CDD$_{10}^{°C}$. This was reflected in the difference between the measured 2019 cooling energy usage (recall Table 5) and the predicted 2020 cooling energy usage (see Table 6).

Despite building B being vacated for much of 2020, it exhibited nearly identical HVAC energy use trends in both 2019 and 2020; building B’s energy use was marginally higher than expected during the lockdown period, even when assuming a business-as-usual approach. During the heating season, this could potentially be a result of reduced internal gains due to fewer occupants and equipment. Conversely, building A’s energy use decreased significantly between the same period. The OCC implementation, reduced occupancy, and sequencing logic corrections in building A’s BAS resulted in almost half as much steam use in 2020 versus 2019 and ~ 16% reduction in chilled water use during this period compared to estimated business-as-usual (i.e., normal occupancy and sequences uncorrected) values, see Table 6. It should be noted that the proportion of savings attributable to each aspect of the operational changes in building A cannot be determined with these data.

4.2. Calibrated energy model

The custom MATLAB script was run using the outlined model hyperparameters and terminated after the maximum number of generations was reached. Cost function values $F$ are presented in Fig. 7. Note that the lowest cost achieved by the genetic algorithm was 0.195 (i.e., an average CV(RMSE) of 19.5% between the measured and simulated steam and chilled water energy use).

The parameter estimates of the best-fit model are summarized in Table 7. Reference values from codes and standards are provided to give context to building B’s envelope properties and operational parameters; recall building B was constructed in 1967 (i.e., before the introduction of commercial building energy codes).

The calibrated energy model indicated that the building’s opaque assemblies had lower R-values for the opaque portions of
the above-grade assembly than those stipulated by code [57]. Similarly, the window U-values were estimated to be 79% higher than later code maximum values [57] and would cause significant amounts of heat transfer through the façades given building B’s high WWRs. Additionally, infiltration was estimated to be six times the published code value [57] per above-grade surface area, characterizing building B as a leaky and poorly insulated building. Given the building’s vintage and poor energy performance – the building’s measured energy use intensity was three times the Canadian national average for office buildings in 2019 [59] – poor envelope qualities such as these were expected. Adjusting for the estimated occupant density, the ventilation rates observed in the pre-pandemic occupied period of 2020 were nearly triple the per person requirements of ASHRAE 62.1–2019 [51]. $T_{\text{SA,c}}$ were verified to fall within ASHRAE Guideline 36–2018 [38] values, while $T_{\text{SA,n}}$ were found to be higher than those suggested by Guideline 36 in both AHUs. $T_{\text{OA,high}}$ and $T_{\text{OA,low}}$ were also found to fall within the range specified in the literature [37,38]. Finally, the minimum and maximum combined plug-in equipment and lighting load were found to fall near the values published by Deru et al. [58].

![Fig. 6. Changepoint models for (a) building A and (b) building B in 2019.](image1)

![Fig. 7. Fitness function values at each generation.](image2)

### Table 5
Measured steam (STM) and chilled water (CW) use.

| Building | Meter | 2019 measured (MWh<sub>eq</sub>) | 2020 measured (MWh<sub>eq</sub>) | % change |
|----------|-------|-------------------------------|-------------------------------|---------|
| A        | CW    | 252.8                         | 239.3                         | -5%     |
|          | STM   | 778.8                         | 406.7                         | -48%    |
| B        | CW    | 535.5                         | 573.9                         | 7%      |
|          | STM   | 1318.4                        | 1163.4                        | -12%    |

### Table 6
Estimated energy use for 2020 using 2019 changepoint models.

| Building | Meter | 2020 measured (MWh<sub>eq</sub>) | 2020 estimated (MWh<sub>eq</sub>) | % change |
|----------|-------|-------------------------------|-------------------------------|---------|
| A        | CW    | 239.3                         | 283.3                         | 16%     |
|          | STM   | 406.7                         | 761.3                         | 47%     |
| B        | CW    | 573.9                         | 549.9                         | -4%     |
|          | STM   | 1163.4                        | 1151.9                        | -1%     |

### Table 7
Calibrated energy model properties.

| Parameter | Units | Published values | Calibrated model |
|-----------|-------|------------------|------------------|
| $U$       | W m<sup>-2</sup>K | 1.9 [57] | 3.4 |
| $SHGC$    | –     | –                | –                |
| $R$       | m<sup>2</sup>K/W | 4 [57] | 3.1 |
| $\dot{q}_{\text{inf}}$ | m<sup>3</sup>/s m<sup>2</sup> | 0.00025 [57] | 0.00150 |
| $V_{\text{m}}$ | m<sup>3</sup>/s m<sup>2</sup> | 0.0005 [51] | 0.0011 |
| $T_{\text{OA,1}}$ | °C | 14 to 18 [38] | 19.5 |
| $T_{\text{OA,2}}$ | °C | 12 to 18 [38] | 12.5 |
| $T_{\text{OA,low}}$ | °C | 12 to 16 [38] | 14.6 |
| $T_{\text{OA,high}}$ | °C | -20 to 0 [37] | -1.3 |
| $T_{\text{OA,low}}$ | °C | -20 to 0 [37] | -0.1 |
| $T_{\text{OA,high}}$ | °C | 5 [37] to 16 [38] | 7.9 |
| $\text{maxP} + L$ | W/m<sup>2</sup> | 21.6 [38] | 20.9 |
| $\text{minP} + L$ | W/m<sup>2</sup> | 4.7 [58] | 4.3 |
The calibrated energy model was simulated using these parameters in 2020 and compared to the measured energy use data. The CV(RMSE) and NMBE for the calibrated energy model are shown in Fig. 8. Recall that ASHRAE Guideline 14 [52] stipulates a maximum CV(RMSE) and NMBE of 30% and 10%, respectively. Further references to the changes in building energy use as different sequences of operation and OCC are implemented will be made with respect to the energy use of the base case model, rather than the measured 2020 energy use itself.

4.2.1. Simulation scenarios

- Scenario A (traditional ventilation, constant supply air temperature)

In scenario A, the SATs remained at the lower cooling season temperatures ($T_{SAT}$) year-round, see Fig. 9(a). To achieve these lower SATs during the shoulder and heating seasons, the OA dampers were allowed to operate above their minimum position and admit higher volumes of outdoor air at lower OATs (i.e., economizer further into the heating season). Specifically, economizing occurred until $-3\,^{\circ}\text{C}$ in AHU 1 (see Fig. 9(b)) and $-10\,^{\circ}\text{C}$ in AHU 2 (see Fig. 9(c)) when a constant SAT was used, compared to $4\,^{\circ}\text{C}$ in AHUs 1 (see Fig. 9(e)) and $3\,^{\circ}\text{C}$ in 2 (see Fig. 9(f)) when an SAT reset was used (i.e., scenario B). The lower SATs also meant that the terminal devices accounted for a larger portion of the heating load as the same ZAT setpoints had to be achieved with these cooler SATs (i.e., the heating coils accounted for 14% of the heating load, whereas the perimeter hydronic and VAV terminal units accounted for the remaining 86%). This prolonged economizing cycle and inefficient use of heating devices resulted in $14.9\%$ reduction in steam energy use and $4.7\%$ increase in hours within $1\,^{\circ}\text{C}$ of ZAT setpoints in scenarios B compared to scenario A as mentioned previously.

- Scenario B (traditional ventilation, supply air temperature reset)

In scenario B, the SAT reset scheme was allowed to function using the higher SATs in the heating season and lower SATs in the cooling season, see Fig. 9(d). To achieve these higher SATs during the shoulder and heating seasons, the OA dampers were reduced to their minimum position earlier in these seasons (i.e., at the higher OATs), thus admitting lower volumes of the relatively cold outdoor air. This resulted in a shorter economizing cycle; recall economizing occurred until $4\,^{\circ}\text{C}$ in AHUs 1 and $3\,^{\circ}\text{C}$ in 2 when an SAT reset was used, compared to $-3\,^{\circ}\text{C}$ in AHU 1 (see Fig. 9(b)) and $-10\,^{\circ}\text{C}$ in AHU 2 (see Fig. 9(c)) when a constant SAT was used (i.e., scenario A). Consequently, more hours (i.e., $1255\,\text{h}$ for scenario B versus $433\,\text{h}$ for scenario A) were spent in OS#1 with the OA dampers at minimum position. The increased SATs increased the load on the AHUs’ heating coils (i.e., from $14\%$ in scenario A up to $48\%$ in scenario B) and reduced the load on the terminal devices (i.e., $86\%$ in scenario A down to $52\%$ in scenario B). The elimination of the prolonged economizing cycle and more efficient distribution of the heating load resulted in the $14.9\%$ reduction in steam energy use and $4.7\%$ increase in hours within $1\,^{\circ}\text{C}$ of ZAT setpoints in scenarios B compared to scenario A as previously mentioned.

- Scenario C (traditional ventilation, supply air temperature reset, economizer high limit)

In the cases of scenarios A and B, there was no difference between chilled water energy use as the changes made to the SATs only impacted operation at OATs observed during the heating season. In scenario C, the SAT reset scheme from scenario B was used in tandem with the high limit of $21\,^{\circ}\text{C}$ for the economizer mode, see Fig. 9(g). Unlike scenarios A and B, this directly impacted the chilled water energy use in the building, while the steam energy use was unchanged between scenario B and C, see Table 8. The addition of the $21\,^{\circ}\text{C}$ limit for the dry-bulb economizers forced the OA dampers to operate at the minimum position and enter OS#4 at all hours above this temperature, see Fig. 9(h) and Fig. 9(i) for AHU 1 and AHU 2, respectively. This resulted in lower volumes of outdoor air requiring conditioning as the OAT approached or exceeded the SAT, causing a $4.6\%$ reduction in the annual chilled water energy use compared to the previous scenarios A and B, see Table 8. The change in the number of hours spent within $1\,^{\circ}\text{C}$ of the SAT was used (i.e., scenario A). Consequently, more hours (i.e., $1255\,\text{h}$ for scenario B versus $433\,\text{h}$ for scenario A) were spent in OS#1 with the OA dampers at minimum position and admit higher volumes of outdoor air at lower OATs (i.e., economizing further into the heating season). However,
because the minimum volume of outdoor air available to achieve these lower SATs was lower in scenario D due to the occupancy-based ventilation, the economizing cycle was extended to even lower OATs (i.e., even further into the heating season compared to scenario A). Recall economizing occurred until \(-10^\circ C\) in AHU 1 and 2, respectively, for scenario A. In scenario D, economizing occurred until \(-8^\circ C\) and \(-13^\circ C\) for AHU 1 and 2, respectively. This resulted in further diminished use of the AHUs heating coils and reliance on terminal heating devices (i.e., the heating coil in scenario D accounted for ...
Table 8
Simulated energy use breakdown for each scenario.

| Scenario | CW (kWh_{sw}) | STM (kWh_{sw}) |
|----------|---------------|---------------|
| A        | 539.5         | 1118.3        |
| B        | 539.5         | 951.7         |
| C        | 514.5         | 951.7         |
| D        | 518.6         | 1069.5        |
| E        | 518.6         | 776.6         |
| F        | 487.5         | 776.6         |

Fig. 10. Distribution of zone air temperatures (ZATs) during occupied hours for each scenario.

12% of the annual steam energy use, compared to 14% for scenario A with no OCC. This prolonged economizing cycle diminished the savings potential attributable to this OCC, as less hours spent in OS#1 (i.e., 167 h in scenario D compared to 433 h in scenario A) resulted in larger volumes of outdoor air which had to be conditioned during the heating season. This can be seen when comparing the annual steam energy use in scenario D with scenario A; scenario D managed to save only 4.4% compared to scenario A (see Table 8), largely attributable to the 10% to 14% reduction in the volume of outdoor air conditioned for the small portion of the year spent in OS#1. However, the addition of the OCC in scenario D did decrease the cooling load compared to scenario A by a modest 2.0% (see Table 8) due to the smaller temperature differential between the outdoor and return air and the SAT during the cooling season. Additionally, the reduced volume of air during OS#1 increased the mean ZAT closer to the 22 °C setpoint compared to scenario A; however, the number of hours spent within 1 °C of the ZAT setpoint remained largely unchanged overall (11.0% for scenario D compared to 10.9% for scenario A), see Fig. 10.

- Scenario E (occupancy-based ventilation, supply air temperature reset)

In scenario E, the SAT reset scheme was allowed to function again using the higher SATs in the heating season and lower SATs in the cooling season, see Fig. 9(m) (i.e., scenario E is analogous to scenario B, except with occupancy-based ventilation instead of traditional ventilation). The same underlying principles that resulted in energy savings in scenario B are at play in scenario E: a narrower economizing cycle compared to the previous scenario (i.e., economizing occurred until −9°C and −13°C in AHU 1 and 2, respectively, for scenario D, compared to 2 °C and 0 °C in AHU 1 (see Fig. 9(n)) and AHU 2 (see Fig. 9(o)) in scenario E), more hours spent in OS#1 (i.e., OA dampers at minimum position), and a more equitable distribution of the heating load (i.e., 48% for the AHU heating coils, compared to 12% in scenario D) reduced the steam energy use by 27.4% compared to scenario D (i.e., when OCC and a constant SAT was used). Compared to its traditional ventilation counterpart (i.e., scenario B), scenario E was able to save 18.4% of steam energy use, see Table 8. These increased savings are due to the lower volume of outdoor air admitted at lower OATs during the heating season (recall the minimum OA damper positions were 30% for traditional ventilation, and 16% to 20% for OCC). However, the number of hours spent more than 1 °C above or below the ZAT setpoint increased by 2.4% in scenario E (i.e., 13.4%) compared to its non-OCC counterpart (i.e., 10.9% for scenario B) due to the lower volumes of outdoor air available and smaller temperature differential for cooling core zones, see Fig. 10.

- Scenario F (occupancy-based ventilation, supply air temperature reset, economizer high limit)

Similar to their non-OCC counterparts, scenarios D and E had no differences between chilled water energy use during the cooling season as the changes made to the SATs only impacted operation at OATs observed during the heating season. The addition of the 21 °C temperature limit for the economizer forced the OA dampers to operate within the minimum position range of 16% to 20% at all hours above this temperature, see Fig. 9(q) and Fig. 9(r) for AHU 1 and AHU 2, respectively. This resulted in lower volumes of outdoor air requiring conditioning as the OAT approached or exceeded the SATs, causing a 6.0% reduction in the annual chilled water energy use compared to the previous OCC scenarios and a 5.2% reduction when compared to its non-OCC counterpart (i.e., scenario C). The change in the number of hours spent within 1 °C of the ZAT setpoint between scenario F and scenario E was negligible (i.e., reduced from 13.4% to 13.2%), see Fig. 10.

4.3. Summary of main findings

In brief, based on the results presented in Table 8, the overall simulated savings in building B with improvements to the sequences of operation and OCC were 30.6% of steam energy use and 9.6% of chilled water energy use (i.e., between scenario A with no OCC and constant SATs, and scenario F with OCC, SAT resets, and an economizer high limit). These interventions resulted in an increase in the number of hours spent 1 °C above or below the ZAT setpoint of 2.3% (i.e., 10.9% for scenario A and 13.2% for scenario E), likely due to lower volumes of outdoor air available for cooling needs in the heating season when occupancy-based ventilated simulation was simulated. Minimum outdoor air requirements (i.e., approximately 10 L/s-person for office-type occupancy with building B’s HVAC configuration [51]) were verified to be met in the building in all scenarios. The addition of an SAT reset alone saved 14.9% and 18.4% of steam energy without and with OCC, respectively, while the economizer high limit saved 4.4% and 5.2% of chilled water energy use without and with OCC, respectively. Essentially, the use of OCC increased the savings potential of both the SAT reset strategy and 21 °C economizer high limit. Conversely, OCC alone without the use of an SAT reset or a 21 °C economizer high limit saved only 4.4% on steam energy use and 3.9% on chilled water energy use. Therefore, the net reduction attributable to OCC in building B when these sequences were included was 15.7% for steam energy use and 5.7% for chilled water energy use; the omission of these changes to the sequences of operation diminished savings by 73% and 32%, respectively.

These simulation results indicate that, despite poor envelope qualities typical in older vintage buildings like building B, there exists significant potential for savings to be realized if sequences of operation are improved and OCC is implemented. This is critical as anecdotal evidence (e.g., [44,60]) suggests building operation’s stakeholders often dismiss the benefits of controls interventions in these types of buildings as esoteric, opting instead for costly and invasive envelope retrofits where energy implications are
more self-evident. However, the energy savings from the implementation of OCC are significantly diminished if sequences of operation are not first upgraded or corrected as exemplified in this simulation exercise. In the case of the measured data from building A, while the proportion of savings attributable to OCC is not known, it can be said that the implementation of OCC would have saved no energy if the sequencing errors affecting the building were not corrected. Demonstrating this phenomenon may help stakeholders justify the funding that may be required to upgrade BASs and sensing infrastructure to facilitate the monitoring, diagnosis, and correction of these inefficiencies and, subsequently, the addition of OCC. This cost may be modest in comparison to whole-building envelope retrofits.

4.4. Limitations and unresolved issues

Advice from ASHRAE at the onset of the pandemic was to drastically increase outdoor air rates, increase filtration, and ventilate overnight regardless of occupancy [61]. These brute force efforts to reduce the transmission of infectious aerosols all contribute to elevated energy use; an increase in energy use is undeniably justifiable for the purpose of safeguarding human health. Therefore, while this analysis takes advantage of the change in occupancy caused by the COVID-19 pandemic, the criticisms levelled against building adaptability to partial occupancy do not necessarily extend to building energy use during the pandemic specifically.

Additionally, this study examined a single OCC (i.e., system-level occupancy-based ventilation) as the timing of the implementation of this OCC and the COVID-19 pandemic presented a unique opportunity to study the impact of this OCC in an extreme case. The sequences of operation explored in this study were also chosen as their impact on AHUs is well understood, though their interactions with OCC are less-so. In essence, this study examined two known-unknowns; there exist numerous other known-unknowns in terms of sequences of operation that could potentially impact AHU operation, and surely a multitude of unknown-unknowns that have yet to be considered or examined exhaustively. With the measured energy use data for building A, it was not possible to determine the proportion of savings attributable to individual control changes in the building; for example, weather-adjusted cooling energy savings in building A were 16%. However, the simulation results from this study and a study by Kingsley and Nagy [50] found that cooling energy savings for similar OCCs were between 1% and 5%. Therefore, it is probable that a large portion of the cooling savings observed in building A were not simply a result of the addition of this OCC, but also due to the correction of the AHU night-cycling issue addressed when this OCC was implemented as discussed in Section 3.1. An energy model may be developed for building A to estimate these proportions in the future. Future work should not only explore other changes to the sequences of operation, but additional OCCs to determine their interaction and impact on building energy use. Of particular note is zone-level OCC, which have been shown to allow for increased occupant comfort and energy savings compared to their system-level counterparts (e.g., [11,21,62–64]).

Finally, this study examined two office buildings in ASHRAE Climate Zone 6A used for institutional purposes. The generalizability of this study’s findings when considering other office buildings, buildings located in other climate zones, or other controls interventions should be carefully considered. It is also highly probable that other control inefficiencies exist in the studied buildings that should be discovered and addressed. Additionally, the global response to the COVID-19 pandemic has varied greatly between jurisdictions within Canada and indeed around the world. Lockdown procedures and policies governing buildingoccupancies and the return to work vary considerably not only across these jurisdictions but also over time. A study of a significantly larger sample of commercial office spaces may help capture the effect of these temporospatial variations in occupancy on energy use and IEQ.

5. Conclusions and future work

This study aimed to evaluate how changes to the sequences of operation impact the energy savings potential of OCC. In the first part of the study, measured energy use data from the two buildings were compared. It was estimated that building A, which had system-level occupancy-based ventilation implemented at the beginning of the pandemic and had two sequencing logic errors corrected in the BAS which stopped economizing during the heating season and enabled the building’s enthalpy wheel, saved 47% on heating and 16% on cooling energy use compared to before the pandemic. Building B, which operated the same before and after the onset of the pandemic, was estimated to have used virtually the same amount of heating and cooling energy, despite the building being essentially vacant. This demonstrated the impact a building’s lack of adaptability can have on energy use. An ASHRAE Guideline 14–2014 [52] compliant calibrated energy model was developed for building B. The simulations indicated that, despite the building’s older vintage and poor envelope, it could have saved 15.7% of its heating and 5.7% of its cooling load had a similar OCC been introduced before the pandemic. The inclusion of a 21 °C economizer high limit increased the cooling savings by 5.2% when OCC was implemented; by contrast, the addition of a 21 °C economizer high limit without OCC was 4.4%. The use of constant SATs increased heating use by 14.9% when no OCC was used, and reduced OCC savings from 18.4% when an SAT reset scheme was used to only 4.4% when a constant SAT was used. Therefore, optimal control of SATs in the case study building was critical for reducing heating loads; the exclusion of an SAT reset scheme nearly eliminated the savings potential of the OCC. Similar to Kati-pamula [46], it was found that implementing an economizer high limit in buildings where one is not already present is a low-effort way to reduce cooling energy use, albeit comparatively modestly.

Future work will examine additional OCCs of increasing granularity and detail considerations that need to be made within the sequences of operation so that the full potential of these OCCs can be realized. These OCCs will be examined and optimized using building performance simulation with the goal of implementing these upgraded or ‘next-generation’ sequences of operation into a real-world testbed where measurement and verification can take place.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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