SIMULATION-BASED DAYLIGHTING DESIGN EDUCATION AND TECHNICAL SUPPORT

Kevin Van Den Wymelenberg[1] and Christopher Meek[2]
[1]University of Idaho, Boise, Idaho, USA
[2]University of Washington, Seattle, Washington, USA

ABSTRACT

Building upon consultations from several hundred building designs aiming to meaningfully incorporate daylight we have created an online resource that provides designers with a suite of fundamentally sound daylighting design *patterns*, titled the *Daylighting Pattern Guide*. The *Guide* presents 19 prime examples of well-designed, daylit spaces around the United States representing common commercial and institutional building types. Each project was photographed, physically measured and simulated. Sensitivity analysis of key daylighting design variables was conducted on each project to demonstrate optimized design outcomes and to illustrate the impact of multiple 'alternate design decisions' (both successful and unsuccessful) on the daylighting performance. This resource illustrates successful daylighting design patterns by placing a strong emphasis on creating visually comfortable spaces because our experience suggests this will help ensure that that occupants accept energy efficiency measures associated with daylight such as automated electric lighting controls. This resource helps to develop a careful understanding of human visual comfort while reaching designers and students in a format that both inspires and instructs them how to design well daylit spaces.

BACKGROUND

Since the year 2000, in order to help ensure the best possible daylighting design and that energy savings from these designs are realized at a high level, a regional energy efficiency organization with utility funding has supported technical design assistance on new construction and major renovation projects. With this funding, we have been able to consult on over 50 substantial building projects per year. Providing this technical assistance has generated a bounty of experience implementing successful daylighting strategies as well as lessons learned. This practice revealed recurrent themes, key variables and architectural principles that were demonstrated by daylit spaces that had proven to be successful over time. Similarly, we identified common impediments to successful daylighting performance. Building upon this practice-based knowledge, and in collaboration with the New Buildings Institute, we have built a series of daylighting patterns that identify and visually represent these successes and lessons learned in an intuitive and visually oriented online resource.

This paper documents the development process and end result of the *Daylighting Pattern Guide* [see www.patternguide.advancedbuildings.net]. This online resource aims to improve the level of daylighting design amongst its users by deconstructing approximately twenty successfully daylit spaces into component parts and highlighting the key interrelationships that produce visually comfortable daylighting designs. We also took these successful spaces, and using simulation methods, pushed them to a level of poor performance in order to illustrate several common points of failure that can be detrimental to otherwise successful daylighting designs. This data is presented in a manner that allows users to scroll through a series of variables for each "pattern" to identify the visual impact of alternate design approaches. The work was completed between June 2009-April 2011.

LITERATURE REVIEW

Daylighting Benefits and Challenges

It is known that daylight and views help to create healthy, comfortable, and productive, work environments for users, and therefore the use of daylight is one of the hallmarks of contemporary "sustainable" design efforts (Boyce 2003; Leslie 2003). The significant inclusion of daylight in buildings also holds tremendous potential to produce energy savings since 15-19% of the total electrical consumption in the United States is represented by

lighting (US-DOE 2006; US-EIA 2008). Furthermore, as a key component of the visual experience, daylight can serve as a dramatic design element and create a striking new generation of spaces. For these reasons most design teams are interested in including daylight in their projects. However, seldom are they equipped with the skills necessary to deliver comfortable and productive daylit spaces that have the potential to integrate with electric lighting systems to effectively save energy. Therefore, the potential benefits of daylighting designs are often under-realized.

Energy savings can be the most difficult daylighting benefit to realize as it spans all phases of the design-construction-occupancy spectrum and implicates multiple design disciplines. Lighting energy savings will only be realized if there is adequate daylight provided, it is provided in a manner that maintains visual comfort and is pleasing to occupants, the electric lighting design supports using daylight as the primary ambient light source, and there are adequate controls designed, installed and they are properly operated. For these reasons, energy savings from 'daylight harvesting' systems can be argued to serve as a good overall indicator of daylighting design performance. Understood in this way, recent research suggests that there is substantial room for improvement in the overall practice of daylighting design. A recent study revealed that less than 25% of the predicted energy savings are realized in spaces with daylight delivered from the side (Heschong et al. 2005). Even more revealing is that over 70% of the reasons identified for failure relate directly to a lack of human satisfaction with the overall daylight performance, with less than 30% explained by hardware components.

This follows our experience, which suggests that poor daylighting design performance stems primarily from the fact that many spaces with daylight fail to meet the visual satisfaction expectations of occupants either due to insufficient daylight, imbalanced distribution of daylight, or challenges maintaining visual comfort with such a highly variable light source. This situation commonly leads to a substantial reduction in daylight available or its excision via blind closure producing spaces where people are reliant on unvarying electric lighting systems to meet their visual needs.

Daylighting Design Process Practice

The sustainability movement is helping to plot a new course where daylight is more meaningfully considered in building design, however it is still uncommon that daylight is designed to provide the primary source of building illumination. This is in part due to limited awareness and lack of design assistance resources to promote successful daylighting design. Designers that aim to incorporate daylight in buildings rarely test their design ideas to arrive at their decisions (Turnbull and Loisos 2000). Instead, the vast majority of early daylighting design decision-making is based upon previous experience and rules of thumb (Reinhart and Fitz 2006). Therefore, the often complex inter-relationship between components of a daylighting design and the ultimate energy and visual comfort performance for a project are generally not well understood by building designers.

To help address these issues, several resource types including design guidelines, spreadsheet calculators, scale modeling tools, and software tools have been developed. Most design guidelines and spreadsheet calculators do not appeal visually to designers and often design teams do not have the financial or technical capabilities to engage in scale modeling or digital simulation analyses. Given this reality researchers have developed a series of hybrid tools, similar to the *Daylighting Pattern Guide*, that use advanced simulation in a pre-processed fashion to reduce the time investment and computational time to explore daylighting design alternatives. A few such tools will be briefly reviewed and limitations discussed.

Pre-Processed Daylighting Analyses

The *Virtual Lighting Simulator* [see http://gaia.lbl.gov/vls/] was developed by the Lawrence Berkeley National Laboratory (LBNL) in 2004-2005. It contains 4,320 pre-rendered Radiance scenes of a theoretical small private office space with one window. The tool allows users to examine aspects of orientation (4), window to wall ratio (4), glass type (5), exterior shading (3), time of year (3), time of day (3), and sky condition (2). In addition to the private office in daylighting conditions the tool illustrates electric lighting designs for a private office, open office, classroom, warehouse and a retail space. The electric lighting tool for the classroom, the private office and the open office allow the user to toggle between a partly cloudy and night sky. The tool is set up for side-by-side comparison of two options and uses a series of drop down selection boxes to select the appropriate pre-rendered results.

Ecoadvisor [see http://www.ecoadvisor.com/] uses a similar format and presents 360 pre-rendered scenes using either Radiance or Lightscape. It was funded by USDOE and is under development by a team led by the Deringer Group. The tool explores daylighting, lighting, and aspects of HVAC systems and integrated design. Three primary aspects of daylighting design are presented; 1)geometry (window head height, room depth, and presence of an

atrium), 2)window design (size, glass type, head height, and interior or exterior sun control), and 3)interior furnishings (partition height, opacity, layout, and window head height).

The *Daylight Designs Variations Book* [available at http://sts.bwk.tue.nl/daylight/varbook/index.htm] was developed by Technische Universiteit Endhoven Centre for Building Research and was last updated in 2000. It presents 66 pre-rendered scenes examining window size and placement and interior surface reflectance in a single room.

The *EU TAREB* project [see http://new-learn.info/learn/packages/tareb/en/dynamic.html] was developed by London Metropolitan University in 2004. It presents approximately 280 pre-rendered scenes to illustrate lessons about blind position, light shelves, integrated daylight and electric light sources, building context and skyview, surface reflectances, window size, window frame shapes, and time-step solar patterns.

The *Façade Design Tool* [see http://www.commercialwindows.org/facade.php] was developed by LBNL and the University of Minnesota from 2004-2008. Different from the tools described thus far, this tool does not explore rendered visualizations of spaces with daylight, rather it examines six metrics pertaining to daylight and energy (annual energy, peak demand, daylight illuminance, carbon emissions, thermal comfort, and glare index). It uses a single private office and presents seven climate choices and allows users to compare four design specifications at once or rank all possible conditions for any of the six metrics. A total of 35,280 possible combinations are available (5,040 for each of 7 climates). Design variables include orientation (4), window area (5), lighting controls (3), interior shades (2), exterior shades (3), and glazing type (14).

This brief literature review of pre-rendered daylighting design resources reveals many strengths and weaknesses of the existing tools. Strengths include a broad range of daylight variables addressed with some attention given to multiple space types. Additionally, most of the existing tools allow users to interact with the optional variables and make direct comparisons, thus promoting learning. Many of the tools use Radiance as the calculation engine and present multiple forms of data including renderings, luminance maps and illuminance maps. There are also several limitations to discuss. There is a strong bias in the data available to private offices and comparatively little information is available for other space types. By extension, most of the data available is presented in the context of a small generic rectilinear space making interpretations of the results more difficult. The rendered scenes are generally not presented with great attention to tone mapping of scene brightness, thus further complicating results interpretation. Very little guidance is provided to users about the differences between alternatives and interpretation of the results is in many cases left completely to (potentially novice) users. Finally, the information is presented so that the user navigates their own path and could therefore miss some very important lessons or comparisons. The *Daylight Pattern Guide* presented herein aimed to address many of these limitations. It seeks to provide architects, engineers, owners, and occupants with a quick reference resource containing high quality pre-processed simulations that cover a range of the most repeatable commercial building conditions.

METHODOLOGY

Similar to the tools just reviewed, the *Daylight Pattern Guide* is a pre-processed tool. Like some of the previous examples we wanted this tool to convey daylighting data in a qualitative and quantitative form. For these reasons we designed an easy to understand, designer-friendly and highly visual format that highlights the changes in interior luminance and illuminance coincident with geometric and spatial architectural design variables. Unlike other tools, the *Pattern Guide* uses detailed simulation analyses of successfully daylit built architectural spaces as the starting point for demonstrating the influences of design variables. We felt that beginning with successful built spaces was critical to support meaningful interpretation and increase confidence in the results. This tool also differs in that it presents daylighting information in a carefully choreographed and narrated fashion. We felt that this approach would best serve user learning by intentionally highlighting specific learning objectives. While this tool still affords some user-directed interaction, it prioritizes important design comparisons by the sequencing and reinforces the lessons via narrative text.

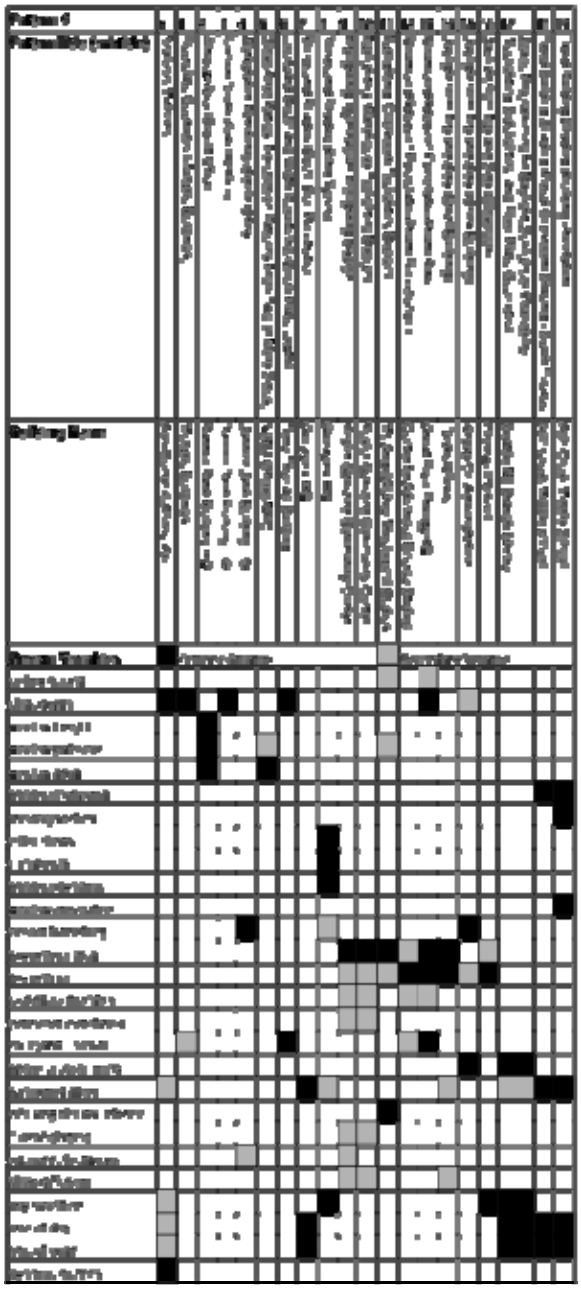
Drawing from our previous daylighting consulting experience we drafted a list of daylighting design strategies and principals and prioritized the most critical variables to overall daylighting success. The prioritized list included 27 critical daylighting variables. We desired to demonstrate the implications of these design variables across multiple space use types and chose to focus on open plan offices, classrooms, libraries, gymnasia, warehouses, and atria design. Next, we developed a matrix (***Table 1***) with daylighting design variables along one axis and possible 'daylighting patterns' along the other. The daylighting patterns (described in more detail below)

included a specific use type and one or more design variables. Approximately 30 daylighting patterns were identified, of which 19 were prioritized for completion. The next step was to identify existing well daylit buildings that could effectively demonstrate the intention of each pattern while also achieving some climatic and geographic diversity (***Figure 1***). We contacted members of the project advisory group made up of daylighting experts from around the country to supply candidate buildings and developed a long list. An initial subgroup of buildings was selected, matched with specific patterns, and site visits were conducted between Aug-Oct 2009. A second group of buildings were selected and site visits conducted between Mar-Jun 2010.

Figure 1 - Geographic Distribution of Buildings Studied

Site visits consisted of collecting illuminance and luminance data of the spaces of interest. High Dynamic Range (HDR) photography techniques (Reinhard et al. 2005) were used to document the luminous conditions of the spaces and were later used to create luminance maps of the scenes investigated with Photosphere (Ward 2006). Sky conditions and time of day were recorded for each photograph. Next, detailed geometry files were created using site measurements, photography and architectural drawings. The geometry files were exported to Radiance where detailed rendering parameters and material properties were input. Rendering cameras were specified to match the field of view of the photographed space. Then a simplified accuracy check was conducted on the Radiance simulations using the HDR photographs of the built spaces. This exercise was not intended as scientific calibrations of the Radiance files given that validation of Radiance has been done elsewhere (Mardaljevic 1995; Reinhart & Walkenhorst 2001; Mardaljevic 2004; Reinhart & Anderson 2006). Instead, this simplified accuracy

Table 1 - Patterns & Design Variables Matrix



check was used to ensure that the simulation output of the as built condition was reasonable in terms of luminance values when compared to the HDR photographs of the built space. This step was conducted to lend confidence to the accuracy of the design iterations that followed.

After the as built simulation was finalized, a series of test conditions were developed in order to explore successful and unsuccessful compositions of daylight distribution. The design variables documented in the patterns matrix were confirmed or adjusted and the

detailed specifications for each 'pattern step' were defined and geometry built. A great deal of attention was paid to the simulation parameters in order to ensure high quality, visually appealing and accurate results. In some cases the predominate sky condition relevant to the building site was employed for simulation cases and the day and time of the site visits were specified. In other cases, specific times of day, year, and sky conditions were selected to best illustrate the design variables examined. The selection and presentation of simulation output will be described in detail in the following section.

RESULTS

The major contribution of this project is the *Daylight Pattern Guide* itself. The decisions related to the selection and presentation of simulation output are documented here. Some specific lessons learned from developing the *Guide* will also be reported.

Page layout

It was a high priority to provide a consistent presentation of data from pattern to pattern and between steps within a given pattern. Care was given to presenting data in a format that prioritized the visual nature of the pattern exploration while also providing supporting quantitative data to assist users in their interpretation of the results. The *Guide* exists as an online tool and in PDF download. The PDFs were created so that each pattern step fit onto a single 11"x17" horizontal format optimized for on screen viewing. The web-based environment limited page space to 750 pixels in width. In either format, prioritizing output data types was necessary due to limited space. Priority was given to the qualitative data; essentially via the color renderings similar to *Figure **2*** and *Figure **3***. In order to support navigation, a series of 'widgets' documenting simulation parameters for time of day, time of year and sky condition were developed. A consistent key was made for illumination plots and the percent of floor area that achieved a specified illumination criterion is called out for each pattern step. A 'filmstrip' reveals the different design variables explored throughout a given pattern and is commonly illustrated with architectural section icons and occasionally other widgets. A text block is incorporated to narrate the progression through pattern steps in order to reveal the important incremental differences.

Single point in time data

Single point in time data is represented instead of dynamic daylighting metrics. This is primarily because of the priority to illustrate instantaneous luminous distribution patterns and brightness relationships resulting from a specific set of design variables. Dynamic daylight metrics (Reinhart et al. 2006) are used to describe the daylighting performance of a space across the period of an entire year. They utilize annual typical weather files to account for hourly and seasonal daylight variation due to changes in sky conditions. It was a conscious decision to avoid the use of dynamic metrics because these outputs are inherently rooted in a specific climate and span an entire year whereas the rendering must be a single point in time. While dynamic metrics are an important aspect of high quality daylighting design, this project focuses primarily on 'point in time' data.

Figure 2 - Tone mapped rendering of a pattern step titled "baseline with minimum aperture area"

Figure 3 - Tone mapped rendering of a pattern step titled "skylights and additional perimeter glazing"

Horizontal illuminance maps

Illuminance maps were provided using 300 lux as the most common sufficiency threshold. We illustrate this threshold since it exceeds IESNA Category C (100 lux) for sufficient ambient space illuminance and meets the visual task requirements described in IESNA Category D. Illuminance Category D recommends 300 lux performance of visual tasks of high contrast and large size. Our intent is to illustrate daylight as the primary source of ambient

illumination, while understanding that fine tasks of high contrast and small size (IESNA Category E) would be illuminated with supplemental task illumination when required. (Rea 2000; Saxena et al. 2010). We indicate 300 lux using a bold red dashed line to highlight performance at our threshold (*Figure **4*** and *Figure **5***). Areas above the threshold are indicated in white while areas below are indicated in gray tones. This enables a user to quickly identify the area and rough percentage of the workplane that meets our ambient illuminance criteria under a given design scenario. We have also indicated 2,000 lux with a "hidden" (short dashed) line to give users a sense of the upper range of illuminace values experienced. These representational methods were used across each pattern set to facilitate ease of interpretation for users without extensive training in lighting science.

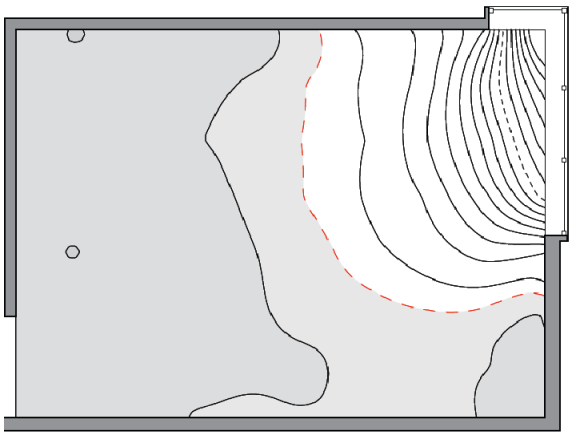


Figure 4 - Horizontal illuminance map of a pattern step titled "baseline with minimum aperture area"

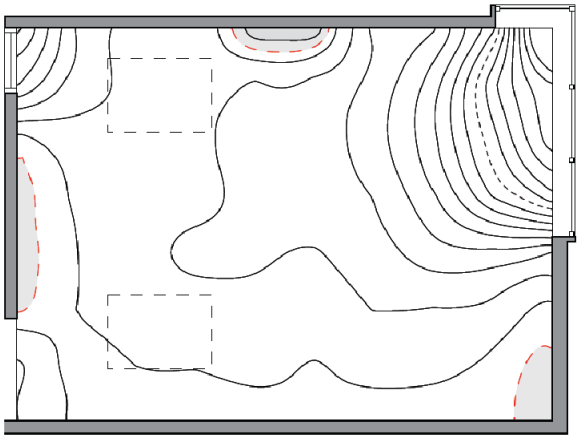


Figure 5 - Horizontal illuminance map of a pattern step titled "skylights and additional perimeter glazing"

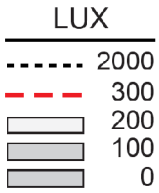


Figure 6 - Illuminance scale in lux

False color image

False color luminance maps enable the representation of a wider range brightness values than true color renderings. They also allow for normalization of the brightness representation across specific patterns and the entire *Guide*. This is critical, in that our objective was to show and compare the distribution, composition, and ratios of interior luminance on key architectural surfaces. Luminance maps are also provided at a consistent scale (1-2500 cd/m^2 in most cases) to facilitate user interpretation of non-technical audiences. The upper threshold of 2,000 – 3,000 cd/m^2 has been used as an indicator of the potential for glare (Lee et al. 2007; Van Den Wymelenberg et al. 2010).

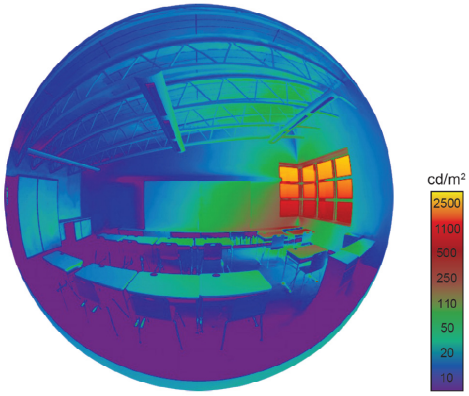


Figure 7 - False color luminance map of "baseline with minimum aperture area"

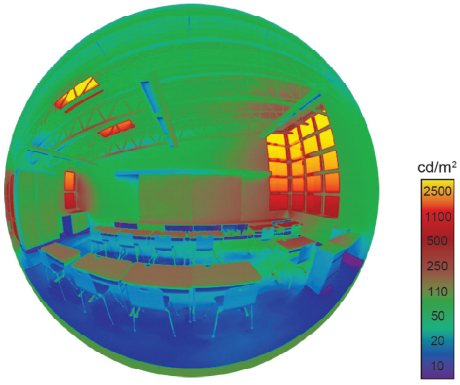


Figure 8 - False color luminance map of "skylights and additional perimeter glazing"

Tone mapping

Representational renderings of simulated interiors were produced from Radiance HDR images using tone mapping algorithms. (Reinhard et al. 2005). Tone mapping is a technique in computer graphics and image processing that attempts to represent an HDR image (representing a wide range of brightness values) to a display medium (computer monitor) that has a far narrower range of possible brightness and colors. Given that the primary objective of this tool was to create a sequence of images that related to one another it was of paramount importance to address tone mapping consistently in the renderings. The general starting point was to use Photosphere's 'auto-human' sensitivity adjustment and then apply a fine tuning routine to ensure the color renderings throughout the pattern steps progressed in a similar manner as that of the false color luminance distribution maps and that the narrative of lessons were adequately represented.

DISCUSSION

Our intention with the *Daylighting Pattern Guide* is to provide a resource that designers can consult to generate ideas for initial concept design, and to showcase the range of critical considerations inherent in any daylighting design. By beginning with existing highly regarded daylighting projects we provide both a level of 'proof of concept' and a measure of real-world feasibility. This methodology affords the luxury of beginning with known quantities for window configurations, orientation, interior surface reflectances, glass transmission, and other variables. In most early daylight design modeling much of this data is yet to be determined. Beginning with a realized outcome enables the true isolation of key performance variables to determine the sensitivity of performance relative to geometric or other modifications.

By identifying, documenting, measuring, simulating, and deconstructing the selected buildings we showcase realizable outcomes and present how they achieve performance relative to other common design configurations. In this sense, we reinforce and make visual some of the commonly accepted 'rules of thumb' for successful inclusion of daylight into buildings. For example, Pattern #3 on Section Depth illustrates that daylight can only penetrate 2-2.5 times as deep as the window height. However, a Pattern #4 on Work Station Partitions reveals that this rule only applies with very short interior partitions. Other rules of thumb are explored and sometimes called into question. For example, Pattern #9 on Toplighting a Gymnasium reveals that the rule recommending a 3-5% Skylight to Floor Area Ratio (SFAR) does not necessarily result in sufficient daylight. Similarly, Pattern #5 on Window Area Ratios reveals that the rule to provide daylight from two sides can also be inadequate. Instead, these patterns reveal the implications that sky condition, surface reflectance, glazing specification, and aperture orientation and position have on these rules of thumb. By adding a visual and spatial component that illustrates light distribution on interior surfaces in conjunction with common points of success and failure in daylighting design, we provide a foundation for evolving rules of thumb in a given context.

We hope that the *Guide* might be informative to design teams as they work with owners and users in making the case for the case for daylight illuminated buildings. The *Guide* can also be useful to promote collaboration and discussion about possible design alternatives among architects, engineers, lighting designers and interior designers. We also think the *Guide* will be useful to students exploring daylighting alternatives in architectural studios.

The *Guide* can not be a replacement for the rigorous testing of specific design ideas—in fact we consider the appropriate use of simulation tools to be critical to effective daylighting design. We do however feel that by illustrating high performance daylit buildings and the design iterations possible within their typological context, that designers might begin at a point closer to a successful daylighting outcome and that any simulation time and effort will be applied toward the most meaningful lines of inquiry. That said, the vast majority of buildings do not benefit from design specific simulation. This *Guide* can serve to raise the bar on daylighting designs for a wide variety of buildings of this nature.

Future Research

While the *Guide* provides direction for a range of building types demonstrating several architectural daylighting strategies, it is an incomplete list. Future priorities for development of the *Guide* include analysis of several additional building types and additional architectural daylighting strategies. Specifically, the *Guide would benefit from* more explicitly investigation of a finer grain suite of design options such as glass specification, surface reflectance, and office layouts. Furthermore, analysis in additional cities and across additional building types would be useful. Beyond daylight analysis alone, we feel this format is well suited to examine integrated electric lighting as well as whole building energy consumption. Integrated holistic lighting design could be explored by introducing alternative electric lighting designs in conjunction with the daylighting design solutions presented in the *Guide*.

This could encompass choice of luminare, luminare layout, lamp color temperature, and lighting control options. Finally, the *Guide* would benefit from energy analysis within each pattern step illustrating the heating, cooling, and lighting energy implications associated with each pattern step. In fact, one goal is to expand the *Guide* such that it can be used as the basis of utility energy efficiency incentive programs aimed at promoting and capturing the energy savings potential of daylighting.

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