U.S. DEPARTMENT OF
ENERGY
Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Healthy Buildings Toolkit: General Services Administration Pilot Study

The U.S. Department of Energy's Federal Energy Management Program (FEMP), in partnership with the General Services Administration (GSA), is investigating how traditional building energy efficiency measures can impact health in the federal sector.

FEMP is currently funding research at Pacific Northwest National Laboratory (PNNL) to develop a framework for evaluating indoor environmental quality (IEQ) metrics and quantifying the potential financial costs and gains related to improving occupant productivity in federal buildings. The goal of this initiative is to facilitate more holistic decision making. This case study uses existing IEQ data from four GSA sites. The case study examines the process for analyzing large amounts of data to prioritize buildings within a portfolio and to provide customized improvement recommendations.

Background

Environmental psychology, medical research, and building technology studies have revealed how IEQ (such as lighting, thermal comfort, and air quality) affects human health, comfort, and performance (such as circadian rhythm, immune system, stress, mood, productivity, and cognitive function). The correlations derived from laboratory and empirical studies have not been directly translated to decision making in building system design and operation.

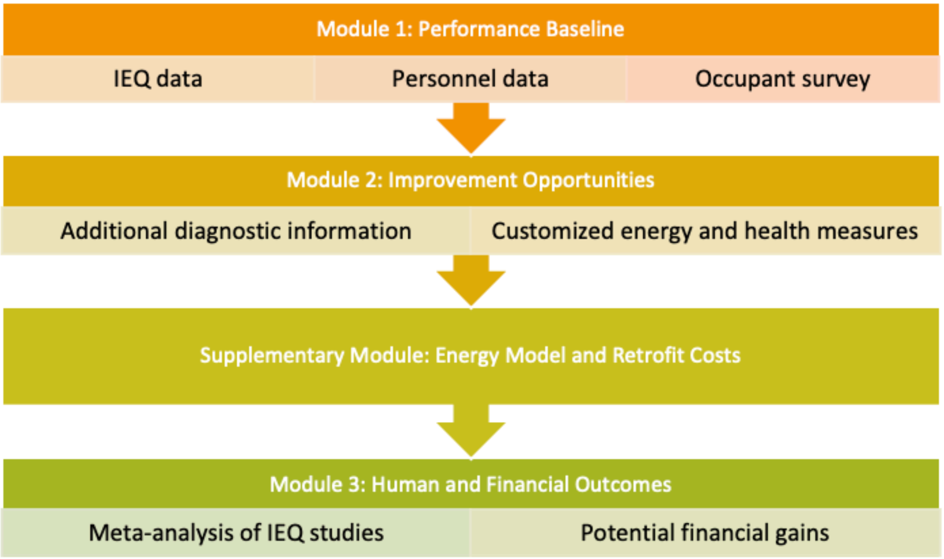

Figure 1. Modules comprising the Healthy Buildings Toolkit methodology.

Comprehensively quantifying a building's health performance can be expensive and time-consuming. Beyond evaluation, a critical need of implementing healthy building research is to identify actionable improvement strategies that target the specific building system and operational issues a building is facing. The Healthy Buildings Toolkit targets these two challenges by providing an easily navigable, low-burden data collection process and streamlined recommendations and financial analysis.

This study attempts to leverage existing building data to 1) compare four buildings at a high level to identify potential productivity gains and 2) delve into the data trends for customized recommendations. Using data from GSA's Wellbuilt for Wellbeing (WB2) project, the PNNL team presents an easy-to-implement process for evaluating IEQ metrics to yield impactful and actionable recommendations for improving occupant health and productivity in office buildings.

Methodology

The methodology developed by PNNL (outlined in Figure 1) estimates the potential financial gains from occupant productivity improvements and identifies specific modifications customized for a building. There are three modules within the overall methodology framework:

Module 1 collects baseline IEQ data by monitoring parameters such as carbon dioxide, temperature, humidity, and light levels, and administering an occupant survey.

Module 2 uses the baseline IEQ data to guide the collection of additional building characteristic, operation, and asset information needed to understand the reasons for IEQ issues. This information is used to identify specific improvement actions to help achieve the IEQ targets.

An optional component of the framework is to create an energy model and provide estimated retrofit costs.

The data from Module 1 is also used in Module 3 to estimate the potential productivity improvement for a building. PNNL developed a series of correlations between IEQ metrics and human productivity from a meta-analysis of 51 experimental conditions from peer-reviewed academic studies. The potential productivity gains between the baseline IEQ values and the target IEQ values are converted to financial gains using the cost of employees in the building.

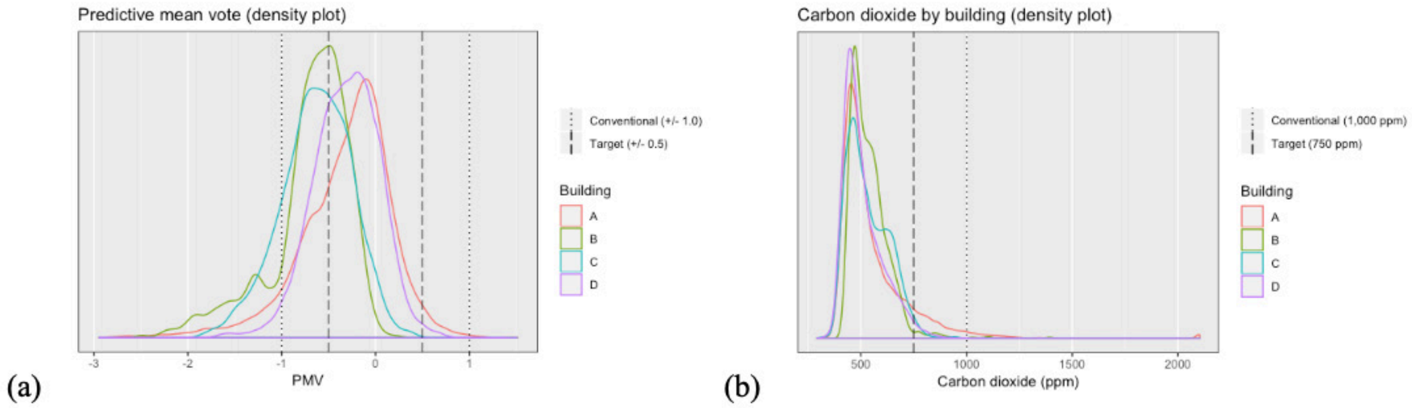

Figure 2. Density plots for PMV on left (a) and CO_2 on right (b) for the four GSA sites.

Case Study Overview

This case study uses the framework in Figure 1 to compare a portfolio of buildings, leveraging the existing WB2 IEQ measurement and survey data. The PNNL team applied the methodology to four GSA sites, representing a combination of new and legacy building systems and a diversity of interior office space designs and uses. The WB2 dataset contains almost 1 year of 5-minute interval measurements (temperature, humidity, CO_2, particulate matter [PM], sound, and others) taken from approximately 100 sensors at each of the four GSA buildings in 2015 and 2016. Each study area within the four buildings – which are located in the Mid-Atlantic region and Texas and are labeled A, B, C, and D in this study for anonymity – covers roughly 50,000 square feet of floor area with 300 staff across several floors.

This case study is divided into two separate analyses. The first analysis calculates the potential financial gains from improving occupant health at the four GSA sites. This analysis shows how IEQ data can be used to prioritize buildings within a portfolio for improvements if there are limited resources for retrofitting the entire portfolio. The data supplied by the WB2 study used for this analysis includes CO_2, representing the indoor air quality (IAQ) category, and air temperature and relativity humidity, which are used to calculate predictive mean vote (PMV),[1] representing the thermal comfort category. The methodology also includes horizontal illuminance (representing lighting), but useful lighting data are not available through the WB2 study. Therefore, lighting is excluded in this study.

The second analysis is a deep dive into one of the sites to illustrate the process that identifies specific problems and recommends building operation and system improvements to promote occupant health. The data for circadian stimulus (CS)[2] and PM are not used for the financial analysis in the first analysis because there are inadequate empirical studies to create economic models. However, they are proven important IEQ parameters and are used to identify healthy building improvements.

Analysis 1: A High-Level Portfolio Comparison

The PMV and CO_2 trends are shown in Figure 2. These density plots reveal a high-level assessment of how the GSA sites compare to optimal IEQ values (defined as "Target". ASHRAE Standard 55, Thermal Environmental Conditions for Human Occupancy, defines the PMV comfort range to be between -0.5 and +0.5, which is used as the target for comfort. CO_2 concentration indicates the extent to which adequate fresh outdoor air is being supplied to the space, which is one part of the overall IAQ picture. Outdoor air is not only important for maintaining low CO_2 levels, but also for removing human bioeffluents (odor, moisture), volatile organic compounds, and other indoor contaminants. Less than 750 ppm of CO_2 is used as a target, based on WELL Building Standard Credit A06 part 2a. The minimum design requirement for CO_2 is shown in Figure 2 based on the minimum ventilation rates in breathing zones in ASHRAE Standard 62.1, which approximates to 1,000 ppm in office spaces. The PMV range of -1.0 to +1.0, which is defined as "slightly cool" to "slightly warm" in the PMV model, is also shown for reference. This study aims to set up a near-optimal building performance goal as the target value.

As shown in the PMV plot in Figure 2(a), Building A has the best performance for thermal comfort (most values within the target range), followed by Building D. All four buildings tend towards the cool side of thermal comfort. In the case of CO_2, all four buildings perform similarly and maintain the majority of readings below the 750-ppm target. Building A has the worst performance for CO_2 (a relatively longer tail beyond the target) among the four buildings.

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[1] PMV is a measure of thermal sensation calculated from temperature, relative humidity, and other factors on a scale from -3 (cold) to +3 (hot). The calculations are based on a large sample of empirical human responses.

[2] Circadian stimulus measures the effectiveness of light to promote biological regulation of sleep cycles based on the intensity and color distribution of the light. These data were retrieved from a daylighting research study conducted at the GSA Central Office Building following the building's 2013 renovation.

Table 1. Financial gains from improving productivity for the four buildings in 10-year net present value per occupant.

	CO_2	PMV	Combined
Building A	<$1K	$15K	$16K
Building B	<$1K	$34K	$34K
Building C	<$1K	$18K	$18K
Building D	$0	$6K	$6K

The results of the studies used in the regression under similar IEQ conditions as the values measured in the buildings demonstrate a prediction range of $0 to $22K for Building A, $0 to $60K for Building B, $0 to $34K for Building C, and $0 to $10 for Building D, all in 10-year NPV per occupant.

Table 1 summarizes results from the net present value (NPV) calculations for potential improvements to IAQ, thermal comfort, and combined values. The results are presented as dollars per occupant per year so that they are comparable between the buildings. The calculations are based on data that show that employees are at their workspaces (desk, conference room) for 60% of a 40-hour workweek. The other 40% is spent on breaks, at other buildings/sites, teleworking, on work travel, and on other activities, and is not accounted for in the financial gains. The cost of employees (salaries and benefits) assumes local average general schedule level and salary. The assumed cost of employees for each building was obtained using average federal employee grade and salary for the respective region and a 0.3 multiplier for the cost of benefits. The number of employees was obtained by counting the number of workstations within the study boundaries.

Table 1 presents the expected potential financial gains based on the meta-analysis regression models. The CO_2 levels are relatively low in these buildings and therefore yield small financial gains. Thermal comfort represents the bulk of gains and should be the focus of IEQ improvements. Building B shows the greatest potential at $34K per person over 10 years. Building C and Building A are close to each other in second with potential gains of $18K and $16K per person per 10 years, respectively. This analysis does not include the cost of improving the thermal comfort of these buildings or the energy cost/savings. Over-cooling or over-heating often can be solved with operational improvements and supplementary thermal devices, which tend to have low implementation costs. The impact on energy use and costs is relatively small compared to productivity. If the HVAC systems cannot meet the thermal loads due to their vintage or poor envelope insulation, building upgrades will need to be considered. In this case, the personnel gains can help justify the higher capital costs in addition to the energy cost savings.

Analysis 2: Customized Recommendations for "Building A"

The PNNL team took a step further from Analysis 1 for Building A. This provided more context to the thermal comfort and IAQ data from the first level of analysis. This analysis includes PM and circadian stimulus (CS) measurements.

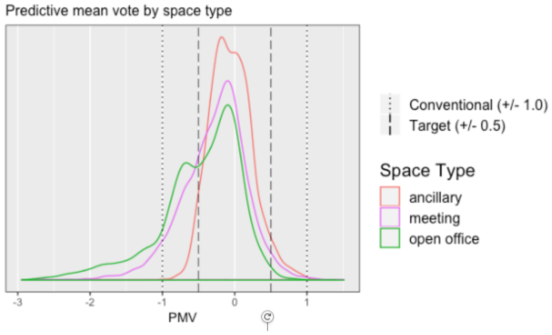
CS is an indicator of how light affects sleep quality. More specifically, it measures the effectiveness of a light source in providing CS. The circadian system is responsible for regulating daily changes in a wide range of behavioral, cognitive, and physiological functions, including the sleep/wake cycle, alertness, mood, hormone suppression/secretion, and core body temperature. The metric ranges from 0 (no stimulus) to 0.7 (full saturation). According to the Rensselaer Polytechnic Institute Lighting Research Center, the recommended exposure is a CS of 0.3 or greater at the eye (the equivalent of 180 lux from daylight) for at least 1 hour in the early part of the day (9 a.m. to 1 p.m.). The PM values are in units of counts of particles 1 µm and larger per liter of air (counts/L). The target for PM is 400 counts/L or less for a 1-hour average value.

These target values are designed for achieving optimal or near-optimal working conditions and are more stringent than conventional or expected values for an office building. Currently, there is no minimum standard for CS. ASHRAE 62.1 requires minimum MERV 8 filters for removing PM from outdoor air, but there is no minimum standard or requirement to measure PM levels.

The PNNL team derived specific insights into the space-level IEQ performance by examining and grouping locations, room function, times of day, days of week, seasons, and other building factors. Building A can be divided into five distinct zones, labeled Wing A through Wing E. Figure 3(a) shows that ancillary spaces (e.g., copy room, break room, corridor) are relatively comfortable and are not as impactful to productivity as meeting rooms and offices. A further investigation of meeting rooms and office spaces exclusively revealed that Wing A has the worst IEQ performance, as seen in Figure 3(b). All room types and especially focus rooms are too cool in Figure 3(c), and spring and summer are too cool and fall and winter are more comfortable in Figure 3(d). Figure 3(d) and (e) suggest that humidity is too low overall and higher humidity in summer is causing poor thermal comfort. With each comparison, the analysis yields more granular information that can better inform decisions about what improvements to make.

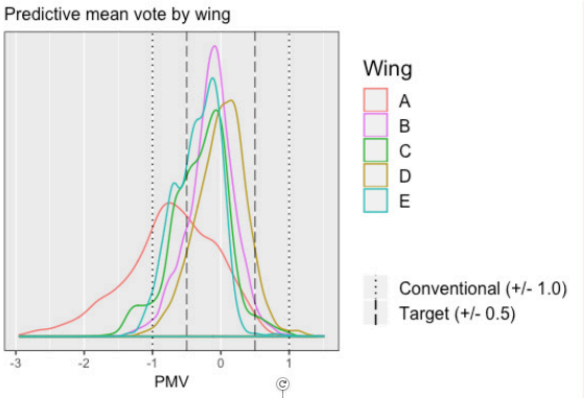
A similar diagnostic process was applied for PM, CO_2, and CS. The following observations are made for Building A:

(a)



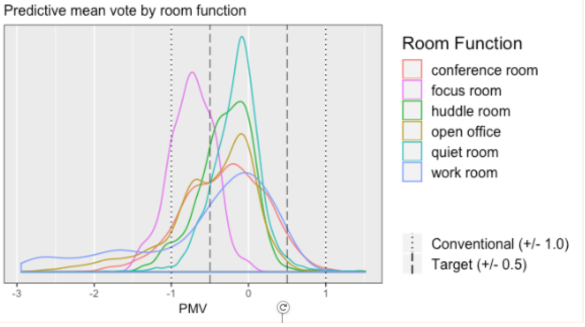
Opportunity to improve thermal comfort in office and meeting spaces. Remove ancillary spaces as these are comfortable and are not occupied for work-related activities.

(b)



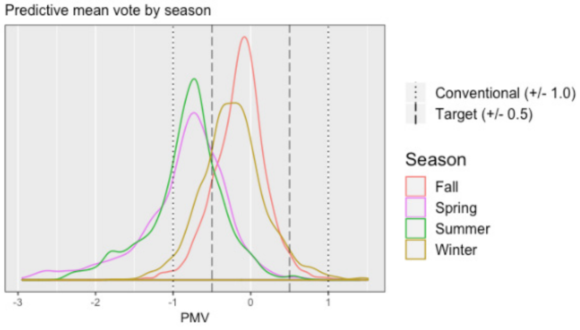
Wing A is the worst performing. All wings have adequate room for improvement, especially for being too cool.

(c)



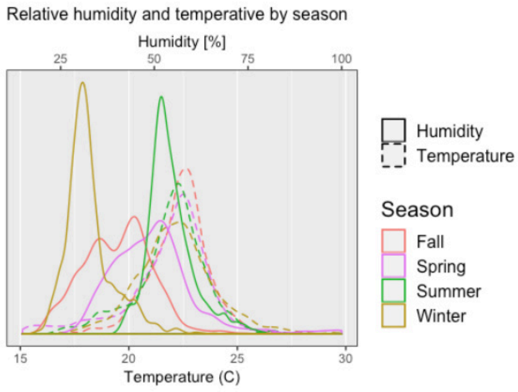
There are long tails on the cool range for most room types. Focus room is especially too cool.

(d)



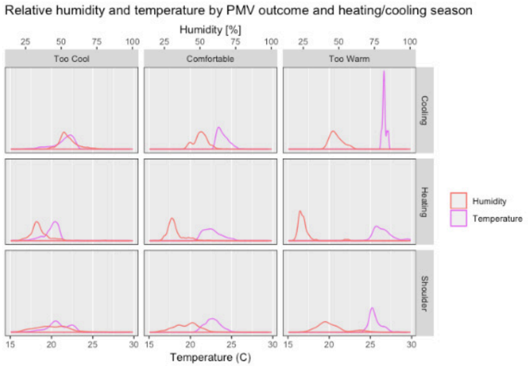
Spring and summer are significantly too cool. Fall and winter are mostly within the comfort range, with some room for improvement.

(e)



There is not much variation in temperature (dashed lines) between the four seasons. Humidity is very low in winter (mostly under 40%) and many low values are observed in fall. Spring and summer are mostly in a comfortable range of 40-60%. This suggests temperature is the issue in summer and spring.

(f)



Temperature is the main difference between the comfortable PMV values (middle column) and the too cool (left column) and too warm (right column) values for each operation season (rows). Humidity is causing the difference between seasons.

Recommendation: Modify the temperature setpoint schedule to account for the most uncomfortable areas:

- Increase temperature setpoint in spring and summer in the building to 20°C to 24°C.
- Humidify outdoor air in winter and fall and tighten the temperature range, especially in the work rooms and conference rooms.
- Monitor temperature and humidity to ensure modifications improve PMV as expected.

Figure 3. Process flow for arriving at recommendation for thermal comfort (PMV). Density plots compare the data by different fields and insights can be drawn about where and how to target improvements.

Table 2. Final recommendations for Building A based on IEQ data and survey results.

IEQ Measurement	Recommendations
Predictive Mean Vote	Increase temperature setpoint in spring and summer in the building to 20°C to 24°C (68°F to 75°F). Humidify the outdoor air intake in fall and winter to get at least 30-40% relative humidity indoors. Monitor temperature and humidity to ensure modifications improve PMV as expected.
Carbon Dioxide	First check damper positions and test economizer functioning to ensure system works properly. If this is not a problem, increase minimum ventilation rates in the afternoon at all locations, especially Tuesdays through Thursdays. Confirm high occupancy in Wing E and investigate the operation of the demand control ventilation system. Inspect the direct exhaust and air circulation in the printer room with high readings. Continue to monitor this room for verification and other similar rooms to see if it is a pattern.
Particulate Matter	One room (meeting/coordination room) with high PM was confirmed to not have ventilation. Install a dedicated exhaust system to remove the pollutants in this room.
Circadian Stimulus	Office pattern layout is already organized for maximizing daylight to occupants. In the below-ground space in Wing A, install dimmable, blue LED task lights that can provide 0.3 CS and educate occupants on the benefits of 1 hour of exposure between 9 a.m. and 1 p.m.

- The highest levels of CO_2 are observed during the afternoon between 2 p.m. and 5 p.m. The peak occurs more often during the middle of a week. There are elevated levels in the Wing B and Wing C and significantly high levels in one printer room.
- The highest PM levels are observed in one meeting/coordination room in Wing A during the spring season.
- CS is lowest in Wing A and below ground level.

Before making final recommendations, the analysis was supplemented with survey results on thermal satisfaction. For example, the survey results revealed that occupants in Wing E were the most satisfied and those in Wing A were the least satisfied.

Building characteristics were collected in the WB2 study and used to inform the recommendations. The characteristics reveal that, on average, 5 to 10 people share a thermostat, which is either hidden or disabled for occupant control. This suggests that occupants lack individual control. On average, two occupants share one air diffuser, which is a centrally controlled variable air volume unit for Wings B, C, and E and locally controlled window unit for Wings A and D. All copy rooms and kitchens have dedicated exhaust except for some in Wing D. More than 90% of occupants have a seated view of a window in Wings B, C, and E, and only 20-40% of occupants have a seated view of a window in Wings A and D (majority of these spaces is below or partially below ground floor with limited window access).

By employing the layered, sequential process of identifying the worst-performing areas, it is easier to make more informed improvement decisions. Table 2 summarizes the recommendations.

Key Takeaways

This case study illustrates the value added in implementing the framework process for assessment and decision-making. For example, in the case of the Building A, a high-level analysis of the CO_2 concentration levels suggested that improvements to IAQ would not be worthwhile because most of the time the readings are better than the target level of 750 ppm. However, by examining spaces and time periods individually, we find that small, localized efforts for the printer room and Wing E, and for the whole building in the afternoons on Tuesdays through Thursdays, can have significant impacts on these subsets and will likely be worth the investment costs and effort.

By following the process to obtain granular insights on the areas with the most improvement potential, building managers can paint a more holistic picture and make more informed decisions on building operation and upgrade. This will ultimately translate to a better built environment that not only is efficient, but plays a positive role in enhancing occupant experience and employee outcomes. ■

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