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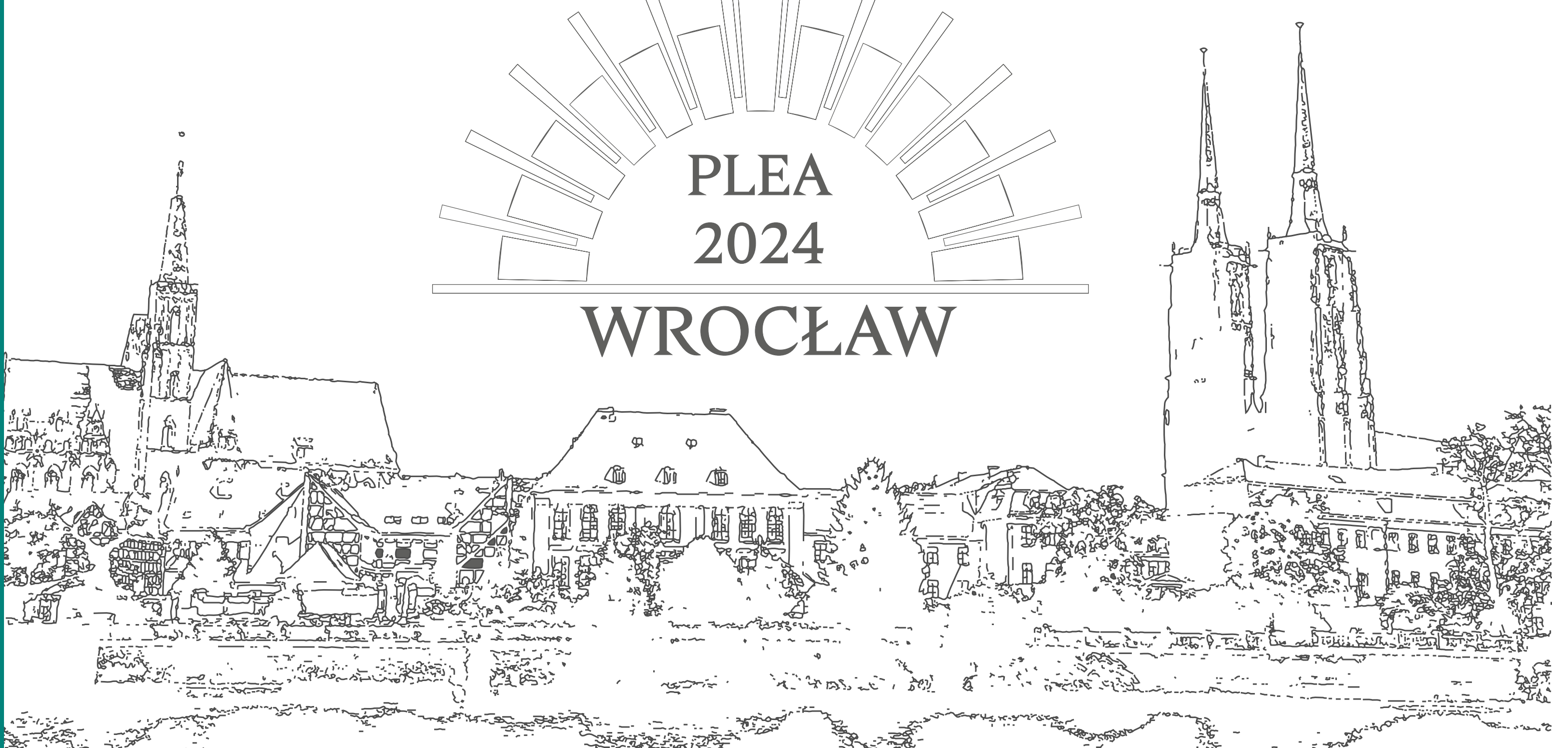

# Optimizing Daylighting:
## Exploring Visual and Non-Visual Effects through Weather, Orientation, and Location

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*ABSTRACT: This paper presents a comprehensive analysis of daylight performance in a standard office across twelve different locations. The assessment covers both the visual and non-visual impacts of daylight, taking into account aspects such as vision, glare, view quality, and circadian rhythms. Evaluation criteria are based on the prerequisites for daylight and view credits outlined in LEED v.4 [1], in conjunction with the WELL 2.0 Building Standard [2] for daylighting evaluations. The assessed space is outfitted with sidelight windows, representing a typical section of an office within a multi-story building. The study's findings shed light on how daylight performance is influenced by geographical location, prevailing weather conditions, window dimensions, shading devices, glass transmittance, and floor plate depth. Notably, the study demonstrates the feasibility of designing spaces that meet the daylight and view credit criteria of LEED v.4 while complying with the circadian lighting requirements of WELL 2.0 in diverse locations. Achieving this goal relies on implementing window systems that provide ample bright light while employing minimal window size and shading devices to control glare at occupants' eye level.*
*KEYWORDS: Daylighting, Equivalent Melanopic Lux, LEED, WELL Standard, Healthy Buildings*

**1. INTRODUCTION**

The benefits of daylighting have been widely documented by numerous researchers. Daylighting serves as an effective strategy to reduce reliance on electric lighting, diminish cooling and heating loads, and enhance human comfort, well-being, and productivity [3]. This paper analyses the application of the daylight metrics developed by the Illuminating Engineering Society (IES) LM-83-12 Standard [4] adopted by LEED v.4 [3], and the WELL 2.0 Q4 2023 [2] Building Standard, across twelve diverse locations. Even though the latest LM-83-23 [5] release, an updated version of the LM-83-12 Standard includes changes such as a reduced illuminance threshold value of 150 lux for spaces with minimal visual tasks, a dirt depreciation factor, and a higher Annual Sun Exposure of up to 20%.

The latest WELL 2.0 Standard mandates an Equivalent Melanopic Lux (EML) exceeding 150 EML (1 point) or 275 EML (3 points) at vertical viewing positions. Moreover, the WELL standard offers an alternative provision for projects with enhanced daylighting, providing 3 points for Circadian Lighting attainment when a project achieves 180 EML and a spatial daylight autonomy (sDA300,50%) of more than 75% and annual sunlight exposure (ASE) less than 10% of occupied floor area, between 8:00 and 18:00 hours.

This paper explores the feasibility of achieving both the LEED v.4 (sDA300,50%> 75%, ASE <10%) and the WELL 2.0 (EML>200, EML>275) points concurrently in regularly occupied spaces.

**2. METHODOLOGY**

Twelve locations were chosen, ranging from latitudes 0° to 65° in the Northern Hemisphere (refer to Table 1). These locations represent a variety of climates, featuring distinct sky conditions that vary from predominantly clear skies (e.g., Phoenix) to consistently overcast skies (e.g., Caracas and Anchorage). Moreover, they experience varying durations of daylight throughout the year, with shorter daylight hours in winter days (around 7.5 hours) and longer summer days (up to 18 hours). In Fig. 1 three sky types (clear, partly cloudy and cloudy) are depicted across three locations (Quito, Phoenix and Anchorage) showcasing their respective monthly percentages (displayed in the left column) and the fluctuating monthly hours (presented in the right column).

A typical south-facing office space was modeled in Rhino, featuring windows on a single façade that represents a section of a deep open-plan office measuring 3.0 m high, 6 m wide, and 9.1 m long. The space includes a window spanning from 4.5 m to 5.7 m wide and 1.5 m to 2 m high, with a visible transmittance (Tvis) ranging from 60% to 70%. Additionally, the window wall ratio (WWR) varies from 40% to 70%. The interior surface reflectances are 0.7 for the ceiling, walls, and shading and 0.2 for the floor. No blinds were used in the simulations.

*Table 1: Locations, latitude, and annual sky types (%).*

| Location | Latitude | Clear Sky | Partly Cloudy | Cloudy |
|---|---|---|---|---|
| Quito | 0.1 | 9 | 87 | 4 |
| Caracas | 10.6 | 10 | 34 | 56 |
| Puerto Rico | 18.4 | 13 | 64 | 22 |
| Miami | 25.8 | 18 | 61 | 21 |
| Houston | 30.0 | 26 | 41 | 33 |
| Phoenix | 33.4 | 69 | 21 | 10 |
| San Francisco | 37.6 | 29 | 48 | 23 |
| New York | 40.7 | 14 | 54 | 32 |
| Boston | 42.3 | 26 | 39 | 35 |
| Seattle | 47.4 | 16 | 30 | 53 |
| Edmonton | 53.6 | 34 | 33 | 33 |
| Anchorage | 61.1 | 14 | 28 | 58 |

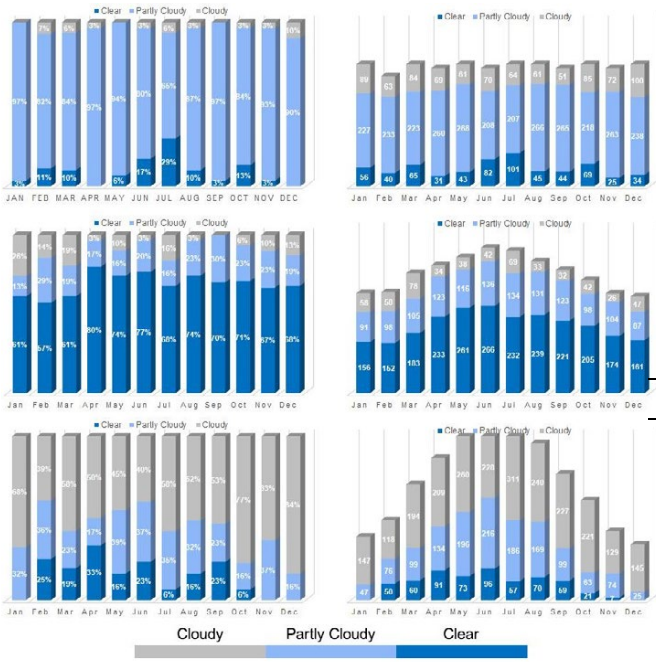


*Figure 1: Sky types of Quito (top), Phoenix (center) and Anchorage (bottom); monthly percentages (left column) and monthly hours (right column).*

The Rhino office model was linked to the RADIANCE-based ClimateStudio 1.9 [6] plugin in Grasshopper to generate climate-based annual hourly illuminance data for 150 sensors within the space. Each location underwent over 1,000 iterations (see Table 2). Simulations meeting the criteria to attain 4 points of LEED v.4 daylight credits were chosen. These selected simulations were compared against WELL's EML circadian metrics, in addition to the mean autonomous UDI (Useful Daylight Illuminance), the disturbing glare across regularly occupied floor area sDG (Spatial Disturbing Glare) and LEED VF (View Factor) 3 or above. For simulating the non-visual effects of light, the Multispectral Lighting Simulation Grasshopper plugin (Lark v.3.0) [7, 8] was utilized. Lark specifically simulated the EML values (over the 150 locations at 1.2 m high of 8 vertical view directions, totaling 1,200) exceeding 200 and 275 EML, in more than 75% of floor area, in spaces that met the criteria for 4 points of LEED v.4 (sDA>75%, ASE>10%, and VF>3) around noon during the solstices (March, September) and equinoxes (June, December).

## 3. RESULTS

The outcomes from the parametric runs of LEED v.4 and WELL 2.0 metrics across the 12 locations are depicted in Fig. 2 and Table 2. A higher number of cases meeting the LEED v.4 criteria were observed in regions with lower latitudes, specifically between 0° and 30°. However, at latitudes above 30°, the number of iterations decreased due to the meticulous selection of windows and shading devices tailored to diverse sky conditions and solar geometry. Notably, Quito demonstrated the highest count of LEED v.4 compliant cases among the locations studied, consistently maintaining partly cloudy sky conditions throughout the year. Surprisingly, despite Phoenix, receiving the highest annual incident daylight (138 lux-hours x 106 [9], positioned at an intermediate latitude with more clear days annually, it only met 1/9 and 1/5 of the LEED v.4 metrics criteria achieved by Quito and Caracas, respectively.

*Table 2: Iterations, LEED v.4, and EML>200 cases over 75% of floor area in June.*

| Location | Iterations | LEED v.4 | 75% EML>200 |
|---|---|---|---|
| Quito | 972 | 962 | 145 |
| Caracas | 972 | 554 | 7 |
| Puerto Rico | 972 | 285 | 35 |
| Miami | 972 | 138 | 20 |
| Houston | 972 | 104 | 90 |
| Phoenix | 128 | 103 | 0 |
| San Francisco | 128 | 81 | 0 |
| New York | 128 | 56 | 0 |
| Boston | 128 | 50 | 0 |
| Seattle | 128 | 47 | 0 |
| Edmonton | 128 | 29 | 0 |
| Anchorage | 128 | 10 | 8 |

### 3.1 sDA, ASE, UDI and sDG

Table 3 presents a summary of four visual metrics for the 12 south-facing locations. Overall, all locations achieved high sDA values. The highest $sDA_{300,50\%}$ of 100% occurred in latitudes 30° and below, with a similar ASE of 7%. Higher latitudes achieved a slightly lower sDA (ranging from 91% to 99%), except for Anchorage, which achieved 85% (refer to Figure 2). Notably, at these latitudes, the sDA is lower at the rear of the space. This decrease in sDA is attributed to extensive shading used to control sunlight.

The average autonomous UDI in low latitudes (0° to 33°) exceeds 80%. However, in higher latitudes (above 37°), UDI declines due to lux values dropping below 100 lux at the back and center of the space, coupled with excessive UDI exceeding 3,000 lux at the front. Overall, the percentage of sDG throughout the floor area remains relatively consistent, ranging from 19% to 28%. Nonetheless, Anchorage showed the highest sDG, reaching 33% of the floor area. This higher sDG in Anchorage is likely attributed to lower sun angles, causing shading devices to obstruct most of the year's sunlight from entering the occupant's eyes (at 1.2 m) and back wall without reaching the work plane.

*Table 3: Summary of visual metrics (%) of the 12 South-facing locations.*

| Location | sDA | ASE | UDI | sDG |
|---|---|---|---|---|
| Quito | 100 | 7 | 77 | 26 |
| Caracas | 100 | 7 | 81 | 19 |
| Puerto Rico | 100 | 7 | 82 | 28 |
| Miami | 100 | 7 | 80 | 19 |
| Houston | 100 | 7 | 80 | 20 |
| Phoenix | 99 | 10 | 80 | 26 |
| San Francisco | 100 | 5 | 77 | 21 |
| New York | 98 | 5 | 71 | 21 |
| Boston | 95 | 1 | 71 | 23 |
| Seattle | 97 | 0 | 68 | 22 |
| Edmonton | 91 | 7 | 64 | 25 |
| Anchorage | 85 | 4 | 57 | 33 |


*Figure 2: sDA, ASE, UDI, and sDG of the South-facing room in Quito (top), Phoenix (center), and Anchorage (bottom).*

### 3.2 Circadian Lighting and Views

The recommendations set forth by the International WELL Building Institute for office spaces require vertical light levels at the occupant eye level that surpass the horizontal task plane illuminance metrics established in LEED v.4 [10].

Table 4 provides a summary of the results derived from parametric simulations, focusing on EML values exceeding 200 and 275 during March, June, September, and December across the twelve locations. June consistently exhibits the lowest EMLs across all locations, while December records the highest. It is evident that none of the locations achieved EML values exceeding 275 over 100% of the floor area throughout the year. In this study, specific workstation locations, as defined by the WELL 2.0 standard, were not determined. Instead, the aim was to attain EML values exceeding 275 (WELL 2023) and 200 (WELL 2029) across 75% of the floor area during the solstices and equinoxes. Observations reveal that EML values exceeding 200 are consistently met throughout the year in lower latitudes (below 30°) from Quito to Houston. Even in Caracas, characterized by predominantly cloudy conditions, EML values exceeding 200 covers over 76% of the floor area in June. The exception among higher latitudes in Anchorage, where over 81% of the floor area meets EML values exceeding 200. In latitudes above 33°, however, EML values surpassing 200 covers less than 72% of the floor areas in June.

None of the 12 locations achieved EML values exceeding 275 across 75% of the floor area in June, with Quito reaching just over 72%. Yet, in other months like December, all locations successfully achieved EML values exceeding 275, ranging between 82% and 100% of the floor area, as illustrated in Table 4 and Fig. 3's right column.

*Table 4: Percentage of the floor area of EML>200 (upper) and EML>275 (lower) at noon.*

| Location | Mar. | Jun. | Sep. | Dec. |
|---|---|---|---|---|
| Quito | 88 | 83 | 85 | 99 |
| | 76 | 72 | 69 | 83 |
| Caracas | 85 | 76 | 84 | 99 |
| | 75 | 66 | 74 | 90 |
| Puerto Rico | 88 | 80 | 91 | 100 |
| | 76 | 69 | 77 | 85 |
| Miami | 83 | 81 | 90 | 100 |
| | 72 | 70 | 77 | 85 |
| Houston | 95 | 81 | 90 | 100 |
| | 80 | 69 | 78 | 89 |
| Phoenix | 80 | 66 | 80 | 96 |
| | 66 | 57 | 69 | 82 |
| San Francisco | 76 | 68 | 78 | 89 |
| | 65 | 56 | 67 | 80 |
| New York | 75 | 70 | 77 | 100 |
| | 64 | 59 | 68 | 92 |
| Boston | 81 | 71 | 75 | 100 |
| | 70 | 59 | 64 | 97 |
| Seattle | 87 | 72 | 89 | 100 |
| | 74 | 61 | 76 | 100 |
| Edmonton | 72 | 70 | 77 | 100 |
| | 61 | 58 | 65 | 99 |
| Anchorage | 97 | 81 | 99 | 97 |
| | 88 | 69 | 92 | 90 |

Fig. 3 depicts the distribution of EML by vertical view directions across the space in Quito, Phoenix, and Anchorage. As expected, areas adjacent to the window plane consistently register the highest EML values across eight vertical view directions throughout the year. These areas, covering approximately one-third to half of the floor area, consistently register high EMLs. Next to this region is an intermediate area, where view directions facing the windows achieve EML values exceeding 275, whereas those facing the back wall fall below 200 EML. Moreover, areas closer to the back wall show EML values exceeding 200 but below 275 EML. The distribution of EML values heavily relies on daylight that reflects off the side and rear walls.

Fig. 4 illustrates the illumination perceived by occupants in December in Quito, Phoenix, and Anchorage. The floating spheres in the space indicate potential workstation locations at the occupant's eye level (1.2 m). In low latitudes, the brightest area (>2,500 lux) is concentrated around the front of the room, creating an overall bright space. However, in Anchorage, due to the low sun position, the side and back wall receive a substantial amount of light. Occupants facing the window also experience bright light, which results in EMLs above 90% of floor area, while the sDG in Fig. 3 confirms the prevalence of disturbing glare mainly in directions facing the window.

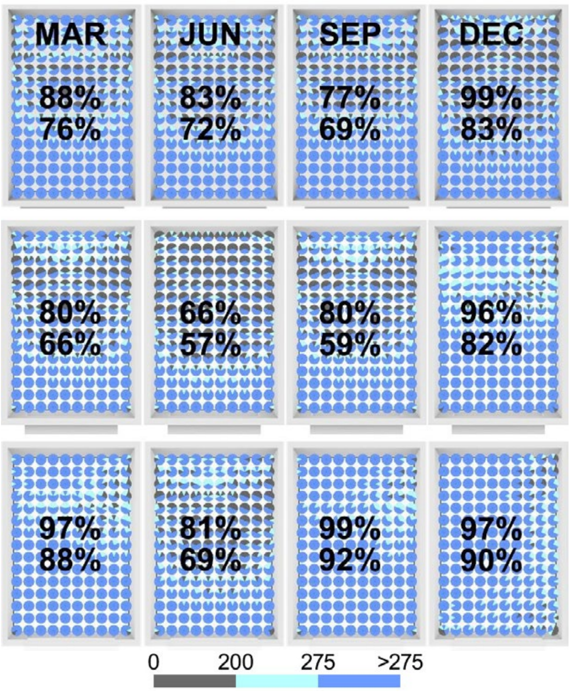


*Figure 3: EML>200 (top number) and EML>275 (bottom number) of Quito (top row), Phoenix (center row), and Anchorage (bottom row) in solstices and equinoxes.*

### 3.3 Views and Projection Factors

The parametric simulations included the selection of shading devices intended to intercept direct sunlight while preserving occupants' external views. The Projection factor (PF) denotes the degree to which daylight penetration through a window is obstructed by external shading. Consequently, higher PF values correspond to lower sDA, ASE, and EMLs. Fig. 5 illustrates the noticeable increase in PFs corresponding to latitudinal changes from 0° to 62°. Specifically, south-facing facades in low latitudes (0°–20°) necessitate minimal shading devices (PF Horizontal, PFH 0.2 to 0.6; PF Vertical, PFV 0 to 0.1) to align with LEED and WELL metrics. In intermediate latitudes (25°–50°), extended shading is required (PFH 0.8-1.4; PFV 0-0.1), while higher latitudes (>50°) mandate extensive shading that substantially obstructs the window glass (PFH 1.3-2, PFV 0.2).

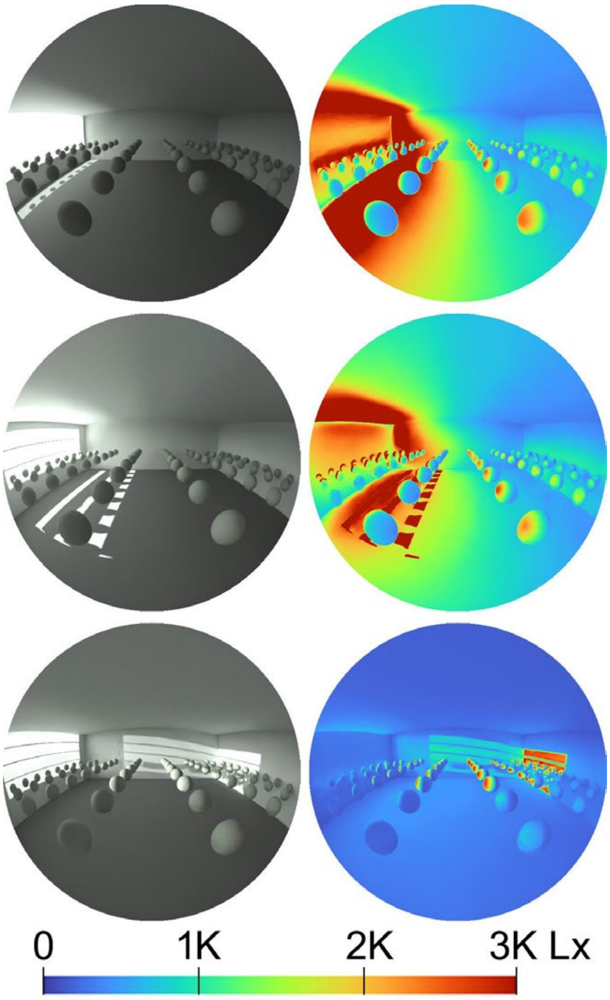


*Figure 4: Renderings and False Colors (illuminance) of Quito, Phoenix, and Anchorage in December.*

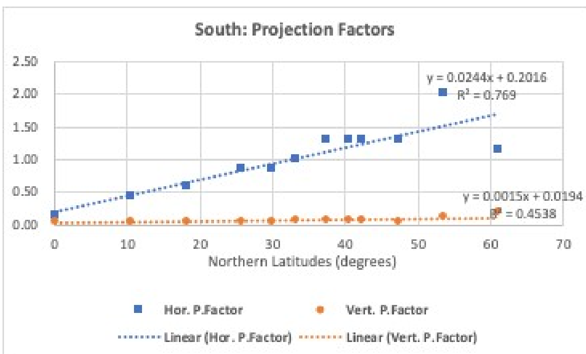

*Figure 5: Horizontal and Vertical Projection Factors.*

All EML cases met the LEED's v.4 View Factor requirement of 3, allowing for vertical and horizontal view angles (hVAs and vVAs) exceeding 40°. Fig. 6 showcases the view angles observed across the twelve locations. As anticipated, the trend lines of view angles contrast with those of the PFs (Fig. 5). The hVAs decreased from 81° to 29° from low to high latitudes, attributed to lower sun angles and the use of deeper shading devices. Conversely, vVAs consistently ranged between 90° and 80°.

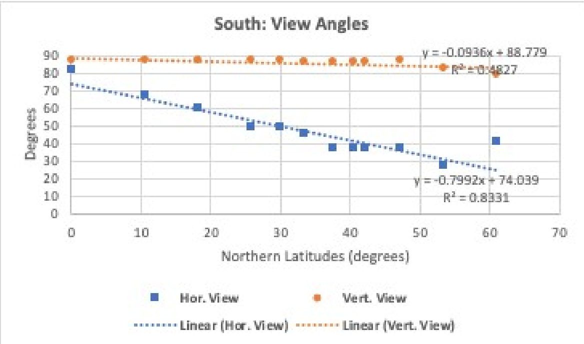

*Figure 6: Horizontal and vertical view angles.*

Table 5 provides a summary of WWR, Tvis, and the overall area of shading devices. Low latitudes exhibited larger window areas, approximately 67% of wall area, with fewer shading devices. This trend was attributed to predominantly cloudy and partly cloudy skies from Quito to Houston. Intermediate latitudes showed a reduced WWR, approximately 30%, compared to low latitudes, with larger shading areas. Higher latitudes (above 47°) displayed a slightly large WWR in comparison to intermediate latitudes, along with extensive shading, such as in Edmonton (Table 5). The Tvis of glass remained consistent across all locations.

*Table 5: WWR, Tvis, and Total Shading Area ($m^2$).*

| Location | WWR | Tvis | Shading Area |
|---|---|---|---|
| Quito | 0.67 | 70% | 3.1 |
| Caracas | 0.67 | 70% | 6.6 |
| Puerto Rico | 0.67 | 70% | 8.4 |
| Miami | 0.67 | 70% | 11.9 |
| Houston | 0.67 | 70% | 11.9 |
| Phoenix | 0.48 | 70% | 10 |
| San Francisco | 0.48 | 70% | 13 |
| New York | 0.48 | 70% | 13 |
| Boston | 0.48 | 70% | 13 |
| Seattle | 0.54 | 70% | 14.5 |
| Edmonton | 0.51 | 70% | 21.2 |
| Anchorage | 0.56 | 70% | 15.8 |

## 4. DISCUSSION

- Despite meeting current LEED v.4 requirements, none of the 12 locations achieved the existing EML>275 recommendations at 100% in all workstations. Achieving higher EML values at 100% of workstations may require narrower or less deep spaces. Additionally, EML values were highest for view directions facing the windows and lowest for those facing the back wall, suggesting that sidelight windows alone may not be the most effective daylighting system. Employing other systems such as additional windows, top lighting (clerestory or skylights), horizontal solar light pipes, supplementary electric lighting, blue-tinted glass, or interior wall colors tinted in blue could augment daylighting. Solar light pipe studies [11] have shown that they can be effectively used in facades oriented toward the East, South, and West. Moreover, increasing window sizes with high thermal performance, like triple-pane low U-value (or high R-value) and low SHGC, could be beneficial. Otherwise, energy-efficient LED lighting can be designed for workstations to achieve the required 275 EML values. An evaluation by researchers at PNNL on an existing building in Chicago, IL revealed challenges in meeting the EML levels of WELL v2 2019 at 100% of workstations in an open office space, even with supplementary electric lighting.
- The control of sunlight beyond ASE metrics is crucial to prevent direct glare in workstations facing southern directions, particularly in high latitudes. Maintaining at least a view factor of 3, in combination with LEED and WELL metrics, can ensure visually comfortable spaces, providing various health benefits to occupants.
- Our parametric lighting simulation, including renderings and false-color images, effectively highlighted interior spaces' responses to glare and high EML values at occupants' view directions. These visual representations provide valuable insights for designers to address lighting issues. However, there is currently a lack of metrics or parametric tools that report outcomes in three dimensions.
- Studies have demonstrated the positive effects of visual connections to the outdoors on occupants' health, well-being, cognitive performance, and stress recovery [12]. Combining LEED and WELL metrics with at least a view factor of 3 can ensure occupants' visual comfort and promote their health. All the cases of this study achieved a view factor of 3.

## 5. CONCLUSION

The results demonstrate the feasibility of meeting the LEED v.4 lighting and view requirements across all 12 locations while managing thermal loads through relatively smaller Window-to-Wall Ratios (WWRs) and minimal shading. In most locations, the WELL 2.0

EML>200 values were consistently achieved throughout the year, except for five high-latitude areas. To improve EML values in these high-latitude regions, larger WWRs and shorter shading devices might be necessary. However, these modifications could potentially impact cooling and lighting loads [13]. It is notable that Spatial Disturbing Glare (sDG) tends to increase with larger WWRs and sun exposure.

Designing for circadian lighting demands a meticulous approach to window system design, aiming to provide bright light, preferably from reflected sunlight bouncing off shading devices and interior reflectors towards the ceiling. Balancing the control of sunlight without compromising outdoor views poses a challenge for architects and lighting designers worldwide. Leveraging daylight has the potential to significantly enhance the quality of life and the overall health of building occupants.


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