A Validation Study of Simulated Illuminance Levels of an Office Space in Gurgaon, India under actual CIE Sky Conditions

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4 authors, including:

Riya Malhotra
The Energy and Resources Institute

Rohit Thakur
Delhi Technological University

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Ankit Bhalla
GRIHA Council, TERI
New Delhi, India
Email: ankit.bhalla@grihaindia.org

Riya Malhotra
Sustainable Habitat Division, TERI
New Delhi, India
Email: riya.malhotra@teri.res.in

Rohit Thakur
Sustainable Habitat Division, TERI
New Delhi, India
Email: rohit.thakur@teri.res.in

Sanjay Seth
Sustainable Habitat Division, TERI
New Delhi, India
Email: Sanjay.seth@teri.res.in

***Abstract* — In the past decade, numerous daylighting practitioners, architects, engineers, and researchers have progressively used daylighting simulation tools to estimate the daylight areas of building design. Most of these tools employ overcast sky conditions for daylight simulations. However, the accuracy and pertinence of such simulation tools for the tropical sky are uncertain. This study aimed to validate the computer-simulated result of overcast and actual sky models with physical test bed results measured under a real tropical sky. The considered space is modelled as per the constructed test bed space (Mahindra-TERI Centre of Excellence (MTCoE), Gurgaon, India) model to be tested under a real sky measurement. The same model was configured in VELUX Daylight visualizer 3.0 to perform daylighting simulation for March 21st, 2022, from 8:00hrs to 18:00hrs. All the illuminance measurements in the test bed were carried out under prevailing sky conditions in Gurgram, India. In contrast, related CIE sky conditions and overcast sky conditions were used for simulations to compare the results using the agreement of the index method. The International Commission on Illumination (CIE) sky conditions are very dissimilar from the actual tropical sky; simulated absolute value results such as external illuminance, absolute work plane illuminance and surface luminance recorded moderate mean differences from the measured results. Results indicate that the accuracy of illuminance levels increased by almost 24% through daylight simulations under actual sky conditions on March 21st (equinox day). Aimed at imminent research, other parameters can be validated, such as orientations, angle of the overhang, glazing, window sizes, colours, environment settings, and electric lighting.**

Keywords- Illuminance; daylight; validation; office; CIE.

I. Introduction

Daylight is an essential and effective aspect of the sustainable development approach for reducing energy consumption [1], the impact of climate change [2], and for improving well-being and productivity [3], visual comfort [4], and the built environment development [5]. For colour rendering, daylight is the best available light source, and its high quality makes it the only light source suitable for human visuals. The internal spaces are brightened by natural daylight, which mainly enters the space via window openings and establishes a visual link between the area of interest and exterior environments. An important stage in daylighting designs is calculating the daylight illuminance for a specific location in a building [6]-[9].

For daylighting, several guidelines and conceptual design strategies are available; the most common way to predict daylight illuminance is to use the Daylight Factor (DF). The method is simple, and analysis can be carried out analytically or derived via particular design aids. The DF calculation is based on overcast sky conditions and does not account for direct sunlight [10]. DF is frequently described in daylight design guidelines and is an extensively used technique for practitioners in many countries [11]. The DF method has effectively established the connection between the daylight controls and efficiency; as per the split-flux theory, the Average Daylight Factor (AFD) required for any area of interest is directly proportional to the window area and involves a smaller amount of data than DF [12][13].

The sky luminance varies as the distance from the sun changes (both in azimuth and altitude), according to recorded sky luminance data from other tropical nations and accepted sky luminance prediction models [14][15]. Aside from that, the Indian design sky does not consider the changes in sky circumstances when climatic zones shift. As detailed above, azimuthal uniformity, climatic invariance, and insufficiency for calculating annual energy savings owing to daylight are among the limitations of the present Indian design sky model. Because of these flaws, the designers had no choice but to use different sky luminance forecast models for window design and annual building energy load estimates. The sky models of Perez [16] and the International Commission on Illumination (CIE) [17] are commonly used for predicting sky brightness distribution.

The daylight availability is primarily determined by the sky's luminance levels and patterns [18]. In 2003, the CIE approved a set of 15 sky types illustrated in Table I, which presents an overall practical framework for representing the skies in various environments, including different climates such as tropical humid and temperate maritime [19][20]. The respective standard sky characterizes a distinct pattern of sky illuminance. However, the mathematical equations can be rather complicated, particularly for the non-overcast sky, which depends on the various sun positions [21]. The shading properties of nearby buildings can dramatically reduce the amount of sunshine entering the interior of the buildings, specifically in densely populated zones [22][23]. With the advancement in computer technology, computer simulation tools can be utilized to evaluate the building's daylight requirement. On the other hand, full-scale computer simulation programs can be highly complex, costly, and time-consuming, particularly during the early stages of design when numerous architectural possibilities and design schemes are studied and evaluated [24]. Simple simulation tools provide insight into the interdependency of numerous daylight variables for building professionals. In earlier investigations, many researchers have used simulation techniques to accurately validate the light environment in the tropics under an overcast sky with no external obstruction [25], however the studies were not performed under real sky conditions. Once the design schemes have been finalized, the practitioner performs computer simulations, and the calculation results will be used to verify the simulated findings.

The provisions, standards, and criteria for adequate natural light in buildings are specified in several regulations, codes of practice and design handbooks. A measuring station at the TERI Gram, Gurugram, Haryana, India, took solar irradiance and sky luminance measurements. All instruments were placed on the roof in a reasonably free of external impediments and easily accessible for examination, cleaning, and maintenance. Every day, data collection for sky luminance begins at 600hrs and ends at 1800hrs; on the other hand, data for solar irradiance is recorded every minute. All of the data was collected roughly simultaneously in true solar time, which aided in the computation of solar geometry and subsequent data comparison at other places.

TABLE I. A SET OF 15 STANDARD SKY TYPES AND THEIR PARAMETRIZATION (CIE, 2003)

Sky Type	Type of Sky	Standard gradation parameters	Standard indicatrix parameters
1	Overcast with the steep gradation and azimuthal uniformity	I: a=4 b=-0.7	1.c=0 d=-1 e=0
2	Overcast with the steep gradation and slight brightening toward sun	I : a=4 b=-0.7	2.c=2 d=-1.5 e=0.15
3	Overcast moderately graded with azimuthal uniformity	II : a=1.1 b=-0.8	1.c=0 d=-1 e=0
4	Overcast moderately graded and slight brightening toward sun	II : a=1.1 b=-0.8	2.c=2 d=-1.5 e=0.15
5	Overcast, foggy or cloudy with overall uniformity	III : a=0 b=-1	1.c=0 d=-1 e=0
6	Partly cloudy with a uniform gradation and slight brightening toward sun	III : a=0 b=-1	2.c=2 d=-1.5 e=0.15
7	Partly cloudy with a brighter circumsolar effect and uniform gradation	III : a=0 b=-1	3.c=5 d=-2.5 e=0.3
8	Partly cloudy, rather uniform with a clear solar corona	III : a=0 b=-1	4.c=10 d=-3 e=0.45
9	Partly cloudy with a shaded sun position	IV : a=-1 b=-0.55	2.c=2 d=-1.5 e=0.15
10	Partly cloudy with brighter circumsolar effect	IV : a=-1 b=-0.55	3.c=5 d=-2.5 e=0.3
11	White-blue sky with a clear solar corona	IV : a=-1 b=-0.55	4.c=10 d=-3 e=0.45
12	Very clear / unturbid with a clear solar corona	V : a=-1 b=-0.32	4.c=10 d=-3 e=0.45
13	Cloudless polluted with a broader solar corona	V : a=-1 b=-0.32	5.c=16 d=-3 e=0.3
14	Cloudless turbid with a broader solar corona	VI : a=-1 b=-0.15	5.c=16 d=-3 e=0.3
15	White-blue turbid sky with a wide solar corona effect	VI : a=-1 b=-0.15	6.c=24 d=-2.8 e=0.15

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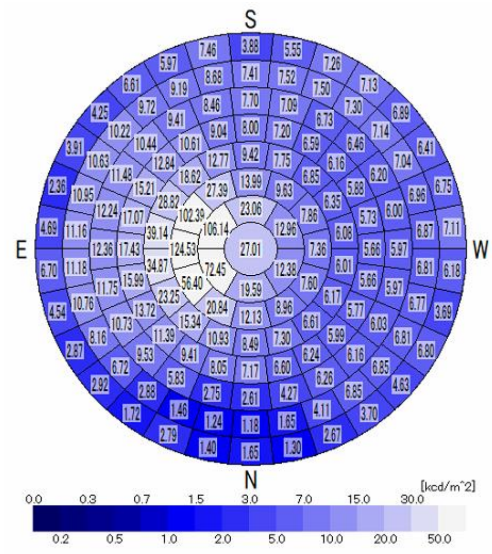


Figure 1. Measurement points for the sky scanner

The EKO MS321LR sky scanner is used to scan the luminance distributions in the sky that presents the sky grid pattern for the sky dome; it records the luminance at 145 sky patches, as shown in Figure 1. The scanner's full view angle is 11 degrees, which allows each sky patch to be regarded as a point source with minimal inaccuracy. This study looks at luminance data measurements and validation of the recorded data by utilizing the VELUX software.

II. METHODOLOGY

The study is divided into four sub-activities where the first activity (see Figure 2) focuses on the CIE analysis of the raw luminance data obtained from the installed sky scanner instrument at the MTCoE lab, Gurugram, India. For the second activity (see Figure 4) of the study, a room was selected in the vicinity of the sky scanner instrument to measure the actual daylight illuminance levels of the space. The considered space is further modelled as per the constructed test bed space as a part of the third activity of the study (see Figure 7). The model was configured in VELUX Daylight Visualizer 3.0 to perform daylighting simulation for equinox day that is 21st March from 800hrs to 1800hrs. All the illuminance measurements in the test bed were carried out under prevailing sky conditions in Gurugram, India. In contrast, related CIE sky conditions and overcast sky conditions were used for simulations to compare the results using the agreement of the index method (see Figure 10).

A. *Activity-1 CIE Analysis of Luminance Distribution Data*

The performance of each CIE standard sky luminance model was evaluated for 21st March 2022 using the Root Mean-Square Errors (RMSE) adapted from ISO 15469:2004 that defines a set of outdoor daylight conditions linking sunlight and skylight for theoretical and practical purposes [18] for the extracted luminance distribution data from the sky scanner instrument. The analyzed measured CIE sky-type for half-hourly data from 800hrs to 1800hrs as mentioned in Table II which is further used as an input for sky type consideration for CIE measured sky simulations as described in Activity-3.

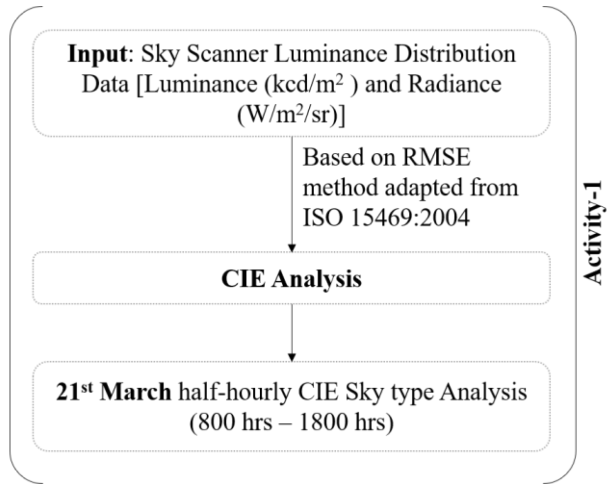


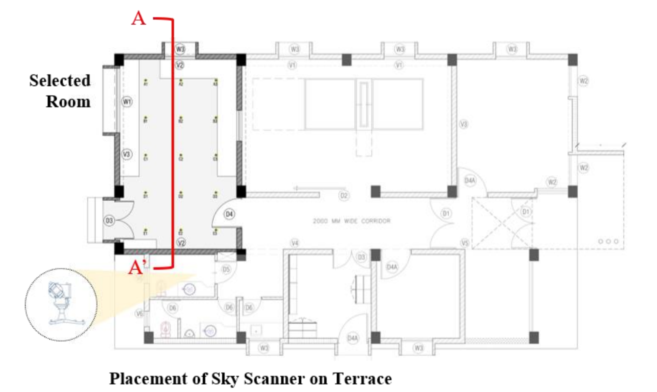
Figure 2. CIE Analysis of Luminance Distribution Data

TABLE II. CIE ANALYSIS MEASURED SKY TYPE FOR 21ST MARCH

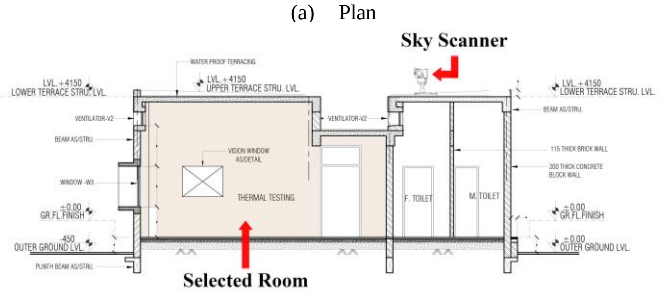
Date	Time (hrs)	CIE Analysis Measured Sky-type	CIE Overcast sky-type
21st Mar 2022	800	14	1
	830	14	1
	900	14	1
	930	14	1
	1000	14	1
	1030	14	1
	1100	12	1
	1130	12	1
	1200	12	1
	1230	12	1
	1300	14	1
	1330	14	1
	1400	14	1
	1430	14	1
	1500	14	1
	1530	14	1
	1600	14	1
	1630	15	1
	1700	14	1
	1730	14	1
	1800	14	1

B. Activity-2 Measurements of Daylight Iluminance levels

For the second activity of the study, a room was selected in the 100m vicinity of the sky scanner instrument, as shown in Figure 3.



(a) Plan



(b) Section A-A'

Figure 3. Placement of the Sky Scanner instrument and the selected room;

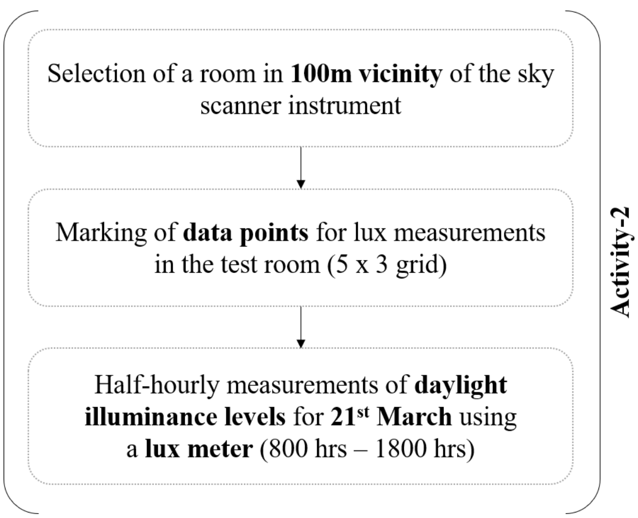


Figure 4. Daylight Illuminance Measurements

Figure 5. Measurements of illuminance levels using a Lux Meter at the MTCoE lab test bed

A set of 15 grid points (see Figure 6) is marked in the selected room and spatially distributed for data set points to measure the daylight illuminance levels for 21st March (800 hrs -1800 hrs) using testo 540 - Light meter, the light sensor is modelled on the spectral sensitivity of the human eye and is ideal for measuring lighting conditions in the workplace at 750mm work plane as shown in Figure 5.

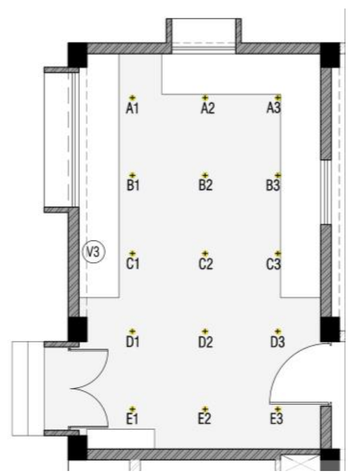


Figure 6. Data points in the selected room

C. Activity-3 Daylight Simulations

A 3D Model of the selected room (MTCoE test bed) was developed to perform the daylight simulations under CIE overcast sky type and CIE measured sky type (see Table II). The simulation results in illuminance (lux) for the same data points as shown in Figure 6 grid as the measured case. Under the scope of the study, the simulations were performed for the 21st of March using VELUX Daylight Visualizer 3.0 software that allows the user to perform daylight simulations considering any sky condition out of the CIE 15 general sky type (see Table I) only for the 21st day of each month.

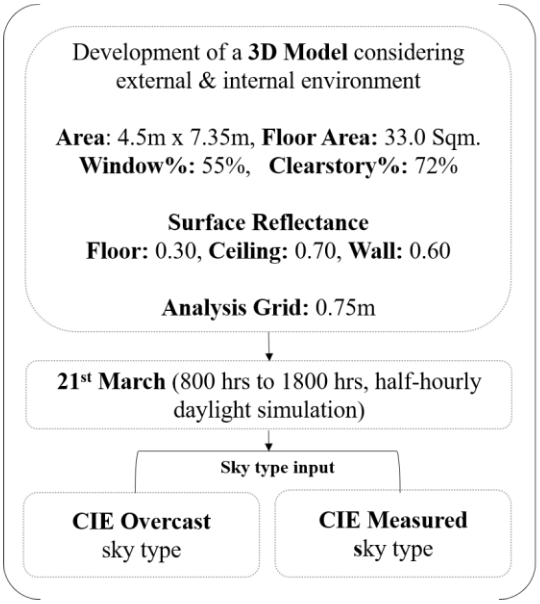


Figure 7. Run Chart for the daylight simulations

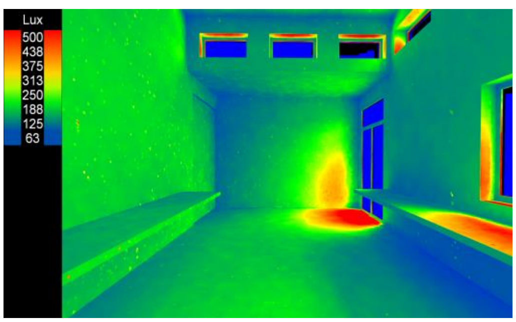


Figure 8. CIE Overcast Sky type daylight simulation for 21st March, 800 hrs with input sky type-1 described as ‘Overcast with a steep gradation and azimuthal uniform’

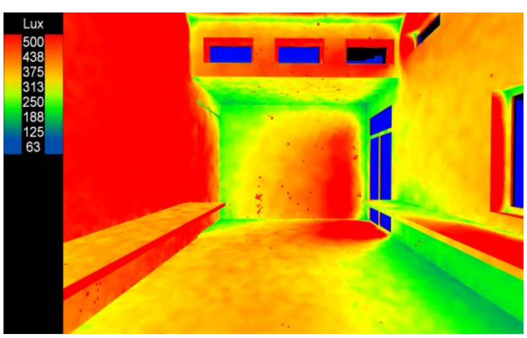


Figure 9. CIE Measured Sky type daylight simulation for 21st March, 800 hrs with input sky type-12 (see Table II) described as ‘Very clear/unturbid with a clear solar corona’

D. Activity-4 Index of Agreement

The daylight illuminance levels obtained from the second activity for actual measurements were compared with the simulated lux levels from the third activity. The index of Agreement method is used to assess the differences between the two cases as shown in Figure 10.

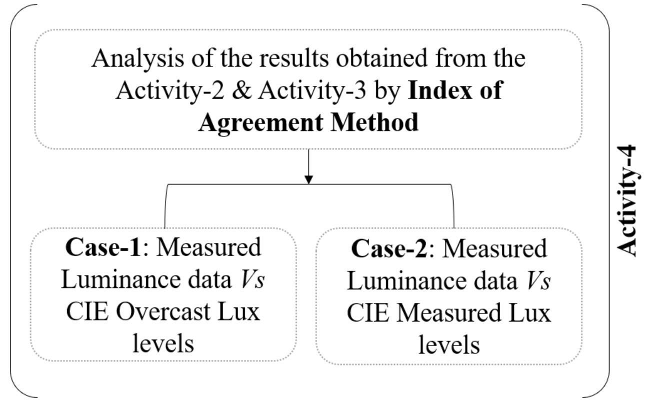


Figure 10. Analysis of the results

The comparison of model-produced estimates with observed/reliable data is an important stage in any modelling investigation. The index of agreement is used to validate this study (also known as the Willmott index); Willmott (1981) recommended a standardized measure of model forecast error called the index of agreement (d), which ranges from 0 to 1 [26]. The index of the agreement represents the ratio of the mean square error and the potential error. A value of one indicates a perfect match, while a value of zero indicates no agreement at all. The index of agreement can identify additive and proportional differences between observed and simulated means and variances; however, due to squared differences, d is susceptible to extreme values.

$$d = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(|P_i - \bar{O}| + |O_i - \bar{O}|)^2}\ , \quad 0 \leq d \leq 1$$

where O_i is the observed value and P_i is the predicted value and O_{bar} is the average observed value.

III. OBSERVATIONS

Results from the index of agreement method (see Table III and Figure 11) reveal that under overcast sky type illuminance levels were 79% closer to the measured lux levels at 800hrs whereas illuminance levels were only 71% closer to the measured lux level under real sky type, however, at 830hrs the lux levels were calculated to be 80% and 60% closer to the measured illuminance results under overcast sky type and measured CIE sky type. At 900hrs, a decrease in the percentage was observed as the illuminance level was 73% closer to the measured data under measured CIE type as compared to overcast sky type data measurement which was 79% closer to the measured data. Further at 930hrs the illuminance level was 85% and 91% closer to the measured lux level under overcast sky type and measured CIE sky type, it is at this time of the day where the percentage difference between overcast sky type and measured CIE type data was just one percent. At 1000hrs the illuminance level under overcast sky type and measured sky type were observed to be 88% and 91% closer to the measured data readings. At 1030hrs the illuminance levels

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under overcast sky type and measure sky type were observed to be 82% and 91% closer to the measure data reading however at 1100hrs there was a dip in percentage observed where the illuminance level was 93% closer to measure data under overcast sky type and 60% closer to the measure data under CIE measured sky type which is the maximum percentage closer to the measure readings and at 1130hrs the percentage dropped to 89% and 91%.

As observed during the noon, the illuminance level under overcast sky type and measured sky type were observed to be 68% and 84% closer to the measured illuminance levels and at 1230hrs the levels further dropped to 62% and 26%. At 1300hrs the illuminance level under overcast and CIE measure sky type were observed to be 75% and 95% closer to the measured data readings. Analysis indicates that at 1330hrs the luminance levels under the overcast and CIE Measured sky type were observed to be 39% and 89% during this hour of the day the difference between CIE measured sky type and overcast sky type was 50%. At 1400hrs the illuminance level under overcast and CIE measured sky type was observed to be 43% and 89% closer to the measured illuminance data, however a decrease in the percentage was observed at 1430hrs as the luminance levels under overcast sky type and CIE measured sky type was 24% and 87% closer to the measured illuminance data.

At 1500hrs the illuminance level under overcast and CIE measured sky type were analyzed to be the lowest, as they were just 3% and 73% close to the measured data, moreover by 1530hrs the percentage increase was observed to be 4% and 66%. The percentage increase continued for the next hour and the illuminance level was under overcast and CIE measured sky type were analyzed to be 6% and 73% at 1600hrs and 6% and 83% at 1630hrs closer to the measured illuminance level. By 1700hrs the illuminance level under overcast and CIE measured sky type were analyzed to be 3% and 23% closer to the measured illuminance data, which was lower than the previous hour this percentage, however, increased to 5% and 85% by 1730hrs.

The last reading of the day at 1800hrs demonstrated that the illuminance level was under overcast and CIE measured sky type were zero percent closer to the measured illuminance data.

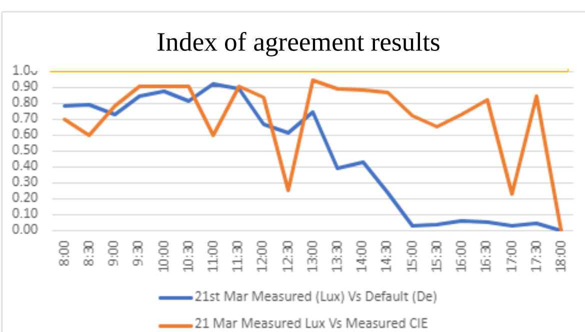

Figure 11. Index of agreement results

TABLE III. EX OF AGREEMENT RESULTS MEASURED LUX LEVEL V/S OVERCAST SKY TYPE (DE) & MEASURED LUX V/S MEASURED CIE SKY TYPE (DA).

Time	**Measured (Lux) V/s Overcast sky type (D_e)**	**Measured Lux V/s Measured CIE sky type (D_a)**
0800	0.79	0.71
0830	0.80	0.60
0900	0.73	0.79
0930	0.85	0.91
1000	0.88	0.91
1030	0.82	0.91
1100	0.93	0.60
1130	0.89	0.91
1200	0.68	0.84
1230	0.62	0.26
1300	0.75	0.95
1330	0.39	0.89
1400	0.43	0.89
1430	0.24	0.87
1500	0.03	0.73
1530	0.04	0.66
1600	0.06	0.73
1630	0.06	0.83
1700	0.03	0.23
1730	0.05	0.85
1800	0.00	0.00
Average	0.48	0.72
Standard Deviation	0.34	0.20
Median	0.68	0.83

For the 21st of March 2022 under overcast sky type the daily average of the illuminance level was 48% closer to the measured illuminance level and under CIE sky type data the illuminance level was 72% closer to the measured illuminance data with a standard deviation of 0.34 and 0.2 was observed for overcast sky type and CIE sky type with respect to measured data.

IV. CONCLUSION

The actual set of CIE design skies given in Table II can be selected for daylight simulation analysis for Gurgaon and Delhi NCR region to get 24% more accurate results than the current practice of analyzing under a worst-case scenario of overcast sky conditions. This would help architects and designers to select the glass with optimum visual light transmission and consider the optimum window-wall ratio of the project.

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REFERENCES

[1] S. Karasu, "The effect of daylight saving time options on electricity consumption of Turkey", Energy vol. 35, no. 9, pp. 3773-3782, 2010.

[2] M.T. Markou, A. Bartzokas, and H.D. Kambezidis, "Generation of daylight reference years for two European cities with different climate" : Athens, Greece and Bratislava, Slovakia, Atmos. Res., vol. 86, no. 3-4, pp. 315-329, 2007.

[3] C. Garnier, T. Muneer and L. McCauley, Super insulated aerogel windows: impact on daylighting and thermal performance, Build. Environ. Vol. 94, pp. 231-238, 2015.

[4] M.S. Alrubaih, M.F.M. Zain, M.A. Alghoul, N.L.N. Ibrahim, M.A. Shameri and O. Elayeb, "Research and development on aspects of daylighting fundamentals", Renew. Sustain. Energy Rev. 21, 2013, 494-505.

[5] T. Hwang and T.K. Jeong, "Effects of indoor lighting on occupants' visual comfort and eye health in a green building", Indoor Built Environ. Vol. 20, no. 1, pp. 75-90, 2011.

[6] D.H.W. Li, "A review of daylight illuminance determinations and energy implications", Appl. Energy vol. 87, no. 7, pp. 2109-2118, 2010.

[7] T. Muneer, N. Abodahab and J. Kubie, "Windows in Buildings: Thermal, Acoustic, Visual and Solar Performance", Architectural Press, Oxford, 2000.

[8] X. Yu and Y. Su, "Daylight availability assessment and its potential energy saving estimation - A literature review", Renew. Sustain. Energy Rev. vol. 52, pp. 494-503, 2015.

[9] A. Das and S. K. Paul, "Artificial illumination during daytime in residential buildings: factors, energy implications and future predictions", Appl. Energy vol. 158, pp. 65-85, 2015.

[10] R. G. Hopkinson, P. Petherbridge and J. Longmore, "Daylighting", Heinemann, London UK, 1966.

[11] J. Hraska, "Criteria of daylighting and sunlight access in sustainable construction evaluation systems, in: Proceedings of the 5th International Conference on Solar Radiation and Daylighting", 10e11 Aug, Brno University of Technology, Czech Republic, pp. 98-103, 2011.

[12] P. J. Littlefair, "Average Daylight Factor: A Simple Basis for Daylight Design", November. BRE Information paper, IP 15/88, 1988.

[13] J. Lynes and P. Littlefair, "Lighting energy savings from daylight: estimation at the sketch design stage", Light Res. Technol. Vol. 22, no. 3, pp. 129-137, 1990.

[14] K. P. Lam, A. Mahdawi, M.B. Ullah, E. Ng, and E. Pal, "Comparative study of sky luminance models in the tropical context" Proceedings, Building Simulation 1997, International Building Performance Simulation Association (eds Spilter, J. D. and Hensen, J. L. M.), CVUT-Czech Technical University, Prague, Czechoslovakia, vol. 1, pp. 339–345, 1997.

[15] S. Janjai, "A satellite-based sky luminance model for the tropics". Int. J. Photoenergy, 2013.

[16] R. Perez, R. Seals, and J. Michalsky, "All-weather model for sky luminance distribution preliminary configuration and validation". Sol. Energy, Vol. 50, no. 3, pp. 235–245, 1993.

[17] S. Darula, and R. Kittler, "CIE general sky standard defining luminance distributions", Proc. Conf. eSim, The Canadian conference on building energy simulation. Montreal, Canada, 2002.

[18] International Standardisation Organisation, "CIE S 011/E:2003, Spatial Distribution Daylight-CIE Standard General Sky", 2004. ISO Standard 15469: 2004, Geneva.

[19] P. R. Tregenza, "Standard skies for maritime climates", Light Res. Technol. Vol. 31, no. 3, pp. 97-106, 1999.

[20] D.H.W. Li, C.C.S. Lau, J.C. Lam, "A study of 15 sky luminance patterns against Hong Kong data", Archit. Sci. Rev. vol. 46, no. 1, pp. 61-68, 2003.

[21] R. Kittler, S. Darula and R. Perez, "A set of standard skies", Polygr. Bratisl., 1998.

[22] D. H. W. Li, S. L. Wong, C. L. Tsang and G. H. W. Cheung, "A study of the daylighting performance and energy use in heavily obstructed residential buildings via computer simulation techniques", Energy Build. Vol. 38, no. 11, pp. 1343-1348, 2006.

[23] D. H. W. Li and S. L. Wong, "Daylighting and energy implications due to shading effects from nearby buildings", Appl. Energy vol. 84, no. 12, pp. 1199-1209, 2007.

[24] M. E. Aizlewood and P.J. Littlefair, "Daylight prediction methods: a survey of their use", in: Proceedings of the CIBSE National Lighting Conference. Bath, UK, pp. 126-140, 1996.

[25] Edward Yan-Yung Ng, Lam Khee Poh, Wu Wei and Takehiko Nagakura, "Advanced lighting simulation in architectural design in the tropics", Automation in Construction, Vol. 10, no. 3, pp. 365-379, 2001.

[26] C. J. Willmott, "On the validation of models". Physical Geography, no. 2, pp. 184-194, 1981.

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