The Impact of Operated Window Shading on Visual Comfort, Non-Visual Health, and Energy Demand from Electric Lighting

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Abstract

This paper introduces a simulation-based workflow to assess annual circadian lighting performance, glare risk and energy demand for an array of seated view positions under operated shading and electric lighting conditions. This workflow uses a combination of 9-band and 81-band simulations to represent daylight and electric lighting respectively. Annual climate-driven calculations rely on python-based code provided by the Lark spectral lighting software, which was used to run 180-degree high dynamic range (HDR) renderings with 9-bands of spectral resolution. The results reveal the impact of shading systems on equivalent melanopic lux (EML) and daylight glare probability (DGP) over time and the energy demand (kWh) from electric lighting systems to supplement eye-level recommendations from the WELL v2 Building Standard (Feature L03).

Highlights

- Quantifying glare and circadian exposure with electric and daylight sources with 9-band and 81-band spectral simulation
- Impacts of shading operation on energy demand from electric lighting
- High difficulty and energy cost of meeting WELL v2 standard for circadian lighting performance

Introduction

Lighting design that supports occupant well-being requires a careful balance between providing *enough* illumination to support visual performance and health, while avoiding *excessive* brightness or contrast that may trigger discomfort or create adverse thermal conditions. Most traditional lighting performance metrics evaluate illuminance on the horizontal plane (a desk-height work surface) and are designed for sources that direct light *downwards from above* (Reinhart and Mardaljevic, 2006). Circadian lighting metrics, on the other hand, evaluate *light at the eye* or onto vertical surfaces within the field-of-view. However, increasing illuminance at the eye can cause discomfort glare, which requires designers to limit excessive brightness and contrast within the field-of-view using shading or redirection systems (Van Den Wymelenberg, 2016). When those shading or redirection systems are deployed at the window to limit glare risk, supplemental electric lighting may be needed to support task performance and circadian health, which can increase energy demand. This complex relationship between visual comfort, physiological need, and energy demand creates a challenging context for lighting design and we are lacking in studies that evaluate lighting design from a holistic human perspective.

Organizations like the WELL Building Institute have promoted eye-level light exposure thresholds to maximize potential circadian benefits. In the case of WELL V2 Q4 2022, both daylight and electric light (including task lights) can be used to meet an equivalent melanopic lux (EML) of either 150 m-lux for 1-point or 275 m-lux for 3-points towards WELL accreditation. These recommended thresholds must be maintained for 4 hours (starting by noon at the latest) for *all occupants* within a space. A previous study has shown that it is difficult to meet recommended thresholds for EML for occupants in a space, even with electric lighting providing illuminance over three times greater than the levels recommended for visual tasks (Safranek et al. 2023).

The relationship between operated shading and electric lighting controls is decades in the making, with existing research focused on task, comfort, energy efficiency and controls integration, and performance (Nezamdoost et al, 2014, 2014; Shen, 2014; Galasiu, 2007). When we integrate circadian light exposure recommendations into the performance of shading systems, the demand for supplemental electric lighting increases, as there is often less light incident at eye-level (perpendicular to the path of distribution) than there is on a horizontal plane half a meter below the eye level. This challenges the idea that ceiling-mounted lighting systems can get the job done without additional sources that distribute light onto the vertical plane.

In this paper, the authors have simulated annual, climate-driven DGP and EML for an array of seated occupant view positions in a side-lit office under daylight conditions, with and without interior shading systems. To supplement workstations that fall below the circadian light levels recommended by WELL V2 Q4 2022, a grid of ceiling-mounted LED luminaires is considered alongside portable task lamps at each workstation. The results will compare each design scenario through its circadian performance, avoidance of glare, and energy use from supplemental electric lighting.

Methods

The simulation workflow presented here was developed to evaluate the impact of an automated window shading system on non-visual health, glare-risk, and energy use

https://doi.org/10.26868/25222708.2023.1152

from supplemental lighting in a side-lit office space. In this workflow, daylight is simulated across the year under climate-driven sky conditions (TMY3 data for Golden, Colorado, USA) and eye-level EML and DGP are computed for each seated view position (Inanici et al., 2015; Wienold and Christofferson, 2006). One limitation to note here is that the annual sky definitions are limited to a generalized static sky spectrum. Dynamic sky spectra definitions are the next step of development for this simulation workflow. When an occupant's EML from daylight falls below the recommended threshold for any seated position between the hours of 9am and 1pm, the overhead electric lighting system is turned on and its contribution is added to the total EML at each position. Indirect-direct luminaires were carefully selected to increase the vertical light level at the eye of occupants while also minimizing glare. The lighting schedule also allows us to sum the wattage from the electric lighting system and calculate the annual energy demand required to meet circadian recommendations.

To evaluate the influence of interior shading operation on annual lighting energy demand and glare potential, the IES-LM-83 manual blinds control algorithm was included in the daylighting simulations. This algorithm requires that less than 2% of the regularly occupied area, which is defined by a horizontal analysis grid positioned at work plane height (76cm above floor), is exposed to direct sunlight (1,000Lux of direct beam sunlight or more) for each simulated timestep between 8:00 and 18:00. Shading is operated until the 2% threshold is met (IES, 2012). The blinds operation schedules and daylight availability results were then used to calculate annual lighting energy use, and in a second round of daylighting simulations to calculate DGP values that account for interior shading.

This paper discusses the challenges of meeting visual comfort and circadian health objectives simultaneously, while minimizing the energy demand of supplemental electric lighting systems that are required when shading systems reduce daylight availability.

Simulation Workflow

Estimating EML requires simulation tools with a higher spectral resolution than traditional lighting simulations for task-plane illuminance, which commonly use 3 spectral bands or omit spectral characteristics of light sources and room surfaces entirely. Abboushi et al (2021) compared the use of 3, 9, and 81 bands to represent the spectral power distribution (SPD) of 1,300 light sources and determined that using 9 bands offered improved accuracy over using 3 bands for calculating spectrally dependent metrics. For annual simulations of daylight, 9 bands allow for accurate spectral simulations, however, 81-band spectral resolution still offers the highest accuracy for simulations of LED light sources.

The simulation workflow implemented in this analysis used a combination of 9-band and 81-band simulations to represent daylight and electric lighting respectively (Inanici et al., 2015, 2016; Solemma, 2017). Annual daylight-driven calculations relied on a python-based code provided in the Lark (v0.0.2 release) simulation engine, which was used to generate front-facing 180-degree high dynamic range (HDR) renderings with 9-bands of spectral resolution for each workstation.

This 9-band method expanded on the Radiance lighting toolkit (Ward, 1994), essentially sub-dividing each of the three default channels (Red, Green, and Blue) into three channels to capture a specific portion of the spectrum and account for peak melanopic sensitivity (480nm) with higher accuracy (Figure 1). These renderings are then used to generate EML and DGP for each vertical calculation point in the model. Electric lighting was simulated separately using Adaptive Lighting for Alertness (ALFA) v0.6, a 81-band simulation tool ideal for point-in-time calculations.

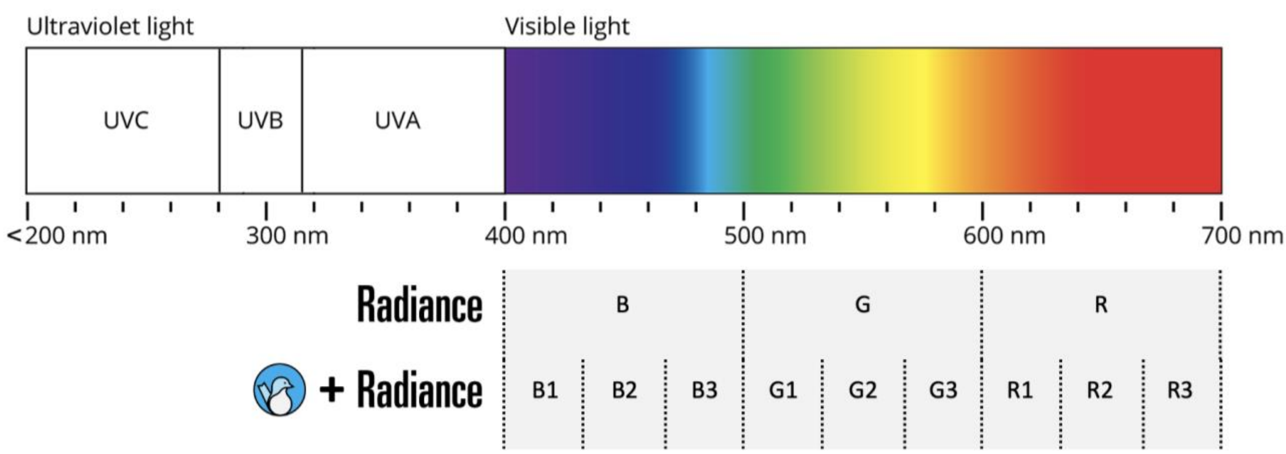

Figure 1: Radiance workflow compared to a Radiance + Lark workflow, which splits each Red, Green, and Blue channels into 3 channels, to provide more accuracy for computing equivalent melanopic lux, which peaks in spectral sensitivity at 480 nm.

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Manufacturer and laboratory data was used as input to characterize luminaire distribution, SPD, and power. Daylight and electric lighting results were combined to estimate the total EML at each vertical calculation point for each timestep under consideration.

Model

For this paper, we used a side-lit reference model for a workspace located in Golden, Colorado. The space is 19.6m wide along the glazing perimeter and 10.0m deep for a total of 196m^2 with a 3m ceiling height. The model was populated with 50 workstations (25 facing East and 25 facing West) and contained a fully glazed façade, South-facing with a 74% visible light reflectance (VLT). Generalized monochromatic materials were defined based on IES-LM-83 defaults with some adjustments. This includes carpeted floor (10% reflectance), interior walls (65% reflectance), perforated ceilings (75% reflectance), and furniture (50% reflectance). Figure 2 shows the model in Rhino. Desk chairs were not simulated, but desk surfaces and computer screens were included (without considering the contribution of light from the screens). One vertical calculation point was located at each workstation, 1.2m above the floor facing toward the computer screen.

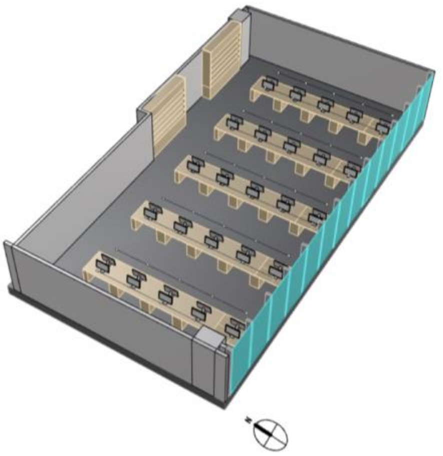


Figure 2: Rhino model of the side-lit office space

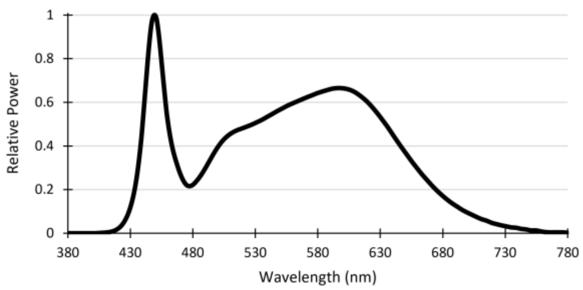


Figure 3: Spectral power distribution for overhead luminaires and task lamps, both with correlated color temperature of 4500 K

The overhead lighting system included 32 recessed 61cm x 61cm LED luminaires evenly distributed throughout the workspace. Portable task lamps were located at each workstation, to the right of the computer screens. Overhead luminaires used 40.5 W each while task lamps used 5 W each and both sets of light sources were assumed to have a correlated color temperature of 4500 K (Figure 3). For this analysis, the hours of operation were assumed to be 9am-5pm (3650 hours annually), and electric lighting was adjusted (either on or off) once per hour.

Simulated Conditions

To compare the impact of shade operation on EML and predicted annual energy-use from supplemental electric light, the following scenarios were simulated to compare the percent of view positions that stay below 0.4 DGP and yet exceed 150/275 EML throughout the year. Window shading controls can be applied to all windows in a single orientation (single group), or they can be applied to each individual window on a façade. We have chosen to compare two window groups to thirteen individual window groups.

<u>Daylight only:</u>

1) No shading systems
2) IES-LM-83 shading for 2 window groups
3) IES-LM-83 shading for 13 individual window groups

<u>Daylight + Electric Lighting:</u>

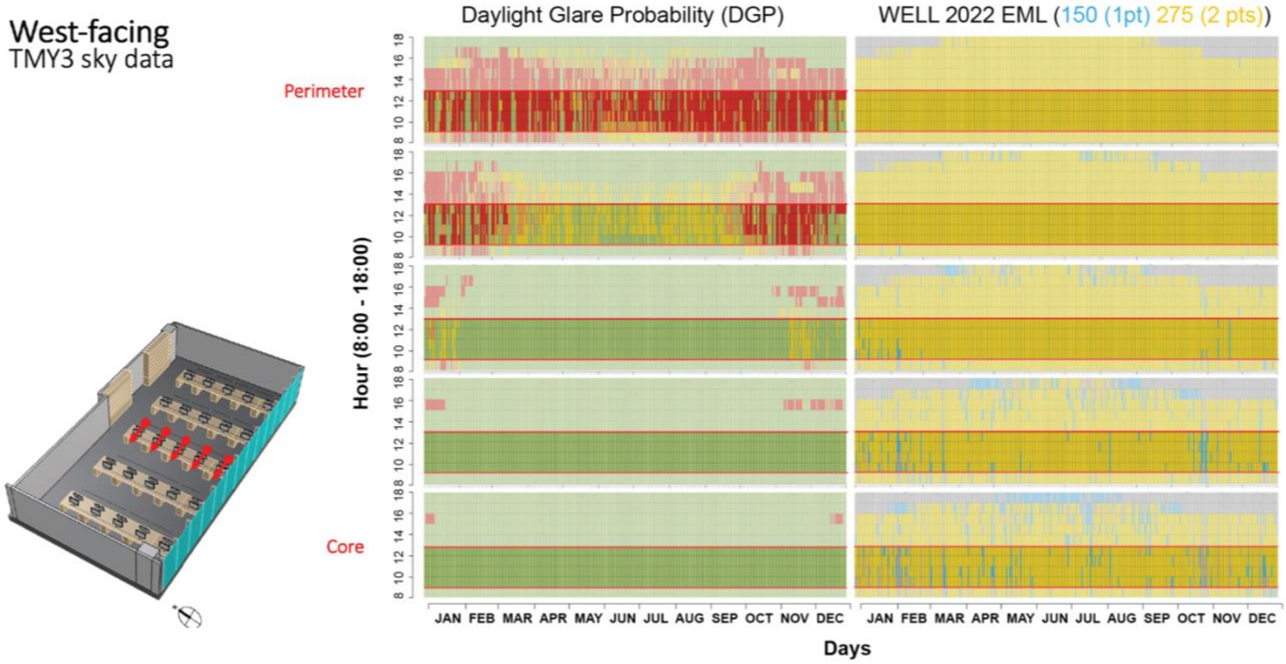
4) Overhead electric lighting turned on as a single zone when any eye-level positions fall below 150/275 EML, no shading
5) Overhead electric lighting turned on as a single zone when any eye-level positions fall below 150/275 EML, IES-LM-83 shading for 2 window groups
6) Task lamps turned on when any eye-level positions fall below 150/275 EML – then, if positions are still deficient, turn on overhead electric lighting, IES-LM-83 shading for 2 window groups
7) Overhead electric lighting turned on as a single zone when any eye-level positions fall below 150/275 EML, IES-LM-83 shading for 13 window groups
8) Task lamps turned on when any eye-level positions fall below 150/275 EML – then, if positions are still deficient, turn on Overhead electric lighting, IES-LM-83 shading for 13 window groups

Results

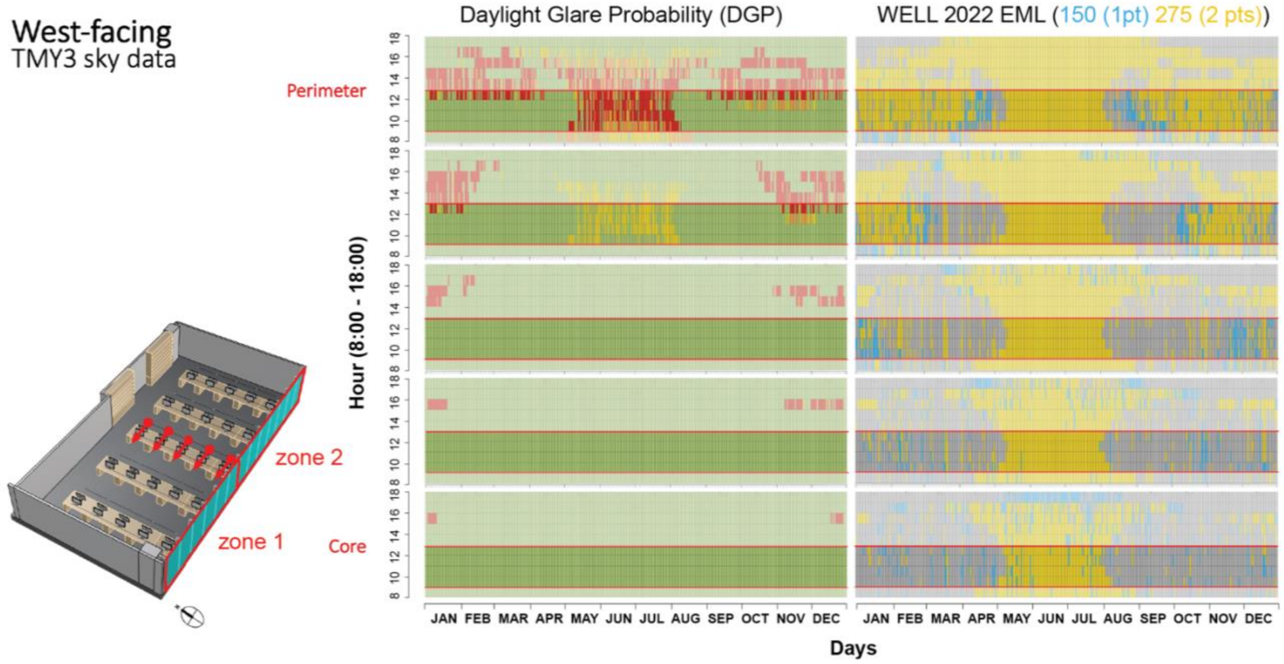
To understand the dynamic relationship between glare-risk and EML for different seating positions within the space, Figure 4 shows annual results for a series of 5 West-facing view directions from the perimeter (near the glazing) to the core. Figure 4a shows these results without operated shading systems and Figure 4b shows them with an IES-LM-83 operated shading algorithm (using 2 independent window groups).

This cross section of results shows the relationship between glare risk and circadian potential. Glare-risk is highest for occupants seated closer to the perimeter windows and it recedes for occupants as they move closer to the core. Conversely, the non-visual health potential is highest closest to the window and recedes as the view positions move farther from the source of daylight.

https://doi.org/10.26868/25222708.2023.1152



a) *No Shading - Results for DGP on the left and EML>=150/275 on the right.*



b) *IES-LM-83 operated shading (two groups) - Results for DGP on the left and EML>=150/275 on the right.*

Figure 4: DGP Time-steps are shown as green for imperceptible glare (DGP < 0.35), yellow for perceptible (0.35 <= DGP < 0.40), orange for disturbing (0.40 <= DGP < 0.45), and red for intolerable glare (DGP >= 0.45) (Wienold, 2009). EML values > 275 are shown in yellow and values between 150 & 275 are blue.

Manually operated interior shading lowers the number of timesteps that are above the 0.40 DGP "disturbing glare" threshold throughout the year. However, since the IES-LM-83 blinds algorithm is operated using horizontal-task illumination and circadian dosing is based on vertical measurements at occupant eye level, DGP is still a problem across the temporal map. At the same time, manual and automated shading devices reduce EML dosing throughout the winter months, when lower sun angles are driving direct sunlight onto the horizontal task plane. This reveals the problematic relationship between comfort and circadian health, whereby optimizing

https://doi.org/10.26868/25222708.2023.1152

performance to improve one of these conditions could result in worse performance for the other. It also reveals a shortcoming in our existing shading control systems, which have not been designed to prioritize circadian needs early in the day when exposure is recommended.

The impact of window shading systems on circadian health and visual comfort

To understand the impact of shading systems on the circadian potential of individual workstations across the year, Figure 5 shows the percentage of time over the year (between 9am and 1pm) that each view position achieves the 275 EML threshold (3-points for WELL v2 Feature L03). While the most recent version of WELL v2 Feature L03 requires 4 continuous hours of light exposure starting by 12pm at the latest, this paper considers the hours of 9am to 1pm to prime exposure and focuses our results on this timeframe (WELL, 2022). This representation does not include the contribution from supplemental electric lighting, but it does reveal the loss of circadian potential as you move farther from the perimeter. It also shows the impact of operating a shading system, where eye-level light exposure values drop below the recommended threshold for a larger percentage of time. In the seating positions closest to the windows, EML 275 drops from 100% of the year without shading to 75% with operated. For the positions farthest from the glass, EML 275 drops from 90% without shading to 25% with operated shading. The timesteps not meeting this threshold would require supplemental electric light to top up EML exposure, increasing annual energy demand.

The impact of shading control scenarios on energy demand from electric lights

Table 1 shows an overview of EML performance across the workstations as well as the annual energy (kWh) required to meet WELL v2 Feature L03 at the 150 and 275 thresholds. Without shading systems, 75% of the hours (between 9am-1pm) pass the 150 EML threshold for all seated positions using daylight only. With shading systems deployed (both the 2 groups and 13 groups), this drops down to 19%. When overhead lighting systems are engaged to ‘top-up’ the EML dose for any given workstation, the percent of hours jumps above 98% for all shading conditions.

When it became clear that our overhead lighting system could not meet the required EML thresholds, we added individual task lights to each desk. These lamps used the same SPD as the overhead lighting system (Figure 3). Columns 4 and 7 show the combined impact of overhead + task lightings. For this condition, our algorithm would first turn on desk lamps at each workstation to supplement positions not meeting the threshold before turning on the overhead lighting system.

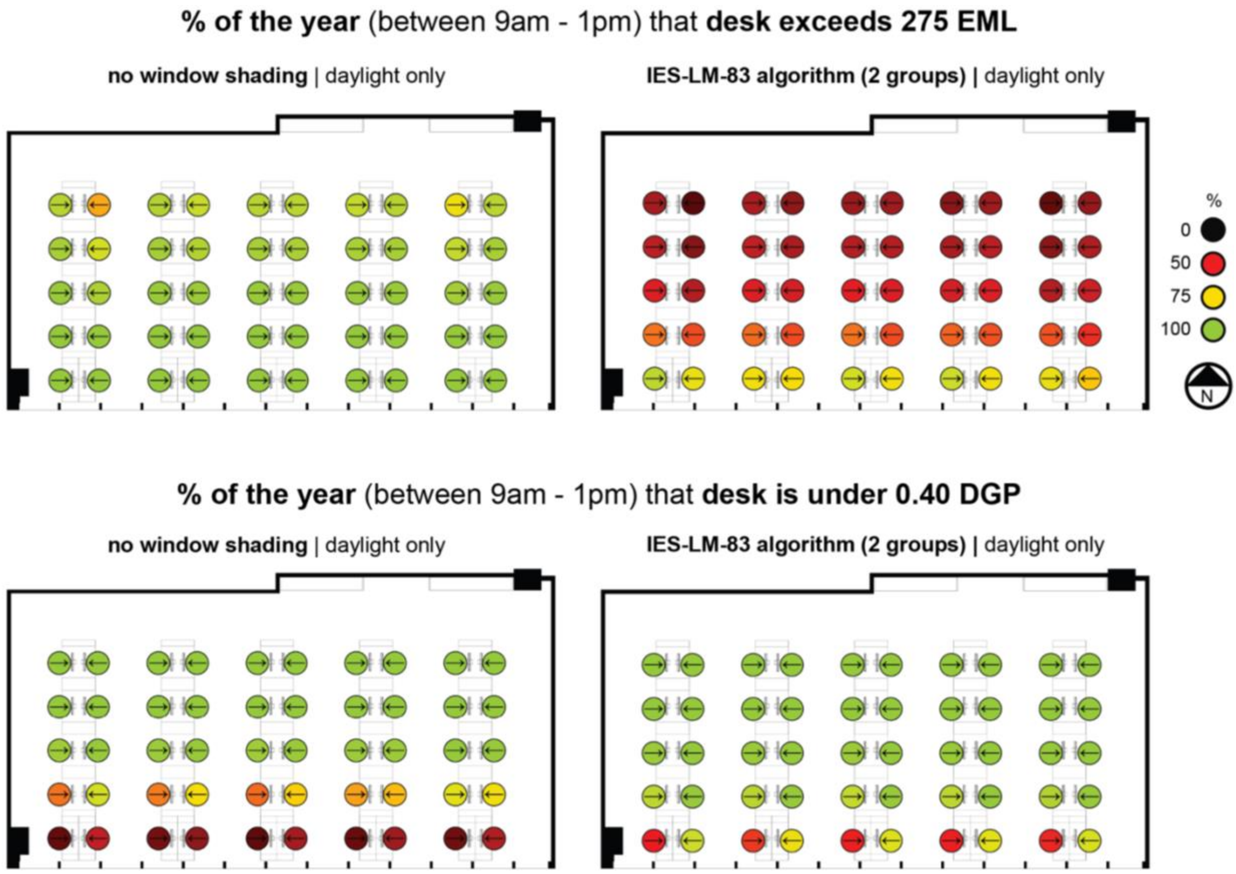


Figure 5: Percent of the year (9am-1pm) that views exceed 275 EML at seated eye-level (top) under no shading (left) and IES-LM-83 - 2 groups (right) and percent of the year (9am – 1pm) that desks are below 0.40 DGP (bottom) with no shading (left) and IES-LM-83 - 2 groups (right).

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150 EML Threshold	Hours passing **daylight only**	Hours passing **daylight + overhead lighting**	Hours passing **daylight + overhead + tasks lamps**	Annual energy (kWh) **overhead lighting only**	Annual energy (kWh) **daylight + overhead lighting**	Annual energy (kWh) **daylight + overhead + tasks lamps**
No shades	75%	100%	100%	3311	1887	1785
2 shading groups	19%	98%	100%	3311	2948	3001
13 shading groups	19%	98%	100%	3311	2946	2885

275 EML Threshold	Hours passing **daylight only**	Hours passing **daylight + overhead lighting**	Hours passing **daylight + overhead + tasks lamps**	Annual energy (kWh) **overhead lighting only**	Annual energy (kWh) **daylight + overhead lighting**	Annual energy (kWh) **daylight + overhead + tasks lamps**
No shades	11%	91%	98%	3311	3099	2890
2 shading groups	0%	32%	39%	3311	3311	3448
13 shading groups	0%	41%	52%	3311	3311	3368

Table 1: Tabulated summary of lighting and energy performance for each simulated condition under each WELL v2 performance threshold (150 and 275 EML) where 100% of workstations pass the threshold.

If EML was still under the desired threshold at that time, the overhead lighting system was then used to top-up the dose as needed. The addition of task lights not only allowed the hours to reach 100% for all three shading conditions (satisfying WELL v2 Feature 3 for 1-point), but it also required less annual energy to do it. With daylight + overhead + task lights (and no shading), the annual energy use was 1887 kWh. For the same condition *without task lights*, the energy use was 3311 kWh. These results illustrate three important findings: 1) electric lighting is needed to comply with the WELL v2 recommendation even for the 150 EML threshold without shading devices, 2) energy savings can be achieved if task lights are considered in tandem with an overhead lighting system, and 3) operated shading systems nearly double the energy demand on electric lighting systems to achieve a supplemental dose.

The challenge of meeting WELL v2 275 EML

One of the biggest advantages that this workflow offers is being able to evaluate whether WELL v2 Feature L03 can be achieved under a given set of shading and lighting control scenarios. The current standard allows EML thresholds to be met using a combination of daylight and electric lighting, but also requires that they be met 100% of the time (for a 4-hour continuous window in the morning) for all occupants. Figure 6 shows temporal plots for the percentage of workstations that meet the 275 EML threshold at any given hourly timestep between 9am and 1pm. As seen here, the overhead lighting system can have difficulty meeting the WELL v2 threshold, even without the added occlusion from the window shading system. As such, it becomes critical that our tools can evaluate shading and lighting control systems in tandem. As WELL requires that thresholds are met for all building occupants during morning hours, these plots use a monotone color scale from 0 to 99% and green when 100% is reached. Daylight + task + overhead lighting systems can meet the 275 EML threshold when shading systems are not present (for nearly 100% of the time), but this is not the case under automated shading controls. When two window groups are used to run the IES-LM-83 shading algorithm, only 39% of the timesteps meet the threshold for 100% of the workstations. If the control algorithm switches to 13 individual window groups, this improves to 52% of workstations. More granular control over the window shading system allows light to come in through some window openings even when others are engaged.

Conclusion

In summary, the workflow presented in this paper allows designers to evaluate the impact of building layout, window shading, and electric lighting controls on circadian and visual comfort across the year. Using 9-band spectral simulations of daylight in combination with 81-band simulations of electric light, we are able to evaluate whether WELL v2 Feature L03 is achieved and the energy use associated with achieving it. This allows us to compare design options and make an informed decision about whether to integrate more daylight, adjust the electric lighting sources systems, or work adapt the window shading control agorithm to prioritize morning light exposure for circadian health and afternoon shading control to reduce glare.

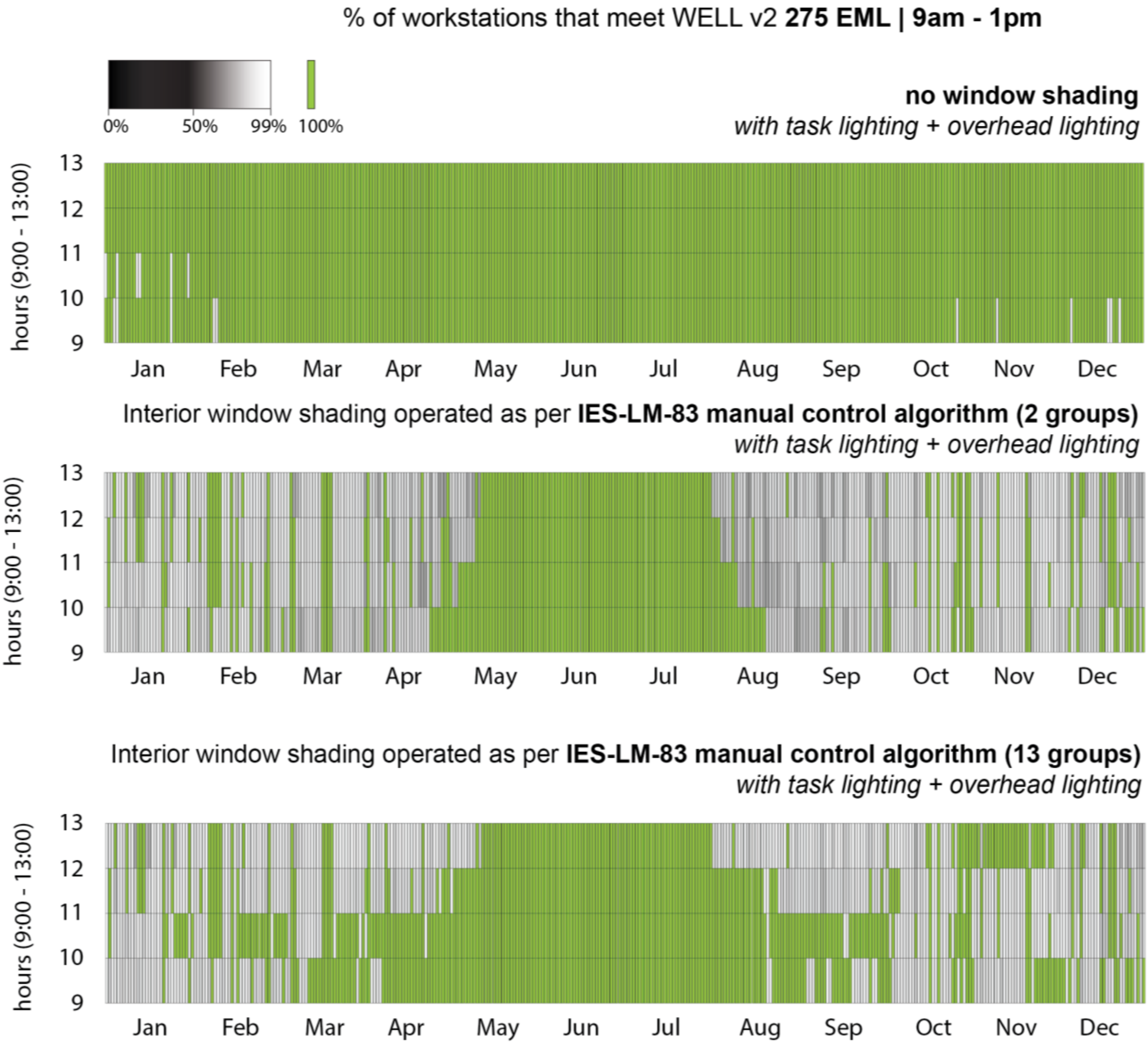

Figure 6: Percent of workstations that achieve WELL v2 (275 EML threshold) between 9am and 1pm between the three design scenarios (no window shading, IES-LM-83 2 window groups, and IES-LM-83 13 window groups)

One key limitation of this study is that light from the overhead electric lighting system was considered as a single zone and without dimming capabilities. While this scenario represents a large number of existing lighting control installations (EIA, 2017), the authors believe that significant energy savings can be realized if electric lights are dimmed and controlled in smaller zones or individually. The more localized our control of electric lighting sources and shading systems, the more energy-efficient our solutions will be. As we move towards a world where luminaire-level lighting control systems can provide granular sensing and demand response control at each individual fixture, our design solutions need to coordinate with manual and operated shading systems to support task, comfort, and health considerations. Furthermore, the results of this paper suggest that individualized task lights located at the desk position could help provide energy savings and improve healthy light exposure for building occupants who have less daylight access. It's important to note that supplementing circadian light exposure with overhead electric lighting can incur substantial energy costs, as shown in Table 1. Demand can be lowered with localized task lighting, while interior shading systems can increase it. However, part of the difficulty in balancing these competing factors can also be attributed to the strict requirements of the WELL standard. There is always room for improvement in how performance is quantified, how controls systems are optimized, and the lighting strategies that can be used to meet both visual and non-visual criteria in the most energy-efficient way possible. Future work is needed to evaluate optimal distributions scenarios for overhead, wall washing, and task-integrated lighting systems to provide healthy light exposure that is also visually pleasing and comfortable.

https://doi.org/10.26868/25222708.2023.1152

Acknowledgement

This work was supported by the U.S. Department of Energy's Lighting R&D Program, part of the Building Technologies Office within the Office of Energy Efficiency and Renewable Energy (EERE). The authors would like to acknowledge Dr. Robert Davis for his support of this research and Dr. Belal Abboushi for his peer-review of this paper and critique throughout the development of our workflow.

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