The Space Between Research and Practice: A Critical Evaluation of Computer-Based Lighting Metrics

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Abstract

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This thesis identifies and explores computer-based lighting metrics, assessing their effectiveness in evaluating the quality and quantity of daylight to bridge the space between research and practice. Ultimately, this thesis will demonstrate why using singular metrics is not as effective as using several, complementary metrics in expressing the luminous environment.

There are many challenges in practice and research- respectively, time or capabilities of a design team and lack of transparency or unrealistic metric criteria. Moreover, each metric- illuminance and luminance, point-in-time and annual- addresses different luminous qualities. It is critical to understand the nuances, as the results and corresponding design recommendations are highly dependent on the metrics used, and each metric carries technical inadequacies and limitations.

Aiming to study these challenges and critique the current landscape of computational lighting design, the objectives of this thesis are to: 1) Evaluate computational lighting metrics for their ability to provide an understanding of the luminous environment, and 2) Investigate the capabilities, assumptions, and methods used in computational lighting metrics as they are developed in the research community and used in practice.

These objectives are examined with exploratory vignettes. The vignettes elucidate each metric's strengths, limitations, and assumptions in a clearer, holistic way so that consultants within the field will be more knowledgeable. The outcome is a compendium of information and guidelines to help designers make informed decisions as they relate to selecting appropriate daylight metrics.

Acknowledgements

This thesis has been a long-term endeavor, starting with a transition from engineering to the sustainability field. The knowledge learned in practice along with the research conducted have all contributed and culminated in this thesis, as have the people I have encountered in these many paths of my life.

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Chapter 1 | Introduction

Natural daylight has many benefits; there have been studies on the ways in which exposure to natural light can improve overall well-being, productivity, and health. However, while the sun is predictable, daylight is highly unpredictable and variable. To characterize the nature of daylight, metrics are established.

Metrics are used in virtually every field. Using only one metric is limiting, as understanding depends on context, experience, knowledge, and perspective. Using metrics in conjunction with each other can be helpful in reaching a fuller understanding and making decisions accordingly. This is true in any field- economics, engineering, medicine, and the focus of this thesis, computational lighting design in the realm of design computing. Often, lighting metrics and their criteria are developed in research, then used directly in practice (Figure 1.1). Not often enough is it recognized that there is a space where research and practice overlap (Figure 1.2).

Computational lighting models and analyses that are in tune with the lighting environment support green design, increasing occupant comfort and reducing energy consumption. With new advances, practitioners are in a place now more than ever to advise smartly and thoughtfully. When working on a project, there should be framing to determine the question and project goals, and the analysis should be shaped around that. Appropriate metrics should then be selected, and if the metric does not answer the questions or goals as is, it is critical to modify or set new criteria and bounds. Similarly, researchers can frame their work around the needs in practice, developing new metrics with realistic criteria, and more clearly convey assumptions. The boundaries are becoming blurred, with practitioners becoming researchers and vice versa.

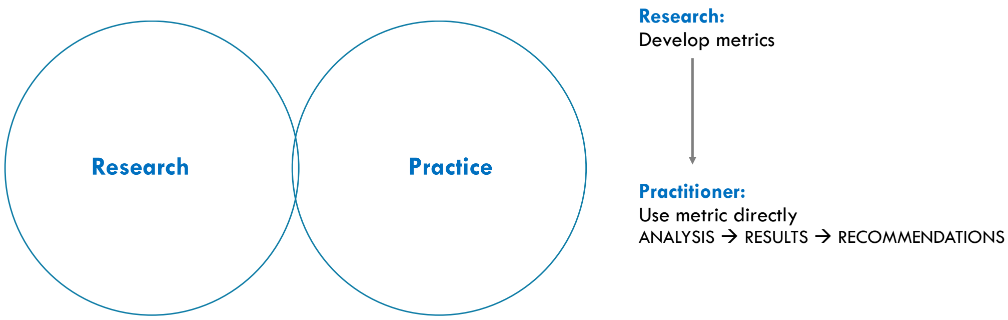


Figure 1.1 Common overlap of research and practice.

Figure 1.2 Ideal overlap of research and practice.

This model of overlapping communities and ideas is ideal, yet there are many challenges in practice, in research, and in metrics. In practice and research, respectively, time or capabilities of a design team and lack of transparency or unrealistic metric criteria are limiting. Moreover, each metric- illuminance and luminance, point-in-time and annual- expresses different luminous qualities. It is critical to understand the nuances, as the results and corresponding design recommendations are highly dependent on the metrics used, and each metric carries technical inadequacies and limitations.

This thesis addresses these challenges, assessing the effectiveness of computer-based daylighting metrics in evaluating the quality and quantity of daylight. To provide a framework, computer-based lighting methods are introduced and a survey of the available computer-based metrics are presented (Chapter 2: Literature Review). Performance of each metric is evaluated and limitations revealed using simulation-based exploratory vignettes, and guidelines are provided (Chapter 3: Evaluation of Metrics). With a better understanding of how these metrics are performing and the ways in which they are best implemented, conclusions are drawn (Chapter 4: Conclusions) with regard to the ways in which metrics are used and that which needs further development within the field, both theoretically and practically.

The intended outcome for the reader is a holistic understanding of computational lighting metrics from both a practice and research standpoint, from background and history to interpretation of simulation results. Although the intended audience is practitioners 'in between'- those who understand the basics, but who are not experts- varying pieces may be useful to a range of lighting professionals.

Chapter 2 | Literature Review

2.1 Background

As daylighting design questions become more complex, and new issues come to the forefront with an increasing emphasis on sustainable building design, the emergent questions center around the availability of adequate lighting methods and metrics. As such, over the years, new capabilities in computer graphics and 3D modeling have forged advances in the field of lighting simulation [1-3].

It is important to recognize the difference between lighting METHODS and METRICS. Lighting methods imply techniques and algorithms developed in a calculation or rendering process. The end goal, what the results of these methods are ultimately expressed as, are metrics.

Various lighting simulation methods have been developed, evolved, and validated, and with them come many metrics and tools. This chapter will first detail these methods, giving background regarding simulation techniques and algorithms, and will subsequently provide a survey of computational lighting design metrics, including their history of development and intended use.

2.2 Simulation Methods

Common to all simulation methods is that they should be accurate, general, and practical [4]. There is a handful of lighting simulation tools available for lighting professionals, and these tools vary in their simulation methods. This section will give background information about the rendering techniques and algorithms, as well as the primary components and processes used in computational lighting simulation.

2.2.1 Rendering Techniques and Algorithms

Each lighting simulation method has a different process, using complex, computationally intensive rendering techniques and algorithms. It is important to understand these computations for several reasons. For one, this understanding can lend in properly using the tools, as well as deciphering and analyzing results. The users who understand the underlying computation mechanisms, limitations, and capabilities know what to expect, with regard to the output and level of accuracy. Significant amount of errors in simulations result from missteps that beginners and non-expert users make during the input process [5]. In addition, knowledge and comprehension of the nuances and processes involved will promote development of better tools and deployment of best practices in this field. That is, it is more likely that positive changes can be made to current methods and tools if the challenges and difficulties are well understood.

Rendering techniques

Two techniques are generally used for rendering: *photo-realistic rendering* and *physically-based rendering*. The former has a focus on visual quality while the latter has a focus on light behavior [2-3]. Historically, photo-realistic rendering has been more widely used by architects and designers as an extension of other abstract representation techniques utilized throughout the design process [4]. Physically-based rendering has a focus on the light behavior and interaction in a model, and is therefore the technique employed for rendering lighting simulations, where accurate depiction of the luminous environment is the goal.

Algorithms

There are two predominant algorithms used in lighting simulation: *radiosity* and *ray-tracing*. Both methods have benefited from new developments over the years. In its generic usage, radiosity can calculate interreflections of light energy using a finite element method. It is view-independent, which makes it possible to generate one simulation model that can be observed from different viewpoints. A major shortcoming is that it is not capable of specular reflection calculations. On the other hand, ray-tracing is view-dependent, producing a single image as the outcome of the computation, but the current capabilities within this technique are more comprehensive and physically accurate with its diffuse, directional diffuse, and specular reflection and refraction algorithms [1].

Programs that use physically-based rendering as a basis employ ray-tracing, radiosity, or a hybrid between the two. The hybrid method is useful, as it combines the strengths of each algorithm and "the results of the combined approach are as close to reality as computers currently can make synthetic scenes appear to be" [6]. It is beyond the scope of this thesis to review all lighting simulation tools; however, a collection of available tools is available on the U.S. Department of Energy's website, in the Building Energy Software Tools Directory [7]. All simulation methods discussed in this paper use RADIANCE software [4], which utilizes Monte Carlo backward ray-tracing.

2.2.2 Inputs and Process

The key components of computational lighting simulation are the following three inputs:

- Geometry
- Materials
- Light sources

Modeling a scene is the first step of lighting simulation. Due to the comprehensive capabilities of computer graphics, creating 3D geometry in most models can be completed with relative ease [1-2]. In most modeling programs, the complexity of geometry is nearly unlimited such that the scene of interest, with any pertinent details, furniture, and immediate surroundings, may be practically and accurately represented. Moreover, the computation time does not grow linearly with the number of surfaces [4]. This feature allows the user to include an appropriate level of detail without sacrificing complexity, and potentially accuracy, for time.

Once the geometry has been created, material properties may be assigned. These properties greatly affect the accuracy of a lighting simulation model. In order to translate what is seen in the real world to the digital domain, there are inevitable simplifications; however, materials should be a dealt with carefully when building a model, since these properties largely dictate the resulting light behavior. As advances are made in the lighting simulation field, it has become feasible to simulate materials that more closely mimic reality. The material properties of interest in lighting simulations include color, reflectance, and transmission. Although a simple local reflectance model may be used to determine reflectance and transmission, it can be useful to calculate these properties more accurately. Therefore, in some physically-based rendering models, reflectance and transmission are calculated with the Bidirectional Reflectance Distribution Function (BRDF). The BRDF "correctly predicts the diffuse, directional diffuse, and specular components of the reflected light. It is a function of the wavelength, surface roughness properties, and the incoming and outgoing directions" [1]. Materials are also defined with color, which is expressed as RGB, and defines the diffuse reflectance of any given material.

Finally, the light sources of a model can drastically change the lighting environment, and as a result, the occupant comfort and energy usage of a building. Light sources as they relate to lighting simulation can be divided into two categories: electric lighting and daylighting. The photometric data for an electric light source model is defined by its spectral content, amount of energy, and the candle power distribution curves. The daylighting environment of a model must reflect the unboundedly complex and dynamic nature of daylight in the real world, which presents a significant challenge. Daylighting for computational lighting simulations is typically defined by the position of the sun in the sky and the distribution of diffuse light in the sky dome via sky models. While the sun position changes predictably based on location, sky conditions are unpredictable [1]. Three sky modeling techniques are used in computational lighting simulation:

- CIE sky models [3]
- Perez All-Weather sky model [3]
- Image-Based sky models [8]

The International Commission on Illumination (CIE) has developed standard sky luminance distribution models to be used in lighting simulations. These "[s]ky models are mathematical constructs, used by computer simulation tools, to describe the sky luminous distribution, i.e. the amount of light coming from different parts of the celestial hemisphere" [9], whether it be direct sunlight or diffuse daylight. There are 16 sky types, ranging from overcast, to intermediate and uniform, to clear. The RADIANCE software can generate three standard CIE skies- clear, intermediate, and overcast- in its 'gensky' program [4]. The main advantage of CIE sky models is that they are accessible. The CIE sky model is rather basic, but more advanced practitioners are able to adjust the sky model to certain parameters. Using gensky with the -B option allows the user to input the diffuse horizontal Irradiance and the -R option allows the user to input direct horizontal Irradiance. The RADIANCE software can also generate Perez All-Weather sky models through its 'gendaylit' program [4]. The Perez All-Weather sky model uses weather data in a mathematical construct, controlled by diffuse horizontal irradiance and direct normal irradiance (gendaylit -W and -G options). This sky model is considered to be less generic due to its use of weather data and is used in annual daylight simulations. While the mathematical sky models are accessible to practitioners and are able to provide a general idea of the daylight performance, Image-Based sky models introduce a new outlook. Based on the premise of "improv[ing] the accuracy of simulations with site specific sky conditions" [8], this method uses high dynamic range (HDR) photographs of the sky in lieu of standard CIE or Perez sky models.

2.2.3 Outputs

The lighting units used to describe luminous environments are *illuminance* and *luminance*. In all simulation methods, once inputs have been included in a model, the simulation engine calculates the transport and the output is presented as a collection of illuminance or luminance values. Illuminance is the total luminous flux incident on a surface per unit area, or in simpler terms, the amount of light falling on a certain plane or analysis grid, calculated based on the light source and the reflecting properties of surrounding surfaces. It is measured in footcandles (fc) or lux (lx), where 1 footcandle is equivalent to approximately 10.8 lux [10]. Luminance is the luminous intensity per unit area, or in simpler terms, the amount of light reflected from a certain surface in a given direction. It is measured in candela per square meter (cd/m^2). As luminance denotes the amount of light in a specific direction, such as the viewpoint or the eye, it correlates better with the human visual comfort and performance. The difference between illuminance and luminance is illustrated in Figure 2.1.

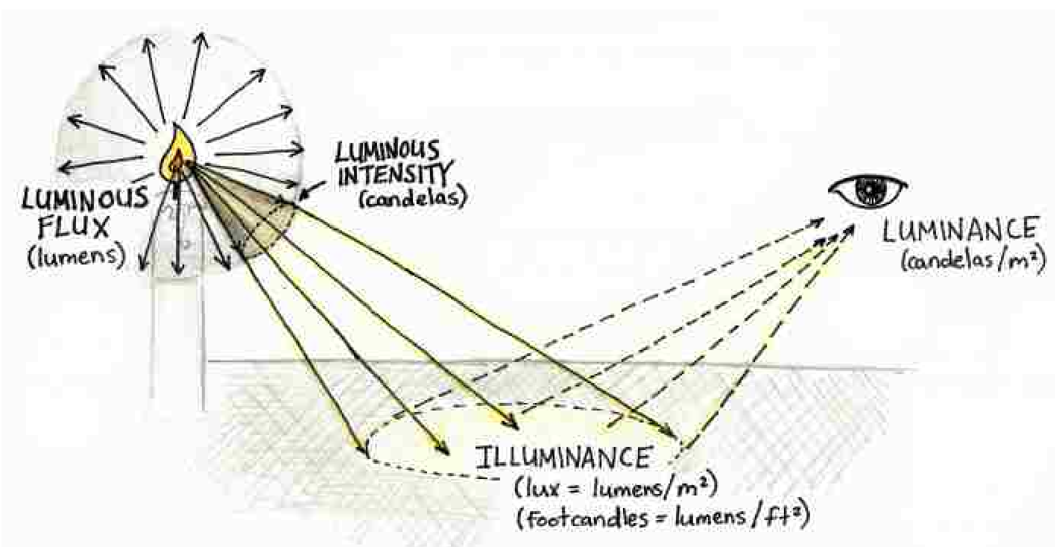


Figure 2.1 Illuminance vs. luminance [11].

A simple example would be a task light at an office desk. The amount of light that falls on the desk is the illuminance, but the light that is reflected off the desk (luminance) would differ depending on the color of the desk (whether it is dark or light) and the directional reflection properties of the desk surface (whether it is matte or glossy: the highlights in glossy surfaces would change in size depending on the glossiness of the material, and the highlights would change in direction depending on the geometric relation of the worker's eye in relation to the desk and the light source). Illuminance typically informs studies on the amount of useful light in a space, while luminance informs the visual effect (intended brightness), comfort (absence or presence of glare) and performance (task visibility) in the given environment.

Computational lighting simulation using physically-based rendering typically generates an image as well as numerical data. Both are necessary to evaluate the results of a lighting simulation, as the process is qualitative and quantitative. Visual outputs containing the illuminance data are typically represented as a horizontal grid, and can be used to evaluate the light levels in a space, as shown in Figure 2.2 below. Outputs containing the luminance data for the area of interest can be used to generate renderings and falsecolor images, contour plots, daylight factors, and glare analysis, as shown in Figures 2.3a and 2.3b below. These images are often generated in a variety of formats, but common to all is the technical difficulty of displaying high dynamic range of lighting values that are typically experienced in daylit and electrically lit spaces on display devices that have much narrower dynamic range display capabilities. This is where numerical values become useful. Images in conjunction with numbers tell the full story of the lighting environment, and can therefore better inform design decisions [1].

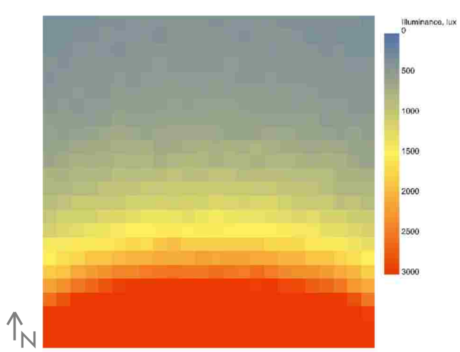


Figure 2.2 Illuminance data.

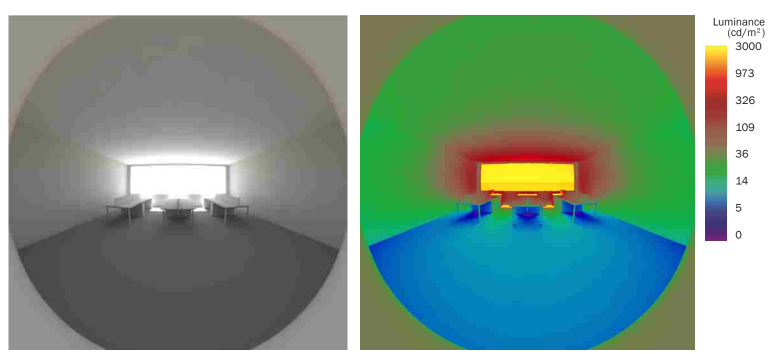


Figure 2.3 Luminance data.
a. Rendering b. Falsecolor

2.3 Computational Lighting Metrics

A myriad of computer-based approaches are available to evaluate quality and quantity of daylight. There are two main layers in computational lighting metrics: illuminance-based versus luminance-based, and point-in-time versus annual.

ILLUMINANCE, task-driven metrics are derived from well-established illuminance recommendations [10], and for this reason they are easy to utilize. However, often the goal is not only to optimize the amount of light falling on a workplane, but also to provide a visually stimulating environment and appropriate distribution. For this reason, in recent years, studies have been performed to provide more well-defined and quantifiable LUMINANCE-based metrics [12-15].

When deciding on appropriate metrics for a project, another compounding factor is whether the analysis should focus on selected POINT-IN-TIME studies or ANNUAL trends.

Table 2.1, below, shows a survey of primary metrics used in computational lighting design and analysis.

	Illuminance	Luminance
Point-in-time	Illuminance (calculation grid)	Luminance (renderings and falsecolors)
	Daylight Factor (DF)	Glare (DGP)
Annual	Daylight Autonomy (DA)	Annual Glare (DGP)
	Useful Daylight Illuminance (UDI)	Annual Contrast and variability metrics
	Average annual illuminance	
	Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)	

Table 2.1: Survey of Computational Lighting Metrics

Note that there are more annual illuminance-based metrics than annual luminance-based metrics. However, with high dynamic range (HDR) photography methods coming to the forefront in recent years, the discussion is moving towards the power of human-centric, luminance-based metrics [12-15].

The subsequent sections will detail each of these metrics, using the following outline:

- Point-in-time
  - Point-in-time, Illuminance-based
  - Point-in-time, Luminance-based
- Annual Metrics
  - Annual, Illuminance-based
  - Annual, Luminance-based

2.3.1 Point-in-time Metrics

Illuminance and luminance point-in-time metrics are the most typical, and oldest, lighting simulation methods discussed in this thesis. Historically, these metrics were implemented using physical models and meters. With advancements in computer science and graphics, the measurement of illuminance and luminance became possible via simulation. Central to these metrics is the interest in one time of a single day at a single condition. Typical practices include selection of key dates and times to study critical boundary conditions within the year such as winter solstice under overcast sky condition, summer solstice under clear sky condition, and one of the equinoxes under intermediate sky condition. Using physically-based rendering, the user can simulate this selected instance and obtain information about the lighting environment at that moment in time. This approach is the foundation for RADIANCE-based simulation engines [3-4,16]. Typically, point-in-time illuminance is presented as a horizontal calculation grid at the workplane, while point-in-time luminance is presented as a rendering and/or falsecolor image. Both contain a numerical and a visual aspect.

Point-in-time, Illuminance-based

POINT-IN-TIME ILLUMINANCE

Point-in-time illuminance is the most common illuminance-based metric used in practice. Target design illuminance is typically determined using Illuminating Engineering Society (IES) guidelines [10], based on the program of the space, or specific recommendations from the lighting designer or the design team. Aside from IES recommendations, there has been much research on maximum allowable illuminance values and ratios. A reasonable maximum illuminance is considered to be approximately 2,000-3,000 lux, beyond which potential for glare risk increases.

With a tangible target, point-in-time illuminance simulations provide a concrete analysis that can determine whether the space is performing as intended. Since it is not view-dependent, it is a straightforward analysis that can be simulated under various conditions to perform comparisons of design options.

While point-in-time illuminance is a common metric in its own right, LEED [17] has cast a wider net, as Indoor Environmental Quality (IEQ) credit 8.1: Daylight prescribes simulation of point-in-time illuminance as an option to achieve the credit. If this approach is selected, the current version of LEED requires the illuminance on the fall equinox at 9am and 3pm, with clear sky condition, to fall between 10-500 footcandles (107-5,382 lux).

DAYLIGHT FACTOR (DF)

A simple variation of point-in-time illuminance is the Daylight Factor (DF). First coined in 1909 by Percy J. Waldram in the United Kingdom [18-19], known then as the Sky Factor, Daylight Factor is one of the oldest daylighting metrics. Developed as a response to light rights, Daylight Factor is defined as the percentage of outdoor illuminance (E) that falls on the indoor workplane:

$$DF = (E_{indoor} / E_{outdoor}) * 100 \%$$

Waldram's original Sky Factor used a uniform luminance sky, but the current Daylight Factor uses the Standard CIE overcast sky model. According to Waldram, and the British Standards Institution, a good target for DF should be above 2% [20], though this varies based on the project program and the designer. It is often considered a 'more is better' approach, providing information regarding the worst-case scenario, when the least amount of light is present. However, an upper limit of 6% is often applied, to discourage overly high daylight levels.

This metric favors projects with toplighting, as the amount of area facing upwards is maximized. Simple calculation methods and guidelines, taking into account window-to-wall ratios, glazing type and area, outside context and obstructions, room dimensions, and material reflectances, have been developed in practice to determine if the target Daylight Factor will be achieved [21].

A benefit of using DF for comparison of design options is its stability; due to the use of an overcast and therefore diffuse sky, the percentage would not vary based on orientation. However, this could also be considered a disadvantage, as it would not realistically predict changes in climate conditions and orientation [20], or potential glare risk. It is more likely to accurately predict daylighting performance in a predominantly overcast climate than in a predominantly clear climate.

The Daylight Factor was adopted for early versions of LEED [17], originally requiring a DF of 2% for 75% of regularly occupied spaces. However, due to its limited scope, and focus on an overcast sky, it has been the subject of much criticism over the years and has been a driver to implement new metrics that better match the complexity and dynamism of daylight. While Daylight Factor can still be a sufficient predictor of a daylight availability particularly in predominantly overcast climates, its deficiency in glare detection has led to its declined use over the years.

Point-in-time, Luminance-based

POINT-IN-TIME LUMINANCE

Point-in-time luminance simulations, expressed with renderings and falsecolor images, provide an understanding of the exprience of a space. As they are time- and view-dependent, it is critical to determine the appropriate questions the simulation is intended to answer, and carefully select useful times and viewpoints. While the viewpoint is typically a 3D view located in the interior of a model, it is also possible to simulate a rendering of a section, cut at a chosen location. The former allows the designer to pinpoint a specific area of the project and gain an understanding of how the space will feel from that particular vantage point. The latter provides a bigger picture viewpoint, showing the distribution of light through the architectural volume.

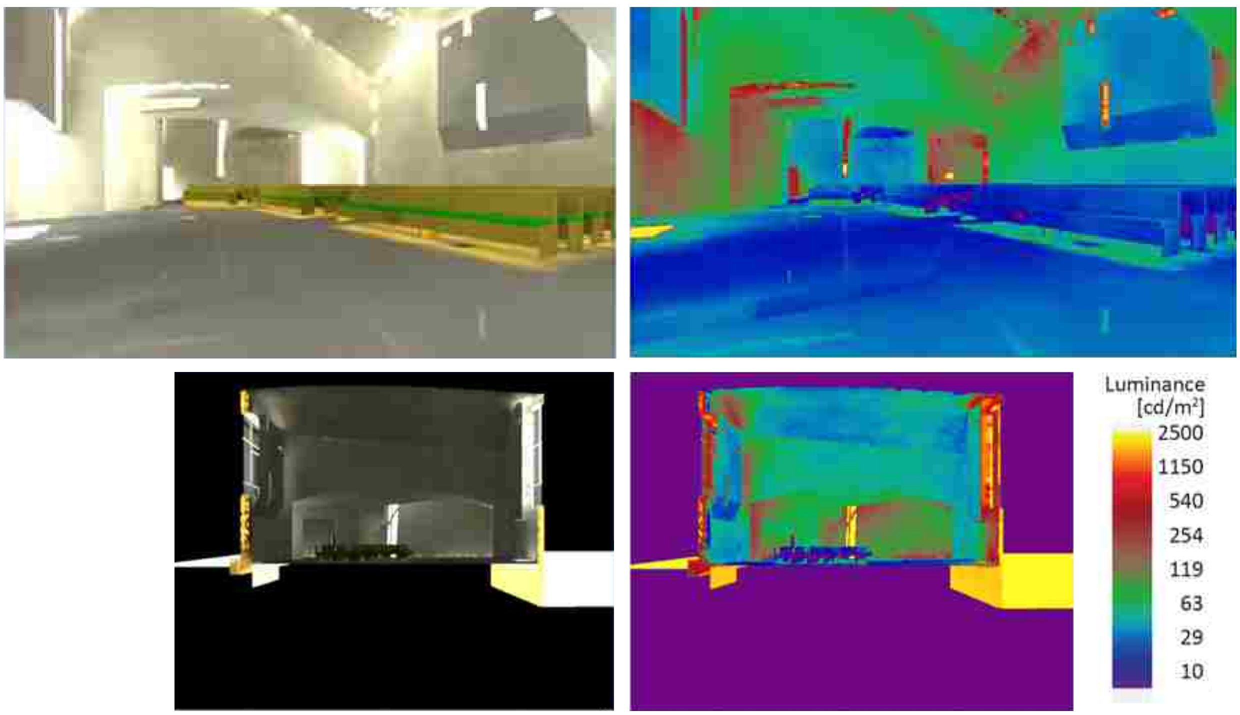


Figure 2.4 3D and section renderings and falsecolors
for Chapel of St. Ignatius, Seattle, WA.

The elements that impact the luminous environment are highly variable. As daylight is also highly variable, "[f]ew previous studies describing preferred luminance ratios in settings with daylight are available" [22]. Although there has been research on acceptable minimums and maximums (a maximum of 3,000 cd/m² is often used in practice), luminance is best understood through a relationship, as it is relative. The eye can adjust to various light levels, so even if a space reaches 3,000 cd/m^2, if it is bright everywhere, there might not be glare risk. One of the most common ways in which to understand luminance renderings is with ratios. It has been noted that "[t]he simplicity of this metric is its greatest strength, but literature is not available to defend the current recommendations" [22]. The following luminance ratios have been developed over the years [22]:

- IES maximum 20:1 between daylight-media and daylight-media-adjacent-surfaces
- Halonen and Lehtovaara 1:2.25-10 with average of 1:5
- Sutter 1:6:20 (task:adjacent:remote)
- Van Den Wymelenberg: up to 1:50
- Van Den Wymelenberg and Mehlika Inanici 22:1 (Mean L Window:Mean L Task)

An appropriate amount of variability is ideal, but too much variability might result in visual discomfort. It has been found that the presence of light levels that are too bright in the periphery is not as bothersome as bright light levels in the direct line of vision; moreover, a half hour of bright light levels is considered acceptable [23].

DAYLIGHT GLARE PROBABILITY (DGP)

Glare metrics are a complex manifestation of luminance, at their core concerned with visual comfort. Although many glare metrics have been developed over the years, most are intended for electrically lit spaces. Discomfort Glare Index (DGI) and Daylight Glare Probability (DGP) are the exception, as both were intended to analyze daylit spaces. DGI was developed using compact fluorescent lamps to mimic natural daylight at Cornell in 1972. It was the predominant glare metric used for many years; however, it does not accurately replicate human response to glare sources in daylit spaces. Introduced by Wienold and Christoffersen in 2006 [24-25], DGP is the predominant glare metric currently in use due to its ability to accurately predict potential glare risk in daylit spaces.

"[A] function of the vertical eye illuminance as well as on the glare source luminance, its solid angle and its position index," DGP indicates 'the probability that a person is disturbed.' Unlike previous metrics, DGP was developed using test spaces with natural sidelighting, at the Danish Building Research Institute in Denmark and the Fraunhofer Institute for Solar Energy Systems in Germany. Each facility was equipped with two test spaces: one with a CCD camera and interior illuminance sensors to capture the luminance distribution and intensity, and another with test subjects asked to comment on their level of visual comfort in the space during various tasks at two viewing directions. The test spaces were capable of being fully rotated, and were equipped with three window configurations and three solar shading devices so that users would experience a range of orientations and conditions. The tests were done over 1 hour, 45 minute periods in the morning and afternoon.

To replicate the detection of glare sources by the human eye, three glare detection algorithms were developed and compiled into an evaluation tool, evalglare [26]. In practice, DGP via evalglare is available in RADIANCE [16], DIVA [27], and hdrscope [28]. As luminance is view-dependent, the viewpoint in question is critical. A view must be set using a 180° fisheye camera (RADIANCE parameters -vta -vh 180 -vv 180), and the simulation will produce a fisheye luminance rendering as shown in Figure 2.5, with colored areas indicating potential glare sources and a calculated value for DGP, as follows:

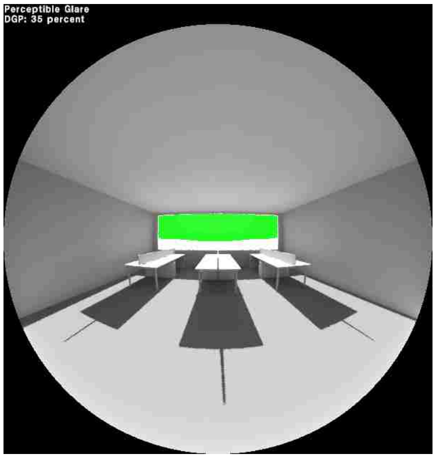


Figure 2.5 DGP image.

There has been much debate regarding the most appropriate thresholds for glare. Wienold and Christoffersen developed the following scale [29]:

Imperceptible glare: DGP $<$ 0.35
Perceptible glare: 0.35 $<$ DGP $<$ 0.40
Disturbing glare: 0.40 $<$ DGP $<$ 0.45
Intolerable glare: DGP $>$ 0.45

However, Kevin Van Den Wymelenberg and Mehlika Inanici's recent research has shown that DGP may underpredict glare, and that a DGP of 27% may be considered "just uncomfortable" [22]. Their research indicates that the following scale might be more appropriate:

Likely to be comfortable: DGP $<$ 23%
Bounded borderline between comfort and discomfort (BCD): DGP 23-25%
Likely to be uncomfortable: DGP $>$ 25%

Van Den Wymelenberg and Inanici suspect that the potential discrepancies between their findings and those from the previous DGP work can be attributed to a different view direction used in the testing environment and sunlight in the task region that may result in missing glare sources. The research indicated that "the metric, as it is currently defined may not be sensitive enough for use as a daylighting design guide or as part of an automated blind control algorithm as a singular metric" [22].

Current Use and RADIANCE

A point-in-time simulation might be preferred if the design team only requires an understanding of the daylight levels for specific days, usually extreme conditions. This is often the case in preliminary design phases. For example, consider a classroom with a deep floorplate and a few potential skylight options. The design team might be interested in comparing the skylight options. Rather than performing a dynamic simulation for the entire year, it would suffice to simulate one day under certain conditions. A reasonable starting point for the study in this case would be an equinox or solstice with both a sunny sky and an overcast sky condition. Once the optimal skylight option has been selected, the design team might be interested in particular dates of interest, or annual studies, to ensure that the design is working optimally.

RADIANCE [4,16] can be used for point-in-time illuminance, Daylight Factor, point-in-time luminance, and DGP studies via programs such as Ecotect [30], DIVA for Rhino [27], or accessing it more directly through command line and the RADIANCE Control Panel. Since RADIANCE is a free program rather than a commercial product, it has remained accessible to its users since its first release in 1989. Due to its accessibility, and despite its steep learning curve, it has found "an enthusiastic, active, and growing user base, which has provided invaluable debugging help and stress-testing of the software" [4]. This program allows users to accurately compute and predict the lighting conditions of a space due to its use of the hybrid deterministic/stochastic Monte Carlo backwards ray-tracing algorithm and its ability to handle most combinations of inputs and conditions [3,16]. RADIANCE was validated as a lighting simulation engine under real sky conditions for both overcast and clear skies [31-33].

Point-in-time simulations using RADIANCE-based engines is the most commonly used computational lighting method. In fact, a survey completed in 2006 among a mix of professionals showed that "50% of program selections were for tools that use the RADIANCE simulation engine" [34]. This percentage is sure to be slightly different now, but it is evident that for the past several years RADIANCE-based engines have evolved to become a useful and commonly used lighting simulation method.

2.3.2 Annual Metrics

Point-in-time and dynamic daylight simulations each have their own place depending on the desired results and information necessary to inform a design. The limitations of using point-in-time metrics in capturing the complexity of daylighting serve to strengthen the case for using dynamic daylighting metrics. With the improved computational capabilities over the years, it has become possible to perform simulations using weather data, which accounts for complex variations in daylight [34]. As opposed to the single instance outputs of point-in-time simulations, dynamic daylight simulations- using the Daylight Coefficient method and the Perez Sky Model- provide information for the entire year.

The Daylight Coefficient method was developed to facilitate dynamic daylighting simulations [35-36]. The aim of this method is to "predict hourly internal daylight illuminance levels for an entire year" [33] by utilizing daylight coefficients. Originally developed by Peter Tregenza in 1983 [37-38], it was not implemented until decades later [39]. The method was validated using the Building Research Establishment's International Daylight Measurement Programme (BRE-IDMP) dataset [31-33]. The premise of the Daylight Coefficient method is that daylighting can be thought of "as a series of transformations of sunlight – scattering in the upper atmosphere, diffusion by clouds, selective transmission by windows, and complex interreflection between many surfaces" [38]. As such, for a lighting simulation to accurately reflect this process and the real-life conditions, "predictions need to be based on the full range of naturally occurring sky conditions" [33]. Thus, this method first calculates daylight coefficients and then uses hourly weather data over an entire year- which is associated with luminance values- to perform calculations. These steps are detailed below.

1) *Split CIE sky models into equal patches.* As mentioned in Section 2.2.2, light sources are defined by CIE sun and sky models. The traditional daylight coefficient method first divides the sky model into 145 equal "patches" [40], as shown in Figure 2.6, although in current use it can be divided further. The original sky subdivision and scanning sequences proposed by Tregenza is shown in Figure 2.6.

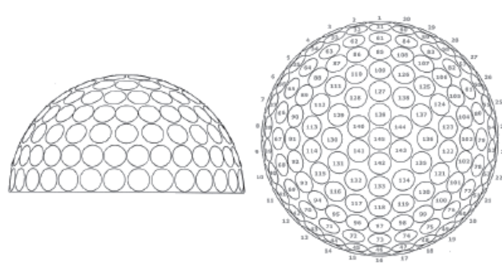


Figure 2.6 Breakdown of 145 equal sky patches [41].

2) *Determine the contribution of each sky patch.* Each sky patch has a different contribution to the daylight entering a scene, which is dependent on the geometry of the scene and the altitude of the sky patch in relation to the scene of interest. For example, in an office with only south facing windows, the portions of the sky that are to the north will have no contribution and the portions of the sky that are to the south will have the largest contributions. The Daylight Coefficient method uses ray-tracing as its computational algorithm; the contribution of each sky patch is determined by tracing from points in the scene to each respective sky patch. Figure 2.7 below illustrates the relationship between the sky patch and the scene of interest.

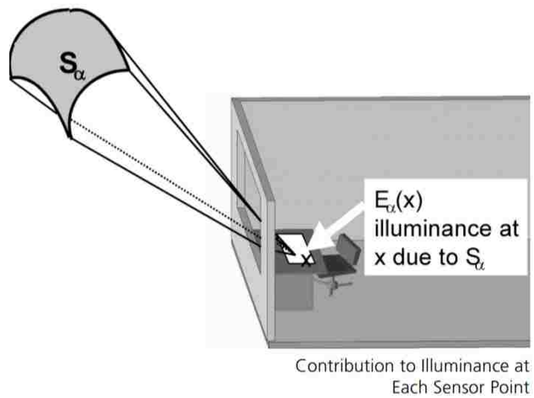


Figure 2.7 Contribution to illuminance E at point x due to sky patch S_α [42].

3) *Calculate daylight coefficients associated with each sky model.* Using the Standard sky model, "[a] set of coefficients are calculated only once prior to simulation start for a given number of elemental patches making up to sky vault and ground" [39]. That is, a bundled set of coefficients is calculated for a uniform sky, which do not require re-calculation for every simulation. The daylight coefficient is defined as "the fraction of the emitted light that finds its way to the" point of interest [43], such as at the desktop in Figure 2.7.

4) *Use annual hourly weather data to calculate actual illuminance (or luminance) values.* The daylight coefficients are used in conjunction with hourly weather data to calculate illuminance for a selected horizontal plane. The Perez All-weather sky model is derived for each hour in the weather data file. Then, "once the daylight coefficients have been calculated, they can be used to find the surface illumination from any sky luminance distribution" [43]. The fundamental equation that governs the Daylight Coefficient method is as follows:

$$Ex_\alpha = L_\alpha s_\alpha dx_\alpha$$

where:
Ex_α = illuminance at the desktop (or other point of interest)
L_α = luminance of the sky patch
s_α = angular size of sky patch
dx_α = daylight coefficient

This method efficiently and accurately computes hourly illuminance values. The data generated can be translated into annual illuminance metrics such as Daylight Autonomy and Useful Daylight Illuminance [35]. The Daylight Coefficient Method is now most widely used in DAYSIM, derived from Daylight Simulation Program [3,44]. DAYSIM is a front-end software interface that works with the RADIANCE engine; it is specifically developed to perform annual lighting calculations.

While DAYSIM is primarily used to implement the Daylight Coefficient Method for annual illuminance-based simulations, rtcontrib can be used in both luminance- and illuminance-based annual simulations. Developed by Greg Ward in 2005 [45] and rewritten in 2012 as rcontrib [46], the program finds the 'ray tracing contributions' of each source or sky patch. A tutorial was developed by Axel Jacobs in 2010 [47] to shed light on the process and show its merits in dynamic daylighting simulations.

It is important to note that "[d]aylight coefficients are invariable to building orientation for a fixed building configuration" [33]. The challenge occurs when a building has more complex façades, including dynamic shading, or variable building configurations. In this case, the daylight coefficients for each sky patch would require re-calculations for any such change. Efforts have been made over the years to remedy this issue but are still in progress [39].

Annual, Illuminance-based

DAYLIGHT AUTONOMY (DA)

The concept for Daylight Autonomy (DA) was first introduced as early as 1989 in a Swiss norm [35,48], and was developed into the current metric by Reinhart and Walkenhorst in 2001 [49]. One of the first metrics to address the dynamic nature of daylight, Daylight Autonomy is defined as the percentage of occupied time that the target illuminance level is achieved at the workplane. Continuous Daylight Autonomy (cDA or DA_{con}), was a more recent development, proposed by Zack Rogers in 2006 [35,50], which gives partial credit to points on the workplane that achieve a percentage of the target illuminance level. For example, if the target illuminance level is 300 lux, and a point receives 250 lux, in standard Daylight Autonomy that point would simply be considered non-compliant. In Continuous Daylight Autonomy, that same point would count as 0.83 towards the final percentage.

As a counterpart to DA and cDA, Rogers introduced maximum Daylight Autonomy (maxDA or DAmax) in response to glare considerations [35,50]. It uses a threshold defined by a "sliding level equal to ten times the design illuminance of a space" [35]. maxDA has not been included in many computational lighting tools explicitly, though it is possible to calculate it by manually post-processing illuminance data.

USEFUL DAYLIGHT ILLUMINANCE (UDI)

In 2005, Nabil and Mardaljevic critiqued the Daylight Factor as a one-dimensional indicator, noting that its non-predictive, singular date and sky condition has contributed to the under-utilization of natural daylight as a resource. Moreover, previous annual illuminance metrics- such as Daylight Autonomy- do not prescribe an upper limit, which led Nabil and Mardaljevic to develop Useful Daylight Illuminance (UDI) [51-52].

Rather than using a single target illuminance value, UDI takes a range of values into account. That is, UDI is an annual calculation of daylight on the workplane within a specific illuminance range that is considered useful for the task. This range was originally defined by Nabil and Mardaljevic as 100-2,000 lux, but was later amended to 100-3,000 lux [35,51-52]. UDI is defined as the percentage of daylight hours that the illuminance is below ($PE < 100$ or UDI_{min}), within (P_{udi}), or above ($PE > 2k$ or UDI_{max}) the target threshold. Only the values within the target range count towards the UDI percentage. UDI_{min} and UDI_{max} are helpful in determining the cause for non-compliance. If there is a high percentage for UDI_{min}, it would indicate that the space has low light levels. Conversely, UDI_{max} takes into account only values that exceed the upper limit; this limit also corresponds to the daylight levels at which glare issues might occur [51-52]. Evaluating for UDI alongside UDI_{min} and UDI_{max} can lead to a better understanding of how the space is performing. Although there is no required value to achieve UDI, a higher percentage indicates a better, more useful daylit space, with 100% being the target.

While UDI is not a direct equivalent of DF, it does share the quality that it is illuminance-based, and measured at the workplane. However, unlike DF, UDI is a climate-based, annual metric. The dynamism of the metric matches the complexity of daylight, and studies have pointed to the merits of this, indicating that it should replace DF [53].

AVERAGE ANNUAL ILLUMINANCE

Rather than expressing the illuminance of a space in terms of a percentage, Average Annual Illuminance provides a node-by-node illuminance value. Average Annual Illuminance can be calculated by post-processing outputs from DAYSIM. It is typically presented on a horizontal calculation grid in terms of illuminance [lux] or as a daylight distribution curve through a section in terms of illuminance [lux] vs. distance from façade [ft]. The benefit of Average Annual Illuminance is that it provides tangible illuminance values over an entire year. The disadvantage is that these values are averages, therefore the results show only trends. Outliers may distort the results, and the results do not show peak maximum and minimums throughout the year.

This metric provides a big picture understanding. This level of detail is useful at the beginning stages of a design, to assess the general daylight levels and distribution of a space, allowing the designer to see the general trend in the space. It can be used to determine daylight potential and façade optimization. It is especially useful when comparing design options quickly, particularly when specific questions and priorities are unknown. Average Annual Illuminance is not a widely used metric, but rather it is used by select environmental design consulting firms [54] and individuals in the daylighting field. The most straightforward approach is to post-process results from DAYSIM, however, new emergences and tools such as Grasshopper [55] make it possible to be implemented in parametric analysis.

SPATIAL DAYLIGHT AUTONOMY (SDA) & ANNUAL SUNLIGHT EXPOSURE (ASE)

In 2012, the IES Daylight Metrics Committee developed a new set of metrics in response to the need of better-defined dynamic daylighting metrics. Spatial Daylight Autonomy (sDA) is a modified version of Daylight Autonomy, wherein the floor area is taken into account; it is defined as the percentage of floor area that achieves 300 lux for a minimum of 50% of occupied hours. Annual Sunlight Exposure (ASE) is defined as the percentage of floor area that achieves at least 1,000 lux for a minimum of 250 occupied hours per year [56]. Other requirements and assumptions are as follows:

- Analysis grid should be no more than 2'x2'. Node groups should be zoned by façade.
- Assumes 8am-6pm schedule (3,650 hrs).
- For the sDA simulation, if any node within a group exceeds 1,000 lux at any given time, shading will be deployed.
- ASE uses 0 ambient bounces, pinpointing only direct sun effects. Only static shading may be present for the ASE simulation.

Presented in conjunction, the goal is to maximize Spatial Daylight Autonomy (sDA) to ensure sufficient daylight levels and minimize Annual Sunlight Exposure (ASE) to mitigate potential glare issues. Their introduction to as a pair highlights the power of two metrics as opposed to one. While these metrics are extremely new and therefore might take a while to become more widely adopted, they have been incorporated into the LEEDv4 daylight credit (Option 1), with the thought that they better determine a well daylit space than the previous LEED 2009 EQc8.1's point-in-time illuminance metrics [17]. That said, it is yet to be determined if these metrics address the shortcomings that previous dynamic daylighting metrics might be lacking.

Annual, Luminance-based

ANNUAL DAYLIGHT GLARE PROBABILITY

Annual Daylight Glare Probability (Annual DGP) uses the same concept of point-in-time DGP, extending the metric to account for the complexity of annual variations, with a slightly different method. Two of the main factors in the DGP calculation are vertical eye illuminance and the glare source luminance. In a point-in-time DGP calculation, both factors are taken into account. Theoretically, annual DGP can be calculated by generating images for each hour of the year for one viewpoint; practically, this process would require simulation times of "over half a year" [57]. Due to the intensive computing time needed to calculate the effect of individual glare sources and produce a corresponding image for each hour of the year, a simplified method that is solely based on vertical eye illuminance was developed. This method is aptly denoted as the Simplified DGP method, or DGPs. However, inclusion of the glare sources would increase the reliability of the metric, and therefore the Enhanced Simplified method was developed. This method, via DAYSIM, involves calculation of the vertical eye illuminance with multiple ambient bounces as specified in rendering parameters along with a rendering for each hour of the year with 0 ambient bounces (direct sunlight only). An ambient bounce sensitivity test was conducted, and the results showed that this would be acceptable in producing reliable results, except in cases with a scattering material, such as a fabric shade [57].

This metric can be very useful to explore the effectiveness of various shading options, as shown in Figure 2.8 comparing the options of ‘No shading,’ ‘Roller blinds,’ and ‘Venetian blinds’ for a central gathering space. The results are typically shown in a plot of hourly annual DGP values that are color-coded to indicate the level of discomfort. The hours marked with red indicate ‘disturbing glare,’ yellow indicate ‘medium glare,’ and the green indicate ‘degree of imperceptible glare.’ As with point-in-time DGP, there has been debate on appropriate thresholds.

Figure 2.8 Annual DGP charts for baseline and shading options.

In 2012, Reinhart and Jakubiec developed the concept of Adaptive Glare [58]. Using the understanding that potential glare risk changes with varying view directions and shading schedules, this method takes into account human flexibility. That is, if an occupant has the ability to turn 90° or deploy blinds when the current viewpoint when is considered ‘disturbing glare’ or ‘intolerable glare,’ the alternate view point might have only ‘perceptible glare’ or ‘imperceptible glare.’ This flexibility could greatly reduce the amount of time during which shading devices are needed, consequently optimizing natural daylight and reducing electric lighting usage and energy consumption.

ANNUAL SPATIAL CONTRAST AND LUMINANCE VARIABILITY

The narrow focus of task-driven, illuminance-based computational lighting metrics has been the subject of criticism in recent years, with the notion that illuminance at the workplane may not serve to be the best indicator to describe all characteristics of the luminous environment [59]. Rockcastle and Andersen offer an alternative perspective and make the case for new metrics based on "perceptual qualities of daylight" [60]. In introducing a new typological language, it becomes possible to discuss such perceptual qualities more tangibly and comparatively rather than simply intuitively.

Their metrics were developed using a matrix composed of imagery of contemporary architecture spaces, categorized as extremely uniform to highly variable. The method involves translating the bright and dark areas in the chosen images into the newly established metrics: Annual Spatial Contrast and Annual Luminance Variability. Annual Spatial Contrast represents localized contrast differences between pixels accumulated across a year, while Annual Luminance Variability "describes the cumulative variation in brightness across the year" [60]. The metrics are intended to be used together to provide a holistic understanding of a space's perceptual environment.

The metrics were applied to simplified models and case studies to illustrate their usefulness. By comparing the new spatio-temporal metrics to task-driven metrics such as DF, DA, and DGP for a variety of space types, the importance of using the appropriate metric depending on program and intended use of the space was reinforced.

2.4 Synthesis

Each lighting simulation metric outlined in this chapter[1] has its own place, each having strengths and weaknesses, as well as different intentions and levels of usefulness in various applications. These are summarized in the following table:

Metric Name		intention	strengths	limitations
Daylight Factor		sufficient daylight	-Quick and easy. -Predicts well for a predominantly overcast location.	-Only takes into account overcast sky conditions, and does not predict well for locations that are not predominantly overcast.
Point-in-time illuminance		horizontal illuminance values to meet IES standards	-Allows specific exploration of a time and sky condition of interest. -Allows quick comparison of design options at typical or extreme conditions.	View- and time-dependent: Each simulation only provides limited, specific data that cannot be extrapolated for other times or sky conditions. Therefore, must test many different times.
Annual illuminance	Daylight Autonomy (DA) Continuous Daylight Autonomy (cDA)	sufficient daylight energy savings	-Provides a bigger picture understanding, indicating whether the design is generally above the target illuminance.	-Does not include an upper limit -Only shows general annual trends
	Useful Daylight Illuminance (UDI) 100-2000lux UDImin <100lux UDImax >2000lux	visual comfort	-Provides a bigger picture understanding, indicating whether the design is generally within the target illuminance range, as well as how often it is below or above the bounds.	-Only shows general annual trends -Upper and lower bounds do not vary based on program.
	Average Annual Illuminance	general range and distribution of daylight	-Provides a bigger picture understanding. -Provides a large amount of data that can be used to pinpoint specific times of interest to explore further.	-Only shows general annual trends. -Is not a widely known metric.
Point-in-time luminance		brightness levels, 'feel' of luminous environment and distribution of light in a volume, idea of what a space will look like	-Allows specific exploration of a time and sky condition of interest.	View- and time-dependent: Each simulation only provides limited, specific data that cannot be extrapolated for other times or sky conditions. Therefore, must test many different times.
Point-in-time glare		visual comfort	-Allows specific exploration of a time and sky condition of interest.	View- and time-dependent: Each simulation only provides limited, specific data that cannot be extrapolated for other times or sky conditions. Therefore, must test many different times.
Annual glare		visual comfort	-Provides a bigger picture understanding. -Provides a large amount of data that can be used to pinpoint specific times of interest to explore further.	View dependent. Uses 0 ab (cannot be directly compared to point-in-time glare). Does not take into account specular reflections.
Adaptive glare		visual comfort, with flexibility	-Expands annual glare such that it a range of views are considered.	-Assumes that the program type and furniture layout allow flexibility.
sDA300/50% ASE1000,250h		Amended LEED credit- intended to provide climate-based illuminance data as opposed to previous point-in-time illuminance LEED metrics. ASE shows potential glare risk while sDA is ensures sufficient daylight.	-Use annual weather data rather than point-in-time. -Together, sDA and ASE complement each other.	-The metrics are intended to be used together, and are not as powerful separately.
Annual Spatial Contrast & Luminance Variability		perceptual qualities of daylight	Provide a new perspective and groundwork to introduce annual luminance-based metrics.	Are not developed sufficiently to be used in computational lighting analysis.

Table 2.2: Metric Intentions, Strengths, and Limitations.

1 Note that Average Annual Illuminance and Annual Spatial Contrast and Luminance Variability will not be further explored, as they are, respectively, not commonly used and not fully developed for use in simulation; for these reasons, they will not be considered in the following chapter.

Point-in-time simulations, still widely considered the standard approach, allow the user to hone in on the analysis and understand specific moments; however, these are restrictive, as they do not allow the user to see more than one instance in time. On the other hand, annual metrics allow the user to see the accumulative results and understand annual trends, but are missing specific point-in-time information that is essential to inform the design. Moreover, illuminance and luminance metrics vary in the information they provide. Illuminance metrics leave out information that relates to brightness and human perception. They can indicate potential glare risk with ratios, but one would need to specifically perform a glare study to support that suspicion. On the other hand, for the most part, luminance-based metrics are view-dependent and require several tuned simulations. Moreover, they do not answer questions related to meeting target IES standards for code requirements, or indicate whether the lighting levels would be adequate for specific tasks, such as intensive reading, or programs, such as a museum with light-sensitive objects.

Such challenges motivate a critical evaluation of the current practices in the field of computational lighting. While the current tools and metrics can be effective if used appropriately, there is much room for improvement. In particular, any given singular metric is lacking in the ability to effectively convey and express the full extent of the luminous environment, and many contain limitations in their assumptions and methods that are not well understood by the entirety of the daylighting community. Using metrics in conjunction with each other can be helpful in achieving such an understanding and making decisions accordingly. To this end, recognizing the strengths and weaknesses of metrics is critical in choosing appropriately, and aptly pairing metrics. In performing a holistic analysis and evaluation of current computer-based lighting metrics, it is possible to understand the gaps and future needs within the field.

Chapter 3 | Evaluation of Metrics

The luminous environment encompasses many elements: *light levels* at the workplane (illuminance), *visual perception* (luminance, ratios), *visual performance* (luminance contrast, illuminance), *visual comfort* (luminance, ratios), and *variability* (annual, spatial). No singular metric provides information related to all aspects of the luminous environment. Kevin Van Den Wymelenberg points to this notion, stating that "it is unlikely that any single measurement type (illuminance, luminance, view quality) will adequately describe the bounds of human acceptance and preference in spaces with daylight." This is not only true due to both the inadequacy of a singular metric to express the full luminous environment, but also due to limitations within methods and algorithms.

This chapter will critically evaluate computational lighting metrics from both a practice and research standpoint, to demonstrate WHY using multiple metrics is more effective than using one singular metric in attaining a full understanding of the luminous environment. To this end, the following objectives have been identified:

1. Design Decisions: Evaluate 9 computational lighting metrics for their ability to singularly provide an understanding of the luminous environment. Illustrate that one singular metric might point to different recommendations than another singular metric.
2. Assumptions: Investigate the capabilities, assumptions, and methods used in computational lighting metrics as they are developed in the research community and used in practice. Reveal any inadequacies.

The intended outcome is a holistic critique of computational lighting metrics, and an understanding of what is lacking in the current metrics. Ultimately, this chapter will end with several sets of guidelines, including contradictory and complementary sets of metrics.

Vignettes are used as research settings to explore these objectives. Within each vignette, the following will be covered: BACKGROUND & MOTIVATION, METHODOLOGY, RESULTS, and DISCUSSION. The following vignettes have been developed as a means of discussing Objectives 1 and 2.

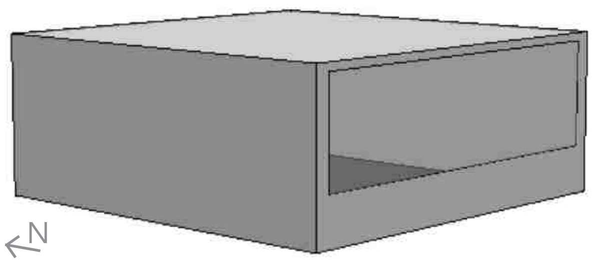
Objective 1 Design Decisions

- Metric-by-metric
- LEED

Objective 2 Assumptions

- Sky Models and Methods

Common to all vignettes is the following BASELINE. This model is intended to be general and simplistic in order to minimize variables and isolate the findings to the performance and limitations of the metrics, rather than the performance of the model itself. It follows rules of thumb for daylight distribution (floorplate depth = 2.5 x the head height of the window), excluding rules of thumb for solar control in order to show the 'worst case scenario.' As south-facing glazing was chosen, all point-in-time metrics were simulated for 12pm unless indicated otherwise. Conventional simulation material properties (20% floor, 50% wall, 80% ceiling reflectance) were used. Except where noted, the model was simulated for Seattle.



Note: This model is comprised of a 25'x25' floorplate and a large south-facing window. 2.5 times the glazing head height (9'-6") is 23'-9", almost the depth of the floorplate.

Figure 3.1 Baseline model.

Although the methodology differed between vignettes, the typical workflow was as follows:

- Illuminance: model (Rhino) > simulation (DIVA[2]) > post-processing (Excel) + image generation-horizontal calculation grid images (Rhino)
- Luminance: model (Rhino) > simulation (DIVA) > post-processing (hdrscope) + image generation (Rhino)
- Miscellaneous images: Ecotect (model geometry, shadow and sun path studies)

Based on sensitivity tests, it was determined that convergence of results occurs with 6 ambient bounces, and therefore this setting was used for all simulations.

2 The simulations in this thesis could be performed with any daylight simulation software. However, this thesis would have been very different had parametric tools such as Grasshopper been used. The 'optimum' would have been defined, which is not the goal. In doing each simulation separately, the author was able to interpret the results and evaluate whether each case met the criteria for each singular metric.

3.1 Objective 1 Design Decisions

3.1.1 Vignette: Metric-by-metric

Practitioners are often limited by time constraints, their software proficiency, and their general perception and understanding of available metrics. Too often, an understanding of one or two metrics develops a methodology and, as it is familiar and time-efficient, it becomes the default analysis approach. Another way of thinking is to push the boundaries on the metrics and analysis approaches as they stand, and frame each unique project with analyses and metrics that answer the questions at hand. This involves not only knowing which metrics to use, but also how to process, interpret, and represent the data. There must be a balance of efficiency (using familiar methods and metrics) and usefulness (tuning methods and metrics to the project). This vignette aims to shed light on ways in which sets of metrics contradict or complement each other. Ultimately, this metric-by-metric approach will give way to guidelines for using metrics in a balanced manner.

Methodology

1. **Pass/fail criteria was established.** This criteria is binary, with the purpose of assessing the relative performance of the metrics. In practice, criteria is often open to interpretation, and such analysis will be provided within the discussion for each metric. As such, it should be noted that the criteria should not be taken as design guidance or concrete criteria that can be generalized to all design. While it relates most closely to criteria for an office typology, it is intended solely for discussions in this thesis. The following table summarizes the established criteria for each metric.

Metric #	Metric Name		minimum	maximum	other criteria
1	Shadow and sun path studies		-	-	No direct sun on horizontal desk surfaces during occupied hours (8am-6pm).
2	Daylight Factor		2%	6%	
3	Point-in-time illuminance	at noon: June 21 clear September 21 intermediate December 21 overcast	300 lux	3000 lux	-Maximum contrast ratio of 10:1 -Uniform distribution
4a	Annual illuminance	Daylight Autonomy (DA) 8am-6pm | 300 lux	60%	-	Maximize
4b		Continuous Daylight Autonomy (cDA) 8am-6pm | 300 lux	60%	-	
5a		Useful Daylight Illuminance (UDI) 100-2000lux	60%	-	Maximize
5b		UDImin <100lux	-	20%	Minimize
5c		UDImax >2000lux	-	20%	Minimize
6	Point-in-time luminance	at noon: June 21 clear December 21 overcast	-	3000 cd/m2	-Maximum 22:1 ratio window:task -Appropriate variability -Should not be too dark throughout the space
7	Point-in-time glare		none	0.3 at 'worst case' condition adjacent to window winter at noon, clear sky	Minimize
8	Annual glare		none	0.3	Minimize. Should not exceed 0.3 for more than 10% of hours.
9a	sDA300/50%		55%	-	Maximize
9b	ASE1000,250h		none	10%	Minimize

Table 3.1 Metric-by-metric pass/fail criteria.

2. **The Baseline case was simulated for each metric.**
3. **Variations of the Baseline case were developed**: Alternate 1 Highly Glazed on South and West (below left) and Alternate 2 Small South-Facing Punched Windows (below right). These variations were intended to be extremes with regard to glazing percentage, and were simulated for each metric. They represent two of the greatest challenges in daylighting: too much glazing and too little glazing.

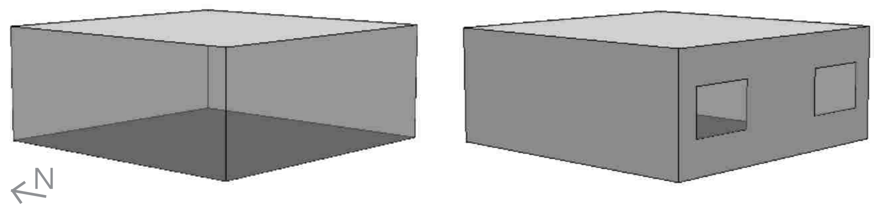


Figure 3.2 Alternate 1 and Alternate 2.

4. **An assessment of the scenarios was made**[3] , evaluating whether each case met the criteria for each singular metric. This assessment was intended to determine the percentage fitness; that is, the amount of times each scenario meets the criteria of a singular metric. The results reveal information about each case separately, as well as the larger context related to the spectrum along which they fall (high to low glazing) and its relationship to using singular metrics to make design decisions.

Results

When performing daylight analysis, the time is typically split into three portions: model setup, simulation, and post-processing and interpretation. The interpretation is highly dependent on a reliable model setup and simulation, and ultimately, the findings impact design decisions. Moreover, the way in which the information is displayed and conveyed, including the scale chosen, is critical in analyzing and reaching effective solutions and recommendations. In this thesis, a select few cases have been simulated and presented directly; however, alternates have been considered in the interpretation. It is important to be mindful that there is almost always an exception, and each project is unique. The scenarios presented in this thesis attempt to show a broad range, but do not cover every eventuality.

For all point-in-time analyses, the criteria was based on the conditions at 12pm. For a

3 It should be noted that this thesis does not attempt to address the concept of what is 'good' or 'bad' design. In this vignette, the cases are assessed in terms of the criteria to determine if they do or do not meet it. This assessment is based solely on the established criteria, based solely on that particular metric. This assessment is made not with the intention of comparing the designs or commenting on the fit or effectiveness of design strategies in a larger context, and is not meant to be generalized. Rather, the goal is to show that each metric engenders understanding of different aspects of the luminous environment and cannot be used singularly.

purely east- or west-facing scenario, it would be critical to understand the daylight levels at 9am or 3pm, respectively, rather than 12pm. In many cases, other times or scenarios were simulated and discussed within select metrics.

The following two pages show the full results for all three cases, after which, each metric will be discussed separately.

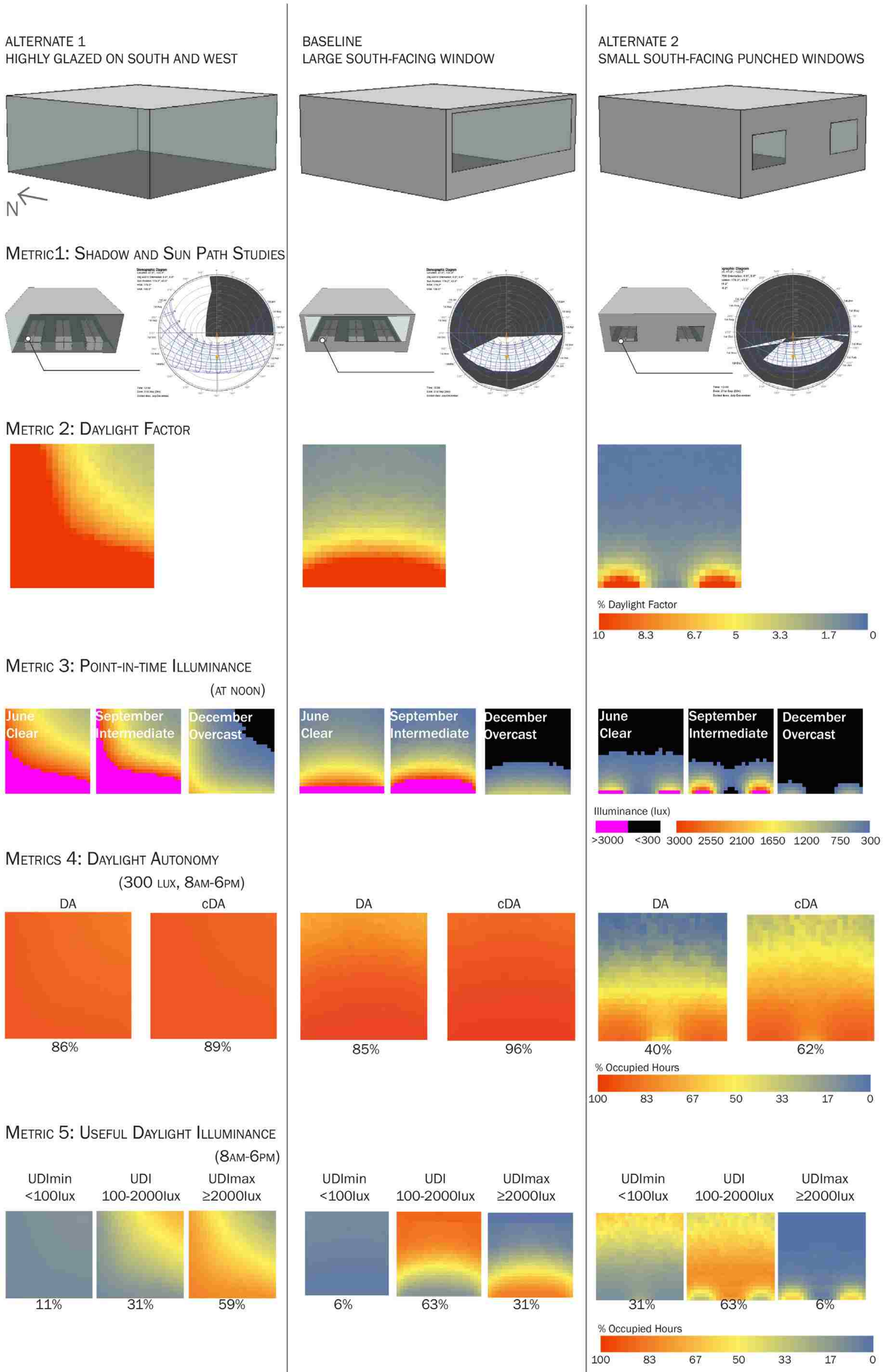


Figure 3.3 Metric-by-metric results.

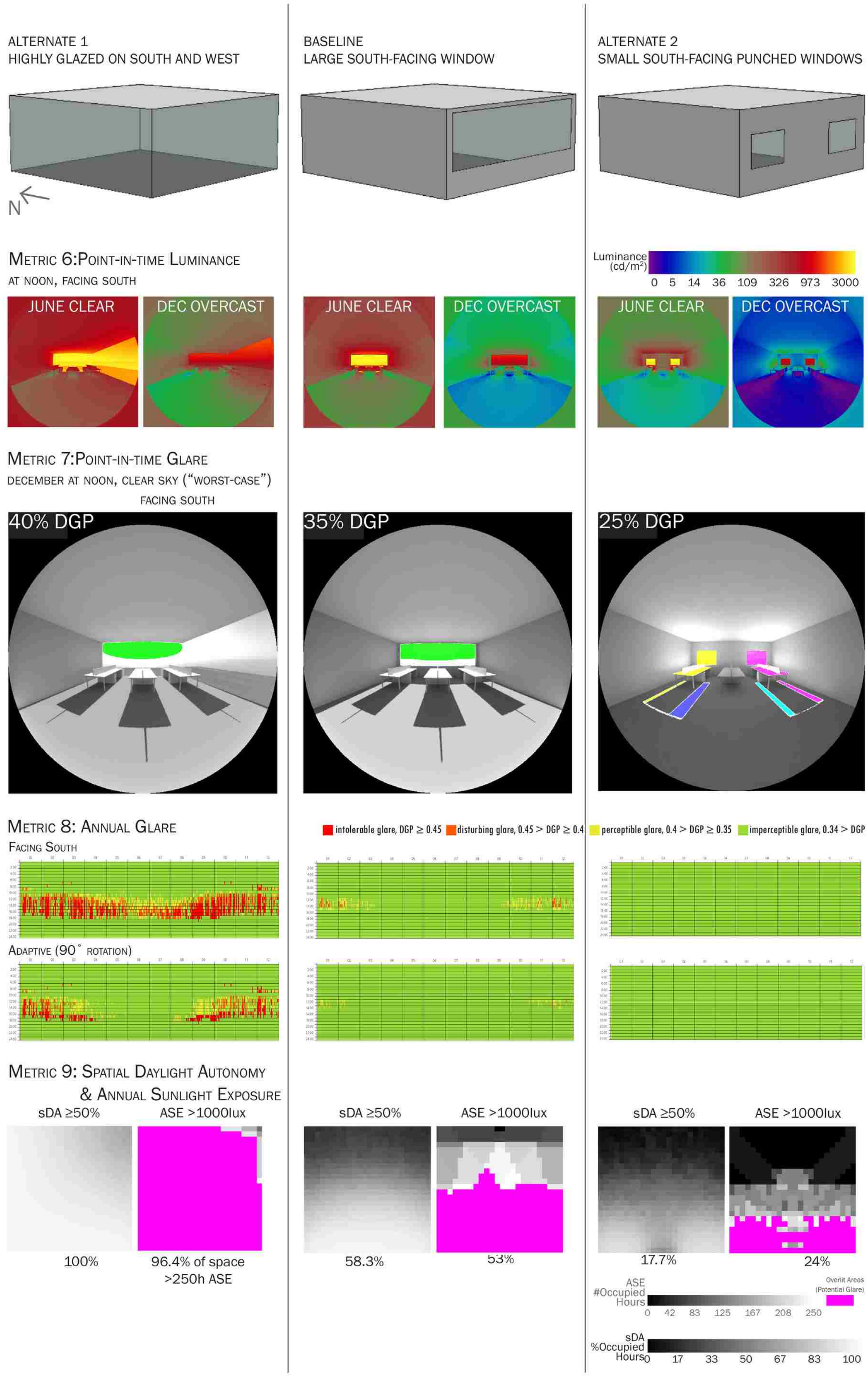
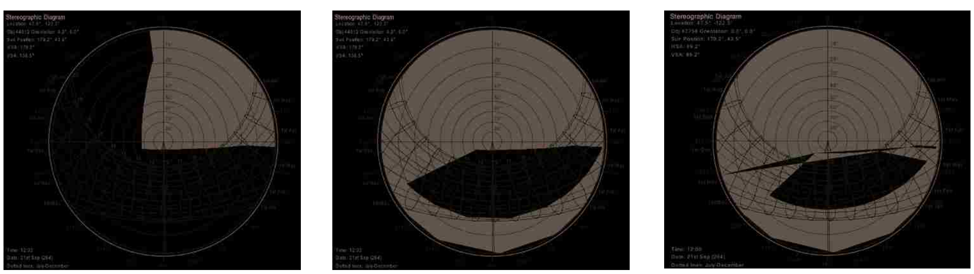


Figure 3.3 Metric-by-metric results.

1. SHADOW AND SUN PATH STUDIES

Not illuminance or luminance-based, shadow and sun path studies are commonly used in computational lighting design. An effective, easy, and quick tool to use early in design, to determine areas of interest, they often precede other studies, particularly point-in-time illuminance and luminance analysis. Another use is to determine areas on a façade that are overshadowed, and can supplement radiation maps. While not numerically-intensive, and therefore lacking in their ability to evaluate most of the qualities of the luminous environment, they are a tool to help the design team understand variability.

The established criteria in this thesis dictates that there should be no direct sun on horizontal desk surfaces during occupied hours (8am-6pm). For all three scenarios, without any shading, this criteria is not met, due to the lack of solar control. The shadow and sun path studies were completed for the southwestern-most desk. In the Baseline, the desk is fully exposed to direct beam sunlight throughout the year. In Alternate 1, the desk is overshadowed November through March during morning and evening hours; the remainder of the year, the desk may receive direct beam sunlight. In Alternate 2, December through February is fully overshadowed throughout the day, while some morning hours are overshadowed during November and March. These scenarios show the worst-case scenario; certainly, with occupants sitting deeper within the space, less direct sunlight would reach the desks, particularly in the morning and evening hours.



Alternate
Highly Glazed

Baseline

Alternate 2
Punched Windows

Figure 3.4 Sun Path Results.

For the same scenarios 1) facing East, the desks are in full sun during the morning, 2) facing West, the desks are in full sun during the afternoon, and 3) facing North, the desks are never in full sun.

In practice, an alternate method for shadow and direct sun analysis are physical models. Using a heliodon, the design team can view a large range of conditions and easily adjust for design or shading alternatives.

2. DAYLIGHT FACTOR

Daylight Factor (DF) can be used at any phase of design, but is often used early on to determine if sufficient daylight levels are being reached. While sometimes known as the 'more is better' approach, for the purposes of this thesis the criteria is a DF of 2-6%; this is a typical range used in practice. The upper limit is applied to encourage mitigating exceedingly bright illuminance values, particularly at the perimeter. None of the scenarios satisfy the criteria for this metric. Alternate 1 reaches the highest DF, 34% at the perimeter, while the Baseline reaches a DF of 19% and Alternate 2 reaches a DF of 13%.

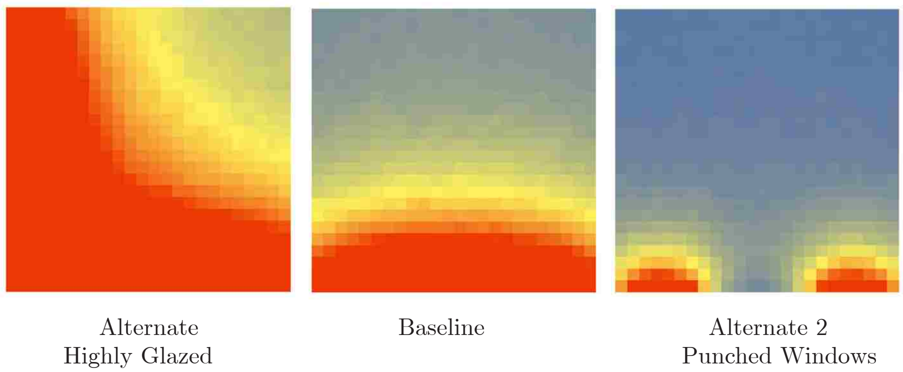


Figure 3.5 Daylight Factor results.

If this metric is simply taken at face value, without much analysis, it does not give sufficient information. However, if the results are post-processed to generate the mean, and percentages below, within, and above the target range- as in the below table- this metric can be applied more effectively. While all scenarios exceed the maximum requirement, the degree to which they exceed it varies greatly. They also vary greatly in the lower range. Alternate 1 has 0% of area below the 2% DF minimum, indicating that it is sufficiently bright. On the other hand, Alternate 2 has 80.7% of area below the 2% DF minimum, indicating that it will be dark in much of the space; combined with some percentage of the space above the 6% DF maximum, it could indicate high illuminance ratios from the window to task areas. However, while these percentages are helpful in such an assessment, and a general understanding where a design is lacking, the results cannot be relied upon to predict glare issues.

	Mean DF	% of area < 2% DF	% of area within 2-6% DF range	% of area > 6% DF
Alternate 1	11.75%	0%	26.4%	73.6%
Baseline 1	5.15%	35.9%	35.1%	29%
Alternate 2	1.55%	80.7%	16.1%	6.2%

Table 3.2 Daylight Factor post-processing.

Moreover, given that the metric is only providing a point-in-time perspective with an overcast sky condition, trends cannot be extrapolated. For these reasons, this metric must be paired with another metric to gain a full understanding of the luminous environment and any project-specific concerns.

Even with a polished process to analyze results, this metric ultimately has a significant shortcoming, as discussed in the Literature Review: while it can be useful in providing a quick assessment of whether a space is meeting miminum requirements or in comparing design options, it is only accurate in predominantly overcast climates. The effectiveness of this metric, therefore, is dependent on location. For example, the results would be more accurate and useful in Seattle than in Phoenix.

In practice, DF can be determined for a new construction or renovation project using an overcast sky simulator. The mirrors inside create an articifial sky, mimicking a perfectly overcast sky. A physical model can be tested by placing sensors inside and outside the model, and calculating the DF from these values. As with the heliodon, this method is effective in allowing the design team to view the project in real-time, while easily and quickly adjusting design or shading options. DF can also be measured within an existing building, using an illuminance meter to measure the illuminance outside and inside a space, and calculating the DF from these values.

3. POINT-IN-TIME ILLUMINANCE

Point-in-time illuminance is one of the most commonly used metrics, particularly to address whether a space is meeting target horizontal illuminance values for a specific program to meet IES standards. However, each simulation only provides limited, specific data that cannot be extrapolated for other times or sky conditions. If a larger understanding of the variability is desired using only this metric, the simulation must be performed for many different times. Even then, an understanding of the brightness or perception would not fully be reached. For this reason, it is best used for specific exploration of a time and sky condition of interest, or for a comparison between design options at typical or extreme conditions.

Several approaches may be taken with point-in-time illuminance. The dates, times, and sky conditions may be determined from:

- A known time of interest.
- Performing shadow or sun path study to explore a specific area of interest (e.g. times of day when direct sun falls on desks in an office, or at the stage of an auditorium or other performance space), and subsequently performing an

illuminance study for the 'worst case scenario.'

- Select rules of thumb.

For the purposes of this thesis, the minimum illuminance target is 300 lux, assuming an office or classroom space with reading-related tasks, and the maximum is 3,000 lux to reduce potential glare risk. These criteria result in a maximum illuminance ratio of 10:1, and a more uniform distribution is preferred. The dates, times, and sky conditions chosen were 1) June 21, noon, clear sky, 2) September 21, noon, intermediate sky, and 3) December 21, noon, overcast sky. These conditions cover a broad range of variables and are often used in practice when a specific time of interest is not in question.

The results show that none of the scenarios satisfy the established criteria for point-in-time illuminance, yet where they are lacking within this singular metric varies. All scenarios exceed 3,000 lux at the perimeter in June clear and September intermediate, and do not meet the 300 lux minimum in December overcast. However, the distribution of each is very different. The Baseline has a comparatively gradual gradation from the perimeter to the back of the space. Alternate 1 Highly Glazed has a more uneven, angled distribution due to glazing on both the South and West, resulting in an overall bright space. Alternate 2 Punched Windows has very high daylight levels at the perimeter, but this falls off quickly, and the remainder of the space is very dark.

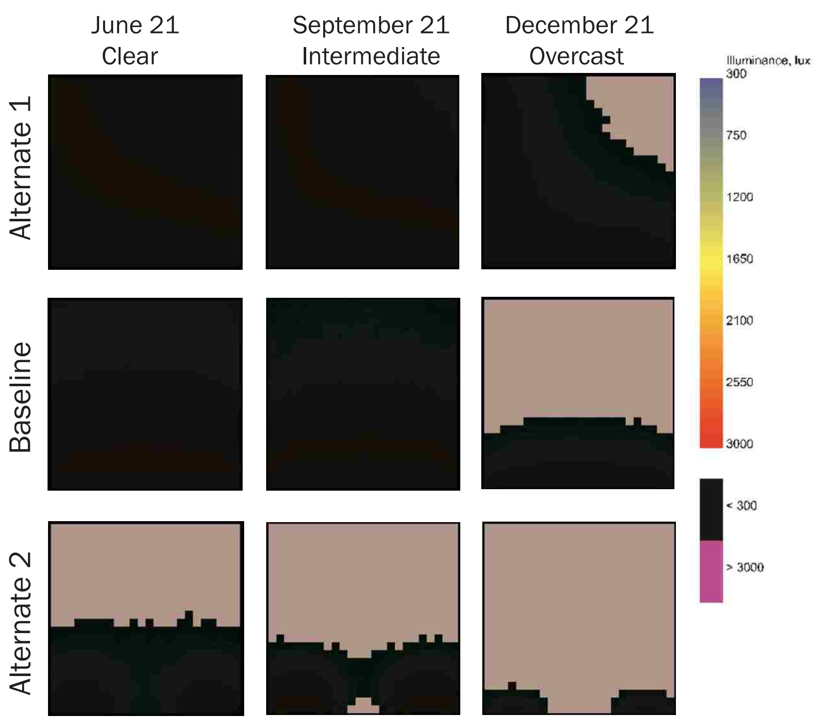


Figure 3.6 Point-in-time Illuminance results.

Overall, the percentage of time that each scenario has illuminance values within the target range varies. While this information is important for interpretation, this vignette does not take into account how close or far from the threshold the scenarios are performing; the criteria are binary, and ultimately, all cases fail to meet the criteria.

This calls into question two factors: the rules of thumb used to generate the baseline model and the established criteria. Rules of thumb for daylight distribution indicate that the depth of the space should be approximately 2.5 times the head height of the window. However, it seems that with this rule of thumb on an overcast day in December, daylight is not falling deep within the space. Perhaps a space designed with a depth 2 times the head height of the window would be more effective in this pursuit. Moreover, the acceptable range for usable daylight is considered to be 300-3,000 lux, based on IES guidelines for reading and visual tasks. This criteria is very difficult to satisfy for all dates and sky conditions. In practice, there is typically more flexibility and, therefore, criteria is applied less stringently; if areas within the space fall below 300 or above 3,000 lux, it is remedied with electric lighting or shading control, respectively. A space's apertures are often designed to meet the minimum requirements, and shading is added as needed to mitigate light levels above the maximum threshold. The exception would be a museum, where curatorial standards strictly dictate the maximum allowable lux-hrs for light sensitive objects.

Ultimately, due to the need for a large number of simulations to address a range of times and sky conditions, along with the limited scope of the information generated, which lacks in visual perception and variability, point-in-time illuminance should not be used singularly. The findings should dictate which metric should be used to supplment it: point-in-time luminance if the feeling inside a space is desired; annual illuminance for larger trends; point-in-time or annual glare if the contrast ratio is extremely high.

4. DAYLIGHT AUTONOMY

Daylight Autonomy is dependent on the target illuminance and time range. A target illuminance of 300 lux was chosen during the hours of 8am-6pm, in line with a typical office environment. For the purposes of this thesis, the criteria is met with an average Daylight Autonomy (DA) and continous daylight autonomy (cDA) of 60% or higher. The Baseline and Alternate 1 meet this criteria, while Alternate 2 has a DA of 40%, not meeting the criteria. Note that the cDA for Alternate 2 is 62%. Continuous Daylight Autonomy tends to more accurately predict energy savings due to the 'partial credit' that is given to nodes in the space that achieve a percentage of the target illuminance level, which more closely matches daylight dimming controls and potential lighting and overall energy savings.

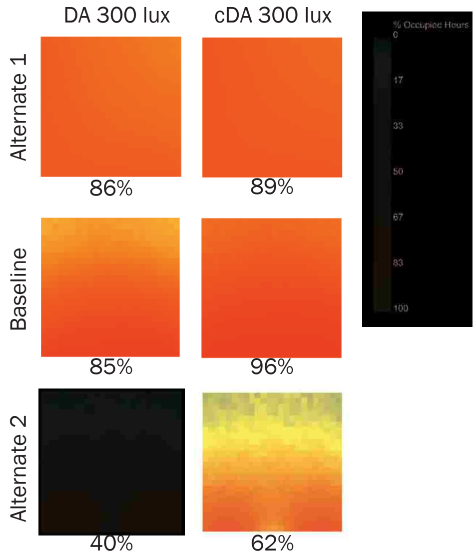


Figure 3.7 Daylight Autonomy results.

The largest shortcoming of Daylight Autonomy is its lack of an upper limit. This limitation will be expanded upon in the discussion for Useful Daylight Illuminance. However, there are also related issues with simulating this metric. Each simulation program varies in its calculation and file outputs. Some provide a results file with only the DA percentage, and if the corresponding illuminance values are desired, a method must be developed to post-process the results.

While Daylight Autonomy addresses light levels and variability, it is best paired with a point-in-time luminance, point-in-time glare, and/or annual glare study to address visual perception, performance, and comfort. In practice, it is most often used during Schematic Design and Design Development. Concept phase is usually too early with not enough detail, and it cannot be measured in post-occupancy.

5. USEFUL DAYLIGHT ILLUMINANCE

The original threshold for Useful Daylight Illuminance (UDI) was 100-2,000 lux. Although this has been amended to 100-3,000 lux in recent years, the original threshold is often used. For this thesis, the scenarios were first evaluated for 100-2,000 lux, and subsequently alternative thresholds were considered. A target UDI of greater than 60% was considered passing the criteria, while the UDI_{min} and UDI_{max} should not exceed 20%. The scenarios vary in meeting these requirements. The Baseline meets the UDI and UDI_{min} requirements, but exceeds UDI_{max}, indicating that the scenario tends towards high daylight levels. Alternate 1 Highly Glazed only meets the UDI_{min} requirements, and the even higher UDI_{max} percentage indicates that the scenario tends towards even higher daylight levels. Alternate 2 meets the UDI requirement, but has a high UDI_{min}, indicating an overall dark space.

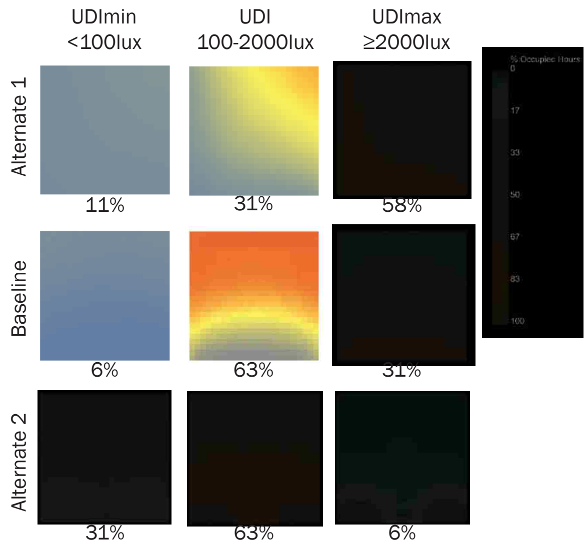


Figure 3.8 Useful Daylight Illuminance results.

Inherent in the annual illuminance metrics currently used are certain boundary conditions. These boundary conditions are founded on past research and practice:

- Daylight Autonomy: custom lower range, no upper range
- Useful Daylight Illuminance: 100-2,000 lux
    - More recently the upper range has been accepted to be 3,000 lux.
    - The lower range has remained at 100 lux. For reading-related tasks, a more appropriate lower range would 300 lux.

In reality, minimum and maximum illuminance ranges vary based on program type and project-specific information. A mixture of Daylight Autonomy and Useful Daylight Illuminance would be ideal: customizable with a lower AND upper range. An example of this is shown as follows, for the Baseline case:

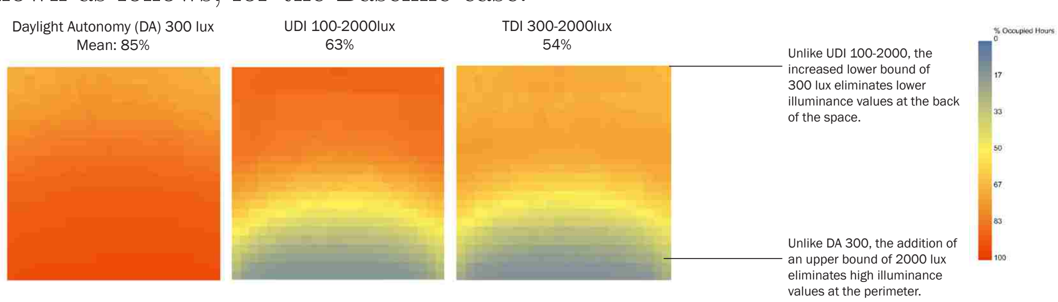


Figure 3.9 Customized Useful Daylight Illuminance:
Target Daylight Illuminance (TDI) 300-2,000 lux.

This can be taken one step further, customizing the results to the target daylight illuminance (TDI) of the program (300-3,000 lux in this case).

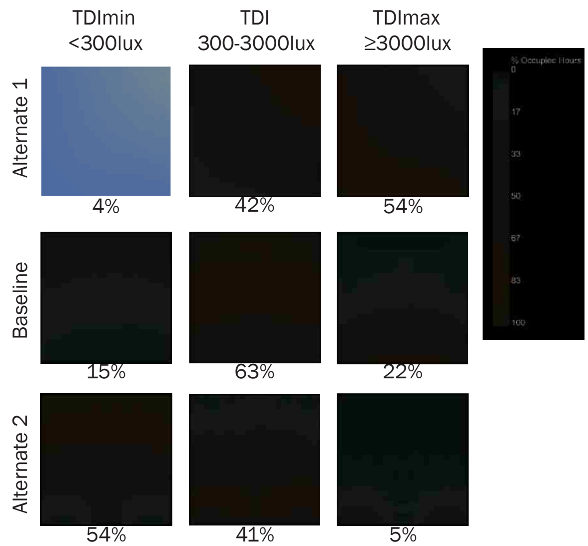


Figure 3.10 Customized Useful Daylight Illuminance:
Target Daylight Illuminance (TDI) 300-3,000 lux.

- The Baseline UDI and TDI values are not significantly different, as the illuminance values are generally mid-range. Using either set of results would likely inform the design similarly.
- Likewise, the results for the standard range of UDI 100-2,000 lux in the Alternate 1 Highly Glazed case would indicate that the majority of values are too high, with values above 2,000 lux 58% of the time. When adjusting to the custom range of 300-3,000 lux, the TDI_{max} 3000 lux only falls to 54%. As this is not a significant decrease, it can be inferred that the majority of values is much higher than 2,000 or 3,000 lux. Using either set of results would likely inform the design similarly.
- However, for the Alternate 2 Punched Window case, using the standard range of 100-2,000 lux, UDI meets the 60% criteria. When adjusting to a custom range of 300-3,000 lux, the low illuminance values are highlighted in TDI_{min} and the TDI drops to 40%. This indicates that if the appropriate range for the program is not used, the results might misdirect or misinform the design.

While the user can manipulate the results generated from the current tools to apply a variation of ranges, some tools use predetermined ranges. This shows a lack of understanding of the flexibility needed. A tool that allows for such customization would be powerful, and can be achieved in numerous ways. In this thesis, post-processing was performed in Excel. However, the capabilities presented in scripting tools- Python script and Grasshopper to name a few- embrace the changing needs of the daylighting field. The current landscape of daylighting is moving towards a combination of illuminance and luminance metrics. If annual illuminance metrics were to allow more flexibility and were to embrace different program types or project-driven, annual illuminance metrics would be more aptly suited to a larger range of simulation scenarios.

Of all the metrics presented in this thesis, UDI, UDI_{min}, and UDI_{max} (particularly if customized, as in TDI) are the most effective in singularly providing an understanding the luminous environment due to the lower and upper limits. Together, all three address the light levels and variability. However, UDI is best paired with a point-in-time luminance rendering to understand the visual perception, performance, and comfort of the luminous environment. Moreover, if UDI_{max} is high, a point-in-time glare and/or annual glare study might be warranted. In practice, UDI is most often used during Schematic Design and Design Development. Concept phase is usually too early with not enough detail, and it cannot be measured in post-occupancy.

6. POINT-IN-TIME LUMINANCE

Point-in-time luminance generates visualizations via renderings and numerics via falsecolor images and image post-processing capabilities. With the former, the 'feel' of the space is conveyed, with the distribution and quality of light expressed via renderings, while the latter provides an understanding of minimums, maximums, distribution, and luminance ratios.

There are many factors involved in the point-in-time luminance criteria used in this thesis. While there is no target minimum, it is preferable to not have an overly dark space. The maximum threshold is 3,000 cd/m^2, to prevent potential glare risk. An appropriate amount of variability is ideal, but a 22:1 luminance ratio between window to task should not be exceeded. Similar to point-in-time illuminance, since specific dates and times of interest are not clear, key dates were chosen: 1) the 'brightest' condition, June 21 at noon, clear sky and 2) the 'darkest' condition, December 21 at noon, overcast sky.

The following falsecolor images show a viewpoint from the back of the space facing South. For the 'brightest' condition of June 21 at noon with a clear sky, it would seem that all cases exceed the target maximum of 3,000 cd/m^2 adjacent to the glazing. Using target distribution analysis, it can be determined that both the Alternate 1 Highly Glazed and the Baseline have a significant amount of values close to 3,000 cd/m^2. Also problematic is the significant presence of direct sun beams falling on the desks. In Alternate 2 Punched Windows, these direct sun beams are minimal and isolated to the perimeter. It is likely that shortly before or shortly after 12pm, these beams would disappear. However, the luminance ratio from window to task is 59%, exceeding the established criteria. Other than these areas, the distribution on the desks is extremely uniform, and the remainder of the space maintains a certain level of variability that is in line with occupant preference. For the 'darkest' condition, December 21 at noon overcast sky, the Alternate 1 Highly Glazed case has variability due to its large glazing surfaces on two orientations. The Baseline has less variability, but is below the maximum threshold throughout, while Alternate 2 Punched Windows is considered too dark overall and has a high luminance ratio from window to task of 62%.

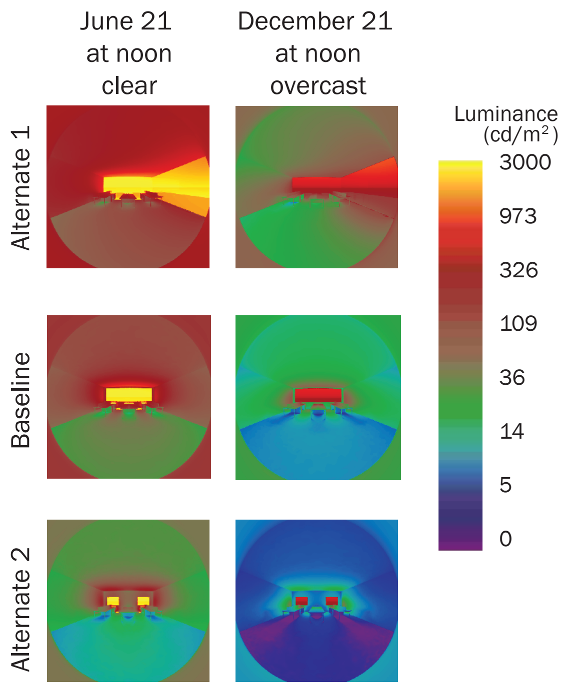


Figure 3.11 Point-in-time Luminance results.

Targeted distribution analysis can be used to interpret point-in-time luminance images via hdrscope. The main analysis methods used in this thesis are as follows:

- Multiple regions of interest
  - Contrast: mean ratio between Window:Task (W:T) < 22:1
- Entire scene
  - Percentile of Image Luminance (upper and lower 10%): histogram values should be 'bunched,' closer together is better, even if the values are high
  - Criterion Rating (CR): percentage greater than 3,000 cd/m^2 should be as low as possible

The images in Figure 3.12, below, show the analysis selections for the Baseline:

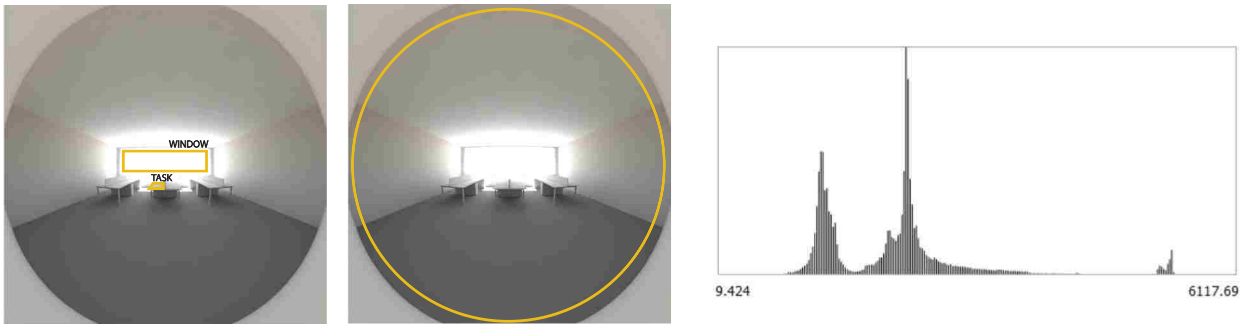


Figure 3.12 Luminance targeted distribution analysis: luminance contrast from window to task (left), entire scene analysis (center), and histogram (right).

The results from this targeted distribution analysis are as follows:

	Alternate 1 Highly Glazed	Baseline	Alternate 2 Punched Windows
Contrast ratio W:T Front of desk	2096/254 = 8	2665/164 = 16	2608/44 = 59
Percentile of Image Luminance (10%)	four peaks, significantly spread out	two large peaks, moderately spread out	two large peaks, moderately spread out
CR > 3000 cd/m^2	0.0573%	0.0549%	0.0102%

Table 3.3 Luminance targeted distribution analysis: June 21 at noon, clear sky.

	Alternate 1 Highly Glazed	Baseline	Alternate 2 Punched Windows
Contrast ratio W:T Front of desk	4701/48 = 9.8	534/32 = 16.7	410/6.6 = 62
Percentile of Image Luminance (10%)	one wide peak	two large peaks, slightly spread out	two large peaks, one small peak, moderately spread out
CR > 3000 cd/m^2	0%	0%	0%

Table 3.4 Luminance targeted distribution analysis: December 21 at noon, overcast sky.

Even with the wide range of methods available to analyze point-in-time luminance images, this metric has its limitations: it is view- and time-dependent. These limitations necessitate multiple simulations if point-in-time luminance were to be used singularly. However, these limitations can be powerful if used to their advantage. If there is an area of interest that might be problematic at a specific time, this metric can provide combined visualizations and numerics in stronger ways than many other metrics. The falsecolor images provide analysis of a high dynamic range that captures the way in which the human eye would view the space, unlike illuminance-based metrics.

Figure 3.13 below illustrates this, showing the default viewpoint from the back of the space facing South, as well as an alternate viewpoint at an interior (not adjacent to the window) workstation angled to face 45° towards the window. It is clear that much of the mid-range 'green' values that were visible in the default viewpoint are not present in the alternate viewpoint. These mid-range values were predominantly at the floor level, not at the workstations. The alternate viewpoint illustrates that this space is even brighter than it appears in the default viewpoint. Moreover, the areas where direct beam sunlight falls on the desks is visible in much more detail; this would therefore be a better viewpoint if shading schemes were being tested to mitigate direct sun beams on desk surfaces.

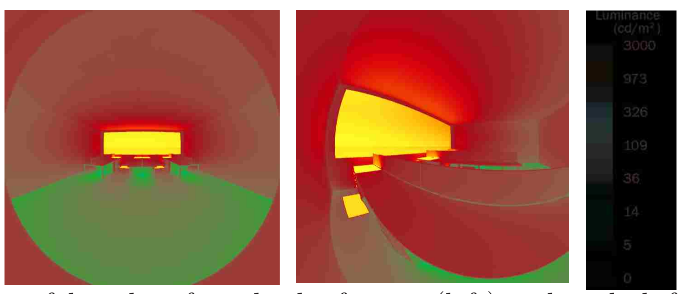


Figure 3.13 Luminance falsecolors from back of space (left) and at desk facing southwest (right).

Additionally, for the purposes of comparison between cases, the falsecolor luminance images were set to one scale. However, in practice, it is critical to tune the scale such that it best shows the distribution. Below, the same viewpoints shown above are scaled with a minimum of 10 cd/m^2 (previously 0 cd/m^2). This new scale shows much more variability, and the areas where there is gradation is much clearer- particularly at the mid-point of the space where the luminance values fall from high (red) to mid-range (green).

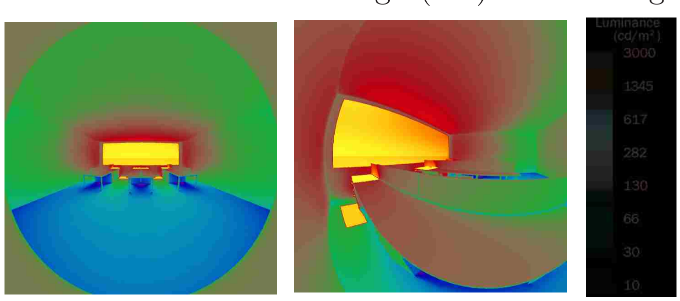


Figure 3.14 Luminance falsecolors from back of space (left) and at desk facing southwest (right) with scale 0-3,000 cd/m^2.

While adjusting scale can be important, it is often much more effective to adjust the minimum, and the upper range should only be adjusted within 2,500-3,000 cd/m². A common practice is to use a standard scale for nearly all projects, only adjusting in unique circumstances. For example, the University of Washington's Integrated Design Lab (IDL) uses a scale of 10-2,500 cd/m², with a rule of thumb that 'green is good:'

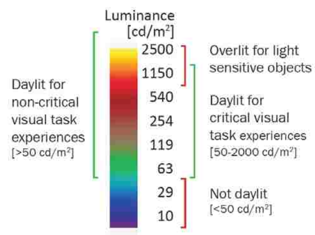


Figure 3.15 University of Washington IDL luminance scale.

Moreover, in practice, the way in which visualizations are presented is critical. The less informed client might assume that the yellow values indicate light, and might see this as ideal. It is essential to express the nuances of these visualizations to successfully move the design forward with the teams' full understanding of the goals of the project as they relate to daylighting.

Ultimately, point-in-time luminance is most often used during Schematic Design and Design Development. Concept phase is usually too early with not enough detail. While not simulated for the scenarios in this chapter, some firms such as the University of Washington's IDL perform a section study with point-in-time luminance as a first pass to understand the luminous environment of the space. The following images show an example of this for the Chapel of St. Ignatius in Seattle, WA:

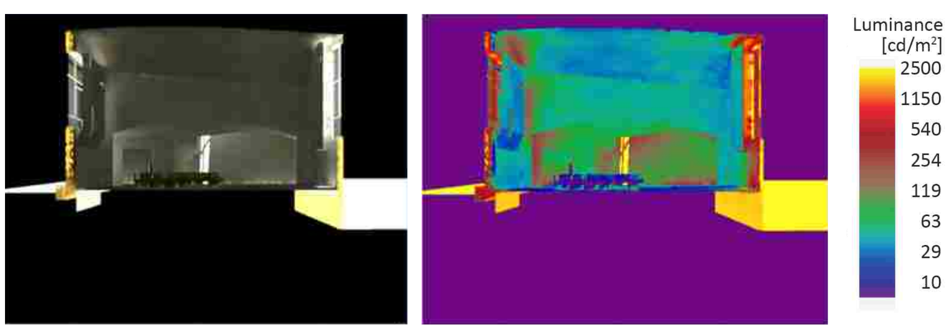


Figure 3.16 Luminance section study. Chapel of St. Ignatius, Seattle, WA.

No matter the format, luminance renderings and falsecolor images address visual perception, performance, and comfort. They are best paired with annual illuminance, and sometimes point-in-time illuminance, to understand light levels and variability.

7. POINT-IN-TIME GLARE

Similar to other point-in-time metrics, point-in-time glare is often best preceded by other metrics. A sun path or annual glare study can be used to determine times with potential glare risk. The simulation generates fisheye views of a space with colored areas indicating potential areas that could have glare issues, along with a DGP value.

Based on the Wienold/Christoffersen and Van Den Wymelenberg/Inanici glare thresholds discussed in Chapter 2, along with current practices, it was determined that a DGP of 30% or above would be considered uncomfortable and was used as the criteria in this vignette. For these cases with predominantly south glazing, the 'worst-case-scenario' would be December 21 at noon with a clear sky condition, when low angle sun is able to penetrate far into the space. A viewpoint from the back of the space facing South was chosen, as it shows a good deal of variation among cases. Other viewpoints were simulated; certainly, if an occupant is seated directly adjacent to the glazing, the visual comfort highly decreases. This is true of all cases. However, it is telling that even from the back of the space, there is still potential glare risk in the Baseline and Alternate 1, at 40% and 35% respectively. Alternate 2 is below the threshold, at 25%, meeting the criteria.

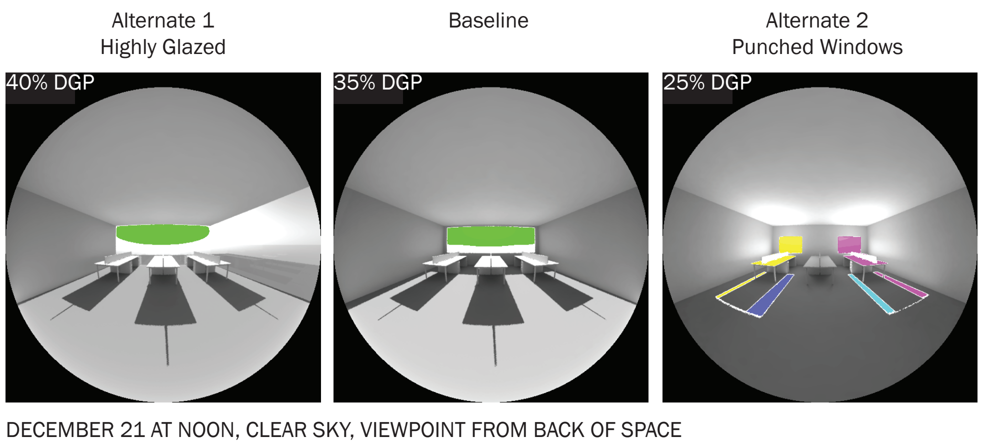


Figure 3.17 Point-in-time Glare results.

One of the largest limitations of this metric is, as in the other point-in-time metrics, it is highly dependent on the times selected. However, unlike point-in-time illuminance or luminance, it is not necessary to perform such a large number of simulations. If glare is a potential concern, and this metric is being used singularly, the critical dates and times can be narrowed down depending on the area of interest and the massing of the building. For example, if the concern is a reception desk facing west, it narrows down the times of day to afternoon; a winter solstice (lowest angle sun) 3pm, clear sky simulation with a viewpoint facing West would likely generate the needed information. Regardless, to illustrate this time-dependency, the DGP for the Baseline on December 21 at noon was

35%, which exceeds the established criteria and would likely be considered uncomfortable by any scale. When simulated for June 21 at noon, clear sky, the DGP is 28%, which meets the established criteria and might be considered comfortable by some, depending on the scale used.

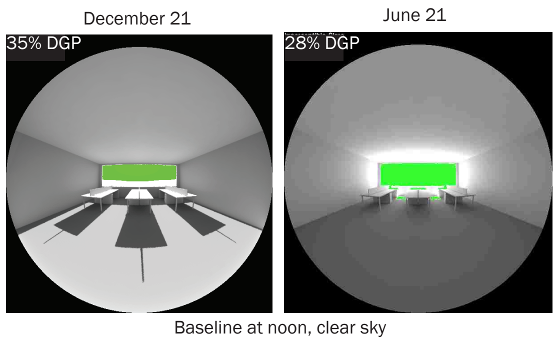


Figure 3.18 Point-in-time Glare, alternate time.

The other key limitation of point-in-time glare is that it is view-dependent. If an appropriate view is not selected, the results are not as meaningful or can misdirect or misinform the design. For the Baseline case with the default viewpoint at the back of the space facing South, the DGP is 35%. This exceeds the established criteria and would likely be considered uncomfortable by any scale. If the primary occupant position is seated at a desk adjacent to the window, without flexibility, the glare risk even higher with a DGP of 100%.

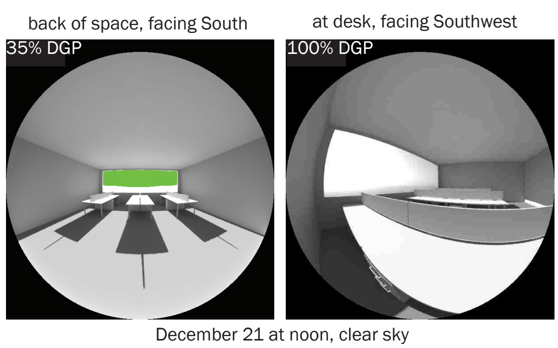


Figure 3.19 Point-in-time Glare, alternate viewpoint.

However, if flexibility to rotate view direction or control blinds is permitted, the high glare risk is not as problematic. Likewise, if the occupants are rarely at the workstations, the analysis should not use this location and viewpoint.

For a full understanding using this singular metric, if there are multiple places at which occupants will be located, many viewpoints must be simulated. Many dates, times, and sky conditions are also needed. This results in a lengthy analysis. This is where the practitioner must make a decision between efficiency and accuracy. If efficiency is needed, due to time constraints or lack of fee or scope, alternate approaches might be sufficient. For example, choosing two viewpoints- the most and least problematic- would show the range of conditions and would save time. The program intention and analysis goals could be further questioned, to narrow down these viewpoints of interest. To determine the most meaningful dates and times to simulate, sun path studies and an annual glare analysis could be performed before the point-in-time simulations. Developing a streamlined process takes experience and time, and even then, the process will likely change from project to project.

In practice, point-in-time glare analysis is most often used during Schematic Design and Design Development. Concept phase is usually too early with not enough detail. While it addresses visual comfort, it does not address annual variability. For this reason, it is best paired with annual illuminance, and sometimes point-in-time illuminance, both of which address light levels. Point-in-time luminance would add to the study by providing more information about visual perception and performance.

8. ANNUAL GLARE

Annual glare is often used for a larger picture understanding of the potential glare risk occurring throughout the year. As in point-in-time glare, it was determined that a DGP of 30% would be considered uncomfortable and was used as the criteria in this vignette: annual DGP should not exceed 30% for more than 10% of hours. This criteria addresses intolerable glare for extended hours or months that cannot be reasonably mitigated with solar control.

Again, a viewpoint from the back of the space facing South was chosen. This viewpoint shows a good deal of variation among cases. Other viewpoints were simulated; certainly, if an occupant is seated directly adjacent to the glazing, the visual comfort highly decreases. This is true of all cases. However, it is telling that from the back of the space, there is still potential glare risk throughout the year in the Alternate 1 Highly Glazed case. On the other hand, it would appear that the Baseline and Alternate 2 Punched Windows cases comply with the criteria. The results are shown in Figure 3.20 on the following page.

Depending on the flexibility of a space, different recommendations would be made. Alternate 1 Highly Glazed is a good example of this. For this case, the annual DGP results indicate that there is potential glare risk throughout the year. However, when the occupant is given the ability to rotate 90^{o}, the Adaptive Glare results show that the potential glare risk is greatly reduced throughout the year, particularly during summer. Not that the Baseline and Alternate 2 do not seem to need this flexibility. Another option to provide such flexibility would be to develop a method to generate multiple viewpoints via scripting. If a client is considering shading controls based on the results of this metric, the adaptive glare results with multiple viewpoints taken into account might show that aggressive shading control is not needed if workstation flexibility is an option.

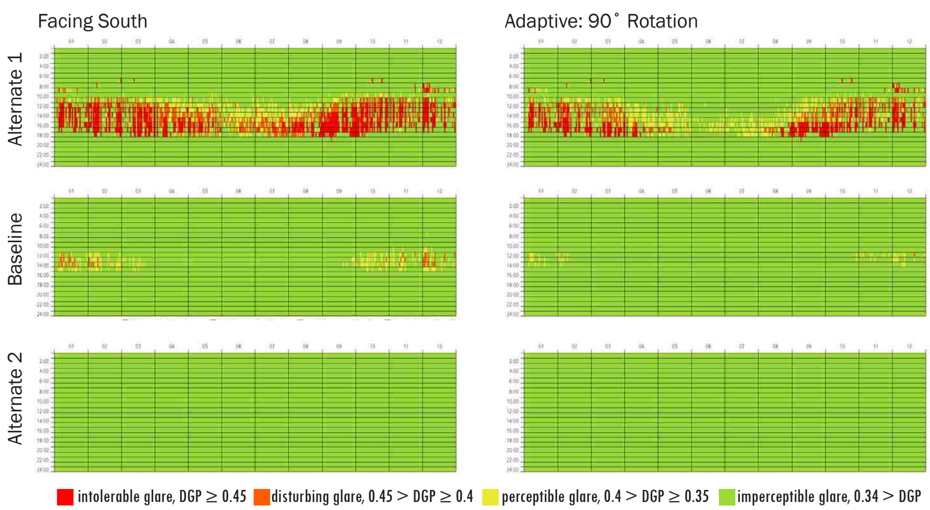


Figure 3.20 Annual Glare results.

Research has been conducted that challenge Wienold and Christoffersen's scale, with the notion that perhaps the threshold for discomfort should be lower. If the annual glare map were adjusted to a custom scale with lower thresholds, the conclusion is much different:

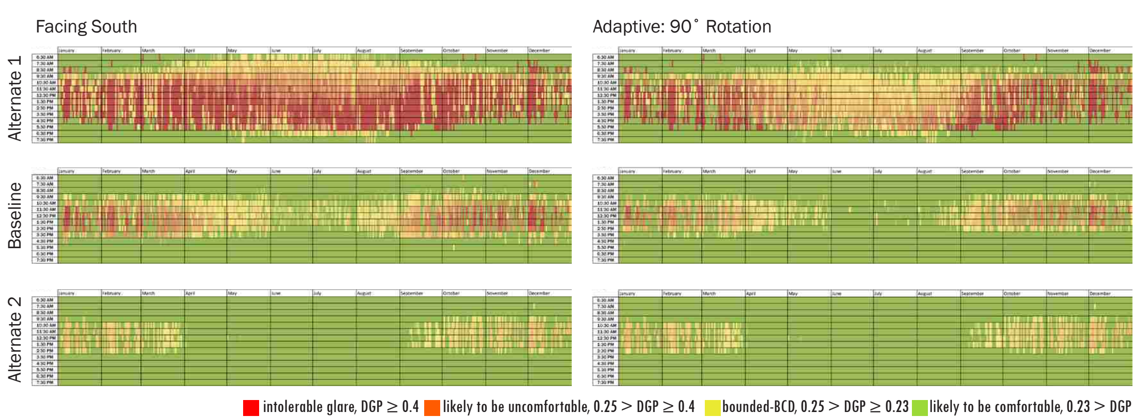


Figure 3.21 Annual Glare, adjusted scale.

Although Alternate 1 Highly Glazed still clearly contains the highest potential glare risk throughout the year, it becomes apparent that the Baseline and Alternate 2 Punched Windows cases do have periods of time that could prove to be problematic in terms of visual comfort, particularly in the shoulder seasons and winter. Unlike the adaptive simulation for Alternate 1 Highly Glazed using the Wienold and Christoffersen scale, the adaptive simulations for all three cases with this scale do not improve the potential glare risk significantly. This indicates that even with the ability to have flexible work spaces, the spaces would pose visual comfort issues unless solar control were to be provided.

Other than disputes about an appropriate scale, annual glare has shortcomings inherent in its method, which will be discussed in the 3.2.1 Sky Models and Methods Vignette. Using annual glare singularly presents issues with regard to reliability of results as well as a lack of understanding of other aspects of the luminous environment. It is often paired with point-in-time glare and luminance renderings, but it can be paired with a number of other metrics depending on the project goal or question of interest. A logical complement would be an illuminance study, either point-in-time or annual, to provide an understanding of light levels. It is most often used during Schematic Design and Design Development, while concept phase is usually too early with not enough detail.

9. SPATIAL DAYLIGHT AUTONOMY AND ANNUAL SUNLIGHT EXPOSURE

The spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) requirements are as follows:

- sDA: The percentage of floor area that achieves 300 lux for a minimum of 50% of occupied hours. The target is sDA≥55%.
- ASE: The percentage of floor area that achieves at least 1,000 lux for a minimum of 250 occupied hours per year. The target is ASE<10%.

The results, Figure 3.22 on the following page, show that none of the scenarios satisfy the requirements for both of these metrics concurrently. The Baseline and Alternate 1 meet sDA but not ASE, indicating that they receive sufficient daylight but allow too much direct sun to enter. Note that the degree to which they do not meet the criteria is vastly different. The Baseline has an sDA of 58.4%, just passing, while Alternate 1 has an sDA of 100%, greatly surpassing the criteria. The Baseline has an ASE of 53%, while Alternate 1 has an ASE of 96%, much more out of range of the criteria. On the other hand, Alternate 2 does not meet either metric, indicating that it does not receive sufficient daylight but has too much direct sun entering.

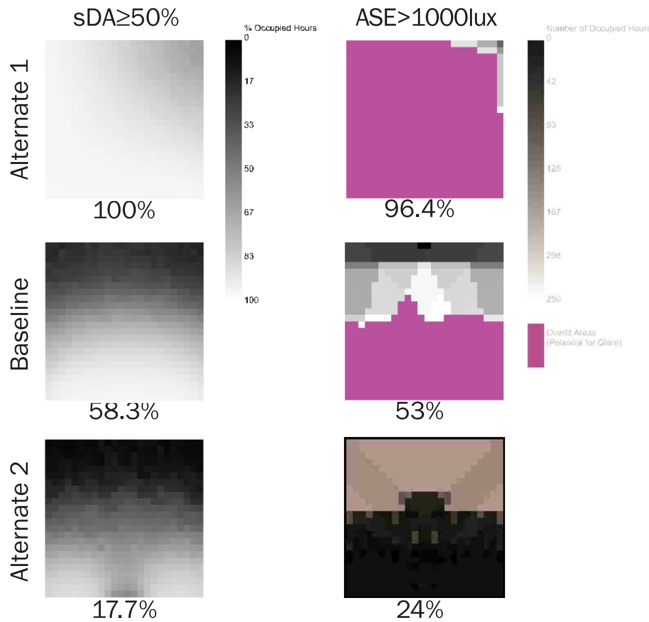


Figure 3.22 Spatial Daylight Autonomy and Annual Sunlight Exposure results.

These metrics are predominantly used during Design Development for LEED calculations, and may be supplemented with follow-up analyses depending on the findings. They were introduced with the intention of applying a pair of metrics to address more than one aspect of the luminous environment- sDA addresses light levels while ASE addresses visual comfort and potential glare risk. Moreover, as they are annual, use weather data as a basis, and are calculated spatially, they address variability. Theoretically, sDA with its minimum threshold and ASE with its maximum threshold would be an effective pair. However, these results indicate that it is quite difficult to achieve the new version of the LEED Daylight credit, particularly ASE. This metric, with more variations, will be further explored in 3.1.2 LEED Vignette.

Discussion

The following table compiles the results from each scenario, showing whether it does (●) or does not (○) meet the criteria for each singular metric, yielding a percentage fitness for each case.

Metric #	Metric Name		Alternate 1	Baseline	Alternate 2
1	Shadow and sun path studies		○	○	○
2	Daylight Factor		○	○	○
3	Point-in-time illuminance	at noon: June 21, clear sky	○	○	○
		September 21, intermediate sky	○	○	○
		December 21, overcast sky	○	○	○
4a	Annual illuminance	Daylight Autonomy (DA) 8am-6pm | 300 lux	●	●	○
4b		Continuous Daylight Autonomy (cDA) 8am-6pm | 300 lux	●	●	●
5a		Useful Daylight Illuminance (UDI) 100-2000lux	○	●	●
5b		UDImin <100lux	●	●	○
5c		UDImax >2000lux	○	○	●
6	Point-in-time luminance	at noon: June 21, clear sky	○	○	○
		December 21, overcast sky	●	●	○
7	Point-in-time glare		○	○	●
8	Annual glare		○	●	●
9a	sDA300/55%		●	●	○
9b	ASE1000,250h		○	○	○
		% fitness	23%	37%	32%

● meets criteria
○ does not meet criteria

Table 3.5 Compliance table for Baseline, Alternate 1, and Alternate 2.

This percentage fitness is not meant to be compared between cases, but rather to demonstrate that when one metric's criteria is met, others are not; each metric provides unique information about the luminous environment for any given space.

This table weighs all metrics with equal importance[4] , as the goal is determine the fitness with the criteria for each singular metric. In reality, the usability of the metrics is variable. For example, in an auditorium or church, it is often crucial to mitigate direct sun beams

4 While each metric was considered equally, submetrics were weighted. For example, for Metric 4: Daylight Autonomy (4a) and Continuous Daylight Autonomy (4b) each contribute ½ credit. The full weighting equation used was as follows: % fitness = [Metric 1 + Metric 2 + (1/3*Metric 3_{June} + 1/3*Metric $3_{September}$ + 1/3*Metric $3_{December}$) + (1/2*Metric 4a + 1/2*Metric 4b) + (1/3*Metric 5a + 1/3*Metric 5b + 1/3*Metric 5c) + (1/2*Metric 6_{June} + ½*Metric $6_{December}$) + Metric 7 + Metric 8 + (1/2*Metric 9a + 1/2*Metric 9b)]/9

at the stage area. Therefore, if this is a concern, shadow and sun path studies cannot be left out.

However, even if some metrics are more useful than others, none are an obvious determinant of space quality; none of the scenarios reach 100% compliance. That is, if a single metric were to be used, it might lead to different design decisions than if several analyses were performed to understand various aspects of the luminous environment: light levels, visual perception, visual performance, visual comfort, and variability. In fact, there is a line along which these cases lie:

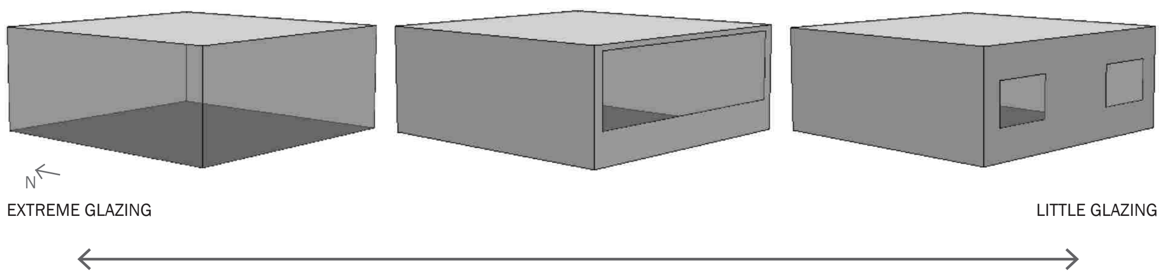


Figure 3.23 Extreme to little glazing.

The results show that, for a space of this size with south-facing glazing in Seattle, there is nowhere along this line where one metric can be used to understand the full luminous environment. There is, however, a point of convergence where there is a balance of glazing that meets more of the criteria and therefore allows more flexibility for design (shading, glazing) options:

- Too much glazing is an easier challenge to correct than too little glazing.
- In the case of too little glazing, if the space is on the top floor, skylights can be added, but some sort of shading would also likely be needed to provide some sort of control- it adds extra layers.
- Ultimately, the driver is typically aesthetics and/or cost. Any challenge can be corrected, but if considerations regarding daylight were brought in earlier to the design process, it would help in keeping the design closer to the balance in the middle, offering more design flexibility as well as reduced energy costs and a more thoughtful, balanced luminous environment.

To take the study a step further, the other cardinal directions were simulated for the baseline and two alternates, as well as several scenarios with skylights, two cases with shorter floorplates, and a case with no glazing. None of the cases simulated reached 100%

fitness, indicating that if one singular metric were to be used, a full understanding of the luminous environment would not be reached. The full table of results is shown on the following page in Table 3.6.

From this, two issues arise: the metric criteria and the lack of solar control. Both were chosen as research settings in this thesis; in reality, criteria is much more open to interpretation and solar control is invariably present. The results perhaps call into question common daylight metric criteria. In particular, the criteria for point-in-time illuminance and daylight factor are almost never met. This might indicate that the criteria is strict, but more likely it shows that these metrics are strong indicators of shading needs and the criteria is simply difficult to meet without solar control. However, these simulations were performed without shading for ease of comparison among many different configurations. Certainly, the percentage fitness changes- increasing in most cases- if shading is included. However, unless a responsive shading system is implemented, the percentage fitness is still unlikely to reach 100%. For example, a static shading system mitigates glare but reduces light levels; there is always a balance. The results from this study are meant to understand the metrics, and it is understood that in most cases, particularly for an office environment, an automated shading system would be indispensable. Future work could include a more robust study with more alternates in geometry and shading options.

Nevertheless, interpreting the results from all cases, the predilections of each metric could be determined. Some interesting obvservations include that DA, cDA, UDI, UDI_{min} are met with all cases, not dependent on orientation. These are the 'easiest' metrics to meet. Metrics with upper bounds are more difficult to meet with southern glazing and easier to meet with northern glazing or skylights, and sometimes with reduced glazing (UDI_{max} is met with Alternate 2 punched windows, but ASE is not). These results aided in identifying guidelines to determine, based on the amount and orientation of glazing, what is favored by each metric [see SECTION 3.3: GUIDELINES].

Metric #	Metric Name		baseline WWR 62%				alternate 1 highly glazed				alternate 2 punched windows WWR 35%				4 skylights 2.5'x2.5'		4 skylights 4'X4'		2skylights	baseline WWR 62% 20' floorplate		no glazing
			south	north	east	west	south-west	north-east	north-south	east-west	south	north	east	west	clear 65%	translucent50%	translucent50%	+northglazing	+north glazing	north	south	
1	Shadow and sun path studies		○	●	○	○	○	○	○	○	○	●	○	○	●	●	●	●	●	●	○	●
2	Daylight Factor		○	○	○	○	○	○	○	○	○	○	○	○	○	○	●	○	○	○	○	○
3	Point-in-time illuminance 9am (east), 12pm (south & north), 3pm (west)	June 21 clear	○	○	○	○	○	○	○	○	○	○	○	○	○	●	○	○	○	●	○	○
		September 21 intermediate	○	○	○	○	○	○	○	○	○	○	○	○	○	○	●	○	●	○	○	○
		December 21 overcast	○	○	○	○	○	○	●	○	○	○	○	○	○	○	○	○			○	○
4a	Annual illuminance	Daylight Autonomy (DA) 8am-6pm | 300 lux	●	●	●	●	●	●	●	●	○	○	○	○	●	●	●	●	●	●	●	○
4b		Continuous Daylight Autonomy (cDA) 8am-6pm | 300 lux	●	●	●	●	●	●	●	●	●	○	○	○	●	●	●	●	●	●	●	○
5a		Useful Daylight Illuminance (UDI) 100-2000lux	●	●	● ●	●	○	○	○	○	●	○	○	●	●	●	●	●	●	●	●	○
5b		UDImin <100lux	●	●	●	●	●	●	●	●	○	○	○	○	●	○	●	●	●	●	●	○
5c		UDImax >2000lux	○	●	●	●	○	○	○	○	●	●	●	●	●	●	○	○	○	●	○	●
6	Point-in-time luminance 9am (east), 12pm (south & north), 3pm (west)	June 21 clear	○	●	●	●	○	○	○	○	○	○	○	○	○	●	●	○	○	●	○	○
		December 21 overcast	○	○	○	○	○	●	●	●	○	○	○	○	○	○	○	●	●	●	●	○
7	Point-in-time glare		○	●	●	●	○	●	○	●	●	●	●	●	●	●	●	●	●	●	○	●
8	Annual glare		●	●	●	●	○	○	○	○	●	●	●	●	●	●	●	●	●	●	○	
9a	sDA300/55%		●	●	●	●	●	●	●	●	○	○	○	○	●	●	●	●	●	●	●	○
9b	ASE1000,250h		○	●	○	○	○	○	○	○	○	●	○	○	○	●	●	●	●	●	○	●
		% fitness	32%	65%	50%	50%	18%	33%	27%	33%	32%	38%	23%	27%	50%	65%	75%	62%	65%	73%	27%	38%

● meets criteria
○ does not meet criteria

Table 3.6 Compliance table for all cases.

3.1.2 Vignette: LEED

The simulation path of the LEED Daylight credit has adapted over the years to account for the changing priorities and new research within the field. Originally, the credit revolved around Daylight Factor, requiring a DF of 2% for 75% of regularly occupied spaces. The credit evolved to require illuminance on the fall equinox at 9am and 3pm, with clear sky condition to fall between 10-500 footcandles (107-5,382 lux) for 75% of regularly occupied spaces. Most recently, in LEEDv4, an option has been added to comply with sDA≥50% and ASE<10%; an extra point can be achieved with this path. This vignette aims to explore the inclinations of the LEED Daylight credit, particularly for the new sDA and ASE requirements.

That is, many of the metrics in 3.1.1 Metric-by-metric Vignette are somewhat intuitive, including point-in-time illuminance as used by LEED2009. In fact, it is quite feasible to qualitatively evaluate a project pursuing the LEED2009 daylight credit before any simulation is completed and determine if the 75% threshold will likely be met. The new LEEDv4 daylight credit is less intuitive. This vignette aims to help combat this, providing information about the types of spaces that might be preferred with these metrics. If used well, these results could be used to predict the LEEDv4 performance for a multi-space project. If a project is designed such that the majority of spaces are favored by the metrics, it becomes more likely to achieve the daylight credit. Information is revealed regarding whether the new sDA and ASE criteria are more stringent than the point-in-time illuminance criteria.

Methodology

1. **The Baseline, Alternate 1, and Alternate 2 cases were simulated for two versions of the LEED Daylight credit,** simulation path: 1) point-in-time illuminance on 9/21 at 9am & 3pm and 2) sDA and ASE.
2. Based on the results from step 1, **iterations were tested** with varying orientation, shading, location/climate, skylights vs sidelights, narrow vs deep floorplate. These were simulated for both versions of the LEED Daylight credit. Potential findings relate to the effectiveness of the new criteria, as well as indications of massing or shading options that it tends to favor.

Results

STANDARD FLOORPLATE 25'x25'
ALL WWR

	Punched Windows *35% WWR*		Baseline *62% WWR*				Highly Glazed: all cases *100% WWR*	Skylights: clear 65% *5% skylight to floor area*	Skylights: translucent 50% *5% skylight to floor area*
	South	North, East, & West	South	North	East	West			
LEED 2009	●	○	●	●	○	○	○	●	●
LEEDv4	●	○	○	●	○	○	○	○	●

● compliant ○ not compliant

Table 3.7 LEED compliance: Baseline, Alternate 1, Alternate 2, and Skylights in Seattle.

For 35% WWR:

- Punched Windows: North does not meet the criteria, as the small openings and the sun angles at the north façade do not allow sufficient light to enter.
- Punched Windows: South meet the criteria, as the small openings are balanced by easy sun access on the south façade.

For 62% WWR:

- The Baseline: South and Skylights: clear comply for LEED2009, but not LEEDv4. Since LEED2009 is calculated at 9am and 3pm, the direct sun at 12pm is not considered an issue. This illustrates that LEED2009 is more flexible in allowing larger aperture exposures when they are not receiving direct beam sunlight. LEEDv4 does not allow such cases to comply on any orientation due to the ASE metric's 0 ab calculation.
- The Baseline East and West cases do not comply with either version of LEED. In general, these façades are more difficult to provide shading.

For 100% WWR:

- None of the Highly Glazed cases meet LEED 2009 or LEEDv4. The results for both versions of LEED overwhelmingly indicate that too much daylight is entering the space, with high sDA and ASE values, and the 50 fc upper threshold of LEED 2009 exceeded in all cases for either 9am or 3pm.

For 5% skylight to floor area:

- Clear skylights with Tvis 65% meets LEED2009 but not LEEDv4.
- Translucent skylights with Tvis 50% meet the criteria for both versions of LEED.

The results show that overall, the only cases that are compliant for both versions of LEED are Baseline: North, Punched Windows: South, and Skylights translucent 50%. Essentially, this shows that balanced diffuse light is favored overall. Moreover, LEED2009 is more tolerant of clear skylight glazing and non-diffuse sunlight (sunlight that enters south glazing at 9am and 3pm, not perfectly direct) i.e. south-facing glazing. LEEDv4 is more stringent and favors translucent skylight glazing and North glazing.

These cases do not have solar control; however, they would not comply even with dynamic shading. As dynamic shading is not taken into account in the ASE calculation (only static shading is counted), this measure would not make it possible to achieve the credit. To this end, the next several iterations will be tested with static shading, to understand what would be needed to comply.

ITERATION A
STANDARD FLOORPLATE 25'x25' WITH STATIC SHADING
BASELINE: 62% WWR (SOUTH & EAST)

Based on these results, the question arises: **What would be required for Baseline: South to be compliant for LEEDv4 in Seattle?** The sDA is just slightly meeting the required criteria, at 58.3%, while the ASE is highly above the minimum threshold at 53%. As dynamic shading is not included in the simulation for ASE, the added measure to reduce the ASE below 10% must be a static shading device. However, with shading, it is likely that the sDA will fall below the requirements. Is it possible to meet both sDA and ASE?

Performing a standard cut-off angle study, it would seem that for Seattle, the following overhang depths would be sufficient to block direct sun:

- Summer (June 21 at 12pm): 3.15'
- Fall (September 21 at 12pm): 6.6'
- Winter (December 21 at 12pm): 20.3'

With this, a range of overhang depths were tested:

	no shading		10' overhang		15' overhang		20' overhang	
sDA300/50%	58.3%	●	45.8%	○	34.9%	○	29%	○
ASE1000,250h	53%	○	37.2%	○	25.2%	○	20.7%	○
compliant?		○		○		○		○

● compliant
○ not compliant

Table 3.8 LEEDv4 compliance: Baseline South in Seattle.

Even with a 20' overhang, which theoretically should block all sun angles throughout the year, ASE still does not fall below 20%. It seems quite difficult to meet both LEED2009 and LEEDv4 with a south-facing façade in Seattle: the Baseline (no shading) case meets LEED2009, but LEEDv4 cannot be met even with shading.

The same question is posed for other climates and locations: **What would be required for Baseline: South to be compliant for LEEDv4?**

	New York 10' overhang		Phoenix 20' overhang		Houston 20' overhang		Houston 30' overhang	
sDA300/50%	31.1%	○	58.5%	●	58.9%	●	49.5%	○
ASE1000,250h	28.1%	○	26%	○	16.7%	○	16.7%	○
compliant?		○		○		○		○

● compliant
○ not compliant

Table 3.9 LEEDv4 compliance: Baseline South in various latitudes.

New York has similar results as Seattle: when an overhang is added to minimize ASE, sDA is also reduced below the target threshold of 55%. These results also show that there is a point of diminishing returns, according to this metric. The 20' and 30 overhangs for Houston yield the same ASE; that is, even at a low latitude, a more aggressive shading device does not sufficiently mitigate direct sun- but yields a lower sDA. Moreover, it shows that a difference in latitude of 4° (Phoenix at 33° and Houston at 29°) results in a 10% difference in ASE.

Similarly, **what would be required for Baseline: East to be compliant for both versions of LEED?**

		no shading		4' overhang	
LEED 2009	9am	65.6%	○	77.4%	●
	3pm	100%	●	100%	●
	compliant?		○		●
LEEDv4	sDA300/50%	72.2%	○	67.2%	●
	ASE1000,250h	41.3%	○	32.5%	○
	compliant?		○		○

● compliant
○ not compliant

Table 3.10 LEED 2009 and LEEDv4 compliance: Baseline East in Seattle.

In order to reduce the illuminance at 9am to meet the upper threshold for LEED2009, a 4' horizontal shading device (overhang or lightshelf) is needed. This translates to an overhang depth to floor-to-floor height ratio of 2:5, or 0.4. However, a 4' overhang is still not sufficient to meet ASE criteria in LEEDv4.

Finally, **what would be required to meet ASE for an east façade and 62% WWR?**

- 10' overhang: 51% sDA / 15.8% ASE
- 15' overhang: 41.7% sDA / 8.3% ASE

Between a 10'-15' overhang would be required. However, with such a large overhang, sDA is then not met. Moreover, an exceedingly large overhang (ratio of overhang depth to floor-to-floor height of 1.5:1) is not typically practical.

This suggests that perhaps the ASE criteria is too stringent. One potential solution would be to amend the criteria such that it is dependent on orientation and climate. The following suggestions are based on reasonable shading depths:

High latitudes:	Low latitudes:
For north façades and toplighting: <10%	For north façades and toplighting: <10%
For south, east, west façades: <50%	For south, east, west façades: <35%

Even with such amendments, it is important to keep in mind that ASE is designed to encourage mitigating direct beam sunlight annually. The metric does not take into account dynamic shading, as it aims to show the 'worst case condition.' However, with other factors considered such as needs for passive heating in certain climates, this might not be the best approach. In practice, a balance is more ideal.

ITERATION B
SHORTER FLOORPLATE 25' wide x 20' deep
BASELINE: 62% WWR

As seen in the previous iterations, it is very difficult to meet ASE in LEEDv4. The following iterations test whether shortening the floorplate depth is a positive or negative measure in terms of ASE. The initial results in Table 3.11 show the 62% WWR case for the north and south façades.

	North	South
LEED 2009	●	○
LEEDv4	●	○

● compliant
○ not compliant

Table 3.11 LEED 2009 and LEEDv4 compliance: shorter floorplate, North and South.

When the floorplate is shortened by 5', LEED2009 (previously met with a 25'x25' floorplate) and LEEDv4 are not met for the south glazing scenario. This is due to the same amount of overly bright illumininance levels in the space, in a smaller overall area, without dark areas at the back of the space to balance the percentage.

The question arises: **What would be required for 62% WWR south glazing to comply for LEEDv4 with a 25'x20' floorplate?** A climate at a lower latitude- Houston- was selected to test the sensitivity of the metric and determine if the LEEDv4 daylight credit could be met if a large enough horizontal overhang were to be implemented.

	Houston 4' overhang		Houston 10' overhang		Houston 20' overhang		Houston 40' overhang	
sDA300/50%	100%	●	100%	●	89.3%	●	63.6%	●
ASE1000,250h	34%	○	22%	○	21.1%	○	21.1%	○
compliant?		○		○		○		○

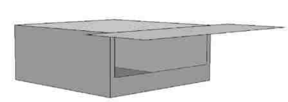
● compliant
○ not compliant

Table 3.12 LEEDv4 compliance: shorter floorplate, south glazing in various latitudes.

There seems to be a convergence: a 40' overhang brings sDA to 63.6% but ASE remains at 21.1%. For all cases, the LEED2009 criteria is met.

However, if the overhang is implemented differently, and extended 5' on each side, meeting ASE becomes more possible.

	Seattle 12' extended overhang		New York 12' extended overhang		Houston 12' extended overhang	
sDA300/50%	63.4%	●	57.7%	●	100%	●
ASE1000,250h	37.3%	○	28.5%	○	2%	●
compliant?		○		○		●



● compliant
○ not compliant

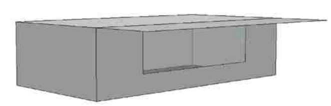
Table 3.13 LEEDv4 compliance: shorter floorplate with extended overhang, south glazing in various latitudes. Note: All locations are compliant in LEED2009 with 98-100% at 9am & 3pm.

With this new configuration, the criteria for ASE is met in Houston. The space would still not comply in Seattle or New York for LEEDv4. Regardless of location, this suggests a ratio of overhang depth to floor-to-floor height of 1.2:1. In most cases, this is not a practical design. However, it suggests that spaces with unconventional shading at low latitudes might be more apt to achieve ASE, and with it, quite possibly the LEEDv4 daylight credit.

ITERATION C
WIDER FLOORPLATE 40' wide x 20' deep
37% WWR

As seen in the shorter floorplate scenario, it is possible to achieve ASE with certain configurations. The following table shows the results for a wider floorplate, 40' wide x 20' deep. The adjustments result in a 37% WWR.

	Seattle 10' overhang		New York 10' overhang		Houston 10' overhang	
sDA300/50%	41.4%	○	60.4%	●	74.1%	●
ASE1000,250h	26.3%	○	23.1%	○	7.4%	●
compliant?		○		○		●



● compliant
○ not compliant

Table 3.14 LEEDv4 compliance: wider floorplate, south glazing in various latitudes. Note: All locations are compliant in LEED2009 with 100% at 9am & 3pm.

With this configuration, it is possible to meet both LEED2009 and LEEDv4 for Houston. New York does not meet the ASE criteria. Neither the sDA and ASE criteria are met for Seattle. Regardless of location, the Houston results suggest a ratio of overhang depth to floor-to-floor height of 1:1. In most cases, this is not a practical design. However, it suggests that spaces with exceedingly large overhangs at low latitudes might be more apt to achieve ASE, and with it, quite possibly the LEEDv4 daylight credit.

ITERATION D
STACKED HORIZONTAL SHADING
BASELINE: 62% WWR

While the previous iterations are thorough in their assessment of multiple scenarios in a variety of locations and floorplate sizes, they focus on one shading strategy: single horizontal overhangs. An alternate solution would be to implement a combination of shading strategies. An overhang with stacked horizontal louvers may be more aggressive, but is more likely to meet the LEEDv4 daylight credit.

Three main shading categories were simulated for the south-facing Baseline case, with overhang depth to spacing ratios of 1:1, 1.5:1, and 2:1.

Overhang depth to spacing ratio 1:1

The first test case was comprised of a 4’ overhang, two (2) 2’ louvers spaced 2’ apart, achieving sDA with 65.6%, but not compliant with ASE at 33%. Even increasing the overhang depth to 6’ and adding a louver so that there would be three (3) 2’ louvers spaced 2’ apart, it did not achieve compliance in Seattle (sDA 57.1/ASE 31.6%). This same configuration was not compliant in New York (sDA 63%/ASE 36.5%), but was compliant in Houston (sDA 76%/ASE 9.2%). This indicates that lower latitudes allow less dense shading.

Overhang depth to spacing ratio 1.5:1

The second test case decreased the spacing between the louvers:
4’ overhang, three (3) 2’ louvers spaced 1.5’ apart

	Seattle		New York		Houston	
sDA300/50%	65.6%	●	75.7%	●	98.3%	●
ASE1000,250h	26.3%	○	36.1%	○	8.3%	●
compliant?		○		○		●

● compliant
○ not compliant

Table 3.15 LEEDv4 compliance: Baseline South with stacked shading in various latitudes.

This was still not sufficient shading for Seattle and New York, but again, was compliant in Houston.

Overhang depth to spacing ratio 2:1

Finally, the third test case decreased the spacing between louvers again, and the results are as follows:

	sDA	ASE
4’ overhang, four (4) 2’ louvers spaced 1’ apart (6’ AFF):	47%	15.6%
4’ overhang, five (5) 2’ louvers spaced 1’ apart:	60.2%	2.4%
4’ overhang, four (4) 2’ louvers spaced 1’ apart (4’ AFF):	64.4%	9.9%
shading mask: 4’ overhang, eight (4) 1’ louvers spaced 6” apart	60.9%	11.6%

It should be noted that in the initial case, the lowest louver was at a distance 6' above finished floor (AFF). When moved up to 4' AFF, the same case was compliant. This indicates that it is important to not only implement an overhang that mitigates sun angles, but covering the lower portion of the window can also be quite critical in achieving ASE. Moreover, the addition of one louver only decreased the sDA by 4.2% while at the same time decreased the ASE by 7%; the correct placement of just one louver could be the difference in achieving the LEEDv4 daylight credit. The final configuration is shown below:

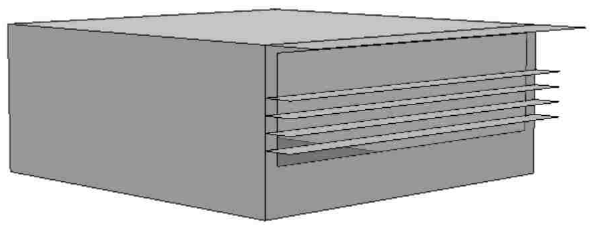


Figure 3.24 Stacked shading configuration with 2:1 overhang depth to spacing ratio.

Once the correct placement of louvers in conjunction with the optimal ratio of overhang depth to spacing was determined, this combination was tested with an equivalent shading mask. This shading mask was very close in achieving the LEED credit (not meeting ASE by only 1.6%), showing that there are in fact rules of thumb that can be followed to meet this credit.

The following conclusions can be formed from this study:

- An overhang depth to spacing ratio of 2:1 complies in higher latitudes (Seattle).
- Overhang depth to spacing ratios of 1:1 and 1.5:1 only comply for lower latitudes (Houston).
- Using shading to cover the lower portion of glazing is just as important as the use of an overhang to cut-off desired sun angles.

These claims could be validated with more of a range of orientations, shading, masks and locations. Additionally, further work could perhaps bring clarity to the following questions: To which sun angle should the overhang be sized? How far down from the overhang should louvers be located? Is there a rule of thumb/equivalent shading masks that always works?

Discussion

The main finding from the iterations in this section is that LEED2009 is possible to achieve with more of a variety of WWR ratios, glazing orientations, and floorplate sizes than LEEDv4. This is primarily due to the nature of the ASE requirements. LEEDv4 becomes more possible to achieve with a wider floorplate and extended shading. The following are guidelines to meet the current criteria for LEED2009 and LEEDv4:

- LEED2009 favors balanced glazing on south and north façades, and skylights (clear or translucent).
  - SHADING GUIDELINES: It is more difficult to meet the criteria for east and west glazing. It seems that an optimal overhang depth to floor-to-floor height ratio would be 2:5, or 0.4.
  - LOCATION GUIDELINES: The ability to meet the criteria does not seem to be latitude or climate dependent.
  - FLOORPLATE GUIDELINES: A square 1:1 width to depth ratio floorplate seems ideal. With a shorter floorplate, 5:4 width to depth ratio, it seemingly becomes more difficult to achieve the criteria.
- LEEDv4 favors balanced glazing on the north façade and translucent skylights.
  - SHADING GUIDELINES: The results for the shorter and wider floorplate iterations suggest that spaces with unconventional shading (e.g. extended overhangs) or exceedingly large overhangs might be more apt to achieve ASE, and with it, quite possibly the LEEDv4 daylight credit. Note that this does not translate to aggressive shading, as overly dense shading might meet the requirements for ASE, but it would not meet the sDA requirements. Less dense shading is needed in locations of lower latitudes e.g. Houston.
  - LOCATION GUIDELINES: It seems that it is more possible to meet ASE in lower latitudes i.e. Houston has a better likelihood than Seattle.
  - FLOORPLATE GUIDELINES: A square 1:1 width to depth ratio floorplate seems ideal. With a shorter floorplate, 5:4 width to depth ratio, it becomes more difficult to achieve the ASE criteria with 62% WWR on the south façade, by approximately 13% in higher latitudes such as Seattle (based on non-shaded case) and 5% in lower latitudes such as Houston (based on shaded cases). With a wider floorplate, 2:1 width to depth ratio, it seemingly becomes easier to achieve the ASE criteria.

As noted previously, the metrics used for the new LEEDv4 daylight credit, particularly ASE, are rather strict. In reality, practice is much more flexible. Specifically, the lack of dynamic shading in the simulation of ASE is not practical; although the intent of understanding the worst-case scenario is good, should this be used as a measure? In all likelihood, in such a condition, blinds would be drawn. This issue aside, if this metric is maintained in future versions of LEED, the author recommends that the appropriate parties (USGBC and the IES Daylight Metrics Committee) amend the thresholds to make it a more attainable goal. The following amendments are recommended, based on orientation and climate:

High latitudes:	Low latitudes:
For north façades and toplighting: <10%	For north façades and toplighting: <10%
For south, east, west façades: <50%	For south, east, west façades: <35%

Moreover, this pair of metrics was implemented such that compliance would be determined on an annual basis rather than point-in-time illuminance. While this combats the use of a singular metric, both sDA and ASE are still illuminance-based. Perhaps a future version of LEED would pair illuminance and luminance metrics. It is understood that illuminance is historically easier to quantify and therefore might be easier for novice daylight analysts; however, with the changing landscape of the field of computational lighting design and changing capabilities, it is only appropriate to reflect all aspects of the luminous environment in environmental benchmarks such as LEED.

Still, the question remains: If a project meets the LEED daylight credit, can it be inferred that the project is well daylit? This question is extremely subjective, and its complexity is beyond the scope of this thesis. However, the predilections of these metrics can be determined, and the designer can determine the answer by deduction. For example, it has been determined that, together, the LEEDv4 metrics favor diffuse lighting from north glazing or skylights. The designer can decide whether such a design is well daylit. It is the belief of this author that this definition is extremely limiting. There are many other ways to design a well daylit, visually stimulating space, and often direct sun can add to the dynamism of the space. By narrowing the definition to mainly diffuse light from less of a variety of apertures, the very idea of ‘daylighting’ is compromised.

Ultimately, it is of the opinion of the author that LEED can be used as a guideline en route to designing a well daylit space, with caution. Too often the design team spends time reconfiguring regularly occupied spaces with the sole aim of achieving the daylight credit regardless of whether the project is well daylit. This approach defeats both the aim of LEED and daylight design. This issue stems from three issues: the designer focusing on prestige or accreditation; the designer not being aware of what a daylit space entails (and therefore relying on guidelines like LEED); and misdirected confidence in the LEED system’s ability to provide guidelines that result in a well daylit space (both on the designer's end for not considering otherwise and the USGBC for advertising as such).

Regardless of the current thresholds, practitioners have the ability to carefully and intelligently interpret the data. Rather than simply using LEED as a measure of a well daylit space, the findings should be incorporated with other metrics, and based on overall goals, the design may move forward accordingly.

Potential work that would expand upon the findings from this study include:

- Further refine the guidelines with more combinations of shading options, including vertical fins.
- Provide guidelines based on a wider range of climates. This would include predominantly clear and predominantly overcast climates at the same latitudes.
- Provide guidelines based on more than one space e.g. 3 spaces: 2 with north-facing glazing and 1 south with south-facing glazing, and obtain an optimal ratio of glazing by orientation.
- Develop a robust spreadsheet with results for a variety of glazing and shading combinations that designers could access early in the design process to predict their LEED compliance. An alternate interface could be real-time Grasshopper results.

3.2 Objective 2 Assumptions

3.2.1 Vignette: Sky Models and Methods

Practitioners are often limited by their understanding of the assumptions and methods behind the available metrics. This is in part due to the practitioners' initiative, resources, and experience level, but also in part due to lack of transparency or failure to convey the assumptions behind certain metrics. This vignette investigates some key assumptions within selected metrics, with the objective of giving practitioners the full knowledge needed to appropriately select and use metrics.

As discussed in section 2.2.2, light sources- specifically sky models- are a critical input for computational lighting simulations. This vignette aims to determine whether there is a significant difference between the results from different sky models and methods, using the Baseline model. The methodology is divided into two sections. The first, 'Actual vs Assumed,' begins with examining weather data to find a clear, intermediate, and overcast day. Results using the Perez All-Weather Model are compared to results using the CIE model with corresponding assumed sky condition (both point-in-time via RADIANCE). The results are also compared to data extracted from the annual illuminance results for the corresponding dates and times, using the Perez All-Weather model via DAYSIM (Daylight Coefficient Method). The second, 'Theoretical vs Actual,' begins with the key dates used in 3.1.1 Metric-by-metric Vignette for CIE model simulation that are theoretically clear, intermediate, and overcast, and compares the results from a simulation performed using the Perez model for actual conditions on the same days; the latter will not necessarily be the same sky condition. Again, the results are compared to the Daylight Coefficient Method. The process will be completed for both illuminance, glare, and luminance:

- Point-in-time illuminance (CIE) vs point-in-time illuminance (Perez via RADIANCE) vs selected date from annual .ill file (Perez via DAYSIM/Daylight Coefficient Method)
- Point-in-time glare (CIE) vs point-in-time glare (Perez via RADIANCE) vs selected date from annual DGP (Perez via DAYSIM/Enhanced Simplified DGP method)
- Point-in-time luminance (CIE) vs point-in-time luminance (Perez via RADIANCE)

Methodology

'Actual vs Assumed'

Perez (clear/intermediate/overcast) vs CIE (clear/intermediate/overcast)

1. The "brightest sunny day" (July 23 at noon), an intermediate day (October 12 at noon), and "most overcast day" (March 5 at noon) in Seattle were determined using the Ecotect Weather Tool.
2. Point-in-time illuminance was simulated using the Baseline model with the CIE sky model for these three times, using a CIE clear sky for July 23, a CIE intermediate

sky for October 12, and a CIE overcast sky for March 5.

3. Point-in-time illuminance with the Perez All-Weather model (via RADIANCE) was simulated for these three times, using the corresponding direct normal Irradiance and diffuse horizontal Irradiance for each day at noon from the Seattle TMY3 weather file.
4. An annual illuminance simulation (Perez via DAYSIM/Daylight Coefficient Method) was performed. Corresponding results were extrapolated for the two dates and times chosen.
5. Results from all three methods were compared.
6. The process was repeated for point-in-time glare and annual glare. This reveals information regarding the 0 ambient bounce assumption for annual DGP.
7. The process was repeated for point-in-time luminance (without step 4).

'Theoretical vs Actual'

CIE (predicted sky conditions for key dates) vs Perez (actual sky conditions)

1. The Baseline model was simulated for point-in-time illuminance with CIE sky models for key dates and times:
    - a. June 21 at noon, clear sky
    - b. September 21 at noon, intermediate sky
    - c. December 21 at noon, overcast sky
2. Point-in-time illuminance was simulated with the Perez All-Weather model (via RADIANCE) for the same dates and times (a-c), *regardless of sky condition*.
3. Results from an annual illuminance simulation (Perez via DAYSIM/Daylight Coefficient Method) were extrapolated for the dates chosen in Step 1.
4. Results from all three methods were compared.
5. The process was repeated for point-in-time glare and annual glare
6. The process was repeated for point-in-time luminance (without step 3).

Results

ILLUMINANCE

ACTUAL VS ASSUMED

The Actual vs Assumed results (Figure 3.25) show that there is a marked difference between both CIE and Perez sky models, and between the point in time simulation and the Daylight Coefficient method. There is a more significant discrepancy with intermediate sky conditions than with clear and overcast sky conditions. This difference is highlighted both by graphs- a daylight distribution section cut through the space from the South façade to the back of the space (Figure 3.26)- and by a direct subtraction of illuminance values from Perez to CIE (Figure 3.27). The findings are summarized as follows:

- Given the clearest day in Seattle, where air quality is high compared to other places, the results of the CIE and Perez sky models are close.
- CIE clear sky models best predict the actual sky conditions, although they do not capture the highest values (perimeter).
- CIE overcast sky models do not predict the actual sky conditions as well as CIE clear, but they predict better than CIE intermediate.
- CIE intermediate sky models do not predict the actual sky conditions well. This is problematic, as weather conditions often fit into an intermediate condition, and cannot be described as purely clear or overcast.

One potential discrepancy is related to the times used. The point-in-time CIE and Perez were simulated for 12pm, while the data extrapolated from the Daylight Coefficient Method was 12:30pm. Moreover, the weather data in the Ecotect Weather Tool was off by one hour from the raw EPW file.

Regardless, based on these results, it is recommended that unless the user is certain that the sky is clear or overcast, a Perez model should be used if accurate illuminance values are desired. A further study was performed for two different intermediate sky conditions: direct normal Irradiances of 685 W/m^2 (October 12) and 359 W/m^2 (September 20). The chosen dates were carefully selected such that both fall within the same season (autumn) to eliminate the variable of sun angle as much as possible, and isolate the differences to the weather data impacts. The results indicate that regardless of the magnitude of the direct normal Irradiance, if it is not a very high (clear) or (very low) overcast sky, the CIE sky model will yield significantly different results than the Perez All-Weather model.

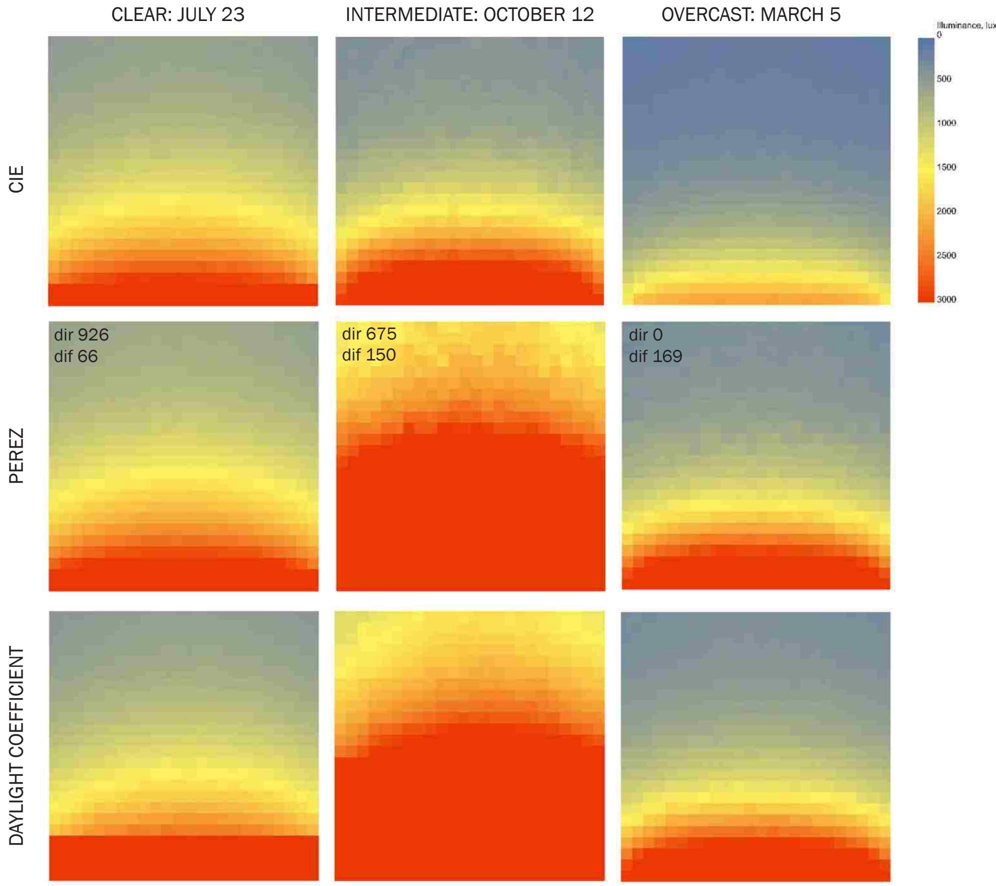


Figure 3.25 Sky model comparison: Illuminance, Actual vs Assumed results.

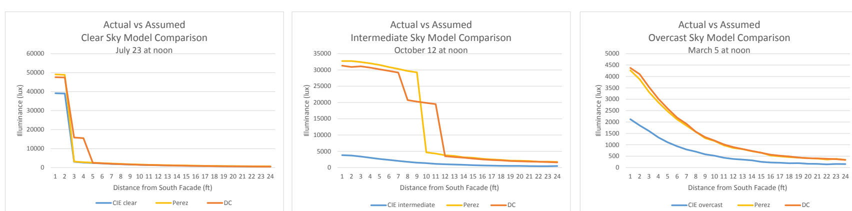


Figure 3.26 Sky model comparison: Illuminance, Actual vs Assumed daylight distribution graphs.

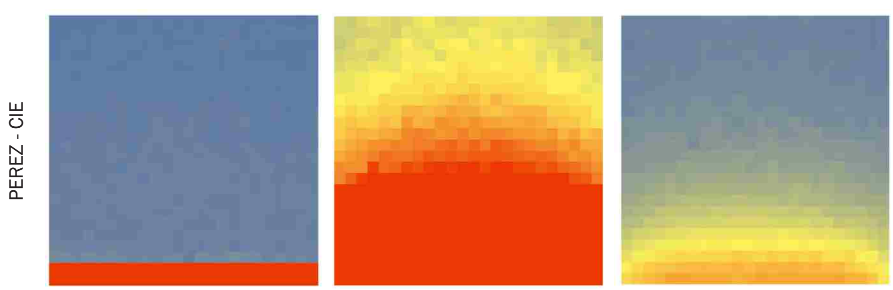


Figure 3.27 Sky model comparison: Illuminance, Actual vs Assumed subtracted results.

THEORETICAL VS ACTUAL

In the Theoretical vs Actual comparison (results shown below in Figure 3.28), the Perez results do not correspond directly to the CIE results. As noted in Step 1, this is due to the difference in sky condition. It is clear from these results that these sky models cannot be used interchangeably for the same date and time without carefully checking the weather data. The CIE models show the results for a theoretically clear, intermediate, and overcast sky. For those same dates and times, the actual sky condition is not necessarily clear, intermediate, and overcast, respectively. This highlights the issue that comes with such assumptions. If a user would like to use the Perez All-Weather model, it is critical that the weather data is first interpreted and then used accordingly. Two methods to do so are as follows:

- The ‘Actual vs Assumed’ method. That is, use weather data to select the dates of interest.
- The ‘Theoretical vs Actual’ method with slight modification. If June, September, and December are truly desired for the analysis, a date other than the 21st might be needed. For example, the weather data for December 21st in Seattle corresponds to a clear day, not overcast. An overcast day in December could be selected by reviewing the weather data. For Seattle, December 23 at noon has direct normal Irradiance of 0 W/m² and diffuse horizontal Irradiance of 81 W/m², which is assumed to be an overcast sky condition.

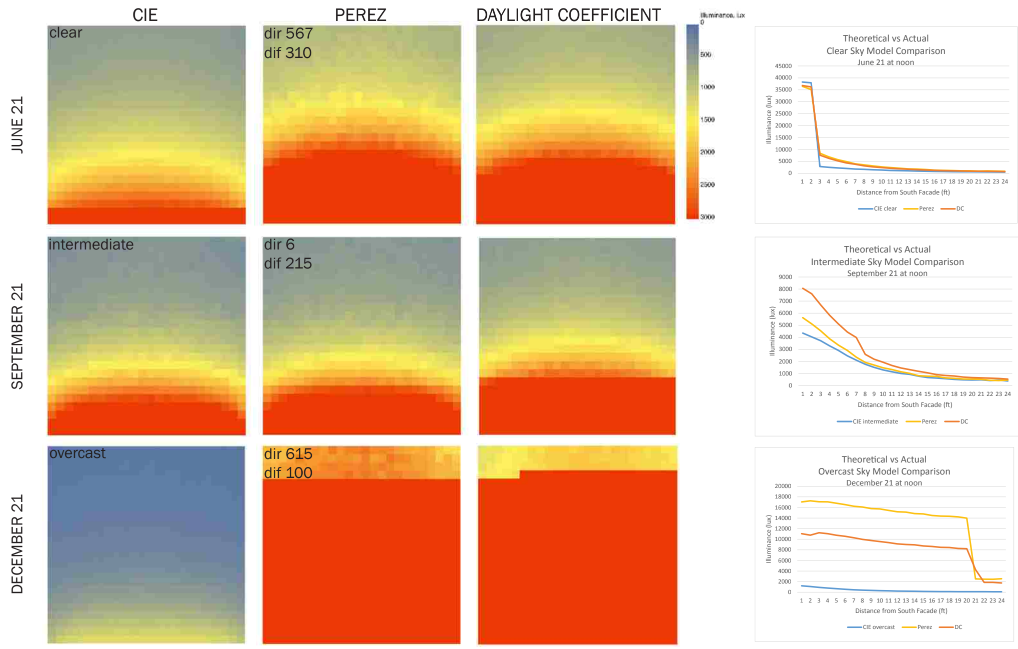
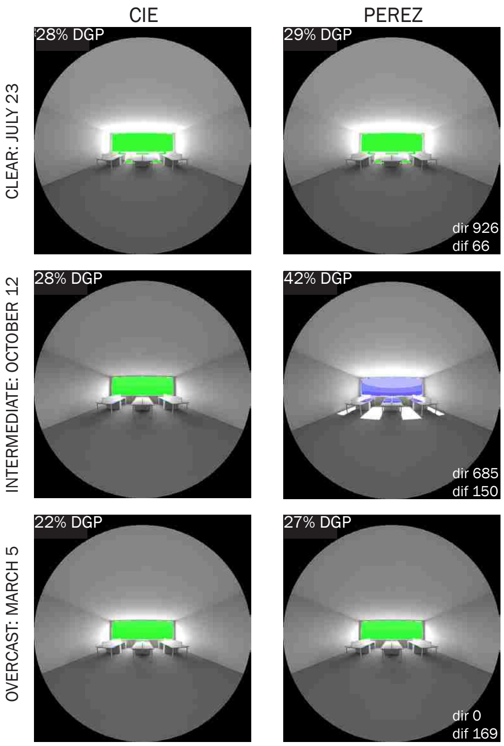
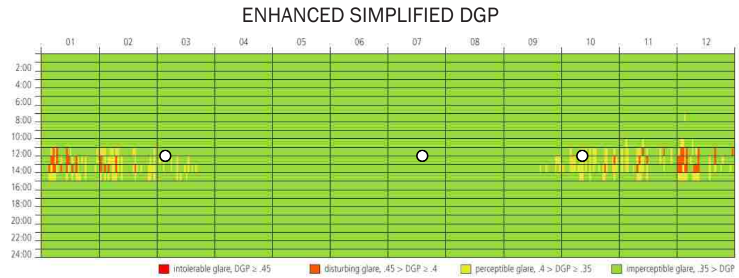


Figure 3.28 Sky model comparison: Illuminance, Theoretical vs Actual results (left) and daylight distribution graphs (right).

GLARE
ACTUAL VS ASSUMED

The results for the Glare, Actual vs Assumed study are as follows:





	CIE	Perez	enhanced simplified DGP
clear: July	28%	29%	21%
int: October	28%	42%	39%
overcast: March	22%	27%	23%

Figure 3.29 Sky model comparison: Glare, Actual vs Assumed results.

Two main findings are revealed from these results. First, for the clear sky in July, the CIE and Perez results are very similar, at 28% and 29% respectively. However, the enhanced simplified DGP is much lower, at 21%. With the challenges on the glare thresholds, particularly the notion that a space could be considered uncomfortable with a DGP of >23% [22] rather than the current standard of 35%, this is significant. This goes against the claim that the 0 ambient bounce parameter used in this method would not result in a significant difference, unless a scattering material such as a fabric shade were to be simulated [57]. The same study was conducted with the addition of a mechoshade, and similar discrepancies were present. Further study might be needed to determine the validity of the 0 ambient bounce setting, both with and without scattering materials.

Secondly, there is a range of DGP values present in CIE, Perez, and enhanced simplified DGP method for the intermediate and overcast sky results. This illustrates that it is critical to be aware of the assumptions (sky models, method, and RADIANCE parameters), as they greatly impact results.

As in the illuminance study, the largest difference for glare lies in the intermediate sky cases. As such, a more detailed comparison between intermediate skies with varying levels of direct normal Irradiances was conducted. The CIE intermediate sky simulations for both dates yielded a 28% DGP. However, the September 20 intermediate sky with a lower direct normal Irradiance (359 W/m^2) was shown to have a DGP of 37%, while the October 12 intermediate sky with higher direct normal Irradiance (685 W/m^2) was shown to have a DGP of 42%. That is, the case with the lower direct normal Irradiance resulted in a slightly smaller difference from the corresponding CIE intermediate sky. However, it seems that regardless of the magnitude of the direct normal Irradiance, if it is not a very high (clear) or (very low) overcast sky, the CIE sky model will yield significantly different results than the Perez sky model.

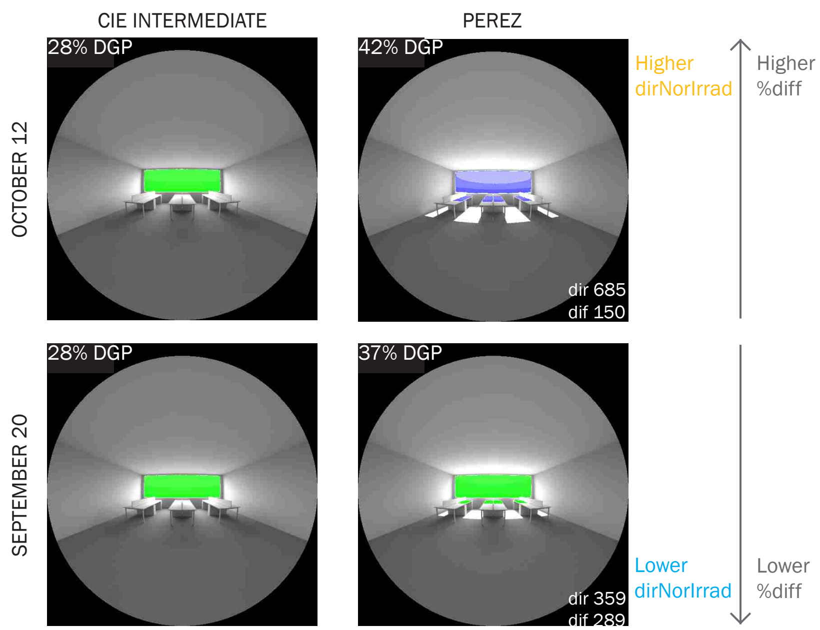
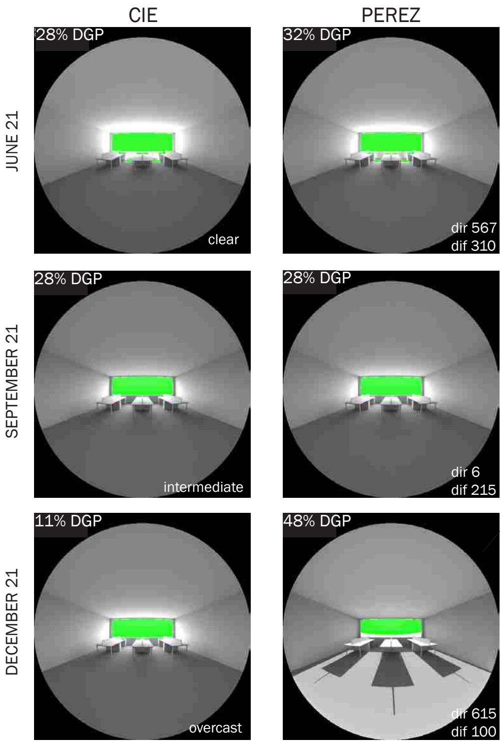


Figure 3.30 Sky model comparison: Glare, Actual vs Assumed, Intermediate sky study.

THEORETICAL VS ACTUAL

The results for the Glare, Theoretical vs Actual study are as follows:



	CIE	Perez	enhanced simplified DGP
June 21	28%	32%	21%
September 21	28%	28%	34%
December 21	11%	48%	23%

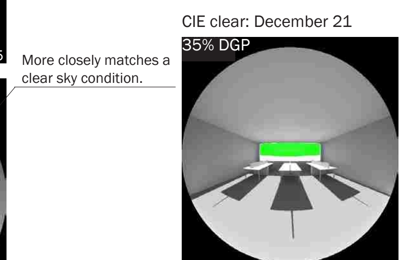


Figure 3.31 Sky model comparison: Glare, Theoretical vs Actual results.

Again, as in the Illuminance Theoretical vs Actual study, the results do not align because the dates were selected without using weather data. This highlights the risks of being unaware of the assumptions used in simulation. In this case, if an understanding of the solstices and equinox are desired, dates (other than the 21st) that match the desired sky conditions must be selected using weather data. This also highlights the difficulty of using Perez sky models: although they may be more accurate, the process is more time-consuming, and potential errors are more likely.

It is important to note that these dates are not indicative of all conditions. Glare is not only dependent on sky condition; the sun angle is also critical. The lowest sun angle with a clear sky is often the most problematic condition. Although a winter date was not selected for a clear sky condition, it seems that the December 21 Perez sky more closely matches a clear sky condition, and consequently this scenario was examined. However, even with this comparison, there is a significant percentage difference.

LUMINANCE
ACTUAL VS ASSUMED

The results for the Luminance, Actual vs Assumed study are as follows:

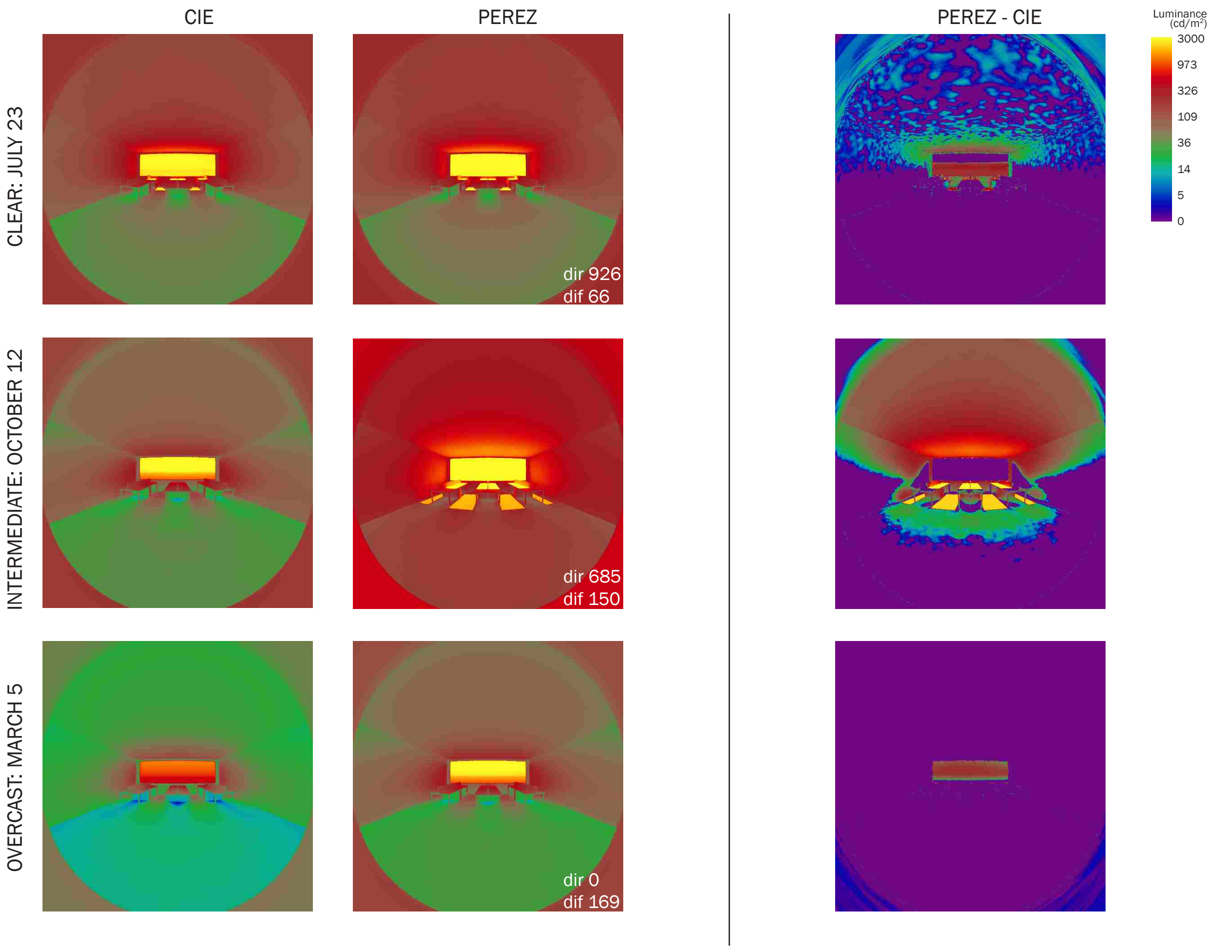


Figure 3.32 Sky model comparison: Luminance, Actual vs Assumed results (left) and subtracted results (right).

These results are slightly more difficult to interpret and compare than the illuminance and glare results. Visually, the CIE and Perez results seem to align best for the clear sky case. However, a subtraction of Perez minus CIE pixel values reveals that the overcast sky case aligns most closely between sky models. Again, the intermediate sky case has the largest differences, particularly at the desk surfaces, which is quite critical in this office environment. This is not only interesting from a research standpoint, but also in practice: luminance is often used for an understanding of the experience of the space and distribution, and such a discrepancy could be critical when making design decisions.

THEORETICAL VS ACTUAL

Finally, the results for the Luminance, Theoretical vs Actual study are as follows:

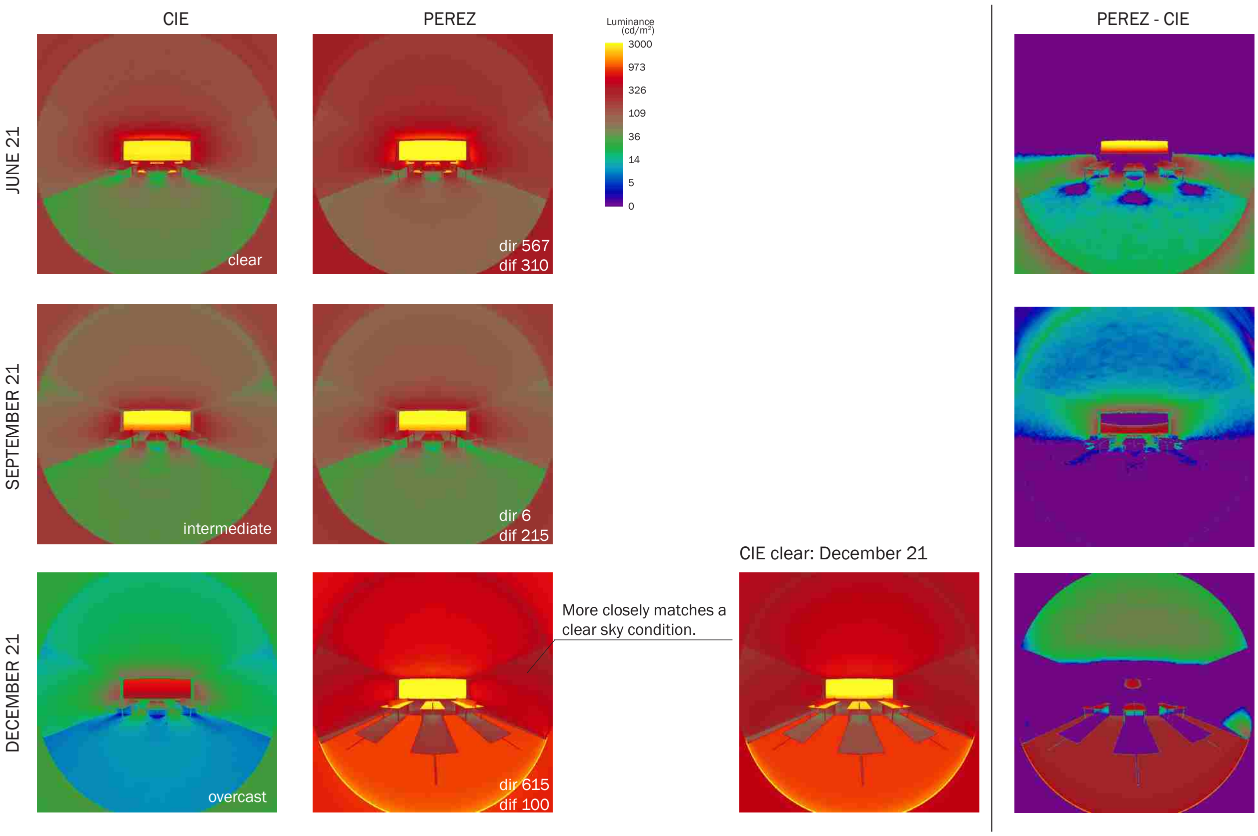


Figure 3.33 Sky model comparison: Luminance, Theoretical vs Actual results (left) and subtracted results (right).

As in the previous Theoretical vs Actual studies, the results do not align because the dates were selected without using weather data. Overall, the differences are apparent visually comparing the CIE and Perez results, and in the subtracted image. Again, the December 21 Perez results more closely match a CIE clear sky than a CIE overcast sky. This highlights the risks of being unaware of the assumptions used in simulation. In this case, if an understanding of the solstices and equinox are desired, dates (other than the 21st) that match the desired sky conditions must be selected using weather data. Again, this highlights the difficulty of using Perez sky models: although they may be more accurate, the process is more time-consuming, and potential errors are more likely.

Discussion

This vignette reveals inadequacies and risks of sky model, method, and RADIANCE parameter assumptions. A point-in-time simulation using a CIE sky model cannot simply be extrapolated to annual data- it is not indicative. Additionally, a point extrapolated from the annual data (Daylight Coefficient Method) cannot be directly compared with point-in-time using a CIE sky model, as they use different methods and sky models. It is critical to determine if abstract or climate-based results are needed in a given project.

In current practice, CIE sky models are often used, no matter the analysis goal. The main advantage is that they are accessible; point-in-time simulation using RADIANCE-based simulation engines with CIE sky models is the most commonly used computational lighting method. These models are sufficient if the design team needs only a general understanding of the luminous environment and for comparing design options, as is often the case in preliminary design phases. However, the results of this vignette reveal that one cannot obtain accurate lighting data using CIE sky models. A sky model based on weather data, such as the Perez All-Weather model, would be needed; it is suggested that a capability for software such as DIVA for Rhino to autofill the Irradiance parameters once a date is selected for ease of use and reducing human error. Another option for more accurate results is Image-Based Lighting; by using an HDR image in lieu of a sky model, site-specific lighting information can be obtained.

One of the largest issues in this field is highlighted by the metrics used in this vignette. While point-in-time luminance for a CIE sky and Perez sky was compared, the respective points-in-time extrapolated from annual luminance data was not, as there is no such metric. One of the largest challenge to the field as a whole is the lack of an annual luminance metric that is not specifically glare-centric. As noted in Section 2.3.2, Rockcastle and Andersen have developed new annual luminance metrics, Annual Spatial Contrast and Luminance Variability [59]. Such metrics provide spatio-temporal information about the luminous environment that all other singular metric lack. In fact, to achieve the same level of understanding, both illuminance and luminance analyses must be performed concurrently, and even then, the aspect of variability is typically lacking. This leads this author to conclude that development of annual luminance metrics should be a focus.

3.3 Guidelines

The results from the three vignettes in this chapter can be used collectively to propose guidelines in three ways: 1) METRIC-CENTRIC (i.e. a new user is interested in understanding the predilections and application of each metric); 2) SPACE-CENTRIC (i.e. a designer has a space with, predominantly, a certain WWR and glazing orientation and is interested in which metrics should be used along with potential concerns and shading options), and 3) COMPLEMENTARY METRICS (i.e. how to pair metrics, metrics to avoid, and proposed workflow in using metrics). While the results of these vignettes are based on a space of this size with primarily south-facing glazing in Seattle, and therefore cannot be generalized, the discussion and subsequent proposed guidelines can be, to a certain extent. These guidelines are presented on the following pages.

1) METRIC-CENTRIC

The following table might be helpful to a newcomer to the daylighting field interested in understanding the predilections and application of each metric. The information can be used to develop a standard workflow for their individual or office use, or frame an analysis approach for a particular project.

Metric #	Metric Name		favors	application
1	Shadow and sun path studies		Only possible with north glazing or any glazing with solar control.	-Can be used at any phase of design. Most effective early in design. -One of the quickest metrics to use early on to determine problematic spaces and times. -Often precedes other studies, such as point-in-time analysis or radiation maps.
2	Daylight Factor		Favors skylights.	-Used at any phase of design. -Often used early on to determine if sufficient daylight levels are being reached. -Should pair with at least 2 other metrics. A strong combination would likely be DF, annual illuminance, and point-in-time luminance.
3	Point-in-time illuminance		Almost impossible to achieve all three dates with same criteria: -Clear sky favors less glazing (or translucent skylights) -Overcast sky favors more glazing	-Used at any phase of design. -Often preceded by a sun path or overshadowing study to determine the key dates and times. -Can be paired with any metric, depending on the findings. Point-in-time luminance if the feeling inside a space is desired; annual illuminance for larger trends; point-in-time or annual glare if the contrast ratio is extremely high.
4a	Annual illuminance	Daylight Autonomy (DA) 8am-6pm | 300 lux	Favors any glazing other than north, and WWR above 35%.	-Most often used during SD and DD. Concept phase is usually too early with not enough detail. Cannot be measured in post-occupancy. -Can be used to estimate lighting power and energy savings. -Is best paired with a point-in-time luminance, point-in-time glare, and/or annual glare study.
4b		Continuous Daylight Autonomy (cDA) 8am-6pm | 300 lux	Favors any glazing other than north.	
5a		Useful Daylight Illuminance (UDI) 100-2000lux	Favors balanced glazing, not orientation-dependent.	-Most often used during SD and DD. Concept phase is usually too early with not enough detail. Cannot be measured in post-occupancy. -Is best paired with a point-in-time luminance rendering. If UDImax is high, a point-in-time glare and/or annual glare study might be needed.
5b		UDImin <100lux	Favors more glazing.	
5c		UDImax >2000lux	Favors less glazing.	
6	Point-in-time luminance			-Most often used during SD and DD. Concept phase is usually too early with not enough detail. -Is best paired with annual illuminance, and sometimes point-in-time illuminance.
7	Point-in-time glare		Very highly dependent on view AND time chosen.	-Most often used during SD and DD. Concept phase is usually too early with not enough detail. -Usually preceded by a sun path or annual glare study to determine times with potential glare risk. -Is best paired with annual illuminance, and sometimes point-in-time illuminance.
8	Annual glare		Favors balance to little glazing; possible to achieve with high glazing only if solar control is included.	-Most often used during SD and DD. Concept phase is usually too early with not enough detail. -Is best paired with annual illuminance and point-in-time luminance renderings, and sometimes point-in-time illuminance.
9a	sDA300/50%		Favors more glazing.	-Predominantly used during DD for LEED calculations. -This pair works well together. However, if the goal is not only LEED, these are best paired with point-in-time luminance. -May be supplemented with follow-up analyses depending on the findings.
9b	ASE1000,250h		Favors balanced glazing on north and translucent skylights.	

Table 3.16 Guidelines: Metric-Centric.

2) SPACE-CENTRIC

The space-centric matrix (Table 3.17 on the following page) might be helpful to a designer who has a space with, predominantly, a certain window-to-wall ratio (WWR) and glazing orientation. By finding their space type within the matrix, the designer may form a better understanding of which metrics should be used, along with potential design adjustments, times of interest/worst case scenario, shading options, and the likelihood of achieving the LEED daylight credit for 2009 or v4.

This matrix should be interpreted with the understanding that every project is unique. The program or climate may call for a particular study that is not mentioned in the matrix. For example, as mentioned in the Discussion for the Metric-by-metric Vignette, in an auditorium or church with a stage that requires projections, it might be crucial to mitigate direct sun beams, and shadow and sun path studies should be used.

While it is unlikely in most cases that the full luminous environment can be understood with only one metric, spaces with extreme designs such as highly glazed or small punched windows may be better able to be described with less metrics. The following are two examples:

100% WWR (highly glazed)
All metrics tend to point to similar notions: too bright.
Most informative metric: illuminance (TDI_{max}) to understand where it is too bright.
Easier to correct than too little glazing.

35% WWR (punched windows)
All metrics tend to point to similar notions: too dark.
Most informative metric: illuminance (TDI_{min}) to understand how far from target illuminance
More difficult to correct than too much glazing.

The 'SIMPLEST CASES' are noted in the matrix: South 35% WWR and North 62-100% WWR. These cases likely require the least amount of analysis, design adjustments, and shading to create a well daylit, visually comfortable environment. They offer the most flexible environments, meaning that the guidelines are less stringent: the designer has the most flexibility in terms of metrics used.

Certainly, this matrix would be more useful if it were to address a combinations of space types. With many more simulations, a more robust matrix could be developed, but ultimately the interpretation and design decisions are left to the designer.

WWR	orientation: South	North	East	West
35%	SIMPLEST CASE -RECOMMENDED STUDIES: Point-in-time or annual illuminance study with upper limit (UDI) to determine what portion of the minimum lighting requirements is being met; point-in-time luminance studies at key times of year to understand distribution in the space. [Even if illuminance studies indicate that the space is dark, the luminance distribution might indicate otherwise.] -POTENTIAL DESIGN ADJUSTMENTS: Provide more light with apertures on other orientations. -SHADING OPTIONS: Possibly needed. Static horizontal shading (overhang or lightshelf); dynamic shading if more control is desired. -TIMES OF INTEREST: June clear and December overcast skies during mid-day 12-2pm -LEED EQc8.1: Likely to achieve 2009.	-RECOMMENDED STUDIES: Point-in-time or annual illuminance study to determine what portion of the minimum lighting requirements is being met; point-in-time luminance studies at key times of year to understand distribution in the space. [Even if illuminance studies indicate that the space is dark, the luminance distribution might indicate otherwise. Daylight factor or glare studies alone should not be used as indicators singularly- they will likely predict that the space is performing well.] -POTENTIAL DESIGN ADJUSTMENTS: Provide more light with increased Tvis and apertures on other orientations. -SHADING OPTIONS: Likely not necessary; manual roller blinds if control is desired. -WORST CASE SCENARIO: Overcast skies during shoulder seasons and winter, depending on climate. -LEED EQC8.1: Not likely to achieve.	-RECOMMENDED STUDIES: Point-in-time or annual illuminance study to determine what portion of the minimum lighting requirements is being met; point-in-time luminance studies at key times of year to understand distribution in the space. -POTENTIAL DESIGN ADJUSTMENTS: Provide more light with apertures on other orientations. -SHADING OPTIONS: Might be needed for clear sky conditions during afternoon hours depending on climate and program. Vertical or horizontal shading should be considered. At minimum, roller blinds might be required to supplement if direct sun beams enter the space for extended periods of time. -WORSE CASE SCENARIO: Overcast skies during afternoon: shoulder seasons and winter, depending on climate. -LEED EQC8.1: Not likely to achieve.	-RECOMMENDED STUDIES: Point-in-time or annual illuminance study to determine what portion of the minimum lighting requirements is being met; point-in-time luminance studies at key times of year to understand distribution in the space. -POTENTIAL DESIGN ADJUSTMENTS: Provide more light with apertures on other orientations. -SHADING OPTIONS: Might be needed for clear sky conditions during afternoon hours depending on climate and program. Vertical or horizontal shading should be considered. At minimum, roller blinds might be required if direct sun beams enter the space for extended periods of time. -WORST CASE SCENARIO: Overcast skies during morning: shoulder seasons and winter, depending on climate. -LEED EQC8.1: Not likely to achieve.
62%	-RECOMMENDED STUDIES: A balance of any illuminance and luminance metrics. If illuminance metric without upper limit is used, it is possible to miss potential glare risk. -SHADING OPTIONS: Likely needed. Static horizontal shading (overhang, lightshelf) is often effective on south façades, but venetian blinds and roller blinds might be desired if more control is desired. -TIMES OF INTEREST: Mid-day. -WORST CASE SCENARIO: Low angle sun with clear skies: December 12-2pm. -LEED EQC8.1: Likely to achieve 2009.	SIMPLEST CASE -RECOMMENDED STUDIES: A balance of any illuminance and luminance metrics. -SHADING OPTIONS: Likely not necessary; manual roller blinds if control is desired. -LEED EQc8.1: Likely to achieve 2009 and v4.	-RECOMMENDED STUDIES: A balance of any illuminance and luminance metrics. [If illuminance metric without upper limit is used, it is possible to miss potential glare risk.] -SHADING OPTIONS: Likely needed. Vertical or horizontal shading should be considered. A dynamic system with venetian blinds and roller blinds might be required to supplement if glare risk is very high and more control is desired. -TIMES OF INTEREST: Morning. -WORST CASE SCENARIO: Low angle sun with clear skies: December 7-9am. -LEED EQc8.1: Not likely to achieve.	-RECOMMENDED STUDIES: A balance of any illuminance and luminance metrics. [If illuminance metric without upper limit is used, it is possible to miss potential glare risk.] -SHADING OPTIONS: Likely needed. Vertical or horizontal shading should be considered. A dynamic system with venetian blinds and roller blinds might be required to supplement if glare risk is very high and more control is desired. -TIMES OF INTEREST: Afternoon. -WORST CASE SCENARIOS: Low angle sun with clear skies: December 2-4pm. -LEED EQc8.1: Not likely to achieve."
100%	-RECOMMENDED STUDIES: Glare or illuminance study with upper limit. [If illuminance metric without upper limit is used, it is highly possible to miss potential glare risk.] -SHADING OPTIONS: Highly likely that shading will be needed. Static horizontal shading (overhang, lightshelf) is often effective on south façades, but due to the large amount of glazing, venetian blinds and roller blinds might be required to supplement if glare risk is very high and more control is desired. -TIMES OF INTEREST: Mid-day. -WORST CASE SCENARIO: Low angle sun with clear skies: December 12-2pm. -LEED EQc8.1: Not likely to achieve.	SIMPLEST CASE -RECOMMENDED STUDIES: A balance of any illuminance and luminance metrics. -SHADING OPTIONS: Might not be necessary; manual roller blinds if control is desired. -LEED EQC8.1: Not likely to achieve.	-RECOMMENDED STUDIES: Glare or illuminance study with upper limit. [If illuminance metric without upper limit is used, it is highly possible to miss potential glare risk.] -SHADING OPTIONS: Highly likely that shading will be needed. Vertical or horizontal shading should be considered. A dynamic system with venetian blinds and roller blinds might be required to supplement if glare risk is very high and more control is desired. -TIMES OF INTEREST: Morning. -WORST CASE SCENARIO: Low angle sun with clear skies: December 7-9am. -LEED EQC8.1: Not likely to achieve.	-RECOMMENDED STUDIES: Glare or illuminance study with upper limit. [If illuminance metric without upper limit is used, it is highly possible to miss potential glare risk.] -SHADING OPTIONS: Highly likely that shading will be needed. Vertical or horizontal shading should be considered. A dynamic system with venetian blinds and roller blinds might be required to supplement if glare risk is very high and more control is desired. -TIMES OF INTEREST: Afternoon clear skies. -WORST CASE SCENARIOS: Low angle sun with clear skies: December 2-4pm. -LEED EQC8.1: Not likely to achieve.

Table 3.17 Guidelines: Space-Centric.

3) METRICS PAIRS

While much information can be found detailing the definitions of each metric, and varying level of detail is available revealing the methods and algorithms involved, there are currently no recommendations outlining pairs of metrics, or which metrics are lacking and should therefore be supplemented. The following pairs of metrics are proposed for better addressing daylight considerations in practice:

- If point-in-time metrics are being used to answer a specific question, one method is to precede them with a shadow or sun path study to determine the dates and times of interest.
- Use point-in-time and annual; illuminance and luminance when possible.
  - point-in-time illuminance and annual glare
  - point-in-time luminance/glare and annual illuminance
- If glare is the specific question of interest, begin with annual glare to determine times of interest and then perform more detailed analysis with point-in-time glare. Conversely, always pair annual glare with point-in-time glare, as the former employs the enhanced simplified DGP method, which uses 0 ambient bounces and can often underpredict.
- Avoid using DA for understanding of the luminous environment, as it does not take into account overly high light levels.
  - If interested in energy savings, cDA should replace DA.
  - If interested in daylight levels, UDI should replace DA.
  - However, if used, DA or cDA should be paired with a metric that has an upper limit such as UDI, annual glare, or even point-in-time illuminance with 3,000 lux as the upper limit. Point-in-time luminance is also an option if using a maximum allowable contrast ratio (tools such as hdrscope offer this capability).
- UDI, UDI_{min}, and UDI_{max} together are effective in telling the full illuminance story, but are missing the piece that tells how the space will feel, and should therefore be paired with a luminance-based metric. Moreover, they depend greatly on the limits used and it is recommended to have a method of simulating or post-processing with adjusted limits according to the project at hand (Target Daylight Illuminance, or TDI).
- The intention behind sDA and ASE is good, but they might in fact be a bit strict. Simply because a space meets them does not mean it is a feasible design e.g. exceedingly large overhangs to comply with ASE. Moreover, they are both annual illuminance metrics and should therefore be paired with point-in-time luminance.
- It is important to recognize when diffuse or direct light should be considered. Metrics that use 0 ambient bounces only account for direct; annual glare, ASE, and shadow studies are better equipped to handle questions related to direct beam sunlight. All three can also address variability. They should be paired with a supplementary metric that takes into account interreflections and uses more than 0 ambient bounces.

Overall, if used well, these guidelines can aid in developing methodologies and approaches to computational lighting analysis and design in a way that allows practitioners to better understand and express the full luminous environment. Behind all guidelines are the following key ideas:

- Illuminance and luminance should be core necessities in any daylighting analysis.
  - Most projects fall in between extremes, and follow this rule. For example, as in the cases outlined in this thesis, both illuminance and luminance are necessary to best design for light levels, visual perception, visual performance, visual comfort, and variability in an office.
  - There are exceptions based on particular combinations of program and project priorities:
    - Program: Office
      Optimize: Energy
      Metric: Illuminance, particularly Continuous Daylight Autonomy (cDA), can be used alone.
    - Program: Chapel
      Optimize: Daylight distribution/visual perception
      Metric: Luminance can provide a very good starting point for programs with more flexible illumination requirements.
- Point-time time and annual metrics have their strengths and weaknesses. An awareness of these strengths and weaknesses is essential to appropriately selecting metrics for a project analysis.
- Performing several analyses is typically warranted, and will provide the most information about the space. However, it is critical to determine if abstract or climate-based results are needed, and prioritize efficiency or accuracy- or a balance between the two.
  - If efficiency is desired: 1) if a time (and viewpoint) of interest is known, a quick point-in-time illuminance or luminance study, or sometimes a sun path or shadow study, would be the most time-efficient; 2) if a time of interest is not known, an annual study will likely provide the most information quickly. On the other hand, if accuracy is desired, metrics that use weather data should be used- this includes any annual illuminance metric or a point-in-time illuminance or luminance study using a Perez sky model or the Image-Based Lighting method.
- Tuning the analysis with reasonable numerics and scales is critical.
  - Many metrics require inputs, such as a target illuminance, or the outputs include a specific standard, such as the scales used for UDI and annual glare. A tuned analysis will challenge the norm and consider alternate ways in which to process and represent the data. For example, rather than using the standard output for UDI, more useful information can be parsed from the output files. By adjusting

the scale from 100-2,000 lux to the target minimum and maximum illuminance levels for the project (as in TDI), the space can be better understood within the context of its intent and program. Similarly, annual DGP is output from DIVA for Rhino with the scale developed by Wienold and Christoffesen. However, these defined thresholds have been challenged by many researchers and practitioners in the field. If, in fact, this scale underpredicts potential glare risk, the reliance on the results as they stand could misinform or misdirect the design direction. If a scale with a lower threshold were to be considered, the conclusions would likely be different. This is the case for the Baseline: South scenario: the standard scale shows no glare issues, yet a scale with lower threshold shows potential glare risk throughout much of the year.

Chapter 4 | Conclusions

This thesis is unique in its holistic approach to identifying what is lacking in the current metrics in terms of both practice and higher level technical assumptions and methods involved in daylighting metrics. The vignettes in Chapter 3 elucidate the reasoning behind why using complementary metrics is more effective than using a singular metric, and propose ways in which to address this issue.

With the technological advancements and available resources in this field, it is essential to take this notion seriously and to be more thoughtful in approaching computer-based daylighting. Metrics should be used in ways that show an acute understanding of the strengths and limitations, both by pairing them appropriately and by being aware of the assumptions behind the algorithms and methods. The vignettes illustrate that:

- Using complementary metrics provides a larger range of perspectives and results, minimizing the possibility of misinforming or misdirecting a design decision.
- The LEED daylight metrics, despite presenting a pair (sDA and ASE), do not allow enough variability in potential designs and should be used alongside other metrics, rather than standing as a definitive determination of a well daylit space.
- The assumptions and methods behind metrics can cause inaccurate results, and using more than one reduces this issue.

Overall, using multiple metrics in an intelligent manner results in a fuller understanding of the luminous environment.

While the field is constantly advancing, it is still difficult to categorize daylight, as it is extremely subjective. As such, it is nearly impossible to provide a standard approach that should always be followed. Some believe that by aiming for a decent Daylight Factor, a well liked space can be achieved with uniform lighting. Others believe that variability is preferred. Many design firms have developed their own approaches [61]. If the goal is to satisfy the intended occupants, the project must be assessed independently- there is no universal solution to guarantee 'success' because it is subjective. The outcome of this thesis is not to identify such a solution, but rather to provide a compendium of information and guidelines to help practitioners make informed decisions as they relate to daylighting. To this end, this thesis compiles a great deal of pertinent information, presents strengths and limitations, and provides guidelines to more fully address daylight issues with metrics. It is the hope that with continued effort in this realm, the space between research and practice might be bridged.

Daylight Considerations in the Larger Context

As for how such daylight can be incorporated into the larger context of environmental considerations, two potential approaches are an environmental section or diagram and a priority matrix. The design team should identify project goals and determine if it is more reasonable or desirable to use an optimization or satisficing approach. That is, will the project be optimized for daylight quality, visual comfort, views, energy, thermal comfort, aesthetics, cost, or satisfy them all to a certain degree? An environmental section or diagram can be used to illustrate all facets of the project. Once an understanding of the project goals is reached, a priority matrix can be used to guide the analysis and ultimately reach a solution. This is already a common practice in many design firms, and should therefore be quite easy to adopt and incorporate daylight considerations.

That said, it is risky to optimize for one quality alone. For example, highly glazed façades have gained popularity over the past two decades. While there are other factors that can be owed to this movement, including pure aesthetics or the desire to explore technologies such as Double-Skin Façades, one of the main motivations has been to optimize daylight. However, while the intentions were good, little to no emphasis was placed on visual comfort. As a result, either 1) occupants lack solar control and adapt with solutions of their own such as taping paper to windows or placing umbrellas at desks, or 2) blinds are drawn causing uneven patterns and electric lights are turned on, consuming even more energy than if an appropriate amount of glazing were to be used. Certainly, responsive façade technologies such as automated shading systems, electrochromic windows, and even adaptive algae [62] provide solutions to some of these issues.

On the other hand, the Bullitt Center in Seattle, WA is an example of a project that used an integrated approach, placing importance on many qualities; this is becoming increasingly possible. Recently recognized as a Living Building, such projects should be exemplars for the future.

Future Directions

It is clear that there are limitations in the current metrics used in the field of computational lighting design. The vignettes discussed in Chapter 3 provide perspectives and analysis from both practice and research standpoints. While the goals in practice and research may be different in the details, overall, both would benefit from similar advancements in the field, particularly:

- Annual illuminance metrics with custom ranges- more research regarding changing lower and upper limits and new practices regarding the post-processing of the data to accommodate such customization.
- Annual luminance metrics that can provide a sense of variability- research to develop these, along with acceptable ranges, and new practices that are open to adopt and integrate such metrics.
- Sky models tuned to the question of interest- research to better understand the full extent of differences between models, as well as more widespread resources to Image-Based Lighting (perhaps access to a database of HDR images), and new practices to more easily and openly switch between sky models depending on the project goals.
- Further study of the LEEDv4 daylight metrics, sDA and ASE- more research regarding the appropriate thresholds and an understanding of their deployment in practice (see more in Section 3.1.2 LEED Vignette - Discussion)
- Increased dynamic shading simulation capabilities - research to develop such tools and increased adoption in practice.

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