U.S. DEPARTMENT OF
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Figure 1. Photo of the exterior of the building analyzed in this case study. *Image courtesy of GSA*

Healthy Buildings Toolkit Fort Worth Pilot Study

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

FEMP is currently funding research at the Pacific Northwest National Laboratory (PNNL) to develop a framework for evaluating indoor environmental quality (IEQ) metrics and quantifying the potential financial implications related to improving occupant productivity in federal buildings. The goal of this initiative is to facilitate more holistic decision making in regard to energy efficiency and IEQ when making building upgrades. This case study uses a federal office building in Fort Worth, TX as a test site for data collection and analysis.

Background

Environmental psychology, medical, and building research have revealed how IEQ factors (lighting, thermal comfort, and air quality) can impact human health, comfort, and perfor-mance.[1] However, the evidence from laboratory and empirical studies on IEQ have not yet been translated to decision making in building system design and operation at a large scale. The Healthy Buildings Toolkit intends to change this by empowering federal agencies to incorporate human health impacts into their facility improvement decision-making process.

Comprehensively quantifying the health performance of a building can be expensive and time-consuming. In addition, there is a critical need to implement healthy building research to identify actionable improvement strategies that target specific building systems and operational issues a facility could be facing. The Toolkit targets these two challenges by providing an easily navigable, low-burden data collection process with streamlined recommendations and financial analysis.

GSA identified six candidate sites in Region 7, Region 8, and the National Capital Region to participate in the PNNL study. The building selected for this study has a history of IEQ complaints, making it a site that could benefit from a healthy building analysis and has interest from the regional GSA point of contact and building manager. The building is a WWII-era, 110,000 square-foot, warehouse-converted office building in Fort Worth, TX. It is occupied by a separate federal agency tenant and used for administration, engineering, and design. Approximately 90 percent of the building floor area does not have any exterior windows. The lighting fixture and bulb type, office design and setup, and use function vary through-out the building, but the majority is comprised of LED lighting and high-partition cubicles. The building underwent a lighting research study in 2016–2017. As a result of the study, five different LED fixture types were installed in various zones throughout the building with the intent to improve energy efficiency. The data for this case study was collected in early March 2020. The timeframe is early enough that we do not expect the COVID-19 pandemic to have significantly affected the number of occupants present.

Methodology

The methodology developed by PNNL (outlined in Figure 2) 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 (CO_2), temperature, humidity, light levels, and occupant survey results.
- Module 2 uses the baseline IEQ data to guide the collection of additional building characteristics, operation, and asset information needed to understand the reasons for any IEQ issues. This information is used to identify specific improvement actions to help achieve the IEQ targets.

[1]Delmas M and S Pekovic. 2013. "Environmental Standards and Labor Productivity: Understanding the Mechanisms that Sustain Sustainability". Journal of Organizational Behavior. 34(2):230–252. doi: 10.1002/job.1827. https://onlinelibrary.wiley.com/doi/10.1002/job.1827.

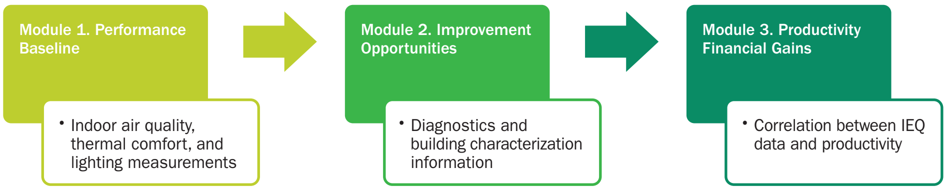

Figure 2. Methodology for customized improvement recommendations and cost-benefit financial analysis.

- Module 3 uses data from Module 1 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.
- Energy savings and retrofit costs can be incorporated into the cost benefit analysis; however, that is not the focus of this case study.

Case Study Overview

PNNL worked with the GSA Greater Southwest Region team to collect basic building information and identify sam-ple locations before the site visit. An on-site meeting was conducted with the tenant agency's management team and GSA facility management team to present the study plan and gain their support. PNNL delivered a two-hour training session to the GSA team who then collected the IEQ data, occupant survey responses, and the necessary personnel data. This data was sent back to PNNL for post processing and analysis.

As part of Module 1, the GSA team collected CO_2, temperature, and humidity measurements at 30-minute intervals for one week with data logging sensors. Humidity and temperature were used to calculate predictive mean vote[2] (PMV), an indicator of thermal comfort. The team conducted these measurements at four locations (two cubicles, one private office, and one conference room), which were spread out across the HVAC and lighting zones. The team also measured horizontal illuminance, circadian stimulus (CS)[3], particulate matter <2.5 µm ($PM_{2.5}$), and particulate matter <10 µm (PM_{10}) at 30 locations throughout the building with handheld sensors. CS was re-sampled at the windowed locations each day for five days to evaluate variation between days due to weather.

The tenant agency administered a short occupant survey to collect level of satisfaction with temperature, electric light, and glare. The survey contained additional questions about potential issues that could be used to supplement the diagnosis. The GSA team engaged the tenant agency's human resources department to obtain the average cost of the employee (average salary and benefits) and number of employees in the building as inputs to the valuation process.

The information collected in Module 1 informed the subsequent modules. After baselining the current building performance, the GSA team completed a questionnaire template with additional building systems and operational information that is used to develop recommendations on how to improve occupant health while balancing energy efficiency in Module 2. Using PNNL's correlations between IEQ and improved productivity, the potential productivity gains were calculated and converted to financial gains based on the cost of employees in the building in Module 3. The net present value of the measures is determined based on the estimated investment costs required to attain those improvements, energy cost/savings, and personnel (health) gains. A 10-year net present value (NPV) with the *FEMP real discount rate* of 3 percent is used to compare the results.

Results

Module 1: Performance Baseline

The PMV and CO_2 trends are shown in Figure 4. These density plots reveal a high-level assessment of how the building compares 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

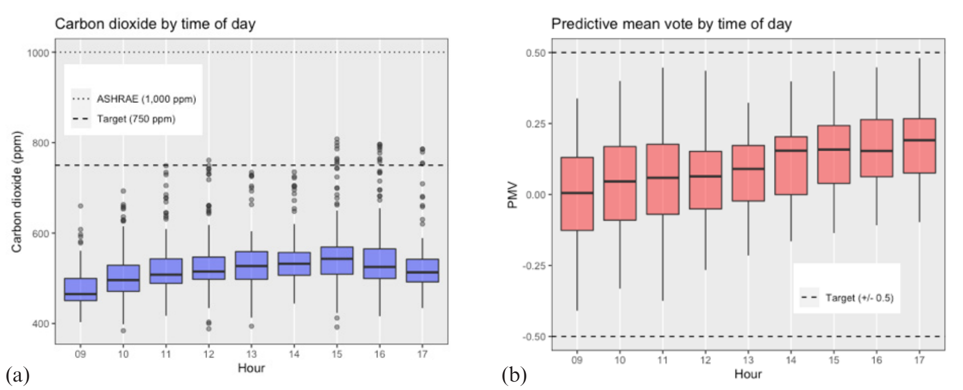

Figure 4. Box and whisker plots for CO_2 on left (a) and PMV on right (b) by time of day.

[2] *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 responses.*

[3] *Circadian stimulus measures the effectiveness of light to promote biological regulation of sleep cycles based on the intensity and color distribution of the light.*

Table 1. Results of occupant survey.

	Odor	Stuffiness	Too Dry	Too Humid	Dust/Allergens
IAQ Complaints	47%	57%	14%	10%	59%
	Too cool	Comfortable	Too warm	NA	
Spring	17%	25%	52%	6%	
Summer	17%	42%	33%	8%	
Autumn	17%	19%	56%	8%	
Winter	37%	14%	45%	4%	
	Very satisfied	Somewhat satisfied	Neither satisfied nor dissatisfied	Somwhat dissatisfied	Very disatisfied
Electric Lighting	31%	24%	14%	18%	12%
Daylighting	4%	6%	16%	14%	59%
	Too dim	Too bright	Glare/contrast	Flickering	Light color
Electric Light Complaints	18%	8%	18%	12%	16%

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* threshold for demand-controlled ven-tilation. The minimum design require-ment for CO_2 shown in Figure 3 is based on the *Minimum Ventilation Rates in Breathing Zones* per ASHRAE Standard 62.1, which is 700 ppm above outdoor concentrations, or approximately 1,000-1,200 ppm indoors. This study aims to set up a near-optimal building performance goal as the target value.

The CO_2 results show that only 1.9 per-cent of values are over the target—all occurring in the afternoon, mostly on Wednesday and Thursday in cubicles and the conference room. Table 1 shows a significant number of indoor air quality complaints from the occupant survey— 47 percent complain of odor, 57 percent of stuffiness, and 59 percent of dust or allergens. IAQ complaints like these sometimes are because of perceived poor air quality, which could be the case since this is an old building. The complaints could also be from isolated or infrequent events.

All the $PM_{2.5}$ and PM_{10} values are sig-nificantly below the target values (0.010 mg/m^3 for $PM_{2.5}$ and 0.020 mg/m^3 for PM_{10}) set in *WELL Building Standard Credit A05 Part 1*.

All the PMV values from the monitored week are in the target range of -0.5 to +0.5. The survey asks respondents to rate their comfort in each season, and the results in Table 1 show that in spring (when the PMV values were collected) 56 percent of occupants are comfortable, 27 percent are too warm, and 18 percent are too cool; this shows some discrep-ancy between the survey results and measured values. There is less thermal comfort satisfaction in summer and winter than the current season.

Horizontal illuminance and CS light-ing spot measurements are shown in Figure 5. The target value for minimum horizontal illuminance in office spaces is 400 lux (40 footcandles) which is estab-lished by the *Illuminating Engineering*

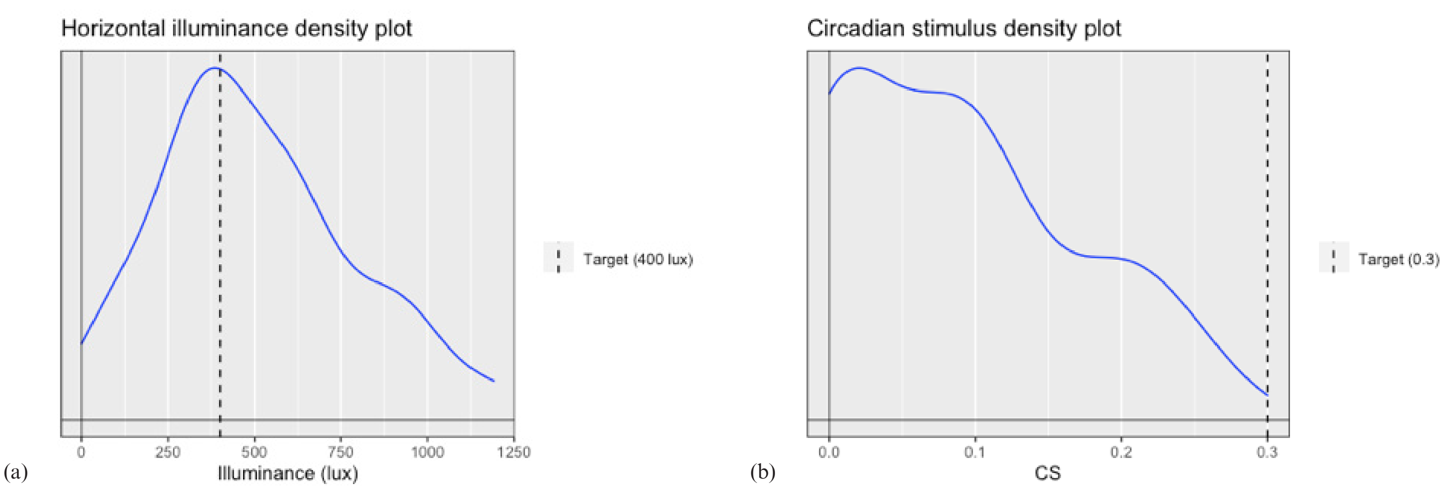

Figure 5. Density plots for horizontal illuminance on left (a) and CS on right (b).

Society Lighting Handbook. There is no established target for too much illuminance, but excessive lighting can cause comfort issues as well. CS is an emerging metric and there is no established target. *The Lighting Research Center* of Rensselaer Polytechnic Institute found that a CS exposure of 0.3 for at least one hour in the morning is effective for entraining circadian rhythms. This value is used as our CS target.

Thirty-eight percent of illuminance values are below target (Figure 5) and some values are very high, over 800 lux. Table 1 shows that 12 percent of occupants are very dissatisfied with electric lighting and 18 percent are somewhat dissatisfied. The team found that the overhead lights in one zone were turned off all the time due to bright light exposure from scanning equipment. This zone was excluded from our analysis. Coping strategies were also observed to reduce the levels of overhead light in two other zones, as can be seen in Figure 6. These zones had the lowest illuminance levels in the building, so the coping could be because of personal preference for lower illuminance levels or because of uncomfortable contrast with the dark-toned partition walls. In Table 1, eight percent of survey respondents complained of electric lights being too bright and 18 percent complained of glare or contrast from electric lights.

All the CS measurements are below the target of 0.3 and 76 percent are significantly below the target (below 0.15). The survey shows 59 percent of occupants are very dissatisfied with daylighting and 14 percent are somewhat dissatisfied, which makes sense given the lack of window access in the building.

Figure 6. Coping strategy for overhead lighting to reduce horizontal illuminance and/or glare.
Image courtesy of PNNL

Module 2: Improvement Opportunities

The following observations and recommendations are made based on the IEQ and survey data collected in Module 1 with some addition diagnostic information collected from the GSA building manager.

PMV – PMV measurements are all within comfort range, although there are high levels of unsatisfaction, especially in summer and winter. We recommend to collect PMV data in summer and winter to see if this could be the cause of the occupant dissatisfaction. Operational setpoint changes would be warranted if this is the case. Is PMV turns out to be good in these seasons, we would recommend personal thermal control devices; however these are not allowed in GSA buildings in this region.

CO_2 – Only 1.9 percent of CO_2 levels are above the target established by WELL of 750 ppm, occurring in the afternoons on Wednesdays and Thursdays, likely due to higher occu-pancy rate. Many complaints are with odor, dust, and allergens. The ventilation rate is designed to ASHRAE 62.1. We recommend checking return air filters to make sure that they are not clogged, which can cause low CO_2 levels because of increase in fan auto-speed and air quality issues with dust and allergens. If the return air filters are well maintained, consider a ventilation rate or fan speed schedule according to the pattern in CO_2 levels to improve pro-ductivity and energy efficiency. Collect data in all spaces to ensure the pattern is consistent across spaces in each air handler unit zone and across longer durations of time. Reduce ventilation when CO_2 is typically low to save energy and increase ventilation when CO_2 is typically above 750 ppm. Continue to monitor room CO_2 to ensure levels are not exceeding the target.

PM – PM values are well below threshold, but there are many complaints of dust and allergens. We recommend checking return air filters to make sure they are not clogged, which can cause issues with dust and allergens.
See the CO_2 recommendation for more information.

CS – There is high dissatisfaction with daylighting from the survey and lack of window accessibility. CS values are significantly below the target. The high cubicle partitions block overhead light and the dark colors of partitions absorb light. We recommend to reduce partition height between desks or incorporate frosted glazing panels into partitions to allow for more light penetration. Educate occupants on the benefits of light exposure on productivity and comfort, and then allow them to opt out of changing partitions if they still prefer a darker working environment. We suggest choosing partitions with light-toned surface colors or reflective interior finishes to reduce contrast.

Horizontal Illuminance – 30 percent of occupants are unsatisfied with electric lighting and 38 percent of the horizon-tal illuminance measurements are below the target. Task lighting is provided to occupants. The cubicle layout does not align with overhead lighting; some cubicles are underlit and others are overlit as a result. The dark colors of partitions create contrast when there is bright overhead light. We recommend lowering partition height or incorporating frosted glazing panels to create a more even horizontal lighting environment and to choose light-toned partition surface colors to reduce contrast. See CS recommendation for more details. We suggest to dim the overhead light in regions where this upgrade creates too much illuminance (more than 500 or 600 lux).

Table 2 synthesizes these observations and recommendations. The recommendations in Table 2 are independent of the financial calculations in Module 3, but are recommended strategies to improve IEQ values to the target values needed to achieve the potential financial gains (Table 3).

Module 3: Productivity Financial Gains

Table 3 summarizes results from the NPV calculations for potential improvements to IAQ, thermal comfort, lighting, and their combined values. The calculation considers the percent of time the occupants spend in private offices, cubicles, and conference rooms (obtained from the survey) and weighs the values mea-sured in those spaces accordingly when multiplying the productivity gain by the average cost of employee.

Also included are the non-monetary benefits of improving IEQ. These include reduction in influenza virus transmission rate from improving humidity and improvement to sleep efficiency[4] and sleep latency[5] from increasing CS. More CS exposure at work has been shown to improve sleep quality, especially in winter when it is more difficult to get access to sunlight outside working hours.[6] For the building in this study, we can expect an average 3.9 percent improvement to sleep efficiency and a 24.7 percent improvement to sleep latency for occupants by increasing to the 0.3 CS target from the current levels. This means that an occupant who spends eight hours in bed each night and takes 20 minutes to

Table 2. Summary of recommendations based on IEQ data and survey results.

IEQ Measurement	Observations	Recommendations
PMV	• PMV is within comfort range • High levels of unsatisfaction	• Collect PMV data in summer and winter
CO_2	• Some high CO_2 on Wednesday and Thursday afternoons • Many complaints of odor, dust, and allergens	• Check return air filters • Consider ventilation schedule
PM	• PM levels well below threshold • Many complaints of dust and allergens	• Check return air filters
CS	• High dissatisfaction and lack of window access • CS significantly below target • High cubicle partitions with dark colors block overhead light	• Reduce partition height or incorporate translucent panels and choose partitions with light-toned surface colors or reflective interior finishes
Horizontal Illuminance	• Some dissatisfaction • Some measurements below the target and some much higher • Cubicle layout makes some too bright and others too dim	• Reduce partition height or incorporate translucent panels and choose partitions with light-toned surface colors or reflective interior finishes • Re-calibrate overhead light levels to achieve 400 to 600 lux

4 Sleep efficiency is the percent of time in bed asleep out of total time in bed throughout the night.
5 Sleep latency is the time taken to fall asleep after lying down in bed.
6 https://www.gsa.gov/governmentwide-initiatives/federal-highperformance-buildings/resource-library/health/circadian-light-for-your-health.
7 https://www.cdc.gov/flu/about/keyfacts.htm

Table 3. Financial gains from improving productivity in 10-year net present value.

	Percent Worse Than Target	Expected Productivity Improvement	Expected 10-yr NPV Gains	Non-Monetary Gains
Indoor Air Quality (CO_2)	1.9%	<0.1%	<$1k	
Thermal Comfort (PMV)	0.0%	0.0%	$0	7.1% flu virus trans. reduction
Lighting (Horizontal Illuminance)	38.0%	0.6%	$965k	3.9% sleep eff. increase; 24.7% sleep latency red.
Combined		0.6%	$966k[a]	All the above

[a]Note: there are uncertainties associated with the predicted productivity gains. The 95 percent prediction interval for this building is from $508k to $1,353k if uncertainties are considered. The values presented in the table are the most probable outcomes.

fall asleep would fall asleep five minutes earlier and avoid 19 minutes of disrupted sleep throughout the night. The flu transmission could be decreased by 7.1 percent. On average, 8 percent of people contract the flu each year[7], which means that a building with 200 occupants could reduce 16 typical yearly cases to 14.9 cases (on average).

The CO_2 and PMV levels are good and therefore yield small financial gains. Lighting represents virtually all the gains and should be the focus of IEQ improvements. This analysis does not include the needed capital investment and the energy cost/savings associated with the recommendations.

Key Takeaways

The Healthy Buildings Toolkit framework applied in this case study gives an estimate for the potential monetary gains from improving IEQ. The Healthy Buildings Toolkit is intended to incorporate healthy building evaluations with an energy efficiency analysis. The recommendation does not predict if a specific measure (operational or retrofit) will result in meeting the target IEQ performance; therefore, the IEQ parameters should be monitored and re-evaluated (using Module 1) after the intervention to verify that actions lead to the desired results. Results should be continuously monitored thereafter to ensure positive results are maintained. The Toolkit leverages existing literature in healthy buildings and provides a robust, tailored analysis for individual buildings at a low cost. There is some uncertainty associated with predicted personnel gains due to the complexity of human physiology, behaviors, and the limited quantitative studies in some areas. It is expected that as more buildings track IEQ data and personnel gains in a standardized and structured framework like what the Healthy Buildings Toolkit offers, the cause and effect relationships between IEQ parameters and the corresponding human outcomes will become clearer and more accurate prediction models can be developed in the future. ■

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