THE CASE FOR MULTICRITERIA ANNUAL SUNLIGHT EXPOSURE GUIDELINES

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ABSTRACT

This paper explored the effects of the current Annual Sunlight Exposure ($ASE_{1000\ lux,\ 250\ hours}$) requirements on energy consumption and thermal comfort in an office space in five cities representing different U.S. climates. Specifically, the goal was to show the extent to which the current ASE metric requirements may be adjusted allowing for more/ less annual sunlight exposure to address climatic differences, energy, and thermal comfort criteria. A south-facing perimeter office space was simulated in the five climates to assess differences in energy and thermal comfort between the current ASE requirements and best-case scenarios. The results highlight the need to incorporate thermal comfort and energy as primary criteria informing target ASE requirements and guidelines. Developing a multicriteria ASE metric has potentials to greatly reduce energy use and improve thermal comfort in offices.

INTRODUCTION

Sunlight is a key design factor that influences the daylighting, thermal, and energy performance of buildings. Green building rating systems such as the Leadership in Energy and Environmental Design (LEED v4) utilizes the Annual Sunlight Exposure metric ($ASE_{1000\ lux,\ 250\ hours}$) which requires that no more than 10-20% of floor area should receive direct sunlight (1,000 lux or more) for more than 250 hours a year (USGBC 2017). Although ASE is the primary metric controlling and determining sunlight exposure in green buildings, this metric is mainly concerned with reducing visual discomfort and does not include specific criteria addressing thermal comfort, building energy consumption, and implications for different climates.

It is important to note that the ASE metric was originally developed as an indicator for glare using responses to the question "The daylight in this space is never too bright" (HMG 2012). The underlying study did not address effects of sunlight exposure on thermal comfort, thermal sensation, or energy use. It included spaces in various locations such as Sacramento, CA.; Seattle, WA.; and Albany, NY., and did not address climatic variations, as acknowledged in the LM-83 document (IES 2013). In addition to influencing heating and cooling energy, such climatic variations might influence occupant's overall preferences towards sunlight presence in space (Ne'Eman 1974), seating location (Wang and Boubekri 2010), and associated effects. Currently, there haven't been enough studies on annual sunlight exposure to delineate the impacts of current ASE requirements on energy consumption and thermal comfort in different climates.

Sunlight Exposure and Visual Comfort

Introducing direct sunlight in interior spaces while maintaining visual comfort has been a challenging task in daylighting design and research. Previous studies on sunlight and visual comfort investigated luminance distributions, contrast ratios, reflections on computer screens, and glare when sunlight is present in space. These studies concluded that occupants tended to be most sensitive to direct sunlight and that different amounts of direct sunlight, in concert with monitor contrast ratio and discomfort glare would generate different impacts on overall visual satisfaction (Jakubiec and Reinhart 2013; Konis 2013). In the New York Times building, automated shades were controlled to limit sunlight penetration to a few feet from the façade (Lee et al. 2013). Yet, questionnaire results showed that 42% of users, who manually overrode shade positions chose to reduce the amount of sunlight in the space. Another study found that most participants chose to allow direct sunlight into space when it was available, and suggested that carefully-positioned sunlight in space may improve satisfaction and thermal comfort (Van den Wymelenberg, Inanici, and Johnson 2010).

The LEED guidelines first required an initial upper limit of $ASE_{1000\ lux,\ 250\ hours}$=10% of floor area, a strict threshold that might promote dull spaces (Reinhart 2015). This threshold has been extended to 20% if a narrative is provided explaining how the space design addresses glare. An important issue that might have hindered our understanding of direct sunlight and its impacts on visual comfort is that current glare metrics have technical limitations to assessing visual comfort when sunlight is present in space (Van Den Wymelenberg and Inanici 2014).

Effects of Sunlight Exposure on Thermal Comfort

Previous studies on thermal comfort examined parameters influencing thermal sensation and developed the Predicted Mean Vote Method (Fanger 1973; Ashrae 2004). Hoffmann, Jedek, and Arens (2012) showed differences in thermal sensation depending on the location of solar radiation and whether it was diffuse or direct. The SolarCal model can help incorporate solar radiation into calculations of PMV according to ASHRAE 55-2013. SolarCal "computes an increase in mean radiant temperature equivalent to shortwave gains from direct, diffuse, and indoor-reflected radiation on a person" (Arens et al. 2015). The main variables used for this calculation were solar radiation (W/m^2), solar altitude, sky vault view fraction, and fraction of body exposed to the sun. Another important variable that influences thermal comfort in sunlit spaces is the duration of exposure to sunlight. Hodder and Parsons (2006) found that thermal sensation increases over time when exposed to solar radiation.

The effect of solar radiation on thermal comfort can be calculated using the CBE thermal comfort tool (CBE 2019) to check compliance using the PMV method with ASHRAE standard 55. However, currently, calculations of solar load and effects on thermal comfort do not interact with metrics determining sunlight exposure in interior spaces such as the ASE metric. It should be noted that while the PMV method promotes thermal neutrality, other studies suggested that sunlight provides stimulating thermal variations that may help avoid thermal boredom (Heschong 1979; De Dear 2006).

Effects of Annual Sunlight Exposure on Energy Consumption

Previous studies have examined the impact of sunlight exposure on cooling, lighting, and heating energy in various climates (Mardaljevic, Heschong, and Lee 2009; Abboushi and Chalfoun 2014; Ihm, Nemri, and Krarti 2009; Tzempelikos and Athienitis 2007). Overall, the impact of sunlight exposure on energy consumption depended on a wide range of variables including building type, shading coefficient, glazing properties, occupancy, etc. Hence, carefully admitting appropriate amounts of sunlight into space is important to ensure energy efficiency. In fact, to ensure passive heating, building codes in several European cities have addressed sunlight exposure on a seasonal basis by specifying the number of sunlight hours for different parts/ seasons of the year (Darula, Christoffersen, and Malikova 2015). Such seasonal guidelines are good starting points to utilize passive heating and cooling, and to reduce energy use.

METHODS

To examine the effects of ASE on thermal comfort and energy consumption, computer simulations were conducted for an open-plan office space (Figure 1). The space chosen for investigation was a south-facing perimeter office space (8.2m deep x 25.2m long x 2.8m height), that was adapted from a previous study that defined parameters for a reference office (Reinhart, Jakubiec, and Ibarra 2013). Parameters related to the envelope, occupancy, space loads, and mechanical systems were set according to the ASHRAE 90.1.2010 Zone 4 baseline. The developed open-plan office space had a window to wall ratio (WWR) of 40% with a visible light transmittance of 0.42 and a solar heat gain coefficient of 0.4. The HVAC system was a VAV Return Air Package. For simplicity, the space was simulated a single thermal zone.

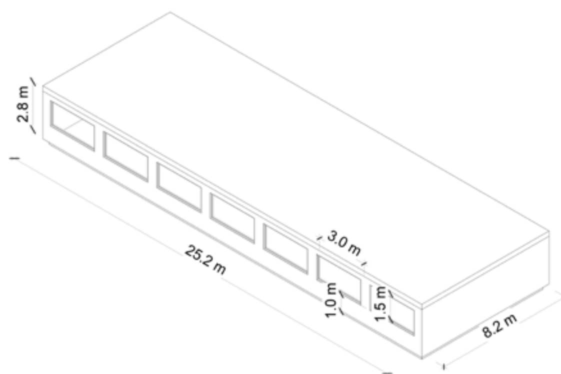

Figure 1: A 3D drawing of the simulated office space.

This space was examined in five U.S. cities that were selected to represent different climates with different levels of annual possible sunshine (NOAA 2004). Table 1 shows the five cities with corresponding ASE values without any shading and the annual percentage of possible sunshine. For consistency in the comparisons, the ASHRAE Zone 4 baseline remained the same for all cities and did not vary by climate zone. To examine thermal comfort and energy use under different ASE levels, the office space was simulated in each of the five cities under different overhang depths (0m-4.65m at 0.33m interval) resulting in 15 simulations for each city. Figure 2 shows ASE range limits explored for each climate, as a result of adjusting the overhang depth. For example, upper limits correspond to unshaded windows, whereas lower limits correspond to an overhang with a depth of 4.65m. Varying the depth of the overhang allowed for a simple way to control ASE without affecting the thermal performance of walls or glazing.

Table 1: The selected five cities and their corresponding ASE for an unshaded office, and average percentage of possible sunshine.

CITY	ASE (UNSHADED)	ANNUAL % AVG POSSIBLE SUNSHINE
Seattle, WA	37%	47%
Phoenix, AZ	42%	85%
Boulder, CO	47%	69%
Chicago, IL	50%	54%
Helena, MT	61%	59%

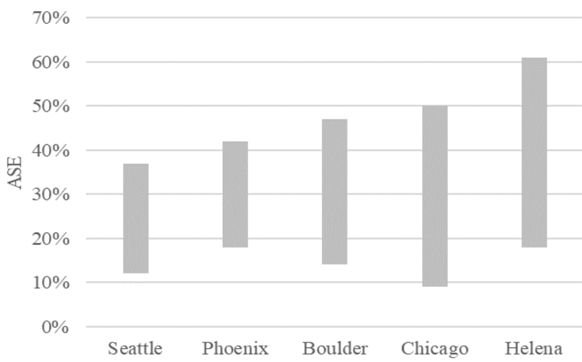

Figure 3: The ranges of ASE included for each city. The lowest ASE corresponded to an overhang of 4.65m, whereas the highest ASE corresponded to an unshaded window.

Simulations were conducted using Sefaira software, which conducts energy and daylight cloud-based simulations utilizing the validated EnergyPlus and Radiance engines, respectively (Sefaira 2019; Truesdell, Corney, and Bajic 2018). The simplicity of the interface and the ability to efficiently conduct both energy and daylight simulations using the same model were advantageous to this study. The results included energy use intensity (EUI), the percentage of occupied hours in which the space is thermally comfortable according to the PMV method, and $ASE_{1000,250h}$. The relationship between ASE, EUI, and thermal comfort was then investigated to demonstrate and quantify the effects of different ASE levels on energy and thermal comfort performance in each of the five climates.

RESULTS

Generally, the relationship between ASE and EUI varied by climates such that for heating-dominated climates (like Helena, Chicago, and Boulder) EUI gradually decreased as ASE increased (Figure 3). On the other hand, in Seattle and Phoenix, EUI gradually increased as ASE increased. With regard to thermal comfort, the percentage of time the space was thermally comfortable increased as ASE increased in Helena, Chicago, and Boulder. For Seattle and Phoenix, thermal comfort was maximized for ASE range between 25%-30%.

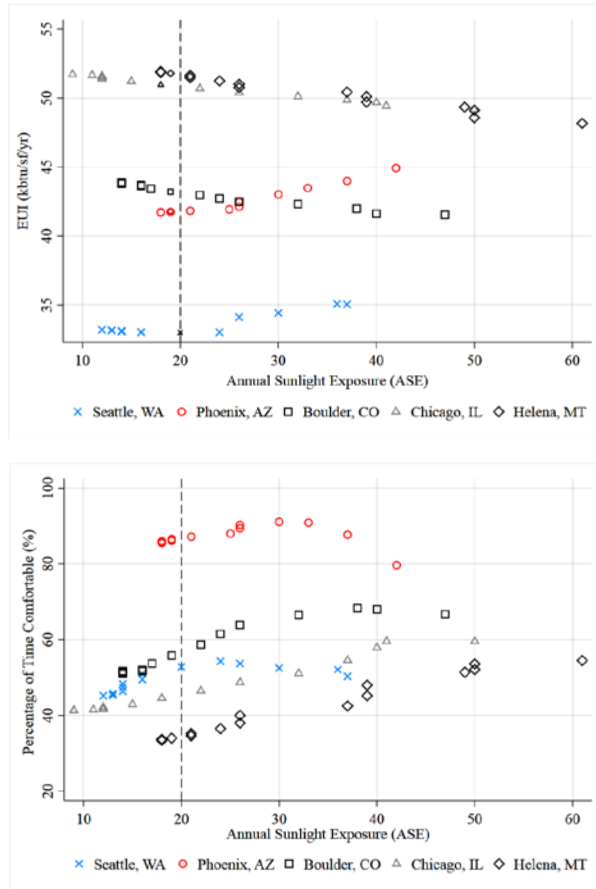

Figure 2: Scatterplots of ASE and EUI (top), ASE and the percentage of time thermally comfortable (bottom).

Thermal comfort and EUI results were further examined by climate to identify best ASE values for maximizing thermal comfort and reducing energy consumption. For Seattle and Phoenix, the best ASE value was 25%. For Boulder, Chicago, and Helena, optimal ASE values were 40%, 50%, and 60%, respectively as shown in Figure 4.

DISCUSSION

The simulations and analysis conducted in this study suggest that thermal comfort and energy consumption were likely to be influenced by changes in ASE. Hence, thermal comfort and energy consumption should be considered to inform the requirements and thresholds of the ASE metric. Climatic differences should also be considered (Darula, Christoffersen, and Malikova 2015). It could be that sunlight exposure requirements are formulated as a function of the climate average possible sunshine hours.

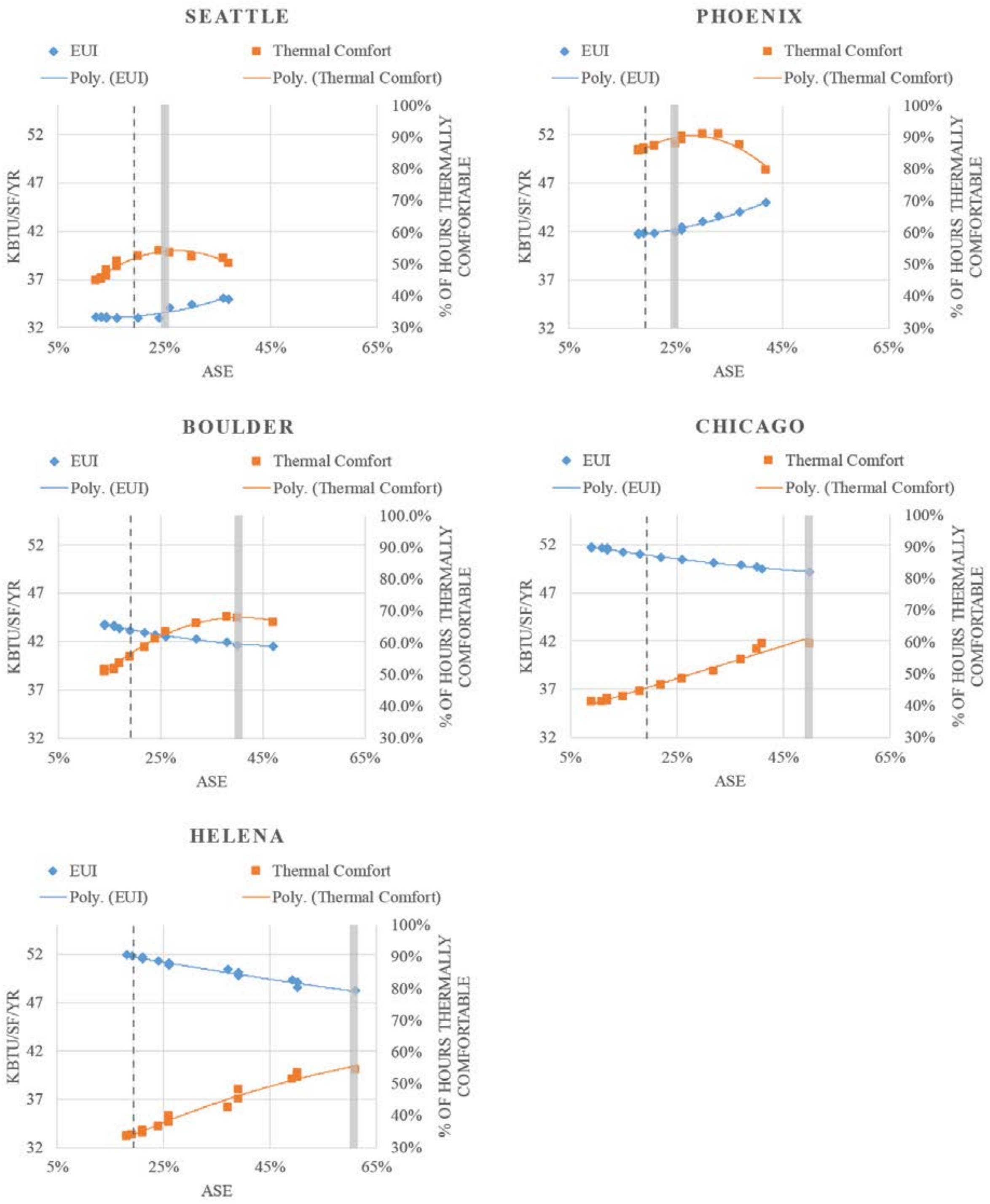

Figure 4: Scatterplots of ASE, EUI, and the percentage of time the space was thermally comfortable for the five cities. The dashed line represents the current upper limit of ASE=20%, whereas the gray thick line represents optimal ASE for improving thermal comfort and reducing EUI. As expected, colder climates like Chicago and Helena can benefit from increasing the ASE threshold more than other climates like Boulder and Seattle.

ASE requirements can also be divided by season such that these requirements can allow for better use of direct passive heating and shading for thermal comfort, and energy efficiency. For the five cities/ climates examined, the best ASE percentages for energy and thermal comfort tended to be considerably higher than the current requirement of ASE=10%-20% (USGBC 2017). This poses an important question of how can thermal comfort, energy, and visual comfort requirements be combined to inform sunlight exposure design guidelines?

The challenge of considering thermal comfort and energy in sunlight exposure metrics can be addressed through two main pathways. The first pathway focuses on informing the current ASE requirements for different climates such that the resultant thresholds are optimized not only for visual comfort but also for thermal comfort and energy efficiency. For instance, higher ASE levels may be allowed in cold climates compared to hot climates. The second pathway requires the integration of innovative fenestration systems, e.g. automated shading, that allow for the thermal and energy benefits of sunlight exposure without compromising visual comfort. Ultimately, these two pathways may be combined to address a wider range of building and occupant related factors. While the current study did not examine the effect of ASE on visual comfort, it is important that future studies do so to highlight these effects.

Towards a Multi-Criteria ASE Metric

The idea of a multi-criteria ASE metric is meant to provide clear guidance (one metric) that addresses visual comfort, thermal comfort, and energy efficiency. Though outside the scope of this paper, other psychophysiological aspects, visual interest, relaxation, and circadian rhythm may be addressed as well once clear annual guidelines have been established.

In order to determine the extent to which current ASE requirements might be modified, it is important to understand the synergies and trade-offs among visual comfort, thermal comfort, and energy consumption. Specifically, given that the ultimate goal of such guidelines is to provide occupant's satisfaction/ comfort while reducing building energy consumption; how do visual comfort and thermal comfort influence overall satisfaction? If a tradeoff is a must, which one should be prioritized? Previous studies that attempted to develop a weighing scheme for indoor environmental quality (IEQ) were inconclusive such that some studies concluded that lighting/ visual comfort has a higher weight than thermal comfort (Heinzerling et al. 2013; Gou, Lau, and Shen 2012) whereas other studies suggested that thermal comfort is more important than lighting/ visual comfort (Chiang and Lai 2002; Wong, Mui, and Hui 2008; Humphreys 2005). While further studies on IEQ and weighing schemes are needed, such weighing schemes might provide more conclusive and clear results if a specific phenomenon was examined (sunlight exposure), as opposed to the broad aspects of IEQ.

Figure 5 shows a conceptual framework for developing multi-criteria ASE guidelines. This framework shows that various aspects can be combined to inform ASE requirements for different climates, but a weighing scheme is necessary to address occupant's overall satisfaction with sunlight exposure.

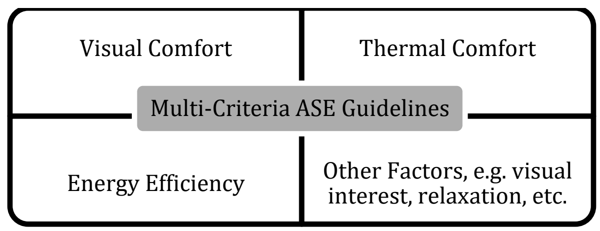

Figure 5: The proposed framework for developing the multi-criteria ASE metric for different climate zones and space types.

The proposed approach for the multi-criteria ASE guidelines can yield better overall satisfaction while reducing energy use. Table 2 shows differences in EUI and percentage of hours thermally comfortable between reference ASE scenarios (18%-20%) and scenarios with lowest EUI and highest thermal comfort. Generally, for Seattle and Phoenix, energy benefits were negligible but thermal comfort could be improved by 1.5-4.5% when increasing ASE to 24% and 30%, respectively. For Boulder, increasing ASE to 47% resulted in 1.67 kBtu/sf/yr reduction in EUI. Furthermore, at ASE=38%, thermal comfort increased by 12.5% in Boulder. Lastly, in Helena, for a scenario with ASE=61%, EUI can be reduced by 3.63 kBtu/sf/yr while increasing thermal comfort by 20.5%.

While the results generally suggest that ASE can be further increased especially for colder climates (Figure 4), this paper does not conclude that ASE can be simply modified to obtain these benefits. If direct sunlight falls on an occupant's body, it might cause thermal and/or visual discomfort. The thermal comfort analyses conducted in this paper did not account for solar load falling directly on occupant's body. Furthermore, this study created different ASE levels by means of adjusting the depth of a shading overhang. This procedure allowed for testing a range of ASE values, specifically leading to reduced solar gain in the summer and higher solar gain in the winter. Other shading systems might influence energy use and thermal comfort differently.

Table 2: Differences in EUI (kBtu/sf/yr) and thermal comfort between scenarios best for energy, or best for thermal comfort, compared to reference scenarios with ASE 18%-20%. A negative difference in EUI suggests energy savings, and a positive percentage for thermal comfort means an increase in thermal comfort, compared to the reference scenarios.

	BEST SCENARIOS FOR ENERGY		**BEST SCENARIOS FOR THERMAL COMFORT**	
	ASE	Diff. in EUI	ASE	Diff. in the % of time thermally comfortable
Seattle, WA	20%	0	24%	+1.5%
Phoenix, AZ	18%	-0.09	30%	+4.5%
Boulder, CO	47%	-1.67	38%	+12.5%
Chicago, IL	50%	-1.78	41%	+15.0%
Helena, MT	61%	-3.63	61%	+20.5%

While the current ASE requirements do not specify the seasonal breakdown of sunlight exposure, architects and designers should aim for increasing sunlight exposure in winter months (direct passive heating) to reduce heating energy use. Lastly, space layout is an important factor that can allow for increasing ASE levels without compromising occupant's comfort. For example, this might be achieved through adaptive workstations that allow for a wider range of seating and viewing directions (Jakubiec and Reinhart 2012).

LIMITATIONS

The results of this study should be interpreted considering the assumptions made and the limitations. Specifically, in this study, only an office space with south facing windows was examined. Including windows on east and west orientations might make it difficult to control solar heat gain. Further, because this study is based on existing guidelines to reduce glare, the study did no examine glare. It is likely that in certain times of the day/year, increased sunlight exposure can create intolerable glare levels. Hence, there is a need to utilize advanced systems that allow for capturing heat gain in colder areas while reducing glare.

Thermal comfort simulations did not account for solar radiation falling directly on occupants. Validation of the results of the study using other simulation tools and field studies in offices should be investigated in future studies. Lastly, it is reasonable to recommend different ASE levels based on space type. Some spaces might generate larger amounts of internal heat gain, hence reducing the need for direct passive heat gain (ASE) in certain times of the year. This topic warrants further studies to help refine the existing ASE metric.

CONCLUSION

This paper demonstrated the relationship between ASE, thermal comfort, and EUI for a south-facing office space in five different U.S. climates. The results showed that different climates required and needed different levels of ASE to achieve the best performance in terms of EUI and thermal comfort. Overall, the current ASE limits of 10%-20% may be further increased, with careful consideration for effects on energy, thermal comfort, and visual comfort. This paper proposes a framework that can be utilized to guide the development of multi-criteria ASE guidelines. Further studies are needed to delineate the relative importance of thermal and visual comfort for influencing occupant's overall satisfaction.

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