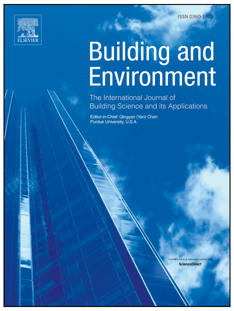


On quantifying building performance adaptability to variable occupancy

Mohamed M. Ouf, William O'Brien, Burak Gunay

PII: S0360-1323(19)30210-0

DOI: https://doi.org/10.1016/j.buildenv.2019.03.048

Reference: BAE 6050

To appear in: *Building and Environment*

Received Date: 6 November 2018

Revised Date: 26 February 2019

Accepted Date: 21 March 2019

Please cite this article as: Ouf MM, O'Brien W, Gunay B, On quantifying building performance adaptability to variable occupancy, *Building and Environment* (2019), doi: https://doi.org/10.1016/j.buildenv.2019.03.048.

On quantifying building performance adaptability to variable occupancy

Mohamed M. Ouf[a*], William O'Brien[b], Burak Gunay[b]

[a] Department of Building, Civil and Environmental Engineering, Concordia University, 1455 De Maisonneuve Blvd. West, EV 6.139, Montreal, Quebec, H3G 1M8, Canada

[b] Department of Civil and Environmental Engineering, Carleton University, 3432 Mackenzie Building, 1125 Colonel By Drive, Ottawa, Ontario K1S 5B6, Canada

[*] Corresponding author
Email address: mohamed.ouf@concordia.ca
Phone: +1 514-848-2424 ext. 3200
Department of Building, Civil and Environmental Engineering, Concordia University, 1455 De Maisonneuve Blvd. West, EV 6.139, Montreal, Quebec, H3G 1M8, Canada

Abstract

Most existing and new buildings adapt poorly to variable occupancy, in part due to technical constraints and common operational practice. Although building automation systems and advanced control strategies aim to address this issue by improving adaptability to partial occupancy, no holistic metrics exist to quantify this aspect of building performance. To this end, we present a technology-independent approach to define adaptability as a building performance attribute and introduce metrics to quantify it. These metrics can be used to evaluate how different building technologies and control strategies influence building operations' adaptability to variable occupancy or estimate their associated energy savings. To demonstrate these metrics, a case study based on simulating a single-story office building was used to compare several control strategies with regards to their effect on improving adaptability. Results showed how the proposed metrics highlighted the additional benefits of these control strategies, especially under low-occupancy scenarios. Performance-based compliance with building energy codes and standards typically assumes full or near full occupancy, which may underestimate the benefits of adaptable building technologies or controls. Therefore, incorporating adaptability metrics in energy codes and operational guidelines would quantify the benefits of adaptable systems, especially under variable occupancy.

1. Introduction

Building occupancy patterns are rapidly changing due to new societal trends such as teleworking, co-working, and home-sharing. A previous study reported that approximately 27% of the American workforce have flexible work schedules [1], while more recent studies show that this percentage exceeds 50% within the Canadian workforce [2]. These percentages will likely keep increasing, in part due technological advances that facilitate remote work and virtual communications. Consequently, occupancy patterns in offices and other types of buildings, such as residential buildings may vary significantly from standard assumptions that suggest offices are nearly fully occupied on weekdays while residential dwellings are nearly fully occupied on weeknights and weekends [3], [4]. Previous studies found that actual occupancy in office buildings rarely exceeds 50% on weekdays, with large variations from one office space to another [5]–[7].

Despite these variations in occupancy patterns, building design and operation is largely based on standard schedules that were developed in the 1980s [8] – before the concepts of telecommuting and virtual communications became commonplace. Furthermore, building operators typically accommodate the uncertainty of occupancy patterns by choosing more conservative schedules, for example by reducing temperature setback periods in an effort to reduce potential occupant complaints [9]. Temperature setback is intended to decrease heating and cooling energy use during unoccupied periods, and consequently overall building energy use. Therefore, reducing temperature setback periods results in maintaining comfortable conditions for a longer period than occupancy, especially if parts of the building remain unoccupied for relatively long periods. The same issues also apply to other building systems such as lighting and ventilation, which are typically controlled under the assumption of full or near full occupancy. In addition to these operational factors, the design of building systems and granularity of available controls can prevent building operations from accommodating occupancy variations. O'Brien et al. [10] showed that the minimum lighting control zone areas specified in the National Energy Code of Canada for Buildings [3] limit energy savings under low occupancy scenarios.

1.1 Defining adaptability

In this paper, the term “adaptability” refers to the degree to which building systems’ operations and energy use is proportional to the number of occupants at both the temporal and spatial scales. Figure 1 shows a conceptual representation of optimal adaptability relative to traditional operational strategies that do not adjust building operations to variable occupancy. Traditional building design and operation is based on the assumption that occupants are continuously present during scheduled periods and that they have identical preferences. In contrast, adaptable operations would decrease energy use under lower occupancy. However, it must be noted that reducing energy use in unoccupied buildings or spaces to zero is practically unfeasible for several reasons such as 1) mandatory safety and security requirements, 2) maintaining temperature and humidity conditions to prevent potential damage (e.g. frozen pipes or moulds), 3) decreasing the response time when occupants arrive, which would be prohibitive if temperatures are to be restored from setback levels.

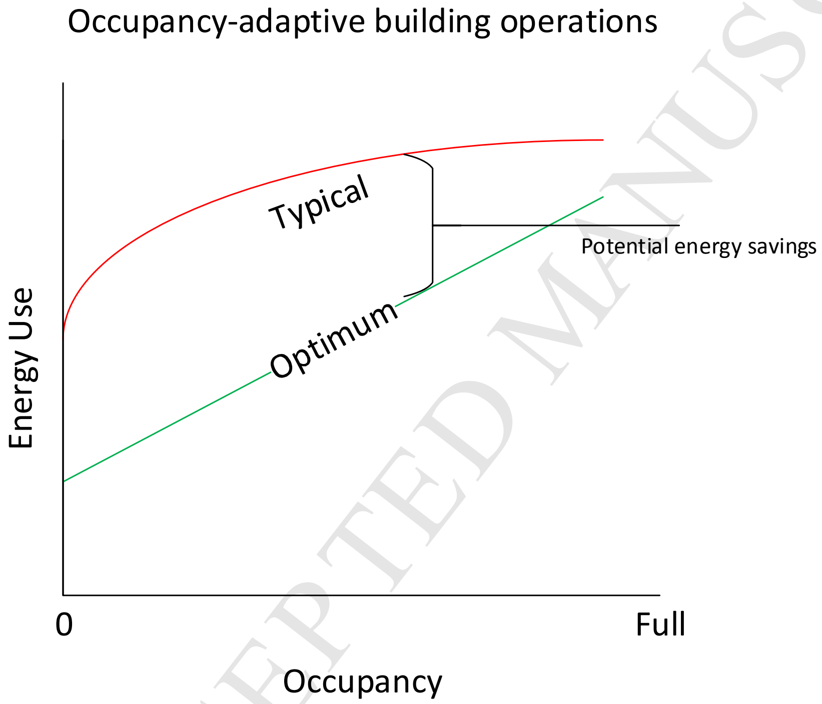


Figure 1 Conceptual overview of adaptable building performance

Several building systems and control strategies can improve buildings’ adaptability such as demand-controlled ventilation (DCV), occupancy-based controls, and model predictive controls. Previous studies showed these systems can achieve significant energy savings for different end-uses such as lighting, heating and cooling. For example, Brandemuehl and Braun [11] demonstrated up to 20% savings in electrical energy use for cooling in an office building because of using demand-controlled ventilation. Gunay et al. [9] also presented an occupancy learning algorithm for terminal heating and cooling units, which reduced space heating and cooling loads by 10-15%. Other adaptable control strategies to control lighting, heating and cooling set-points were also found to achieve significant energy savings in previous studies [12]–[18]. However, Woolley et al. [19] suggested that the performance of these systems is highly sensitive to their application mechanism and their responsiveness to occupancy variations. For example, the performance of model predictive controls is highly dependant on the accuracy and consistency of the short-term predictions that are used to identify optimal control decisions [20]. Therefore, beside quantifying associated energy savings, evaluation of these systems' performance should reflect the degree to which they improve buildings' adaptability to occupancy variations.

Due to the lack of building performance metrics that specifically focus on adaptability, this aspect is not typically evaluated nor quantified at both the design and operational phases. Therefore, building energy codes and standards only rely on prescriptive requirements to increase buildings' adaptability. For example, ASHRAE Standard 90.1 [4] requires DCV for spaces larger than 50 m^2 with a design occupancy greater than 25 people per 100 m^2 of floor area and served by a specific list of HVAC systems. Furthermore, occupancy-based lighting controls are only specified for certain building and space types, for example to automatically reduce lighting by at least 50% within 20 minutes of occupants' departure [4]. However, there is a growing trend towards performance-based code compliance using building simulation, although this approach does not address adaptability in part due to the absence of relevant metrics. It also relies on standard schedules that assume repetitive and near full occupancy, which downplays the potential advantages of adaptable building technologies whose benefits are more significant under low and variable occupancy scenarios [10].

Metrics for evaluating building performance are defined as any measurable quantity that assesses an aspect of building performance such as its structural reliability, aesthetic quality, or environmental impact. They should reflect progress towards achieving a specific performance goal with a clear definition of the boundaries of their measurement [21]. Existing building performance metrics cover many domains such as energy and cost performance, lighting, and indoor environmental quality [22], [23]. However, the occupant domain is relatively under-developed with regards to building performance metrics, despite its significant effect [24]. O'Brien et al. [24] suggested the first step towards developing meaningful performance metrics is defining the performance objective they intend to quantify and identifying the critical variable(s) they measure. This can be expressed as a qualitative statement, such as "minimize energy use", where different variables that ensure the achievement of this objective could be quantified [25].

1.2 Goal and objectives

The main goal of this paper is to introduce a new set of technology-independent building performance metrics to evaluate adaptability and estimate associated energy savings. The metrics can be widely applied to different building systems to assess their contribution to improving adaptability. They focus on evaluating different energy end-uses relative to occupancy patterns and reporting energy consumption normalized to occupancy. They can be calculated from building performance simulation outputs or using data collected from building energy management systems (BEMS) in existing buildings. The objectives of this paper focus on providing detailed descriptions of the proposed metrics and their calculation methods. A simulation-based investigation of an office building is then used to demonstrate this approach to evaluate some building technologies and control strategies that improve adaptability. Finally, two approaches to estimate the energy savings associated with these technologies are presented.

Calculating some of the introduced metrics requires detailed occupancy data, which may not be available in existing or new buildings, especially for new buildings at the design stage. Therefore, alternative calculation methods and simulation approaches to represent variable occupancy are also discussed. With the shift towards occupant-centric building design and operations, this paper's contributions are relevant for building energy codes and rating schemes as they provide widely applicable and reproducible metrics to evaluate adaptability - a typically overlooked aspect of building performance. Furthermore, the metrics can be used to compare different building technologies and evaluate building operations focusing on their ability to adapt to variable occupancy.

2. Adaptability metrics

The performance objective to be quantified using the proposed metrics is defined as "building operations' adaptability to variable occupancy". The hierarchical organization of these metrics is shown in Figure 2, and categorized based on conceptual, spatial, or temporal attributes.

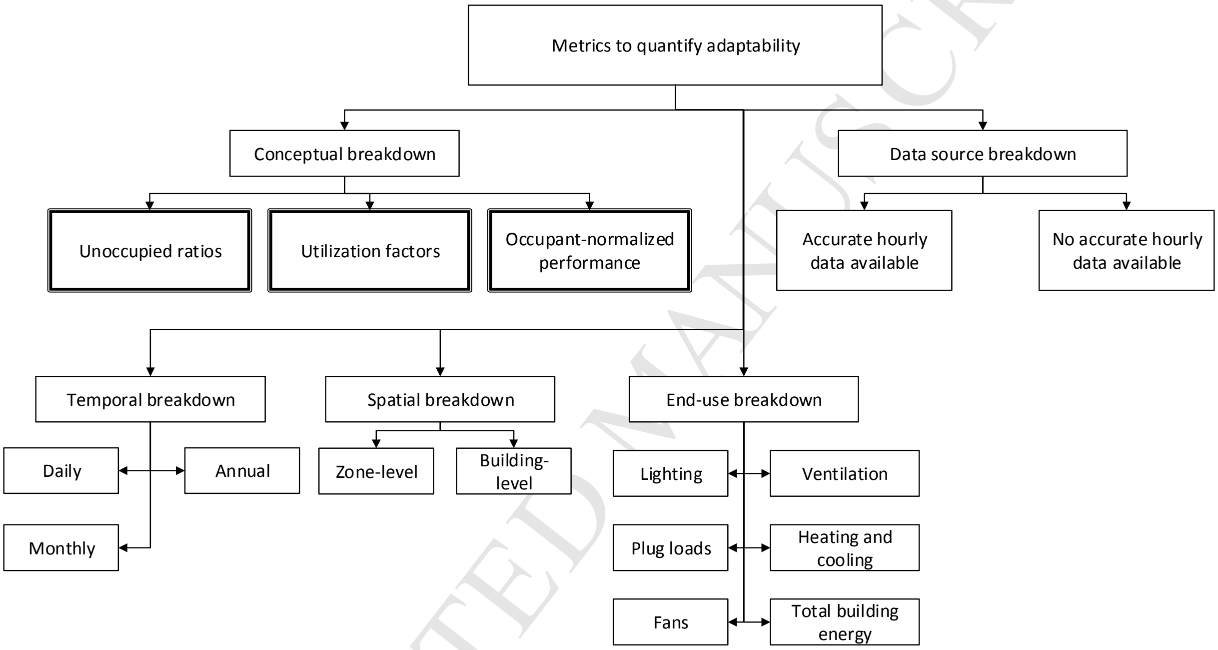


Figure 2 Hierarchical breakdown of the proposed adaptability metrics

The conceptual framework used to categorize the proposed metrics resulted in three distinctive groups that measure different aspects of adaptability as follows:

1. Metrics that focus on quantifying occupied vs. unoccupied energy use
2. Metrics that focus on measuring the utilization of different building systems at full capacity relative to equivalent occupancy at full capacity
3. Metrics that focus on using hourly occupancy as the normalizing factor for building performance reporting

These metrics can be reported for specific energy end-uses or to evaluate total building energy use. Another layer of categorization of these metrics is based on their temporal and spatial attributes. They can be reported at annual, monthly, or daily resolutions, and can also focus on specific building zones or entire buildings. If the goal is to assess overall building operations, adaptability metrics should be calculated at the building scale over annual periods. However, a more detailed analysis focusing on specific building zones during certain parts of the year may also provide useful insight. For example, calculating adaptability metrics (e.g. unoccupied ratio) for a sparsely occupied zone at certain times of the year can provide a quick indication of non-adaptable performance and prompt operational changes to its mechanical or lighting systems.

Given the importance of data availability for calculating the proposed metrics, another layer of categorizing them focuses on presenting alternative calculation methods if detailed occupancy data is unavailable. In addition to detailed occupancy data, calculating the proposed metrics also requires hourly energy use data for different end-uses. This granular energy use data can be obtained from building simulations at the design stage but may require sub-metering or data collection from BEMS in existing buildings. The following sub-sections provide more details on the proposed metrics and discuss different calculation approaches depending on data availability.

2.1 Unoccupied energy use

The first category of adaptability metrics focuses on energy use during occupied vs. unoccupied hours. This category of metrics provides a preliminary indication of the amount of energy used while the building or specific zone is unoccupied. Previous studies showed that energy use during non-working hours can reach up to 56% in office buildings, relative to their total energy use [26], [27]. Harris and Higgins [27] proposed an "overnight ratio" to quantify daytime vs. nighttime energy use which inspired the proposed metrics in this category. For buildings in which accurate occupancy data is available, the adaptability metrics proposed in this category focus on quantifying building use during unoccupied hours relative to total use. If accurate hourly occupancy data is unavailable, the same metrics can be estimated based on the projected occupancy patterns. For example, an overnight ratio can be used for office buildings where nighttime occupancy is expected to be zero. Selecting the exact timing of night hours for such analysis may vary from one building to another based on its type and any known information about its typical use.

The proposed unoccupied ratios, which are unitless metrics, can be calculated using equations 1 – 5 for lights, plug loads, fans, heating and cooling, respectively. The time scale used for calculating these metrics can vary from one day to a whole year depending on the analysis objective and available data. Similarly, these metrics can be calculated for an entire building or can focus on specific zones (i.e. they are applicable at different spatial scales). However, it should be noted that the type of mechanical systems used in the building affects the possibility of calculating these metrics at the zone level. For example, if the building's mechanical system does not include terminal fans, fan energy use would be calculated for air handling units serving multiple zones. Furthermore, metric users may opt to add weighting factors to account for different sizes of zones or light and plug load intensity and ventilation requirements.

$$Unoccupied\ light\ use\ ratio = \frac{\sum_{i=1}^{i=n} L_{unoccupied,\ i}}{\sum L_{total}} \tag{1}$$

$$Unoccupied\ plug\ loads\ use\ ratio = \frac{\sum_{i=1}^{i=n} P_{unoccupied,\ i}}{\sum P_{total}} \tag{2}$$

$$Unoccupied\ fan\ use\ ratio = \frac{\sum_{i=1}^{i=n} F_{unoccupied,\ i}}{\sum F_{total}} \tag{3}$$

$$Unoccupied\ heating\ ratio = \frac{\sum_{i=1}^{i=n} H_{unoccupied,\ i}}{\sum_{i=1}^{i=n} H_{total,\ i}} \tag{4}$$

$$Unoccupied\ cooling\ ratio = \frac{\sum_{i=1}^{i=n} C_{unoccupied,\ i}}{\sum_{i=1}^{i=n} C_{total,\ i}} \qquad (5)$$

where n is the total number of zones in the building, $L_{unoccupied}$ is light use during unoccupied hours, L_{total} is total light use, $P_{unoccupied}$ is plug loads use during unoccupied hours, P_{total} is total plug loads use, $F_{unoccupied}$ is fan energy use during unoccupied hours, F_{total} is total fan energy use, $H_{unoccupied}$ is heating energy use during unoccupied hours, H_{total} is total heating energy use, $C_{unoccupied}$ is cooling energy use during unoccupied hours, C_{total} is total cooling energy use.

*Note that these metrics can be calculated at different temporal and spatial scales

A lower unoccupied ratio is more desirable for all end-uses since it indicates that less energy is used when the building or zone is unoccupied. Theoretically, the minimum unoccupied energy use would be zero, but practical limitations due to safety and operational requirements mean that energy use is still needed even when the building is completely unoccupied. The minimum unoccupied ratio would also change for different end-uses and in different jurisdictions based on safety standards (e.g. for emergency lighting) and climatic conditions (e.g. for overnight heating). That said, the goal of building designers and operators should be minimizing unoccupied ratios to the lowest attainable value, to increase buildings' adaptability.

2.2 Utilization factors

The second category of adaptability metrics focuses on the utilization of different building systems. This set of metrics is partially inspired by a common metric used in electrical engineering which is called utilization factor. It represents the ratio of time a piece of equipment is in use relative to the total time at which it could have been in use [28]. In other words, this metric focuses on the duration of energy end use as a measure of its utilization. In the context of buildings' adaptability, the proposed utilization factors quantify the equivalent duration of energy use at full capacity relative to the equivalent duration of occupancy at full capacity. O'Brien et al. [24] introduced a similar metric focusing on light use, which was called light utilization ratio (LUR). It measured the duration of light use relative to occupied time. Although calculating the metric was illustrated by simulating light use in a single office in [24], the details for calculating this metric in buildings with multiple zones and occupants were not demonstrated. The proposed set of utilization factors can be calculated using equations 6 – 10 for lights, plug loads, fans, heating, and cooling, respectively. Although granular occupancy data is required to calculate these factors, the equivalent hours of occupancy at full capacity can also be estimated based on occupancy schedules used at the design phase or information about the building's typical use. Similar to unoccupied use ratios, the proposed utilization factors can be calculated at various temporal and spatial scales depending on available data and the analysis objective.

$$Light\ utilization\ factor = \sum_{i=1}^{i=n} \frac{L_i}{L_{max,\ i}} \Big/ \sum_{i=1}^{i=n} \frac{O_i}{O_{max,\ i}} \qquad (6)$$

$$Plug\ loads\ utilization\ factor = \sum_{i=1}^{i=n} \frac{P_i}{P_{max,\ i}} \Big/ \sum_{i=1}^{i=n} \frac{O_i}{O_{max,\ i}} \qquad (7)$$

$$Fans\ utilization\ factor = \sum_{i=1}^{i=n} \frac{F_i}{F_{max,\ i}} \Big/ \sum_{i=1}^{i=n} \frac{O_i}{O_{max,\ i}} \qquad (8)$$

$$Heating\ utilization\ factor = \sum_{i=1}^{i=n} \frac{H_i}{H_{max,\ i}} \Big/ \sum_{i=1}^{i=n} \frac{O_i}{O_{max,\ i_i}} \qquad (9)$$

$$Cooling\ utilization\ factor = \sum_{i=1}^{i=n} \frac{C_{max,\ i}}{H_{max,\ i}} / \sum_{i=1}^{i=n} \frac{O_i}{O_{max,\ i}} \quad (10)$$

Where L_i is the total hourly light use in zone i, $L_{max,\ i}$ is the design peak light use in zone i, O_i is the sum of occupant-hours in zone i, $O_{max,\ i}$ is the design peak number of occupants in zone i, P_i is the total hourly plug loads use in zone i, $P_{max,\ i}$ is the design peak plug loads use in zone i, F_i is the total fan energy use in zone i, $F_{max,\ i}$ is the design peak fan energy use in zone i, H_i is the total heating energy use in zone i, $H_{max,\ i}$ is the design peak heating energy for zone i, C_i is the total cooling energy use in zone i, $C_{max,\ i}$ is the design peak cooling energy for zone i.

Although utilization factor is a unitless metric, a lower value indicates less energy is used relative to occupancy. A utilization factor of one means that building systems are used proportionally to the number of occupants (i.e. the equivalent duration of energy use at full capacity is equal to the equivalent duration of occupancy at full capacity). In some cases, the utilization factor may be lower than one if the equivalent duration of using building systems at full capacity is lower than the equivalent duration of occupancy at full capacity. This would result from building systems that adapt to external factors other than the number of occupants. For example, lighting controls based on occupancy as well as daylight availability could result in a light utilization factor below one. Utilization factors can also take any higher value up to infinity if the equivalent duration of occupancy at full capacity approaches zero.

2.3 Occupant-normalized energy use

The third category of adaptability metrics focuses on the normalization factors used to report building performance. Typically, building floor area is used for reporting building performance although it represents a static normalization factor, especially when considering variable occupancy. Since the actual purpose of most buildings is to provide a functional and comfortable environment to their occupants [24], using floor area as the normalization factor may not be representative. An example by Norman et al. [29] illustrated that normalizing greenhouse gas emissions by floor area suggested that large suburban homes perform nearly as well as dense multi unit residential buildings (MURBs). However, normalization by the number of occupants revealed that MURBs are twice as energy efficient as large suburban homes. In a different example, Kampel et al. [30] indicated that energy use in recreational facilities is most strongly correlated to the number of visitors, which should be used as the normalization factor when reporting energy use rather than floor areas. The proposed set of metrics in this category focus on normalizing energy use by the aggregate hourly number of occupants (i.e. occupant-hours), which implicitly accounts for occupancy variations. This set of metrics can be calculated using equations 11 – 15 for lights, plug loads, and fans, heating and cooling respectively. They can be calculated at various temporal and spatial scales depending on available data and the analysis objective similar to the previous metrics.

$$\text{Occupant-normalized light use} = \frac{\sum_{i=1}^{i=n} \mathrm{L}_i}{\sum_{i=1}^{i=n} \mathrm{O}_i} \quad (11)$$

$$\text{Occupant-normalized plug loads use} = \frac{\sum_{i=1}^{i=n} P_i}{\sum_{i=1}^{i=n} \mathrm{O}_i} \quad (12)$$

$$\text{Occupant-normalized fan use} = \frac{\sum \mathrm{F}_{total}}{\sum \mathrm{O}_{total}} \quad (13)$$

$$\text{Occupant-normalized heating energy use} = \frac{\sum \mathrm{F}_{total}}{\sum \mathrm{O}_{total}} \quad (14)$$

$$\text{Occupant-normalized cooling energy use} = \frac{\sum \mathrm{F}_{total}}{\sum \mathrm{O}_{total}} \quad (15)$$

where L_i is the total hourly light use in zone i, O_i is the total hourly occupancy in zone i, P_i is the total hourly plug loads use in zone i, F_{total} is the total fan energy use in the building, and O_{total} is the total hourly occupancy across the building.

The unit for reporting occupant-normalized energy use metrics would be energy use per occupant-hour. Similar to reporting energy use per floor area, a lower value for occupant-normalized energy use is desirable since it implies better adaptability. However, since many other factors affect energy use, this category of metrics may be influenced by other building-specific parameters, such as the type of mechanical systems used or envelope characteristics, or by outdoor weather conditions which are not occupant-related. Despite these influences, normalizing energy use to the number of occupants rather than floor area under the same conditions (e.g. for the same building and under similar weather conditions) provides an indication for adaptability. Designers and operators should aim to decrease the value of occupant-normalized energy use to the lowest attainable levels to reflect improved adaptability.

2.4 Whole building metrics

Two approaches are presented to assess overall building adaptability. The first focuses on quantifying average unoccupied ratios and utilization factors based on these calculated metrics for all end-uses. These averages represent the overall adaptability performance of different building systems and end-uses. An alternative approach entails calculating the three categories of adaptability metrics using total energy use and overall building occupancy as shown in equations 16 – 18. If detailed occupancy data does not exist for the building, occupancy profiles may also be estimated based on available information regarding the building’s typical use.

$$Unoccupied\ total\ energy\ use\ ratio = \frac{\sum E_{unoccupied}}{\sum E_{total}} \quad (16)$$

$$Total\ energy\ utilization\ factor = \sum \frac{E_{total}}{E_{max}} / \sum \frac{O_{total}}{O_{max}} \quad (17)$$

$$Occupant - normalized\ total\ energy\ use\ = \frac{\sum \mathrm{E}_{total}}{\sum \mathrm{O}_{total}} \quad (18)$$

where $E_{unoccupied}$ is the aggregate hourly energy use during unoccupied hours, E_{total} is the total energy use, E_{max} is peak energy use, O_{total} is aggregate hourly occupancy, and O_{max} is the peak design occupancy of the building.

This group of metrics is only applicable at the building level but may be calculated at different temporal scales. A benchmark or minimum threshold for these metrics would vary based on building type, location and other factors. However, a lower value is generally desirable as it indicates better adaptability and should be the objective of design teams and building operators.

2.5 Metrics characteristics

The proposed metrics were assessed relative to the key characteristics for effective building performance metrics outlined in previous studies [21], [24], [31], [32]. Table 1 provides an overview of these key characteristics and qualitatively evaluates the proposed metrics relative to them. The main objective of the proposed adaptability metrics is providing actionable information to enable designers or building operators to take the necessary steps towards improving their buildings. However, these metrics do not provide information on how adaptability can be improved, which is a general limitation of performance metrics. Instead, they allow designers to compare different technologies and control strategies that improve adaptability by quantifying this aspect.

Table 1 Evaluation of the proposed metrics relative to the key characteristics of effective performance metrics adapted from O'Brien et al. [24]

Characteristic	Definition	Unoccupied use ratios	Utilization factors	Occupancy-normalized metrics
Fit for purpose	It should embody the objective it is designed to measure and should accurately quantify and communicate it	Moderate – Although they quantify one aspect of adaptability, they do not capture adaptability to partial occupancy	Good – They quantify more aspects of adaptability, since they account for adaptability to partial occupancy	Moderate – They quantify some aspects of adaptability, but implicitly account for other factors such as building systems' and envelope efficiency
Reproducible	It should give reproducible results when simulated and/or measured under similar scenarios and conditions	Good – All of the proposed metrics can be easily reproduced in under similar conditions if the required data is available		
Easy to obtain	It should be readily calculated by building measurements and/or simulation results	Good – Although hourly occupancy data is required, occupancy estimates can also be used to calculate these metrics	Good - Although hourly occupancy data is required, occupancy estimates can also be used to calculate these metrics	Poor – They strictly require detailed hourly occupancy and energy use data to be calculated
Comparable	It should enable the comparison of results to other buildings to facilitate benchmarking and understanding of relative performance	Good – They can be easily compared between different buildings	Good – They can be easily compared between different buildings	Moderate – Since they implicitly account for other building parameters, comparison between different buildings should interpreted with caution
Quantitative	It should provide a numerical quantitative measure	Good – All of the proposed metrics provide a quantitative measure to evaluate aspects of adaptability		
Accessible	It should be straightforward and should not be based on complicated indexes that designers do not know how to interpret or influence	Good – They are fairly straightforward since they simply represent the percentage of use during unoccupied hours	Moderate – They may require some explanation as they report the ratio of equivalent use at full capacity to equivalent occupancy at full capacity	Good – They are fairly straightforward since they simply represent the amount of energy used per occupant-hour over the analysis period

Actionable	It should present information that allows the user to take action	Good – They provide actionable information since they quantify the amount of energy use during unoccupied times	Good – They provide actionable information since they quantify overall energy use duration relative to occupancy	Moderate – They provide actionable information regarding adaptability but also account for other building parameters
Unbiased	It should offer a neutral indication of building performance	Good – They are un-biased since they do not implicitly account for other aspects of building performance	Good – They are un-biased since they do not implicitly account for other aspects of building performance	Poor – They may be biased due to other building related factors they implicitly account for

3. Calculating adaptability metrics

A simulation case study of a single-story office building, shown in Figure 3, is presented in this section. The main objective of this case study is demonstrating the calculation of some of the proposed metrics and using them to evaluate different technologies and control strategies that aim to improve adaptability. The building envelope specifications were chosen based on ASHRAE Standard 90.1's (2016) requirements for climate zone 6a, while its mechanical system was modelled as a dedicated outdoor air system. A central air handling unit (AHU) was modelled to supply outdoor air, with fan coil units in each zone for recirculation.

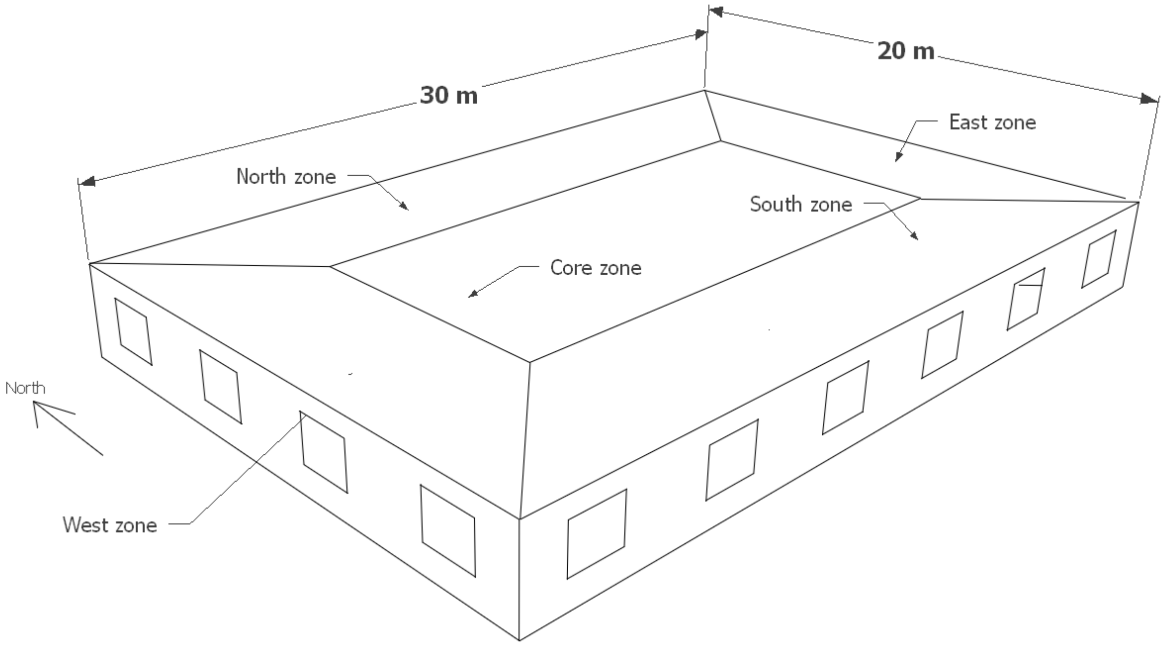


Figure 3 Dimensions of the modelled singe-story office building

Results of an annual simulation of this building were used to calculate the proposed metrics, which are presented in Table 2. This simulation was based on assumptions specified in ASHRAE Standard 90.1 for office buildings (i.e. occupant density was specified as 25 m2/person, plug loads density was specified as 8.1 W/m2, and lighting power density was specified as 8.5 W/m2, including daylight controls to reduce electric lighting using continuous dimming with a target workplane illuminance level of 500 lux). Unoccupied use ratios and utilization factors were lowest for cooling energy use because the building was simulated in a heating-dominated climate. Furthermore, the cooling availability schedule based on standard schedules assumes no overnight cooling for this climate. On the other hand, metrics related other end-uses, such as heating, lights and fans were relatively higher. Therefore, other control strategies were tested to investigate their effect on improving some of these metrics, which are presented in the following subsections.

Table 2 Adaptability metrics calculated based on simulation results of a single-story office building in ASHRAE climate zone 6a

Metric	Unit	Value

Unoccupied use ratios		
Unoccupied light use ratio	-	0.07
Unoccupied plug loads use ratio	-	0.22
Unoccupied fan use ratio	-	0.12
Unoccupied heating ratio	-	0.46
Unoccupied cooling ratio	-	0.01
Utilization factors		
Light utilization factor	-	1.39
Plug loads utilization factor	-	1.96
Fans utilization factor	-	1.12
Heating utilization factor		0.14
Cooling utilization factor	-	0.056
Occupant-normalized energy use		
Occupant-normalized light use	kWh/occupant-hour/year	0.23
Occupant-normalized plug loads use		0.36
Occupant-normalized fan use		0.1
Occupant-normalized heating energy use		0.29
Occupant-normalized cooling energy use		0.04
Whole building metrics		
Average unoccupied use ratio	-	0.098
Average utilization factor	-	0.92
Unoccupied total energy use ratio	-	0.15
Total energy utilization factor	-	0.21

3.1 Demand-controlled ventilation

To evaluate demand-controlled ventilation's potential for improving adaptability, relevant metrics that focus on fan energy use were calculated under different occupancy scenarios. To represent these occupancy scenarios, ASHRAE standard 90.1 occupancy schedules were multiplied by 0.8, 0.6, and 0.4 to represent high, medium and low occupancy, respectively in accordance with measured occupancy levels described in previous studies [33]–[35]. Figure 4 shows the daily occupancy profiles under these scenarios which were used as simulation inputs. Based on the specified occupancy profiles and occupant density of 25 m2/person, the cumulative number of occupant-hours per year for this office building was 53538, 40154, and 26769 for high, medium and low occupancy, respectively. Using the outputs of these simulations, fan utilization factors and occupant-normalized fan use were calculated under each occupancy scenario with and without DCV, as shown in Figure 5.

To simulate the office building without DCV, outdoor air rate was set to the peak value of 2.5 L/s/person + 0.3 L/s/m^2 between 7AM and 8PM as specified in ASHRAE Standard 62.1. For simulations with DCV, outdoor air rate was controlled based on the number of occupants in each zone (i.e. N×2.5 L/s/person + 0.3 L/s/m^2) where (N) is the number of occupants at each simulation timestep based on the specified occupancy profiles.

Overall, DCV improved adaptability as it decreased fans' utilization factor relative to simulations without DCV. Recall that utilization factors are a measure of the equivalent duration of using the AHU fans at full capacity relative to the equivalent duration of full occupancy. Results for occupant-normalized fan energy use, which are also shown in Figure 5, demonstrated that DCV decreased fan energy use per occupant-hour relative to simulations without DCV.

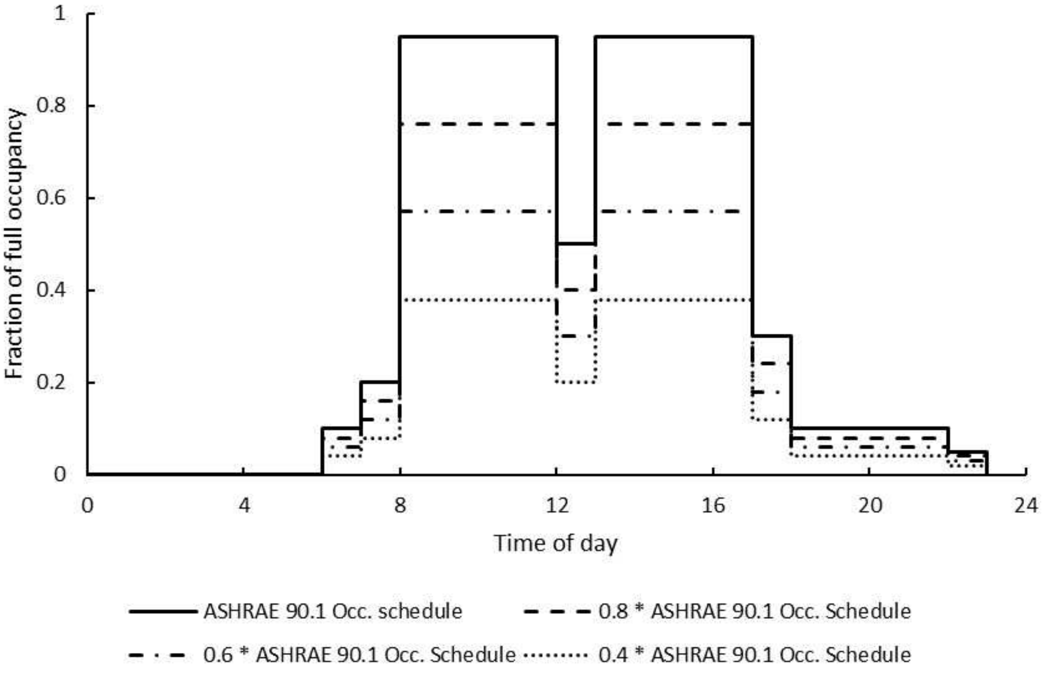


Figure 4 Weekday occupancy scenarios used in the simulation

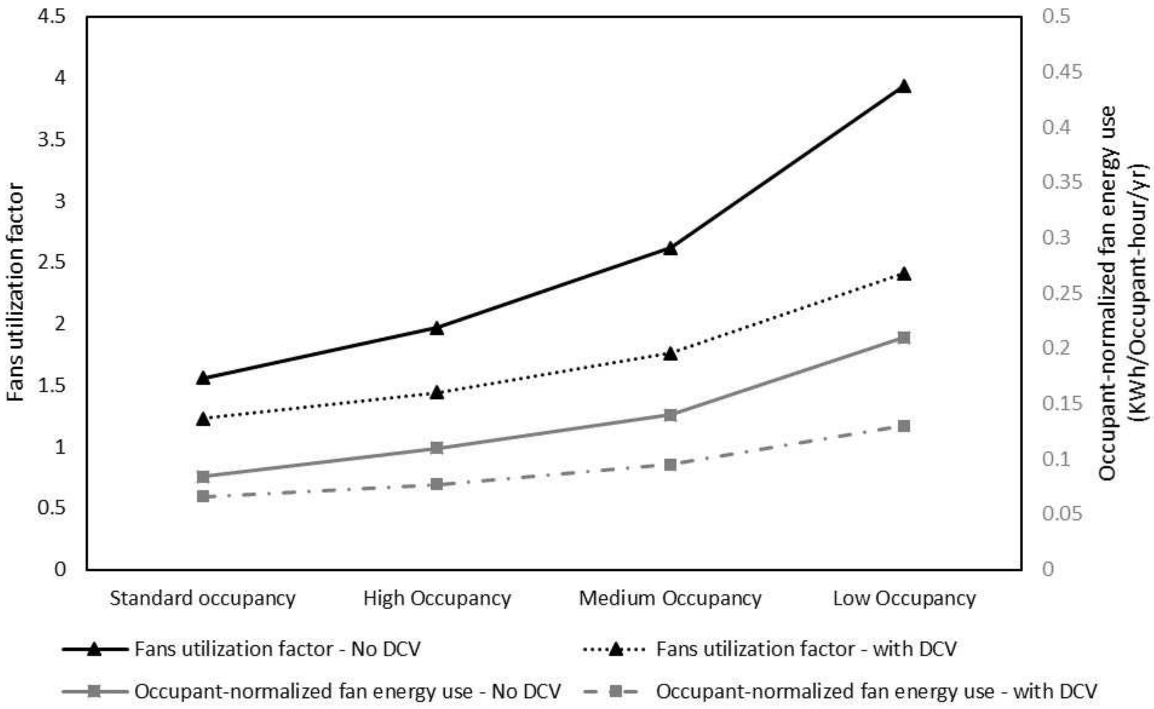


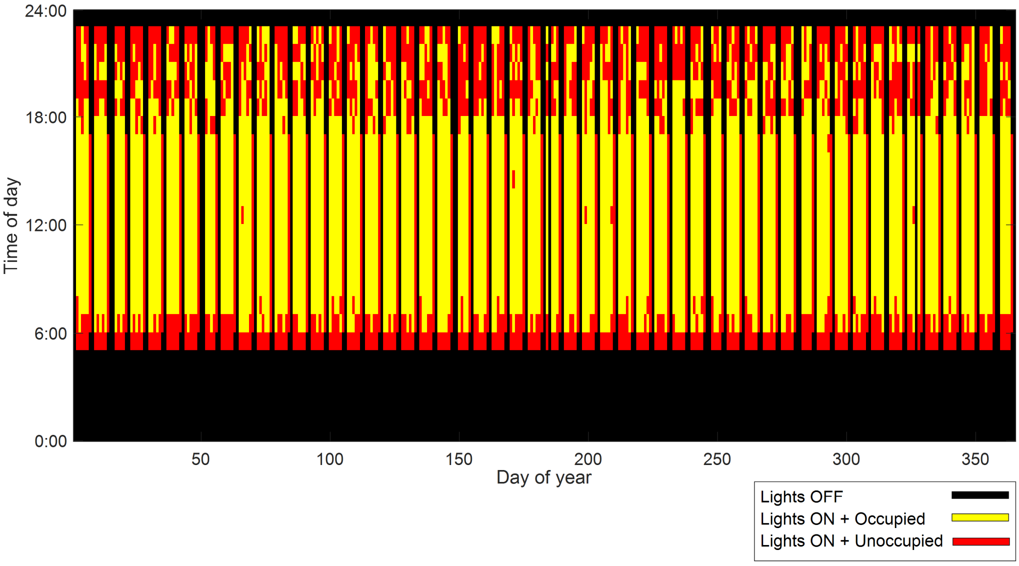
Figure 5 Changes in fans utilization factor and occupant-normalized fan energy use with and without DCV under different occupancy scenarios

One of the main observations was the increase in fan utilization factor and occupant-normalized fan use under lower occupancy scenarios, which indicates that adaptability decreased. This trend was found for simulations with and without DCV, however, the rate of increase in fan utilization factor and occupant-normalized fan use was lower with DCV. In other words, the difference between fan utilization factors and occupant-normalized fan use between simulations with and without DCV was highest under low occupancy. These findings suggest that the improvements in adaptability due to DCV are better realized under lower occupancy, which previous studies suggest is more common in today's office buildings [36]. These proposed metrics also allow designers to quantify improvements in adaptability and assess technologies under different occupancy scenarios, to highlight their benefits under non-standard occupancy patterns.

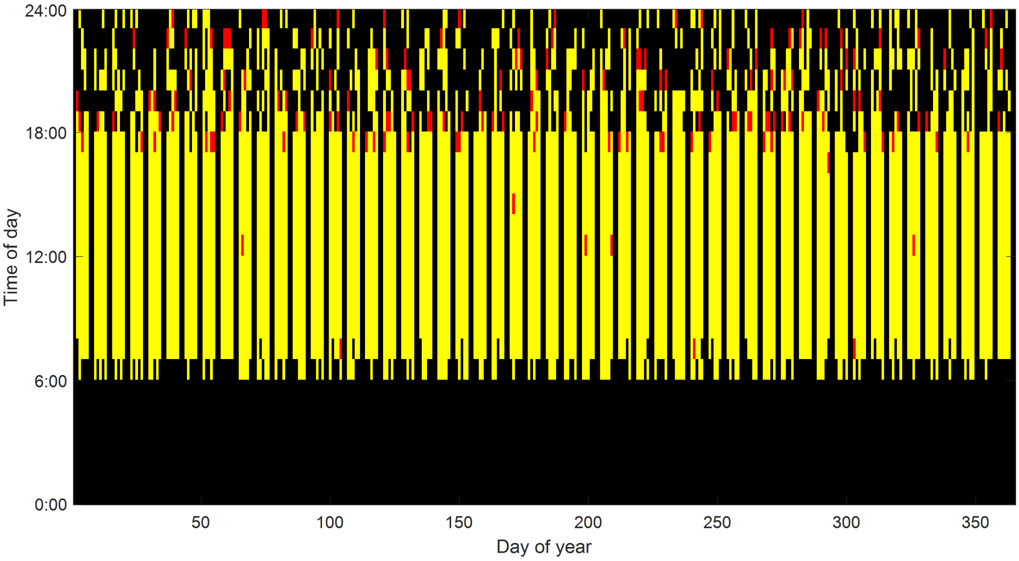
3.2 Lighting controls

To evaluate the potential of different lighting control strategies for improving adaptability, relevant metrics that focus on light use were also calculated under different occupancy scenarios. However, some of the evaluated lighting control strategies included occupancy-based controls which required more precise information about each occupant's presence within the building. Therefore, individual occupants' presence was simulated using the Page et al. [37] model, which is a stochastic agent-based model that treats occupants as individuals. The input schedule used for the Page et al. [37] model was ASHRAE standard 90.1 office occupancy schedule multiplied by 0.8, 0.6, and 0.4, representing high, medium, and low occupancy, respectively. Since these occupancy-based lighting controls also respond to occupancy changes at short intervals, five-minute timesteps were used in the simulations. Another required input to the Page et al. [37] model is the mobility parameter, which was specified as 0.1 and indicated the frequency of occupants arriving and leaving within a day. Note that Page et al. [37] occupancy model was developed and calibrated based on data collected form an institutional building in Switzerland, thus its assumptions about occupancy patterns in offices may not be universally applicable (e.g. coffee break times). It is only used in this case study to demonstrate the benefits of using adaptability metrics under variable occupancy scenarios, but this should not be interpreted as an endorsement of using the results of this case study in other contexts and locations.

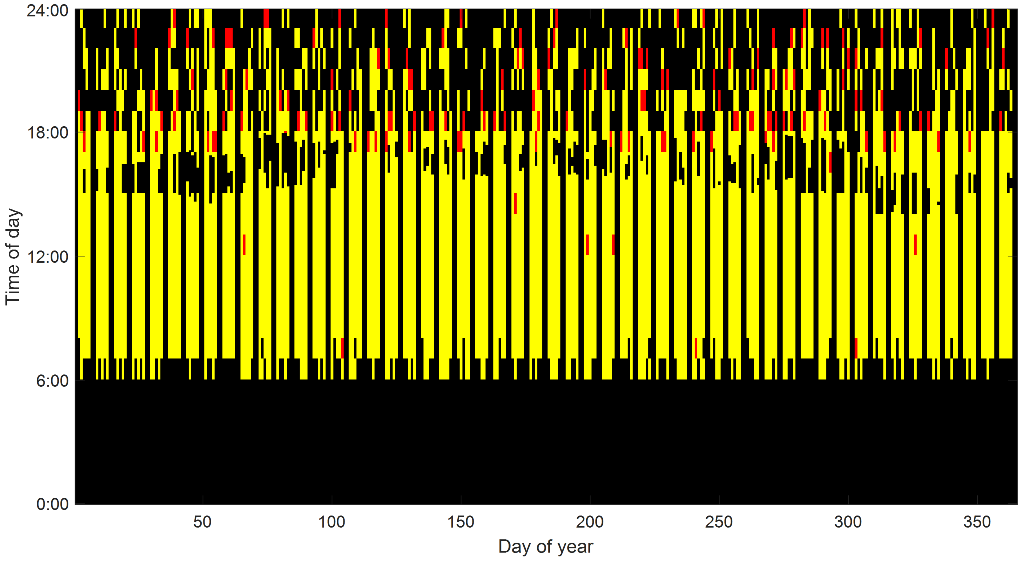
The analysis of lighting controls only focused on the west-facing perimeter zone of the building as an example since some of the implemented controls included daylight controls. Four different lighting control strategies were investigated. The first strategy, which represented the baseline case for this analysis, entailed using ASHRAE standard 90.1 lighting schedules for offices (i.e. schedule-based controls). The second strategy focused on occupancy-based controls where lights are automatically turned on as soon as the occupant arrived in the zone, and turned off after 15 minutes from the occupant's departure. The third strategy included the same occupancy-based controls in addition to daylight controls with continuous dimming to maintain workplane illuminance at 500 lux. The fourth controls strategy used the same control logic for occupancy-based and daylight controls used in the third case, but without the 15-minute delay in switching lights off upon occupants' departure. For non-schedule-based controls (i.e. the latter three control strategies), light use in this zone was assumed to be proportional to the number of occupants present at each time step (where the total number of modelled occupants was four). In other words, 25% of the west zone's light use was controlled based on each occupant's presence profile. Figure 6 shows a visual comparison of annual light use relative to low occupancy given each of the investigated lighting control strategies. The goal of increasing adaptability is minimizing instances where lights are used in this zone while it is unoccupied (i.e. red dots).


24:00
18:00
12:00
6:00
0:00
Time of day
50
100
150
200
250
300
350
Day of year
Lights OFF
Lights ON + Occupied
Lights ON + Unoccupied

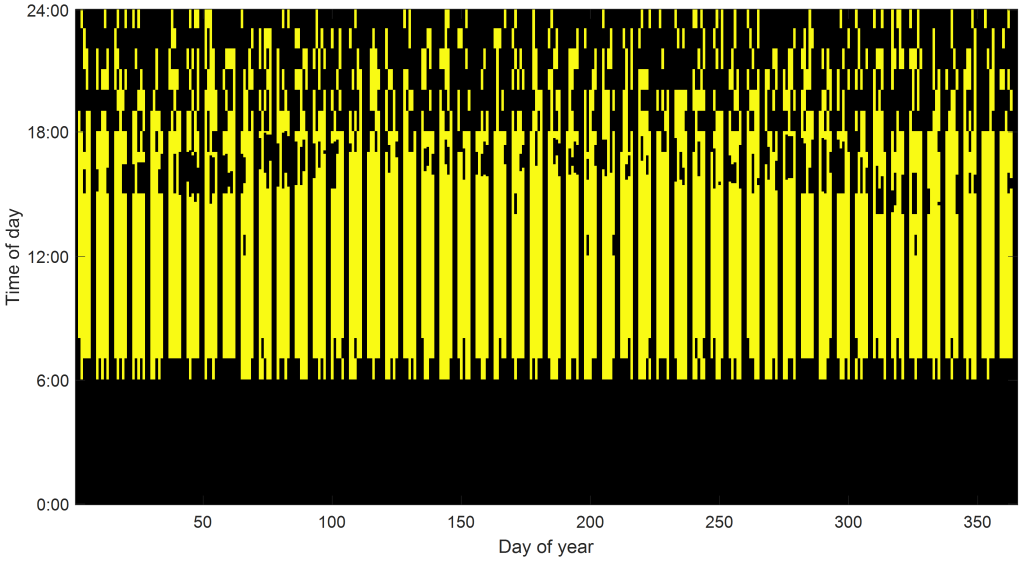
a


24:00
18:00
12:00
6:00
0:00
Time of day
50
100
150
200
250
300
350
Day of year

b



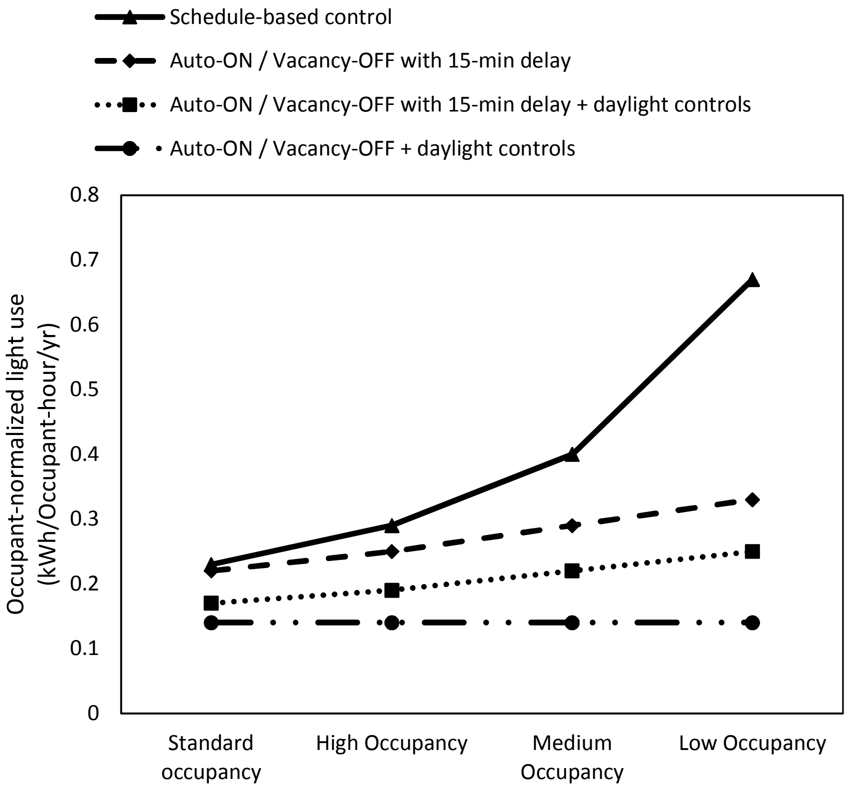
c



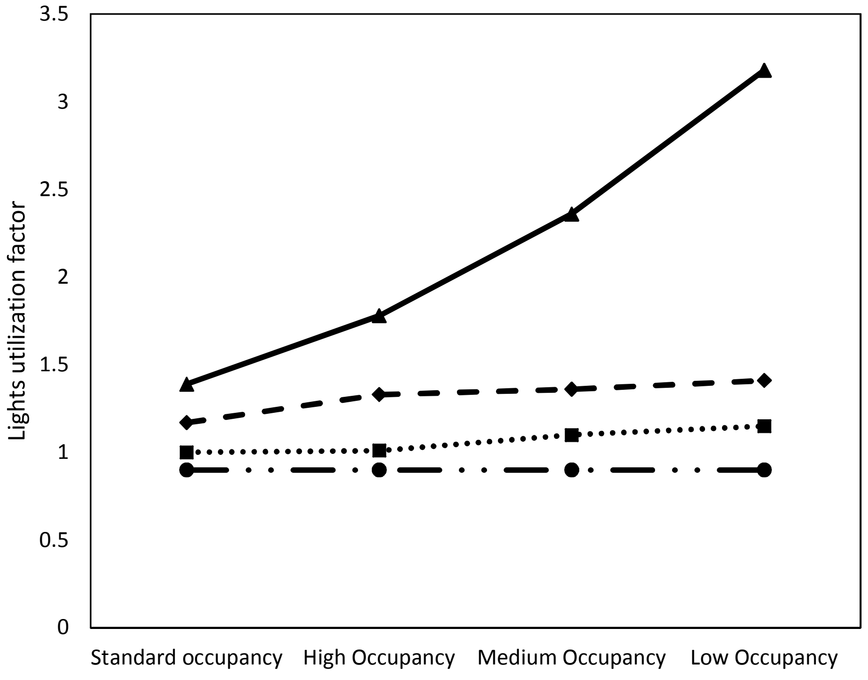
d

Figure 6 Light use relative to occupancy under low occupancy and a) schedule-based controls b) occupancy-based controls with a 15-minute delay, c) occupancy-based controls with a 15-minute delay and daylight controls, d) occupancy-based controls without vacancy delay and daylight controls

To quantify the effect of these control strategies on improving adaptability, light utilization factors were calculated under the different occupancy scenarios described above. Figure 7 shows the results of these calculations which confirm that lighting controls improved adaptability relative to the baseline case with schedule-based controls. Occupancy-based controls with a 15-minute delay combined with daylight controls maintained light utilization factor in this zone close to one, even under lower occupancy scenarios. In contrast, simulating light use based on ASHRAE Standard 90.1 schedules only (i.e. with schedule-based controls) significantly increased light utilization factor, especially under low occupancy. Similar observations were also found for occupant-normalized light use which decreased with additional controls, relative to the baseline case. It is worth noting that the fourth control strategy resulted in decreasing light utilization factor to approximately 0.9. This control strategy assumed automatic light switch on and off upon occupants' arrival and departure in addition to daylight controls. Therefore, the equivalent duration of light use at full capacity was lower than the equivalent duration of occupancy at full capacity. However, implementing this occupancy-based control strategy where lights are switched off upon vacancy may lead to occupant discomfort, especially if it entails frequent false absence detections.



a



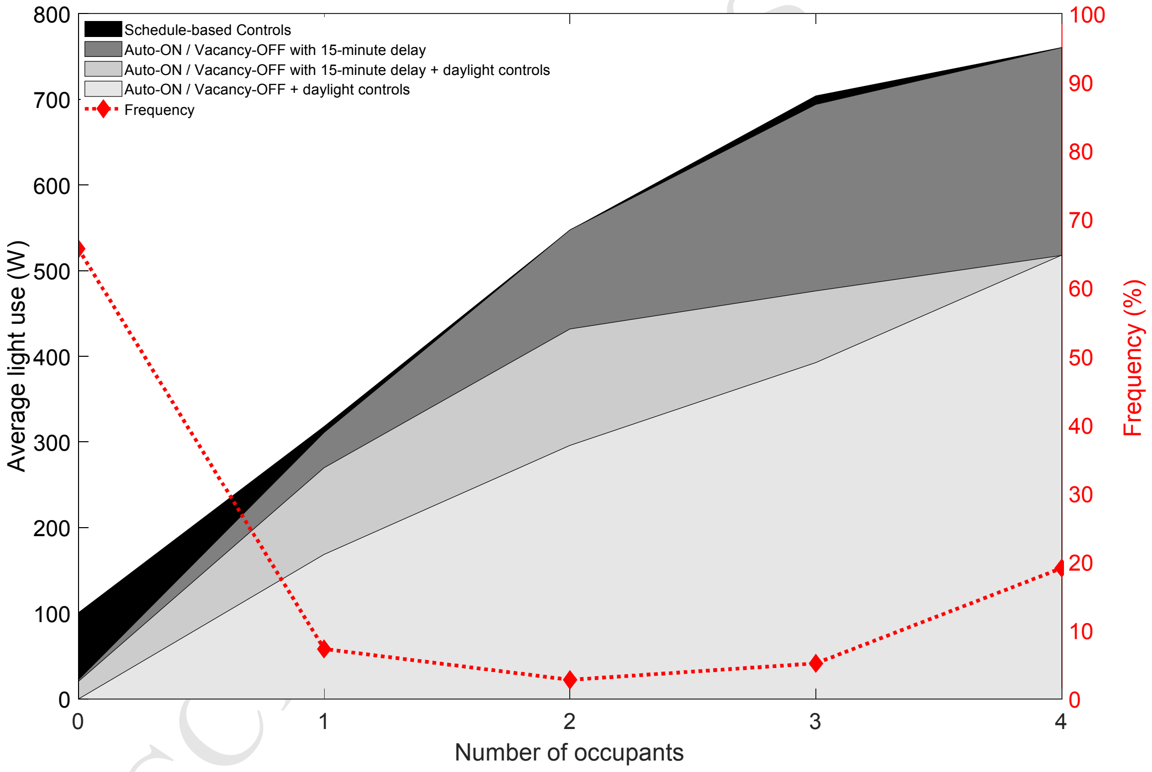
b

Figure 7 Changes in occupant-normalized light energy use and lights utilization factor with different control strategies and occupancy scenarios

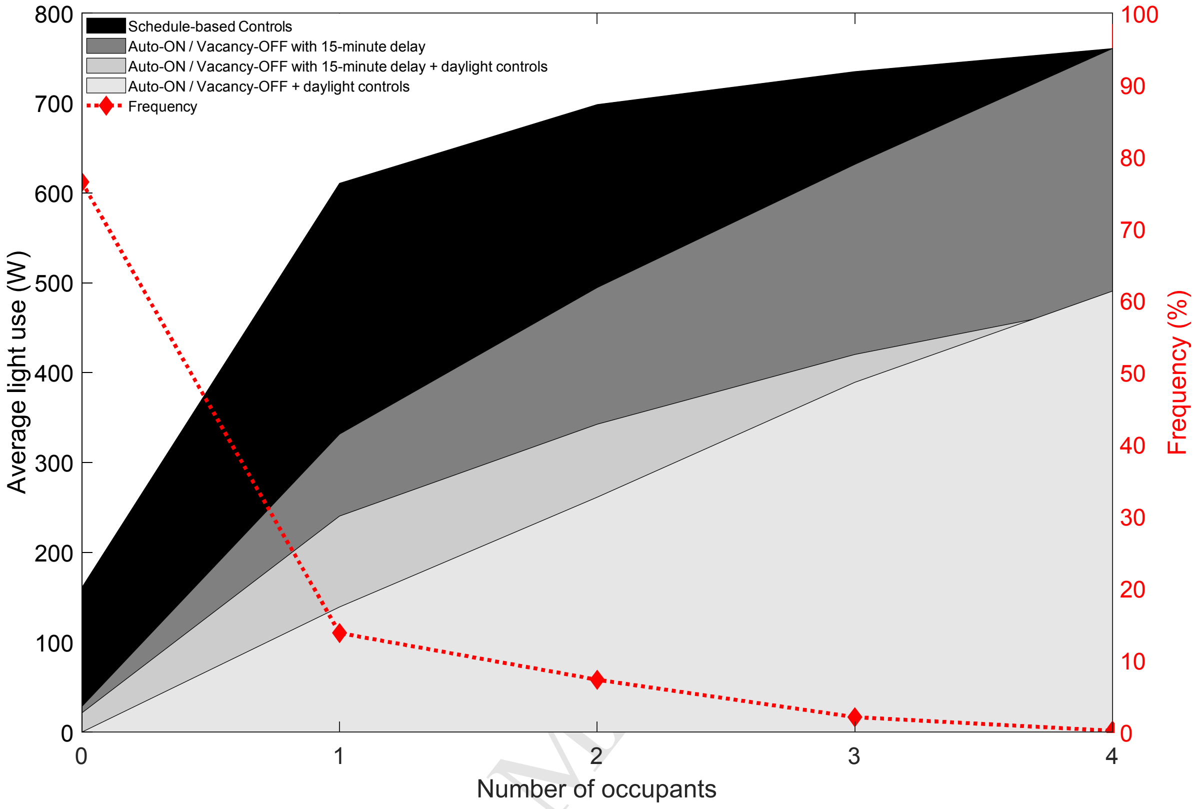
4. Estimating energy savings

Two approaches are presented in this section to estimate energy savings of different building technologies within the context of adaptability. The first focuses on calculating the difference in energy use between a baseline case and other cases where technologies and control strategies are being evaluated. Average energy use corresponding to the number of occupants can also be plotted against the number of occupants. This provides a visual representation of building adaptability where a linear relationship suggests higher adaptability. These charts can then be used to estimate and compare energy use under different building technologies and control strategies to quantify potential savings. However, to calculate the differences in energy savings between each control strategy, weighting the calculated area under the curve by the percentage of time each occupant number represents (i.e. its frequency) is required. The second approach focuses on calculating avoidable energy use, which is a measure of the portion of energy use that can be reduced if adaptability improves. Avoidable energy use would decrease for technologies that increase adaptability, thus it would reach zero if adaptability cannot be further improved.

To demonstrate the different approaches for estimating energy savings, light use in the west zone of the simulated office building was re-analyzed. Figure 8a shows the average light use relative to the number of occupants given the different lighting control strategies and based on standard occupancy (i.e. 100% of ASHRAE Standard 90.1 occupancy schedule). Figure 8b shows the same relationship under low occupancy profile (i.e. 40% of ASHRAE Standard 90.1 occupancy schedule). To calculate this value, the average hourly light use given a number of occupants (from 1 to 4), was calculated from the results of an annual simulation. Visual inspection of these plots indicates that occupancy-based controls combined with daylight controls increase adaptability relative to other control strategies since they result in a more linear relationship between the number of occupants and average light use. Calculating energy savings based on these plots requires weighting to the frequency of occupancy at different levels. For example, this zone remains unoccupied for more than 50% of the time, thus energy use during unoccupied periods would be weighted differently than energy use when the zone is fully occupied. Given the percentage of hours per year at which the zone is occupied at different levels, which is shown in Figure 8, energy use corresponding to different control strategies can be estimated. By calculating the difference in energy use between these control strategies, their associated energy savings (relative to the baseline case with schedule-based controls) can be quantified as shown in Table 3.



a



b

Figure 8 Average light use relative to the number of occupants under a) standard and b) low occupancy scenarios

Table 3 Annual light use savings for different control strategies relative to the baseline case with schedule-based controls

Control strategy	**Annual light use savings (kWh/year)**	
	Standard occupancy	Low occupancy
Auto-ON / Vacancy-OFF with 15-minute delay	373.6	1374
Auto-ON / Vacancy-OFF with 15-minute delay + daylight controls	941.6	1680.3
Auto-ON / Vacancy-OFF + daylight controls	1198	2003.8

The second proposed approach to estimate potential energy savings is using utilization factors to calculate avoidable energy use as shown in Equation 19. However, this calculation is only applicable if the utilization factor is greater than or equal to one, otherwise avoidable energy use would be zero. This means that for utilization factors of less than one, which result from technologies that adapt to other external factors (e.g. daylight), energy use cannot be further reduced by improving adaptability to variable occupancy. Table 4 shows the estimated avoidable light use for the lighting control strategies described in the previous section under different occupancy scenarios. Control strategies that combine occupancy-based controls with daylight controls resulted in eliminating avoidable energy use or significantly minimizing it under low occupancy.

$$Avoidable\ energy\ use = energy\ end\ use - \frac{energy\ end\ use}{utlization\ factor} \qquad (19)$$

Table 4 Avoidable light use given different control strategies and occupancy scenarios

	Avoidable light use (kWh/year)			
Control strategy	Standard occupancy	High Occupancy	Medium Occupancy	Low Occupancy
Schedule-based controls	435.5	811	1205.5	1589.3
Auto-ON / Vacancy-OFF with 15-minute delay	305.3	465.2	527.7	648.9
Auto-ON / Vacancy-OFF with 15-minute delay + daylight controls	0	0	95.7	152.2
Auto-ON / Vacancy-OFF + daylight controls	0	0	0	0

5. Discussion

The introduced metrics provide a new approach to assess building performance by focusing on adaptability to variable occupancy. Although this is a commonly overlooked performance attribute, previous studies suggest that building occupancy is typically lower than assumed. While technologies and control strategies exist to adapt building operations and energy use to lower occupancy, these metrics would enable evaluating and comparing the ability of these technologies to improve or maintain adaptability. Despite this benefit, some of the proposed metrics have limitations since they may not capture all aspects of adaptability. For example, unoccupied ratios do not account for occupancy variations while the building is occupied. In other words, this specific set of metrics only focuses on minimizing energy use during unoccupied periods, but it does not capture additional energy use under partial occupancy. The proposed utilization factors address this issue by analyzing building energy use relative to variable occupancy. However, calculating these utilization factors for some end-uses such as heating, and cooling can be relatively more difficult than others. This is especially true at smaller spatial resolutions if heating and cooling energy of specific zones cannot be separated and because occupancy directly affects the heat balance of these zones. On the other hand, normalizing energy use to occupant-hours may implicitly account for energy efficiency due to factors other than increasing adaptability. For example, a more efficient building envelope would decrease energy use per occupant-hour without improving adaptability. Therefore, results of applying the proposed metrics should be interpreted within the context of their potential limitations in quantifying adaptability.

To quantify adaptability to variable occupancy, it is imperative that access to data regarding occupancy patterns is a key requirement. Detailed occupancy data for different building zones is typically unavailable at the design phase. However, different occupancy scenarios can be evaluated instead, which can be further investigated given the advances in occupant modelling that enable stochastic occupancy predictions [37], [38]. Furthermore, estimates of expected occupancy patterns and sensitivity analyses to different occupancy levels can be used to evaluate adaptability, as shown in the presented simulation case study. During the operational phase of a building, occupancy data may exist, yet its granularity and accuracy also varies widely. However, the proliferation of new technologies and occupant sensing infrastructure are key developments that enable collecting occupancy data at higher temporal and spatial resolutions [24]. Shen et al. [39] provided an overview of these technologies which range from PIR, to radio frequency identification (RFID) and wireless sensors, as well as image-based detection systems, since they facilitate collecting occupancy counts at fine resolutions. PIR sensors are the most commonly used type to detect occupants' presence in buildings, although other systems such as ultrasonic, CO_2 or acoustic sensors are also used [40]. Other new approaches to collect occupancy data include detecting WiFi counts, or processing of surveillance camera feeds [41].

To calculate the proposed metrics in existing buildings, hourly energy use data is also required. Therefore, the availability of sub-meters for energy end-uses in different building spaces is an important consideration. Alternatively, the BEMS system in existing buildings can be used to collect hourly end-use data for different building zones. These systems enable remote collection of granular energy use data [42], which can be used to calculate the proposed adaptability metrics. As a result of ASHRAE Standard 90.1's requirement for energy end-uses to be separately sub-metered at 15-minute intervals and archived for three years, the availability of granular energy use data is also expected to increase. These developments facilitate proposing building performance metrics that focus on adaptability which would be measured at different lifecycle stages to be continuously evaluated.

6. Conclusion

The main goal of introducing adaptability metrics is to provide an occupant-centric building performance evaluation framework that rewards building technologies and control strategies that adapt to occupancy variations. Previous studies demonstrated the energy savings potential of these technologies, yet no metrics exist to quantify how well these systems adapt to partial occupancy. By providing reproducible and comparable metrics that fit the purpose of evaluating adaptability, building designers and operators can quickly evaluate the effect of different operational strategies on this aspect of building performance. Using the proposed metrics to evaluate building operations would penalize building systems that disregard occupancy variations and allow for estimating potential energy savings. However, one of the challenges of calculating the proposed metrics is the requirement for granular occupancy and energy use data, which may not be available in some existing buildings. To address this issue, alternative calculation methods based on estimating occupancy profiles and performing sensitivity analyses were also proposed to evaluate adaptability. Future research should focus on standardizing building performance data collection and processing methods as well as the protocols for calculating adaptability metrics to ensure their reproducibility as benchmarks to evaluate building performance. Furthermore, developing algorithms that can quickly generate these metrics from building simulation outputs or BMS data is critical to accelerate their adoption within the industry and use for benchmarking across portfolios of buildings.

As building energy codes and standards shift towards performance-based compliance that relies on building simulations, adaptability requirements can be mandated using the proposed metrics. Current energy codes and standards only address the issue of adaptability through prescriptive requirements to include occupancy-based controls (e.g. for lighting or ventilation). On the other hand, performance-based compliance paths assume full or near full occupancy, which would undermine the potential benefits of these occupancy-based controls. Therefore, calculating the proposed metrics based on simulation results should include an evaluation of adaptability under different occupancy conditions, as shown in the presented case study. Energy code requirements can mandate reporting the results of such analysis in order to evaluate and improve adaptability. Although this paper did not provide benchmarks for the proposed metrics, future work on this topic should focus on identifying adaptability benchmarks for different building types and climate zones which can be incorporated in building energy codes and standards.

Acknowledgements

This research was supported by Natural Resources Canada (NRCan), under the Clean Energy Innovation (CEI) component of the Energy Innovation Program (EIP). The authors greatly benefited from discussion with project partners RWDI, Autodesk, and the National Research Council Canada, and would like to acknowledge their generous support for this research. This work was also developed thanks to the excellent research networking provided by IEA EBC Annex 79 “Occupant-Centric Building Design and Operation”.

References

[1] L. Golden, “Flexible Work Schedules: Which Workers Get Them?,” *Am. Behav. Sci.*, vol. 44, no. 7, pp. 1157–1178, 2001.

[2] I. U. Zeytinoglu, G. B. Cooke, and S. L. Mann, “Flexibility : Whose Choice Is It Anyway?,” *Relations Ind.*, vol. 64, no. 4, p. 555, 2009.

[3] National Research Council, “National Energy Code of Canada for Buildings 2015.” Ottawa, ON, 2015.

[4] ASHRAE, “ANSI/ASHRAE Standard 90.1-2016 Energy Standard for Buildings Except Low-Rise Residential Buildings.” Atlanta, GA, 2016.

[5] A. Mahdavi, A. Mohammadi, E. Kabir, and L. Lambeva, “Occupants’ operation of lighting and shading systems in office buildings,” *J. Build. Perform. Simul.*, vol. 1, no. September 2014, pp. 57–65, 2008.

[6] Z. Yang and B. Becerik-Gerber, “The coupled effects of personalized occupancy profile based HVAC schedules and room reassignment on building energy use,” *Energy Build.*, vol. 78, pp. 113–122, 2014.

[7] Z. Yang and B. Becerik-Gerber, “Modeling personalized occupancy profiles for representing long term patterns by using ambient context,” *Build. Environ.*, vol. 78, pp. 23–35, 2014.

[8] B. Abushakra, J. S. Haberl, and D. E. Claridge, “Overview of existing literature on diversity factors and schedules for energy and cooling load calculations,” *ASHRAE Trans.*, vol. 110 PART 1, pp. 164–176, 2004.

[9] H. Burak Gunay, W. O’Brien, and I. Beausoleil-Morrison, “Development of an occupancy learning algorithm for terminal heating and cooling units,” *Build. Environ.*, vol. 93, no. P2, pp. 71–85, 2015.

[10] W. O’Brien and A. Abdelaliem, “Do building energy codes adequately reward buildings that adapt

to partial occupancy?," *Sci. Technol. Built Environ.*

[11] J. Brandemuehl, Michael J Braun, "The impact of demand-controlled and economizer ventilation strategies on energy use in buildings," *ASHRAE Trans.*, vol. 105, 1999.

[12] Z. Nagy, F. Y. Yong, M. Frei, and A. Schlueter, "Occupant centered lighting control for comfort and energy efficient building operation," *Energy Build.*, vol. 94, pp. 100–108, 2015.

[13] Y. Peng, A. Rysanek, Z. Nagy, and A. Schlüter, "Occupancy learning-based demand-driven cooling control for office spaces," *Build. Environ.*, vol. 122, pp. 145–160, 2017.

[14] H. B. Gunay, W. O'Brien, I. Beausoleil-morrison, and J. Bursill, "Development and implementation of a thermostat learning algorithm," *Sci. Technol. Built Environ.*, vol. 4731, no. December 2017, pp. 1–14, 2017.

[15] G. P. Henze, D. E. Kalz, S. Liu, and C. Felsmann, "Experimental analysis of model-based predictive optimal control for active and passive building thermal storage inventory," *HVAC R Res.*, vol. 11, no. 2, pp. 189–213, 2005.

[16] Z. Ma, P. Cooper, D. Daly, and L. Ledo, "Existing building retrofits: Methodology and state-of-the-art," *Energy Build.*, vol. 55, pp. 889–902, 2012.

[17] P.-D. Moroşan, R. Bourdais, D. Dumur, and J. Buisson, "Building temperature regulation using a distributed model predictive control," *Energy Build.*, vol. 42, no. 9, pp. 1445–1452, 2010.

[18] H. B. Gunay, W. O'Brien, I. Beausoleil-Morrison, and S. Gilani, "Development and implementation of an adaptive lighting and blinds control algorithm," *Build. Environ.*, vol. 113, pp. 185–199, 2017.

[19] J. Woolley, M. Pritoni, M. Modera, and W. Center, "Why Occupancy-Responsive Adaptive Thermostats Do Not Always Save-and the Limits for When They Should," *ACEEE Summer Study Energy Effic. Build.*, pp. 337–350, 2014.

[20] H. B. Gunay, J. Bursill, B. Huchuk, W. O'Brien, and I. Beausoleil-Morrison, "Shortest-prediction-horizon model-based predictive control for individual offices," *Build. Environ.*, vol. 82, pp. 408–419, 2014.

[21] M. Deru, P. Torcellini, and N. R. E. Laboratory, "Performance Metrics Research Project - Final Report," no. October, 2005.

[22] D. T. J. O'Sullivan, M. M. Keane, D. Kelliher, and R. J. Hitchcock, "Improving building operation by tracking performance metrics throughout the building lifecycle (BLC)," *Energy Build.*, vol. 36, no. 11, pp. 1075–1090, 2004.

[23] C. F. Reinhart, J. Mardaljevic, and Z. Rogers, "Dynamic daylight performance metrics for sustainable building design," *LEUKOS - J. Illum. Eng. Soc. North Am.*, vol. 3, no. 1, pp. 7–31, 2006.

[24] O'Brien, I. Gaetani, S. Carlucci, P.-J. Hoes, and J. L. M. Hensen, "On occupant-centric building performance metrics," *Build. Environ.*, vol. 122, pp. 373–385, 2017.

[25] R. Hitchcock, "High-Performance Commercial Building Systems Program," *Stand. Build. Perform. Metrics–Final*, pp. 1–36, 2003.

[26] O. T. Masoso and L. J. Grobler, "The dark side of occupants' behaviour on building energy use," *Energy Build.*, vol. 42, pp. 173–177, 2010.

[27] D. Harris and C. Higgins, "Methodology for Reporting Commercial Office Plug Load Energy Use," no. March, 2013.

[28] C. R. Bayliss and B. J. Hardy, *Transmission and Distribution Electrical Engineering*, Fourth Edi. Elsevier Ltd, 2012.

[29] J. Norman, H. L. Maclean, M. Asce, and C. A. Kennedy, "Comparing High and Low Residential Density : Life-Cycle Analysis of Energy Use and Greenhouse Gas Emissions," vol. 132, no. March, pp. 10–21, 2006.

[30] W. Kampel, S. Carlucci, B. Aas, and A. Bruland, "A proposal of energy performance indicators for a reliable benchmark of swimming facilities," *Energy Build.*, vol. 129, pp. 186–198, 2016.

[31] R. J. Hitchcock, M. A. Piette, and S. E. Selkowitz, "Performance Metrics and Life-Cycle Information Management for Building Performance Assurance," 1998.

[32] K. M. Fowler, A. E. Solana, and K. L. Spees, "Building Cost and Performance Metrics : Data Collection Protocol Revision 1 . 1," *Pacific Northwest Natl. Lab.*, no. September, 2005.

[33] N. Nassif, "A robust CO 2-based demand-controlled ventilation control strategy for multi-zone HVAC systems," *Energy Build.*, vol. 45, pp. 72–81, 2012.

[34] W. J. Fisk and A. T. De Almeida, "Sensor-based demand-controlled ventilation: a review," *Energy Build.*, vol. 29, no. 1, pp. 35–45, 1998.

[35] T. Hong and W. J. Fisk, "Assessment of energy savings potential from the use of demand controlled ventilation in general office spaces in California," pp. 117–124, 2010.

[36] I. E. Bennet and W. O'Brien, "Office building plug and light loads: Comparison of a multi-tenant office tower to conventional assumptions," *Energy Build.*, vol. 153, pp. 461–475, 2017.

[37] J. Page, D. Robinson, N. Morel, and J. Scartezzini, "A generalised stochastic model for the simulation of occupant presence," vol. 40, pp. 83–98, 2008.

[38] D. Wang, C. C. Federspiel, and F. Rubinstein, "Modeling occupancy in single person offices," *Energy Build.*, vol. 37, no. 2, pp. 121–126, 2005.

[39] W. Shen, G. Newsham, and B. Gunay, "Leveraging existing occupancy-related data for optimal control of commercial office buildings : A review," *Adv. Eng. Informatics*, vol. 33, pp. 230–242, 2017.

[40] K. Christensen, R. Melfi, B. Nordman, B. Rosenblum, and R. Viera, "Using existing network infrastructure to estimate building occupancy and control plugged-in devices in user workspaces," *Int. J. Commun. Networks Distrib. Syst.*, vol. 12, no. 1, pp. 4–29, 2014.

[41] H. B. Gunay, A. F. Fuller, W. O'Brien, and I. Beausoleil-Morrison, "Detecting occupants' presence in office spaces: A case study," *eSim 2016*, no. October, 2016.

[42] D. Minoli, K. Sohraby, and B. Occhiogrosso, "IoT Considerations, Requirements, and Architectures for Smart Buildings – Energy Optimization and Next Generation Building Management Systems," *IEEE Internet Things J.*, vol. 4, no. 1, pp. 269–283, 2017.

Highlights

- A new set of performance metrics to quantify buildings' adaptability are proposed
- Adaptability is defined as the degree to which energy use is proportional to occupancy
- The metrics are used to evaluate building operations under variable occupancy scenarios
- Contrary to energy-centric metrics, they highlight the benefits of adaptable controls