Validation of CIE sky models using luminance data from Gurgaon and Chennai, India

Ankit Bhalla [1,*], Swetha AB [2], Sanjay Seth [2] , Shabnam Bassi [1], Anjana R [3], Shailee Goswami [3], Srivathsan S K [3],
Pradeep Adithyan[3]
1 Green Rating for Integrated Habitat Assessment, New Delhi - 110 003, India
2 The Energy and Resources Institute, New Delhi - 110 003, India
3 Saint-Gobain Research India, Chennai – 600 113, India
*Corresponding Author: ankit.bhalla@grihaindia.org

Abstract

Accurate modeling of sky luminance is essential for architectural design, daylighting analysis, and climate-responsive building performance. However, standard sky models such as those developed by the International Commission on Illumination (CIE) are based on generalized sky conditions and often fail to capture the climatic variability found in different geographic regions. This study addresses the limitations of applying standard sky models in diverse climatic contexts by validating them against measured sky luminance data from two climatically distinct Indian cities: Gurugram and Chennai.

Luminance data were collected from 2022 onward using a calibrated sky scanner (EKO MS-321LR), and analyzed to evaluate the performance of the CIE sky models in replicating observed luminance distributions and angular variations. The analysis revealed considerable differences in sky luminance patterns between the two cities. In Gurugram, the CIE models showed moderate alignment with measured data, with an average Index of Agreement of 0.32. In contrast, Chennai exhibited a lower average Index of Agreement of 0.27, attributed to higher humidity levels and more variable sky conditions, particularly during the monsoon season.

To assess the implications of these findings for daylight design, the same test beds were modeled using VELUX Daylight Visualizer 3.0, a simulation tool capable of integrating real-time luminance data. This enabled optimization of window-to-wall ratios (WWR) and glazing specifications to improve both energy efficiency and visual comfort. The results emphasize the need for localized sky luminance models that reflect actual atmospheric conditions. Integrating such real-time, region-specific data into simulation tools can significantly enhance the accuracy of daylighting predictions and support more informed, climate-responsive architectural design.

Key Innovations

- Defining the prevailing sky distribution model for India at locations of Gurugram, Haryana and Chennai, Tamil Nadu through CIE standard skies, using real time Sky luminance measurement.
- Evaluation of prediction accuracy of existing sky model using validated real time luminance data in daylight simulations
- Expanded sky monitoring infrastructure and collaboration among academic and government bodies can lead to more precise, localized sky type data.

Practical Implications

Daylight Plugin tool integrated with the exhaustive data from Prevailing sky distribution model for India at locations of Gurugram, Haryana and Chennai, Tamil Nadu through CIE standard skies, using real time Sky luminance measurement would be used as a simulation tool for increased accuracy of daylight analysis results, to take conscious decision for optimizing Window to Wall Ratio (WWR) and Visual Light Transmittance of glazing at Design stage by designers

Introduction

Daylighting plays a crucial role in enhancing the energy efficiency of buildings by reducing reliance on artificial lighting. Proper daylight integration into building spaces significantly improves visual comfort by providing a uniform and dynamic light distribution, this enhances the occupant experience while contributing to energy savings. Research has demonstrated that daylighting strategies, when effectively implemented, can reduce lighting energy consumption by up to 40% in commercial and office buildings (Chirarattananon, 2000).

Visual comfort is a key factor in occupant satisfaction and productivity. Excessive brightness contrast, glare, and uneven light distribution can lead to visual discomfort and eye strain. Sky modelling enables designers to evaluate daylight distribution and develop strategies for optimal window placement, shading configurations, and interior surface reflectance (Karsten Voss, 2003). By ensuring a well-lit environment with controlled luminance levels, buildings can provide a comfortable and productive workspace.

Studies have shown that exposure to natural daylight enhances cognitive function, mood, and overall well-being. In workplaces and educational institutions, optimized daylighting has been linked to increased productivity and better learning outcomes (Heschong, 2003). In healthcare settings, access to daylight has been associated with faster patient recovery times (JEFFREY M. WALCH, 2005). The integration of daylighting into building design requires a holistic approach that considers heat gain, material selection, visual comfort, and occupant productivity. Sky modelling serves as a valuable tool in optimizing these parameters, ensuring energy-efficient, comfortable, and sustainable built environments. By integrating daylighting strategies informed by sky modelling, built environment in India can be designed to promote a healthier and more stimulating indoor environment.

Data collection and Processing systems

There is a notable lack of measurement data on diffused sky irradiance, illumination, direct solar radiation, and global radiation. This study focuses on the sky dome in India, where luminance and radiance data of the sky were captured using a scanner. The collected data was then compared to a room modeled with daylight exposure, using the measured Sky types as per CIE Sky model to the actual indoor illuminance (lux) measurements and simulated indoor illuminance (lux) levels. To acquire data for indoor space, a specific analytical methodology was developed for unique measurement systems, a state-of-the-art 15-sensor Illuminance sensor network. The focus of the study also revolves around development of analytical frameworks that respect the distinct characteristics of each dataset while effectively addressing the complexities of big data management. The innovative methodology paves the way for a deeper understanding of indoor illuminance levels and the intricate patterns of sky dome luminance and radiance distribution, thereby providing valuable insights that can significantly enhance the simulation outputs, with the inclusion of real-time measurement data inputs.

The rapid advancement of environmental sensing technologies has resulted in an immense volume of data, presenting both remarkable opportunities and considerable challenges. This study examines two complementary luminance monitoring systems: the Skyscanner, which generates approximately 35,00,000 data points yearly, and the indoor Illuminance sensor network, which accumulates around 1,29,000 points annually. Each system offers distinct insights where the Skyscanner excels in characterizing external sky conditions with exceptional directional accuracy, while the Illuminance network effectively captures the subtleties of internal light distribution.

Despite the strengths, both systems face data quality challenges, including missing values and measurement inconsistencies, although these issues manifest differently within each framework. The research also aims to develop comprehensive data handling approaches that apply universal principles while accommodating each system's specific requirements. This holistic approach addresses the entire data lifecycle, from meticulous collection to insightful analysis, ensuring that we derive meaningful and actionable insights from the vast amounts of data produced.

Methodology

The sky luminance model evaluation is based on the measured luminance data collected in Chennai and Gurugram, India from November 2023 to October 2024. Statistical methods will be further used to identify which subset of the CIE standard general skies is the best fit to describe the daylight climate in Chennai. Comparative, correlation and predictive analysis methodology will be used to analyse the dataset.

The detailed methodology chart for the study is showcased in the below Figure 1.

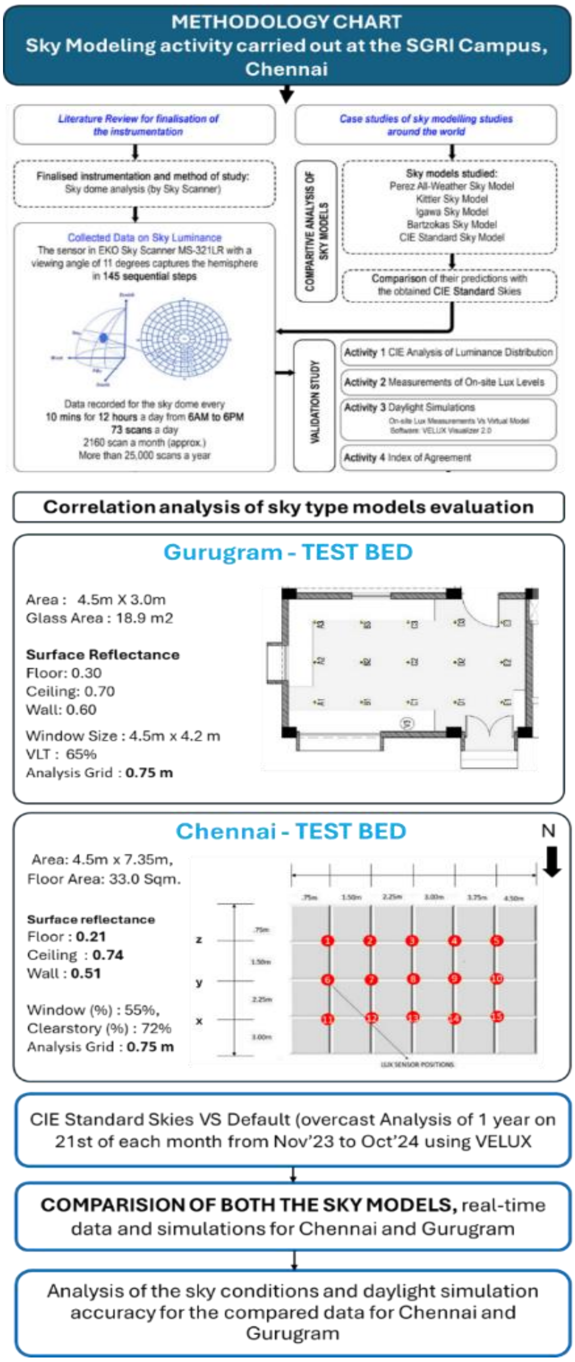

Figure 1 Methodology chart for the study.

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Data Collection Systems and Measurements

The Skyscanner

The Skyscanner analysis plays a crucial role in understanding atmospheric dynamics by focusing on characterizing directional light patterns and classifying various sky conditions.

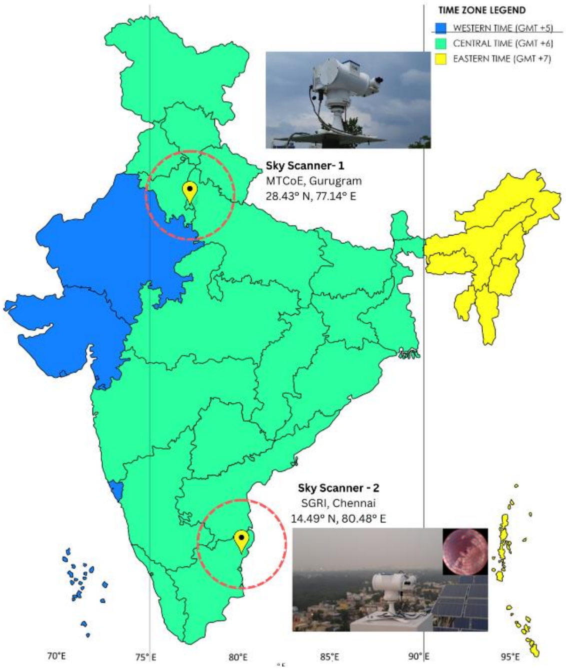


Figure 2 Location of sky scanners in India

Figure 3 Scanner installed in Chennai.

Data is collected using a sophisticated 145-patch structure every 10 minutes over a continuous 12-hour monitoring period each day. This results in 72 luminance and radiance scans per day. The hemisphere is captured by the sensor in 145 successive steps, each with a viewing angle of 11 degrees. Each scan consists of 145 readings, following the pattern recommended by the CIE, and takes approximately 2 seconds to complete a reading. The scanning range is about 100 meters in radius, and the sensor is mounted on a two-axis tracker positioner.

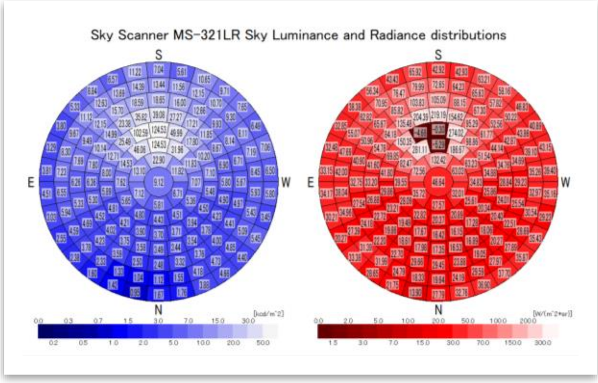


Figure 4 Illuminance and Radiance data recorded by scanner

The measurements are based on the International Daylight Measurement Program (IDMP) and adhere to the CIE 108-1994 guidelines. Brightness and radiance values are expressed in kcd/m² and W/m²/sr, respectively. This comprehensive collection process enables a detailed spatial analysis of luminance and radiance distribution, allowing for the accurate identification of predominant sky conditions (Igawa, 2001). Additionally, it facilitates the classification of these measurements according to established standardized sky types, providing deeper insights into the interactions between daylight and atmospheric conditions, such as cloud cover and sun position.

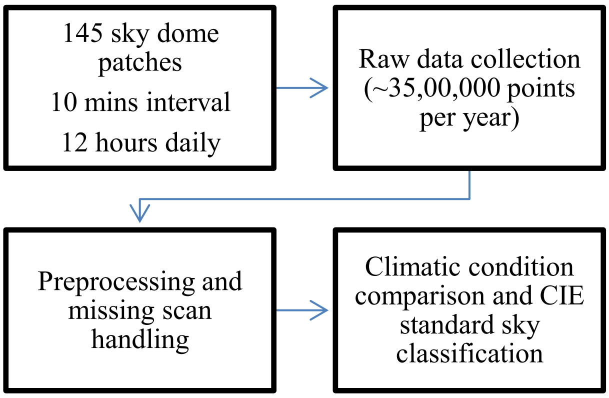
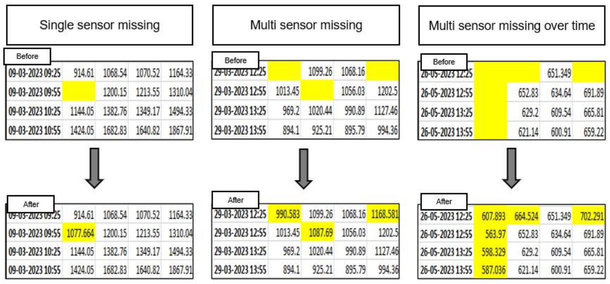


Figure 5 Skyscanner System Data Flow

Data Post-Processing Techniques

In this big data collection process, significant challenges emerge that fundamentally compromise the dataset's usability, particularly the presence of persistent data gaps. These challenges arise from multifaceted sources, including sensor malfunction, communication infrastructure failures, and environmental interferences that interrupt continuous data collection. The methodology establishes baseline relationships which serves as a foundation for formulating transformation procedures. These procedures are crucial for adjusting measurements, thereby ensuring that the data we analyse accurately reflects the real-world conditions it aims to represent.

The proposed methodology presents an innovative approach to data reconstruction by capturing the complex interrelationships between datasets. By analyzing light readings within comparable timeframes, the algorithm produces statistically reliable estimates that maintain the original data patterns. For example, this method acknowledges that sensors within an Indoor Illuminance network that are physically close to one another are more likely to encounter similar environmental conditions, offering a more precise foundation for reconstructing missing data.



Single sensor missing

Before

09-03-2023 09:25	914.61	1068.54	1070.52	1164.33
09-03-2023 09:55		1200.15	1213.55	1310.04
09-03-2023 10:25	1144.05	1382.76	1349.17	1494.33
09-03-2023 10:55	1424.05	1682.83	1640.82	1867.91

After

09-03-2023 09:25	914.61	1068.54	1070.52	1164.33
09-03-2023 09:55	1077.664	1200.15	1213.55	1310.04
09-03-2023 10:25	1144.05	1382.76	1349.17	1494.33
09-03-2023 10:55	1424.05	1682.83	1640.82	1867.91

Multi sensor missing

Before

29-03-2023 12:25		1099.26	1068.16	
29-03-2023 12:55	1013.45		1056.03	1202.5
29-03-2023 13:25	969.2	1020.44	990.89	1127.46
29-03-2023 13:55	894.1	925.21	895.79	994.36

After

29-03-2023 12:25	990.583	1099.26	1068.16	1168.581
29-03-2023 12:55	1013.45	1087.69	1056.03	1202.5
29-03-2023 13:25	969.2	1020.44	990.89	1127.46
29-03-2023 13:55	894.1	925.21	895.79	994.36

Multi sensor missing over time

Before

26-05-2023 12:25			651.349	
26-05-2023 12:55		652.83	634.64	691.89
26-05-2023 13:25		629.2	609.54	665.81
26-05-2023 13:55		621.14	600.91	659.22

After

26-05-2023 12:25	607.893	664.524	651.349	702.291
26-05-2023 12:55	563.97	652.83	634.64	691.89
26-05-2023 13:25	598.329	629.2	609.54	665.81
26-05-2023 13:55	587.036	621.14	600.91	659.22

Figure 6 Data Imputation of indoor Illuminance network- Examples

A comprehensive validation strategy was implemented using Root Mean Square Error (RMSE) (Pan, 2015) (RUBIN, 1976) as the primary metric of accuracy. The validation process involved a deliberate artificial data removal approach, where complete data points were systematically removed from the dataset to simulate missing values. This methodology allows for a rigorous assessment of the imputation algorithm's performance by comparing the imputed values against known, original measurements. Preliminary results demonstrated the algorithm's effectiveness, with RMSE values indicating a high degree of precision in reconstructing missing data.

Validation Study

A verification of data was performed for the validation of the study where 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. In VELUX Daylight Visualizer 3.0 is a professional lighting simulation tool for analysis of daylight conditions in buildings to document and quantify daylight (Anon., 2025), the model was set up to simulate daylighting on March 21 from 900 hrs to 1800 hrs (Seth, 2022). The test bed's illumination measurements were all gathered under the local sky conditions in Chennai and Gurugram, India through a illuminance sensor.

The flow of the sub-activities for the validation study is as follows:

Activity-1 CIE Analysis of Luminance Distribution Data

The performance of each CIE standard sky luminance model was assessed for March 21, 2023, using the extracted luminance distribution data from the sky scanner equipment and further analysed using the root-mean-square errors (RMSE) The analysis method is adapted from ISO 15469:2004 (International Standardisation Organisation, 2004) (Bhalla, et al., 2022). The procedures for every measured luminance scan are assessed by an in-house excel based calculator where the inferred CIE General sky is the one with the lowest RMSE in each scan. The analysed measured CIE sky-type for half-hourly data from 900hrs to 1800hrs which is further used as an input for sky type consideration for CIE measured sky simulations as described in Activity-3.

Based on climatic sky classification using the CIE Standard General Skies, it has been observed that partly cloudy sky with solar corona, predominates in both Chennai and Delhi for most of the year. This sky type aligns with the typical high solar radiation and intermediate cloud conditions prevalent in these regions. However, during the monsoon months, there is a marked shift in sky conditions, corresponding to a uniformly overcast sky, becoming more dominant due to increased cloud cover and reduced direct solar irradiance.

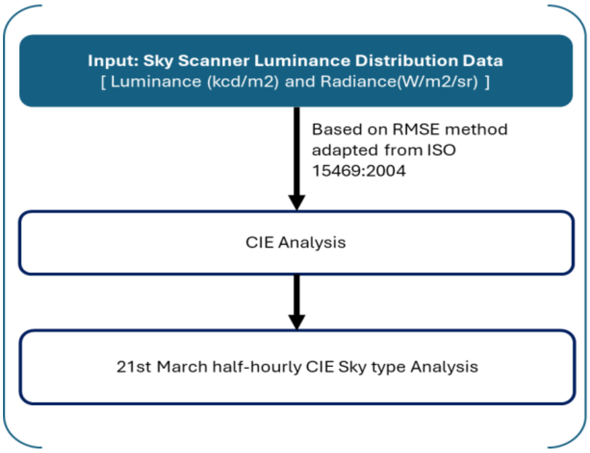


Figure 7 CIE Analysis of Luminance Distribution Data

Activity-2 Measurements of Daylight Illuminance levels

For the second activity of the study, In Gurugram, a room was selected in the 100m vicinity of the sky scanner instrument (Fig-9) at the MT CoE lab. A 5x3 grid (Fig-10) is marked in the selected room for data set points to measure the daylight illuminance levels for 21st March (900-1800 hrs) using Testo 540 - Light meter at 750mm work plane (Fig.-8). The instrument Testo 540 is calibrated once per year as per the standards and requirement.

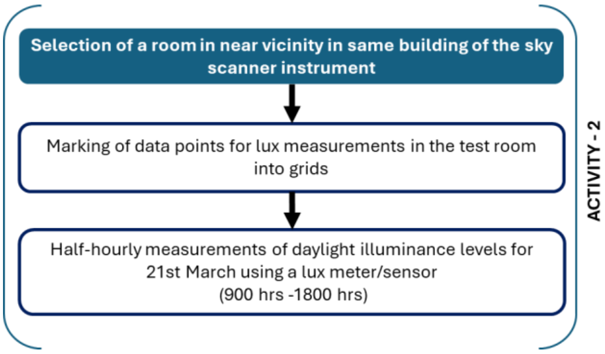


Figure 8 Daylight Illuminance Measurements

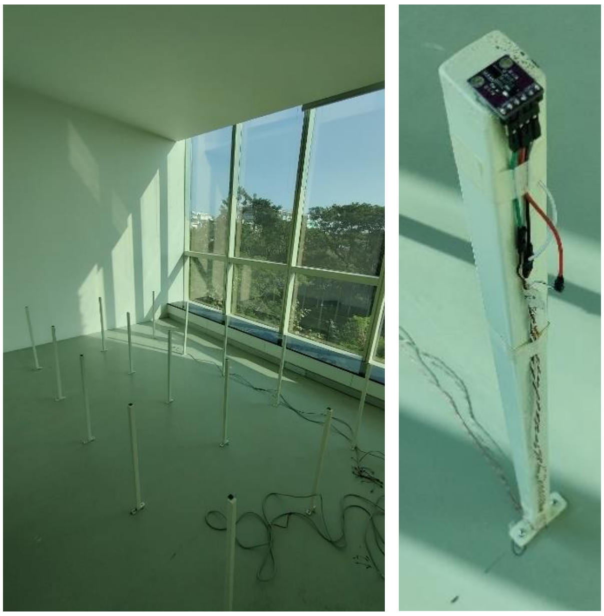


Figure 9 Measurements of illuminance levels using a Illuminance Sensor at the SGRI lab test bed

Figure 10 Measurements of illuminance levels using a Illuminance Meter at the MTCoE lab test bed.

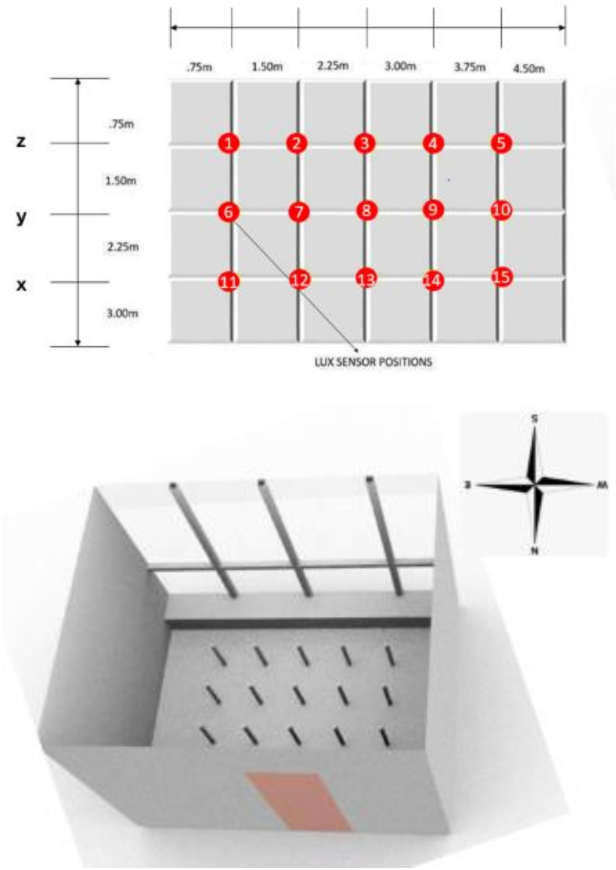


Figure 11 Data points in the selected room at SGRI facility, Chennai, Tamil Nadu.

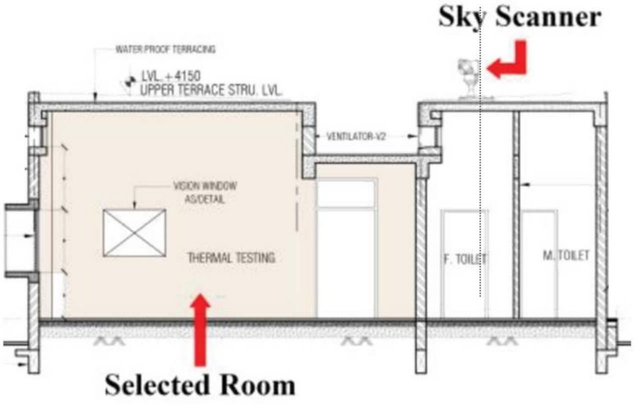


Figure 12 Placement of the Sky Scanner instrument and the selected room at MTCoE, Gurugram, Haryana

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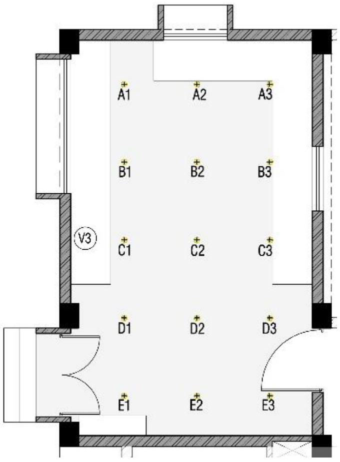

Figure 13 Data points in the selected room at MTCoE, Gurugram

In both the test beds, The data is being recorded for the Illuminance measurements on daily basis at a one-hour interval and on every 21st day of the month at a half-hour interval. This collected data set will be further used for validation purposes during the development of the plugin tool and for analysing the trends of luminance data collected from Gurugram and Chennai in India.

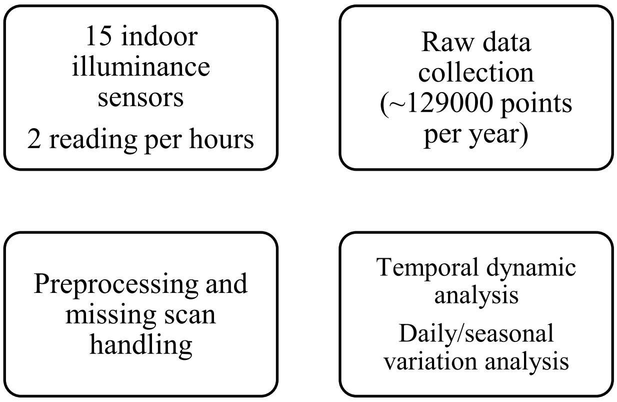

Figure 14 Indoor Illuminance sensor Network Dataflow

Activity-3 Daylight Simulations

Based on the inference from the initial study at Gurugram, Sky Modelling for the location of Gurugram (Seth, 2022) (Bhalla, et al., 2022). The daylight simulations under CIE measured sky type, a 3D Model of the chosen room at both locations (SGRI and MTCoE test bed) were created (fig 10 , 11). Illuminance (lux) for the same data points in the simulation's grid (Fig. 10) is assessed in comparison to the measured example. The simulations were carried out for the 21st of each month as part of the validation study using the VELUX daylight visualizer 3.0 software. The Run chart for the same is showcased in Figure 14.

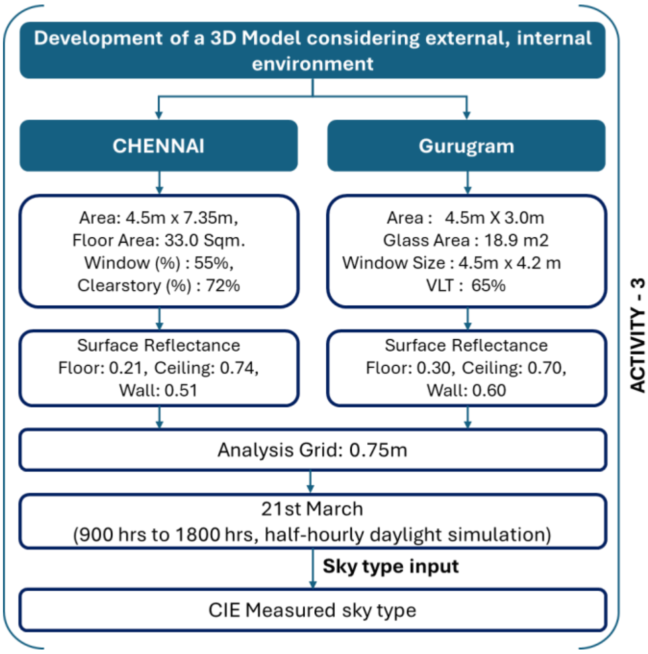

Figure 15 Run Chart for the daylight simulations

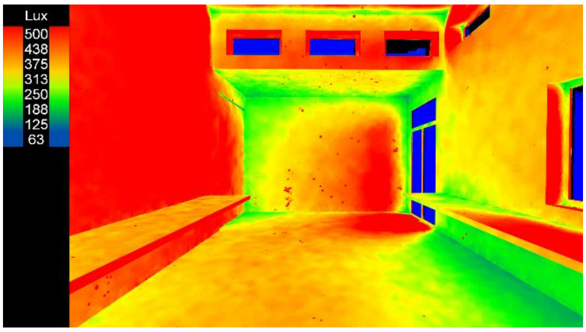

Figure 16 CIE Measured Sky Type for 21st March, 900hrs

CIE Measured Sky type daylight simulation for 21st March, 900 hrs with input sky type-12 described as Very clear/unturbid with a clear solar corona.

Activity-4 Index of Agreement

The daylight illuminance levels obtained from the second activity for actual measurements were compared with the simulated illuminance levels from the third activity. The index of Agreement method is used to assess the differences between the two cases as showcased in Figure 16.

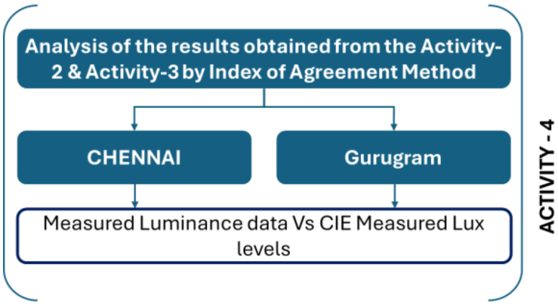

Figure 17 Analysis of the results

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This report presents an analysis of the calculated Index of Agreement for both Gurugram and Chennai based on actual sky conditions and measured illuminance levels in the test bed locations over a year. The Index of Agreement is used to assess the level of agreement between the predicted sky luminance values, derived from a specific sky model, and the actual measured values. The data collected for each month has been analysed to determine how well the sky model predictions align with real-world measurements, and the results for both cities are compared.

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 (Willmott, 1981). 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.

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

Equation 1 Index of agreement

Where Oi is the observed value and Pi is the predicted value and Obar is the average observed value.

Results

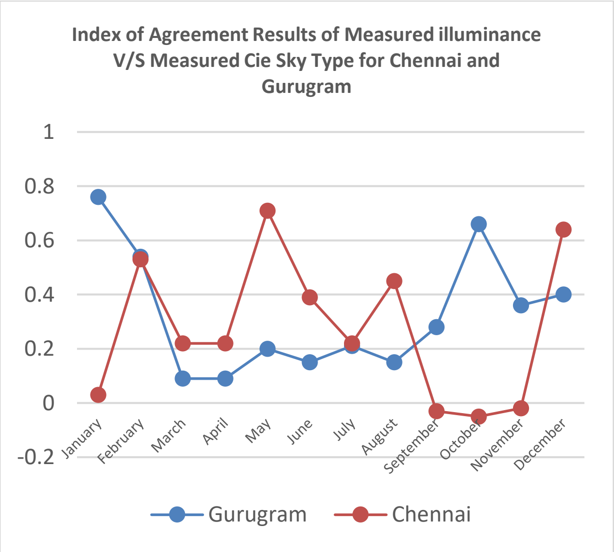

Figure 18 Index of agreement results for both locations.

Table 1 Index of Agreement Results of Measured illuminance levels V/S Measured Cie Sky Type

Index of Agreement Results of Measured Illuminance V/S Measured Cie Sky Type		
	Gurugram	**Chennai**
January	0.76	0.03
February	0.54	0.53
March	0.09	0.22
April	0.09	0.22
May	0.20	0.71
June	0.15	0.39
July	0.21	0.22
August	0.15	0.45
September	0.28	-0.03
October	0.66	-0.05
November	0.36	-0.02
December	0.40	0.64
Average	**0.32**	**0.27**

Monthly Analysis of Gurugram

In Gurugram, the Index of Agreement values exhibit a degree of variability throughout the year, reflecting fluctuations in the accuracy of the model's ability to predict actual sky luminance levels.

January showed the highest level of agreement with an Index of Agreement value of 0.76, indicating a strong alignment between the predicted and actual illuminance levels. This suggests that the sky model performed well during this month, due to stable weather conditions typical of the winter season in Gurugram, characterized by clear skies and minimal cloud cover. In February, the Index of Agreement dropped to 0.54, suggesting a moderate agreement between the model and actual measured values. This decrease can be attributed to the beginning of the transition towards the warmer months, which may introduce variations in sky conditions, such as increased cloud cover or occasional haze, affecting the model's predictions. The lowest Index of Agreement values in Gurugram were recorded in March and April, both at **0.09**. These months are transitional in nature, with rapidly changing weather conditions, such as the onset of the pre-monsoon period, which can introduce variability in sky luminance. The significant discrepancy between predicted and actual values during these months indicates that the model struggled to account for the rapid changes in sky conditions, leading to poor predictive accuracy.

May, June, July, and August show a gradual improvement in the agreement between the predicted and measured values, with the Index of Agreement ranging from 0.15 to 0.21. However, these values are still relatively low, reflecting the growing complexity of predicting sky luminance as the monsoon season approaches. The atmospheric conditions during this period are subject to

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increased humidity and sporadic cloud cover, which are difficult to model accurately. In

September, the Index of Agreement further improved to 0.28, but this value is still relatively low. The month is transitional, with unpredictable weather patterns associated with the end of the monsoon season and the return of more clear conditions, resulting in inconsistent model performance. October saw an improvement in the agreement with a value of 0.66, which is indicative of better predictive accuracy. This could be attributed to the more stable atmospheric conditions in the post-monsoon season, which are easier for the model to predict. The Index of Agreement for November and December remained moderate at 0.36 and 0.40, respectively, suggesting that while the model performed better than in the summer months, it still showed inconsistencies, possibly due to the transitioning weather patterns at the end of the year.

The average annual Index of Agreement for Gurugram stands at 0.32, indicating an overall moderate level of agreement between the predicted and actual illuminance values. The results highlight that while the model performs reasonably well during certain periods of the year, it faces challenges in accurately predicting sky luminance during transitional and monsoon months.

Monthly Analysis of Chennai

In Chennai, the Index of Agreement values show greater variability across the months, suggesting that the sky model faced more significant challenges in accurately predicting the actual sky conditions compared to Gurugram.

In January, the Index of Agreement was extremely low at 0.03, indicating a very poor fit between the predicted and actual luminance levels. This could be attributed to factors such as high humidity, cloud cover, and atmospheric disturbances that are common during the early months of the year in Chennai, which the model was unable to capture accurately. In February a moderate improvement with a Index of Agreement value of 0.53, showing that the model was better able to predict sky conditions during this time, though still demonstrating notable discrepancies in its predictions. In March and April, the Index of Agreement remained relatively low at 0.22 for both months. The poor performance could be attributed to Chennai's tropical climate, which often experiences high levels of humidity, cloud cover, and atmospheric instability. These factors can complicate sky luminance prediction models, leading to discrepancies in predicted and actual illuminance levels. May exhibited a notable improvement with an Index of Agreement value of 0.71, indicating that the model performed relatively better during this period. This could be due to the more consistent atmospheric conditions that typically prevail before the onset of the monsoon season, which the model can more accurately predict. In the months of June, July, and August experienced moderate levels of agreement, with the Index of Agreement ranging from 0.39 to 0.45. These months are marked by the monsoon season in Chennai, which introduces greater variability in sky conditions due to frequent rainfall and cloud cover. The model's moderate performance during these months reflects the challenges of accurately predicting sky luminance during such dynamic conditions. September saw a slight decline in the Index of Agreement to -0.03, indicating that the model was unable to predict the sky luminance effectively during this transitional period when the monsoon season was ending, and the weather was highly variable. October showed a similar poor performance with an Index of Agreement value of -0.05, highlighting the difficulties the model faces in predicting sky conditions during the post-monsoon months, which are typically marked by high humidity and varying cloud cover. November saw a slight improvement with an Index of Agreement value of -0.02, which is still below the acceptable threshold for accurate sky modelling. December performed comparatively better, with an Index of Agreement value of 0.64, indicating that the model was more accurate in predicting sky luminance towards the end of the year when the weather was generally clearer and more stable.

The average annual Index of Agreement for Chennai stands at 0.27, indicating a relatively low overall agreement between the predicted and actual illuminance levels. This reflects the significant challenges posed by Chennai's tropical climate, particularly during the monsoon season, when cloud cover and humidity can drastically alter sky conditions.

Discussions

When comparing the Index of Agreement values of Gurugram and Chennai, it is evident that the model performed more consistently and with higher accuracy in Gurugram than in Chennai. While Gurugram showed relatively better alignment with actual illuminance values, especially in January, October, and December, Chennai experienced greater fluctuations in agreement, with several months showing negative or very low values, particularly during the monsoon season.

The lower Index of Agreement in Chennai highlights the difficulties of accurately predicting sky luminance in regions with a tropical climate, where high humidity, frequent cloud cover, and the monsoon season significantly impact sky conditions. In contrast, Gurugram, with its more temperate climate, showed relatively higher and more consistent agreement between predicted and actual illuminance levels.

The present study evaluates the classification of sky types in two climatically distinct Indian cities—Chennai and Gurugram—by applying a methodology adapted from ISO 15469:2004, which outlines the standard procedure for modeling the spatial distribution of daylight. This method has been widely recognized for its relevance in

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architectural daylighting simulations and climate-responsive design.

In 2024, the International Commission on Illumination (CIE), through its Technical Committee 3-15 on Spatial Distribution of Daylight, in collaboration with ISO Technical Committee ISO/TC 274 on Light and Lighting, introduced a revised draft standard—ISO/CIE DIS 15469:2024(en). This updated version redefines the approach to calculating sky luminance distributions by integrating improved classification techniques and more accurate angular luminance profiles. These enhancements are intended to address the limitations of earlier models, particularly in capturing the dynamic and region-specific nature of daylight conditions. The revised standard offers a more robust framework for use in daylighting design procedures and simulation tools, making it highly relevant for evaluating sky conditions in diverse climatic zones such as those observed in Chennai and Gurugram (International Commission on Illumination, 2024).

By utilizing this updated methodology, the study aims to provide more reliable inputs for climate-responsive design and simulation practices in the Indian context, where standard sky models may not adequately represent localized atmospheric variability.

Conclusion

In conclusion, this analysis reveals the varying performance of the sky model in predicting luminance levels for Gurugram and Chennai. The model demonstrated better accuracy in Gurugram, particularly during stable weather periods, with a moderate average Index of Agreement (IoA) of 0.32.

Conversely, Chennai's tropical climate, characterized by high humidity and seasonal variability, presented significant challenges, resulting in a lower average IoA of 0.27. These findings highlight the necessity for refining modeling techniques to better capture the dynamic atmospheric conditions, particularly in regions with highly variable weather patterns.

Furthermore, the development of plug-in tools for daylight simulation, incorporating real-time luminance data, could enhance the model's accuracy and correlation with actual conditions. This would provide designers with the necessary insights to make informed decisions regarding the optimization of window-to-wall ratios (WWR) and the selection of appropriate glazing solutions, ultimately contributing to energy efficiency and visual comfort in building design.

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