CIRCADIAN DAYLIGHT IN PRACTICE

Determining a simulation method for the design process

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ABSTRACT

Light is essential. It enables our perception of form, color, and texture. It is critical to human health, influencing circadian rhythms and our energy, mood, and productivity. Light is the major synchronizer of the human circadian system and suppresses melatonin, the hormone that induces sleep and can cause drowsiness, loss of productivity and insomnia. People spend much of their time in buildings, and the building façade is the membrane that allows and controls access to daylight and thus circadian function.

Emerging research into circadian stimulus led the Well Building Standard to propose and implement new metrics for assessing the circadian stimulus provided by both daylight and electric light. These new metrics require innovative approaches to simulation and means of interpreting data to assess circadian lighting potential during the design process.

Though designers are beginning to look to electric lighting to provide improved circadian function, the first step in designing to support circadian system function should be to ensure access to daylight through massing and façade optimization. Undertaking daylight simulation early in the design process is critical to carry this out for any complex building design. This team has developed two distinct circadian daylight simulation workflows for analyzing the effectiveness of a building design for delivering circadian system benefits, as measured using Equivalent Melanopic Lux (EML). The first method is based on illuminance on a horizontal plane. The second examines multi-directional vertical illuminance. This paper explains each simulation process and evaluates the comparative benefits of undertaking each simulation method.

Daylight is the most effective way to provide the health benefits of circadian lighting, and new methods for measuring and simulating daylight in buildings are critical to ensuring that façade and building designs respond to the most appropriate drivers.

KEYWORDS

daylighting - glare - shading, circadian lighting, WELL Building Standard, design processes, codes - standards - rating systems
computational design, advanced numerical computations, design optimization, Radiance, Honeybee, Grasshopper, DIVA

INTRODUCTION

The provision of lighting that delivers circadian system benefits is growing to be an important health factor in the built environment. Burgeoning research on this topic is contributing to an ever-increasing body of evidence that our circadian response to sky glow, light trespass, glare and over- or under-illumination affect our health and well-being (Panda et. al. 2015). While the scientific research linking circadian light, health, and buildings is still emerging, the impetus seems clear – to the extent possible, building design should enable occupant access to optimal levels of daylight whenever possible, supplemented with appropriate electrical light when necessary.

Practically speaking, implementing this imperative can be tricky and difficult to verify in terms of effectiveness during the course of design process. For daylighting in a project, well-known rules of thumb are useful as initial design guidance for simple buildings. However, buildings with complex floorplates, ambiguous or changeable floorplan layouts, and heterogeneous façade strategies require more detailed analysis to verify that the design fulfills the intent to provide quality circadian lighting primarily through daylight.

This paper seeks to explore and elucidate two viable methods for conducting daylight simulations that verify whether a design achieves effective implementation of circadian daylight. The purpose is to weigh the relative efficacy of each of these emerging analysis methods, as well as their relative merits in interaction with other daylighting metrics.

The proposed simulation methods reinterpret standard daylight simulation results in light of emerging circadian lighting metric. Neither of these simulation methods have been verified or benchmarked against actual circadian stimulus performance in a built project, although the underlying Radiance and Daysim simulation engines have been extensively validated (Reinhart, 2009).

BACKGROUND

The WELL Building Standard recently emerged as a viable benchmarking standard for the human health and wellness performance of a building. GBCI, the same certification body that manages LEED project certifications, administers certifications under the standard. The WELL Building Standard uses evidence-based metrics for measuring and monitoring the performance of building features that affect health and well-being, including circadian lighting. The illumination guidelines of WELL Building Standard for Light are aimed to minimize disruption to the body's circadian system, enhance productivity, support good sleep quality and provide appropriate visual acuity where needed (WELL, 2016).

The WELL Building Standard uses Equivalent Melanopic Lux (EML) as a metric for measuring the biological effects of light on humans. Photosensitive retinal ganglion cells (ipRGCs) regulate the human circadian response to light. These are non-image forming photoreceptors within the eye. Lux is the traditional SI measurement of illuminance and the eye's response to light, and is associated with the cones within the eye. EML as a metric is weighted to the ipRGCs response to light and translates how much the spectrum of a light source stimulates ipRGCs and affects the circadian system (WELL, 2016).

Below is an excerpt from the WELL Building Standard describing the proposed measurement method for the circadian lighting requirement:

> "Light models or light calculations (which may incorporate daylight) show that at least 250 equivalent melanopic lux is present at 75% or more of workstations, measured on the vertical plane facing forward, 1.2 m [4 ft] above finished floor (to simulate the view of the occupant). This light level is present for at least 4 hours per day for every day of the year" (WELL, 2016).

The EML metric, measurement method, and type of analysis proposed above is easier to apply in a fully resolved design with established workstation locations. It is more difficult to apply to a design that is not fully developed or a project with a program with flexible workspaces where the location and orientation of workstations may change throughout the day and year.

At the time this paper was written, the WELL Building Standard certified just eight projects and the authors were unable to find published case studies showing applications of an analysis method for the WELL EML requirement. As such, design teams adopting this metric face the challenge of interpreting the language of the standard despite a lack of background information or precedent. For a design that is in flux, what is the best way to approach the EML metric to evaluate design options?

One of the most important factors to evaluate when designing to meet the EML target is the availability of daylight. Not all light sources are equal in terms of circadian stimulus (CS). Daylight is the best option for both energy efficiency and CS because it requires no energy input and the wavelength spectrum of daylight closely aligns with circadian stimulus (al-Enezi, 2011). If daylight is not available or sufficient, electric lighting can be used to provide circadian stimulus, but requires additional energy and has a greater first cost. Color variable LEDs are available that are designed to provide circadian stimulus with low energy consumption. During the design process, the energy efficiency of a light source should be weighed against its performance as a circadian stimulus. If the design team does not optimize a building for daylight access while considering the EML requirement, the project will require a more expensive electric lighting system that consumes more energy than would otherwise be needed in order to achieve the EML target. This results in increased lighting first cost, operational cost, and carbon emissions over time. See the table below, provided by WELL building standard that shows the factors applied to each light source's efficacy with respect to melanopic lux:

CCT (K)	LIGHT SOURCE	RATIO
2700	LED	0.45
3000	Fluorescent	0.45
2800	Incandescent	0.54
4000	Fluorescent	0.58
4000	LED	0.76
5450	CIE E (Equal Energy)	1.00
6500	Fluorescent	1.02
6500	Daylight	1.10
7500	Fluorescent	1.11

Table 1: Melanopic Ratio provided by the WELL Building Standard (WELL, 2016)

Table 1 assigns a melanopic lux ratio to each source of light based on its Correlated Color Temperature (CCT). It is clear in looking at the Melanopic ratio table, daylight is one of the most effective light sources for melanopic lux. Daylight is a source of 'free' lighting if the tradeoffs with solar heat gains and thermal losses are carefully controlled.

METHOD

Two methods used to determine achievement of the Equivalent Melanopic Lux metric are compared here. These methods can be used early in the design process, when floor plans may not be determined, to assess circadian daylight potential. These proposed methods also allow for the integration of dynamic façade controls and automated blinds, which significantly affect daylight levels, but are not accounted for in the WELL standard.

This study does not account for other considerations that may influence the introduction of useable daylight in a space, including useful illuminance levels, potential for glare, thermal comfort, and heat gains.

METHOD 1 – TRANSFORMED HORIZONTAL ILLUMINANCE

The WELL standard requires a circadian lighting level of 250 lux at the vertical eye level, which translates to 227 lux from daylight when the daylight multiplier from the WELL Appendix Table L1 is applied. The vertical illuminance at eye level from daylight is estimated by dividing the horizontal illuminance at the workplane by two, which is based on the calculation methodology described in "Conceptual design metrics for daylighting" (Leslie et al, 2011). Based on this calculation, an analysis point on the horizontal plane achieves circadian autonomy when it demonstrates at least 466 lux from daylight for at least four hours a day.

An annual daylight analysis was conducted for a grid of points applied to the horizontal workplane of a typical office floorplate using DIVA for Rhino, a graphical interface for the Radiance ray-tracing program suite. The Radiance analysis produces an illuminance file that contains a daylight illuminance level at each point for every hour of the year. A python script was used to post-process the file and determine which points met the circadian daylight threshold for the minimum hours per day. The results were re-imported into Rhino for visualization as well as to determine the area of the floorplate meeting the WELL threshold.

METHOD 2– MULITI-DIRECTIONAL VERTICAL ILLUMINANCE

This method does not use horizontal values to estimate vertical illuminance, but instead accounts for differences in orientation and location by testing vertical illuminance in multiple orientations for a grid of points applied across a study area. The vertical illuminance for every hour of every day in eight evenly oriented directions was calculated for each point using the Radiance program accessed through the Rhino/Grasshopper/Honeybee environment, which allows for detailed manipulation of daylight simulations. The resulting illuminance file was then post-processed with a custom python scrip that determined the number of days per year that each orientation for each point met the WELL Building circadian standard.

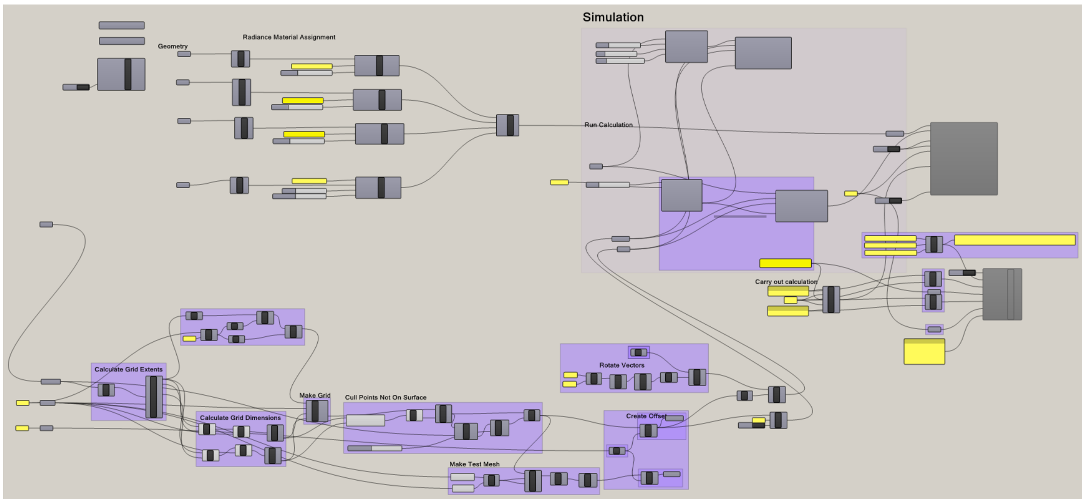

Figure 1: Grasshopper definition used to calculate vertical illuminance in multiple orientation for multiple points (Image courtesy of the author).

DATA

The results for both methods, tested on a typical office floorplate are shown below. A detailed comparative study of the two methods is also included.

METHOD 1 RESULTS – TRANSFORMED HORIZONTAL ILLUMINANCE

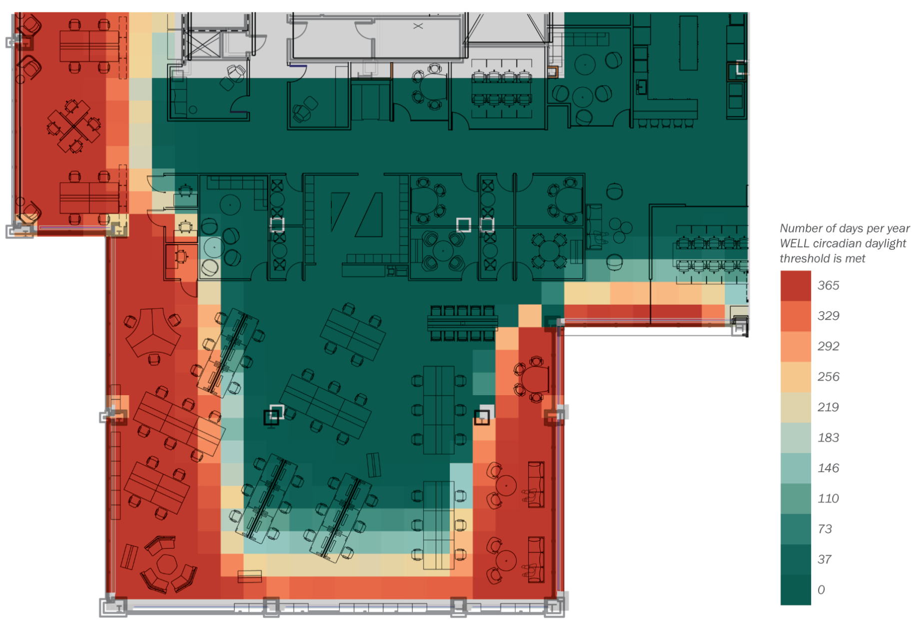

Figure 2: Method 1 circadian daylight results. The areas in red are projected to meet the threshold of at least 4 hours per day every day of the year (image courtesy of Atelier Ten).

METHOD 2 RESULTS – MULITI-DIRECTIONAL VERTICAL ILLUMINANCE

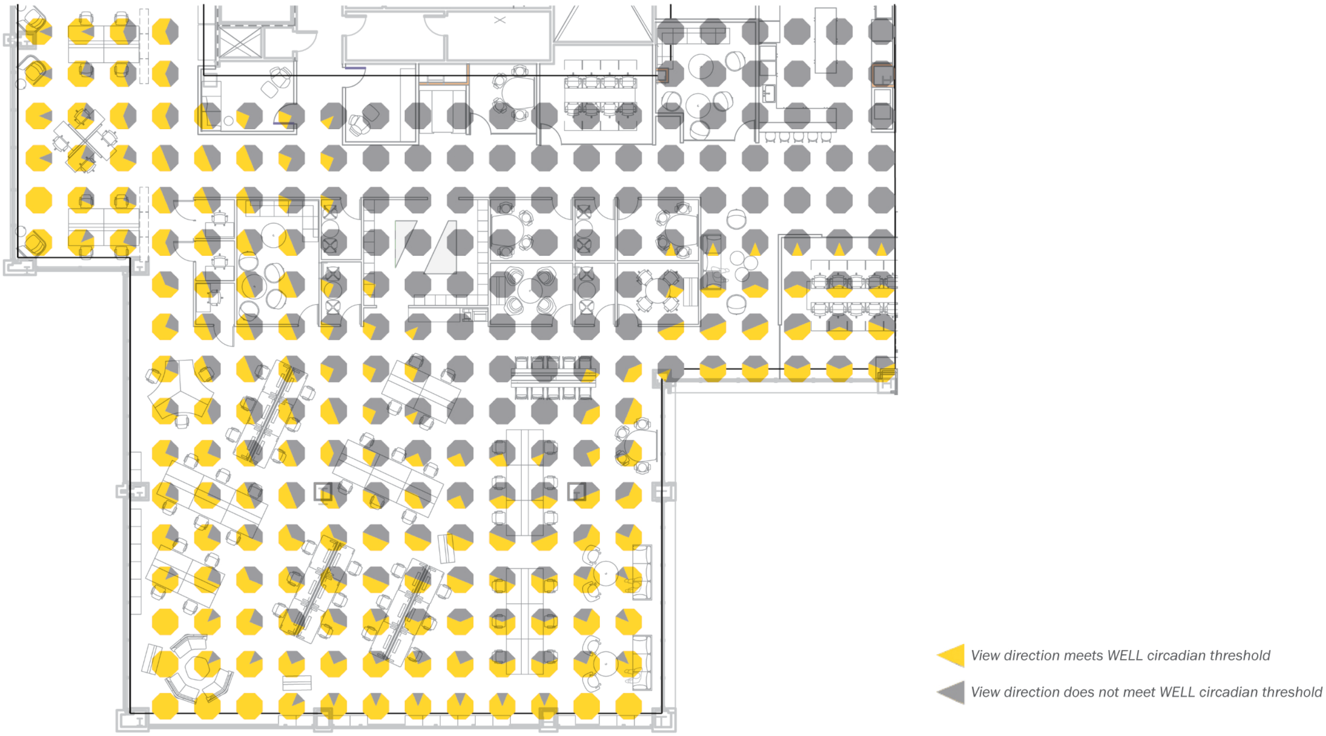

Figure 3: Method 2 circadian daylight results. A point with a view facing any of the yellow orientations in a given location meets the WELL circadian threshold (image courtesy of Atelier Ten).

COMPARATIVE RESULTS – DETAILED STUDY

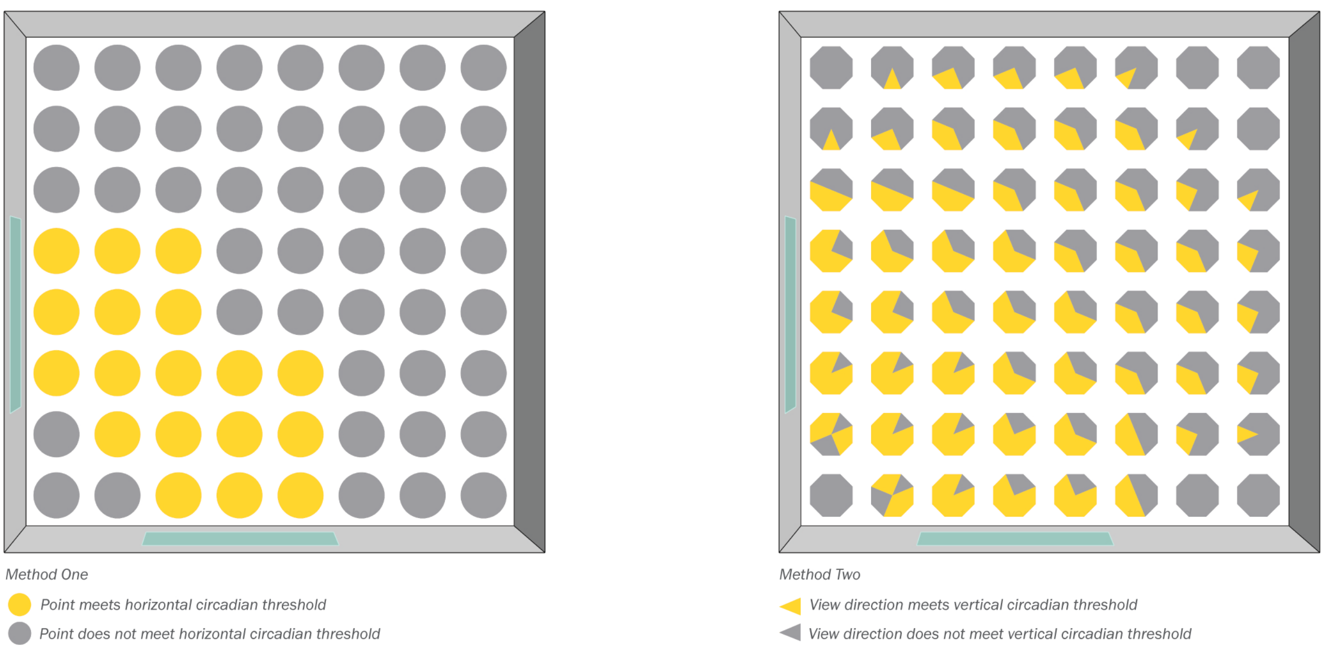

Figure 4: Results showing a direct detailed comparison of the two simulation methods (image courtesy of the author).

DISCUSSION

Method 1 can be simulated in Radiance through DIVA for Rhino or other Radiance interface and can be post-processed from a standard illuminance file produced with less computational resources than Method 2. Method 2 requires approximately eight times the computational resources than Method 1 because multiple illuminance values are calculated for each point.

While Method 1, the horizontal plane analysis method, allows a relatively quick general indicator of the circadian daylight level achieved, this study shows that it underestimates access to circadian daylight at a given point on the plane. This method does not account for directionality of light and workstation orientation at any location, but gives a good general idea of circadian daylight levels in a space and the simulation can be run quickly. Because the method does not account for the directionality of daylight when translating horizontal illuminance to vertical illuminance, the results may not accurately reflect the amount of circadian light available to an occupant, because light levels at the eye will change depending of the orientation of the occupant. However, the quick computation time and general assessment of circadian daylight can be useful to a designer. Also, the metric and representational method of a graduated color scale indicates whether a point is close to the threshold, allowing designers to assess whether design changes will be effective in increasing the area with circadian daylight.

Method 2, which shows multi-directional vertical illuminance, while more complex to set up and run, gives a clearer understanding of the opportunities available to maximize access to circadian daylight at each point on the grid. The directional display allows seating layout and orientation to be optimized to provide view orientations that achieve circadian levels through daylight alone. By correlating seating layout views to the circadian daylight available, as well as strategically placing transient program areas in locations that do not have adequate access to circadian daylight, the necessity for supplemental circadian electric lighting in workstation areas can be minimized. As currently displayed, Figure 3 shows whether a direction at a point meets the circadian daylight standard—essentially binary compliance/non-compliance information. This limits the amount of information available to a designer.

Figure 4 shows a direct comparison of the two methods and illustrates how Method 1 underestimates the amount of circadian daylight available within a space. The complaint area in Method 1 is clustered near the windows, which the Method 2 compliant areas are spread throughout the space, although weighted towards the window. The orientation of the view at each point also significantly affects compliance in Method 2. Overall, about 40% of the area included in the Method 2 study is compliant, while almost 30% of the area is compliant in Method 1. Comparing the simulation methods shows that Method 2 should always be used when time and computational resources allow because of increased accuracy and finer grained results. The translation of horizontal to vertical illuminance in Method 1 introduces problematic risk of inaccuracy into the results, making this method only appropriate as an initial general indicator and not for detailed design decision making.

DAYLIGHT ASSESSMENT LIMITATION

Circadian daylight does not operate independently of other daylight metrics. Because the WELL building standard uses a minimum daylight level to show compliance, the potential for over-illuminance is not considered. High levels of illuminance, including direct daylight, may cause localized glare causing occupants to draw blinds or orient away from the light source, which reduces the potential for circadian stimulus not accounted for by the metric. Because the WELL standard does not explicitly call for blinds to be part of the simulation, simulations may overestimate the circadian daylight available. Automated blinds may be preserve more of the useable daylight in a space, but manual blind deployment is unpredictable and occupants may leave blinds deployed when daylight is available, eliminating the desired circadian stimulus.

The circadian metric may not accurately reflect useable daylight within a space because it is based on a minimum threshold of four hours a day. Meeting the WELL circadian standard does not demonstrate useable daylight in a space. Useful Daylight Illuminance or Spatial Daylight Autonomy is more appropriate to determine useable daylight as these metrics are percentage based and account for all potential daylight hours.

CONCLUSION AND FUTURE WORK

Either of the proposed analysis methods can be used throughout the design process to assess circadian daylight in a space. Because both metrics assess circadian daylight across the entire floorplate, neither metric complies perfectly with the WELL Building standard. However, the results can be used early in the design process to determine if progress is being made towards the standard.

Method 1 is easier and faster to implement, but is less accurate and may be appropriate for quick circadian studies for making massing and rough electric lighting decisions. It may be only appropriate for comparative studies of multiple options when time and computational resources are constrained.

Method 2 is approximately eight times more computationally intensive than Method 1, but more accurately reflects circadian daylight within a space by accounting for directionality. Use of this method can help make fine-grained decisions about use zoning within a building, floorplate layout, and workstation orientation and further refine a design.

The proposed circadian daylight analysis methods easily integrate into the design process to assess circadian daylight potential, but do not holistically address the full range of daylighting concerns in a project. Circadian daylight simulation should be used early in the design process, but must be coupled with traditional daylight analysis to evaluate illuminance levels and glare potential throughout the year. Because the proposed simulation methods look at such a narrow issue, the impact of design decisions based on circadian daylight need to be assessed in relation to potential for increased energy consumption from conditioning energy, visual glare potential, and useable daylight.

FUTURE WORK

Using these results, this team will develop a tool to verify designs for the WELL building standard. This will ideally take place in collaboration with WELL or GBCI, to verify the methodology and get approval for use of this type of analysis within the benchmarking workflow. Analysis option 2 may be appropriate for documenting compliance with the WELL Building Standard 54 Circadian lighting design, which could eliminate or reduce the need to simulate each workstation individually in a flexible workspace, reducing the time needed to produce documentation.

Method 2 requires further refinement of the graphic representation to convey more information to the designer about degree of compliance with the circadian lighting threshold, not only compliance/noncompliance information.

Future work to integrate dynamic electric lighting into simulations can determine the minimum amount of electric lighting needed to provide sufficient circadian daylight, minimize energy consumption, and reduce first cost of combined electric lighting system and automated shading system. In addition, a more detailed assessment of how circadian daylight interacts with other daylight metrics including glare and useable daylight is needed.

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