5 Occupant-Centric Performance Metrics and Performance Targets

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Summary

In this chapter, we will describe occupant-centric performance metrics and their main use cases in the building life cycle. We will start with the background of occupant metrics in relation to occupant needs, and then describe a suite of occupant metrics within a classification framework. Next, we will present methods to quantify the occupant metrics. Finally, we will discuss the basis to set the energy and environmental performance targets.

5.1 Introduction

Building performance is mainly determined by six factors, as studied in the International Energy Agency's (IEA) Energy in Buildings and Communities Programme (EBC) Annex 53 (Yoshino *et al*., 2017): climate, building envelope, building services and energy systems, building operation and maintenance, occupants' activities and behavior, and indoor environmental quality (IEQ). To quantify building performance, metrics have been developed and widely used to guide building design, code compliance, and performance benchmarking and rating. However, most building performance metrics adopted by current building standards (e.g., ASHRAE 90.1, ASHRAE 189.1, ISO 17772, ISO 52000) and certifications (e.g., LEED, BREEAM, and DGNB) focus on either whole-building (Coleman *et al*., 2015), system-level (Li *et al*., 2020), or equipment-level energy use, peak demand, or energy efficiency. They are usually normalized by the floor area of a building; for example, the energy use intensity (EUI) in kilowatt-hours per square meter (kWh/m^2) or thousand Btu per square foot ($kBtu/ft^2$) represents the annual whole-building energy use per building floor area. The peak demand intensity, in watts per square meter or square foot (W/m^2 or W/ft^2) represents the annual peak electricity demand per building floor area. Most existing metrics do not explicitly consider occupants, which can lead to significant bias in evaluating building performance (O'Brien *et al*., 2017).

With increasing concerns over each building's environmental performance by building owners and occupants, it is critical to consider building

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performance with regard to occupants rather than merely normalizing by floor area. Unlike normalizing by floor area, normalizing performance by occupants simultaneously credits buildings for both space utilization efficiency and energy performance. New space utilization models for occupancy (e.g., co-working, Airbnb, hoteling, post-COVID-19 pandemic hybrid working schedules) are challenging conventional assumptions upon which traditional metrics were developed.

More frequent extreme weather events and the increasing penetration of distributed energy resources (DER)—including renewable energy, storage, and electric vehicles—impose a need to quantify building energy flexibility and resilience to support research and development of grid-interactive efficient buildings (GEBs) (Neukomm *et al*., 2019). Occupant-centric performance metrics are essential for evaluating how passive building designs and demand-flexible operations affect occupants in the GEB context.

Meanwhile, occupant needs (described in Chapter 2) in current building energy codes and standards (e.g., ISO 7730, ASHRAE 62.1, ASHRAE 55) and design guidelines are usually represented as static and homogeneous criteria for IEQ. These include indoor air temperature and humidity within a narrow comfort zone, illuminance levels based on space type, maximal allowable carbon dioxide (CO_2) concentration based on activity type, and occupancy duration (O'Brien *et al*., 2020). These metrics often miss usability, individual comfort, exposure (e.g., to viruses and light), and space utilization. They are not designed specifically from an occupant perspective and do not consider occupants' diverse and dynamic needs and interactions with building systems or the latest research (e.g., see Chapter 1 for a list of misconceptions about building occupants).

With major energy end uses such as lighting and heating, ventilation, and air conditioning (HVAC) being continuously improved via efficiency measures, occupant-related performance is considered increasingly important (Coleman *et al*., 2015; D'Oca *et al*., 2018) to improve occupant wellness, comfort, and health (e.g., via the WELL international standard, concerns for COVID-19). Not including occupant perspectives in most metrics downplays occupants' importance during the design process and discussion, and it precludes opportunities to benchmark and diagnose building performance from those perspectives.

Occupant-centric perspectives include: (1) use of resources, such as energy, water, and space; (2) environmental impacts, such as greenhouse gas (GHG) emissions and solid waste management; (3) indoor environmental quality, including thermal, visual, acoustic, and indoor air quality (IAQ); and (4) human-building interactions. The critical human-building interactions are represented as the degree and flexibility of adjustments that occupants can make to building systems (e.g., operable windows, movable shades, thermostats, dimmable lights, ceiling/portable fans) for maintaining comfort and health—as well as means for providing feedback to building operators or managers on IEQ or other needs.

The widely deployed sensors, meters, and Internet of Things (IoT) devices in buildings have been collecting a growing volume of data, including occupancy (e.g., people count, presence), IEQ, energy end uses, building system operational parameters, and outdoor weather conditions. Those data enable quantification and tracking of occupant-centric metrics, which can enable performance goals to be achieved or maintained throughout the building life cycle. With the advancements in occupant modeling and simulation (see, for example, Chapters 6–8 of this book and Hong *et al.*, 2016), it is feasible to calculate the occupant-centric performance metrics in building performance simulation to enable their use for informing building design options and technology evaluation. The new approach is in contrast to previous modeling approaches, which allowed fractional occupants and rarely considered individual behaviors, exposure to the environment, or presence.

In this chapter, we define occupant-centric performance metrics as those that capture the quality of services occupants receive and the degree of a building's flexibility to accommodate occupants' interactions with the building systems that influence building operations and, consequently, resource usage and environmental performance. It should be noted that the examples of occupant-centric performance metrics we present in this chapter are not intended to be exclusive. These metrics are intended to be used by building designers, architects, engineers, building owners, and occupants, and can be adopted in post-occupancy evaluation as well as in design charrettes.

This chapter builds on the occupant needs discussed in Chapters 2–4. In Section 5.2, we describe a framework to define and exemplify a suite of occupant-centric performance metrics. These metrics aim to cover the main use cases in the building life cycle representing performance of (1) resource uses to provide services for occupants and their environmental impacts; (2) IEQ, ensuring a comfortable and healthy indoor environment for occupants; and (3) human-building interactions, which entails the degree of freedom for occupants to interact with buildings and systems and to provide feedback. In Section 5.3, we describe calculations or measurements to quantify these metrics and corresponding visualization techniques used to facilitate communications with architects, building designers and engineers, occupants, building operators, and policymakers. In Section 5.4, we further discuss the basis of setting occupant-centric performance targets.

5.2 Occupant-Centric Building Performance Metrics

In this section, we first introduce the key attributes of occupant-centric metrics, and then present a framework that covers their important aspects. We review building performance considerations in existing literature, building codes, and standards from the occupant perspective. The review includes current limitations and future improvement opportunities of occupant-centric building performance evaluations. Finally, we provide example use cases of occupant-centric metrics in the building design phase.

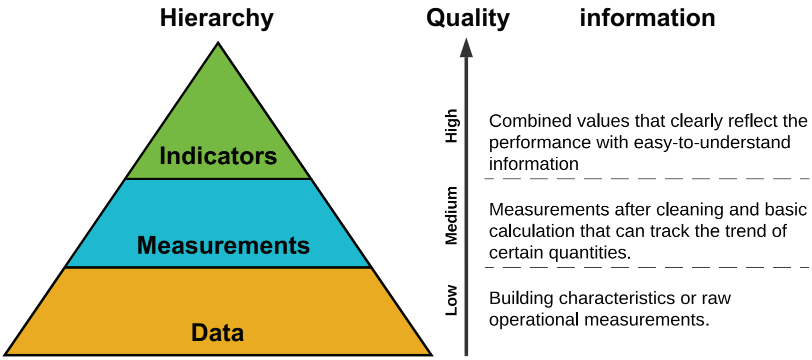

Figure 5.1 Hierarchy, quality, and information for building performance quantification.

5.2.1 Key Attributes of Building Performance Metrics

de Wilde (2018) describes a hierarchical structure of quality and information for use in the analysis and quantification of building performance (Figure 5.1). The term *occupant-centric metric* in this section is used to describe indicators.

Performance metrics translate raw data into actionable information that is easy to understand and can be incorporated into a clear performance evaluation target, such as energy use, IEQ, or space utilization. The following are the key attributes of performance metrics:

- **Accessibility/reproducibility:** Metrics should be easy to obtain repeatedly with existing infrastructure and technologies and reasonable effort and cost. Specifically, the sources of data and how they can be measured should be straightforward.
- **Quantifiability:** Metrics should have a clear definition of either direct measurements or robust and straightforward formulas for calculating the values. For example, the metric definition should be clear about which sensor, meter, and building characteristics are needed for the calculation. Quantifiability is the foundation of performance tracking, verification, and benchmarking.
- **Actionability:** Metrics should be target-oriented. They should provide actionable information to inform solutions to specific problems; for example, reducing lighting energy consumption per person by improving the lighting control.
- **Comparability:** Ideally, metrics should be easy to compare across different scales, countries, building types, and other settings, to maximize utility. A good metric should be generic and not building-specific.
- **Unbiased:** Metrics should be fair and objective. For example, performance metrics normalized for real-time vs. designed occupant count may be misleading.

5.2.2 A Framework of Occupant-Centric Metrics

Occupants are the main recipients of building services. They interact with the building and its systems to ensure their needs are met. At the same time, buildings and their systems consume resources to provide the required services, while byproducts such as waste and GHG emissions influence the environment. Therefore, occupant-centric building performance can be represented by three aspects (Li *et al*., 2021): (1) resource use and environmental impact, (2) IEQ and other services provided by the building and their influence on occupant comfort and health, and (3) human-building interactions. Figure 5.2 depicts these three interlinked aspects. For resource use and environmental impact, examples are building- or zone-level energy consumption, peak power demand, water usage, and GHG emissions during partial and full occupancy. For building services, we consider five categories, which include four key components of IEQ—thermal quality, visual quality, acoustic quality, and indoor air quality—as well as other services, such as the use of miscellaneous electric devices, service water, internet connection, and space. For human-building interactions, we consider the building's capability to accept occupant inputs and provide feedback and control system operations with respect to occupant-centric needs.

There are diverse factors to consider when defining or selecting occupant-centric metrics. For instance, there are different levels of granularity in

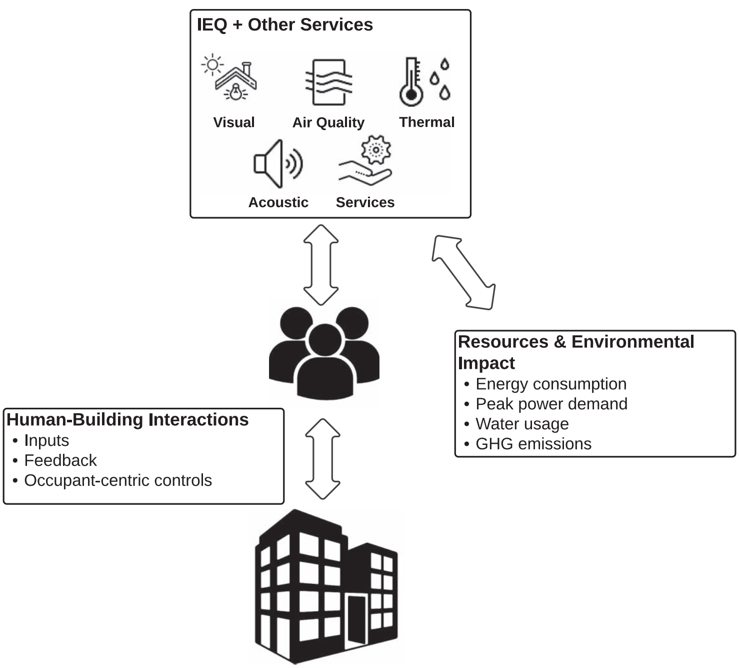

Figure 5.2 A framework of occupant-centric building performance metrics.

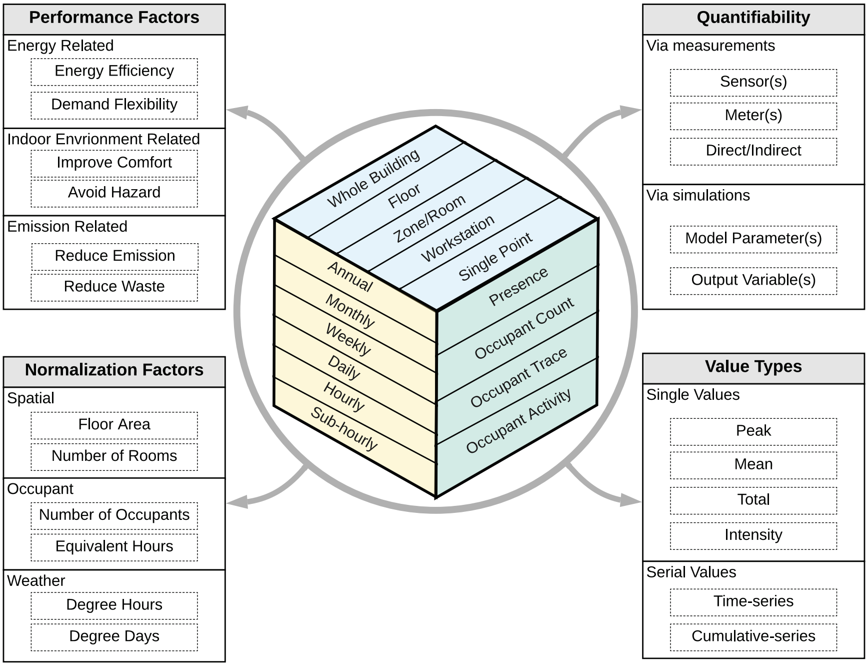

Figure 5.3 Examples of dimensions and important factors of occupant-centric metrics.

terms of occupant and other related data. In the temporal dimension, the resolution ranges from the annual to the hourly or sub-hourly level. In the spatial dimension, the resolution ranges from the whole building to a specific point. In the occupant dimension, the resolution ranges from occupant count at the building or zone level to individual occupants and their activities. In addition to the three dimensions, other factors such as the performance goal, quantifiability, normalization factors, and value types should be considered. Figure 5.3 shows the dimensions and important factors to consider when choosing occupant-centric metrics.

5.2.3 Examples of Occupant-Centric Metrics

Table 5.1 shows examples of metrics covering the three categories. A comprehensive list of occupant-centric metrics and factors is available in Li *et al.* (2021). The example metrics are for demonstration purposes and may not be applicable to all scenarios.

In addition to the normal operating conditions, occupant-centric metrics can also cover extreme scenarios, such as when occupants are in extreme

Table 5.1 Examples of occupant-centric metrics

Category	*Sub-category*	*Metric name*	*Metric definition*
Resource and environmental impact	Energy Use	kWh/ OccupantHour	Annual total site energy use (kWh)/annual total occupant-weighted hours for the whole building
	Water Use	kg water/person	Annual water use (kg)/ number of maximum occupants
	GHG Emissions	kg CO_2e/person	Annual CO_2 equivalent emission (kg)/number of maximum occupants
Building Services	Lighting	Underlit Occupancy Hours	The hours when the indoor light level is below the adaptive setpoints for a particular occupant when the room is occupied
	Thermal	Degree-Occupant-Hour Criterion (DOHC)	Sum of occupied hours multiplied by the number of occupants and operative temperature exceeding the corresponding comfort range
	Air Quality	Weighted CO_2 Exceedance × Occupant Hour	The sum of CO_2 concentration exceeding a reference level, multiplied by the number of occupants during each occupied hour, weighted by the range in which the CO_2 concentration is in (e.g., higher weights when CO_2 concentration is unhealthy)
	Acoustic Quality	Global Index of the Acoustic Quality	A global index that is the weighted function of five partial indices, namely: reverberation index, intelligibility of speech index, uniformity of loudness index, external disturbance index, and music sound quality index
	Other services	Hoteling Potential	Minimum ratio of the required number of workstations to the number of employees if they relocate on a weekly or daily basis for 95% and 99% of the time

(*continued*)

Table 5.1 Continued

Category	*Sub-category*	*Metric name*	*Metric definition*
Human-Building Interaction	Controllability	Controllability of HVAC	Percent of occupants who can adjust thermostat settings for their local environment
	Controllability	Accessibility of operable windows	Percent of occupants who can open/close the operable windows
	Occupant and Response	Accessibility to Building Information	Percent of occupants who have access to building information (e.g., a dashboard to see energy use, demand, space use, and IAQ of their floor or space)
	Occupant Feedback	Mechanism to provide feedback	Can occupants provide feedback about their IEQ needs? Is there a periodic survey of occupant satisfaction?

environments, e.g., very high or very low indoor air temperature during extreme weather events such as heat waves or cold snaps due to power outages. In such cases, traditional thermal comfort metrics, such as predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) are not sufficient; other metrics may be more appropriate to represent the thermal hazard (Sun *et al.*, 2020). For example, heat index (HI) considers both indoor air temperature and relative humidity to measure the human-perceived equivalent temperature. It is widely used for assessing outdoor thermal comfort and thermal resilience in the United States. There are five levels of risk based on the heat index: (1) Safe (HI ≤ 26.7°C); (2) Caution (26.7°C < HI ≤ 32.2°C, fatigue possible); (3) Extreme Caution (32.2°C < HI ≤ 39.4°C, muscle cramps and/or heat exhaustion possible); (4) Danger (39.4°C < HI ≤ 51.7°C, muscle cramps and/or heat exhaustion likely); and (5) Extreme Danger (HI > 51.7°C, heat stroke highly likely).

5.3 Methods to Quantify Occupant Metrics

This section describes methods to quantify the occupant metrics using measurements or simulations, taking into account fundamental differences between users (e.g., age, gender) to properly reflect their conditions and preferences, as well as to address potential inequities. Several examples are provided to demonstrate how occupant metrics can be calculated using building automation system (BAS) and IoT data, and from simulations.

Table 5.2 Types of data needed for occupant-centric metrics calculations

Data type	*Example*
Occupancy information	Occupant presence/absence and/or people count at the space or whole-building level
IEQ parameters	Air temperature, humidity, CO_2 concentration, volatile organic compounds, illuminance level, and acoustic level
Resource usage	Energy use of the whole building or major end uses including lighting, HVAC, plug-in equipment, and service water heating. Water use for the whole building or broken down into HVAC (cooling tower), drinking, and other uses (washing, flushing toilet, etc.)
Environmental impacts	GHG emissions and solid waste associated with building services
Human-building interaction measurements	Percent of occupants able to interact with building systems and components, e.g., open/close windows, adjust thermostat settings, open/close shades, turn on/off or dim lights, turn on/off plug-in equipment, occupant feedback system

5.3.1 Methods based on Measured Data

Occupant-centric metrics can be either directly measured or calculated using measured data for existing buildings. As per the framework in Figure 5.2, the data needed for calculating occupant-centric metrics have multidimensional traits (i.e., temporal, spatial, and occupant) and can have a range of resolutions. Depending on the selected metrics, the types of data and examples at various temporal resolutions (from minutes to hourly to monthly to annual) shown in Table 5.2 may be needed for measurements.

Occupancy information is essential for occupant-centric metric calculations. Numerous methods can be used to measure occupant presence or absence in a space. They are differentiated by whether occupants are counted implicitly or explicitly (Dong *et al.*, 2018). Implicit methods determine occupancy indirectly, via a secondary signal. The most common example is measurement of CO_2 as an indication and variation of occupancy over time. Other measurements have also been suggested and used with varying degrees of success. For example, in office-work types of environments, plug loads can indicate operation of computers and thus, occupancy. Indirect methods need to be calibrated and often recalibrated to avoid drift and maintain accuracy.

Explicit methods link a measurement count directly to a person without the need for complex calibration. A common example is motion detectors, typically based on passive infrared (PIR) sensing. PIR sensor data, however, are not usually logged in building management systems, but rather directly linked to, for example, lighting control. Recently, methods that use available IT infrastructure have emerged. Most notably, the use of Wi-Fi signals. Analyzing connected mobile phones (or other Wi-Fi-capable devices) gives an indirect count of the number of people in the vicinity of the wireless access point, which is linked to a certain space/zone in the building (Hobson *et al.*, 2019).

The study by Hahn *et al.* (2020) demonstrates the value and implementation of occupant-centric performance indicators and targets in energy analysis through a post-occupancy evaluation (POE). The study examined high-efficiency residential buildings in the south of Germany within the context of the POE process, and included monitoring, occupant information and training, and surveying. The objective was to draw a comparison between the calculated energy demand according to standards, such as in energy certificates, and the actual monitored consumption (thermal energy for domestic hot water and space heating, electricity for appliances/plug loads) over several years (2013–2016). The study was conducted annually from 2013 to 2016.

With the dimensions and factors (Figure 5.4) in mind, traditional building energy performance metrics (e.g., from current standards) usually only consider intensity normalized by floor area, which overlooks heterogeneous occupant density and variety of behavior. However, occupant factors are known to be among the most influential ones affecting building energy consumption, and so they must be included. To keep the basis of comparison, the measured floor heating energy was normalized by heating degree days (HDD) and adapted to the test-reference year (TRY). The individual units were considered. In addition, the number of permanent residents from POE in each unit was used to obtain an occupant-centric indicator. The inclusion of occupant-centric indicators enables energy consumption and subsequent emissions to be compared considering the occupant factors, which informs decision-making of building designers and energy modelers. It demonstrated that, for example, “wasters” or “savers” were not necessarily wasteful or saving when the number of inhabitants was taken into account. In addition, the observation over several years discovered “personal fingerprints,” as the normalized energy consumption remains relatively constant

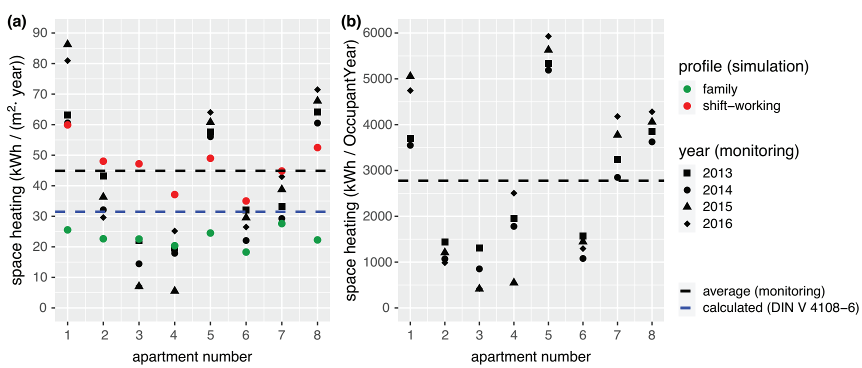

Figure 5.4 Thermal energy for space heating in the example building with eight units: kWh/(m^2×year) (left) and kWh/OccupantYear (right). Both metrics are weather-normalized (Hahn *et al.*, 2020).

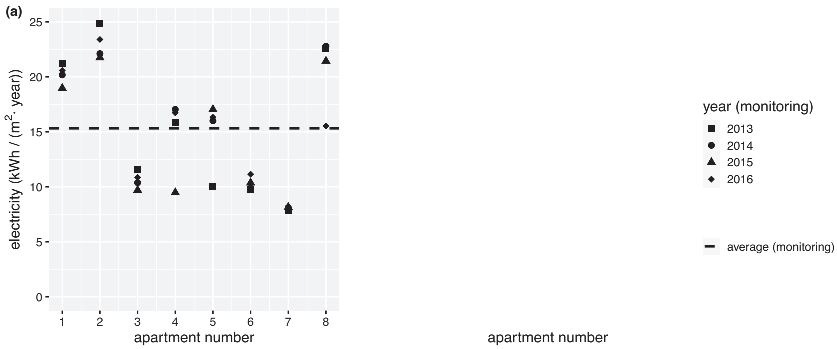

Figure 5.5 Annual electricity use of the example building with eight units: kWh/(m^2 × year) (left) and kWh/OccupantYear (right) (Hahn *et al.*, 2020).

with low variations (Figure 5.5). Figure 5.4 shows the annual space heating energy for the building with eight units and energy consumption scenarios with simulated profiles for "'families" and "shift-working."

Further improvements regarding the indicators can be achieved by counting the real occupancy hours. This can lead to a higher temporal resolution (kWh/OccupantHour). Considering the topology of residents, these metrics can be grouped by life and work style to provide a more reasonable peer-to-peer comparison. For example, working families' and seniors' houses should be considered in different groups.

5.3.2 Methods based on Building Performance and Occupant Modeling

Building performance simulation (BPS) provides an approach to quantifying different performance aspects such as energy demand and IEQ, which are important bases of comparing different design alternatives for new buildings and operation strategies for existing buildings (Hong *et al.*, 2018). Recent advancements in BPS (Yan *et al.*, 2017) have made it more feasible to calculate occupant-centric performance metrics.

Getting realistic occupant-related assumptions is essential for occupant-centric metrics. There are many ongoing efforts to improve occupant-related assumptions. Table 5.3 summarizes recent advancements based on the occupants' presence and actions (OPA) framework (Schweiker *et al.*, 2018) in building occupant modeling, and how they benefit occupant-centric metrics calculations.

In addition to the occupant modeling assumptions, another necessary step to quantify occupant-centric metric is post-processing. This step involves looking up the metric formulas, processing the simulation outputs,

Table 5.3 Advancements in occupancy estimation and occupant behavior modeling improvements

Occupant behavior modeling	*Recent advancements*	*Benefit*
Presence/Movement	1. Occupancy estimation and prediction with easy-to-measure environmental parameters, Wi-Fi connections 2. Stochastic occupant movement modeling	Provides high temporal and spatial resolution of occupancy information and helps users convert them into occupancy schedules for simulations.
Actions	Modeling of the adaptive behaviors 1. Window operation 2. Solar shading operation 3. Lighting operation 4. Thermostat adjustment 5. Appliance use 6. Clothing adjustment	Provides insight into occupants' individual IEQ preferences and helps users calculate occupant-centric metrics with respect to realistic occupant demand

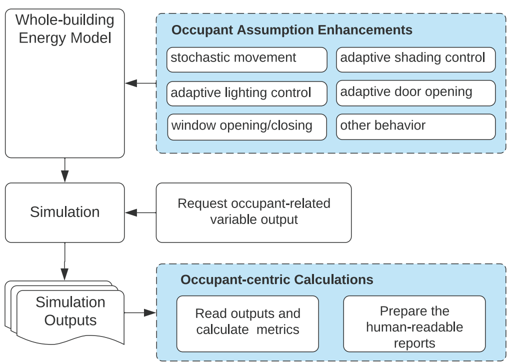

Figure 5.6 Calculation of occupant-centric metrics from simulations.

and calculating the metrics, which can be tedious and error-prone for energy modelers. Therefore, easily accessible tools that provide automatic, standardized occupant-centric performance metric calculations could be very helpful. Figure 5.6 shows how the occupant modeling assumption enhancement module and automatic occupant-centric metric calculation module could be integrated into the five-step process introduced previously (Li *et al.*, 2021). The occupant assumption enhancement module reads a whole-building energy model, generates more realistic occupant-related assumptions that can consider climate and cultural differences, and injects the improved assumptions into the simulation. The occupant-centric metric calculation module adds required variables to the simulation, extracts the outputs after the simulation, calculates the metrics, and reports them in a user-friendly manner. This way, the occupant assumption enhancements and metric calculating and reporting are encapsulated, which helps to streamline and standardize the process.

Some tools have been developed recently following the paradigm described above. For example, researchers at Lawrence Berkeley National Laboratory have developed an occupancy simulator (Chen *et al.*, 2018) that models stochastic occupant movements in office buildings and converts it into occupancy schedules. This tool is integrated into an OpenStudio measure (Li and Hong, 2020) that could be easily adopted in the EnergyPlus and OpenStudio simulation processes. Following the same idea, an occupant-centric metric OpenStudio reporting measure was developed. This measure also can be adopted in EnergyPlus and OpenStudio simulations and automatically calculate and report the occupant-centric metrics in a standardized way. The improved occupant modeling and standardized occupant-centric performance metrics calculation measures allow building designers and modelers to evaluate how building and system designs influence occupants, and vice versa.

5.4 Setting Targets of Occupant-Centric Performance Metrics

Traditionally, throughout the building life cycle, building performance targets have mostly avoided consideration of occupants out of convenience, technological limitations, and uncertainty about occupancy. For example, energy is primarily normalized by floor area through detailed design (e.g., using simulation) and operations (e.g., using meter data), given the ease of accessing floor area data. Meanwhile, comfort may be defined using some abstract metric (e.g., PMV or hours within a certain air temperature range) that focuses on the space rather than the occupants and their exposure to conditions. Previously, without the tools to accurately predict occupancy through the design process (e.g., via simulation tools) and the ability to measure occupancy in an operating building (e.g., via sensors), occupant-centric metrics have been difficult to quantify. Performance risks and user requirements should be assessed at every stage, together with suggestions on how this should happen with regard to sustainability (RIBA, 2019). For instance, the Plan of Works (RIBA, 2020) refers to the RIBA (2019) for numerical targets and implementation strategies and suggests the appointment of a sustainability champion to integrate sustainable strategies to client requirements and the business case, as well as to further develop the strategy as the project progresses.

In the context of the design process, traditional performance metrics such as EUI have several important limitations. For instance, focusing on energy performance per unit of floor area sidesteps the design strategy of improving space utilization to reduce energy use. Normalizing resource use by person, in contrast, can provide a better indication of occupant needs together with what the building affords. For example, how does the subject building compare in floor area per person to other buildings of that type? Are appropriate levels of outdoor air, water, and lighting provided to occupants once the real occupant utilization in a space has been considered? Moreover, occupant-centric metrics have the implicit benefit of reframing design discussions to be about occupants, who are the ultimate users of the building (see Chapter 4 for further discussion). Such metrics are also more relatable and informative for occupants during a building's operational stage since they are expressed at the occupant scale.

In the upcoming section, we argue and demonstrate how occupant-centric building performance metrics or other indicators can be set early in the design process and evaluated from design development through operations. These metrics can be used to benchmark a particular building (or part of a building, such as a tenant or apartment) with respect to others or to detect and possibly address undesirable anomalies. Moreover, they may help to explain outliers that cannot be explained via traditional metrics. For example, an open-plan office space that is converted to hoteling/hot desking may experience a significant increase in plug loads, but this would be completely justifiable if the average occupancy is increased. Of course, IEQ-related occupant-centric metrics such as noise exposure also could be tracked to quantify the potential consequences of increased occupancy density. The following section is divided into two interrelated parts: the first part focuses on setting targets, while the second part discusses the application of targets through the building life cycle.

5.4.1 Approaches to Setting Targets for Occupant-Centric Performance Metrics

We consider two complementary approaches to quantifying occupant-centric performance methods: top-down and bottom-up. These terms are used in the engineering sense, where top-down means a disaggregation of the sum and bottom-up means aggregation of the parts. Top-down methods start with high-level metrics to derive occupant-centric performance metrics. For example, the annual energy use of a building can be divided by the number of nominal occupants or occupant-hours per year to obtain occupant-centric metrics. For a more specific example, Canada's residential building sector consumes about 1,600 petajoules (PJ) ($1,600\times10^{15}$ J) total, or about 42 gigajoules (GJ) per person (Government of Canada, 2020). This value could be used as a starting point for a target, e.g., 21 GJ per person (or a 50% reduction from the current housing stock).

Bottom-up methods start with individual occupants and their needs and may aggregate these up to the building level. For instance, we might consider the daily water needs for occupants and then use this information to estimate building-level water use (e.g., 100 occupants times 50 liters (L)/day of water leads to expected water use of 5,000 L/day).

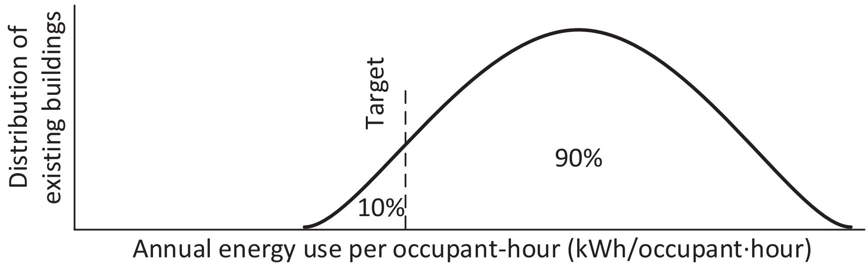

Figure 5.7 Example of a top-down approach, where an occupant-centric metric target is based on the distribution of energy use per person for existing buildings.

Top-down methods are generally easier to apply, as they stem from conventional metrics that may be available using national statistics on building energy or existing targets, such as net-zero energy. For nearly all occupant-centric performance metrics of interest, occupancy is a needed input. Thus, estimates must still be made for real or designed occupancy (e.g., by collecting these data from real buildings or via occupancy schedules in simulation). To set targets, we may aim for a building to be in the 10th percentile of existing buildings of that type (e.g., Figure 5.7) or use population-level targets for guidance.

While bottom-up methods may be more challenging to generate, they more closely follow the intent of occupant-centric performance metrics. The bottom-up approach can be built up and aggregated from individual occupant needs. The targets may be obtained based on standards, such as normalizing lighting or ventilation by occupancy instead of floor area, and other available data, such as the best available office equipment. For example, Coleman *et al.* (2015) benchmarked their office equipment (computer, monitor, task lamp, and phone) per occupant (nominal power of 56 W) against more typical equipment (367 W). This target can be used through simulation-aided design, procurement, and eventually be measured once the building is occupied.

The low-level bottom-up metrics may or may not be directly additive, as has been previously done for energy and costs (Hitchcock *et al.*, 1998). Consider the example of Figure 5.8. A variety of occupant resource requirements are separated and quantified using a bottom-up approach. The values are obtained using measurements, statistics, or engineering judgment, and then summed to estimate a higher (e.g., floor or building) level at different temporal scales (e.g., annual).

In some cases, the resources are fixed (e.g., the refrigerator is likely to run regardless of occupancy), whereas others vary with time of day and year (e.g., lighting or ventilation, if occupancy-controlled). Notably, in some cases, resources are required for building operations even if the building

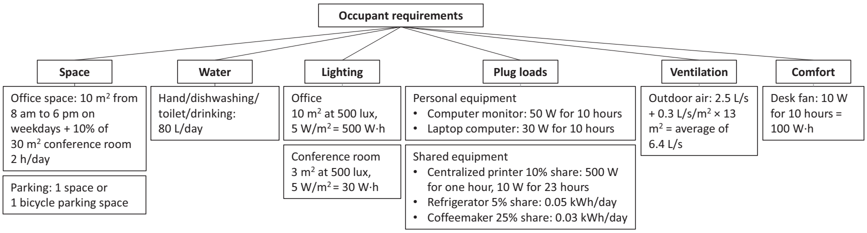

Figure 5.8 Example of a bottom-up approach to establish occupant metrics and targets.

Figure 5.9 Example of measuring occupant-level exposure using a wearable dosimeter (see red device worn by the occupant on their belt).

is vacant—for example, overnight. These include systems such as HVAC to prevent freezing and to ensure conditions are comfortable when occupants return, as well as emergency/security lighting. Moreover, some resources, such as heating, are difficult to allocate to individual occupants (e.g., space heating supplied by a centralized HVAC system).

Another class of bottom-up occupant-centric metrics involves individual occupant exposure of environmental conditions. Rather than the classic approach of imposing targets or limits on spaces (e.g., ventilation rate, noise dose limits), advanced occupant simulation and sensing allow us to quantify the exposure dose for individual occupants. For example, if we use an occupant model that involves the occupant traveling between multiple rooms in a building, we can quantify their exposure to noise over the course of a day and compare it to standards. For buildings with hazardous exposures, occupants may wear dosimeters to measure the severity and duration of exposure to conditions (e.g., noise, radiation) that individuals encounter (Figure 5.9)

In the future, we recommend that a database be developed to improve the ease of benchmarking and setting targets for occupant-centric building performance metrics, as has been done for energy performance and comfort (Chung, 2011). Ideal design situations should be made of several iterations between top-down and bottom-up approaches in which aggregations and disaggregation are negotiated among the design team until all design objectives referring to occupancy and building performance are properly satisfied. This promotes transparency in setting up occupancy data for spaces, which are normally provided by architects to mechanical engineers, so that more realistic ranges of use can be agreed upon. Agreeing on ranges and tolerances within design teams is important when abiding by tight environmental targets. Architects will set up provisional building layouts based on a series of discussions with clients following principles of functionality and ergonomics (Neufert and Neufert, 2012), whereas engineers will need to attribute ranges and tolerances to these principles to account for heating and cooling risks.

5.4.2 Use of Occupant-Centric Performance Metric Targets through the Building Life Cycle

Using any of the approaches above, occupant-centric performance metric targets can be set early in design or in planning and then maintained and monitored throughout the building life cycle. At the start of the building design process, normally occupancy can only be estimated, and IEQ and usability can only be predicted based on the proposed building systems and design. Aspirational targets can be set, but they likely need to be refined as more information becomes available from BPS (or other tools) and the design matures. Designers—and even operators—should be prepared to update assumptions about occupancy.

BPS tools are now at the stage where individual occupants can be modeled and significant detail on IEQ can be obtained. BPS tool outputs are of sufficient resolution during design that they can be compared to measured data during the use stage. A sample of occupant-centric metrics through the building life cycle is summarized in Table 5.4.

Subsequent design stages that follow the definition of the design brief (i.e., the report with building design details) integrate these performance metric targets into design solutions, thus increasing the level of detail as the project progresses. The stage in which spatial coordination is supposed to happen—and planning, certification, and building regulations applications are being prepared together with more detailed costs—is normally a point for assessment and feedback for sustainability outcomes, as well as for more detailed coordination of them with health and well-being of occupants. This stage normally happens at the end of the schematic/conceptual design stage and the beginning of the detailed design/specification stage. In the pre-construction design stage, targets are updated in accordance with final specifications, and risk assessments are undertaken with potential Plan Bs for contractors, so sustainable outputs and well-being targets can fit within updated specifications.

Table 5.4 Example available data and a comparison of conventional versus occupant-centric metrics

	Life-cycle stage			
	Programming/ design brief	*Schematic/ conceptual design*	*Detailed design/ specification*	*Use*
Typical available data/ information	Planned occupancy, space uses, estimated floor area	Early BPS results with simple HVAC and lighting systems	Detailed BPS outputs, including occupancy and IEQ predictions	Measured data for energy, IEQ, etc.; subjective post-occupancy evaluation
Conventional metrics	Floor area per activity; target EUI	Total energy use	Total energy use or energy use intensity; energy end-use breakdown; unmet hours; overheating hours; nominal lighting and plug load power density	Energy use intensity; end-use breakdown at the building level or submeter
Sample occupant-centric metrics	Energy use/ person (based on similar buildings or national statistics)	Total energy use normalized by nominal occupancy	Energy/occupant-hour (including end uses); ventilation per person; lighting energy per person; IEQ exposure per person—all based on estimated occupancy; plug-in equipment power per occupant	Energy/-occupant-hour (including end uses); ventilation per person; lighting energy per person; IEQ exposure at occupant resolution

When delivery guidance such as the BG 38/2018 Soft Landings core principles are followed and design and occupied buildings are seen as a continuum, a tangible procedure should be followed with regard to monitoring. For example, BSRIA's Soft Landings (BG 38/2018) guidance recommends that a Year 1 assessment should be designed for settling down adjustments until stable operation is achieved. Year 2 should be used for a post-occupancy evaluation (POE). Year 3 should be used for responding to the POE and maintaining monitoring, using the POE to gauge energy performance, IEQ,

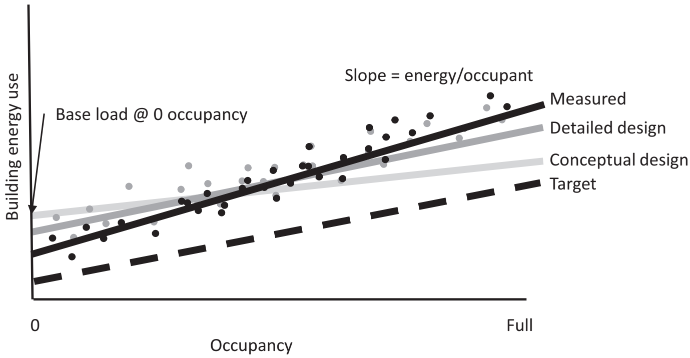

Figure 5.10 Building energy use vs. occupancy plotted as a means to track building performance throughout the building life cycle. Note the lines are not necessarily linear.

and occupant satisfaction against what was initially specified by the client, with the flexibility that "…performance targets should be revisited, checked and altered where necessary" (BG 38/2018). Feedback loops should be in place so designers can be informed about the performance of earlier projects when designing subsequent ones, thus providing a reality check to design decision-making. Involvement by end-users is strongly recommended to inform the design team of their needs and expectations, especially if they are heavily involved in controlling indoor environmental conditions.

Metrics and their targets may include single values (e.g., energy per occupant-hour) but may also include curves (Hitchcock *et al*., 1998). For example, Figure 5.10 shows the relationship between occupancy and building energy use for a hypothetical building. By fitting hourly data to a line, the building can be characterized according to its ability to adapt to varying levels of occupancy. The y-intercept represents the average building energy use when the building is vacant, and the slope indicates the additional energy per occupant (e.g., in kWh per occupied hour). Kim and Srebric (2017) used measured data to show that the slope and intercept values can differ by an order of magnitude due to building function and operations. In an ideal case, the y-intercept is 0 and the slope is minimized. However, as noted above, many buildings have base functionality during vacancy for the safety and security of the building. Nevertheless, the y-intercept should be minimized via passive measures (e.g., well-insulated envelope) and active measures (e.g., occupancy-controlled lighting and ventilation).

5.5 Closing Remarks

In this chapter, we described the motivation and a framework to define occupant-centric performance metrics in three major categories: resource use and environmental impact, indoor environmental quality, and human-building interaction. These metrics are intended to complement current practices of representing and evaluating building performance and can be adopted by stakeholders to quantify building performance from the occupants' perspectives, which can inform decision-making in the building life cycle. We described two methods—using measurement and using building performance simulation—to quantify these metrics. We also provided a suite of occupant-centric performance metrics as examples to illustrate their potential use. We closed the chapter with a discussion of the basis for setting reasonable targets for these metrics and provided recommendations for stakeholder communication on building performance using these metrics. The next two chapters provide an overview of occupant modeling methods and discuss various aspects to consider in selecting the most appropriate occupant models for a specific application in the building life cycle.

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