Improving Prediction of Daylighting Performance

Lisa Heschong and Mudit Saxena, Heschong Mahone Group, Inc.
Randall Higa, Southern California Edison

ABSTRACT

Daylighting is an essential strategy to get to zero energy commercial buildings. However, simplistic metrics that cannot account for climate, location, orientation or advanced technologies have made it difficult to design programs that require daylighting, promote optimized design or technologies, ensure occupant comfort in daylit spaces, or estimate energy use. New climate-based performance metrics generated from annual simulation programs offer improved capability in assessing daylighting design, and thus will improve the prediction of the energy and comfort performance of resulting buildings.

This paper discusses the variety of user needs that will help inform the choice of those metrics, such as code development, program design and post-occupancy verification, from simple to detailed modeling, from pessimistic to optimistic assumptions. It presents a Daylighting Analysis Framework that describes all the inputs and outputs of an idealized simulation tool. The Framework can also help to describe what information is needed for which purposes, and could help prioritize the development of analysis tools, metrics and methods for describing daylighting performance according to program needs. The paper goes on to describe a new simulation tool with advanced daylight modeling capabilities developed to support the needs of this project and the initial findings from analysis of its output on 61 field study spaces compared to occupant and expert assessments of daylight quality in those spaces.

Introduction

Daylighting is often touted as one of the best win-win strategies for “high performance” or “sustainable” buildings. It provides the highly visible benefits of an architecturally beautiful and memorably lit space, and one that is potentially low maintenance and low energy while also enhancing the comfort and well-being of the occupants. However, there is also often a presumption that because daylighting is “natural” it should also be very simple. We are all familiar with older buildings that provide beautifully daylit spaces, suggesting that good daylighting design can be very low-tech, even intuitive. However, such an assumption belies the centuries of building experience that went into developing those traditional buildings. Now, with many new sophisticated fenestration technologies available, and vastly more demands on the performance of our buildings, especially for dramatically reducing energy performance while maintaining human health and comfort, we need advanced metrics and analysis methods to help us optimize daylighting design under these new conditions.

Daylighting Involves a Lot of Moving Parts

Everyone understands intuitively that daylighting illumination will vary throughout the day. Between dawn and dusk the sun changes position and intensity as it moves across the sky, shining through various atmospheric conditions and reflecting off surfaces. The same window, will produce very different illuminance levels inside when there is fresh snow on barren trees in spring and tall grass and leafy trees outside in fall, even given the exact same sun position and sky conditions.

Seasons and weather are just the beginning of the moving parts, or dynamic variables, that influence daylight availability and efficiency. The glazing required for daylighting also has an impact on cooling and heating loads of buildings as a result of radiant and conductive heat transfer. Intuitively, smaller and darker windows should reduce cooling and heating as the thermal conductivity of windows are higher than walls and darker glass allows less radiant heat gain. However, because daylight transmits less heat into a building space for given amount of light as compared to electric lights, there is not only a savings of lighting energy when lights are turned off or dimmed, but the reduced internal gains can also result in either cooling energy savings or increased heat loads. The balance point between such losses and gains is a complex equation, which can not only vary seasonally, but even hourly, depending not only on the climate, but also building operation and equipment efficiency. For large, internal load dominated buildings, cooling savings often predominate.

A case could be made that daylighting is one of the most interdependent functions in a building, requiring careful integration with all building systems. It is deceptively simple—since we experience daylight directly every day—but devilishly difficult to predict with precision. Over the years we have developed simplified approaches that help us estimate how much daylight to expect within a given space. The accuracy of those predictions has evolved over time, along with the available tools.

A Brief History of Daylighting Performance Metrics

The science of determining adequate levels of daylighting for buildings began to develop in the early decades of the twentieth century. Urban density was increasing, along with industrial smog, reducing daylight access to workplaces and schools, and electric lighting industry began to take over the role of providing illumination during the daytime. It is not coincidental that Britain experienced a rash of childhood rickets at this time, making prediction of adequate daylight a growing concern.

In the 1940s and 1950s, the British Building Research Establishment (BRE) began to develop manual calculation tools, such as nomographs and "pepper pot" diagrams that supported more precise estimation of a "daylight factor" or the ratio of daylight illumination available outside to that resulting inside of a space. The method greatly simplified the problem by ignoring the contribution of direct sunlight, calculating only the contribution from a standardized overcast sky—a simplification that was deemed sufficient given the British climate.

In the 1950s and 1960s, these BRE methods were widely adopted; for example, in California, the State Architect required such hand-calculations to show that all school classroom designs would achieve minimum levels of daylight illumination, while preventing sun penetration during normal classroom hours. The concern was with lighting quality. Today these classrooms still provide admirable daylighting illumination, but their energy performance can be worrisome, due to single pane windows and the subsequent addition of air conditioning.

In the 1970s and 1980s, rapidly raising oil prices sparked interest in building energy efficiency and the efficiency potential of daylighting. A surge in national research funding helped to develop such advancements as low-e windows, insulated window frames, and photosensors which could control newly invented dimming ballasts. The first energy simulation programs such as Blast and DOE2 were developed to support whole building energy optimization, along with ray-tracing programs such as Radiance to produce accurate renderings of illuminance patterns.

The Current Situation

Fast forward 30 to 40 years and, after decades of relative neglect, practitioners find themselves still citing the daylighting performance research work done in that period. In spite of vast advancements in computational capability, and interface expectations based on i-Phones and 3D animation, the basic computer analysis tools for daylighting are those developed in the 1980s.

We also currently have various codes and standards that rely on very simple prescriptive criteria, such as window head heights, or the daylight factor inherited from the BRE, to specify daylight performance. Although these simple prescriptive requirements might encourage greater use of daylighting, they cannot distinguish between better or worse approaches. For example, using the geometric prescriptive measure of head height, all spaces with windows at a 8' head height appear to have equally good daylighting, regardless of orientation, climate location, glass type, exterior obstructions, shading devices, or the use of the space. And without greater ability to predict daylighting performance, advancements in daylighting technology and design optimization have been inhibited—if better and worse performance between products or strategies cannot be differentiated, there is no added value to sell, and there is no basis for optimizing and improving performance.

In an effort to improve on such limited prescriptive measures, some groups setting standards for high performance buildings, such as USGBC, are scrambling to adopt new metrics of annual daylighting performance. However, to date, they have had little guidance on what the numbers mean or defining methodologies to achieve them. The Collaborative for High Performance Schools (CHPS) was one of the first of these groups to adopt a suite of daylighting performance alternative paths in 2004, but did so with little basis for choosing any of the published values[1].

Goals for Annual Performance Metrics

In 2006, a subcommittee of the IES was formed to help guide research and development of a set of new annual simulation-based performance metrics that could be used to specify the need for daylighting performance in buildings (hereafter referred to as "the committee."). The committee made a number of key decisions about the needs for and likely uses of the metrics, which logically led to determining the outcome of the metrics format and methodologies. Some of these key decisions are described below:

- **Analysis by space, not by building.** The unit of analysis chosen was a space, not a building much as it is for electric lighting. Much as an HVAC zone is a semi-autonomous area served by one HVAC control system, a "space" for the sake of this analysis has a coherent daylighting illumination pattern created by one or multiple

[1] One of the authors of this paper served on the technical committee developing the daylighting performance criteria for CHPS, and so has first hand knowledge of the lack of information available at that time.

- apertures that all contribute daylighting into an overlapping area. A daylit space could be subdivided by translucent partitions if they allow the daylight to mostly pass through or around them.
- **Comparison of alternative strategies and populations of spaces.** This mandated that the methodology to generate the metrics could support any spatial geometry or daylighting strategy, and be equally fair to all strategies and spatial configurations. For example, illumination gradients are difficult to describe without a clear starting point, and many daylit spaces don't have an obvious front or a back, or even orthogonal relationships. Likewise, glare criteria that require a fixed point of view would not be useful if the point of view chosen was not comparable across all spaces.

- **Focus on visual comfort.** The subcommittee agreed that daylighting illumination performance was poorly defined and not well served by metrics developed for electric lighting. For example, task and ambient illuminance will inevitably fluctuate in a daylit space. How wide a range of illuminance over time or across a space is acceptable? Likewise, contrast ratios that might be considered glaring in an electrically lit space might be welcomed in a daylit space, especially when looking out a window. None of the existing electric lighting metrics are capable of addressing the dynamic nature of daylighting, nor are they likely to match occupants' expectations of how lighting in a daylit space might differ from that in a wholly electrically lit space. Thus, the committee set as a goal achieving a suite of metrics that would include daylight sufficiency (task illuminance) over space and time, but also metrics that could help qualify the occupants' experience of visual comfort achieved within the space.

- **Focus on illumination quality, not energy performance.** The quantity and quality of daylighting in a space should be important determinants of electric lighting use in the space, but there are far too many additional variables to predict electric lighting energy use directly from daylight availability. Once daylight patterns are understood, an appropriate electric lighting design strategy and control logic can be crafted. Thus, the committee agreed that daylighting performance should first be a basic human comfort criterion, similar to adequate electric lighting or adequate ventilation. (It is well understood that humans have needs for minimum ventilation and air quality that must be met by an HVAC system, even though additional ventilation may add to the energy needs of a building to maintain thermal comfort.)

  Likewise, HVAC energy use cannot be predicted directly from the daylight performance of the space. Consider that the daylight illumination quality in two geometrically identical spaces could be identical while the HVAC requirements for the spaces could be very different. As a thought exercise, imagine a set of sister classrooms with a large south facing windows. The fenestration in one classroom might be a tinted single-glazed window with very poor U-value and SHGC while next door an identical classroom had been retrofitted with a triple glazed assembly with exemplary thermal performance. However, both windows could have the same visible light transmittance at 50% Tvis, resulting in identical daylighting conditions. Furthermore, if we set a pair of these classrooms in San Francisco and Saint Louis, two cities with nearly identical sun paths but very different seasonal climates, we will get radically different thermal comfort needs and resulting energy impacts of the daylighting design. Thus, daylighting performance cannot be taken as a proxy for whole building energy impacts.

- **Useful in codes, standards and specifications.** While there were numerous methodologies available to study and guide the design of daylight spaces, such as physical models and 3D renderings, we found there was no consensus on how to compare performance across spaces or specify that a space would achieve acceptable daylighting performance. A wide variety of users, owners and regulators needed a way to request that daylighting be provided in their buildings and to verify that their request had been met. By implication, these users needed a set of metrics that would be useful for comparison throughout the full sequence of a building's life from conceptual design through construction and operational phases. The ability to compare relative performance across spaces and design strategies with a consistent methodology thus becomes more important than single-point-in-time accuracy for a single application. This requirement led to a committee recommendation for a hierarchy of "levels of analysis" (discussed further below) and rule sets that would create a 'level playing field' with standard default assumptions and methodologies.

- **Capable of optimizing annual performance.** While some single-point-in-time metrics, such as Daylight Factor or "achieving 25 footcandles at noon on equinox", do provide a performance criteria, they do not provide enough information to evaluate whether a given design strategy will perform better or worse over the course of a normal year's weather conditions. Without the ability to optimize over a year's weather, it is not possible to differentiate between many advanced technologies, or gauge their impact on a building's other dynamic energy systems. Simulation programs which are used to derive the annual performance metrics must therefore accurately model daylighting systems that have a variable performance over the course of a year, such as highly variable light transmission as a function of solar angle (as do light shelves and shaped skylights) or dynamic response, like window blinds.

- **Standardize metrics methodology, not criteria.** Eventually, once the format of metrics and the methodology for generating them are agreed upon, the committee will be able turn its attention to discussing performance criteria, which can vary by application. Following the example of mileage ratings for vehicles, strict EPA protocols must be followed in testing a vehicle's miles per gallon rating so that comparisons between product lines is valid, but the acceptance criteria can vary depending on the drivers needs. Similarly, a standardized daylighting performance metric should have a well understood format and methodology that can be universally compared across spaces, but the application criteria could vary by space type, climate location, or stringency needs.

- **Set a path for the future.** It is important to have a path that can guide not only the development of immediately feasible metrics, given the limitations of current simulation tools, but also gives a logical progression for refinement as tools became more capable, and for inclusion of additional performance metrics as further research became available. Simplistic metrics that might quickly become technically obsolete need to be avoided as they have a tendency to persist through cultural inertia. The subcommittee hoped to create a public forum where research needs could be prioritized in support of the development of better daylight performance metrics and understanding of visual comfort and human physiological needs under daylit conditions. As such, the project needed to push the limits of what was feasible with current methods, and anticipate future needs and capabilities.

For example, analysis by luminance (what we see, as opposed to footcandles, that we can more easily measure) is clearly important, but out of reach for the time being until research and simulation tools provide a better basis for universal analysis. And, given the complexity of human motivations for having interior spaces with windows and daylight, the future daylight metrics might additionally address the quality of views or circadian stimulus provided in those spaces. A few researchers [Reinhart 06, Howlett 07, Peachacek 08] have started to tackle these issues, but with the very limited funding currently available for research in these areas it is unlikely that progress will be made quickly.

Three Levels of Analysis

A key decision in the modeling methodology was to define three levels of analysis that would satisfy a variety of user needs for daylight metrics. These were defined as follows:

Level One is the simplest level of detail, appropriate to test the performance of alternative design strategies. This level of analysis would be appropriate to guide early schematic design, allowing quick iterative runs, or to show compliance with daylight performance standards, such as LEED or CHPS or the International Green Construction Code, for simple buildings. A requirement for quick and easy modeling suggests reduced granularity of geometric detail and analysis grids, and also implies that a variety of professional-grade tools would be available to generate the required metrics. This level would use default assumptions for most conditions that are not knowable during early design, and optimistic assumptions about user operation and reflectances, to define the upper limit of the "daylight potential" for the space. Window conditions would be defined with simplified two-dimensional openings, surface reflectance as standard defaults, furniture ignored, and exterior conditions simplified to just a few inputs such as ground reflectance.

Level Two contains higher level of detail, appropriate for demonstrating compliance with codes or standards at the completion of construction documents. Logically, the input details and assumptions at this phase should be verifiable from construction documents and an approved calculation methodology. For these purposes, Level Two should generally make pessimistic assumptions about interior furnishing and operating schedules using defaults to define a minimally acceptable condition that is likely to be maintained in typical, rather than idealized operating conditions. Window details should be three dimensional to include inter-reflections and shelf-shading from framing elements. Operating schedules, window treatments and obstructions should follow standardized rules to avoid gaming.

Level Three contains the greatest simulation detail, appropriate for modeling existing buildings for research or verification purposes, where actual furniture layouts, window treatments, surface colors, operating schedules and exterior obstructions are known. This level includes measured data where available, such as surface reflectance and operating schedules, or level two defaults when not available. Exterior details should be fully modeled, including vegetation. The goal of level three is to provide as realistic a comparison as possible to actual occupant experience. Logically, for field verification, comparable results should be derivable from both simulation input and field data, such as monitored illuminance levels or photographic luminance capture techniques. Because analysis at this level is most interested in realistic models, research-grade simulation tools that favor accuracy over ease-of-use simplifications would be most appropriate.

A Daylighting Analysis Framework

Given the needs defined above, it is useful to envision the scope of a future comprehensive daylighting analysis capability. Figure 1 illustrates the range of issues that might be considered in such an idealized analysis of daylighting performance. This idealized framework can:

- Help guide our thinking in terms of what kind of daylight performance metrics are desirable versus those that are feasible, given current simulation capabilities.
- Clarify the conversation about what information is necessary for which purposes, and the priorities for developing the tools that are needed to support those needs.
- Clarify the differences between these simulation programs, or how two programs might be complementary.
- Help define the minimum capability requirements for a code compliance tool, or energy efficiency program needs.

Figure 1: A Daylighting Analysis Framework

1		2		A		B		C		D		E		F
Human Comfort	+	Energy Impacts	=	Space Description	+	Fenestration Description	+	Climate Inputs	+	Exterior Context	+	Occupant Behavior	+	Building Energy Systems
Illuminance Sufficiency Uniformity Gradients Spatial plots		**Lighting energy** Full load equiv Annual kWh Peak kW Load profiles		**Geometry** boxes complex orthogonals furniture overhangs, fins mullions, rods angles curves		**Windows** size & location Tvis diffuse glazing framing effects angular dependence variable TVIS optically complex glazing dynamic BSDF		**Sun** altitude azimuth hourly intensity terrain adjustments		**Ground** diffuse reflectance slope multiple conditions specular reflectance seasonal variation weather variation		**Task** task type furniture layouts task location view direction		**Lighting** installed KHz control zones perfect dimming complex switching control logic multiple systems fixture type and layout
Luminance Contrast ratios Uniformity Glare Gradients 3D imaging View quality		**Cooling** Additional load Annual kWh Peak kW Load profiles		**Orientation** cardinal precise latitude longitude		**Skylights** size & location TVIS framing and well effects glazing geometry photometrics variable TVIS dynamic BSDF		**Sky** uniform distribution hourly intensity Perez distribution partly cloudy fog/haze precipitation		**Buildings** horizon shape opaque boxes diffuse reflectance specular reflectance complex shapes transparency		**Blinds operation** solar trigger response time glare trigger angle setting auto override privacy, security maintenance		**Heating** annual load dynamic response system efficiency
Thermal Radiant		**Heating** Additional load Annual kWh Peak kW Load profiles		**Visual Properties** diffuse reflectance specular reflectance internal transparency		**Int. blinds, shades** Tvis direct v diffuse operating schedule multiple schedules multiple triggers angle, shape dynamic BSDF		**Thermal** CDD/HDD hourly temps relative humidity radiant component wind speed microclimate		**Vegetation** shape & location reflectance transparency seasonal variation		**Lighting Choices** control logic task light control auto override maintenance		**Cooling** annual load dynamic response system efficiency
Circadian Timing Duration Intensity Spectrum Relative context		**Ventilation** Additional load Annual kWh Peak kW Load profiles		**Thermal Properties** U-value SHGC capacitance blinds interactions						**Other** view quality cars water		**Occupant schedules** occupancy type hourly schedules comfort needs window operation bldg management style		**Ventilation** annual load dynamic response variable windows
				Sensor locations one or two horizontal plane vertical plane any view direction sensor photometrics 3D imaging		**Ext.blinds, awnings** Tvis direct v diffuse angle, shape operating schedule						**Demographics** age health circadian sensitivity circadian status		

This Daylighting Analysis Framework allows comparison between the output of different program needs, the capabilities of tools, and the input data and analysis levels required to support them.

The framework is organized like an equation, with outcomes on the left and inputs on the right. **Outcomes** of interest, shown on the left of the equation, are grouped into two columns: (1) Human Comfort issues and (2) Energy Impacts. Under Energy Impacts, the four concerns are logically Lighting Energy, Cooling Energy, Heating Energy and Ventilation Energy. Under each of these subtopics, examples of various types of metrics or data are listed in approximate order of detail, complexity and significance. More detail could be generated for the topic introduced within each cell.

Inputs include a comprehensive list of determinants of daylighting performance as well as influences on the other outputs, including:

A. A thorough description of the three dimensional space,
B. Description of fenestration geometry, properties and operation,
C. Local climate data,
D. The exterior context that influences the availability of daylight in the space, such as exterior obstructions,
E. Occupant descriptors, including tasks determining illumination needs and operating schedules, and
F. Interactions with other building systems.

As in the Outcomes discussion above, each cell lists additional data input descriptors, from the simplest format to increasingly detailed and nuanced. For example, under Space Description/Geometry the simplest analysis approach might be limited to simple boxes, whereas more sophisticated analysis could include complex orthogonal shapes, details of window overhangs, fins, mullions, and angled and curved room shapes.

An idealized simulation tool based on this framework would answer any question we might choose to ask and consider every significant variable with appropriate precision, while providing an intuitive user interface and instantaneous results. We are, of course, far from having such comprehensive simulation capabilities.

Beginning with the universe of possibilities outlined in the Daylighting Analysis Framework, the IES subcommittee quickly winnowed the list down to prioritize those metrics that might be feasible in the near term, given current knowledge and simulation tool capabilities. The group chose to focus on three metric types, summarized annually over space and time: 1.) Illuminance sufficiency, 2.) Uniformity 3.) Glare proxies.

Glare proxies that might indicate the probability for the creation of a glare condition based on data which could be derived from annual illuminance runs, instead of direct glare analysis, were chosen because while glare is one of the most discussed concerns about daylighting, it remains one of the least understood and most poorly defined. While commonly recognized glare metrics have been developed for electric lighting conditions, their application to daylighting conditions is highly controversial. Furthermore, all current glare metrics require luminance values and a defined occupant view-point, both of which are inconsistent with other objectives of the project: luminance values were determined to be too time-intensive to calculate and defining a single-point-of-view was in conflict with the requirement for metrics that could universally compare any given space.

A Field Study of 61 Spaces

A research plan was formulated to support goals for the metrics described above, given current software capabilities and budget realities. Important objectives included testing the applicability of any proposed metrics to real-world situations, and creating consensus among the experts both within and outside the committee. A field study was funded from a number of sources (see acknowledgments) that would collect qualitative assessments from both experts and occupants on the quality of the daylight in the spaces that could be compared to candidate metrics generated from sophisticated annual simulation tools. The project team was composed of many members of the committee. First the committee and project team agreed to focus the study on three space types that represented commonly daylit spaces that would most benefit from advanced metrics, and which represented three different types of visual tasks—classrooms, open offices, and libraries/lobbies. (The field study methodology is described in a companion ACEEE 2010 paper—Saxena 2010.)

The project challenged the committee with many intermediate decisions about simulation methodology that needed to be resolved in order to proceed. Based on an assessment of the simulation tools available at that time, it was determined that using a combination of Ecotech to generate three-dimensional models and DaySim [Bourgeois 2008] to perform the annual simulations as a pre- and post-processor to Radiance, would provide the most modeling accuracy and support any parametric studies that might be determined to be important to the project goals. A private, research-grade version of DaySim was modified by its author and project team member, Christoph Reinhart, to provide the output requested by the project team.

Simulation Challenges

Translating from one software program to another involved inevitable challenges, such as rectifying the orientation grids, unifying naming conventions and data formats, and assuring that rounding errors did not cause additional errors. While DaySim had previously been validated for accuracy under laboratory conditions and used extensively for preliminary design studies by both students and practitioners, it had never been used on this scale—i.e. to model real field spaces and compare results across multiple design strategies.

We quickly encountered a number of limitations, the most serious of which were the modeling assumptions for window blinds. While DaySim had the ability to operate blinds according to a solar trigger, it was limited to one schedule, such that all blinds in a given space had to operate on the same schedule. In other words, if blinds came down when the sun penetrated through an east window in the morning, they also would come down on the west and north windows simultaneously. Since 2/3 of our study spaces had windows facing in more than one direction, this was judged by the project team to be an overly pessimistic assumption about occlusion of windows by blinds. Furthermore, as a simplification DaySim assumed that only 20% of available skylight (diffuse component), and 0% of sunlight (direct component), made it through the blinds once they were operated. While this might have been a reasonable approximation for predominantly cloudy locations, it resulted in a serious under-estimation of daylight illumination levels in predominantly sunny locations. Changes were made to the program to allow for independent blind operation by two or three orientations, but we were not able to modify the assumptions about the relationship of direct versus diffuse transmission through blinds.

As part of the project specifications, DaySim was also modified to provide additional output for analysis, beyond that from the typical task illuminance sensor grid: an illuminance grid for the reflected ceiling plan, hours of sun penetration and percent of skydome visible from an eye-level grid. The project team hoped the ceiling grid would provide useful data for a uniformity metric, and that the output from the eye-level grid could be used to develop a glare proxy, as requested by the committee, to estimate the probability that glare would experienced by an occupant who might be seated anywhere in the space.

Ultimately, achieving full functionality for the new blinds operation and output functions in DaySim was not possible within the timeframe and resources of the project. Considering many alternatives, the project team eventually decided to commission the writing of a new annual simulation program. This program would build on DaySim's achievements and, using similar daylight-coefficient methodology, provide the desired functionality for blinds operation and data output, and add an important new capability—the ability to model dynamic fenestration performance via a three-step calculation process using a BSDF[2] matrix.

The Creation of Dynamic Radiance

With funds from Southern California Edison (SCE), Greg Ward, the original author of Radiance, was commissioned to produce this new software. He subsequently continued to refine the program with additional funds from Lawrence Berkeley National Labs (LNBL). The project team spent six months beta-testing this new program. Once it could competently[3] produce the requested files for our 61 study spaces, the project team declared victory and named it, "Dynamic Radiance." As of the writing of this paper, the scripts developed for Dynamic Radiance are available on the Radiance website, and will soon be available in a 4.0 version, but without users' instructions or a graphical users' interface. The intent, as with all Radiance applications, is to manage it as an open-source code, effectively putting it in the public domain and allowing many users to continuously upgrade its interface and capabilities.

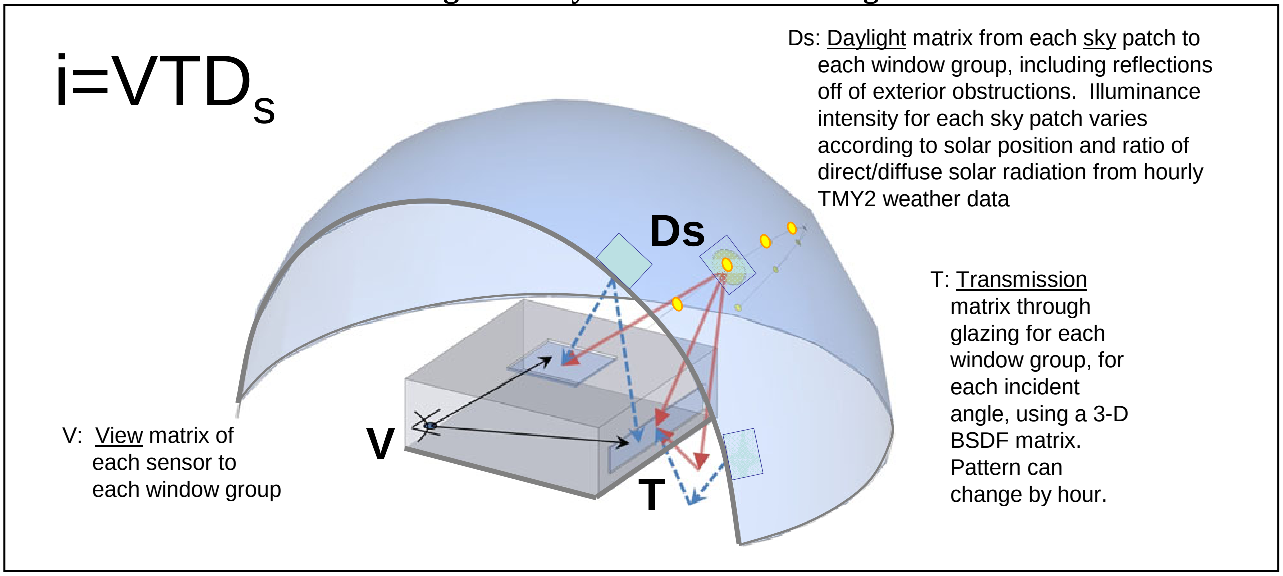
Dynamic Radiance was built on the annual daylight illuminance simulation capabilities previous developed in DaySim [ref]. It has extended the two-step Daylight Coefficient approach, which it allows for faster simulation of annual weather conditions by reducing the number of hourly computations, into a three step approach, which inserted a BSDF matrix describing fenestration light transmission properties into the calculation of room illuminance. This three step process described by the equation: $\mathbf{i} = \mathbf{VTDs}$ **[**where $\mathbf{i}$ = resultant illuminance vector, $\mathbf{V}$ = a "view matrix" that defines the relation between measurements and exiting window

[2] BSDF= Bi-directional Scatter Distribution Function, describes the proportional intensity of the three dimensional scattering of light through a complex glazing assembly, as a function of the angle of incoming light. Products such as blinds, shades or optically complex glazing materials can be either tested in a photo-goniometer, such as exists at LBNL, or simulated using WINDOW-6 software, to generate a matrix file for each angle of incoming light. BSDF is a new name, that combines the functions of the two versions, BTDF and BRDF used in the past (T=transmittance and R=reflectance)

[3] Dynamic Radiance output was reviewed using graphic visualization methods to ensure logical illumination patterns, given solar position and blinds operation, and also compared to the original DaySim output for validation. Comparable runs between Radiance and DaySim were found to be within 1% of each other overall. As would be expected, the BSDF method does tend to result in "smudged shadows" or "fuzzy sunlight" that result in a higher percentage of sensor readings at the lower illumination levels and a lower percentage at the highest (direct sunlight) illumination levels.

directions; **T** = the transmission portion of the BSDF; **Ds** = the "daylight matrix" that defines the relation between incoming window directions and sky patches, varied by **s** = skypatch intensity] is illustrated below in Figure 2.

Figure 2: Dynamic Radiance Diagram



The three step calculation procedure used by Dynamic Radiance to calculate the resulting illuminance at a given sensor point inside a room, given variable transmission properties at a window group.

The use of a BSDF matrix as an intermediary between the exterior and interior illuminance conditions of the simulation model allows the visible light transmittance and distribution through the windows to be varied by hour, according to any schedule or trigger than can be calculated by the program or provided by the user. This three-step calculation process gives Dynamic Radiance the capability to model angularly dependant complex glazings and dynamic fenestration, from simple systems such as manually operated Venetian blinds to highly sophisticated optically tracking skylights.

Currently BSDF files can be created in WINDOW-6 for one condition at a time. Thus, a given Venetian blind profile can be modeled for a 45 degree tilt. In order to create a dynamic BSDF matrix, a sequence of tilt angles from 0 degrees to 180 degrees should be created and stored in a matrix. Dynamic Radiance would then be instructed which tilt angle to apply according to a time step or other trigger.

Eventually it is hoped that libraries of BSDF matrix files will be created via the physical testing of products, on equipment such as currently exists at Lawrence Berkeley National Labs. Other labs, at MIT and in Europe, are developing digital photography-based test equipment which promises to greatly expedite the creation of BSDF files for a variety of fenestration product scales, from micro to macro. When there is a clear pathway from product design optimization, to standard reporting formats, to simulation tools that can accept that data and compare annual performance outcomes, then we will have the ability to have programs that promote those products which provide the best daylighting performance.

Conclusion

It is clear that the development of new performance metrics for daylighting must be an **iterative** process between understanding needs and tool development. Understanding organizational needs of all likely users helps to define the functional requirements for simulation tools, but the current capabilities of simulation tools define the limits of what metrics can be considered.

With the field study of 61 daylit spaces, we have made great strides towards the future, where there will be well-understood annual performance metrics for daylit spaces. The project team believes that with the development of Dynamic Radiance, they have improved the prediction of annual illuminance values for the 61 study spaces. In the process of pursuing this field study, many methodological issues have been resolved that will be useful in defining standard procedures for defining performance metrics.

As this paper is written, a suite of metrics are under study by the committee, summarized below, described generically where details or nomenclature have yet to be resolved. The committee is intending to submit a document defining recommended metrics to IES for review and approval by the end of this year.

Metrics Under Study:

- **Illuminance sufficiency**, or percentage of time that a given threshold of daylight illuminance is achieved over the course of the year, throughout the space, given weather data for the location. Importantly, these values are defined as illumination levels after operation of blinds to block direct sunlight. Operational hours are standardized at a ten-hour day, from 8 am to 6 pm. The choice of a threshold value, such as 200 lux or 500 lux, seems to be less important than simply consistently reporting at the same threshold. This is because for all spaces studied the dynamic rise and fall of illuminance levels over all the hours of a year follows a fairly consistent pattern, such that the probability of occurrence at one illuminance level strongly predicts that occurrence at another.
- **Excess illuminance** or percentage of time that a maximum illuminance threshold is exceeded, has not been found useful in predicting any limits of visual comfort in the space. In general, all of our subject data shows that people prefer brighter spaces. Brighter spaces predict fewer reports of problems from glare and reflections, and essentially every other positive assessment of the space considered in the survey instrument. Our observations may be limited by the fact that the data set of 61 spaces does not include enough egregiously overlit spaces, and so we may not be encountering upper limits.
- **Sun penetration** into the space seems to have the most promise as a proxy for glare probability. Sun penetration may be computed directly, before blinds operation, as a function of hours of occurrence, square footage affected, solar intensity, or a combination of all three. Alternatively it may be calculated by number of hours of blinds operation required to block the sun, or the change in illumination levels resulting from that operation.
- **Uniformity of hourly illumination** distribution is under study, at either the task or the ceiling level. A variety of metrics are being considered, based on various ratios or standard deviation of the hourly data. Assessment of daylight sufficiency seems to be

correlated to some degree by the hourly uniformity of daylight across the space. Those interacting relationships are being explored.

- **Sky view**, or the percent of the sky dome that is visible from the space, was not found to predict reports of glare or excessive brightness. It was, however, found to correlate with occupants' assessment of view quality. The more sky that was visible from the space, the more the occupants liked the view and the overall appearance of the space. Our observations may be limited by the physical conditions included in the 61 study spaces, where very large window areas tended to be well shaded or face north.

All of the data analysis supporting this work is dependent upon having a simulation tool capable of accurately modeling both the geometric behavior of daylight in the space and the operation of blinds. In the future, with perhaps even greater computational capacity, and new research on human comfort and well-being under daylit conditions, other metrics can be considered.

Once metrics, and the methodology required to generate them, have been defined, it is hoped that an array of professional-grade simulation tools will start to incorporate them into their standard offerings, and that professionals will learn how to apply them to emerging standards that have adopted criteria based on these metrics. Furthermore, it is hoped that with the adoption of new analysis capabilities in the simulation software, such the BSDF matrix approach pioneered in Dynamic Radiance, the testing and reporting of advanced fenestration product performance can progress and become universally available.

Again, it is the iterative relationship between all the steps in the optimization process—simulation capabilities, product development, more stringent energy codes and design specifications that mandate daylighting performance, design methods, code compliance review, and field verification of performance—that will help realize the potential of daylighting to both reduce energy use in buildings and meet human needs for comfort and well-being inside those buildings.

Acknowledgements

The paper reports on work undertaken by the IES Daylighting Metric Subcommittee and a supporting project funded by the California Energy Commission's PIER program, the Northwest Energy Efficiency Alliance, Southern California Edison, the New York Energy Development and Research Authority, and National Research Canada. Lisa Heschong served as Principal Investigator for the research team, which included Kevin Van den Wymelenberg, Marilyne Andersen, Christoph Reinhart, Joel Loveland, and George Loisos. Simulation models were developed at the Integrated Design Lab at the University of Washington under the direction of Christopher Meek. Greg Ward developed Dynamic Radiance. Project staff at the Heschong Mahone Group included Mudit Saxena, Seth Wayland, Tim Perry, Katie Eberle, and Derrick Leung. Member of the IES Subcommittee contributed oversight and many also helped evaluate the study sites.

References

Final reports on this project will eventually be posted at www.h-m-g.com/daylightplus

Howlett O., L. Heschong., J. McHugh 2007. "**Scoping Study for Daylight Metrics From Luminance Maps**" Leukos, Vol 3, Number 3, Jan 2007

Mardaljevic J., L. Heschong, E. Lee, 2009. "**Daylight Metrics and Energy Savings**." *Lighting Research & Technology* 41(3):261-283.

Pechacek C. S., M. Andersen, S. W. Lockley, 2008. "**Preliminary Method for Prospective Analysis of the Circadian Efficacy of (Day)Light with Applications to Healthcare Architecture**", Leukos, Vol. 5, No. 1, July 2008

Bourgeois D, Reinhart CF, Ward G, "**A Standard Daylight Coefficient Model for Dynamic Daylighting Simulations**" Building Research & Information 36:1 pp. 68 – 82, 2008

Reinhart, C.F., J. Mardaljevic, Z. Rogers, 2006. "**Dynamic Daylight Performance Metrics for Sustainable Building Design**." *Leukos* 3(1):7-31.

Saxena, M., G. Ward, T. Perry, L. Heschong, R. Higa. 2010. "**Dynamic Radiance – Predicting Annual Daylighting with Variable Fenestration Optics Using BSDFs**." In *Proceeding of the SimBuild 2010 4th National Conference of IBPSA-USA*. New York: International Building Performance Simulation Association.