The Role of Daylighting in LEED Certification: A Comparative Evaluation of Documentation Methods

Karen Carrier, Susan Ubbelohde

Loisos+
Ubbelohde

THE ROLE OF DAYLIGHTING IN LEED™ CERTIFICATION: A COMPARATIVE EVALUATION OF DOCUMENTATION METHODS

Karen Carrier
M. Susan Ubbelohde
University of California, Berkeley
Department of Architecture #1800
232 Wurster Hall
Berkeley, CA, 94720-1800

ABSTRACT

In this paper, the LEED™ Daylighting Credit (IEQ 8.1) is examined with reference to currently accepted calculation techniques in daylighting. A review of the derivation and use of the Daylight Factor requirement reveals that the LEED™ use of the metric is not well defined or constrained to the useful scientific understanding of the term. The Apple Flagship Store in Los Angeles, California, is used to develop a comparative example for four compliance documentation procedures. The quantitative daylight factor results from the LEED™ spreadsheet calculations are presented in detail and compared with results from a RADIANCE computer simulation, physical model testing in a calibrated mirror box sky, and on-site measurements.

The conclusions firmly indicate that the LEED™ spreadsheet method significantly over-predicts the levels of daylight due to problematic modifications in the Daylight Factor rules of thumb developed by R.G. Hopkinson. The RADIANCE and physical models are both in line with expected levels and distributions of daylight intensity, while the on-site measurements are similar to the software and physical model simulations, but skewed by changing exterior sky conditions.

1. INTRODUCTION

The Leadership in Energy and Environmental Design (LEED™) rating and certification system developed by the United States Green Building Council (USGBC) for sustainable building design and construction has quickly penetrated and transformed the building design industry. The LEED™ system awards credits toward sustainable certification for achieving specified performance goals in a wide variety of sustainable areas, including site selection, water retention, material selection, energy use, and interior environmental quality. With adoption by an increasing number of clients, architects, and institutional and government agencies, the scientific basis of the credit system has come under examination.

This paper examines Daylighting Credit 8.1 in the Interior Environmental Quality category and the methods of compliance documentation accepted. The credit intends to: "provide for the building occupants a connection between indoor spaces and the outdoors through the introduction of daylight and views into the regularly occupied areas of the building." In order to be awarded the IEQ 8.1 credit a building has to "achieve a minimum daylight factor of 2% (excluding all direct sunlight penetration) in 75% of all spaces occupied for critical visual tasks. Spaces excluded from this requirement include copy rooms, storage areas, mechanical plant rooms, laundry, and other low occupancy support areas."

1.1 The Daylight Factor Metric

As a function of ever changing sky conditions, absolute values of interior illuminance will vary greatly. Although representative of a building's performance at a single moment in time, absolute illuminance levels do not allow comparative evaluation to take place. Alternatively, the daylight factor has become a widely used measure as it represents a more constant approach to determining daylighting performance. The daylight factor is defined in the CIE International Lighting Vocabulary as the ratio of the illuminance (E_i) at a point on a given plane due to the light received directly or indirectly from a sky of assumed or known luminance distribution, to the illuminance (E_o) on a horizontal plane due to an unobstructed hemisphere of this sky.

$$DF = E_i / E_o * 100\%$$

The contribution of direct sunlight to both illuminances is excluded. Unless stated otherwise the sky luminance distribution is assumed to be that of the CIE standard overcast sky. There are two assumptions resulting from this definition: a) The internal and external illuminance values occur simultaneously and b) The sky luminance distribution is known and remains constant over time. This last assumption is important because it insures that daylight factors are reproducible and comparable to other daylight factors associated with this particular sky. Since the CIE distribution algorithm of the fully overcast sky is constant and independent of changes in absolute sky luminance, an overcast sky is most often assumed when calculating daylight factors. While a perfectly clear sky also has a known sky luminance distribution, it is rarely used, because its luminance distribution varies with changing sun position and daylight factor measurements must exclude direct sun. With all other skies daylight factors will vary as a result of instable sky luminance distributions due to varying degrees of cloud cover.

While the daylight factor is a tool to quantify daylighting within a space, it does not reveal the quality of daylighting. Potential glare problems, for example, might go unnoticed if the daylight factor is the sole method for evaluating daylighting performance. The LEED[TM] daylighting requirement addresses this to some degree by requiring all openings to include some means of glare control, such as adjustable blinds, light-shelves, exterior shading, louvers, or fins. However, more often than not, additional daylight analysis is required to insure good daylighting design.

1.2 Documentation Methods

For current LEED[TM] documentation, illumination levels can be predicted or measured using methods widely accepted in practice; Daylight Factor calculations, physical modeling, computer simulations, and field measurements. The methods vary greatly in terms of the time, facilities, expertise, and equipment required and no protocols or sample methods are included in the LEED[TM] documents beyond a calculation method developed by the USGBC.

The LEED[TM] documentation for submittals includes a spreadsheet-based calculation method to produce daylight factors for each room or zone and calculate an overall percent of floor area that meets the 2% daylight factor criterion. As later sections illustrate, this calculation method is inherently flawed. Yet, since it produces an overestimate of daylighting illumination levels, anyone using the more accurate methods will be at a significant disadvantage in documenting sufficient daylight to receive Interior Environmental Quality Credit 8.1.

1.3 The Apple Flagship Store at Farmer's Grove

The Apple Flagship Store in Los Angeles, California, completed in 2002 was chosen for this study as it combines top lighting and side lighting techniques that successfully test the various procedures while not posing an unduly complex architecture or geometry to the calculations and simulation protocols (Figures 1-3). This design is a good example of a project requiring substantial modification to the LEED[TM] daylighting calculator because it deviates from a typical daylighting scenario.

Fig. 1: Apple Store at Farmer's Grove, Los Angeles, CA. Architect: Bohlin Cywinski Jackson.

2. DAYLIGHT FACTOR CALCULATION METHODS

Calculation methods of varying complexity (and related accuracy) have been developed to predict the daylight factor levels in standard or idealized side lighting and top lighting conditions. Graphic methods, such as nomographs and Waldram diagrams, have been developed from these equations. The most influential equations arguably have been the simplified rules of thumb proposed by R.G. Hopkinson. They form the basis of the LEED[TM] spreadsheet.

2.1 Hopkinson's Average Daylight Factor Rule of Thumb

Hopkinson developed average daylight factor equations for a variety of apertures under overcast sky conditions. The primary factor determining illuminance levels in a space is the ratio of glazing to floor area, followed by room dimensions, location and spacing of glazing, internal and external obstruction, and interior surface reflections. Useful for the initial design stage, the average daylight factor is related directly to its unobstructed net glazed area.

Hopkinson's generalized rules of thumb (Table 1) assume average room proportions, no exterior obstructions, and an average internal reflectance of 40%. Considering the equations were published in 1966 in the U.K. it is also safe to assume that they are based on clear, single glazing.

TABLE 1: AVERAGE DAYLIGHT FACTOR EQUATIONS BY R.G. HOPKINSON

For Side-lighting:	DF avg = 0.2	*	$\dfrac{\text{Net glazing area}}{\text{Floor area}}$	%
	DF min = 0.1	*	$\dfrac{\text{Net glazing area}}{\text{Floor area}}$	%
For vertical monitors:	DF avg = 0.2	*	$\dfrac{\text{Net glazing area}}{\text{Floor area}}$	%
For sloping shed and north lighting:	DF avg = 0.33	*	$\dfrac{\text{Net glazing area}}{\text{Floor area}}$	%
For horizontal glazing:	DF avg = 0.5	*	$\dfrac{\text{Net glazing area}}{\text{Floor area}}$	%

2.2 LEED™ Daylighting Calculator

The LEED™ daylight factor formula was developed in an effort to provide a calculation method requiring only a small and readily available set of input data: glazing area, floor area, and visual glazing transmittance. Similar to Hopkinson's equations, the LEED™ daylight factor calculation takes into account the type of aperture by way of a geometry factor (GF). A total of five equations, two for side-lighting and three for top-lighting conditions, are defined in Table 2.

The LEED™ geometry factor for side-lighting conditions is equivalent to the geometry factor in Hopkinson's minimum daylight factor equation, which calculates the daylight factor at the back of a side-lit space. The LEED™ geometry factors for skylights directly correspond to those in Hopkinson's average daylight factor equations for top-lighting. In contrast to the Hopkinson calculation, glazing below 2'-6" is not included in the LEED™ side-lighting daylight factor equation. A height factor (HF) is introduced to distinguish between daylight glazing located above, and vision glazing located below 7'-6".

The HF multiplier for daylight glazing increases the Daylight Factor contribution from this glazing while that for the vision glazing decreases the contribution. Mathematically, however, both side-lighting equations are identical when the minimum T(vis) is factored into the equation. Recognizing

TABLE 2: LEED™ DAYLIGHT FACTOR EQUATIONS

Window Type	DF= GF	*	$\dfrac{\text{Window Area}}{\text{Floor Area}}$	*	$\dfrac{\text{T(vis)}}{\text{T(min)}}$	* HF
Side-lighting (Vision Glazing):	DF = 0.1	*	$\dfrac{\text{Window Area}}{\text{Floor Area}}$	*	$\dfrac{\text{T(vis)}}{0.4}$	* 0.8
Side-lighting (Daylight Glazing):	DF = 0.1	*	$\dfrac{\text{Window Area}}{\text{Floor Area}}$	*	$\dfrac{\text{T(vis)}}{0.7}$	* 1.4
Top-lighting (Vertical Monitor):	DF = 0.2	*	$\dfrac{\text{Window Area}}{\text{Floor Area}}$	*	$\dfrac{\text{T(vis)}}{0.4}$	* 1.0
Top-lighting (Sloped Monitor):	DF = 0.33	*	$\dfrac{\text{Window Area}}{\text{Floor Area}}$	*	$\dfrac{\text{T(vis)}}{0.4}$	* 1.0
Top-lighting (Horiz. Skylight):	DF = 0.5	*	$\dfrac{\text{Window Area}}{\text{Floor Area}}$	*	$\dfrac{\text{T(vis)}}{0.4}$	* 1.0

the wide range of glazing types used in today's building industry, a transmittance factor is built into the LEED™ formula. To encourage the use of high transmittance glazing, the project transmittance is weighted by including a divisor of minimum recommended transmittance of 0.7 for daylight glazing and 0.4 for vision glazing and skylights.

This weighting will result in over-prediction, as it effectively multiplies the expression by a value larger than one. Consequently, the LEED™ side-lighting equations result in daylight factors 80% higher than daylight factors calculated with Hopkinson's equations. The LEED™ top-lighting equations overestimate daylight factors by 125% compared to Hopkinson's rule of thumb formulas. These comparisons assume no obstructions and the average reflectance of surfaces to be 40%. Projects with large internal or external obstructions or extremely dark surfaces

will therefore result in still lower daylight illumination, and even more exaggerated over-prediction.

No expertise or even understanding of daylighting is required to fill in the blanks and generate the information required for submission. Any member of the design or construction team can complete the spreadsheet on a standard office computer and produce the print out necessary for documentation. No special software, facilities, expertise, equipment, or weather conditions are therefore required to calculate the Daylight Factors for each room or zone in the building using the LEED[TM] spreadsheet.

Like any simplified system in daylighting, the LEED[TM] calculator is designed for standard rooms with typical or idealized daylighting apertures. Applying it to any design beyond a rectangular room with straightforward windows or skylights requires judgment as to how the entry should be modified within the intent of the credit and the behavior of daylight.

2.3 Apple Store LEED[TM] DF Calculation

While a south facing glass façade on the first floor represents a traditional side lighting condition, the top lighting in the case study building is significantly more complex due to a glass stair positioned directly under a large skylight over the second floor. The stair creates a mezzanine condition not easily addressed by the spreadsheet. Also, the custom shape of the skylight above has to be correctly figured into the equation.

The first floor opening represents a typical side-lighting condition with some of the window qualifying as daylight glazing and some as vision glazing. The transmittance of the first floor glazing was calculated with the program Optics 5, giving us a T(vis) of 0.79. The daylight contributed to the first floor through the glass stair under the skylight can be thought of as a virtual horizontal light source. The transmittance of this virtual light source can be arrived at by multiplying the transmittance of the skylight (0.31) with that of the stair (0.85), giving us a total transmittance of 0.26. When the resulting daylight factor is added to the daylight from the south storefront windows, the total daylight factor is 4.6%. It is extremely high, because the calculations do not take into account the distance between the stair opening and the outside sky; treating the stair opening as the virtual skylight has in fact calculated a daylight factor as though the first floor ceiling was the roof of the building.

Similar to the first floor calculations, the all-glass skylight monitor on the second floor can best be approximated with a virtual light source concept. Although it consists of a sloped top and vertical sidewalls, it is in effect a horizontal top lighting aperture with the virtual glazing area equaling the dimension of the roof opening. A glazing transmittance of

0.31 results in a daylight factor of 3.2% for the space. The required glare control is met by way of a ceramic frit pattern on the skylight glazing.

Since these results are based on extreme simplifications of an already simplified calculation method, it is highly debatable which modifiers to apply, or even if this project is applicable to the spreadsheet calculation at all. Currently LEED[TM] does not provide guidelines for these types of decisions, leaving it up to the individual project teams to use their own judgment.

Fig. 2: Interior view of 2nd floor and skylight

Fig. 3: Interior view of 1st floor and glass stair

In calculating the floor area, for example, a first instinct might be to exclude the stair opening from the total. This would raise the daylight factor for the second floor by 0.3%. In reality however, the absence of the floor decreases the daylight available to the second level, because light falling on this area is now shared with the lower floor rather than reflected back into the space. Similarly an incorrect classification of the skylight monitor as "vertical monitor"

and "sawtooth monitor" geometry types will result in gross over-estimation of its contribution to the daylight factor; in this case by an additional 0.9% Daylight Factor.

When such adaptations are added to the overestimation inherent in the LEED[TM] calculator, many more buildings will receive the daylighting credit than actually provide a 2% Daylight Factor to their occupants.

3. ALTERNATE DOCUMENTATION METHODS

The documentation necessary for the LEED[TM] daylighting credit does not require the use of the spreadsheet. Physical models, computer simulations, or on-site measurements of the completed building are also allowed as methods to document the 2% daylight factor requirements, although no protocols or directions are available from the USGCB. The Apple Store daylighting was documented using each of these methods.

3.1 Physical Model

A physical model at ½"=1'-0" was constructed and measured with Licor photosensors in the mirror box artificial sky at the Building Science Lab at the University of California, Berkeley. Measured daylight factors for the first floor are represented in Figure 4. Shaded areas indicate zones with daylight factors greater than 2%, lighter shaded areas stand for Daylight Factors greater than 1%.

Although the model produced overall higher daylight factors than those measured in the existing building or resulting from RADIANCE simulations (see Sections 3.2 and 3.3), they still did not fall within the LEED[TM] 2% Daylight Factor requirement for most of the retail area. The higher daylight factors as compared to those measured in the store are explained by the absence of furniture in the model as well as a high visual transmittance material used to model the façade glazing. Furthermore, obstructing neighboring buildings such as the four story parking garage behind the store were not included in the model.
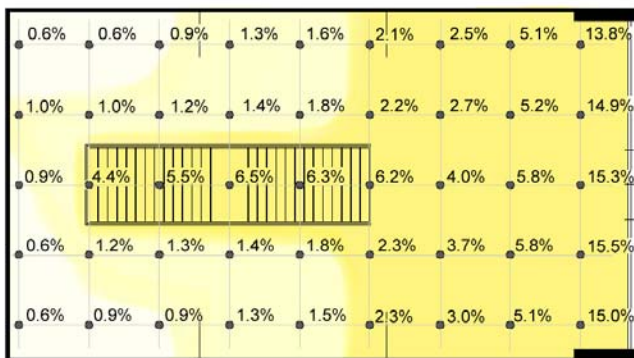
Fig. 4: Physical model results for first floor

The limitations in using physical models for LEED[TM] documentation lie in three areas. First, the type of model useful for accurate daylight predictions must be purpose built and is rarely a model the architect would construct as part of the design process; this adds both cost and the requirement of expertise to the documentation process. Second, photosensors that are small and can be remotely read are required to meter the illumination levels; these are expensive and must usually be borrowed from an architecture research lab or a daylighting consultant. Third, to be sure of the results, one needs access to a calibrated artificial sky or stable exterior overcast sky conditions under which to take measurements.

3.2 Computer Simulation

The Linux-based program RADIANCE, like a physical model, can handle non-conventional geometries and apertures, and has the added advantage of being able to readily predict illumination levels under a wide range of sky conditions. The limitations of the software lie primarily in the difficulty of learning and using the program, as well as the computing power and time required. The use of RADIANCE, similar to the use of physical models, would likely require a daylighting consultant for LEED[TM] documentation.

An existing CAD model was rebuilt specific to RADIANCE requirements and illumination levels were run for a 10,000 lux CIE overcast sky (Figure 5). Similar to the physical model and the field testing results, the RADIANCE calculated daylight factors do not fall within the LEED[TM] required 2% except for areas near the skylight and adjacent to the glass façade.
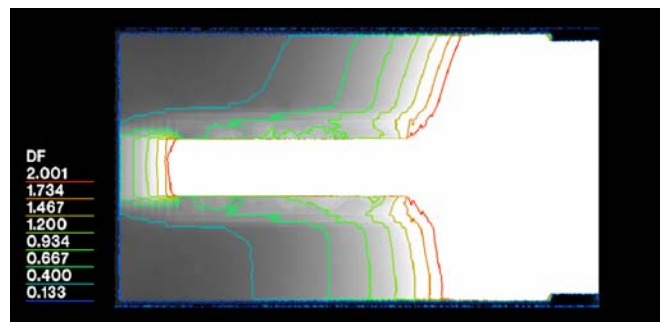
Fig. 5: RADIANCE daylight factor contours for first floor

3.3 On-Site Measurements

The store was metered on a Saturday morning before business hours, allowing us to take illumination measurements in an empty store with all lights turned off. The sky was covered in thick, high clouds, and although the sun was breaking through a little in the southeast, no sun

disc was visible. During the testing period exterior illumination levels ranged from 3,000 to 3,300 fc (32,300 to 35,500 lux) translating to approximately 60 to 66 fc (645 to 710 lux) necessary inside the building to meet the 2% Daylight Factor requirement. Calibrated photosensors were used simultaneously inside and out to record illumination levels, from which daylight factors were calculated.

As Figure 6 illustrates, less than half of the floor area meets the LEED[TM] required minimum 2% Daylight Factor. The goal of daylight reaching far back into the space is also not accomplished according to these results.
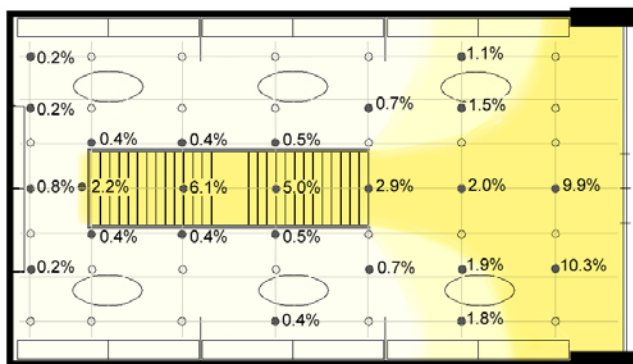

Fig. 6: On-site measurements for first floor

While on-site metering is a fast and potentially highly accurate method of performance evaluation, its main drawback lies in the unpredictability and instability of real skies. In addition some expertise is required to insure accurate results.

4. CONCLUSIONS

The LEED[TM] calculator radically over-predicts daylight illumination levels. The physical model over-predicted daylight factors partially due to the high transmittance glazing used, but also for the reason that no exterior obstructions were modeled. The daylight factors measured in the store, although overall slightly lower, match those simulated by the RADIANCE program closely, and have practically identical areas with daylight factors above 2%. While the LEED[TM] spreadsheet, when modified to include light attributed to the glass stair, calculated a daylight factor well above 2% for both floors, none of the three alternative documentation results met the credit requirements.

It can be argued that the credit intent (providing a connection between indoor and outdoor spaces through the introduction of natural light) as well as the design intent has been met in this building. The store is filled with good quality daylight that allows views into the store from the outside and lends a sparkle to the interior. Tasks that require low light levels such as computer screen reading take place in less illuminated areas, while the visual focus of the store, the glass stair and skylight above, are showcased to further amplify ones awareness of daylight within the store.

5. ACKNOWLEDGEMENTS

6. REFERENCES

(1) Baker, N., Fanchiotti A., Steemers K. ed., Daylighting in Architecture: A European Reference Book. London: James and James Ltd., 1993.

(2) Benton, C.C., Diminutive Design, Physical Models in Daylighting Education and Practice. Lighting Design and Application. 20(5): 4-23, 1990.

(3) CIE, Spatial distribution of daylight - CIE standard overcast sky and clear sky. ISO 15469/CIE S003, 1996.

(4) CIE, Spatial distribution of daylight - CIE standard general sky, Draft Standard, CIE DS 011.1/E, 2001.

(5) IESNA. Handbook of the Illuminating Engineering Society of North America, 9th edition (Ed. Rea MS), Illuminating Society of North America, New York, NY 2000.

(6) Hopkinson, R.G., et al., Daylighting. London: Heinemann, 1966.

(7) Littlefair, P.J., M. E. Aizlewood, Measuring daylight in real buildings. Proceedings CIBSE National Conference. Bath, 1996.

(8) Mardaljevic, J., Validation of a lighting simulation program under real sky conditions. International Journal of Lighting Research and Technology. 27(4): 181-188, 1995.

(9) Moore, Fuller, Concepts and practice of architectural daylighting. New York: Van Nostrand Reinhold, 1991.

(10) Robbins, Claude L., Daylighting: Design and Analysis. New York: Van Nostrand Reinhold, 1986.

 (11) US Green Building Council, LEED[TM] Reference Guide version 2.0, Paladino Consulting LLC, (URL:)www.usgbc.org

(12) Ward, G., Shakespeare R., Rendering with Radiance: The Art and Science of Lighting Visualization. Los Altos, California: Morgan Kaufmann 1998.