Topic 12. Integration of technologies and tools for building design and operation

Automated Calculation of Lighting Regulations

Yi Chun Huang* and Khee Poh Lam

Center for Building Performance and Diagnostics, Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

**Corresponding email: yihuang@andrew.cmu.edu*

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SUMMARY

While the compliance with lighting regulations serves as a useful indicator on the quality of lighting designs, the calculation for such regulations is often a time consuming task, even when data is available from a lighting simulation tool. Recent research and surveys have shown that there is a strong industry demand for automated regulations checking tools. This paper presents algorithms for automated calculation of the lighting related benchmarks within the Leadership in Energy and Environmental Design (LEED) Green Building Rating System.

INTRODUCTION

The LEED rating system is a popular benchmark in the United States for high performance green buildings and includes two credits for lighting performance: daylight availability and external view availability in building spaces. While the LEED rating system is a voluntary rating system, the widespread adoption by both governmental and private industry (Landman, 2005) has led to its use as a standard in many building projects. Correspondingly, the consideration of the LEED benchmarks is increasingly a requirement.

These benchmarks, like most regulatory metrics, are typically calculated only post-design in actual practice due to the logistical and resource burden. Specifically, the procedure for calculating the two lighting benchmarks involve manual processes and data collective that is time-consuming and error-prone. It is noted however, that such benchmarks can potentially serve as performance indicators as the design is being developed; there is much benefit in making the results to these metrics available throughout the design process.

This paper formulates the LEED benchmarks as metrics and show how computational techniques lend naturally to their calculation. Following an analysis of the context of building design, an algorithm is designed that calculates the benchmarks in real-time without compromising the quality of the solution. By further capitalizing on developments in Building Information Models (BIM) and scalability, an automated implementation of the algorithm is presented and tested.

Additionally, the formulation of regulation metrics as computational problems allows insight into performance metrics. In this paper, we show how various aspects of the benchmarks are questioned and suggestions as to how they can be improved are presented.

CALCULATION OF LEED CREDIT EQ 8.1

LEED Credit EQ 8.1 is a benchmark that quantifies the amount of daylight availability in regularly occupied areas of a building. The benchmark allows three methods of calculation: by glazing factors, computer simulation and actual on-site measurements. The last case is obviously for built projects and not considered here. Glazing Factors (Equation 1) is an estimation of daylighting conditions based on window positions and visible transmittance for overcast sky conditions. The Glazing Factor for each window is calculated separately and added together for each occupied space in the building. If the total Glazing Factor is 2% or greater in a space, then the entire area of that space is applicable to the credit. The credit is awarded when 75% or more of the occupied areas have satisfied the required Glazing Factor.

$$\text{Glazing Factor} = \frac{\text{Window Area}}{\text{Floor area}} \times \text{Window GF} \times \frac{\text{Actual } T_{vis}}{\text{Min } T_{vis}} \times \text{Window HF} \quad (1)$$

where T_{vis} is the visible transmittance if each window, and Window Geometry Factor (GF) and Height Factor (HF) are defined as:

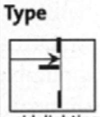
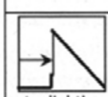
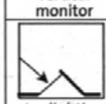
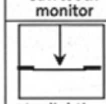
Window Type	Geometry Factor	Minimum T_{vis}	Height Factor
 sidelighting daylight glazing	0.1	0.7	1.4
 sidelighting vision glazing	0.1	0.4	0.8
 toplighting vertical monitor	0.2	0.4	1.0
 toplighting sawtooth monitor	0.33	0.4	1.0
 toplighting horizontal skylights	0.5	0.4	1.0

Table 1. Types of windows (*USGBC, 2005)*

Implementation

The calculation of the glazing factor requires the determination of the type for each window according to Table 1, the relevant areas as well as the tabulation of visible transmittance values. In lighting tools that contain building geometry information and material data, this calculation can be done with relative ease. The steps in an algorithm that does so are:

Step 1: find the list of occupied spaces
Step 2: find the list of windows in each space
Step 3: determine the window types (subdivide the window if necessary)

Step 4: retrieve T_{vis} and calculate the GF of the windows
Step 5: tabulate the GFs in space and determine if equal or greater than 2%
Step 6: tabulate the eligible floor area in the building and determine if equal or greater than 75%

Most of the steps in the algorithm involve only logistical tasks, such as the sorting and tabulation of occupied spaces and windows. Only Step 3 involves actual computation, but this can be done with relative ease. By retrieving the geometry of the window and the space it is in, the height, orientation, and consequently type, of the window can be calculated very quickly.

As a demonstration, this algorithm is implemented in a new lighting simulation tool (Lam et. al, 2008). The tool automatically processes Building Information Models (BIM) from design modelling tools and references an externalized project database. The algorithm then calculates if the LEED credit is achieved instantaneously. There is no need for user intervention from the design model to obtaining the results and the process is dynamic; changes to the LEED results are shown immediately when there is any modification made to the building model.

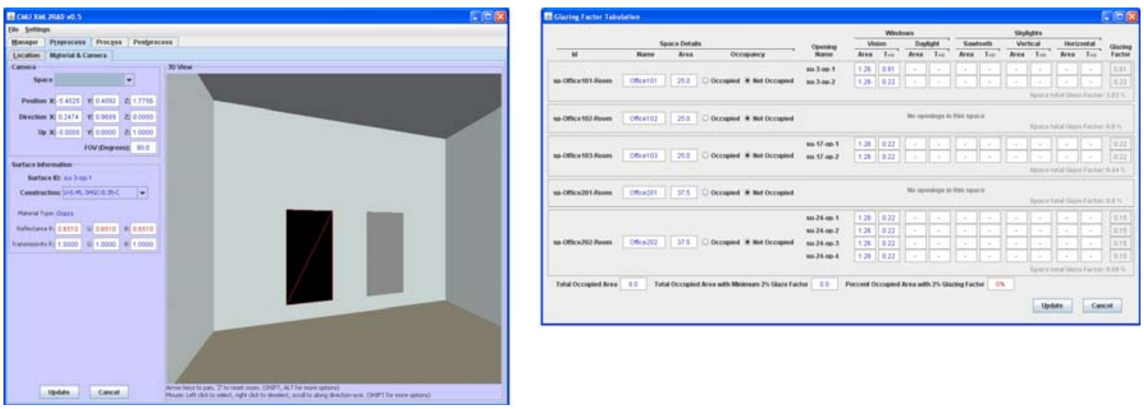


Figure 1. Automated calculation and tabulation of LEED Credit EQ 8.1 in the new lighting tool. Building model viewer and editor (left) and dynamically updated tabulation of LEED credit (right)

CALCULATION OF LEED CREDIT EQ 8.2

LEED Credit EQ 8.2 is a benchmark that quantifies the percentage of occupied spaces that have exterior view. Specifically, the credit is awarded when 90% of all regularly occupied areas have a view to an exterior vision window. Vision windows are defined as portions of exterior windows between 2’6” (762mm) and 7’6” (2286mm) above finish floor levels of each room considered. The credit can be formulated as thus:

$$EQ_{8.2} = \begin{cases} 1 \mid \sum(V(Room_n) \div Area_n) \geq (0.9 \times Area_{total}) \\ 0 \mid otherwise \end{cases} \quad (2)$$

where $Room_n \in$ Regulary Occupied Spaces in Building, $Area_n =$ Floor Area of $Room_n$, $Area_{total} = \sum Area_n$ and $V(Room_n)$ = Floor Area of $Room_n$ with view to Vision Window .

The documentation also stipulates that the entire areas of single-occupied rooms are eligible for consideration if 75% or more of the room area has a view to some vision window;

otherwise the actual area with views to vision windows is to be used. For multi-occupant rooms, actual areas with view to vision windows are used. This can be formulated as:

$$V(Room_n) = \begin{cases} Area_n & | \; single\ occupant \ \wedge \ \left(V_{actual}(Room_n) \geq (0.75 \times Room_n)\right) \\ V_{actual}(Room_n) & | \; single\ occupant \ \wedge \ \left(V_{actual}(Room_n) < (0.75 \times Room_n)\right) \\ V_{actual}(Room_n) & | \; multi\ occupant \end{cases}$$

$$= \begin{cases} Area_n & | \; single\ occupant \ \wedge \ \left(V_{actual}(Room_n) \geq (0.75 \times Room_n)\right) \\ V_{actual}(Room_n) & | \; otherwise \end{cases} \quad (3)$$

where $V_{actual}(Room_n)$ = Actual Calculated Floor Area of $Room_n$ with view to Vision Window

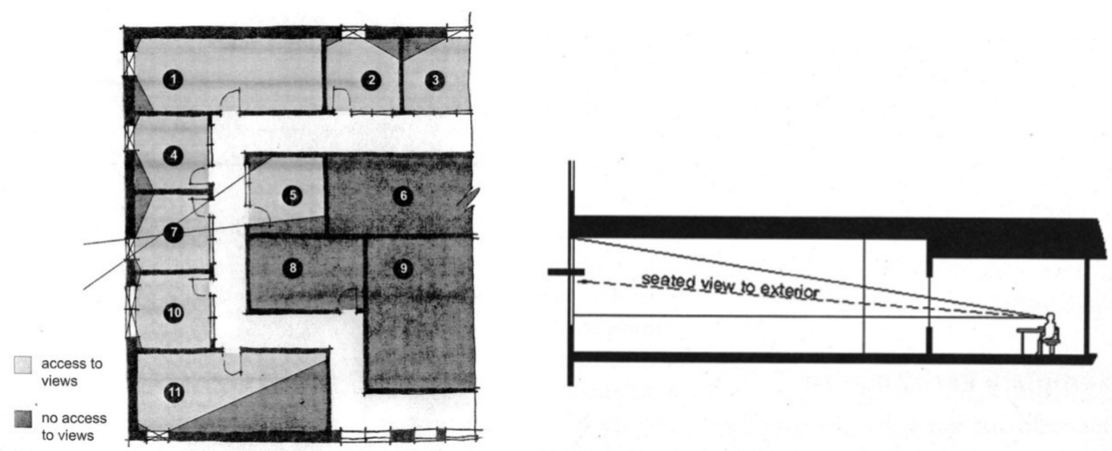


Figure 2. Drawing sightlines on plan (left) and section (right) to determine view to vision window. (USGBC, 2005)

The procedure for determining the floor area with view to vision window in each room is described graphically (Figure 2). The documentation describes a 2-step process; sightlines are drawn on plan to calculate an interim area with view to perimeter windows, sightlines are then drawn for each eligible window in representative section to confirm if unobstructed view conforms to vision window definitions. The line of sight heights used in sections are defined to be 42” (1067 mm) above finish floor levels representing average seated eye heights.

While the narrative and graphical description for calculating the availability of vision windows suggests a geometric approach, the formulation of the procedures shows the possibility of a finite-element approach. While further analysis is required to determine which is computationally faster, the latter lends to faster computer implementation. In this case, the floor plane is discretized and each point checked for access to vision windows. The procedure can be formulated as:

$$V_{actual}(Room_n) = \sum_{i=0}^{p} A(i) \quad (4)$$

where $i \in$ { p points in $Room_n$ 42" above finish floor level} and A(i) = Availability of view to vision windows at point *i*.

By enumerating the vision windows in the building as $W = \{vision\ windows,\ w_{1,2,\ldots l}\}$, $A(i)$ can be defined more accurately as $A(i, W)$, which expresses the availability of view to any of the windows in set W. $A(i, W)$ can then be expressed as a recursive algorithm:

$$A(i,W) = \left(E(i,w_l) \vee A\left(i,\{W\text{-}w_l\}\right) \right) \quad (5)$$

$$E(i, w_l) = Availability\ of\ view\ to\ w_l\ from\ point\ i \quad (6)$$

$E(i, w_l)$ can be evaluated by standard ray-tracing by testing for opaque obstructions between point i and points on vision window w_l.

Implementation

Following the preliminary definition of $E(i, w_l)$, two shortcomings are obvious in the current procedure stipulated by LEED. First, infinitesimally small areas of vision windows constitute a view to the exterior. Second, there is no consideration of the combined visual effects from several windows. To address these two issues and improve Credit EQ 8.2 as a benchmark of exterior view availability, some changes can be introduced with minimal change in computational expense.

The definition of vision windows reflects an attempt to quantify typical visual behavior and the areas of visual sensitivity. Using the same 1067mm eye height, the current vision window height limits describe a 22˚ field of vision (10˚ above horizon, 12˚ below horizon) 4m away from the window, which is roughly consistent with cone of temporal vision sensitivity. However, such visual behavior consideration becomes moot with the current stipulated calculation method. Regardless, the current definition also becomes problematic when the distances increase. At 10m (a reasonable distance in large buildings), the current limits describe only a 7˚ field of vision, which is obviously too narrow for exterior context awareness.

The use of visual angles is thus advantageous. By stipulating a minimally required viewing angle to constitute a valid view to the exterior, infinitesimally small areas become invalidated. Furthermore, the description of visual behavior becomes consistent regardless of distance; a larger vision window is required for deep spaces. On the other hand, window sections above or below the current limits or even finish floor levels become eligible if there is a direct view. This actually increases flexibility for design.

The steradians subtended by each window can be used together with the recommended visual angles to better describe the visual impact of windows. A minimal limit for individual and cumulative steradians subtended by the windows can then be used to eliminate views that are too restrictive to constitute exterior awareness (such as narrow slits), as well as account for combined effects of multiple views (a series of slit-like views may actually allow for exterior awareness. In the latter case, an additional visual angle between candidate views may be necessary to define acceptable cases. Using the same example of multiple slit-like views, exterior awareness may be negated when the slits are too far apart and not present together a coherent view.

Since Credit EQ 8.2 is granted upon achieving 90% of the building floor area, the calculations only have to achieve accuracy to the nearest percentage. Correspondingly, $V_{actual}(Room_n)$ (Equation 4), only have to achieve this accuracy and the number of samples per room, p can be limited. Likewise, if visual angles are implemented to improve the accuracy of the benchmark, the number of samples in $E(i, w_l)$ (Equation 6) to be taken for each window can correspondingly limited.

To reduce the computational load in evaluating $E(i, w_l)$ by ray-tracing, the set of external windows is pre-processed into a smaller set of eligible vision windows as defined by the more accurate viewing angles. A smaller list of possible obstructions is obtained from the set of all building surfaces and organized as a kd-tree. Since these two processes are essentially linear to the number of elements, the additional computational load is near negligible.

The steps in the algorithm are:

Step 1: find the list of occupied spaces
Step 2: generate the list of points in each space
Step 3: generate the list of candidate rays from the points to vision windows
Step 4: trace the candidate rays for obstruction
Step 5: calculate the steradians subtended by external views
Step 6: tabulate the floor area with view to exterior
Step 7: determine if eligible floor area in building is equal or greater than 90%

In preliminary tests where the algorithm is implemented in the aforementioned new lighting tool, Credit EQ 8.2 can be calculated within seconds. Like the previous benchmark, the results can be calculated and presented in a dynamic manner to help guide design developments.

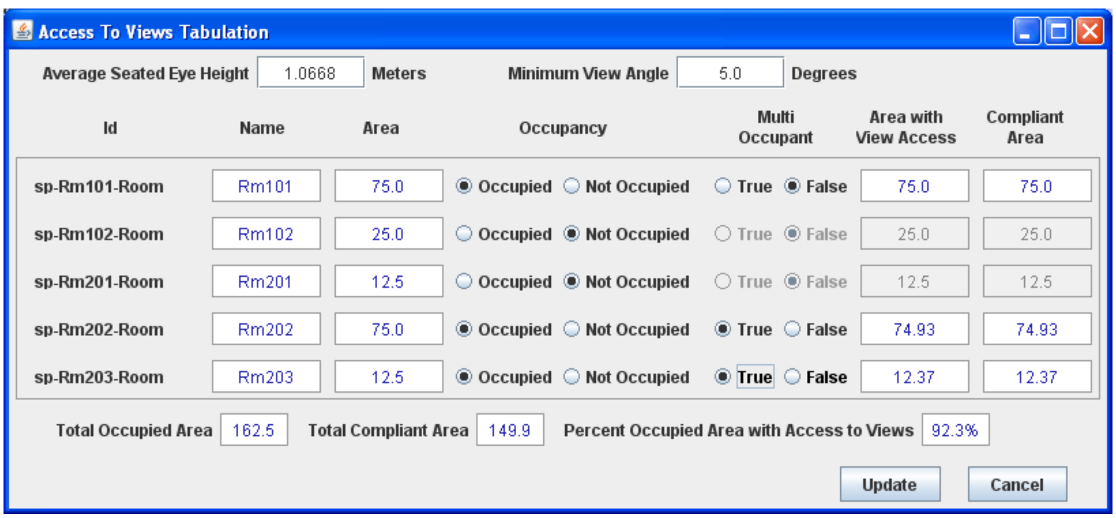


Figure 3. Automated calculation and tabulation of LEED Credit EQ 8.2in the new lighting tool

DISCUSSION & CONCLUSION

The formulation of the two LEED benchmarks, especially credit EQ 8.2, as computer algorithms allows them to be easily used in design. As demonstrated by implementation in the new lighting tool, results to the two benchmarks are provided automatically and quickly without any additional user input. This allows the benchmarks to be used to effectively guide design development towards quantitative performance mandates.

For credit EQ 8.1, Glazing factors do not account for varying sky conditions at different locations, room geometry, or varying reflectance values across different surfaces in the room. Glazing factors as a performance indicator thus perform poorly when the room is non-convex, has high aspect ratios, or when the surfaces encompass a wide range of reflectance values. Further work is required to investigate the computation of this credit via the second option of irradiance simulations. Current simulation tools that are physically accurate, such as Radiance, take a long time to compute and would not be able to furnish results with the time-frames required to support integrated design activities. The advantage of glazing factors is that it can be computed very easily; current implementation achieves real-time performance. Much work has to be done in reformulating simulation engines to meet the time constraints for the second option to be feasible for integrated design.

While the use of viewing angles in credit EQ 8.2 have contributed to the clarification and definition of external view, the same concept may extended to describe asymmetrical visual behavior by use of separate horizontal and vertical minimal viewing angles. This would entail further review of empirical research.

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