USING PHYSICAL EXPERIMENT FOR PREDICTING HOURLY DAYLIGHT QUANTITY IN ARCHITECTURAL SPACES WITH COEFFICIENT OF UTILIZATION METHOD

Jianxin Hu, PhD.
College of Design
North Carolina State University
Brooks Hall, Box 7701
Raleigh, NC 27695
e-mail: jhu3@ncsu.edu

Wane Place, Ph.D.
College of Design
North Carolina State University
Brooks Hall, Box 7701
Raleigh, NC 27695
e-mail: wayne_place@ncsu.edu

Christoph Konradi
College of Design
North Carolina State University
Brooks Hall, Box 7701
Raleigh, NC 27695
e-mail: ckonrad@ncsu.edu

ABSTRACT

Developed from physical experiments, Coefficient of Utilization (CU – the ratio of interior illuminance to unobstructed exterior illuminance) was examined in a previous paper in terms of its effectiveness in predicting hourly daylight quantity in wall-based sidelighting designs [1]. The results showed that the CU method, which was based on exterior illuminance on a vertical plane, was effective in studying climate-based daylighting performance in building spaces with vertical glazing (Wall-based). In the present paper, the validity of the CU method is examined for spaces with upward-facing apertures (Roof-based). The results show that the CU method significantly improves the accuracy of the daylight performance assessment for toplighting systems with upward facing apertures. This study, along with the previous one focusing on wall-based apertures, provides an effective and efficient method for predicting hourly daylight quantity in buildings on a year-round basis by using an approach based on physical experiment testing.

Key Words: Daylighting, Coefficient of Utilization, Climate-based Daylight Modelling, Light Quantity

1. INTRODUCTION

There has been little effort made in the literature to use experimental testing to assess climate-based daylighting performance in buildings, simply because assessing annual light quantity by testing physical models can be difficult. Monitoring a physical model on an annual basis is normally not practical for most design projects. The concept of Coefficient of Utilization (CU) was developed by the authors as a simplified experimental method to serve as a reliable and feasible alternative to computer simulations for Climate-Based Daylight Modeling (CBDM).

In a previous paper [1], the CU method was validated for wall-based daylighting systems. For these vertical daylighting systems (windows), Coefficient of Utilization was defined as the ratio of the interior illuminance to the simultaneous exterior ***vertical*** illuminance.

$$\mathbf{CU = Ez / Ev} \qquad \textbf{[1]}$$

Where:

Ez = Illuminance at a point of interest on interior task plane, in Lux.

Ev = Illuminance from sky incident on an exterior ***vertical*** plane near windows, in Lux.

It is noted in this case a CU relates the interior illuminance to exterior *vertical* illuminance. It was proven that the exterior vertical illuminance, which was taken at the window surface, provided a direct measurement of how much light actually entered the room. Therefore, vertical illuminance was expected to be a better indicator of daylighting performance for evaluating wall-based sidelighting designs than the traditional Daylight Factor (DF) method [2]. The testing results showed that, when using experimental testing as the simulation method, CU was a more effective indicator than DF for predicting Climate-Based daylighting performance in sidelit spaces.

Based upon the previous work, this present study is intended to:

- Validate the CU method in building interior spaces with upward facing daylight apertures (e.g. horizontal skylights); and
- Develop a database to streamline the use of CU method for predicting daylight quantity in buildings.

2. METHODS

2.1 Establishing the Daylight Climate

The first step of conducting CBDM research is to establish the daylight climate at the project site. The following hourly daylight climate data were collected by an IDMP Research Grade station located in Raleigh, North Carolina:

- Global horizontal illuminance (Evg)
- Diffuse horizontal illuminance (Evd)
- Illuminance on vertical surfaces facing North, East, South and West (Evgn, Evge, Evgs, Evgw),
- Global horizontal irradiance (Eeg)
- Diffuse horizontal irradiance (Eed)

Sensors measuring diffuse illuminance and irradiance are screened from direct sunlight by a shadow band with a width between 0.2 and 0.24 of the band radius. Sensors measuring illuminance on vertical surfaces are screened from ground-reflected light by a black and a white screen forming an artificial horizon (Figure 1).

Figure 1: Photocell and irradiance sensors

2.2 Scale Model

A 30’x30’ space with shaded horizontal linear apertures is tested. A scale model (1/2” = 1’-0”) of this space is constructed to simulate this space. The interior space is divided into multiple daylit zones with one light sensor placed in each zone for measuring light quantities on a year-round basis (Figure 3). The surface reflectances are: ceiling and walls: 90%; floor: 20%; lightshelf top and bottom surfaces: 90%; overhang top and bottom surfaces: 15%; exterior ground reflectance is assumed at 20%; glazing transmittance: 70%.

Figure 2: Experimental testing station

A shaded light sensor was placed on a horizontal plane with an unobstructed view to the sky. The illuminance reading from this sensor will be used to calculate the CUs at each zone within the model. Note that instead of using exterior illuminance on a vertical plane, the horizontal reading is used in this case, because the latter value measures directly how much daylight arrives at the horizontal apertures. This horizontal exterior sensor is also shaded due to the fact the linear apertures on the roof are shaded from the solar component of the daylight source (Figure 3).

3. DATA ANALYSES AND DISCUSSIONS

3.1 Coefficient of Utilization Calculations

A CU can then be developed for each zone to establish the relationship between the sky and interior illuminances. Using Zone 1 as an example (Figure 3), the CU is calculated by the following formulas:

$$\mathbf{CU_1 = E_{z1} / E_d} \qquad [2]$$

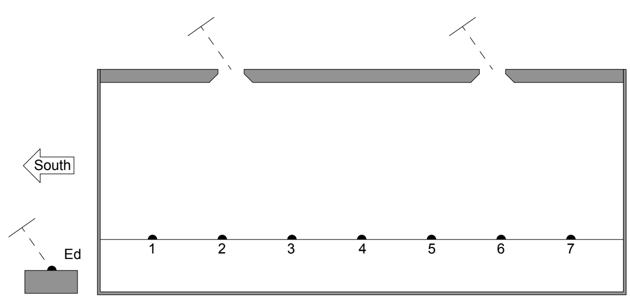


Figure 3: Model being tested under mostly cloudy sky

The model is tested under various sky conditions with different solar angles. Based on formula [2], CUs can be derived from the exterior and interior illuminances for each daylit zone. There are totally 7 zones defined in the model. Figure 4 through 6 shows the CU distribution for three zones: Zone 2, 4 and 6. The X axis represents various solar angles during the day when the testing is conducted:

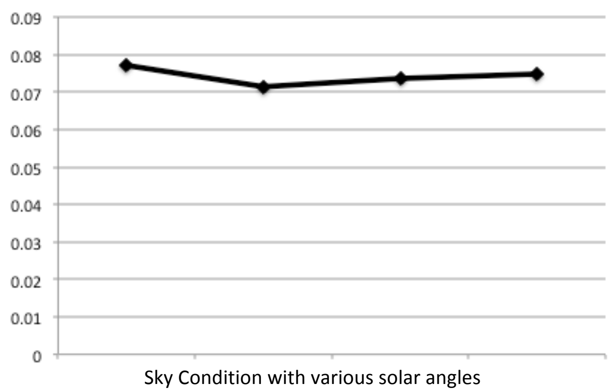


Figure 4: CU Distribution in Zone 2

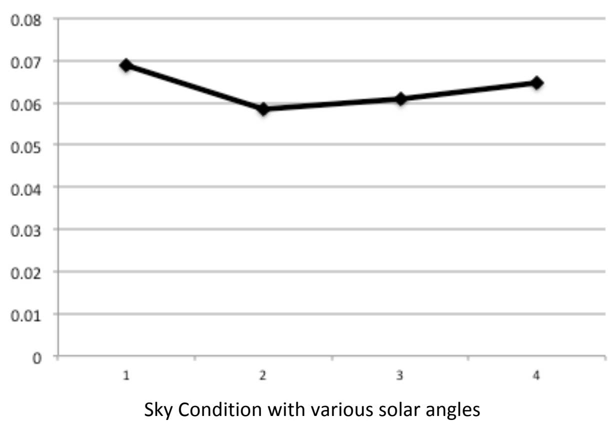


Figure 5: CU Distribution in Zone 4

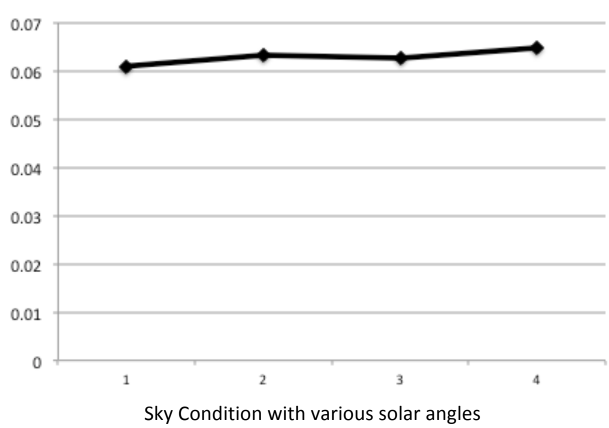


Figure 6: CU Distribution in Zone 6

The results show that, for each daylight zone, the CU values are fairly stable across different sky and solar conditions. The data from Zone 1, 3, 5 and 7 also show the same pattern – the fluctuation of the CU values is low. This suggests that CU tends to be stable throughout the year and relatively independent of sky conditions, solar angles, and seasons. This also suggests that CU is an effective indicator of the ability for a daylighting system to deliver light into a particular space. This is a significant finding in that it justifies a potential approach to predicting annual daylight quantity in building by a simplified experimental testing procedure: For evaluating a daylighting design with diffused/shaded horizontal aperture, a scale model of this design can be built and tested under a random sky condition. The CUs derived from the data are representative of the distribution of the actual CUs measured across various sky and solar conditions of the year.

3.2 Using CUs to Predict Daylight Quantity

By reconfiguring Formula [2], daylight quantity (in Lux) can be obtained by:

$$\mathbf{Ez = Ed * CU} \qquad \mathbf{[3]}$$

Where

Ez = Interior Illuminance at a point of interest, in lux.
Ed = Exterior diffuse illuminance on a horizontal plane. Hour values of Ed are made available by the climate data collection or by local weather data files.
CU = CU developed in Section 3.1.

By multiplying Ed by a CU, daylight quantity Ez can be predicted at each time step in each zone of a model. Hourly daylight levels in all seven zones can be predicted in a full year. For wall-based daylighting systems, Ev will be used in lieu of Ed in Formula [3].

The annual exterior illuminance data (Ev and Ed) were made available by the IDMP Research Grade station located at the Daylighting Research Lab in NC State University. The data set, including hourly exterior illuminance values in a full year (from 5:00am to 7:00pm, solar time), was collected in a one-year period in Raleigh, North Carolina.

In order to develop a database to streamline the use of CU method for predicting daylight quantity in buildings, CU values starting from 1% to 20% with 1% increment are assumed. For each CU value, such as 1%, hourly interior illuminance levels can be calculated by multiplying this CU value (1%) by the hourly exterior illuminances.

There are three common climate-based daylighting performance metrics derived from interior illuminance values:

- Daylight Autonomy (DA) is the first of a string of annual daylight metrics. It is represented as a percentage of annual daytime hours that a given point in a space is above a specified illumination level. The user is free to set the threshold above which Daylight Autonomy is calculated, however the common threshold is 500Lux (DA500).

- Useful Daylight Index (UDI) is defined as the annual occurrence of illuminances at any given point on the work plane that are within a range considered "useful" by occupants. The "useful" range was identified based on a survey of previous studies on occupant perceptions and preferences. The widely accepted range is 200 Lux to 2000 Lux.

- Continuous Daylight Autonomy (cDA) is another metric that considers partial credit when the daylight illuminance lies below the minimum illuminance level. For example, in the case where 300 lux are required and 150 lux are provided by daylight at a given time step, a partial credit of 150lux/300lux=0.5 is given for that time step. An upper threshold, which is usually equal to ten times the design illuminance, is also established to address overlit (glare) issues. For the purpose of this paper, the upper threshold would be 300lux X 10 = 3000 lux. If the daylight level falls between 300lux and 3000lux, the cDA is 1.

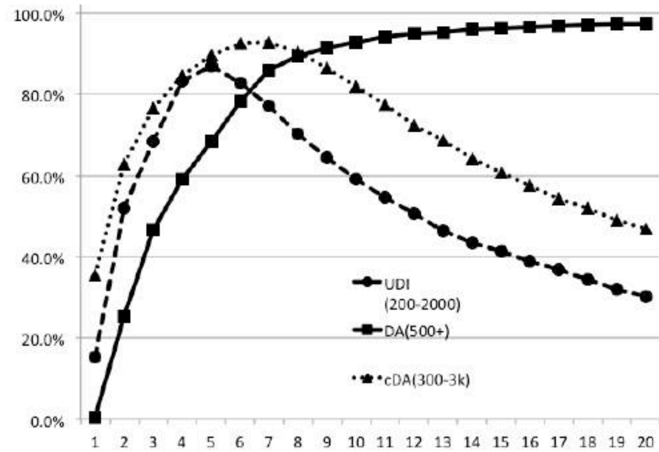
For each daylit zone in a model, a set of daylight performance metrics: DA, UDI and cDA, can be developed from interior illuminances. Table 1 through 3 show the derived daylight metrics associated with CU values ranging from 1% to 20% with 1% increment.

Table 1: Daylight Performance Metrics for Spaces with Diffuse/shaded Upward Facing Apertures

CU	UDI (200-2000)	DA(500+)	cDA(300-3k)
1%	15.2%	0.4%	35.5%
2%	51.9%	25.3%	63.0%
3%	68.3%	46.6%	76.6%
4%	83.2%	59.0%	84.5%
5%	86.9%	68.3%	89.7%
6%	82.7%	78.2%	92.7%
7%	77.3%	85.8%	92.9%
8%	70.3%	89.4%	90.6%
9%	64.5%	91.5%	86.5%
10%	59.2%	92.8%	81.9%
11%	54.6%	94.0%	77.3%
12%	50.6%	94.9%	72.5%
13%	46.3%	95.3%	68.6%
14%	43.6%	95.9%	64.2%
15%	41.3%	96.2%	60.8%
16%	39.1%	96.5%	57.6%
17%	36.7%	96.8%	54.4%
18%	34.5%	97.0%	52.0%
19%	31.9%	97.2%	48.9%
20%	30.3%	97.3%	46.9%

Table 1 shows the performance metric distributions for spaces with diffused/shaded upward facing daylighting apertures, such as the system illustrated in Figure 3. The calculations are based on the exterior horizontal diffuse illuminance. The distributions of the three metrics in Table 1 can also be illustrated by Figure 7.

Percentage of Daylight Performance Metrics



CU Percentages

Figure 7: Daylight Performance Metrics Based on Diffuse Horizontal Exterior Illuminances for Upward Facing Daylight Apertures

The DA value increases with the increase of the CU and it is close to 100% when CU value is over 10%. This is because the definition of the DA does not involve any upper limit. In this case, overlit conditions are not captured. This is one of the drawbacks of the DA method, because the glare issue caused by too much daylight cannot be detected with this method.

Both UDI and cDA show similar trends: their values increase with the increase of the CU until the CU reaches approximately 6% or 7%. After this threshold, the UDI and cDA values drop. This is because both of these metrics have upper limits. When too much daylight is introduced, the performance of a daylighting system suffers due to glare problems.

Table 2 shows the performance metric distributions for spaces with south facing daylighting apertures, such as the lightshelf system studied in the previous paper [1]. The calculations are based on the exterior south-facing illuminance.

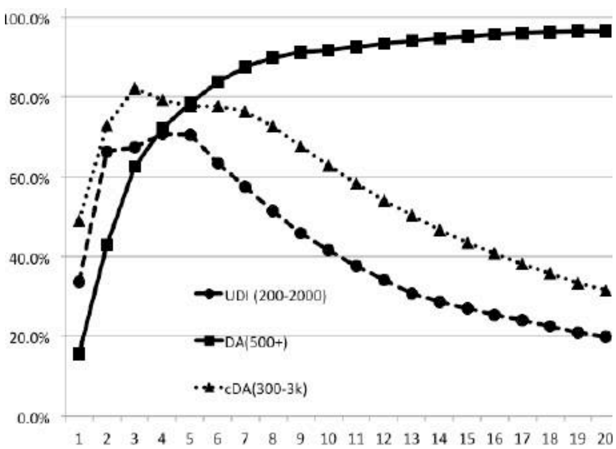
Exterior illuminances on a vertical plane that arrive at a window wall also depend on the ground reflection. For example, lighter ground surface will increase the light level. For the purpose of this paper, 30% ground reflection is assumed. This percentage is approximately the reflection value of a lawn, which is common to most building sites.

Table 2: Daylight Performance Metrics for Spaces with South Facing Apertures

CU	UPI (200-2000)	DA(500+)	cDA(300-3k)
1%	33.7%	15.5%	48.9%
2%	66.3%	43.0%	72.8%
3%	67.3%	62.5%	82.3%
4%	70.8%	72.2%	79.4%
5%	70.4%	78.4%	77.8%
6%	63.4%	83.7%	77.7%
7%	57.6%	87.4%	76.3%
8%	51.3%	89.8%	72.6%
9%	45.9%	91.1%	67.5%
10%	41.5%	91.9%	62.8%
11%	37.6%	92.7%	58.4%
12%	34.1%	93.4%	54.1%
13%	30.7%	94.2%	50.4%
14%	28.7%	94.6%	46.5%
15%	27.1%	95.1%	43.5%
16%	25.5%	95.6%	40.7%
17%	24.0%	96.0%	38.1%
18%	22.4%	96.3%	35.8%
19%	20.8%	96.5%	33.4%
20%	19.8%	96.6%	31.6%

Similarly, the distributions of the three metrics in Table 2 can be illustrated in a graph (Figure 8).

Percentage of Daylight Performance Metrics



CU Percentages

Figure 8: Daylight Performance Metrics Based on South-facing Exterior Illuminances for South-facing Daylight Apertures

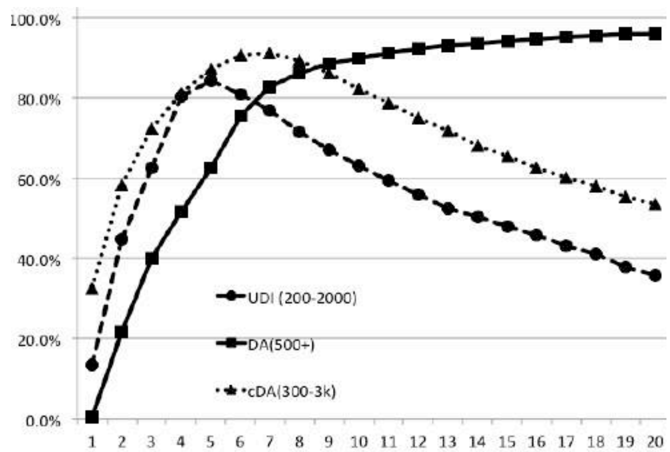
The DA, UDI and cDA distributions across CU values are similar to the last case shown in Figure 7. However, the maximum UDI and cDA metrics are associated with a lower CU value, in this case, approximately 3% to 4%. This suggests that overall south facing exterior illuminances are higher than diffuse horizontal illuminances. Table 3 shows the data for north-facing apertures. The calculations are based on the north-facing exterior illuminances. The results can be interpreted in a similar manner.

Table 3: Daylight Performance Metrics for Spaces with North Facing Apertures

CU	UPI (200-2000)	DA(500+)	cDA(300-3k)
1%	13.5%	0.4%	32.7%
2%	44.7%	21.6%	58.4%
3%	62.4%	40.1%	72.3%
4%	80.5%	51.7%	81.2%
5%	84.2%	62.4%	87.3%
6%	80.8%	75.5%	90.7%
7%	76.9%	82.7%	91.1%
8%	71.6%	86.2%	89.5%
9%	67.2%	88.5%	86.1%
10%	63.0%	89.8%	82.3%
11%	59.3%	91.2%	78.8%
12%	55.9%	92.3%	75.0%
13%	52.5%	93.1%	71.9%
14%	50.2%	93.7%	68.2%
15%	48.0%	94.2%	65.5%
16%	45.7%	94.7%	62.7%
17%	43.3%	95.1%	60.2%
18%	40.9%	95.5%	57.9%
19%	37.9%	95.9%	55.4%
20%	35.6%	96.0%	53.6%

Figure 9 shows the maximum UDI and cDA are associated higher CUs due to the lower north facing illuminances.

Percentage of Daylight Performance Metrics



CU Percentages

Figure 9: Daylight Performance Metrics Based on North-facing Exterior Illuminances for North-facing Daylight Apertures

4. CONCLUSION

Based on the concept of Coefficient of Utilization, a simplified experimental method is developed to predict interior daylight quantity by using all three daylight performance metrics. The method involves building a physical model and testing it to obtain a CU for each daylit zone. By fitting the CU in the above Tables or Graphs, daylight metrics can be developed in a timely manner.

Although computer-based simulation is increasingly used for daylighting studies, conducting physical experiments is still crucial for this type of research, because light quality and spatial perception can be difficult to assess by computer simulations. A scale model, such as the one used in this study, allows people to assess light quality by observing through the view ports provided on the walls, so that the observer can be immersed in the luminous surround. However the experiment-based CU methods proposed in this paper is limited by the availability of testing equipment and facilities. In addition, the data presented in this study is limited by its location, which is Raleigh, North Carolina. In order to evaluate daylit space in other locations, similar calculations need to be performed to address those design tasks.

As the next step of this research, a computer-based program will be created. It will import standard climate date files that are made available online for locations across the country. Once a CU is developed by experimental testing, daylight performance metrics will be derived by inputting the CU into the program.

5. REFERENCES

[1] Hu, J., W. Place & C. Konradi, "Using Coefficient of Utilization as A Performance Indicator for Climate-based Daylight Modeling by Physical Experiments", American Solar Energy Society-Solar 2012.

[2] Hu, J., J. Du & W. Place, "The Performance Evaluation of an Advanced Daylighting System in Multi-story Office Buildings: Measurement and Simulation," Proceedings of PLEA 2011