Lawrence Berkeley National Laboratory

Recent Work

Title

Occupant-Centric key performance indicators to inform building design and operations

Permalink

<https://escholarship.org/uc/item/5mt490kr>

Journal

Journal of Building Performance Simulation, 14(6)

ISSN

1940-1493

Authors

Li, H

Wang, Z

Hong, T

Publication Date

2021

DOI

10.1080/19401493.2021.1876771

Peer reviewed

Building Technologies & Urban Systems Division
Energy Technologies Area
Lawrence Berkeley National Laboratory

Occupant-Centric Key Performance Indicators to Inform Building Design and Operations

Han Li, Zhe Wang, Tianzhen Hong

Building Technology and Urban Systems Division
Lawrence Berkeley National Laboratory

Energy Technologies Area
February 2021

DOI: 10.1080/19401493.2021.1876771

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy,
Building Technologies Office, of the U.S. Department of Energy
under Contract No. DE-AC02-05CH11231.

Disclaimer:

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

Occupant-Centric Key Performance Indicators to Inform Building Design and Operations

Han Li, Zhe Wang, Tianzhen Hong*
Building Technology and Urban Systems Division
Lawrence Berkeley National Laboratory
*Corresponding author: T. Hong, thong@lbl.gov

Highlights

- Occupant-centric metrics are currently ad hoc and limited, yet crucial to inform building design and operations.
- Literature was reviewed to reveal the state-of-the-art and gaps of occupant-centric metrics.
- A suite of occupant-centric key performance indicators (KPIs) covering five groups of building services were synthesized.
- Proposed occupant KPIs represent three aspects of performance: resource use and demand, occupant comfort and health, and human–building interactions.
- A case study using whole building simulation was conducted to demonstrate the use of occupant-centric KPIs in evaluating building operations during a power outage.

Abstract

Building performance indicators are widely used to guide building design and track and benchmark operational performance. Traditional building performance indicators mostly focus on the energy efficiency perspective. Yet, the increasing penetration of renewable energy resources, distributed energy technologies, and frequent extreme weather events impose a need to quantify building energy flexibility and resilience to support research and development of grid-interactive efficient buildings (GEBs). One key factor to consider in the GEB context is occupant comfort and well-being, since occupants are the primary building service recipients in residential and most commercial buildings. This study first identified significant attributes of occupant-centric key performance indicators (KPIs) and analyzed the diverse factors that should be considered in formulating an occupant-centric KPI. Then a suite of occupant-centric KPIs were synthesized from the review and enhancement of existing occupant-related performance metrics. The proposed occupant KPIs represent the occupant lens on three integrative aspects of building performance: resource use (including energy and water), indoor environmental quality, and human–building interactions. A simulation-based case study was conducted to demonstrate how occupant-centric KPIs can be used to quantify the impacts of building operation changes from the occupants' point of view.

Keywords: Building performance, occupant, KPIs, human building interaction, occupant behavior, indoor environmental quality

1. Introduction

The building sector consumes more than one-third of global primary energy, and is the main focus of global efforts to reduce energy use and greenhouse gas (GHG) emissions in buildings to achieve a clean economy and mitigate climate change. Large-scale international collaborative research projects, including Annex 53 (Yoshino, Hong, and Nord 2017), Annex 66 (Yan et al. 2017, 66), and Annex 79 (O'Brien, Wagner, et al.

2020) have identified occupant behavior as a key driver to building energy performance. The human dimension of energy use in buildings is as important as the technological and policy dimensions (D'Oca, Hong, and Langevin 2018).

Occupants play two roles in buildings. First, occupants are the drivers of building system operations and controls. Occupants release sensible and latent heat, and need ventilation air, which contributes to a building's heating, cooling and ventilating HVAC loads. Their preferences of the indoor environment, and the needs to perform certain tasks, are the main reasons for behaviors such as opening and closing windows, adjusting shading devices, changing lighting and thermostat controls, moving among building spaces, and using miscellaneous electric equipment (Hong et al. 2016). In addition, recent studies have identified that other factors, such as personality traits, influence human–building interactions (Hong, Chen, et al. 2020). Those diverse behaviors affect building energy consumption and indoor environment quality (IEQ) significantly (B. Li and Lim 2013; Hong et al. 2017). In their other role, occupants are the primary recipients of services provided by building systems. People spend more than 85% of their time indoors (Klepeis et al. 2001). The quality of the building design and system operations can influence occupant comfort and well-being considerably (Altomonte et al. 2020). Conventional building performance metrics (e.g., energy use intensity, EUI) can overlook the influence of the built environment on occupants. This study focused on occupant related building performance indicators, as occupants are the ultimate beneficiaries of the built environment. We demonstrated that a comprehensive suite of occupant-centric KPIs can not only guide building design and operation to satisfy occupant demands, but also quantify the influence of human–building interaction (HBI) on energy consumption and indoor environmental quality.

1.1. Overview of the existing building performance metrics

The saying “what gets measured gets done” is widely accepted by the building performance field. Existing studies have proposed a range of metrics that are used to capture building performance. The applications of those metrics span the whole life-cycle of buildings (O'Sullivan et al. 2004), which include building certification from the plan and design phase (Reinhart, Mardaljevic, and Rogers 2006), risk and sustainability management in the construction phase (Hanna 2016), and performance tracking (Costa et al. 2013), benchmarking (H. Li et al. 2019), and controlling (Zhang et al. 2019) in the operation phase. However, the majority of metrics focus on energy efficiency and indoor environmental quality. Bogatu et al. assessed the IEQ metrics available in building standards (ISO 7730-2006, ASHRAE 55-2017, ISO 17772-2018, EN 16798-2019) and certifications (WELL, BREEAM, LEED, and DGNB) (Bogatu, Byg, and Coakley 2020). They found that, although the metrics are clearly defined, there is no clear methodology for benchmarking and correlating those metrics with occupants' subjective responses. Mahdavi et al. reviewed current state-of-art IEQ evaluation approaches and indicated that existing approaches tend to be mono-dimensional, and people's evaluation of the IEQ are often overlooked (Mahdavi et al. 2020).

Moreover, many of the IEQ metrics are either not designed specifically for occupant-centric building operations or are short of guidance on what should be done if there is a problem. Some IEQ metrics, such as thermal comfort or predicted mean vote (PMV) quantify the indoor environment of a single location at a specific time, which cannot be used to evaluate the whole building across a certain time period. Among the existing building performance metrics, only a small portion of them are involved with occupant-building interactions. Those metrics are usually developed for specific purposes such as reducing plug-load, service hot water, and space utilizations. A major reason for the lack of occupant-centric metrics is the high cost of

measuring occupant-related information like occupant count and activities, in addition to privacy concerns. As sensing and Internet of Things (IoT) technologies and occupant predicting methods become more mature, it becomes more affordable and reliable to collect occupant-related information. Those developments have incentivized efforts to develop actionable performance metrics, which aim at quantifying building performance from the building-occupant interaction perspective (Langevin, Wen, and Gurian 2016; Xie et al. 2020). O'Brien et al. reviewed existing occupant-related performance metrics, summarized the characteristics of good performance metrics, and demonstrated example uses of those metrics (O'Brien et al. 2017). Those efforts have shed lights on what good occupant-centric metrics should be like. However, there is still a lack of a systematic review and summary of existing metrics from the lens of occupants.

In addition, although the field of building performance usually uses the terminologies - “metrics”, “measures”, and “indicators” as synonyms (de Wilde 2018), they do have different implications. “Metrics” usually represent how performance changes over time or in different dimensions. “Measures” are the values or quantities that represent the performance. “Indicators” are usually combined values that reflect the performance with easy-to-understand information rather than raw operational measurements. Originating from the business world, key performance indicators (KPIs) are critical navigational instruments that monitor performance and draw attention when a project is veering off the right path. Good KPIs not only measure the performance, but are also objective and actionable (“What Gets Measured Gets Done: Key Performance Indicators” 2010), which help managers measure what matters the most in their business. In this study, we review existing occupant-centric metrics, measures, and indicators, and synthesize them as KPIs. The objective is to help stakeholders identify the reasons and solutions of problems in building performance field from the occupant-centric perspective. It should be noted that the occupant-centric KPIs are not proposed to replace the existing building performance metrics but rather to provide an integrative set of KPIs focusing on the occupant perspectives for use cases that emphasize human factors and related performance.

1.2. Emerging needs for occupant-centric KPIs

Another limitation of the existing occupant-centric metrics is that they have not caught up with some of the emerging trends such as energy flexibility and resilience. For instance, instead of purely improving energy efficiency of buildings and systems, new research has begun to focus on making them more intelligent. The grid-interactive efficient building (GEB) concept aims to modulate energy load to improve flexibility, optimize energy use for grid services, and save energy while satisfying occupant needs via distributed energy resources and advanced sensor and control technologies (Neukomm, Nubbe, and Fares 2019). It is critical to quantify how those changes would affect the indoor environment since there is no intent to sacrifice occupant comfort and well-being to achieve the GEB goals. Several studies have investigated the influence of demand response on thermal comfort and energy cost (Alimohammadisagvand et al. 2017; W. Li and Xu 2016). However, there is a lack of well-defined metrics to measure the impacts of GEB on occupant comfort, health, and well-being.

Another emerging topic in the built environment is resilience, which refers to a building's capability to respond to (i.e., resist and recover from) extreme weather and hazardous events. Extreme events such as heat waves, hurricanes, wildfires, and power outages pose significant risks to occupant comfort, health, and even safety (Penman et al. 2014; Anderson et al. 2013; Schenck et al. 2010). In this context, occupant-centric KPIs are important to quantify the impact of those extreme events and guide building design and

operations. For example, Sun et al. (Sun, Specian, and Hong 2020) utilized the heat index to measure the impacts of heat waves on building thermal conditions and risks, and recommended improvements to mitigate the risks. Despite those efforts, a summary of occupant-centric KPIs that can be used to quantify different aspects of resilience (e.g., thermal, air quality) is still missing.

Modern building technologies have greatly changed the way occupants interact with the built environment. For instance, occupants' behaviors such as opening and closing the windows, adjusting thermostat setpoints, and raising and lowering louvers have been overtaken by building automation systems (BAS) (Domingues et al. 2016). In the foreseeable future, the introduction of IoT enabled infrastructures, and artificial intelligence (AI) driven building controls (Ngarambe, Yun, and Santamouris 2020; Merabet et al. 2020) will keep changing the way occupants interact with buildings. Moreover, new business models such as workplace sharing or coworking can also change occupants' spatial and physical needs for buildings. Human–building interaction (HBI) is becoming an emerging domain of interest; it focuses on addressing people's interactions with the built environment from physical-material, spatial-configurational, and social-cultural perspectives (Alavi et al. 2019). Occupant-centric KPIs should also bridge the gap of missing metrics for evaluating human–building interactivity.

1.3. Scope of this study

In this study, we first summarized key features of good occupant-centric KPIs and areas of interest they should cover in the modern context. Then, we critically and comprehensively reviewed the existing occupant-related metrics, with the aim of identifying their limitations and opportunities of improvements. Based on the review results, a suite of metrics was selected/complemented to synthesize a set of occupant-centric KPIs. Next, a use case of the occupant-centric KPIs was presented to illustrate how those indicators could be used to enhance building performance and inform decision making. The key findings and main contribution of this paper are discussed at the end.

2. Occupant-centric KPIs for building performance

2.1. Basis of building performance consideration

Occupants are the main recipients of building services. They interact with the building systems to address their needs. At the same time, building systems consume resources to provide the required services while by-products such as waste and GHG influence the environment. Therefore, occupant-centric building performance can be quantified from three aspects: (1) resource use and environmental impact, (2) indoor environmental quality provided by building services and influencing occupant comfort and health, and (3) human–building interactions. *Figure 1* depicts these three interlinked aspects.

Figure 1. Occupant-centric building performance aspects

For resource use and environmental impact, we considered whole building-level energy consumption during partial and full occupancy, peak power demand, water usage, and GHG emissions. For human–building interactions, we considered the occupants’ controllability of the building systems, and whether and how they provide feedback to building operations. *Table 1* summarizes KPIs that indicate the building performance from a high level. For building services, we considered five categories, which include four key components of indoor environmental quality (IEQ)—thermal quality, visual quality, acoustic quality, and indoor air quality—as well as other services (e.g., use of miscellaneous electric devices, space utilization). The more detailed, service-specific KPIs, are presented in Section 2.4

Table 1. High-level Occupant-centric KPIs

Performance Aspect	Category	KPI
Resource use and environmental impacts	Overall	Total OccupantHour: Annual total occupant hour of a building
		kWh/person: Annual total site energy use (kWh) / number of maximum occupants for the whole building
		kWh/OccupantHour: Annual total site energy use (kWh) / annual total occupant-weighted hours for the whole building
		% energy-unoccupied: Percent of energy use as annual total site energy during unoccupied hours for the whole building
		% energy-25 percentile occupancy: Percent of energy use as annual total site energy during 0%–25% occupancy
		% energy-50 percentile occupancy: Percent of energy use as annual total site energy during 25%–50% occupancy
		% energy-75 percentile occupancy: Percent of energy use as annual total site energy during 50%–75% occupancy
	Energy use	% energy-100 percentile occupancy: Percent of energy use as annual total site energy during 75%–100% occupancy
	Electricity demand	peak kW/person: Annual peak electricity demand / number of maximum occupants

	Water use	kg water/person: Annual water use (kg) / number of maximum occupants
	Carbon emission	kg CO ₂ e/person: Annual carbon dioxide equivalent emission / number of maximum occupants
	Solid waste	kg waste/person: Annual solid waste generated on-site per person
Human– Building Interaction	Controllability of building envelope	Percent occupants who can open/close windows
		Percent occupants who can open/close blinds
	Controllability of lighting systems	Percent occupants who can switch on/off or dim lights
	Controllability of HVAC systems	Percent occupants who can adjust thermostat setting
		Percent occupants who can adjust air diffusers or air dampers or water valves
		Percent occupants who have personal fans or heaters
	Controllability of personal devices and space	Percent occupants who have personal air purifiers
		Percent occupants who have enclosed working station (can close the door for privacy)
	Occupant feedback	Occupants have access to a dashboard to see energy use, demand, space use, and IAQ of their floor or space or the whole building
		Occupants have access to an app to report in real-time their thermal comfort, IAQ, acoustic, or visual issues
		Building operators or managers have periodic (quarterly or annual) surveys to collect occupant feedback

2.2. Attributes of KPIs

A vast amount of data are generated from modern building energy management systems (BEMs) and building automation systems (BAS) every day, and this amount of data can be overwhelming to decision makers and stakeholders. Good KPIs turn data into strategic assets by distilling them into actionable information. The following three critical attributes characterize good KPIs:

- **Accessibility:** KPIs should be easy to obtain with the existing infrastructure, technologies and reasonable amounts of efforts and costs. The sources of the data and how they can be measured should be straightforward.
- **Quantifiability:** This is the fundamental of performance tracking, verification, and benchmarking. Good KPIs should have a clear definition of either direct measurements or robust formulas for calculating the values.
- **Actionability:** Good KPIs should be target-oriented. They should provide actionable information to inform solutions to specific problems, e.g., reducing lighting energy consumption per person by improving the lighting control.

2.3. Factors that occupant-centric KPIs should consider

While the attributes of good KPIs are easy to understand, it is often difficult to choose the right ones. There are plenty of factors to be considered. Therefore, a clear definition of the factors can help us select, calculate, and interpret the occupant-centric KPIs for different purposes. Previously, there has been no

clear and consistent factoring of occupant-centric metrics. In Figure 2, we propose eight categories of factors to consider.

Figure 2. Factors that good occupant-centric KPIs should consider

- Temporal factors:** Resolution is the main factor in this category; it refers to the discrete resolution of a measurement with respect to time. In the building performance field, typical temporal resolutions include annual, monthly, weekly, daily, hourly, and sub-hourly. Depending on the goal of the KPI, different resolutions may apply. For instance, KPIs with large time-steps like monthly or annual resolution are usually used to compare and benchmark a performance metric at a high level, while KPIs with small time-steps are useful in tracking performance change with high volatility. KPIs with high temporal resolution require more frequent measurements and larger data storage. Meanwhile, KPIs with finer temporal resolutions could be aggregated to have values with coarser temporal resolution if necessary.
- Spatial factors:** Spatial resolution refers to the smallest geometry area in space that a KPI can resolve. Common spatial resolutions include work-plane, workstation, zone/room, floor, and whole building. For occupant-centric KPIs, the selection of spatial resolution is largely determined by the target—KPIs for individual occupants need higher spatial resolution, while KPIs for occupant groups can have a lower spatial resolution. KPIs with high spatial resolution usually require more sensors and larger data storage. Similarly, KPIs also can be spatially down-sampled when necessary.
- Occupant factors:** Resolution and object are two key factors in this category. Occupant resolution refers to the level of detail that occupant-related information is collected. Typical options include presence (whether an occupant is at a space at a given time), count (the number of occupants in a space at a given time), and activity type (the type and intensity occupant activity). Object is the

scope of occupant that a KPI aims to cover, which can be either an individual person or a group of people. KPIs with higher resolution and finer scope are useful in tasks such as individual behavior tracking and personal comfort evaluation, while KPIs with lower resolution are useful in cases like group comfort evaluations.

- **Normalization factors:** Normalization is a process that changes the values of a certain variable so that it is in a common scale with other variables, but without losing patterns within its own range. There are three types of normalization factors in occupant-centric KPIs: (1) spatial normalization factors (e.g., floor area, number of rooms/zones), (2) occupant normalization factors (e.g., number of occupants, occupant equivalent full hours), and (3) weather normalization factors (e.g., degree hours, degree days). Normalization is necessary for fair comparisons of KPIs, as it avoids the influence of unrelated factors.
- **Value types:** Value types refer to the formats of the KPIs. Single-value KPIs provide a snapshot of a metric, while serial-value KPIs could reveal the trend and dynamics of the metrics of interest.
- **Quantifiability:** Quantifiability refers to the feasibility of collecting the required data and deriving the KPIs from the data. If the data are collected from real measurements, key factors are the required sensors and meters, the cost of them, and whether the data are directly measured or inferred by proxy. If the data are generated from simulations, the key factors are the required model parameters and the output variables. If the data are from surveys or audits, the key factors are questions and objectives. Understanding the quantifiability helps users to decide whether it is realistic and cost-effective to select certain occupant-centric KPIs.
- **Applicable Scenarios:** Applicable scenarios indicate how the occupant-centric KPIs can be used in different phases of the building life-cycle. This study was mainly concerned with the design and operation phases. In the design phase, occupant-centric KPIs could be incorporated in the performance-based path of building energy codes and standards (O'Brien, Tahmasebi, et al. 2020) to address emerging needs (e.g., resilience and energy flexibility) of new buildings. In the operation phase, occupant-centric KPIs can be used to monitor the system operations, serve as control goals, or alert abnormal or dangerous events in the alarm systems.
- **Performance Goals:** Last, but not least, performance goals are what the occupant-centric KPIs aim to improve. Energy efficiency and indoor environmental quality are two of the most popular goals. Energy-related performance goals involve those such as improving energy efficiency, reducing demand power demand, curtailing carbon emissions, and increasing energy flexibility. A priority hierarchy applies to indoor environmental quality (Altomonte et al. 2020), which suggests that occupants' basic safety and reliability needs must be met before improving comfort and well-being. Therefore, the indoor environment-related performance goals of the occupant-centric KPIs should also address this hierarchy: (1) avoid hazards, (2) maintain comfort, and (3) promote well-being.

The eight feature groups of factors not only characterize the occupant-centric KPIs but also help users select a subset of KPIs for specific applications. For instance, building designers who are interested in visual quality and lighting energy consumption might select “visual quality” and “energy efficiency” as the performance goal from the visual KPIs group.

2.4. Review of existing occupant-centric KPIs

In this section, we first review the literature concerning occupant-related performance metrics in each service category discussed in Section 2.3. We then examine whether those existing metrics consider the factors that are discussed in sections 2.1 and 2.2. Missing factors are complemented based on the description of original literature and our knowledge. Next, an occupant-centric KPI summary table for each service category is synthesized. In each service category, the performance goals columns describe which of the three performance aspects discussed in Section 2.3 a KPI can indicate. Based on the literature review, the limitations and future needs for the occupant-centric KPIs also are identified.

2.4.1. Visual Quality

Visual quality refers to the luminous environmental quality that is influenced by a mixture of physical parameters including lighting, daylighting, self-illuminating screens, and indoor and outdoor views. On the one hand, a good visual quality ensures sufficient illuminance for visual tasks and avoids glares, as well as promotes lighting environments and views that stimulate occupants' feelings of well-being (Altomonte et al. 2020; Board, National Academies of Sciences, and Medicine 2004). On the other, artificial lighting consumes a large portion of the total building energy consumption (Ryckaert et al. 2010). Previous studies have identified a strong correlation between occupant patterns and lighting energy consumption (Yun, Kim, and Kim 2012). Therefore, the synthesized occupant-centric KPIs mainly focus on visual quality and occupant-related lighting energy consumption, which is summarized in *Table 2* below.

2.4.2. Thermal Quality

Thermal condition is a major aspect of indoor environmental quality in buildings. A large portion of the energy consumed by building systems is to maintain desirable thermal conditions. Moreover, thermal quality has proven impacts on occupants' health (Parsons 2014) and productivity (Kaushik et al. 2020). Assessing indoor thermal quality and its impacts on occupants has always been an important task. A variety of methods and metrics have been proposed to assess the human response to the thermal environment (Carlucci and Pagliano 2012). The purpose of those metrics ranges from evaluating the risks of being exposed to extreme thermal conditions to assessing the thermal comfort of individuals or occupant groups. From the formation perspective, those metrics could be grouped into three categories (Parsons 2014; Epstein and Moran 2006): (1) rational indices, which are based on heat balances; (2) empirical indices, which are based on a combination of objective and subjective measures; and (3) direct indices, which can be quantifiable via measurements of occupant and environmental variables. Since good KPIs should be accessible and quantifiable, the review and synthesis of occupant-centric KPIs focuses on the third category. *Table 3* summarizes the occupant-centric KPIs for thermal quality.

2.4.3. Air Quality

Indoor air quality (IAQ) refers to the physical, chemical, and biological characteristics of air in the built environment. Extensive studies have shown that IAQ has impacts on occupant health, comfort (Milton, Glencross, and Walters 2000), and work performance (Wargocki and Wyon 2017). Quantifying IAQ has always been a challenge, despite many efforts. The main reason for the difficulty is the high complexity of the air's composition. Different types of pollutants, including physical contaminants (e.g., particulate matter), chemical contaminants (e.g., CO_x, NO_x, SO_x, and VOCs), and biological contaminants (e.g., airborne viruses, bacteria, and fungi) can be present in the air. And the pollutants' mechanisms that affect

human health and the harmful concentrations vary considerably. Two main groups of metrics are used to evaluate air quality. The first group measures the IAQ with the concentration of one or several types of pollutants. The second group of metrics use proxies, such as CO₂ concentration and ventilation rate, to evaluate the IAQ. Those metrics are mainly used in building certifications (Wei, Ramalho, and Mandin 2015) for building design guidance, and for HVAC system controls (Emmerich, Mitchell, and Beckman 1994) and monitoring (Saad et al. 2017) in building operations.

Table 4 summarizes the IAQ related occupant-centric KPIs.

2.4.4. Acoustic Quality

Compared with thermal quality and indoor air quality, indoor acoustic quality is often overlooked in building design (Jalil, Din, and Daud 2013; Paradis 2016). Traditional design of the acoustic environment focuses on reducing negative effects as noises and unwanted reverberations. Recent study has shown the acoustic quality's considerable impacts on occupant health and productivity (Peretti and Schiavon 2011). In fact, occupants' dissatisfaction with acoustic privacy and comfort are among the most frequent complaints in occupant surveys (Altomonte et al. 2020; Brager and Baker 2009). Thus, there is great potential and an increasing need to improve the indoor acoustic environment beyond the basic requirements. Those needs include improved speech privacy, sound intelligibility, and overall comfort. *Table 5* summarizes the occupant-centric KPIs for acoustic quality.

2.4.5. Other Needs

In addition to a safe, comfortable indoor environment, buildings need to provide occupants with other services for their indoor activities. Those activities include miscellaneous tasks using plug-load devices, service hot water consumption, space utilization, and wireless network connection. Metrics in this category help us to better understand the service quality and energy efficiency that the building and systems provide. Corresponding occupant-centric KPIs are summarized in *Table 6*.

Table 2. Occupant-centric KPIs for visual service

KPI Characteristics					Input Data Resolution			Normalization Factors				Quantifiability via Measurements		Quantifiability via Simulations		Performance Goal		Applicability		
KPI	Definition	Occupant Object	Value Type	dimensional	Temporal	Spatial	Occupancy	Temporal	Spatial	Occupant	Weather	Sensors/Devices	Measurement & calculation Effort	Software	Modeling Effort	Resources	IEQ	Lifecycle Phase	Year	Source
Spatial Daylight Autonomy (sDA)	The percentage of time that daylight levels are above a specified target illuminance within a physical space.	n.a.	single	no	annual	zone	n.a.	n.a.	n.a.	n.a.	n.a.	illuminance sensor	medium	Radiance, DiVa	high	energy	comfort	design, operation	2012	(I. D. M. Committee and others 2012)
Annual Sunlight Exposure (ASE)	The percentage of floor area that receives at least 1,000 lux for at least 250 occupied hours per year	n.a.	single	no	annual	zone	n.a.	hours	n.a.	occupant count	n.a.	illuminance sensor	medium	Radiance, DiVa	high	n.a.	comfort	design, operation	2012	(I. D. M. Committee and others 2012)
Useful Daylight Illuminance	A daylight availability metric that corresponds to the percentage of the occupied time when a target range of illuminances at a point in a space is met by daylight.	occupant group	single	no	n.a.	zone	presence	hours	n.a.	occupant count	n.a.	illuminance sensor	medium	Radiance	medium	energy	comfort	design, operation	2012	(Mardaljevic et al. 2012)
Workplane Illuminance	The illuminance level of a horizontal workplane	individual person	single	yes	n.a.	workplane	n.a.	n.a.	n.a.	n.a.	n.a.	illuminance sensor	low	Radiance	medium	energy	comfort	operation	N.A.	N.A.
Daylight Glare Probability (DGP)	A probability to evaluate glare from daylight at a vertical surface considering eye level illuminance, light source luminance, and solid angle of the light source view.	individual person	single or serial	no	n.a.	single point	n.a.	n.a.	n.a.	n.a.	n.a.	illuminance sensor, angle meter	high	Radiance, DiVa	high	n.a.	comfort	design, operation	2009	(Wienold 2009)
Unified Glare Ratio (UGR)	A metric that evaluates how likely a luminaire is to cause discomfort to occupants considering the luminance level of the luminaire and the background, as well as the occupant's view point.	individual person	single	no	n.a.	single point	n.a.	n.a.	n.a.	n.a.	n.a.	illuminance sensor, angle meter	high	Radiance, DiVa	high	n.a.	comfort	design, operation	1995	(C. T. Committee and others 1995)
Visual Comfort Availability (VCA)	The local availability of sufficient visual comfort in the considered period (e.g., Visual comfort: DGP < 0.35).	individual person	single or serial	no	percent of time	single point	n.a.	n.a.	n.a.	n.a.	n.a.	illuminance sensor, angle meter	high	Radiance, DiVa	high	n.a.	comfort	design, operation	2016	(Atzeri et al. 2016)
Visual Comfort Probability (VCP)	The percentage of people that will find a certain scene (viewpoint and direction) comfortable with regard to visual glare.	occupant group	single	no	n.a.	zone	n.a.	n.a.	n.a.	n.a.	n.a.	illuminance sensor, angle meter	very high	Radiance, DiVa	very high	n.a.	comfort	design	1966	(Guth 1963)
Hours of Occupancy in the Dark (HOD)	The hours when the indoor light level is below the adaptive setpoints for a particular occupant when the room is occupied.	occupant group	single	yes	n.a.	zone	presence	hours	n.a.	occupant count	n.a.	occupancy sensor, lighting meter	medium	EnergyPlus	medium	n.a.	health	operation	2016	(Nagy, Yong, and Schlueter 2016)
View Type	Total number of rays that hit each type of outdoor view element: sky, landmarks, buildings, landscape, and ground.	individual person	single	yes	hourly	single point	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	very high	Rhinoceros, Grasshopper plugin, DIVA-for-Rhino plugin	high	n.a.	wellbeing	design, operation	2019	(Turan, Reinhart, and Kocher 2019)
View Diversity	The total count of unique exterior objects (excluding sky and ground) that are intersected by rays from one point.	individual person	single	yes	n.a.	single point	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	very high	Rhinoceros, Grasshopper plugin, DIVA-for-Rhino plugin	high	n.a.	wellbeing	design	2019	(Turan, Reinhart, and Kocher 2019)
View Depth-of-Field	The difference between the nearest exterior object and farthest exterior object (excluding sky) that is intersected by rays from a single origin.	individual person	single	yes	n.a.	single point	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	very high	Rhinoceros, Grasshopper plugin, DIVA-for-Rhino plugin	high	n.a.	wellbeing	design	2019	(Turan, Reinhart, and Kocher 2019)
Light Utilization Ratio (LUR)	The ratio of lights-on time to occupied time in a specific space.	occupant group	single	no	hourly	n.a.	presence	hours	n.a.	occupant count	n.a.	occupancy sensor, lighting meter	medium	EnergyPlus	low	energy	n.a.	operation	2017	(O'Brien et al. 2017)

Lighting energy consumption per full equivalent occupied hours	Interior lighting energy consumption per full equivalent occupied hours in a space.	occupant group	single	yes	hourly	n.a.	occupant count	hours	n.a.	occupant count	n.a.	occupant count sensor, lighting meter	high	EnergyPlus	low	energy	n.a.	operation	2020	(H. Li, Hong, et al. 2020)
Lighting energy consumption per daylight hours	Interior lighting energy consumption per daily daylight hours.	n.a.	single or serial	yes	daily	n.a.	n.a.	hours	n.a.	n.a.	daylight hours	lighting meter	medium	EnergyPlus	medium	energy	n.a.	operation	2020	(H. Li, Hong, et al. 2020)
Peak lighting power demand per occupant	The peak lighting electric power demand divided by the maximum number of occupants.	occupant group	single or serial	yes	hourly	building	occupant count	n.a.	n.a.	occupant count	n.a.	occupant count sensor, lighting meter	high	EnergyPlus	low	demand	n.a.	operation	n.a.	n.a.

Table 3. Occupant-centric KPIs for thermal quality

KPI Characteristics					Input Data Resolution			Normalization Factors				Quantifiability via Measurements		Quantifiability via Simulations		Performance Goal		Applicability		
KPI	Definition	Occupant Object	Value Type	dimensional	Temporal	Spatial	Occupancy	Temporal	Spatial	Occupant	Weather	Sensors/Devices	Measurement & calculation Effort	Software	Modeling Effort	Resources	IEQ	Lifecycle Phase	Year	Source
Predicted Mean Vote (PMV) & Predicted Percentage of Dissatisfied (PPD) model	A model to quantify thermal comfort for a group of occupants with a particular combination of air temperature, mean radiant temperature, relative humidity, air speed, metabolic rate, and clothing insulation.	occupant group	single or serial	no	n.a.	zone	n.a.	n.a.	n.a.	n.a.	n.a.	temperature sensor, humidity sensor, air velocity sensor	very high	EnergyPlus (Crawley et al. 2001), CBE Thermal Comfort Tool (Tartarini et al. 2020)	low	n.a.	comfort	design, operation	2005	(Iso 2005)
Average PPD	The average PPD over occupied hours during a time period.	occupant group	single	no	hourly	zone	presence	n.a.	n.a.	n.a.	n.a.	temperature sensor, humidity sensor, air velocity sensor	very high	EnergyPlus	low	n.a.	comfort	design, operation	2005	(Iso 2005)
Accumulated PPD (Sum_PPD)	Summation of all the PPDs over time (with a time-step of one hour) during occupied hours.	occupant group	single	yes	hourly	zone	presence	n.a.	n.a.	n.a.	n.a.	temperature sensor, humidity sensor, air velocity sensor, heat flux meter, timer	very high	EnergyPlus	medium	n.a.	comfort	design, operation	2012	(Olesen 2012)
PPD-weighted Criterion (PPDwC)	Summation of the weighted discomfort (PMV beyond or below comfort limits) hours.	occupant group	single	no	hourly	zone	n.a.	n.a.	n.a.	n.a.	n.a.	temperature sensor, humidity sensor, air velocity sensor, heat flux meter, timer	very high	EnergyPlus	medium	n.a.	comfort	design, operation	1986	(Gagge, Fobelets , and Berglund 1986)
Standard Effective Temperature (SET)	The temperature of an imaginary environment at 50% relative humidity, less than 0.1 m/s air speed, and same mean radiant temperature and air temperature, in which the total heat loss from the skin of an imaginary occupant with an activity level of 1.0 met and a clothing level of 0.6 clo is the same as that from a person in the actual environment, with actual clothing and activity level.	individual person	single or serial	yes	n.a.	zone	activity level	n.a.	n.a.	n.a.	n.a.	temperature sensor, humidity sensor, air velocity sensor, heat flux meter	very high	n.a.	n.a.	n.a.	comfort	design, operation	2012	(Olesen 2012)
POR[PMV]	Percentage of time outside the comfort PMV range.	occupant group	single	no	percent of time	n.a.	presence	time duration	zone	n.a.	n.a.	temperature sensor, humidity sensor, air velocity sensor, timer	very high	EnergyPlus	low	n.a.	comfort	design, operation	2012	(Olesen 2012)
POR[RT]	Percentage of occupied hours outside of a reference temperature (usually operative temperature) range.	occupant group	single	no	percent of time	n.a.	presence	time duration	zone	n.a.	n.a.	temperature sensor, radiant temperature sensor, heat flux meter, timer	very high	EnergyPlus	low	n.a.	comfort	design, operation	2005	(Iso 2005)
Degree-Hour Criterion (DHC)	Sum of occupied hours multiplied by actual operative temperature exceeding the corresponding comfort range.	occupant group	single	yes	hourly	zone	presence	n.a.	n.a.	n.a.	n.a.	temperature sensor, radiant temperature sensor, humidity	very high	EnergyPlus	medium	n.a.	comfort	design, operation	n.a.	n.a.

												sensor, air velocity sensor, occupancy sensor								
Degree-Occupant-Hour Criterion (DOHC)	Sum of occupied hours multiplied by number of occupants and operative temperature exceeding the corresponding comfort range.	occupant group	single	yes	hourly	zone	occupant count	n.a.	n.a.	n.a.	n.a.	temperature sensor, radiant temperature sensor, humidity sensor, air velocity sensor, occupant count sensor	very high	EnergyPlus	medium	n.a.	comfort	design, operation	2010	(Borges on and Brager 2011)
Exceedance [PPD]	Sum of hours multiplied by the number of occupants when the thermal condition exceeds a threshold of 20% of dissatisfaction, divided by the sum of hours multiplied by the number of occupants.	occupant group	single	yes	hourly	zone	occupant count	n.a.	n.a.	n.a.	n.a.	temperature sensor, humidity sensor, air velocity sensor, heat flux meter, occupant count sensor	very high	EnergyPlus	medium	n.a.	comfort	operation	2019	(Estrella Guillén, Samuels on, and Cedeño Laurent 2019)
Discomfort Degree Days	The degree days when the indoor air temperature is outside the adaptive comfort temperature range. This metric can be divided into Cold Discomfort Degree Days and Hot Discomfort Degree Days.	occupant group	single	yes	hourly	zone	n.a.	n.a.	n.a.	n.a.	n.a.	temperature sensor, radiant temperature sensor, humidity sensor, air velocity sensor, occupant count sensor	very high	EnergyPlus	medium	n.a.	comfort	operation	2019	(Estrella Guillén, Samuels on, and Cedeño Laurent 2019)
Overheating/Overcooling Degree Days	The degree days that measure the degree of discomfort opposite of the building's assumed mode of operation (e.g., hot discomfort when the weather is cold, or cold discomfort when the weather is hot).	occupant group	single	yes	hourly	zone	n.a.	n.a.	n.a.	n.a.	n.a.	temperature sensor, radiant temperature sensor, humidity sensor, air velocity sensor, occupant count sensor	very high	EnergyPlus	medium	energy	comfort	operation	2004	(Mosch andreas and Sofuogl u 2004)
Indoor Discomfort Index	The absolute distance of the observed value to the defined optimum value (22°C with 45% relative humidity) relative to the preset comfort range (3°C and 10% relative humidity deltas) is used to estimate the IDI.	occupant group	single	yes	n.a.	zone	n.a.	n.a.	n.a.	n.a.	n.a.	temperature sensor, humidity sensor	low	EnergyPlus	low	n.a.	comfort	operation	2008	(Robins on and Haldi 2008)
Overheating Risk Index	A metric indicating occupants' satisfaction to accumulated overheating stimuli (e.g., exceedance of a reference temperature of 25 °C).	occupant group	single	no	hourly	zone	presence	n.a.	n.a.	n.a.	n.a.	temperature sensor, timer	medium	EnergyPlus	medium	n.a.	health	operation	1957	(Minard , Belding, and Kingsto n 1957)
Wet Bulb Globe Temperature (WBGT)	A weighted combination of web-bulb and dry-bulb temperature for evaluating the risk of heat exposure.	n.a.	single or serial	yes	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	temperature sensor (dry-bulb and wet-bulb)	low	EnergyPlus	low	n.a.	health	operation	2005	(Wallac e et al. 2005)
Cumulative Daily Average WBGT	The sum of daily average WBGT over a few consecutive days.	n.a.	single or serial	yes	daily	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	temperature sensor (dry-bulb and wet-bulb)	low	EnergyPlus	low	n.a.	health	operation	1998	(I. Standar d and ISO 1998)
Radiant Asymmetry	The combined radiant temperature asymmetry in different directions at a point in a space.	n.a.	single or serial	yes	n.a.	single point	n.a.	n.a.	n.a.	n.a.	n.a.	radiant temperature sensor	low	EnergyPlus	low	n.a.	comfort	operation	2013	(L.-S. Wang et al. 2014)
Thermal Autonomy	The percent of occupied time over a period where a thermal zone meets a set of thermal comfort criteria (e.g., operative temperature range) through passive means only.	occupant group	single	no	percent of time	zone	presence	time duration	n.a.	n.a.	n.a.	occupancy sensor	low	EnergyPlus	medium	n.a.	comfort	operation	2015	(Candac e Pearson 2015)

Percent of Time Outside Livable Temperature Range	The percentage of time that the standard effective temperature is outside of a livable range (12.2°C and 30°F).	occupant group	single or serial	no	percent of time	zone	n.a.	time duration	n.a.	n.a.	n.a.	temperature sensor, humidity sensor, air velocity sensor, heat flux meter	very high	n.a.	n.a.	n.a.	health	operation	1979	(Masterton and Richardson 1979)
Humidex	An index number used to describe how hot the weather feels to the average person, by combining the effect of heat and humidity.	n.a.	single or serial	yes	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	dry-bulb temperature sensor, dew-point temperature sensor	low	EnergyPlus	low	n.a.	comfort	operation	n.a.	n.a.

Table 4. Occupant-centric KPIs for indoor air quality

KPI Characteristics					Input Data Resolution			Normalization Factors				Quantifiability via Measurements		Quantifiability via Simulations		Performance Goal		Applicability		
KPI	Definition	Occupant Object	Value Type	dimensional	Temporal	Spatial	Occupancy	Temporal	Spatial	Occupant	Weather	Sensors/Devices	Measurement & calculation Effort	Software	Modeling Effort	Resources	IEQ	Lifecycle Phase	Year	Source
CO ₂ *Occupant Hour	The CO ₂ concentration multiplied by occupant hour in a space.	occupant group	single	yes	hourly	zone	occupant count	n.a.	n.a.	n.a.	n.a.	CO ₂ concentration sensor, occupancy count sensor	high	EnergyPlus	low	n.a.	comfort	design, operation	2020	(“NREL/EnergyPlus” 2020)
Weighted Relative CO ₂ Exceedance * Occupant Hour	The relative value of CO ₂ exceeding a reference level, multiplied by the number of occupants and hours.	occupant group	single	yes	hourly	zone	occupant count	n.a.	n.a.	n.a.	n.a.	CO ₂ concentration sensor, occupancy count sensor	high	EnergyPlus	low	n.a.	comfort	design, operation	2020	n.a.
tCO ₂	The duration of time a space may be fully occupied before it becomes hazardous.	occupant group	single	yes	sub-hourly	zone	occupant count	n.a.	n.a.	n.a.	n.a.	outdoor CO ₂ concentration sensor, occupant count sensor, outdoor airflow sensor	high	EnergyPlus	high	n.a.	comfort	design	2018	(Saad et al. 2017)
Radon Level	Radon concentration.	n.a.	single or serial	yes	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	radon sensor	low	n.a.	n.a.	n.a.	health	operation	2016	(Teichman et al. 2016)
Total Volatile Organic Compounds (TVOCs) * Occupant Hour	The total concentration of multiple airborne VOCs present simultaneously in the air multiplied by occupant hour in a space.	occupant group	single or serial	yes	hourly	zone	occupant count	n.a.	n.a.	n.a.	n.a.	TVOC sensor, occupancy count sensor	high	n.a.	n.a.	n.a.	health	operation	2020	(“Introduction to VOCS and Health Indoor Air Quality (IAQ) Scientific Findings Resource Bank (IAQ-SFRB)” 2020)
Air Quality Index (AQI)	A score with a range from 0 to 500 used to evaluate the air quality considering five major pollutants.	n.a.	single or serial	no	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	ozone sensor, particle matter sensor, carbon monoxide sensor, sulfur dioxide sensor, nitrogen dioxide sensor	very high	EnergyPlus	medium	n.a.	health	operation	1968	(“Air Quality Index (AQI) Basics” 2020)

Table 5. Occupant-centric KPIs for acoustic quality

KPI Characteristics					Input Data Resolution			Normalization Factors				Quantifiability via Measurements		Quantifiability via Simulations		Performance Goal		Applicability		
KPI	Definition	Occupant Object	Value Type	dimensional	Temporal	Spatial	Occupancy	Temporal	Spatial	Occupant	Weather	Sensors/Devices	Measurement & calculation Effort	Software	Modeling Effort	Resources	IEQ	Lifecycle Phase	Year	Source
Overall Sound Level	A frequency weighting curve to measure sound pressure level (usually refers to dB(A)).	n.a.	single	yes	n.a.	zone	n.a.	n.a.	n.a.	n.a.	n.a.	decibel sound level meter	low	I-Simpa, noise3D, Acoustic Determinator	n.a.	n.a.	comfort	operation	1928	(Laboratories 1928)

Time-averaged Sound Pressure Level (SPL)	The time-averaged sound pressure level that is used to indicate the sound level over a defined number of hours (usually for 8 working hours).	n.a.	single	yes	daily	zone	n.a.	hours	n.a.	n.a.	n.a.	decibel sound level meter, timer	medium	I-Simpa, noise3D, Acoustic Determinator	n.a.	n.a.	comfort	operation	2008	(Brown 2008)
Reverberation Time (RT60)	The time required for the sound to reduce to a level 60 decibels below its original level.	n.a.	single	yes	sub-hourly	zone	n.a.	n.a.	n.a.	n.a.	n.a.	decibel sound level meter, timer	low	Ecophon	low	n.a.	comfort	design, operation	1930	(Rakerd et al. 2018)
Clarity Factor (C50)	The ratio of sound power present within at the beginning of the impulse response (usually 50 milliseconds), when early reflections occur, to the sound power present thereafter.	n.a.	single	no	n.a.	zone	n.a.	n.a.	n.a.	n.a.	n.a.	decibel sound level meter, timer	medium	Ecophon	low	n.a.	comfort	design, operation	1972	(Haas 1972)
Psychoacoustic Annoyance (PA)	A metric indicating the relative annoyance degree of different noises, considering their loudness, sharpness, fluctuation strength, and roughness.	n.a.	single	no	n.a.	zone	n.a.	n.a.	n.a.	n.a.	n.a.	decibel sound level meter, sound recorder	high	n.a.	n.a.	n.a.	well-being	operation	1998	(Zwicker and Fastl 2013; Di et al. 2016)
Speech Transmission Index (STI)	A measure of speech transmission quality in noisy and/or reverberant environments.	n.a.	single	no	n.a.	zone	n.a.	n.a.	n.a.	n.a.	n.a.	decibel sound level meter, timer	high	n.a.	n.a.	n.a.	comfort	operation	1971	(Houtgast and Steeneken 1971)
Speech Intelligibility Index (SII)	A measure of speech intelligibility under adverse hearing conditions	n.a.	single	no	n.a.	zone	n.a.	n.a.	n.a.	n.a.	n.a.	decibel sound level meter, timer	high	n.a.	n.a.	n.a.	comfort	operation	1997	(“ANSI/ASA S3.5-1997 (R2017) - Methods for Calculation of the Speech Intelligibility Index” 2020)
Speech Privacy Potential (SPP)	A metric indicating the level of perceived privacy between rooms (quantified by the sum of background noise level with the noise reduction)	n.a.	single	no	n.a.	zone	n.a.	n.a.	n.a.	n.a.	n.a.	decibel sound level meter	low	n.a.	n.a.	n.a.	comfort	operation	1977	(Spalding and Niedzielski 1978; “Standard WELL V2” 2020)
Global Index of the Acoustic Quality	A global index that is the weighted function of five partial indices, namely: the reverberation index, the intelligibility of speech index, the uniformity of loudness index, the external disturbance index, and the music sound quality index.	n.a.	single	no	n.a.	zone	n.a.	n.a.	n.a.	n.a.	n.a.	decibel sound level meter, timer	high	n.a.	n.a.	n.a.	comfort	operation	2007	(Engel and Kosala 2007)

Table 6. Occupant-centric KPIs for other needs

KPI Characteristics					Input Data Resolution			Normalization Factors				Quantifiability via Measurements		Quantifiability via Simulations		Performance Goal		Applicability		
KPI	Definition	Occupant Object	Value Type	Dimensional	Temporal	Spatial	Occupancy	Temporal	Spatial	Occupant	Weather	Sensors/Devices	Measurement & calculation Effort	Software	Modeling Effort	Resources	IEQ	Lifecycle Phase	Year	Source
Partial Occupancy Demand Performance	The sum of the percent of time when the occupancy rate is between 0%–25%, 25%–50%, 50%–75%, and 75%–100%, multiplied by the corresponding electricity demand.	occupant group	serial	no	hourly	building	occupant count	n.a.	n.a.	n.a.	n.a.	electricity meter, occupant count sensor	high	EnergyPlus	low	demand	n.a.	operation	n.a.	n.a.
Miscellaneous Electric Loads (MELs) [W/(occupant count)]	MELs power demand per person at a certain timestamp.	n.a.	single or serial	yes	sub-hourly	n.a.	occupant count	n.a.	n.a.	occupant count	n.a.	plug-load meter, occupant count sensor	high	EnergyPlus	low	demand	n.a.	operation	2020	(H. Li, Hong, et al. 2020)

MELs[kWh/occupant hour]	MELs consumption divided by occupant hour.	n.a.	single or serial	yes	hourly	n.a.	occupant count	hours	n.a.	occupant count	n.a.	plug-load meter, occupant count sensor	high	EnergyPlus	low	energy	n.a.	operation	2020	(H. Li, Hong, et al. 2020)
Wi-Fi access point per occupant count	The number of devices connected to the Wi-Fi network divided by the number of occupants.	n.a.	single or serial	yes	sub-hourly	zone	occupant count	n.a.	n.a.	occupant count	n.a.	Wi-Fi router, occupant count sensor	high	n.a.	n.a.	n.a.	n.a.	design, operation	n.a.	n.a.
Wi-Fi access point per floor area	The number of devices connected to the Wi-Fi network divided by the floor area.	n.a.	single or serial	yes	sub-hourly	zone	occupant count	n.a.	floor area	n.a.	n.a.	Wi-Fi router	medium	n.a.	n.a.	n.a.	n.a.	design, operation	n.a.	(Sapiezynski et al. 2015)
Wi-Fi Received Signal Strength Indication (RSSI)	A measurement of how well a device can receive the Wi-Fi signal in a location.	n.a.	single or serial	no	n.a.	single point	n.a.	n.a.	n.a.	n.a.	n.a.	individual devices	medium	n.a.	n.a.	n.a.	n.a.	design, operation	n.a.	(Sapiezynski et al. 2015)
Service water per occupant capacity	Annual service water consumption divided by total occupant capacity.	occupant group	single	yes	annual	building	occupant count	n.a.	n.a.	n.a.	n.a.	service waterflow meter	medium	EnergyPlus	low	water	n.a.	operation	2008	(Jiang and Delgrossi 2008; Zhu et al. 2014)
Hoteling Potential (HP)	Minimum ratio of required number of workstations to number of employees if employees relocate on a weekly or daily basis for 95% and 99% of the time.	occupant group	single	no	weekly or daily	n.a.	occupant count	n.a.	number of work stations	n.a.	n.a.	occupant count sensor	medium	n.a.	n.a.	n.a.	n.a.	design, operation	1982	(Jones 1982)

2.5 Occupant KPIs Selection and Applications

Section 2.4 introduced a total of 59 KPIs in five groups. However, not all KPIs are relevant for all use cases. Also, the cost and effort needed to measure or calculate the KPIs vary significantly. When evaluating building performance, too few indicators may lead people in the wrong direction, while too many indicators may bring confusion (Bordass 2020). Thus, it is important to identify the right subset of KPIs for specific purposes. In addition to the individual KPIs, an overall evaluation of building performance can be useful because it can help users compare the performance of multiple buildings quickly at a high level, which is important to inform building design and operation decision-making. The main challenges of aggregating individual KPIs into high-level performance ratings include: (1) not all KPIs are relevant to all buildings, (2) KPIs have different scales, and (3) some KPIs are the categorical type, meaning the numeric values do not indicate the performance quality. Larsen et al. developed an IEQ-Compass to holistically evaluate the IEQ of residential buildings. They selected 16 parameters. A group of building professionals were surveyed to weight each of the parameters, and then used those to calculate an aggregated score of the building's IEQ performance (Larsen et al. 2020). Other studies tried to solve similar problems with Multiple Criteria Decision-Making (MCDM) methods. For example, D'Amico et al. applied a multi-criteria assessment approach to compare different building thermal energy demand prediction methods (D'Amico et al. 2020). Verbeke et al. also adopted the MCDM method to assess the numerous building services and their performance impact criteria in the development of Smart Readiness Indicators (SRIs) (Verbeke et al.). As shown in *Figure 3*, we propose a workflow to select and calculate the KPIs that fit for a certain purpose and can be used to compare overall performance.

Figure 3. Workflow to select and use the KPIs

For example, the KPIs can be used to compare different options in the early design phase. We could apply a set of constraints such as the performance goal to improve energy efficiency, reduce peak demand, and maintain good occupant comfort levels. Because this comparison would be for early design only, we would

calculate the KPIs via simulations with moderate effort. Thus, we would filter the KPIs with the modeling tools and corresponding level of effort to get a subset of KPIs. Then, following the instructions in the KPI tables and the source literature, we would calculate and compare the individual KPIs for different design alternatives. The individual KPIs provide very specific insights into a building's performance, such as the occupant-related lighting energy consumption, occupant group overheating potentials, non-occupied hour peak demand, and other factors. Those actionable insights can guide the selection of design alternatives. However, even with that information it still can be difficult to identify the best of the different design strategies. For example, some KPIs good at quantifying the energy efficiency do not provide insight into comfort. And there are trade-offs between some KPIs, such as the light utilization ratio (LUR) and the lighting energy consumption per person. Therefore, we need an overall performance quantification method. We can first normalize the individual KPIs to a consistent scale (e.g., a zero to ten range), and then weight each individual KPI that emphasizes our performance goal. For instance, higher weights can be given to comfort-favoring KPIs than energy-efficiency-favoring KPIs if occupant comfort is more important. We can then derive aggregated scores for each category and an overall performance score. Finally, we can conduct a multiple criteria selection analysis to choose the design strategies that maximize the overall performance score, with the criteria specified by building code and standard.

Figure 4 shows two illustrative rose charts of the overall performance of two design alternatives. The chart is color-coded by the KPI categories: IEQ (blue), HBI (red), and resources and emissions (green). The chart has a polar coordinate where the larger radius of a fan-shaped area corresponds to better performance in that category. By using the overall rating by performance categories, we can compare the strengths and weaknesses of different alternatives.

Figure 4. Illustrative rose charts of the overall performance ratings using occupant KPIs under three aspects: IEQ, HBI, and resource use and emissions

3. Case Study

A case study was conducted to demonstrate the significance of the factors defined in Section 2.3 and applications of the occupant-centric KPIs during building electric power outages. With the help of occupant-centric KPIs, we can better quantify the influence of power outages on occupants' well-being, which is difficult to do with conventional building performance indicators. The calculations of the KPIs are based on the whole building energy simulation using EnergyPlus.

3.1. Baseline Model Setup

The detailed version of the DOE reference medium office building model (Deru et al. 2011) was used as the baseline model. *Table 7* shows the model overview.

Table 7. Model overview

Building Type	Medium Office (detailed)
Number of Floors	3
Locations	Miami, San Francisco, Chicago
Climate Zones	1A, 3C, 5A
Vintage	ASHRAE 90.1-2010
Total Floor Area (m ²)	4982.22
Geometry
Zoning	<div style="display: flex; flex-wrap: wrap; justify-content: center; margin-top: 10px;"> <div style="display: flex; align-items: center; margin-right: 10px;"> <div style="width: 15px; height: 15px; background-color: blue; border: 1px solid black; margin-right: 5px;"></div> <div>Office</div> </div> <div style="display: flex; align-items: center; margin-right: 10px;"> <div style="width: 15px; height: 15px; background-color: green; border: 1px solid black; margin-right: 5px;"></div> <div>Mechanical</div> </div> <div style="display: flex; align-items: center; margin-right: 10px;"> <div style="width: 15px; height: 15px; background-color: pink; border: 1px solid black; margin-right: 5px;"></div> <div>Lobby</div> </div> <div style="display: flex; align-items: center; margin-right: 10px;"> <div style="width: 15px; height: 15px; background-color: purple; border: 1px solid black; margin-right: 5px;"></div> <div>Conference</div> </div> <div style="display: flex; align-items: center; margin-right: 10px;"> <div style="width: 15px; height: 15px; background-color: lightgreen; border: 1px solid black; margin-right: 5px;"></div> <div>Restroom</div> </div> <div style="display: flex; align-items: center;"> <div style="width: 15px; height: 15px; background-color: darkred; border: 1px solid black; margin-right: 5px;"></div> <div>Corridor</div> </div> <div style="display: flex; align-items: center; margin-top: 5px;"> <div style="width: 15px; height: 15px; background-color: darkpurple; border: 1px solid black; margin-right: 5px;"></div> <div>Storage</div> </div> </div>

Traditional building energy modeling uses simplified fixed occupancy and system operation schedules. In actual buildings, occupant movements and interactions with building systems are highly dynamic and stochastic. Hong et al. (Hong, Macumber, et al. 2020) proposed a methodology to simulate those dynamics. In our study, it is helpful to use more realistic occupancy schedules to demonstrate the occupant-centric KPIs. We adopted the previously developed OpenStudio extension gems (H. Li, Luo, Hong, et al. 2020, 1; H. Li, Luo, Chandra Putra, et al. 2020, 0) to simulate the occupant and related system dynamics. Figure 5 shows the comparison of the fixed and stochastic occupancy schedules in an open-plan office in the model.

Figure 5. Comparison of fixed and stochastic occupancy schedules

3.2. Occupant-centric KPIs during a power outage

Three baseline models (Miami, San Francisco, and Chicago) were tweaked to simulate power outages. Two power outage scenarios with different durations were considered in each model (Table 8).

Table 8. Power outage scenarios

Scenario	Period 1 (January)	Period 2 (July)
Power Outage 1 (3-day)	2017-1-3 0:00 to 2017-1-5 23:50	2017-7-18 0:00 to 2017-7-20 23:50
Power Outage 2 (1-day)	2017-1-4 0:00 to 2017-1-4 23:50	2017-7-19 0:00 to 2017-7-19 23:50

The availability of HVAC systems, electric lighting systems, and electric equipment systems were set to “off” during the power outages, to represent the disruption of those services. To evaluate the impacts of the power outage on occupants, two visual KPIs, one thermal KPI, and one air quality KPI were selected. The KPI values for an open-plan office space were calculated based on the simulation outputs for demonstrations. The data used were from the weekdays of the week in which power outages occurred.

Visual Quality

Artificial lighting is not available during power outages, and that can lead to insufficient indoor illumination when the daylight alone cannot meet illuminance requirements. According to the United States General Services Administration (GSA), the recommended illuminance level for office spaces is 500 lux (“6.15 Lighting” 2020). Therefore, 500 lux was used as the light level setpoint for the reference point (zone center at 0.8 meters [m] height) in the space. Figure 6 shows the illuminance level trends at the reference point for the normal and power outage scenarios during the weekdays of two periods (one in January and the other in July).

Figure 6. Illuminance level trends for different scenarios during two power outage periods

During both power outage Period 1 and Period 2, the illuminance level of the normal scenario was always equal or greater to the 500-lux setpoint during occupied hours; whereas, the illuminance level during the days of the power outage were sometimes below 500 lux. A larger number of hours where the illuminance level was below 500 lux can be observed in Period 1 than in Period 2 because the daylight hours in January are shorter than those in July in the northern hemisphere. To evaluate the impacts of power outages on visual quality, two occupant-centric KPIs—the total underlit hours (a.k.a hours in the dark) and the weighted total underlit occupant hours—were selected. Equation 1 and 2 show the formulas to calculate those KPIs. Note that the weights in Equation 2 are example values; they can be adjusted accordingly.

$$Total(Hours_{underlit}) = \sum W_i, \quad W_i = \begin{cases} 0, & \text{unoccupied} \\ 1, & \text{occupied and } lux_i < lux_{sp} \end{cases} \quad \text{Eq. 1}$$

$$Weighted\ Total(Occ \cdot Hours_{underlit}) = \sum nOcc_i \cdot W_i, \quad W_i = \begin{cases} 0, & 500 \geq lux_i \\ 1, & 300\ lux \leq lux_i < 500\ lux \\ 3, & 100\ lux \leq lux_i < 300\ lux \\ 9, & lux_i < 100\ lux \end{cases} \quad \text{Eq. 2}$$

Figure 7 and Figure 8 show the comparisons of both KPIs in different cases.

Figure 7. Underlit occupied hours comparison

Figure 8. Weighted underlit occupant-hours comparison

As expected, both the total underlit occupied hours and weighted underlit occupant hours were zero in the normal scenario, and values in the one-day power outage scenario were lower than the three-day power outage scenario. And both KPIs in the climate 5A case had the lowest values among three climate zones, which was due to the higher daylight illuminance levels during the power outage periods. In all climate zones, the differences of the underlit occupant-hours between the July and January periods (Figure 7) were smaller than the differences of the weighted underlit occupant-hours between July and January periods (Figure 8). This is because of the additional weighting of the illuminance level in the later KPI. With those KPIs, users can quickly evaluate the impacts of power outage on visual quality. The same approach can be applied to all spaces in a building, to identify the most vulnerable areas. If this building has limited uninterruptible power supply (UPS) resources, the occupant-centric KPIs could help us to determine how the limited resources should be distributed. In this case, a UPS should be used to support the lighting of the zones with the highest weighted total underlit occupant hours first.

Thermal Quality

Indoor thermal conditions cannot be actively controlled during a power loss. Figure 9 shows the operative temperature trends in the three scenarios, three climates, and two power outage periods.

Figure 9. Operative temperature trends for different scenarios during two power outage periods

The comfort range of the operative temperature can be described with the adaptive thermal comfort model defined in ASHRAE Standard 55 (A. Standard 2017). The adaptive comfort model was selected rather than PMV-PPD model, because when a power outage happens, the building is unconditioned. The adaptive comfort model depends on the prevailing outdoor temperature, indoor air speed, occupants' metabolic rates, and adaptive clothing factors to calculate the acceptable temperature range. We employed the CBE Thermal Comfort Tool (Tartarini et al. 2020) to calculate the comfort operative temperature ranges. The assumptions and comfort ranges are summarized in *Table 9*.

Table 9. Comfort operative temperature ranges

	Climate	Period 1 (January)	Period 2 (July)
Occupant Clothing Factor	All	1	0.5
Activity Rate (W)	All	110	110
Air Speed (m/s)	All	0.3	0.3
Prevailing Outdoor Air Temperature (°C)	1A	24.4	29.4
	3C	10.5	16.6
	5A	-4.9	30
Comfort Operative Temperature (°C) Range (80% acceptability)	1A	21.9 to 28.9	23.4 to 30.4
	3C	17.6 to 24.6	19.4 to 26.4
	5A	12.8 to 19.8	23.6 to 30.6
Comfort Operative Temperature (°C) Range (90% acceptability)	1A	22.9 to 27.9	24.4 to 29.4
	3C	18.6 to 23.6	20.4 to 25.4
	5A	13.8 to 18.8	24.6 to 29.6

The occupant-centric KPI, Degree-Occupant-Hour Criterion (DOHC), was selected to evaluate the impacts of a power outage on thermal quality. DOHC is defined as the sum of occupied hours multiplied by number of occupants and operative temperature exceeding the corresponding comfort range. Its formula can be described by Equation 3.

$$DOHC = \sum nOcc_i \cdot abs(T_{operative,i} - T_{operative_limit})_i,$$

$$T_{operative_limit} = \begin{cases} T_{operative_lower}, & T_{operative,i} < T_{operative_lower} \\ T_{operative_upper}, & T_{operative,i} > T_{operative_upper} \end{cases} \quad \text{Eq. 3}$$

The DOHC values were calculated with the simulated occupant counts and operative temperature. For the normal scenario, the operative temperature was always within the comfort range for all three climate zones. For power outage scenarios, there was no case that the zone became too cold (operative temperature below the comfort range) during the January period, because the selected zone was an inner zone. Therefore, although the outdoor air temperature was low during the power outage periods, the internal heat loads were large enough to maintain a relatively high operative temperature. As for the July period, the operative temperature exceeded the upper bound of the comfort range in all climate zones for the three-day power outage scenario, and exceeded the upper bound only in climate 3C for the one-day power outage scenario. Figure 10 shows the DOHC values for those scenarios.

Figure 10. Degree-Occupant-Hour Criterion (DOHC) in July

Two key pieces of information can be extracted from the results. First, in all three climate zones, the DOHC values with the 90% acceptability were higher than the values with 80% acceptability. This was due to the more stringent comfort operative temperature range with the 90% acceptability—it was more difficult to make more people comfortable. Second, for the one-day power outage scenario, only the climate 3C case had a small DOHC value, with a 90% acceptability. That means the one-day power outage had very minor impacts on the thermal environment.

Air Quality

Power outages also disable mechanical ventilation, which could result in insufficient outdoor air supply and increased indoor pollutant concentration. Here, we used indoor CO₂ concentration as a proxy of air quality. Figure 11 shows the CO₂ concentration trends in different cases. The CO₂ concentration of the normal scenarios in both periods were under 1,000 ppm, while the concentration in the power outage scenarios reached as high as 2,500 ppm. For the three-day power outage scenarios, the daily peak CO₂ concentration increased day by day, due to the accumulation of the CO₂ exhaled by occupants when no mechanical ventilation was available.

Figure 11. CO₂ concentration trends for different scenarios during two power outage periods

The overall impacts of high CO₂ concentration on a group of occupants consist of multiple factors, including the CO₂ level, number of occupants, and time duration when occupants are present. According to ASHRAE Standard 62.1-2016 [104], for typical office spaces, an indoor CO₂ concentration within 700 ppm above the outdoor levels indicates that the space is well-ventilated and would satisfy the majority (about 80%) of the occupants. However, air quality becomes risky when the CO₂ concentration exceeds 5,000 ppm. In this case study, the Weighted Relative CO₂ Exceedance Occupant Hour KPI was selected for the demonstration. This KPI is defined as the relative value of CO₂ exceeding a reference level, multiplied by the number of occupants and hours (Equation 4).

$$\text{Weighted Total}(\text{CO}_2 \text{ Exceedance}) = \sum \frac{CO_{2,i} - CO_{2,reference}}{CO_{2,reference}} \cdot nOcc_i \cdot W_i,$$

$$W_i = \begin{cases} 0, & CO_{2,i} < CO_{2,reference} \\ 1, & CO_{2,reference} < CO_{2,i} \leq CO_{2,threshold_1} \\ 5, & CO_{2,i} > CO_{2,threshold_1} \end{cases} \quad \text{Eq. 4}$$

The outdoor CO₂ concentration was 400 ppm in the simulation, therefore the reference concentration was 1,100 ppm. The study team selected 5,000 ppm as the dangerous threshold beyond which the weighting factor will be very high. Note that there can be multiple thresholds and different weighting factors in actual applications. Figure 12 shows the KPI calculation results.

Figure 12. Weighted relative CO₂ exceedance occupant hours

The results indicate that CO₂ concentrations were always under the 1,100 ppm reference level in the normal scenario. For power outage cases, the KPI values for the three-day power outage scenarios in all three climate zones were significantly higher than the values of the one-day power outage scenario. This means that while a one-day power outage does not cause much problem, the loss of ventilation has cumulative effects on increases of indoor CO₂ concentrations, which can be harmful over longer times. Another interesting finding is that in both climate zone 1A and 5A cases, the power outage in July had higher impacts than it did in January. The situation was reversed in the climate zone 3C case. This is because the wind speed in San Francisco was higher in July than it was in January, which led to a higher infiltration rate and slowed the rise of the indoor CO₂ concentration.

4. Discussion

4.1 Occupant-Oriented Performance Metrics

Occupants are a key aspect of building performance. Occupants' influence on building performance is complicated because they are both a key driver of building system operations and the main recipient of building services. Therefore, occupants should not be ignored when evaluating building performance. However, a literature review of existing building performance metrics regarding occupants shows two major inadequacies. First, due to the lack of easily accessible sensing techniques and infrastructures, it was challenging to collect the indoor environment and occupant data. Although plenty of occupant-related metrics are defined, it was very difficult to use them in actual buildings. Second, as sensing techniques have become popular in recent years, monitoring and quantifying building operations have become more feasible. However, many of the existing metrics are not designed from an occupants' point of view. For example, some of the existing metrics are purely indoor environmental metrics. Though we can measure whether the indoor environment is safe and comfortable to occupants with those metrics, it is still challenging to quantify the scale and extent of the indoor environment's impacts. Increasing penetration of renewable energy resources, distributed energy technologies, and frequent extreme weather events imposes a need for buildings to achieve better energy flexibility and resiliency, in addition to energy efficiency. Under this context, building performance has become a multidimensional target, with considerations for occupant comfort and well-being becoming essential. The existing performance metrics are insufficient to understand how those changes would affect occupant comfort and well-being.

4.2 Review and Synthesis of Occupant-Centric KPIs

With the need for better occupant-centric performance metrics, this paper outlines three key attributes of good KPIs: (1) accessibility, (2) quantifiability, and (3) actionability. Good KPIs should be easy to obtain and can provide quantitative insights into building performance from an occupants' perspective for specific goals. Alongside these traits, we also identified the key factors that occupant-centric KPIs should consider. Those factors include spatial, temporal, and occupant data resolutions; normalizations; values types; quantifiability via sensing or simulations; applicable scenarios; and performance goals. The traits and key factors together form a framework for choosing or defining occupant-centric KPIs.

A thorough review and synthesis of occupant-centric KPIs was conducted under the framework. The KPIs were grouped into five categories defined by the services that buildings and systems provide to occupants. These are (1) visual quality, (2) thermal quality, (3) air quality, (4) acoustic quality, and (5) other needs. We selected the commonly used performance metrics from previous literature and examined whether they met the requirements of the proposed framework. For metrics that are good candidates as occupant-centric KPIs, we collected information regarding the key factors defined in Section 2.2, such as required sensors and data collection efforts, simulation tools, and applicable scenarios. We also defined some new KPIs based on the existing metrics, with improvements from the occupant-centric point of view. The final set of occupant-centric KPIs are summarized in a tabular format and can be used by building designers, modelers, operators, and researchers for their own purposes. An overall rating of the building performance can help stakeholders to quickly identify the strengths and weakness of each building. We proposed a schematic approach using MCDM methods to select and aggregate the individual KPIs. In the future, efforts are needed to determine the impacts and significances of individual KPIs to derive the overall occupant-centric performance scores. The review of existing metrics revealed several limitations and future improvement opportunities:

- Existing KPIs primarily focus on avoiding hazards and maintaining acceptable conditions; more attention is needed to promote occupants' well-being. As (Altomonte et al. 2020) indicates, this limitation is due to the hierarchy of needs for the built environment. Moving into the future, our needs will evolve from habitable-living to well-living. New occupant-centric KPIs should be developed to measure occupant well-being.
- Most existing KPIs are at an aggregated level, and as such, do not distinguish lower-level occupant characteristics. This is in harmony with the findings from a review of field implementation of occupant-centric controls which reveals that there are more practices that only require occupancy or occupant count information (occupancy-centric controls) than practices that require individual behavioral information (occupant-behavior-centric controls) (Park et al. 2019). It is clear that occupants have diverse preferences for the indoor environment. For example, multiple factors like gender, age, body build, and cultural background can affect an occupant's thermal perception and sensitivity (Z. Wang et al. 2020). The availability of highly-granular occupant-related information is limited due to the lack of occupant-related sensing and privacy concerns. As the sensing technologies evolve, occupant-centric KPIs should also take into consideration those individual and group diversities to achieve a deeper understanding of occupant-centric building performance.
- There is no comprehensive method to evaluate and select occupant-centric KPIs. It is unrealistic and unnecessary to have all the KPIs in different applications. An idea selection method can help users pick the most important KPIs with the smallest amount of time and cost. A multi-criteria evaluation that considers sensor deployment, data collection, actionable insights, and return on investment could be a potential approach.
- There is a lack of KPIs to quantify the availability and quality of human–building interactions. Technologies like the IoT and artificial intelligence are revolutionizing the way occupants interact with buildings. Future studies are needed to describe and evaluate those new forms of interactions.
- Some KPIs might need other complementary information to indicate whether a building is performing well. For example, percent of occupants who has access to personal heaters can indicate a building's level of personalized controllable thermal environment, but it can also indicate a potential failure of the centralized heating system to meet individual occupant's heating needs. In this case, other inputs like surveys and occupant complaints are needed to evaluate the building performance for diagnostics purpose.

4.3 OpenStudio Reporting Measure

In Section 2.2, we presented the summary tables of the occupant-centric KPIs where some of the KPIs can be quantified with simulations. We developed a software measure (“Occupant-Centric KPI Report | Building Component Library” 2020) to enable automatic calculation and visualization of the KPIs using EnergyPlus and OpenStudio (Guglielmetti, Macumber, and Long 2011). The OpenStudio measure provides a standard and easy way for energy modelers and researchers to understand building performance from an occupant-centric perspective using whole building simulations.

4.4 Occupant-centric KPIs Case Study

In the case study, we demonstrated several occupant-centric KPIs in evaluating the impacts of power outage on occupants, from visual, thermal, and air quality perspectives. The case study was based on a whole building energy simulation that considered three climate zones and two power outage scenarios. Simulated

indoor environmental variables were visualized, followed by calculation and interpretation of related occupant-centric KPIs. The case study is an example of how the occupant-centric KPIs can be used to bridge the gap between building operations and occupants.

4.5 Future Work

In the future, a database of occupant-centric KPIs could be developed with data from actual measurements and simulations. Such data could be used for various purposes, including building performance evaluation, benchmarking, rating, and code compliance. Moreover, recent studies on occupant-centric controls have proposed methods to simulate occupants' adaptive behaviors under special operation scenarios (e.g., heat waves, poor outdoor air quality due to wild fires, and power outages) (Ouf, Park, and Gunay 2020). Case studies that consider occupants' adaptivity to those special operations could be conducted to further illustrate the applications of occupant-centric KPIs. Last but not the least, feedback on occupant-centric KPIs from key stakeholders could help refine the KPIs.

5. Conclusions

This paper provides an overview of the state-of-the-art on occupant-related building performance metrics. It identifies the shortcomings of the metrics in measuring building performance from an occupant's point of view and meeting emerging needs such as quantifying the change of building operations in GEBs and resilience scenarios. The paper proposes key attributes of good occupant-centric KPIs and the diverse factors they should consider, based on which, a comprehensive review and synthesis of occupant-centric KPIs was conducted. The main contributions are (1) a proposed framework that can inform the definition and selection of good occupant-centric KPIs and (2) synthesis of a set of high-level occupant-centric KPIs regarding the resources and environmental impact, and human-building interactions, as well as a set of service-specific KPIs from five building service perspectives. A simulation-based case study demonstrated how occupant-centric KPIs can help quantify the impacts of power outages on occupants' thermal comfort, visual comfort, and indoor air quality. The findings of this study can help practitioners and researchers define, select, and apply occupant-centric KPIs for diverse building performance goals.

Acknowledgements

This research was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technologies of the United States Department of Energy, under Contract No. DE-AC02-05CH11231. The authors appreciate the feedback on the human–building interaction KPIs from Jared Langevin of LBNL.

References

- “6.15 Lighting.” 2020. Accessed July 28. <https://www.gsa.gov/node/82715>.
- “Air Quality Index (AQI) Basics.” 2020. Accessed July 29. <https://cfpub.epa.gov/airnow/index.cfm?action=aqibasics.aqi>.
- Alavi, Hamed S., Elizabeth F. Churchill, Mikael Wiberg, Denis Lalanne, Peter Dalsgaard, Ava Fatah gen Schieck, and Yvonne Rogers. 2019. “Introduction to Human-Building Interaction (HBI): Interfacing HCI with Architecture and Urban Design.” *ACM Transactions on Computer-Human Interaction* 26 (2): 1–10. doi:10.1145/3309714.
- Alimohammadisagvand, Behrang, Sadaf Alam, Mubbashir Ali, Merkebu Degefa, Juha Jokisalo, and Kai Sirén. 2017. “Influence of Energy Demand Response Actions on Thermal Comfort and Energy

- Cost in Electrically Heated Residential Houses.” *Indoor and Built Environment* 26 (3): 298–316. doi:10.1177/1420326X15608514.
- Altomonte, Sergio, Joseph Allen, Philomena M. Bluysen, Gail Brager, Lisa Hescong, Angela Loder, Stefano Schiavon, Jennifer A. Veitch, Lily Wang, and Pawel Wargocki. 2020. “Ten Questions Concerning Well-Being in the Built Environment.” *Building and Environment* 180 (August): 106949. doi:10.1016/j.buildenv.2020.106949.
- Anderson, Mindy, Catriona Carmichael, Virginia Murray, Andy Dengel, and Michael Swainson. 2013. “Defining Indoor Heat Thresholds for Health in the UK.” *Perspectives in Public Health* 133 (3): 158–164. doi:10.1177/1757913912453411.
- “ANSI/ASA S3.5-1997 (R2017) - Methods for Calculation of the Speech Intelligibility Index.” 2020. Accessed July 29. <https://webstore.ansi.org/standards/asa/ansiasas31997r2017>.
- Atzeri, Anna Maria, Francesca Cappelletti, Athanasios Tzempelikos, and Andrea Gasparella. 2016. “Comfort Metrics for an Integrated Evaluation of Buildings Performance.” *Energy and Buildings* 127 (September): 411–424. doi:10.1016/j.enbuild.2016.06.007.
- Board, Transportation Research, National Academies of Sciences Engineering, and Medicine. 2004. *Effective Methods for Environmental Justice Assessment*. Washington, DC: The National Academies Press. doi:10.17226/13694.
- Bogatu, Dragos-Ioan, DTU Byg, and Daniel Coakley. 2020. “Long-Term IEQ Evaluation Metrics Based on Standards and Certification Schemes,” 13.
- Bordass, Bill. 2020. “Metrics for Energy Performance in Operation: The Fallacy of Single Indicators.” *Buildings and Cities* 1 (1). Ubiquity Press: 260–276. doi:10.5334/bc.35.
- Borgeson, Sam, and Gail Brager. 2011. “Comfort Standards and Variations in Exceedance for Mixed-Mode Buildings.” *Building Research & Information* 39 (2). Routledge: 118–133. doi:10.1080/09613218.2011.556345.
- Brager, Gail, and Lindsay Baker. 2009. “Occupant Satisfaction in Mixed-Mode Buildings.” *Building Research & Information* 37 (4). Routledge: 369–380. doi:10.1080/09613210902899785.
- Brown, Stephen K. 2008. “HIGH QUALITY INDOOR ENVIRONMENTS FOR SUSTAINABLE OFFICE BUILDINGS,” 13.
- Candace Pearson. 2015. “Resilient Design Pilot Credits Added to LEED.” *BuildingGreen*. <https://www.buildinggreen.com/newsbrief/resilient-design-pilot-credits-added-leed>.
- Carlucci, Salvatore, and Lorenzo Pagliano. 2012. “A Review of Indices for the Long-Term Evaluation of the General Thermal Comfort Conditions in Buildings.” *Energy and Buildings* 53 (October): 194–205. doi:10.1016/j.enbuild.2012.06.015.
- Committee, CIE Technical, and others. 1995. *CIE 117-1995 Discomfort Glare in Interior Lighting*. Commission internationale de l’éclairage.
- Committee, IES Daylight Metrics, and others. 2012. “IES Spatial Daylight Autonomy (SDA) and Annual Sunlight Exposure (ASE), Daylight Metrics Committee. Approved Method IES LM-83-12.” *Illuminating Engineering Society of North America*.
- Costa, Andrea, Marcus M. Keane, J. Ignacio Torrens, and Edward Corry. 2013. “Building Operation and Energy Performance: Monitoring, Analysis and Optimisation Toolkit.” *Applied Energy, Sustainable Development of Energy, Water and Environment Systems*, 101 (January): 310–316. doi:10.1016/j.apenergy.2011.10.037.
- Crawley, Drury B., Linda K. Lawrie, Frederick C. Winkelmann, W. F. Buhl, Y. Joe Huang, Curtis O. Pedersen, Richard K. Strand, et al. 2001. “EnergyPlus: Creating a New-Generation Building Energy Simulation Program.” *Energy and Buildings*, Special Issue: BUILDING SIMULATION’99, 33 (4): 319–331. doi:10.1016/S0378-7788(00)00114-6.
- D’Amico, A., G. Ciulla, L. Tupenaite, and A. Kaklauskas. 2020. “Multiple Criteria Assessment of Methods for Forecasting Building Thermal Energy Demand.” *Energy and Buildings* 224 (October): 110220. doi:10.1016/j.enbuild.2020.110220.
- de Wilde, Pieter. 2018. “Fundamentals of Building Performance.” In *Building Performance Analysis*, 117–170. John Wiley & Sons, Ltd. doi:10.1002/9781119341901.ch4.

- Deru, M., K. Field, D. Studer, K. Benne, B. Griffith, P. Torcellini, B. Liu, et al. 2011. *U.S. Department of Energy Commercial Reference Building Models of the National Building Stock*. NREL/TP-5500-46861, 1009264. doi:10.2172/1009264.
- Di, Guo-Qing, Xing-Wang Chen, Kai Song, Bing Zhou, and Chun-Ming Pei. 2016. "Improvement of Zwicker's Psychoacoustic Annoyance Model Aiming at Tonal Noises." *Applied Acoustics* 105 (April): 164–170. doi:10.1016/j.apacoust.2015.12.006.
- D'Oca, Simona, Tianzhen Hong, and Jared Langevin. 2018. "The Human Dimensions of Energy Use in Buildings: A Review." *Renewable and Sustainable Energy Reviews* 81 (January): 731–742. doi:10.1016/j.rser.2017.08.019.
- Domingues, Pedro, Paulo Carreira, Renato Vieira, and Wolfgang Kastner. 2016. "Building Automation Systems: Concepts and Technology Review." *Computer Standards & Interfaces* 45 (March): 1–12. doi:10.1016/j.csi.2015.11.005.
- Emmerich, S.J., J.W. Mitchell, and W.A. Beckman. 1994. "Demand-Controlled Ventilation in a Multi-Zone Office Building." *Indoor Environment* 3 (6): 331–340. doi:10.1177/1420326X9400300607.
- Engel, Zbigniew, and Krzysztof Kosala. 2007. "Index Method of the Acoustic Quality Assessment of Sacral Buildings." *Archives of Acoustics* 32 (3): 455–474–474.
- Epstein, Yoram, and Daniel S. Moran. 2006. "Thermal Comfort and the Heat Stress Indices." *Industrial Health* 44 (3): 388–398. doi:10.2486/indhealth.44.388.
- Estrella Guillén, Esteban, Holly W. Samuelson, and Jose G. Cedeño Laurent. 2019. "Comparing Energy and Comfort Metrics for Building Benchmarking." *Energy and Buildings* 205 (December): 109539. doi:10.1016/j.enbuild.2019.109539.
- Gagge, A. P., A. P. Fobelets, and L. G. Berglund. 1986. "A Standard Predictive Index of Human Response to the Thermal Environment." *ASHRAE Trans.; (United States)* 92:2B (January). <https://www.osti.gov/biblio/6494216-standard-predictive-index-human-response-thermal-environment>.
- Guglielmetti, R., D. Macumber, and N. Long. 2011. *OpenStudio: An Open Source Integrated Analysis Platform*. NREL/CP-5500-51836. National Renewable Energy Lab. (NREL), Golden, CO (United States). <https://www.osti.gov/biblio/1032670>.
- Guth, Sylvester K. 1963. "A Method for the Evaluation of Discomfort Glare." *Illuminating Engineering* 58 (5): 351–364.
- Haas, Helmut. 1972. "The Influence of a Single Echo on the Audibility of Speech." *J. Audio Eng. Soc* 20 (2): 146–159.
- Hanna, Awad S. 2016. "Benchmark Performance Metrics for Integrated Project Delivery." *Journal of Construction Engineering and Management* 142 (9). American Society of Civil Engineers: 04016040. doi:10.1061/(ASCE)CO.1943-7862.0001151.
- Hong, Tianzhen, Chien-fei Chen, Zhe Wang, and Xiaojing Xu. 2020. "Linking Human-Building Interactions in Shared Offices with Personality Traits." *Building and Environment* 170 (March): 106602. doi:10.1016/j.buildenv.2019.106602.
- Hong, Tianzhen, Daniel Macumber, Han Li, Katherine Fleming, and Zhe Wang. 2020. "Generation and Representation of Synthetic Smart Meter Data." *Building Simulation*, June. doi:10.1007/s12273-020-0661-y.
- Hong, Tianzhen, Sarah C. Taylor-Lange, Simona D'Oca, Da Yan, and Stefano P. Corgnati. 2016. "Advances in Research and Applications of Energy-Related Occupant Behavior in Buildings." *Energy and Buildings* 116 (March): 694–702. doi:10.1016/j.enbuild.2015.11.052.
- Hong, Tianzhen, Da Yan, Simona D'Oca, and Chien-fei Chen. 2017. "Ten Questions Concerning Occupant Behavior in Buildings: The Big Picture." *Building and Environment* 114 (March): 518–530. doi:10.1016/j.buildenv.2016.12.006.
- Houtgast, T., and H. J. M. Steeneken. 1971. "Evaluation of Speech Transmission Channels by Using Artificial Signals." *Acta Acustica United with Acustica* 25 (6): 355–367.
- "Introduction to VOCS and Health | Indoor Air Quality (IAQ) Scientific Findings Resource Bank (IAQ-SFRB)." 2020. Accessed July 29. <https://iaqscience.lbl.gov/voc-intro>.

- Iso, En. 2005. "7730: 2005." *Ergonomics of the Thermal Environment-Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria*.
- Jalil, Nurul Amira Abd, Nazli Bin Che Din, and Nila Inangda Manyam Keumala Daud. 2013. "A Literature Analysis on Acoustical Environment in Green Building Design Strategies." *Applied Mechanics and Materials* 471 (December): 138–142. doi:10.4028/www.scientific.net/AMM.471.138.
- Jiang, Daniel, and Luca Delgrossi. 2008. "IEEE 802.11p: Towards an International Standard for Wireless Access in Vehicular Environments." In *VTC Spring 2008 - IEEE Vehicular Technology Conference*, 2036–2040. doi:10.1109/VETECS.2008.458.
- Jones, P. G. 1982. "The Consumption of Hot Water in Commercial Buildings." *Building Services Engineering Research and Technology* 3 (3): 95–109. doi:10.1177/014362448200300301.
- Kaushik, Amit, Mohammed Arif, Prasad Tumula, and Obas John Ebohon. 2020. "Effect of Thermal Comfort on Occupant Productivity in Office Buildings: Response Surface Analysis." *Building and Environment* 180 (August): 107021. doi:10.1016/j.buildenv.2020.107021.
- Klepeis, Neil E., William C. Nelson, Wayne R. Ott, John P. Robinson, Andy M. Tsang, Paul Switzer, Joseph V. Behar, Stephen C. Hern, and William H. Engelmann. 2001. "The National Human Activity Pattern Survey (NHAPS): A Resource for Assessing Exposure to Environmental Pollutants." *Journal of Exposure Science & Environmental Epidemiology* 11 (3). Nature Publishing Group: 231–252. doi:10.1038/sj.jea.7500165.
- Laboratories, Bell Telephone. 1928. *Bell Laboratories Record*. Bell Telephone Laboratories.
- Langevin, Jared, Jin Wen, and Patrick L. Gurian. 2016. "Quantifying the Human–Building Interaction: Considering the Active, Adaptive Occupant in Building Performance Simulation." *Energy and Buildings* 117 (April): 372–386. doi:10.1016/j.enbuild.2015.09.026.
- Larsen, Tine Steen, Lasse Rohde, Kim Trangbæk Jønsson, Birgit Rasmussen, Rasmus Lund Jensen, Henrik N. Knudsen, Thomas Witterseh, and Gabriel Bekö. 2020. "IEQ-Compass – A Tool for Holistic Evaluation of Potential Indoor Environmental Quality." *Building and Environment* 172 (April): 106707. doi:10.1016/j.buildenv.2020.106707.
- Li, Baizhan, and David Lim. 2013. "Occupant Behavior and Building Performance." In *Design and Management of Sustainable Built Environments*, edited by Runming Yao, 279–304. London: Springer. doi:10.1007/978-1-4471-4781-7_14.
- Li, Han, Ahmed Bekhit, Carolyn Szum, Clay Nesler, Sara Lissauskas, and Steven C. Snyder. 2019. "Targeting Building Energy Efficiency Opportunities: An Open-Source Analytical & Benchmarking Tool." *ASHRAE Transactions* 125: 470–478.
- Li, Han, Tianzhen Hong, Sang Hoon Lee, and Marina Sofos. 2020. "System-Level Key Performance Indicators for Building Performance Evaluation." *Energy and Buildings* 209 (February): 109703. doi:10.1016/j.enbuild.2019.109703.
- Li, Han, Na Luo, Handi Chandra Putra, Tianzhen Hong, and USDOE. 2020. *OpenStudio-Variability-Gem v1.0*. Lawrence Berkeley National Lab. (LBNL), Berkeley, CA (United States). doi:10.11578/dc.20200611.3.
- Li, Han, Xuan Luo, Tianzhen Hong, and USDOE. 2020. *OpenStudio-Occupant-Variability-Gem v1.0*. Lawrence Berkeley National Lab. (LBNL), Berkeley, CA (United States). doi:10.11578/dc.20200611.5.
- Li, Weilin, and Peng Xu. 2016. "A Fast Method to Predict the Demand Response Peak Load Reductions of Commercial Buildings." *Science and Technology for the Built Environment* 22 (6): 633–642. doi:10.1080/23744731.2016.1145533.
- Mahdavi, Ardeshtir, Christiane Berger, Veselina Bochukova, Leonidas Bourikas, Runa T. Hellwig, Quan Jin, Anna Laura Pisello, and Marcel Schweiker. 2020. "Necessary Conditions for Multi-Domain Indoor Environmental Quality Standards." *Sustainability* 12 (20). Multidisciplinary Digital Publishing Institute: 8439. doi:10.3390/su12208439.

- Mardaljevic, John, Marilyne Andersen, Nicolas Roy, and Jens Christoffersen. 2012. "Daylighting, Artificial Lighting and Non-Visual Effects Study for a Residential Building." *Infoscience*. <https://infoscience.epfl.ch/record/181055>.
- Masterton, Joan Mary, and FA Richardson. 1979. *Humidex: A Method of Quantifying Human Discomfort Due to Excessive Heat and Humidity*. Environment Canada, Atmospheric Environment.
- Merabet, Ghezlane Halhoul, Mohamed Essaïdi, Mohamed Ben-Haddou, Basheer Qolomany, Junaid Qadir, Muhammad Anan, Ala Al-Fuqaha, Riduan Mohamed Abid, and Driss Benhaddou. 2020. "Artificial Intelligence-Assisted Energy and Thermal Comfort Control for Sustainable Buildings: An Extended Representation of the Systematic Review." *ArXiv:2006.12559 [Cs, Eess]*, August. <http://arxiv.org/abs/2006.12559>.
- Milton, D. K., P. M. Glencross, and M. D. Walters. 2000. "Risk of Sick Leave Associated with Outdoor Air Supply Rate, Humidification, and Occupant Complaints." *Indoor Air* 10 (4): 212–221. doi:10.1034/j.1600-0668.2000.010004212.x.
- Minard, David, Harwood S. Belding, and James R. Kingston. 1957. "PREVENTION OF HEAT CASUALTIES." *Journal of the American Medical Association* 165 (14): 1813–1818. doi:10.1001/jama.1957.02980320043010.
- Moschandreas, Demetrios J., and Sait C. Sofuoglu. 2004. "The Indoor Environmental Index and Its Relationship with Symptoms of Office Building Occupants." *Journal of the Air & Waste Management Association* 54 (11): 1440–1451. doi:10.1080/10473289.2004.10470999.
- Nagy, Zoltán, Fah Yik Yong, and Arno Schlueter. 2016. "Occupant Centered Lighting Control: A User Study on Balancing Comfort, Acceptance, and Energy Consumption." *Energy and Buildings* 126 (August): 310–322. doi:10.1016/j.enbuild.2016.05.075.
- Neukomm, Monica, Valerie Nubbe, and Robert Fares. 2019. *Grid-Interactive Efficient Buildings*. DOE/EE-1968. U.S. Dept. of Energy (USDOE), Washington DC (United States); Navigant Consulting, Inc., Chicago, IL (United States). doi:10.2172/1508212.
- Ngarambe, Jack, Geun Young Yun, and Mat Santamouris. 2020. "The Use of Artificial Intelligence (AI) Methods in the Prediction of Thermal Comfort in Buildings: Energy Implications of AI-Based Thermal Comfort Controls." *Energy and Buildings* 211 (March): 109807. doi:10.1016/j.enbuild.2020.109807.
- "NREL/EnergyPlus." 2020. *GitHub*. Accessed July 29. <https://github.com/NREL/EnergyPlus>.
- O'Brien, William, Isabella Gaetani, Salvatore Carlucci, Pieter-Jan Hoes, and Jan L. M. Hensen. 2017. "On Occupant-Centric Building Performance Metrics." *Building and Environment* 122 (September): 373–385. doi:10.1016/j.buildenv.2017.06.028.
- O'Brien, William, Farhang Tahmasebi, Rune Korsholm Andersen, Elie Azar, Verena Barthelmes, Zsafia Deme Belafi, Christiane Berger, et al. 2020. "An International Review of Occupant-Related Aspects of Building Energy Codes and Standards." *Building and Environment* 179 (July): 106906. doi:10.1016/j.buildenv.2020.106906.
- O'Brien, William, Andreas Wagner, Marcel Schweiker, Ardeshir Mahdavi, Julia Day, Mikkel Baun Kjærgaard, Salvatore Carlucci, et al. 2020. "Introducing IEA EBC Annex 79: Key Challenges and Opportunities in the Field of Occupant-Centric Building Design and Operation." *Building and Environment* 178 (July): 106738. doi:10.1016/j.buildenv.2020.106738.
- "Occupant-Centric KPI Report | Building Component Library." 2020. Accessed October 4. <https://bcl.nrel.gov/node/85332>.
- Olesen, Bjarne W. 2012. "Revision of EN 15251: Indoor Environmental Criteria." *REHVA Journal* 49 (4): 6–12.
- O'Sullivan, D. T. J., M. M. Keane, D. Kelliher, and R. J. Hitchcock. 2004. "Improving Building Operation by Tracking Performance Metrics throughout the Building Lifecycle (BLC)." *Energy and Buildings* 36 (11): 1075–1090. doi:10.1016/j.enbuild.2004.03.003.
- Ouf, Mohamed M., June Young Park, and H. Burak Gunay. 2020. "A Simulation-Based Method to Investigate Occupant-Centric Controls." *Building Simulation*, October. doi:10.1007/s12273-020-0726-y.

- Paradis, Richard. 2016. "Acoustic Comfort | WBDG - Whole Building Design Guide." <https://www.wbdg.org/resources/acoustic-comfort>.
- Park, June Young, Mohamed M. Ouf, Burak Gunay, Yuzhen Peng, William O'Brien, Mikkel Baun Kjærgaard, and Zoltan Nagy. 2019. "A Critical Review of Field Implementations of Occupant-Centric Building Controls." *Building and Environment* 165 (November): 106351. doi:10.1016/j.buildenv.2019.106351.
- Parsons, Ken. 2014. *Human Thermal Environments: The Effects of Hot, Moderate, and Cold Environments on Human Health, Comfort, and Performance, Third Edition*. CRC Press.
- Penman, Trent D., Luke Collins, Alexandra D. Syphard, Jon E. Keeley, and Ross A. Bradstock. 2014. "Influence of Fuels, Weather and the Built Environment on the Exposure of Property to Wildfire." *PLOS ONE* 9 (10). Public Library of Science: e111414. doi:10.1371/journal.pone.0111414.
- Peretti, Clara, and Stefano Schiavon. 2011. "Indoor Environmental Quality Surveys. A Brief Literature Review." <https://escholarship.org/uc/item/0wblv0ss>.
- Rakerd, Brad, Eric J. Hunter, Mark Berardi, and Pasquale Bottalico. 2018. "Assessing the Acoustic Characteristics of Rooms: A Tutorial with Examples." *Perspectives of the ASHA Special Interest Groups* 3 (19): 8–24. doi:10.1044/persp3.SIG19.8.
- Reinhart, Christoph F., John Mardaljevic, and Zack Rogers. 2006. "Dynamic Daylight Performance Metrics for Sustainable Building Design." *LEUKOS* 3 (1). Taylor & Francis: 7–31. doi:10.1582/LEUKOS.2006.03.01.001.
- Robinson, Darren, and Frédéric Haldi. 2008. "Model to Predict Overheating Risk Based on an Electrical Capacitor Analogy." *Energy and Buildings* 40 (7): 1240–1245. doi:10.1016/j.enbuild.2007.11.003.
- Ryckaert, Wouter R., Catherine Lootens, Jonas Geldof, and Peter Hanselaer. 2010. "Criteria for Energy Efficient Lighting in Buildings." *Energy and Buildings* 42 (3): 341–347. doi:10.1016/j.enbuild.2009.09.012.
- Saad, S. M., A. Y. M. Shakaff, A. R. M. Saad, A. M. Yusof, A. M. Andrew, A. Zakaria, and A. H. Adom. 2017. "Development of Indoor Environmental Index: Air Quality Index and Thermal Comfort Index." In , 020043. Penang, Malaysia. doi:10.1063/1.4975276.
- Sapiezynski, Piotr, Arkadiusz Stopczynski, Radu Gatej, and Sune Lehmann. 2015. "Tracking Human Mobility Using WiFi Signals." *PLOS ONE* 10 (7). Public Library of Science: e0130824. doi:10.1371/journal.pone.0130824.
- Schenck, Paula, A Karim Ahmed, Anne Bracker, and R DeBernardo. 2010. "Climate Change, Indoor Air Quality and Health." *US Environmental Protection Agency*.
- Spalding, G. R., and J. Niedzielski. 1978. "A Comparison of NIC' and Δ dB A Rating Schemes for Determining Speech-Privacy Potential of Open-Plan Office Space." *Acta Acustica United with Acustica* 41 (1): 28–31.
- "Standard | WELL V2." 2020. Accessed July 29. <https://v2.wellcertified.com/v/en/overview>.
- Standard, ASHRAE. 2017. "Standard 55–2017 Thermal Environmental Conditions for Human Occupancy." *Ashrae: Atlanta, GA, USA*.
- Standard, ISO, and BSEN ISO. 1998. "Ergonomics of the Thermal Environment—Instruments for Measuring Physical Quantities." International Organization for Standardization.
- Sun, Kaiyu, Michael Specian, and Tianzhen Hong. 2020. "Nexus of Thermal Resilience and Energy Efficiency in Buildings: A Case Study of a Nursing Home." *Building and Environment* 177 (June): 106842. doi:10.1016/j.buildenv.2020.106842.
- Tartarini, Federico, Stefano Schiavon, Toby Cheung, and Tyler Hoyt. 2020. "CBE Thermal Comfort Tool: Online Tool for Thermal Comfort Calculations and Visualizations." *SoftwareX* 12 (July): 100563. doi:10.1016/j.softx.2020.100563.
- Teichman, Kevin, Cynthia Howard-Reed, Andrew Persily, and Steve Emmerich. 2016. *Characterizing Indoor Air Quality Performance Using a Graphical Approach*. NIST TN 1868. National Institute of Standards and Technology. doi:10.6028/NIST.TN.1868.

- Turan, Irmak, Christoph Reinhart, and Michael Kocher. 2019. "Evaluating Spatially-Distributed Views in Open Plan Work Spaces." In *Proceedings of the IBPSA International Building Simulation Conference, BS*.
- Verbeke, Stijn, Yixiao Ma, Paul Van Tichelen, Sarah Bogaert, Mathias Uslar, Judith Schulte, Kjell Bettgenhäuser, et al. "Support for Setting up a Smart Readiness Indicator for Buildings and Related Impact Assessment Second Progress Report," 276.
- Wallace, Robert F., David Kriebel, Laura Punnett, David H. Wegman, C Bruce Wenger, John W. Gardner, and Richard R. Gonzalez. 2005. "The Effects of Continuous Hot Weather Training on Risk of Exertional Heat Illness." *Medicine & Science in Sports & Exercise* 37 (1): 84–90. doi:10.1249/01.MSS.0000150018.90213.AA.
- Wang, Lin-Shu, Peizheng Ma, Enyuan Hu, David Giza-Sisson, Gregory Mueller, and Nianhua Guo. 2014. "A Study of Building Envelope and Thermal Mass Requirements for Achieving Thermal Autonomy in an Office Building." *Energy and Buildings* 78 (August): 79–88. doi:10.1016/j.enbuild.2014.04.015.
- Wang, Zhe, Hui Zhang, Yingdong He, Maohui Luo, Ziwei Li, Tianzhen Hong, and Borong Lin. 2020. "Revisiting Individual and Group Differences in Thermal Comfort Based on ASHRAE Database." *Energy and Buildings* 219 (July): 110017. doi:10.1016/j.enbuild.2020.110017.
- Wargocki, Pawel, and David P. Wyon. 2017. "Ten Questions Concerning Thermal and Indoor Air Quality Effects on the Performance of Office Work and Schoolwork." *Building and Environment* 112 (February): 359–366. doi:10.1016/j.buildenv.2016.11.020.
- Wei, Wenjuan, Olivier Ramalho, and Corinne Mandin. 2015. "Indoor Air Quality Requirements in Green Building Certifications." *Building and Environment* 92 (October): 10–19. doi:10.1016/j.buildenv.2015.03.035.
- "What Gets Measured Gets Done: Key Performance Indicators." 2010. *California Digital Library*. <https://cdlib.org/cdlinfo/2010/09/15/what-gets-measured-gets-done-key-performance-indicators/>.
- Wienold, Jan. 2009. "Dynamic Daylight Glare Evaluation." In *Proceedings of Building Simulation*, 944–951.
- Xie, Jiaqing, Haoyang Li, Chuting Li, Jingsi Zhang, and Maohui Luo. 2020. "Review on Occupant-Centric Thermal Comfort Sensing, Predicting, and Controlling." *Energy and Buildings* 226 (November): 110392. doi:10.1016/j.enbuild.2020.110392.
- Yan, Da, Tianzhen Hong, Bing Dong, Ardeshir Mahdavi, Simona D'Oca, Isabella Gaetani, and Xiaohang Feng. 2017. "IEA EBC Annex 66: Definition and Simulation of Occupant Behavior in Buildings." *Energy and Buildings* 156 (December): 258–270. doi:10.1016/j.enbuild.2017.09.084.
- Yoshino, Hiroshi, Tianzhen Hong, and Natasa Nord. 2017. "IEA EBC Annex 53: Total Energy Use in Buildings—Analysis and Evaluation Methods." *Energy and Buildings* 152 (October): 124–136. doi:10.1016/j.enbuild.2017.07.038.
- Yun, Geun Young, Hyoin Kim, and Jeong Tai Kim. 2012. "Effects of Occupancy and Lighting Use Patterns on Lighting Energy Consumption." *Energy and Buildings, Sustainable and healthy buildings*, 46 (March): 152–158. doi:10.1016/j.enbuild.2011.10.034.
- Zhang, Zhiang, Adrian Chong, Yuqi Pan, Chenlu Zhang, and Khee Poh Lam. 2019. "Whole Building Energy Model for HVAC Optimal Control: A Practical Framework Based on Deep Reinforcement Learning." *Energy and Buildings* 199 (September): 472–490. doi:10.1016/j.enbuild.2019.07.029.
- Zhu, Julie Yixuan, Jialing Xu, Anny Xijia Zheng, Jiaju He, Chaoyi Wu, and Victor O. K. Li. 2014. "WiFi Fingerprinting Indoor Localization System Based on Spatio-Temporal (S-T) Metrics." In *2014 International Conference on Indoor Positioning and Indoor Navigation (IPIN)*, 611–614. Busan, South Korea: IEEE. doi:10.1109/IPIN.2014.7275534.
- Zwicker, Eberhard, and Hugo Fastl. 2013. *Psychoacoustics: Facts and Models*. Springer Science & Business Media.