DETERMINING CRITICAL POINTS TO CONTROL ELECTRIC LIGHTING TO MEET CIRCADIAN LIGHTING REQUIREMENTS AND MINIMIZE ENERGY USE

Belal Abboushi
Sarah Safranek

Pacific Northwest National Laboratory
620 SW 5th Ave, Portland, OR 97204, USA
Belal.Abboushi@gmail.com,
Sarah.Safranek@pnnl.gov

ABSTRACT

Designing electric lighting systems to meet circadian lighting requirements may raise light levels and consequently energy use compared to existing practices. To reduce energy use, electric lighting can be controlled to be dimmed or turned off when sufficient daylight levels are available in space. This requires input from one or a few critical measurement points. However, it is unclear how critical points can be determined to ensure that all occupants receive the needed light levels while reducing electric lighting energy. This paper discusses three approaches for selecting critical points and utilizes annual daylight simulations modified to account for sky spectra and coupled with spectral electric lighting simulations. Among the three evaluated approaches, the use of continuous daylight autonomy (modified to use EML measured at eye positions) is helpful for estimating electric lighting energy for dimmable electric lighting systems, and for identifying energy-saving strategies.

Keywords: electric lighting, critical point, energy use, circadian lighting

LIST OF ABBREVIATIONS

Abbreviation	Explanation
CCT	Correlated color temperature
cDA_{EML}	Continuous daylight autonomy using EML
CS	Circadian Stimulus
DA_{EML}	Daylight Autonomy using EML
EML	Equivalent melanopic lux
LD	Lowest daylight
LED	Light-emitting diode
LPD	Lighting power density
M/P	Melanopic to photopic ratio
mEDI	Melanopic equivalent daylight illuminance
NIF	Non-image-forming
SPD	Spectral power distribution
WWR	Window to wall ratio

1 INTRODUCTION

Previous studies showed that lighting can elicit non-image-forming (NIF) effects of light such as melatonin suppression, circadian phase resetting, and alertness (Brown, 2020; Figueiro *et al.* 2019; Rea *et al.* 2012; Vetter *et al.* 2021). In buildings, these NIF effects require higher illuminance at the eye and higher correlated color temperature (CCT), compared to those needed for visibility and office task performance. For instance, providing an equivalent melanopic lux (EML) of at least 240 m-lux at the eye for all occupants in an office space using 6200 K 2x2 troffers alone was shown to more than double the horizontal illuminance at desks, and subsequently increasing energy use by 50-100%, versus designing to meet a horizontal illuminance of 300 lux as recommended by the Illuminating Engineering Society (Safranek *et al.*, 2020). Another study showed that providing a circadian stimulus (CS) of 0.3 or higher was more successful when targeting 500 lux of horizontal illuminance, rather than 300 lux (Jarobe, Snyder, and Figueiro 2020).

By considering daylight contributions, it may be possible to increase light levels throughout a space to meet circadian lighting requirements while reducing electric lighting energy. A recent study showed that for a small office in Chongqing, China with three recessed 4000 K lighting fixtures providing 300 lux of horizontal illuminance and 250 m-lux at the eye, annual lighting energy was about 35% less for a north-facing office with 39% window to wall ratio (WWR) compared to a windowless office (Zeng, Sun, and Lin 2021). The same study demonstrated that electric lighting energy savings varied by façade orientation, WWR, and geographic location. This shows potential for using integrated daylight-electric lighting systems to minimize electric lighting energy needed to meet circadian lighting requirements.

In annual simulations of daylight harvesting systems, estimating electric lighting energy often requires determining a single or few measurement points in the space, referred to hereafter as critical points, that control the operation of electric lighting. These critical points may control overhead lighting for the whole space or a single lighting zone, thereby affecting lighting levels and energy use (Mistrick *et al.* 2015).

1.1 Decisions Relevant to The Determination of Critical Points

The determination of critical points is closely related to several decisions such as selecting a circadian lighting metric, timing of exposure, and position and orientation of measurement points. Several circadian light metrics have been proposed including EML (Lucas *et al.*, 2014), melanopic equivalent daylight illuminance (mEDI) (CIE, 2020), and CS (Rea and Figueiro 2018). This is important to consider because different metrics can be associated with different requirements. For example, WELL (v2. Q4 2021) uses EML and mEDI and requires at least four-hour exposure that can start as late as 12:00 noon for all regularly occupied workstations. UL Design Guideline 24480 uses CS and requires that circadian-effective lighting is provided 7:00-16:00 (UL, 2019). While the recommendations for timing vary between WELL and UL, the selection of exposure timing may depend on space type, occupancy schedule, and types of tasks done in space (Houser and Esposito 2021).

In addition to selecting a metric and exposure timing, another decision is to determine which workstations to consider. WELL (v2. Q4 2021) considers all workstations in regularly occupied spaces where an individual spends at least one continuous hour or cumulatively two hours per day (WELL 2021). It is important to note that this does not ensure occupancy during timing of exposure such as scenarios where office workers may have flexible schedules or a hybrid work arrangement.

Lastly, regarding the measurement position and direction, WELL requires light levels to be measured 18 inches above the work plane on a vertical plane to simulate light entering the eye (WELL, 2021). The work plane may be for a sitting or a standing desk, so the distance above the finished floor may vary. Another issue is determining the view direction. It is understood that increasing the distance between the measurement point and a window will impact daylight levels at the eye (Andersen, Mardaljevic, and Lockley 2012; Gochenour and Andersen 2009; Vaz and Inanici 2020). Even while remaining relatively close to a window, light levels will see a considerable decrease as an occupant rotates towards the interior of the room (Konis, 2018). Although it is not explicitly stated in WELL (v2. Q4 2021), it is reasonable to assume that the view orientation would be directed at the center of a computer monitor.

Overall, given the need to effectively provide circadian lighting with low energy penalty, there is a need to evaluate different approaches that can be used to determine critical points. The following section discusses existing approaches and proposes two new approaches that can be considered.

1.2 Approaches for Determining Critical Points

The determination of critical points to meet target light levels while minimizing energy use was investigated in previous studies (Doulos, Tsangrassoulis, and Topalis 2014; Zeng, Sun, and Lin 2021). For instance, Zeng *et al.* (2021) proposed a workflow to calculate electric lighting energy based on the relationship between the output of each luminaire, horizontal illuminance at the desk, and vertical illuminance at the eye for an office space with six desks. Their workflow allows all measurement points to participate in optimizing the dimming level for each luminaire while minimizing energy use.

In lieu of designating all measurement points as critical points, a few measurement points may consistently receive lower daylight levels than others (worst case scenario), such as points at workstations farthest from a window and facing a wall. Identifying critical points with lowest daylight levels would allow for estimating supplemental electric lighting energy during design and verifying compliance when taking measurements in field studies. In this case, only the few critical points would have to be checked to ensure that all other points meet a certain requirement.

One of the approaches that allows for determining a few critical points requires identifying the measurement point that received the lowest daylight levels at each hour of the year, then tallying the number of hours at which each measurement point received the lowest amount of daylight (Mistrick *et al.* 2015; Mistrick and Casey 2011). The point or points with highest number of hours can be the critical points. In this paper, we refer to this approach as 'lowest daylight' (LD) because it identifies points that receive lowest daylight levels for the longest time in a year. Mistrick *et al.* suggested that at least two critical points should be used and stated that critical points are typically located near an east or west-facing wall in a south-facing space. This approach can be extended for circadian lighting applications using EML measured at the eye position for each occupant instead of horizontal illuminance measurements.

While the LD approach may be able to identify one or a few critical points that represent worst-case scenarios, this approach does not account for target EML threshold. It also does not show how other measurement points are performing. Therefore, we propose considering two new approaches inspired by two existing annual daylight metrics (IES 2020). The first approach is similar to the Daylight Autonomy metric but uses EML measured at the eye for setting the threshold. This approach is referred to as Daylight Autonomy using EML (DA_{EML}). DA_{EML} checks every hour within the timing of exposure and assigns a full credit point (value of 1) if the threshold is met or exceeded, and a zero if not met (*i.e.*, pass/ fail evaluation). The calculated DA_{EML} represents the percent of the time at which each measurement point met the required threshold. Because this approach operates in a binary fashion, it is relevant to traditional electric lighting systems with on/off operation and no dimming capability.

For dimmable electric lighting systems, we propose another approach 'Continuous Daylight Autonomy using EML' (cDA_{EML}), which also uses EML measured at the eye. Similar to the Continuous Daylight Autonomy metric (IES, 2020), cDA_{EML} assigns a full credit (value of 1) for hours meeting or above the EML threshold, and a partial credit continuously mapped from zero (0 m-lux) to 1 (EML threshold) for hours below the threshold. This approach considers that light levels below a certain threshold still have partial impacts on NIF aspects such as circadian phase resetting, melatonin suppression, and subjective alertness (Brown 2020). Accounting for EML levels below a certain threshold is also helpful to infer the amount of supplemental electric lighting needed when using a dimmable electric lighting system. Figure 1 shows a graphical representation of the two proposed approaches.

In this paper, we evaluate these three approaches (LD, DA_{EML}, and cDA_{EML}) that can be used to determine critical points. These approaches are applied to a simulated case-study office space in Golden, Colorado. to discuss how they might inform critical point determination and other design decisions. Given that the focus of this paper is on NIF effects, horizontal illuminance at the desk is not discussed as that would require a separate set of horizontal measurement points. Please note that this paper does not examine hardware issues related to physical sensors such as spectral sensitivity, mounting on room surfaces, masking of sensors, and directionality.

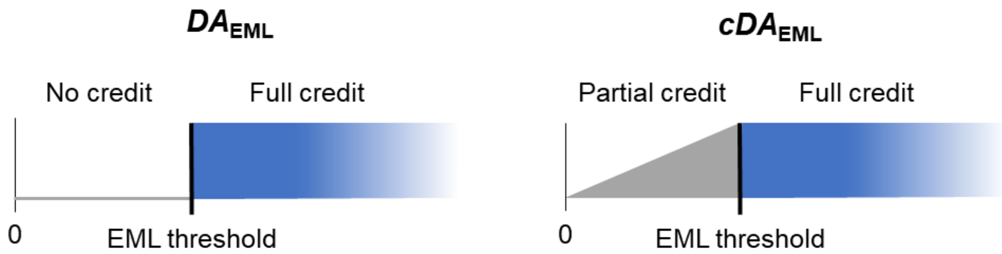


Figure 1: Graphical representations of two approaches that evaluate daylight contributions to EML at the eye over the year. Daylight autonomy using EML (DA_{EML}) and continuous daylight autonomy using EML cDA_{EML}.

2 METHOD

A 2100 ft^2 (195 m^2) open-plan office model with 40 workstations was used for all lighting simulations (A similar Rhino3D open-office model template can be found at: www.solemma.com/alfa). The southern facing wall of the office had floor-to-ceiling windows with a WWR of 90%. Workstations were assumed to be 2.5 ft (0.76 m) tall and computer monitors were included but not considered to be light sources for this analysis. Vertical measurement points were located at each workstation, 4 ft (1.22 m) above the fixed floor, facing forward toward the monitor, to represent the field of view of a person seated at each workstation. Figure 2 shows a perspective view and floor plan of the office with the measurement points. Surface materials were spectrally neutral with reflectance representing those typically found in office spaces (Figure 3).

Golden, Colorado was selected as the location based on the availability of annual sky spectra. For this paper, a method was established for estimating the EML contributions from daylight combining annual illuminance estimates from Ladybug/Honeybee (Roudsari and Pak 2013) with spectral measurements captured by the National Renewable Energy Laboratory (NREL). A spectrophotometer, managed and maintained by NREL (Andreas and Stoffel 1981) collects the global horizontal sky dome spectrum in Golden, CO, USA in 1-nm increments every 5 minutes throughout the entire year. A complete set of measurements from 2018 was used to create annual spectral sky conditions from 8:00-17:00 for every day of the year. The melanopic to photopic ratio (M/P) was calculated using the daylight spectral power distribution (SPD) for each hour, using the method outlined in WELL (WELL 2014). These M/P values were used to convert photopic illuminance at the eye to EML values. Given annual simulations of daylight are currently limited, this method for estimating EML contributions of daylight assumes that interior surface materials will not significantly alter the light spectrum at the different measurement points. This assumption is reasonable given the surface spectral reflectance used for simulation were relatively flat (Figure 3).

Thirty-two 3800 K 2x2 ft (0.61x0.61m) light-emitting diode (LED) luminaires were positioned 8 ft (2.43 m) on center and modeled using the spectral simulation software tool called Adaptive Lighting for Alertness (ALFA). Colorimetric and electrical data for the luminaires were supplied from photometric testing of one luminaire sample in an integrating sphere at Pacific Northwest Laboratory's Lighting Metrology Laboratory in Richland, Washington. ALFA allows for higher resolution spectral simulations and uses 81-bins to represent the spectral distributions of light sources and surface materials. For simplicity, all luminaires were assumed to be a single lighting zone. Photometric testing data of a luminaire sample captured with an integrating sphere was used for the colorimetric and electrical inputs for the lighting system. The maximum power draw of the luminaire averaged 40.5 W with a linear relationship between lumen output and luminaire power when the luminaire was dimmed. The analysis considered three timings of exposure: an 8-hour exposure (8:00-17:00), and two four-hour exposures (8:00-12:00 and 10:00-14:00). The EML thresholds of 150 and 275 m-lux that were set by WELL for a space without 'enhanced daylight' credits were used in this analysis. (WELL v2. Q4 2021).

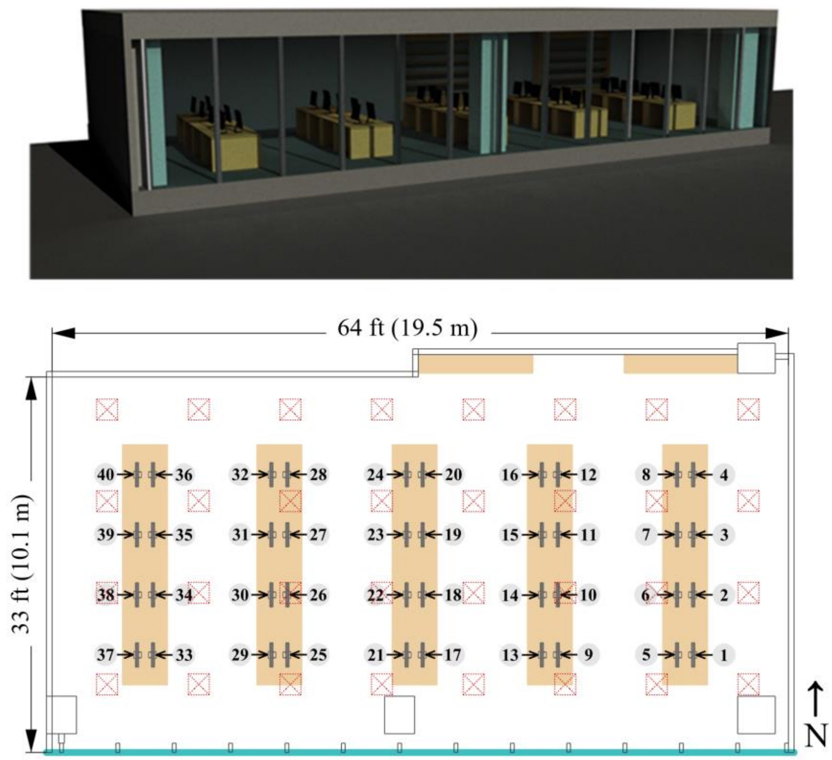
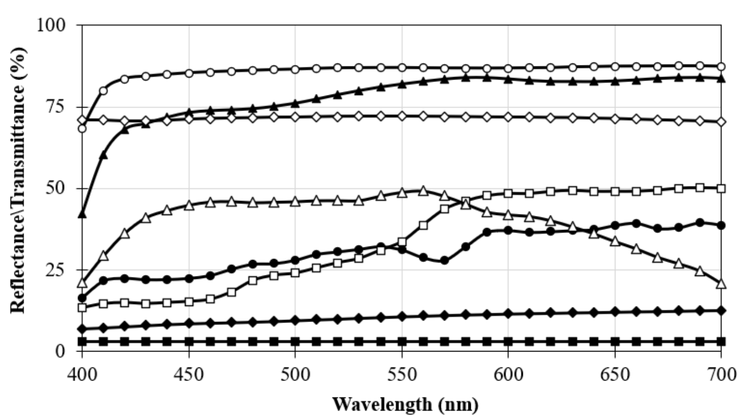


Figure 2: Perspective view and floor plan of the simulated office space. The numbers on the floor plan refer to vertical measurement points. Luminaire locations are indicated by the red squares.



Surface Material	Average
White Ceiling Tile	86%
White Wall Paint	78%
Silver Window Frame	71%
Flooring - Dark Grey	30%
Blonde Wood	34%
Monitors	3%
Exterior Ground Plane	10%
Glazing	40%

Figure 3: A plot of spectral reflectance of interior surfaces and spectral transmission of glazing (left), and average values from 400 to 700 nm (right).

3 RESULTS

Using the LD approach, point #4 which pertains to an occupant sitting in the upper right workstation was the critical point for more than 97% of the time for the three exposure timings. This means that this point received the lowest EML levels from daylight for the longest duration throughout the year. Given that point #4 was predominantly the only critical point for most of the year, other critical points could not be identified using this approach.

The second approach using DA_{EML} allows for ranking the measurement points based on their compliance with different thresholds (Figure 4). For an electric lighting system with on/off controls and no dimming capability, the percent of the time at which a point does not meet the threshold indicates the percent of the time when electric lighting needs to be switched on to meet the required threshold. For example, when aiming for an EML of 150 m-lux, if point #4 was to be the critical point, it would require that electric lighting be turned on for almost the entire year, regardless of the targeted duration. If design changes were to be made such that point #8 becomes the critical point, it would allow electric lighting to be turned off for 11-23% of the time, depending on the targeted timing of exposure. Aiming to meet an EML of 275 m-lux shows that multiple points had low DA_{EML} close to zero and would require supplemental electric lighting for almost the entire year.

The third approach considered was cDA_{EML} (Figure 5). For a target EML of 150 m-lux, the ranking of $cDA_{EML=150}$ is mostly similar to the ranking using $DA_{EML=150}$ with slight differences to the order of a few points. However, when aiming for 275 m-lux, unlike DA_{EML} where multiple points had similar values, cDA_{EML} allows for differentiating between points with low levels.

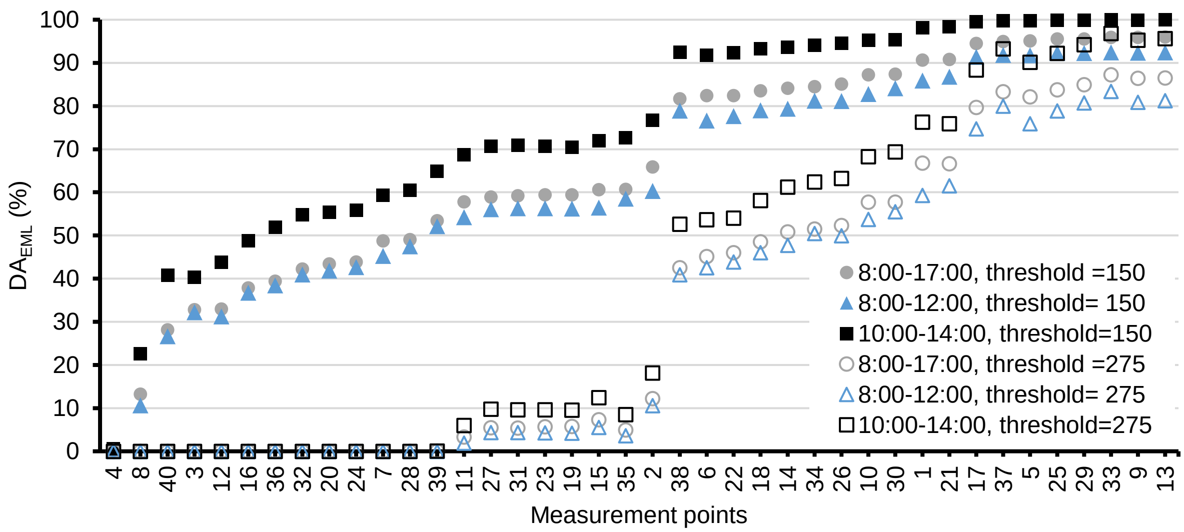


Figure 4: Results using DA_{EML} for all vertical measurement points in the office space with 8-hour exposure (8:00-17:00) and two four-hour exposures (8:00-12:00 or 10:00-14:00). Two target EML thresholds were considered: 150 m-lux represented with solid markers and 275 m-lux represented with hollowed markers.

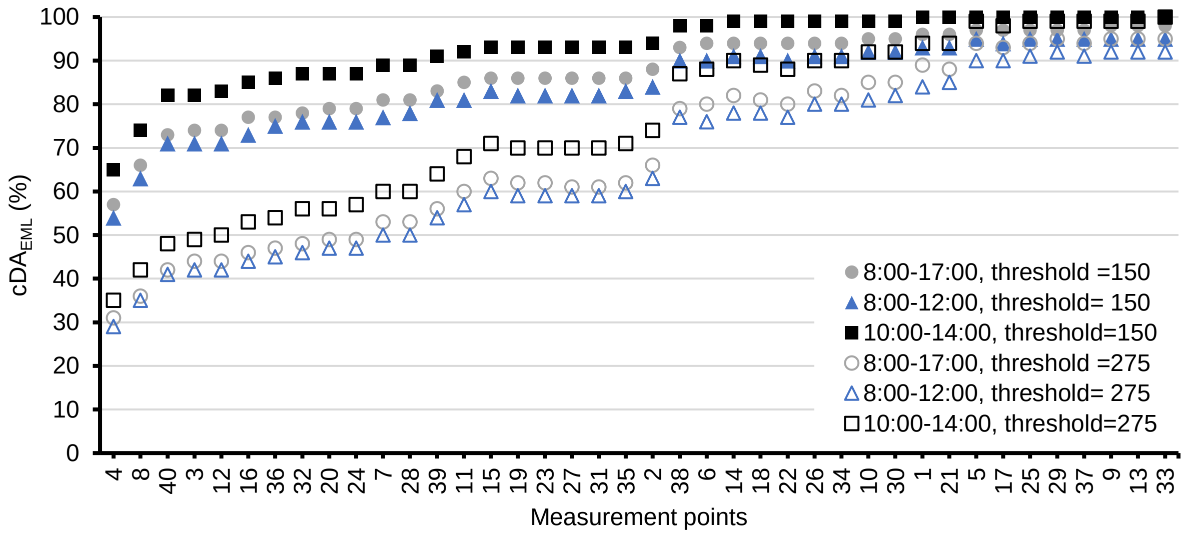


Figure 5: Results using cDA_{EML} for all vertical measurement points in the office space with 8-hour exposure (8:00-17:00) and two four-hour exposures (8:00-12:00 or 10:00-14:00). Two target EML thresholds were considered: 150 m-lux represented with solid markers and 275 m-lux represented with hollowed markers.

4 DISCUSSION

The analyses conducted showed that point #4 was consistently found to receive the lowest amount of daylight as evaluated using the three approaches. However, compared to the LD approach that focuses on identifying extreme points that consistently receive the lowest EML, DA_{EML} and cDA_{EML} allow for ranking all points showing the percentage of time when electric lighting is needed. Specifically, cDA_{EML} can be helpful for dimmable electric lighting to estimate energy using Equation 1. In this equation, cDA_{EML} is that for the critical point, *E* is the hourly lighting energy for the controlled luminaires needed to satisfy target EML at all points using electric lighting only [kWh], and *H* is the annual number of circadian lighting exposure hours.

$$Annual\ circadian\ lighting\ energy = (100 - cDA_{EML}) \times H \times E \quad (1)$$

For the case study office space, Table 1 shows annual circadian lighting energy for scenarios assuming different critical points. In these estimates, lamp-level energy is used and is scaled from 0 to 1 not accounting for standby power. While we do not suggest dismissing a few points to save energy, the analysis in Table 1 highlights two key points: 1) controlling overhead lighting based on an anomalous point will likely lead to excessive lighting energy use; 2) calculating cDA_{EML} can inform design decisions that can lead to energy savings while meeting target EML levels for all occupants.

cDA_{EML} allows for examining differences between the point with lowest cDA_{EML} and successive points. Large differences between the lowest point and successive points highlight an energy-saving opportunity. When such differences occur, a potential strategy is to consider the use of personal lighting at a few points (*i.e.*, workstations), which is allowed using WELL (WELL 2021). A previous study that used the CS metric and simulated different overhead lighting fixtures in an open office found that a desktop luminaire that provided 14-25 lx of blue light at the eye and used a lighting power density (LPD) of 0.04-0.07 W/ft^2, provided more CS at lower LPD than the use overhead lighting with CCTs below 6500 K (Jarboe, Snyder, and Figueiro 2020). For a 2x2 troffer that delivers CS of 0.4, Jarobe and colleagues found that the daily energy use was 4.91 Wh/ft^2/day compared to 3.85 Wh/ft^2/day with a desktop luminaire. For the current analysis, point #4 could be supplemented with a desktop luminaire, allowing point #8 to become the critical point and resulting in 21% circadian lighting energy savings.

Table 1: Annual circadian lighting energy savings associated with the selection of different critical points. These estimates are for 8:00-17:00 exposure to meet 150 m-lux (3,285 hours a year).

Critical point	**100- cDA_{EML150} (%)**	**Hourly energy[†] (kWh)**	**Annual energy (kWh)**	**Energy Savings (%)**
4 (baseline)	43	1.05	1483	0
8	34	1.05	1173	21
40	27	1.05	931	37
3 or 12	26	1.05	897	40
16	23	1.05	793	47

[†] Hourly energy was estimated for all 32 luminaires at a CCT of 3800 K using ALFA without daylight. At full power, the luminaires would use 1.3 kWh (40.5 W x 32 luminaires) but the lighting could be dimmed to 81% of full output using 3800 K (0.81 x 1.3 kWh).

When aiming for a four-hour exposure, cDA_{EML} allows for identifying the best 4-hour exposure timings with the lowest electric lighting energy use. For example, for the simulated south-facing office space, cDA_{EML} values for 10:00-14:00 were 7% higher than those for 8:00-12:00. This suggests that if the timing of exposure can be adjusted, selecting an exposure from 10:00-14:00 will reduce lighting energy while still meeting WELL requirements.

Both DA_{EML} and cDA_{EML} allow for evaluating the annual contribution of daylight to EML at the eye for different occupants, which can inform the zoning of electric lighting. It is currently unclear whether existing zoning practices for horizontal illuminance can be applied to spaces aiming to meet circadian lighting requirements. For simplicity, the current analysis considered only one lighting zone. Analysis using cDA_{EML} may inform zoning practices to reduce energy use, though this was not investigated in this paper.

5 LIMITATIONS

A number of assumptions were necessary to complete the analyses in this article. The calculations of lighting energy in Equation 1 and Table 1 assume uniform EML from electric lighting across all occupants. In reality, there could be some variation in EML distribution from electric lighting depending on fixture type, fixture placement and layout, and room surfaces. While only one CCT was considered for this analysis, light source SPD will influence estimated energy savings. Higher CCTs with increased short-wavelength spectral content provide higher levels of EML with lower lumen output (Safranek *et al.*, 2020).

Another potential limitation is our assumption that daylight spectrum inside the space will not differ from one measurement point to another. While this assumption might apply to the simulated office, it may not be true in spaces where some measurement points are close to a colored surface. This warrants further investigation to inform future simulation workflows.

The measurement points in this analysis assumed static positioning and horizontal view directions based on the design recommendations from WELL. It is understood that occupant behavior, including shifts in view direction or movement throughout the space, will influence lighting exposure. Future simulation studies should consider more dynamic placement of measurement points.

6 CONCLUSION

In this paper we evaluated three approaches that can be used to identify critical points (LD, DA_{EML}, and cDA_{EML}). Compared to the LD approach, the use of DA_{EML} and cDA_{EML} provides several advantages that can be summarized with the following points:

- DA_{EML} and cDA_{EML} allow for ranking all measurement points based on annual daylight levels at the eye. This can help evaluate whether the point with lowest DA_{EML} or cDA_{EML} is anomalous, in which case it would likely lead to excessive energy use.
- Supplemental desktop luminaires or different zoning arrangements can be explored to reduce circadian lighting energy while meeting circadian lighting requirements at all workstations.
- In situations where a four-hour exposure is appropriate, DA_{EML} and cDA_{EML} can help identify the timing of exposure with lowest lighting energy penalty.

REFERENCES

Andreas, A. and T. Stoffel, 1981. NREL Solar Radiation Research Laboratory (SRRL): Baseline Measurement System (BMS); Golden, Colorado (Data); NREL Report No. DA-5500-56488.

Andersen, M., J. Mardaljevic, and S. W. Lockley. 2012. "A Framework for Predicting the Non-Visual Effects of Daylight-Part I: Photobiology-Based Model." *Lighting Research and Technology* vol. 46, pp. 388–406.

Brown, T. M. 2020. "Melanopic Illuminance Defines the Magnitude of Human Circadian Light Responses under a Wide Range of Conditions." *Journal of Pineal Research* vol 69 (1): e12655.

CIE. 2020. "CIE S 026 Toolbox." 2020. https://cie.co.at/news/launch-cie-s-026-toolbox-and-user-guide. Access July 2, 2022.

Doulos, L, A Tsangrassoulis, and F V Topalis. 2014. "Multi-Criteria Decision Analysis to Select the Optimum Position and Proper Field of View of a Photosensor." *Energy Conversion and Management* vol. 86, pp. 1069–77.

Figueiro, M. G., M. Kalsher, B. C. Steverson, J. Heerwagen, K. Kampschroer, and M. S. Rea. 2019. "Circadian-Effective Light and Its Impact on Alertness in Office Workers." *Lighting Research and Technology* vol. 51 (2), pp. 171–83.

Gochenour, S., and M. Andersen. 2009. "Circadian Effects of Daylighting in a Residential Environment." In *Proceedings LuxEuropa 2009*. Istanbul: Turkish National Committee on Illumination (ATMK).

Houser, K. W., and T. Esposito. 2021. "Human-Centric Lighting: Foundational Considerations and a Five-Step Design Process." *Frontiers in Neurology* vol. 12 (January), pp. 1–13.

IES. 2020. "ANSI/IES LS-1-20, Lighting Science: Nomenclature and Definitions for Illuminating Engineering – Illuminating Engineering Society." https://www.ies.org/standards/definitions/. Accessed July 2, 2022.

Jarboe, C, J Snyder, and M G Figueiro. 2020. "The Effectiveness of Light-Emitting Diode Lighting for Providing Circadian Stimulus in Office Spaces While Minimizing Energy Use." *Lighting Research \& Technology* vol. 52 (2), pp. 167–88.

Konis, K. 2018. "Field Evaluation of the Circadian Stimulus Potential of Daylit and Non-Daylit Spaces in Dementia Care Facilities." *Building and Environment* vol. 135, pp. 112–23.

Lucas, R J., S. N. Peirson, D. M. Berson, T. M. Brown, H. M. Cooper, C. A. Czeisler, M. G. Figueiro, et al. 2014. "Measuring and Using Light in the Melanopsin Age." *Trends in Neurosciences*.

Mistrick, R, C. Casey, L. Chen, and S. Subramaniam. 2015. "Computer Modeling of Daylight-Integrated Photocontrol of Electric Lighting Systems." Buildings vol. 5 (2), pp. 449–66.

Mistrick, R. G, and C. A Casey. 2011. "Performance Modeling of Daylight Integrated Photosensor-Controlled Lighting Systems." In *Proceedings of the 2011 Winter Simulation Conference (WSC)*, Phoenix, AZ, USA.

Rea, M. S., M. G. Figueiro, A. Bierman, and R. Hamner. 2012. "Modelling the Spectral Sensitivity of the Human Circadian System." *Lighting Research and Technology*.

Rea, M S, and M G Figueiro. 2018. "Light as a Circadian Stimulus for Architectural Lighting." *Lighting Research & Technology* vol. 50 (4), pp. 497–510. https://doi.org/10.1177/1477153516682368.

Safranek, S., J. M Collier, A. Wilkerson, and R. G Davis. 2020. "Energy Impact of Human Health and Wellness Lighting Recommendations for Office and Classroom Applications." *Energy and Buildings* vol. 226, art. 110365.

UL. 2019. "Recommended Practice and Design Guideline for Promoting Circadian Entrainment with Light for Day-Active People DG 24480." Northbrook, Illinois, USA. https://www.ul.com/news/ul-publishes-lighting-design-guideline-circadian-entrainment. Accessed July 2, 2022.

Vaz, N. A., and M. Inanici. 2020. "Syncing with the Sky: Daylight-Driven Circadian Lighting Design." LEUKOS pp.1–19.

Vetter, C., P. M. Pattison, K. Houser, M. Herf, A. J.K. Phillips, K. P. Wright, D. J. Skene, G. C. Brainard, D. B. Boivin, and G. Glickman. 2021. "A Review of Human Physiological Responses to Light: Implications for the Development of Integrative Lighting Solutions." LEUKOS - *Journal of Illuminating Engineering Society of North America* pp. 1–28.

WELL. 2014. "Appendix L1." 2014. https://v2.wellcertified.com/en/wellv2/appendix/l1. Accessed July 2, 2022.

WELL. 2021. "Circadian Lighting Design." WELL v2. Q4 2021. 2021. https://v2.wellcertified.com/en/wellv2/light/feature/3. Accessed July 2, 2022.

Zeng, Y., H. Sun, and B. Lin. 2021. "Optimized Lighting Energy Consumption for Non-Visual Effects: A Case Study in Office Spaces Based on Field Test and Simulation." *Building and Environment* vol. 205, art. 108238.

AUTHOR BIOGRAPHIES

BELAL ABBOUSHI is a Senior Associate Lighting Research Engineer at the Pacific Northwest National Laboratory. Belal conducts research in the areas of daylight-electric lighting integration, lighting quality, and effects of lighting on occupant comfort and well-being. He holds a Ph.D. in Architecture from the University of Oregon. His email address is Belal.Abboushi@gmail.com.

SARAH SAFRANEK is a Senior Associate Lighting Research Engineer at the Pacific Northwest National Laboratory. Sarah's current work is focused on conducting research on a range of technology and application topics surrounding advanced Solid State Lighting systems and technologies. Her email address is: Sarah.Safranek@pnnl.gov