Indoor Environmental Quality Performance of a Double LEED™ Platinum Commercial Office Building Pre- and Post-Retrofit

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ABSTRACT

A late 1960's commercial office building was transformed into a state-of-the-art double platinum-rated LEED™ (USGBC LEED v3 Core and Shell and Commercial Interiors) corporate headquarters over an extensive 18 month renovation period. The traditional floor plan with perimeter offices and central workstations was reconfigured into an open concept office space with central workstations, perimeter hallways and collaborative space. The existing building was stripped down to the steel and concrete structure and enclosed in a high performance building envelope and glass façade. The interior open-plan office space was designed to maximize occupant comfort, as well as improve the health and well-being of the employees.

The paper will describe the extensive improvements to the building envelope, interior space and mechanical systems. Results of a systematic indoor environmental quality (multi-comfort) assessment for several open-plan zoneswas conducted pre- and post-retrofit, using continuous and intermittent measurements to quantify indoor thermal, visual and acoustical comfort, as well as air quality will be presented. Thermal and visual comfort characteristics were measured and visually illustrated through graphical and photographic techniques. Acoustical measurements were conducted to visualize speech privacy in the open-plan space between workstations. Design strategies employed to improve indoor environmental quality will be highlighted and connected to the results of the assessment, as well as correlated with the occupant's surveyed experience.

INTRODUCTION

Employers, building owners, designers, developers, and investors throughout the world are persuaded, in response to an increasing marketing campaign by the building industry, that office design affects the health and well-being of occupants in many ways (Elzeyadi, 2017). With staff accounting for 90% of business operating costs, a 1% improvement in productivity can have a major impact on the bottom line and competitiveness of any business (Kats, 2003). Building developers, owners, and investors are also discovering the business value of delivering healthy and green buildings to their markets. For example in a 2016 survey of Canadian building owners, 38% of respondents that reported increased property value said that healthy buildings were worth at least 7% more than normal buildings, 46% said the buildings were easier to lease, and 28% said green buildings commanded premium rents (WGBC, 2016).

A longitudinal, indoor environmental quality (IEQ) investigation of a double platinum-rated LEED™ open concept office building (USGBC LEED v3 Core and Shell and Commercial Interiors) was performed after an extensive 18 month renovation. A comprehensive Pre-Post Occupancy Evaluation protocol (PPOE) was employed to assess and analyze multi-comfort parameters and metrics of the thermal, visual, acoustical and air quality environment over a one year period, both before and after occupancy (Elzeyadi and Gatland 2017). The interactional impact of

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better visual and acoustic comfort on the health and well-being of occupants for the same building was reported by Elzeyadi, Gatland and Abboushi (2017).

BUILDING DESIGN

An abandoned 1960s-era corporate site was transformed into a double LEED Platinum (USGBC LEED v3 Core and Shell and Commercial Interiors) building over an extensive 18 month renovation. The building complex consisted of two buildings connected by a multistory hallway at the center. The building core and shell was stripped down to the steel and concrete structure and enclosed with a high performance building envelope and glass façade. The two buildings were connected by a common space that includes a secure main entrance lobby with stairwells, individual floor lobbies, a training room and a café, see Figure 1. The interior open concept office space was designed to maximize occupant comfort, as well as improve the health and well-being of the employees.

The four-story 276,998 ft^2 (25,734 m^2) headquarters is located on 2,831,404 ft^2 (263,046 m^2) mature landscaped site, 25 miles (40 km) west of Philadelphia in Malvern, Pennsylvania. The corporate site includes 193,750 ft^2 (18,000 m^2) of open-plan office area, 116 collaborative spaces, a cafeteria, pantry areas, a fitness center, a pond, outdoor workspaces by a rainwater fountain and 1.3 miles (2.1 km) of walking trails to further enhance the employee experience.

The state-of-the-art facility was designed to promote cross-collaboration, as well as attract and retain talent. Furniture layout and the provision of flexible working spaces around the perimeter without workstations and opaque partitions create sweeping views of nature that provide an abundance of natural light with views possible from 92 percent of the interior space. Continuous fresh air ventilation and no- or low emitting materials were employed to create excellent indoor air quality. Acoustic comfort at the 800 plus workstations was created through the thoughtful placement of sound absorbing surfaces, noise reducing interior partitions and an active sound masking system.

Figure 1 The building complex before (right) and after retrofit (left).

Glass Façade System

The renovated all-glass building employs two high-performance glass facade systems consisting of a double-glazed argon gas-filled system and a dynamic electrochromic glazing system. The latter was installed on the entire west-facing façade, the south-facing façade of the building's south wing, and the north-west corner. On the other building wing, a high-performance double-glazed argon gas filled system was installed on the north- and east-facing facades as well as the south-facing façade of the building. In addition, manually controlled microperforation roller shades were installed on the north-, east- and south-facing façade interiors.

Daylight glare is dynamically controlled with an electrochromic glazing system and the manually adjusted, gray micro-perforated sun shade system with a visible light transmission of 0.07%. The majority of the vertical surfaces in the new building have high light reflectance values of 70% and above. Additional space lighting was created using a slim profile LED luminaire with a sharp cut-off angle integrated into the suspended acoustical ceiling.

The original building's curtain wall consisted of a double-glazed air filled system having structural glass panes and a thermally unbroken aluminum frame. A typical floor plan comprised of perimeter offices and centrally located cubicle workstations. The offices were separated from the workstation areas by interior partitions. A dark window film was adhered to the glass surface on the south and west facing orientations of the building. The glazing system thermal performance properties for the original and retrofitted buildings are listed in Table 1.

Table 1. Glazing System Thermal Performance Properties

Façade Type	Level of Tint	Visible Light Transmission Tvis (%)	Solar Heat Gain Coefficient SHGC (%)	Thermal Transmittance U-Factor (Btu/h ft^2 °F) U-Factor [W/m^2 °C]
Original Building	Clear	---	0.37	0.647 [3.674]
Original Building	Film	---	0.02	0.647 [3.674]
Dynamic Electrochromic	Clear	60	0.41	0.280 [1.590]
Dynamic Electrochromic	Intermediate 1	18	0.15	0.280 [1.590]
Dynamic Electrochromic	Intermediate 2	6	0.10	0.280 [1.590]
Dynamic Electrochromic	Fully tinted	1	0.09	0.280 [1.590]
High Thermal Performance	Clear	28	0.32	0.230 [1.306]

Commercial Roofing System

The original building complex was comprised of two buildings connected by a multi-floor hallway. Building's A and B had a 4 inch (102 mm) thick concrete slab and corrugated steel panel roof deck, respectively. The existing low-slope commercial roofing systems were removed and replaced with a new self-adhered styrene-butadiene-styrene (SBS) modified bitumen roof system (Figure 2). The surface was covered with a white, torch grade, solar reflective granule surface APP-modified cap membrane. The concrete slab roof deck was insulated with two layers of 2 in. (51 mm) polyisocyanurate foam board (R23/RSI4.05). The corrugated steel panel roof deck over the new common space and Building B was insulated with three layers of 2 in. (51 mm) polyisocyanurate foam board (R36/RSI6.34).

Above-Grade Walls and Foundation

The original Building A façade was a combination of glass curtain wall and spandrel panels with an exterior steel structure designed to weather and blend into the surrounding environment. Perimeter stairwell and utility space wall sections were finished with a brick façade. Building B had a more typical 1970's glass curtain wall and spandrel panel building envelope system, see Figure 3. The above-grade wall systems were comprised of 3.5 inch (89 mm) steel studs

spaced 16 in. (406 mm) on center. Both stud cavities and spandrel panels were filled with 3.5 in. (89 mm) fiberglass insulation batts (R11/RSI1.94). The structural concrete foundation walls and slabs were not insulated.

Figure 2 Low-slope commercial roofing system installation.

Figure 3 Original building satellite view (left), exterior steel structure glass curtainwall (center), typical glass curtain wall and spandrel panels (right)

Existing above-grade brick walls were coated with a liquid applied water resistive barrier system and finished with an insulated metal panel wall system. Insulation consisted of 2 in. (51 mm) rigid mineral fiber board (R10/RSI1.76). In addition, the 2 in. (51 mm) mineral board (R10/RSI1.76) insulated metal wall panel systems were attached to a metal framed wall system through ⅝ in. (16 mm) exterior gypsum sheathing using 2 inch (51 mm) metal Z clips spaced 16 in. (406 mm) on center vertically and 24 in. (610 mm) on center horizontally. The exterior gypsum sheathing was coated with a liquid applied water resistive barrier and fastened to a 6 in. (153 mm) steel frame with studs spaced 16 in. (406 mm) on center. The stud cavity was filled with 6 in. (153 mm) fiberglass batt insulation (R19/RSI3.35) and the interior frame was finished with ⅝ in. (16 mm) Type X gypsum board. Glass spandrel panels were insulated in a similar way, see Figure 4.

Figure 4 Retrofitted building above-grade wall and glass spandrel panels.

The new below-grade foundation walls and slab edges were covered with a 1/16 in. (1.5 mm) flexible, pre-formed waterproofing membrane which combines a high performance, cross laminated, HDPE carrier film with a super tacky, self-adhesive rubberized asphalt compound. The surface was finished with a 2 in. (51 mm) rigid, extruded polystyrene foam insulation board (R10/RSI1.76). The building envelope thermal performance properties for the original and retrofitted buildings are listed in Table 2.

Table 2. Building Envelope Thermal Performance Properties

Building Type	Building Envelope	Thermal Transmittance U-Factor (Btu/h ft^2 °F) U-Factor [W/m^2 °C]
Original	Roof	0.048 [0.273]
Original	Above-Grade Brick Wall	0.101 [0.574]
Original	Above-Grade Spandrel Wall	0.101 [0.574]
Original	Foundation	0.119 [0.676]
Retrofit	Roof	0.031 [0.176]
Retrofit	Above-Grade Brick Wall	0.062 [0.352]
Retrofit	Above-Grade Spandrel Wall	0.074 [0.420]
Retrofit	Foundation	0.064 [0.363]

HVAC System

The core and shell was comprised of new HVAC piping, ductwork, 54 water source heat pumps, a cooling tower, a packaged roof top unit and ventilation fans to serve new common areas such as lobbies, stair towers and restrooms. The fit-out was comprised of more than 300 additional water source heat pumps for the various open plan office spaces, conference rooms, a fitness center, and a cafeteria. Hot water generated by an existing boiler located in the power house and chilled water generated by the new roof top cooling tower combined with a heat exchanger supply's the various water source heat pumps with conditioned water. Eight existing dedicated outdoor air units located at the perimeter of the building provide approximately 10 percent pre-conditioned air to the distribution system on a continuous basis.

INDOOR ENVIRONMENTAL QUALITY AND MULTI-COMFORT ANALYSIS

Multi-comfort parameters and metrics of the indoor environment were assessed and analyzed at the Malvern corporate headquarters for thermal, visual, and acoustical comfort, as well as air quality pre- and post-building retrofit. Both instantaneous and long-term field measurement data of the physical environment and multi-comfort parameters were collected at the level of the building as well as the scale of the occupant's work setting. Environmental sensors and data loggers measuring light levels, temperature, relative humidity, air velocity, and air movement at sampled workstations stratified across the different floor levels of the buildings were deployed over the winter, spring, and summer seasons, respectively. In addition, infrared (IR) and high dynamic range images (HDRI) were taken over the course of sampled seasonal days for the occupant's workstations and from their direct view-sheds employing wide angle and fisheye lenses to simulate the occupant's perspectives and fields of vision. The different imaging techniques were employed to document surface temperature, mean radiant temperature, and glare indices over the study period. In addition, acoustic attenuation, sound levels and speech intelligibility measurements were recorded for typical office simulated conditions in the field at different times after the retrofit. Prior to occupancy and one year post-move the indoor air was evaluated for thermal comfort and quality through on-site measurements and sampling.

An occupant space performance evaluation questionnaire (SPEQ™) survey was administered to the entire employee population before and one year after the move into the retrofitted high performance, LEED™ certified office building. Response to the survey was very high with 289 employees completing the questionnaire before the move and 320 completing after the move. Data tabulation and coding were performed on both the physical and human-response data sets. Physical measurements and survey responses were spatially tagged and statistically analyzed using SPSS software. In addition, data visualizations and multi-comfort parameters were computed using a suite of software that spatially analyzed the occupant's visual, thermal, as well as other indoor environmental quality outcome metrics across various locations of the building.

Thermal Comfort Assessment

Thermal comfort metrics were calculated using the measured data and equations described in ANSI/ASHRAE Standard 55 (2013). Thermal comfort was visualized for sampled locations using a Thermal Comfort Plot on a psychrometric chart for both the pre- and post-building retrofit conditions, while acknowledging the occupant's presumed metabolic rate (met) and clothing level (clo).

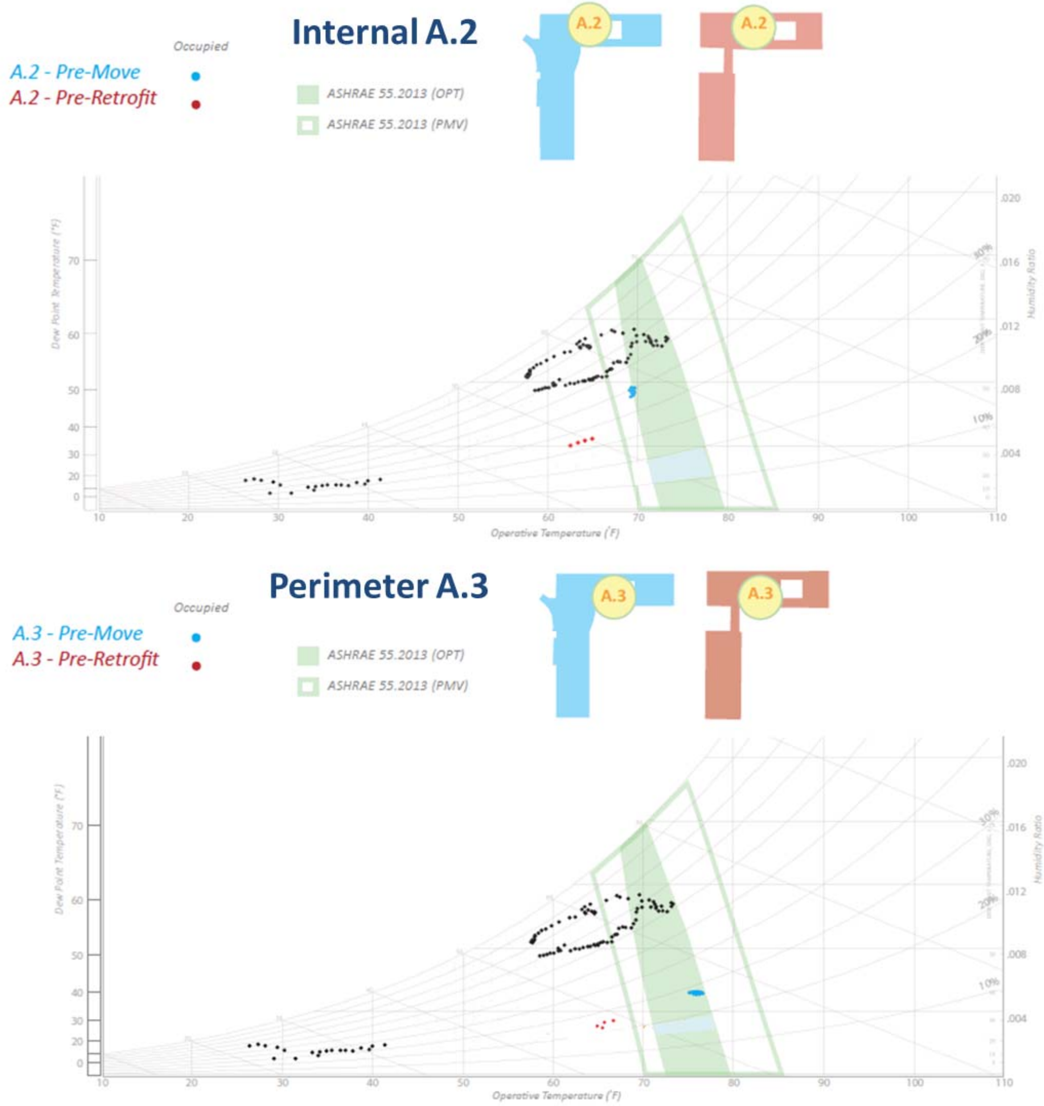

Figure 5 Comparative analysis of thermal comfort psychrometric charts during spring season for internal (top) and perimeter (bottom) floor areas (blue pre-move/post-retrofit, red pre-retrofit and black outdoor).

Figure 5 provides a comparative plot of occupied hours for a typical workstation in the spring season for both phases of the building. Each dot in the psychrometric chart represents the thermal averaged conditions for one occupied hour during a typical equinox work day. Thermal conditions pre-retrofit were completely outside the comfort zone for both workstation locations (red dots). In contrast, most of the thermal conditions after pre-move/post-retrofit (blue dots) fit nicely within the thermal comfort zones yet provide enough variation to avoid falling in thermal boredom conditions and still reflect diversity in thermal conditions suitable for occupant's different clothing and metabolic levels within the space at different times of the day.

Visual Comfort Assessment

Lighting distribution metrics, spatial daylight autonomy (sDA300-50%), visual asymmetry, and glare in the field of vision were measured to evaluate visual comfort inside multiple work environments. A comparative analysis pre- and post-building retrofit reveals how different spatial configurations, glazing properties and natural light reflectance value (LRV) proportions impact both daylight distribution and glare. The retrofitted building showed a 64 and 28 percent improvement in daylight distribution at the internal and perimeter workstation areas, respectively, due to the optimization of the glazing system's solar properties (Tvis and SHGC), as well as higher light reflectance values (LRV) of interior surface finishes. In addition, furniture layout and the provision of flexible working spaces around the perimeter without cubicles and partitions showed substantial impacts on daylighting performance and glare management of the retrofitted space (Figure 6). The renovated building provided better daylighting distribution over the pre-retrofit condition for both the representative internal and perimeter workspaces. Useful daylight illuminance (UDI) was considered in the range between 100 and 1000 lux.

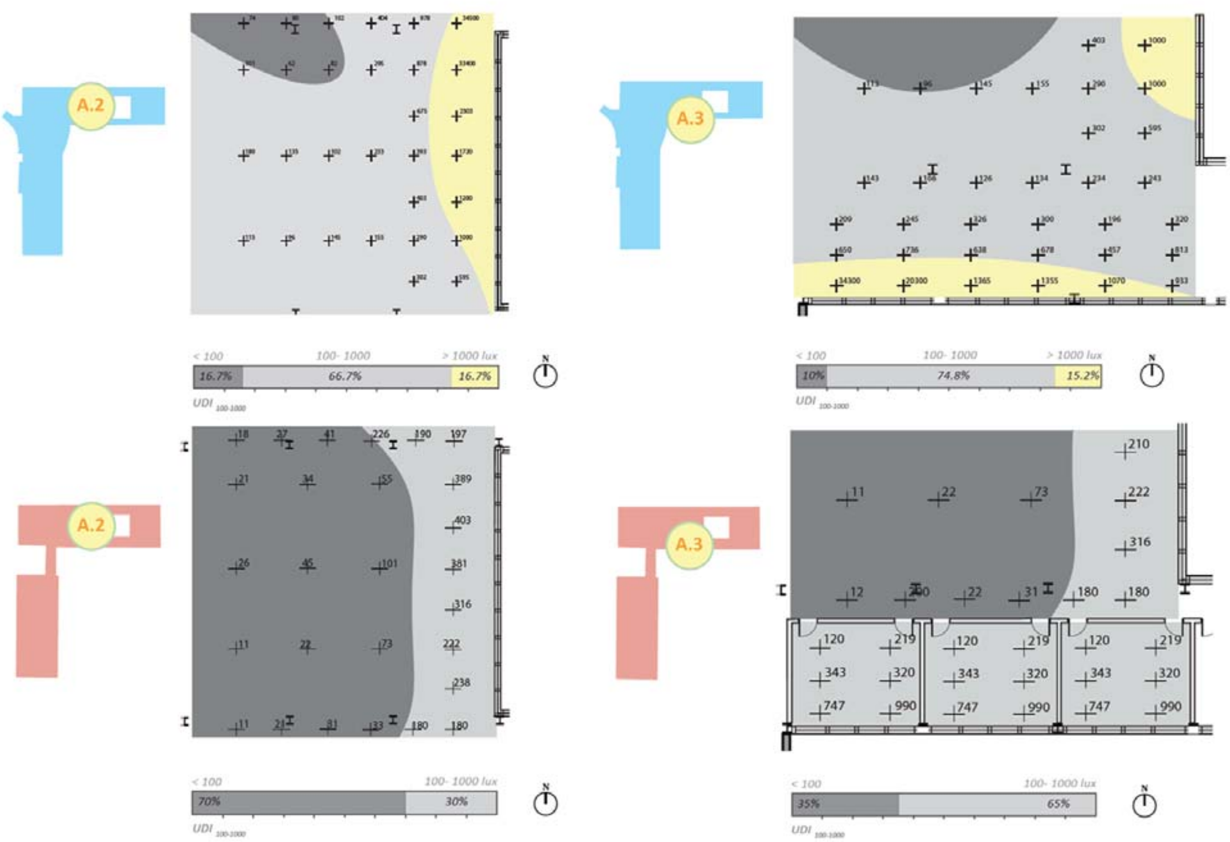

Figure 6 Comparative analysis of visual comfort metrics for internal (left) and perimeter (right) floor areas of the building (pre-move/post-retrofit, top and pre-retrofit, bottom).

A comparative analysis of glare metrics is visually illustrated in Figure 7. The majority of the pre-move/post-retrofit workstation composite luminance map scenes were in the medium luminance range (between 20-1000 cd/m^2) having percentages of 75 and 51 for the internal (A.2) and perimeter (A.3) areas, respectively. While the majority of the pre-retrofit scenes were in the low luminance range at 86% and 52% for the internal (A.2) and perimeter (A.3) areas, respectively (Figure 7).

Figure 7 Comparative analysis of visual glare metrics for an internal (A.2) and perimeter (A.3) workstation of the pre-move/post-retrofit building (left) and the pre-retrofit building (right).

Spatial Daylight Autonomy (sDA) represents the percentage of floor area receiving sufficient daylight. Sufficient daylight constitutes a minimum of 300 lux for at least 50 percent of the annual occupied hours. Average Daylight Factor is the ratio of internal light level to external light level. Useful daylight is considered when the average daylight factor is between 2 and 10 percent.

Daylight Glare Probability (DGP) considers contrast ratios created by direct daylight and specular reflections between glare sources and predicts the probability that a person is disturbed by glare. Below 0.30 is considered barely perceptible and above 0.45 is considered intolerable. The luminance ratio is the luminance relationship between the working area and the normal field of view. The comfort range for luminance ratio is defined as 7 times the background luminance. The percent outside comfort is the percent of the visual scene that is above the contrast threshold of 7x the background luminance. Figure 8 compares visual comfort metrics between the building phases.

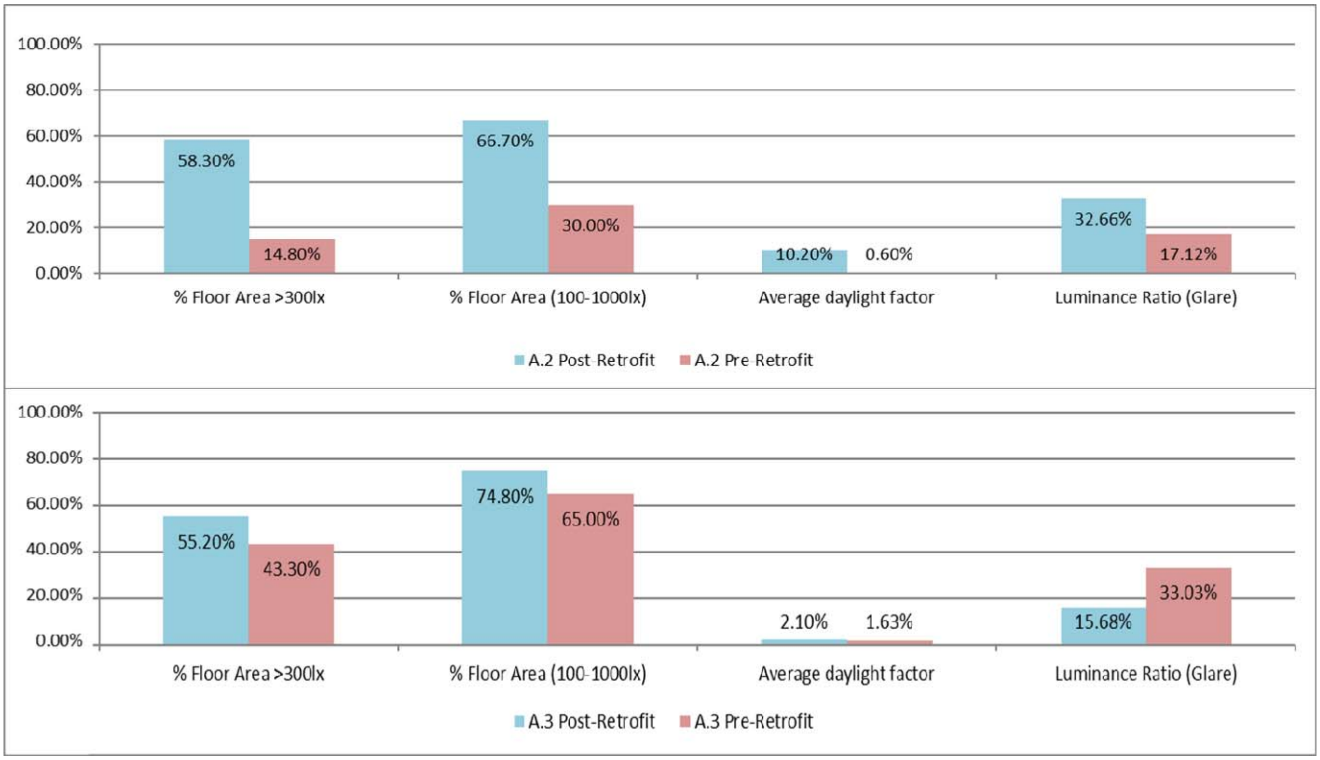

Figure 8 Comparative analysis of visual comfort metrics for internal (top) and south perimeter (bottom) workstation areas of the pre-move/post-retrofit and pre-retrofit building.

The pre-move/post-retrofit building provided better daylighting distribution (sDA = 58.3%, DF = 10.2%, DGP = 1%) over the pre-retrofit building (sDA = 14.8%, DF = 0.6%, DGP = 1%) for a representative internal workspace. The pre-move/post-retrofit building provided better daylighting distribution (sDA = 55.2%, DF = 2.1%, DGP = 13%) over the pre-retrofit building space (sDA = 43.3%, DF = 1.6% and DGP = 1%) for a representative perimeter workspace.

Acoustic Comfort Assessment

The challenge of acoustic design in open concept office spaces is to limit sound reflections and noise levels in large spaces, while creating acoustical privacy at individual workstations. Acoustic comfort can be achieved through the use of sound absorbing surfaces, high performance noise reducing interior partitions and exterior facades, as well as sound masking systems. Managing speech intelligibility between workstations is the goal, so that employees are not distracted by their colleagues' conversations. Speech intelligibility is affected by space absorption, room geometry, distance, speech level, and background noise level, see Figure 9.

Sound masking systems generate white noise to increase the background noise level. The recommended noise criteria (NC) curve limit for open plan office spaces (ASA S12.2 2008) with forced air distribution systems is NC-40 or less. Noise criteria are single numbers used to define goals for maximum allowable noise in a given space. The equivalent average sound pressure level range for NC-40 is 46 dB_A to 48 dB_A.

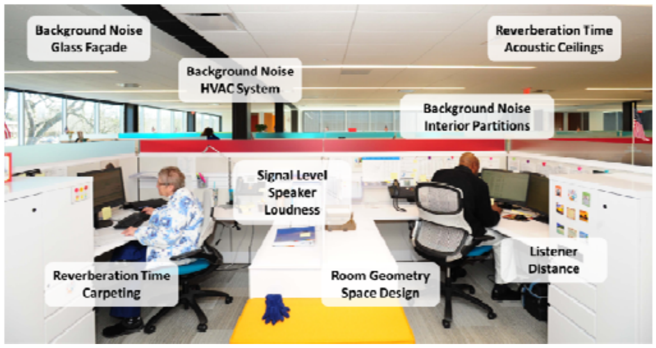

Figure 9 Factors that affect speech intelligibility.

Open-plan office spaces can be evaluated for spatial decay and distraction distance using ISO 3382-3 (2012). Speech transmission index (STI) is a physical quantity representing the transmission quality of speech with respect to intelligibility. Workstations in the LEED™ retrofitted building were evaluated for spatial sound distribution of the speech transmission index to assess the distraction distance from the speaker where the speech transmission index falls below 0.50. The goal is to have STI values drop below 0.50 between 6 and 12 feet (1.8 and 3.7 m).

Acoustic comfort mapping for spatial decay and distraction distance with STI is illustrated in Figure 10 for an internal and perimeter workstation. Concentric semicircles were placed at 6 foot (~2 m) intervals from the simulated speaker in a sitting position. Semicircles highlighted in green, yellow and red indicate distances at which the STI value was less than 0.50, between 0.50 and 0.60, or greater than 0.60, respectively. In general, results indicate that the desired distraction distance was achieved within 6 to 12 feet (1.8 to 3.7 m) from the speaker.

Figure 10 Acoustic comfort mapping with STI in north wing of LEED™ office building.

Air Quality Assessment

Continuous filtered and conditioned outdoor air ventilation, pollutant source control, formaldehyde scavenging materials, building envelope moisture flow management and air leakage control strategies were employed to meet the requirements of ASHRAE Standard 62.1 (2016). The indoor air was evaluated for thermal comfort and quality through on-site measurements and sampling based on recommendations by the United States Environmental

Protection Agency (EPA 1991). Conditions were evaluated at two locations per floor (north and south wing) pre-move/post-retrofit and one year later.

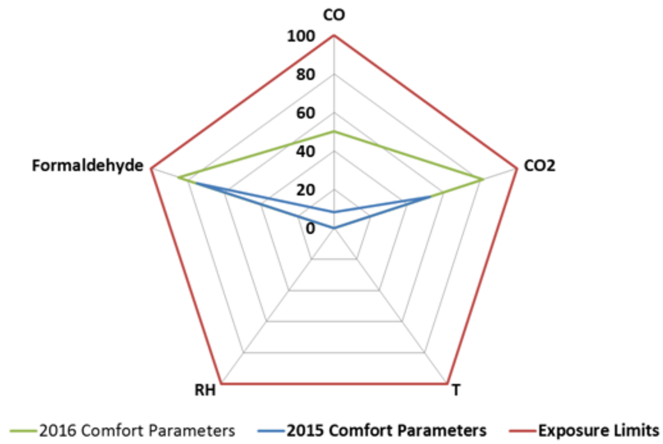

Figure 11 Comfort parameters to exposure limits of LEED™ office building.

A portable air monitor simultaneously measured the air temperature, relative humidity, carbon monoxide and carbon dioxide concentrations using a thermistor, thin-film capacitive, electro-chemical and non-dispersive infrared sensor, respectively. Also, formaldehyde gas concentration was evaluated in conformance with EPA Method TO-11 (EPA 1999). Approximately 15 liters of air was sampled using collection pumps with flow rates operating at 0.125 l/min. The samples were transported to an accredited laboratory for extraction and analysis using high performance liquid chromatography (HPLC).

Results of the 1 year post-move/post-retrofit indoor air quality evaluation compared with the pre-move/post-retrofit results are graphically displayed in Figure 11. Values were normalized to comfort range and exposure limits for each parameter and scaled to 100 percent. Indoor environmental conditions for comfort and gas concentrations were within the thermal comfort range and below exposure limits for each category, respectively. The acceptable thermal comfort range as recommended by ASHRAE Standard 55 (ASHRAE 2013) for air temperature and relative humidity were 74°F to 79°F (23.3°C to 26.1°C) for cooling conditions, 69°F to 74°F (20.6°C to 23.3°C) for heating conditions, and 30 to 60 percent relative humidity, respectively. The graphed air temperature (T) and relative humidity (RH) comfort parameter of zero means that the measured values were within the acceptable range. The selected gas concentration exposure limits for carbon monoxide (CO), carbon dioxide (CO2) and formaldehyde of 1 ppm, 1000 ppm and 0.027 ppm, respectively were at or below recommended levels for US EPA (2010), ASHRAE (2016) and LEED Version 4 (2017).

Indoor Environmental Quality - Occupants Perspective Analysis

In addition to the multi-comfort assessment of the different indoor environments, an occupant questionnaire (SPEQ™) was administered to capture the employee's perceptions of satisfaction, productivity, health and well-being for the previously occupied corporate headquarters in Valley Forge, Pennsylvania and the high performance, LEED platinum certified retrofitted building in Malvern, Pennsylvania. A large sample of employees completed the questionnaire with an average of 36% of the employees in the traditional building and 40% of the employees in the high performance building completed the questionnaire. Employees' multi-comfort perception of visual and acoustic comfort, as well as air quality of the LEED™ certified building in Malvern (MR) was much higher than in the traditional cellular office building in Valley Forge (VF), as illustrated in Figure 12.

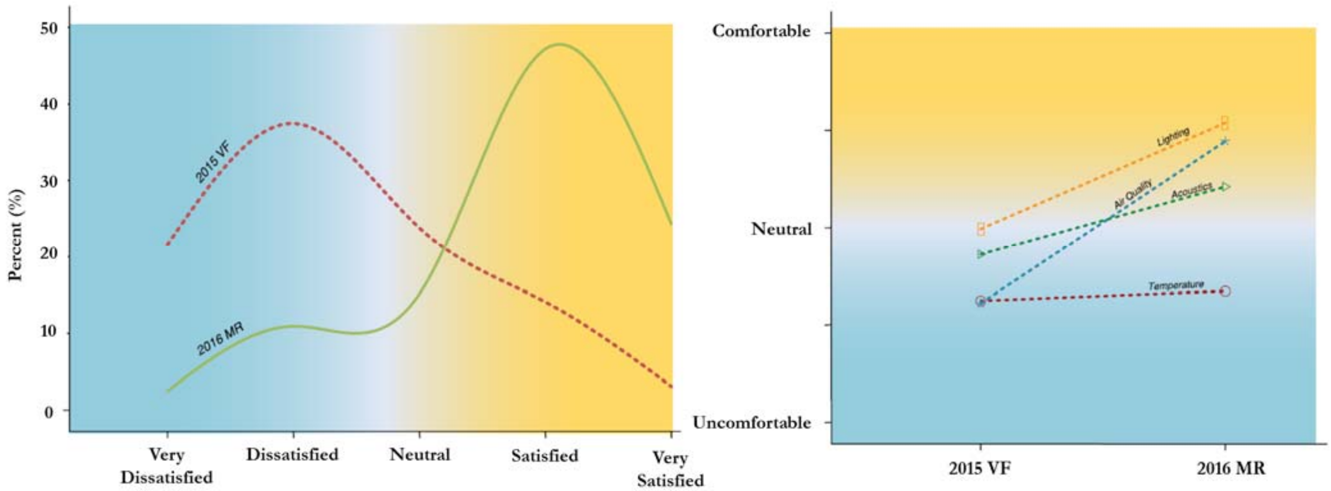

Figure 12 Correlation of physical environment with occupant satisfaction (left) and multi-comfort parameters.

CONCLUSION

A double LEED Platinum (USGBC LEED v3 Core and Shell and Commercial Interiors) certified building was achieved by combining a high performance building envelope with thermally improved traditional and dynamic glass facades. Furniture layout and the provision of flexible working spaces around the perimeter without workstations and opaque partitions created sweeping views of nature that provide an abundance of natural light with views possible from 92 percent of the interior space. Continuous fresh air ventilation and the use of no- or low emitting materials created excellent indoor air quality. Acoustic comfort was achieved at the 800 plus workstations through the thoughtful placement of sound absorbing surfaces, noise reducing interior partitions and an active sound masking system.

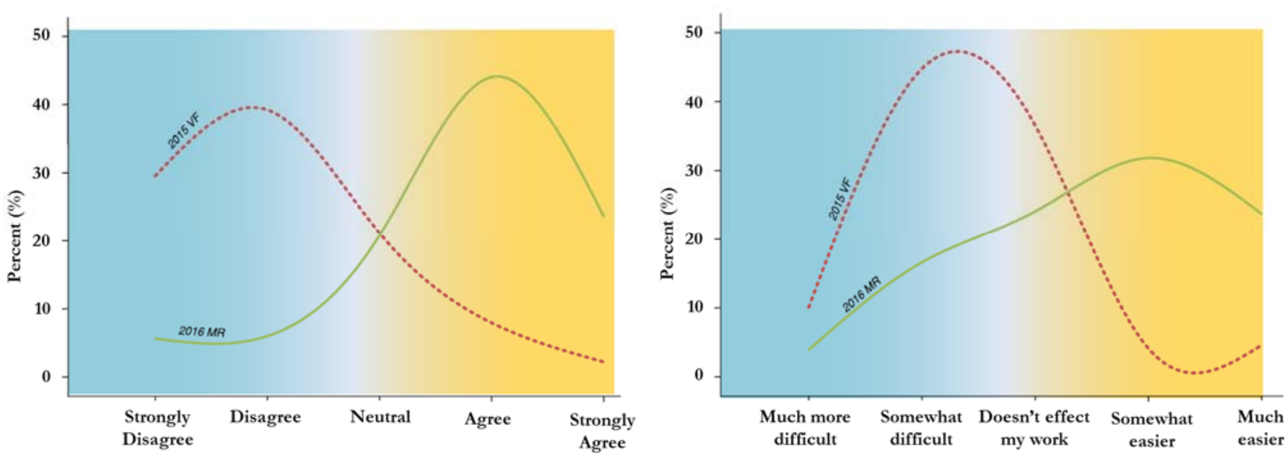

Figure 13 Correlation of building impact on worker health and well-being (left), and worker productivity (right).

Results show strong correlations between improved visual, acoustic, and indoor air qualities of the retrofitted, high performance LEED™ certified building environment and increased employee satisfaction and improved employee productivity. A comparative analysis of the occupants' attitudes and perceptions of the impact of the building on their productivity reveal a shift in attitude as to the impact of the building design on their work performance and well-being (Figure 13). Proving that, for high performance buildings both the occupants and the buildings require on-going dialogue to ensure the occupants are able to manage the building to achieve its desired levels of performance.

One of the objectives of this paper is to provide detailed as well as context-specific information to assess IEQ inside high performance, green buildings from a comprehensive approach. By establishing a comparative approach between a traditional building pre-retrofit and its green retrofitted LEED™ certified platinum phase, the study provides an evidence-based case study of green building design strategies that impact IEQ parameters.

ACKNOWLEDGMENTS

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