The influence of latitude and sky conditions on daylight harvesting in buildings

A influência da latitude e das condições do céu no aproveitamento da luz natural

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Abstract

The potential of daylight harvesting is related to the building location. However, climatic zonings adopted by energy efficiency programs focus only on the thermal performance, neglecting important variables of the buildings' luminous performance. This paper aims to investigate the relationship between the angle of solar incidence, the annual occurrence of clear sky, and the annual lighting energy consumption when daylight harvesting is practiced. The lighting consumption of a square floor space, orientated in the cardinal directions, was simulated for 20 Brazilian cities. The frequency of the 15 CIE sky types was determined for each city using weather files and the angle of solar incidence was calculated for each hour of the year. The analysis comprised graphical exploration, Pearson's correlation, and multiple regression. The sensitivity of the consumption to the other two variables could be perceived in the hourly but not the annual analysis. The correlation between annual consumption and latitude was more robust for the intertropical range, with increased consumption moving south, and varied significantly for each orientation. It was concluded that, although relevant, the variables are not representative of variations in annual lighting consumption for application in climate zoning.

keywords: Daylight. Energy efficiency. Buildings location. Climate. Latitude.

Resumo

O aproveitamento da luz natural está relacionado à localização do edifício. Tadavia, os zoneamentos climáticos dos programas de eficiência energética focam no desempenho térmico, negligenciando importantes variáveis do desempenho luminoso das edificações. Este trabalho objetivou investigar a relação entre o ângulo de incidência solar, a ocorrência anual de céu claro e o consumo anual de iluminação, considerando o aproveitamento da luz natural. Simulou-se o consumo de iluminação de um ambiente quadrado, orientado aos pontos cardeais, para 20 cidades brasileiras. Determinou-se a frequência dos 15 tipos de céu CIE para cada cidade, usando-se arquivos climáticos, e calculou-se o ângulo de incidência solar para cada hora do ano. A análise compreendeu exploração gráfica, correlação de Pearson e regressão múltipla. A sensibilidade do consumo às outras duas variáveis pode ser percebida na análise horária, mas não na anual. A correlação entre consumo anual e latitude foi mais robusta para a faixa intertropical, com o consumo aumentando para o sul, e variando significativamente para cada orientação. Concluiu-se que, embora relevantes, as variáveis não são representativas das variações de consumo anual de iluminação para aplicação em zoneamentos climáticos.

Palavras-chave*: Iluminação natural. Eficiência energética. Localização do edifício. Clima. Latitutde.*

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Introduction

Buildings' daylighting performance is directly related to the local climatic conditions. The relative sunshine duration, the cloud type and cover, and turbidity factors are some aspects that interfere with the availability of daylight (KITTLER; RUCK, 1984). Moreover, the characteristics of the site location and the immediate surroundings define daylight accessibility. Lastly, the buildings' features determine the daylight harvesting potential.

One of the complexities to predict daylight availability is its dynamic condition. In this context, climate-based daylight modelling (CBDM) predicts any amount of daylight expressed as luminance and/or illuminance, considering realistic sun and sky conditions derived from standardized climate data (MARDALJEVIC, 2000; REINHART; HERKEL, 2000). Evaluations based on CBDM are generally carried out for the entire year, with an interval of an hour or less, to capture the daylight's daily and seasonal dynamics (MARDALJEVIC; CHRISTOFFERSEN, 2017). CBDM application embraces daylight metrics of human comfort and energy impact (HESCHONG, 2012). The most popular CBDM metrics are based on a target illuminance with a time (a certain fraction of the operating hours per year) and space (the area in that both illuminance and time targets are reached) approach, such as spatial daylight autonomy (sDA) and sunlight beam index (SBI) (ILLUMINATING…, 2012; DARULA; CHRISTOFFERSEN; MALIKOVA, 2015; MARDALJEVIC; ROY, 2016).

Concerning the energy impact, the influence on the penetration depth of daylight is considered for the sensor placement guidelines and for setting the lighting fixtures under their control in the lighting project. The arrangement of these fixtures grouped under sensors' control is important for the system's energy efficiency as it can strongly affect the potential for savings. Parise, Martirano, and Parise (2016) showed a variation of up to 50% in the lighting consumption when trying out different lighting scenarios for the same indoor space, varying only the control switching mode and the arrangements of the light controls due to daylighting.

Therefore, for both area-based CBDM and energy impact, it is not relevant how much the illuminance surpasses its target, but the percentage of time along with the percentage of area for which this occurs. Thus, even if a site offers abundant daylight, if indoor space is not favourable to the angle of solar incidence, its illuminated area may be smaller than that of a space whose availability of natural light is less, but where the light reaches greater depth. This happens as long as the target illuminance is reached. As the daylight penetration depth depends on the angle of incidence of direct solar radiation, the frequency of clear sky assumes importance in the characterization of the daylit zone.

The angle of solar incidence happens because of the latitude, the azimuth, and the time of the day. However, latitude is inherent to the buildings' location and impacts the daylighting performance affecting the daylit zone size, the daylight provision measures, exposure to sunlight, and glare. Due to this relevance, standards such as BREEAM[1] (BUILDING…, 2013) and BS EN 17037[2] (EUROPEAN..., 2018) have specific guidelines for buildings located at different latitudes. Since daylight metrics are often assessed by certifications and codes worldwide, it is important to adapt the daylight metrics to each location, considering latitude and the local climate (ILLUMINATING…, 2012; EUROPEAN…, 2018; MARDALJEVIC; CHRISTOFFERSEN, 2017; U.S. GREEN…, 2019; INTERNATIONAL…, 2020). In this respect, latitude is a relevant parameter to be considered when establishing climatic zoning, a key element for the conception of policies and regulations that aim to ensure good energy efficiency and quality of buildings.

Brazil has an enormous territory, with latitudes ranging between 3.8441°N and 33.68°S. The current Brazilian bioclimatic zoning covers only the thermal performance of buildings (ABNT, 2005). Aiming to fill the gap regarding daylight performance, Pereira, Schmitt, and Moraes (2015) proposed climatic zoning based on diffuse daylight illuminance, as seen in Figure 1a. The proposal consists of two zones[3] based on the similarity of the profiles of histograms for the cumulative frequency of occurrence of external diffuse horizontal illuminance. The database used originates from weather files EPW[4]-INMET[5]-2012 related to 181 sites. Aiming to include the direct sunlight component in this zoning, Fonseca, Fernandes, and Pereira (2017) proposed a new territory subdivision, shown in Figure 1b. For this subdivision, four databases were used: the

[1]Building Research Establishment (BREEAM).

[2]EN 17037:2018 - Daylight in buildings.

[3]The average profile of the cumulative frequency of occurrence histograms representative of Zone I adopts the overcoming of the external illuminance of 30,000 lx as a reference in 50% of the working hours throughout the year. Nevertheless, the average profile representative of Zone II exceeds the same illuminance in 30% of the period.

[4]EnergyPlus Weather File (EPW).

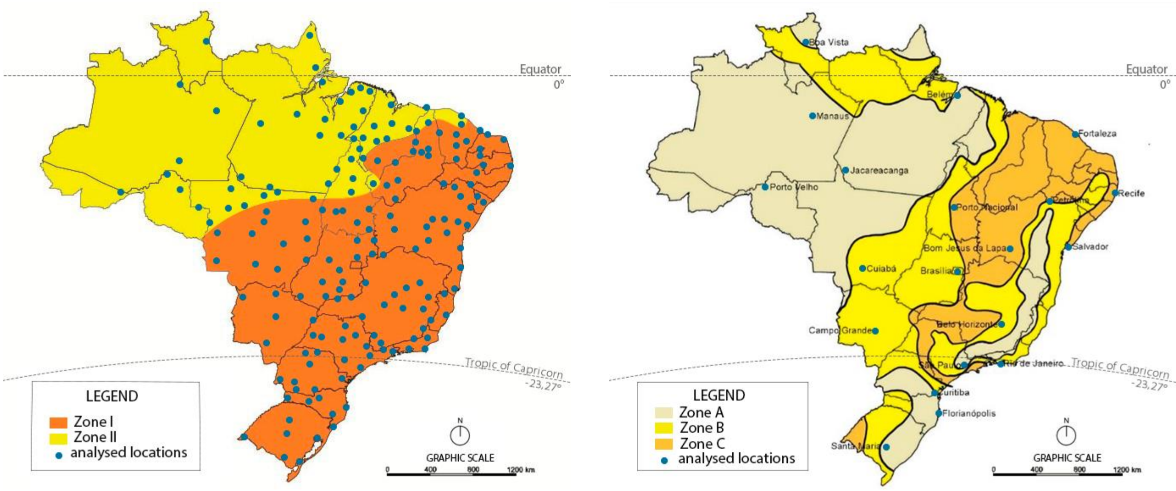
[5]National Institute of Meteorology [Instituto Nacional de Meteorologia] (INMET).

climatic zoning of diffuse daylight illuminance (PEREIRA; SCHMITT; MORAES, 2015); contour maps of two Brazilian solarimetric atlases (TIBA *et al*., 2000; PEREIRA *et al*., 2006); and weather files of the type EPW-SWERA[6] for 20 sites (UNITED…, 2017). The three resulting zones[7] combine an analysis of the number of daily sun hours and profiles of histograms for the cumulative frequency of occurrence of horizontal external global illuminance and cloudiness.

However, the Brazilian climatic zoning based on daylight availability presented limitations concerning the lighting energy performance estimation (FONSECA, 2017). In some cases, estimates for the same building resulted in higher consumption when it was in a city with greater daylight availability than when it was located in another one with less availability. This trend was observed for determined orientations and between cities with a wide variation of latitude; for instance, facing north, comparing the city of Curitiba (25.4809° S), located in Zone A, with lower daylight availability, with the city of Salvador (12.9777° S), located in Zone C, with higher daylight availability (as shown in Figure 1b). Analysis of the annual cumulative global radiation incident in a hemisphere of unitary radius and point-in-time analysis of illuminance distributed in the work plane of a hypothetical indoor space confirmed higher daylight penetration in the southernmost city, considering specific orientations and dates, even if that city has lower daylight availability, according to the zoning (FONSECA *et al*., 2019).

The shortcoming pointed out during the climatic zoning application highlights the importance of considering the performance variable to which the zoning will be used during its conception. Traditionally, zoning is based on climatic, geographic variables, and administrative divisions with no consensus on the techniques to be used (WALSH; CÓSTOLA; LABAKI, 2017). As a result of an extensive review of the climatic zoning methodologies applied in energy efficiency programs in 54 countries, Walsh, Cóstola, and Labaki (2017) recommended a combination of simulating building performance and cluster analysis as the only tool that is sufficiently robust for the characterization of the relationship between climate and performance. These authors proposed a quality index and a procedure to support the validation of climatic zoning aimed at building energy efficiency (WALSH; CÓSTOLA; LABAKI, 2018).

Figure 1 – **Maps showing bioclimatic zoning based on daylight**



(a) Climatic zoning of Brazil based on diffuse daylight illuminance (PEREIRA; SCHMITT; MORAES, 2015)

(b) Climatic zoning of Brazil based on daylight availability (FONSECA; FERNANDES; PEREIRA, 2017)

[6]Solar and Wind Energy Resource Assessment (SWERA).

[7]Zone A - Daily average insolation: approx. 5 h/day. Global horizontal illuminance: less than 48,000 lx - occurrence between 1,800 h to 2,500 h / yr.; and greater than 84,000 lx - between 400 h and 600 h /yr. Cloudiness: from 0 to 3 parts of the sky covered - occurrence between 400h and 1,000 h /yr.; and 8 to 10 sky parts covered - between 2,000 h and 2,500 h /yr. Zone B - Daily average insolation: approx. 6 h/day. Global horizontal illuminance: less than 48,000 lx - occurrence between 1,500 h to 2,400 h / yr.; and greater than 84,000 lx - between 400 h and 900 h /yr. Cloudiness: from 0 to 3 parts of the sky covered - occurrence between 100 and 1,500 h /yr.; and 8 to 10 sky parts covered - between 1,400 h and 2,800 h /yr. Zone C - Daily average insolation: approx. 7 h/day. Global horizontal illuminance: less than 48,000 lx - occurrence between 1,400 h to 1,700 h / yr.; and greater than 84,000 lx - between 800 h and 1000 h /yr. Cloudiness: from 0 to 3 parts of the sky covered - occurrence between 400 and 1,600 h /yr.; and 8 to 10 sky parts covered - between 1,000 h and 1,400 h /yr.

Thus, characterizing the influence of the key variables related to the building context that influence the building performance is fundamental. This characterization is important to help choose parameters considered in the zoning procedure, regardless of the method to be used. In the case of cluster zoning, a knowledge of the key variables would help define objects and their attributes. To contribute to this characterization, this paper aims to investigate the relationship between the angle of incidence of direct solar radiation, the annual frequency of clear sky conditions, and the lighting energy consumption when daylight harvesting is practiced. The hypothesis tested was that assuming similar clear sky conditions, places, where the incidence of solar radiation allows deeper daylight penetration inside indoor environments, would be associated with lower lighting energy consumption.

Method

The climate data adopted were obtained from weather files, which enabled the computer simulations to be carried out followed by a comparison of the consumption results with the input information associated with the daylight availability at the location. Furthermore, these data were more suitable than measured values due to the continental dimensions of Brazil and the relation sought with the annual simulation.

The method procedure involved the following steps:

(a) simulation of annual lighting energy consumption;

(b) survey on the frequency of clear sky conditions;

(c) calculation of the solar incidence angle at the façade;

(d) analysis of the relationship between the three variables (the clear sky frequency, the solar incidence angle and the percentage of lighting power used for every hour of building occupation of the year – lighting power used percentage – LPUP); and

(e) relation between the annual lighting consumption, geographic location variables, sky conditions, and daylighting sufficiency performance variables.

Simulation of annual lighting energy consumption

The annual lighting energy consumption was simulated for a hypothetical square floor space for the 20 Brazilian cities [8] (Figure 1b), as previously published by Fonseca *et al.* (2019). Besides the annual consumption, the LPUP was obtained for every hour of building occupation of the year. The simulations were carried out with the plug-in DIVA-for-Rhino (SOLEMMA LLC, 2014) (MCNEEL, R.; ASSOCIATES, 2014).

The cities selected correspond to those for which *.epw SWERA (TMY[9]) weather files (UNITED…, 2017) are available in Brazil. In addition to the SWERA weather files, at the time this study was conducted, TRY[10] (2005 or older), INMET[11] (TMY), and IWEC[12] Brazilian weather files also existed. However, the IWEC files are not available for many cities and although TRY files are available for 17 cities, the data have a higher deviation for the solar radiation concerning the Solarimetric Atlas when compared to SWERA (SCHELLER *et al*, 2015). At the time the study was carried out, the INMET weather files (LABORATÓRIO…, 2015) used constant values for cloudiness, sky opacity, visibility, and sky height, which are important to describe local daylight availability.

A model of the indoor space with a square floor plan was used (6.0 m width x 6.0 m depth) with a floor-to-ceiling height of 3.0 m, as shown in Figure 2. It has a strip window (5.8 m length x 1.0 m height) with a sill 1.1 m from the floor. This configuration resulted in a window-to-floor ratio (WFR) of 16.11% and a window-to-wall ratio (WWR) of 32.22%. The analysis area corresponds to the total area of the floor plan, with a height of 0.75 m about the floor. In the grid analysis, the spacing was 0.5 m both ways, keeping the same distance related to the walls. The optical properties of the surfaces are shown in Table 1. The target illuminance used was 300 lx as this is a reference value for daylight (ILLUMINATING…, 2012). The Radiance (WARD, 1994)

[8]Belém, Belo Horizonte, Boa Vista, Bom Jesus da Lapa, Brasília, Campo Grande, Cuiabá, Curitiba, Florianópolis, Fortaleza, Jacareacanga, Manaus, Petrolina, Porto Nacional, Porto Velho, Recife, Rio de Janeiro, Salvador, Santa Maria, São Paulo.

[9]Typical Meteorological Year (TMY).

[10]Test Reference Year (TRY).

[11]Instituto Nacional de Meteorologia (INMET).

[12]International Weather for Energy Calculations (IWEC).

parameters used are given in Table 2. The simulations for the 20 Brazilian cities considered the orientations of north, south, east, and west.

The period of occupation was 10 h, from 08:00 to 18:00, for all days, all year round. It was considered that an ideal linear dimming system controlled all of the lighting power installed. The control device of the electric lighting system used for the annual lighting consumption simulation was configured according to Table 3. The program adopted considers hourly readings at the point of the zone with the lowest illuminance as a reference to establish the functioning of the electric lighting system for the whole zone. No internal or external shading system was considered to capture the effect of direct solar radiation on indoor environments. Otherwise, the results regarding the relationship between the type of sky and light penetration due to the angle of incidence could lead to erroneous conclusions.

Figure 2 – **Scheme showing a 3D model of the indoor space considered in this study**

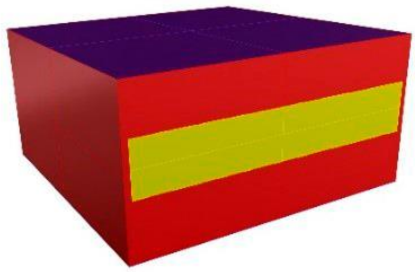


Table 1 – **Surface optical properties**

Surface	Surface properties	
	Reflectance [%]	Visible transmission [%]
Walls	50	-
Ceiling	70	-
Floor	20	-
Glass	-	88
Ground plane	0	-

Table 2 – **Radiance parameters**

Parameter	Value
Ambient bounces (ab)	5
Ambient divisions (ad)	1000
Ambient super-samples (as)	256
Ambient accuracy (aa)	0.1
Ambient resolution (ar)	300
Direct threshold	0
Sampling threshold	0

Table 3 – **Lighting system settings**

Operation	Dimmer with occupancy sensor on/off
Lighting power (W):	250
Target illuminance “setpoint” (lx):	300
Ballast loss factor (%):	20
Standby power (W):	0

The results were evaluated considering each orientation individually and grouped; the latter condition is called global performance. The global performance was obtained through the sum of the lighting energy consumption from the four different orientations. The lighting energy consumption results were considered as a function of the latitude of the location, including correlation analysis. Due to the continental dimensions of Brazil, the correlation analysis was also carried out for different ranges of latitude. Three groups were created, and the latitude coordinates were converted into decimal degrees, dividing the territory into 3 proportional ranges. The northern limit was the Oiapoque at a latitude of 3.84°N, and the southern limit was the Chuí, at 33.68°S. Thus, the following three groups were obtained: Group 1 [3.84° to -8.66°], Group 2 [-8.67° to -21.17°], and Group 3 [-21.18° to -33.68°].

Survey on the frequency of clear sky conditions

The software APOLUX IV (CLARO, 2017) was used to determine the frequency of clear sky conditions. It was adopted the International Commission on Illumination (CIE) sky type classification published by ISO 15469[13] (INTERNATIONAL…, 2004). According to Claro (2015), the determination of the hourly annual frequency of 15 types of sky ISO 15469 (INTERNATIONAL…, 2004) is carried out based on the data obtained from weather files and derived through the application of the formulas presented by Perez *et al.* (1990). The data spreadsheets generated by the program provide information on the solar azimuth, the height of the solar angle, atmosphere clouding, the relative optical air mass, the sky category ISO 15469 (INTERNATIONAL…, 2004), the global horizontal illuminance, the direct horizontal illuminance, the diffuse horizontal illuminance, and the zenith illuminance. The data relating to the sky category were selected for this stage of the study.

The ISO 15469 (INTERNATIONAL…, 2004) sky categories were surveyed hour by hour, considering the time range from 08:00 to 18:00 for the 365 days of the year for the 20 cities mentioned above. Firstly, the frequency of each one of the 15 sky categories was calculated. Next, the classification was summarized to give 3 types of sky: overcast; partly cloudy; and clear. Considering the categories detailed in ISO 15469 (INTERNATIONAL…, 2004), 'overcast sky' includes the sky categories 1 to 5, 'partly cloudy sky' includes 6 to 10, and 'clear sky' includes 11 to 15. The results obtained for the frequency of the three sky types ISO 15469 (INTERNATIONAL…, 2004) were evaluated concerning the latitude and the simulation data for consumption.

Calculation of the solar incidence angle at the façade

The data used to calculate the angle of incidence of direct solar radiation were obtained from the software APOLUX (CLARO, 2015). As described in Section Survey on the frequency of clear sky conditions the spreadsheets generated by the program provide information on the solar azimuth and the height of the solar angle. The data on these variables were selected for each day of the year. The angle of incidence of the direct solar radiation in the façade (vertical plane) was calculated for each hour throughout the year for the 20 cities according to Equation 1.

$$\beta = arccos\ [cos\gamma . cos\ |\alpha - \alpha_p|] \quad \text{Eq. 1}$$

where:

β= solar incidence angle [°];

γ= solar angle height [°];

α = solar azimuth [°]; and

α_p= wall azimuth [°].

The angles of solar incidence at the façade were calculated for orientations in the directions north, east, south, and west, considering the following azimuth angles of the façade: 0°, 90°, 180°, and 270°, respectively. The results were filtered to correspond to the period of occupation (from 08:00 to 18:00). The data referring to the hours of the day when the angle of incidence was higher than 90º (solar position behind the reference façade) were discarded.

[13]ISO 15469:2004: CIE standard general sky.

Analysis of the relationship between the three variables

In this stage, the lighting energy consumption was addressed through the lighting power used percentage (LPUP) for each hour throughout the year, to observe the daylight potential regardless of the technology used by the lighting system. The hourly data for the LPUP were obtained through computer simulations, as described in the section Simulation of annual lighting energy consumption. The computer program DIVA-for-Rhino (SOLEMMA LLC, 2014) generates a file with the hourly profile for the operation of electric lighting as a function of daylight performance. This file informs the percentage of power used for each hour, respecting the previously selected type of lighting control, occupancy profile, and target illuminance. Besides these factors, the standby power and ballast loss factor are also considered.

The first analyses comprised only a graphical exploration of the data. The analysis of the relationship between the clear sky frequency, the angle of incidence of the direct solar radiation, and the LPUP was carried out using visual analysis of dispersion graphs (3D and 4D). The graphs, generated in MatLab software, were based on annual hourly information on the three variables. Then, simple correlation graphs and the Pearson correlation coefficient were also obtained, plotting LPUP against each of the three variables: the sky type ISO-CIE; the angle of solar incidence; and the latitude. The statistical hypothesis test adopted for the causality test was a t-test with significance $\rho = 5\%$. The evaluation considered the angle of solar incidence, the type of sky ISO 15469 (INTERNATIONAL…, 2004), and the latitude as independent variables, and the LPUP as a dependent variable. A global analysis was carried out considering all of the data related to the 20 cities.

Relation between the annual lighting energy consumption, geographic location variables, sky conditions, and daylighting sufficiency performance variables

The relation between the annual lighting consumption and other variables was evaluated statistically by Pearson's correlation and through multiple regression (linear and exponential) using the computer program Excel. The analysis was carried out considering the following groups:

(a) the annual lighting consumption, the latitude, the frequency of clear sky conditions, and the climatic zoning of Brazil based on diffuse daylight illuminance (PEREIRA; SCHMITT; MORAES, 2015);

(b) the annual lighting consumption, the latitude, the orientation, and the frequency of clear sky conditions; and

(c) the annual lighting consumption and that for each orientation with the daylight sufficiency metrics: sDA, DA_{mean}, and DA_{median}.

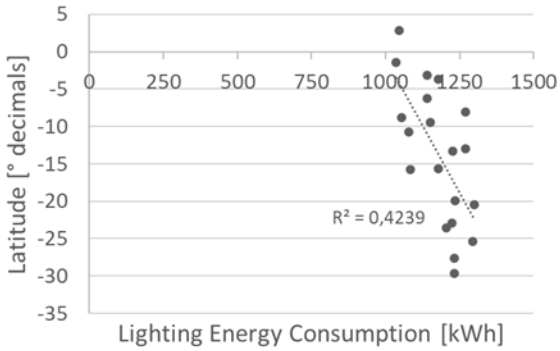
For the indicators of the performance of daylight sufficiency, three variations of the concept of daylight autonomy (DA) were considered. The analysis of these three indicators was included to verify the feasibility of expanding the lighting consumption climatic zoning scope for daylighting sufficiency evaluation. This extension would be useful as these indicators are being quoted to be included in Brazilian standards for building performance.

The first performance indicator was spatial daylight autonomy ($sDA_{300lx,50\%}$), which represents the percentage of the analysis area (in this case, the entire space of Figure 2) that reaches 300 lx during at least 50% of the annual operating hours of the building. The second indicator was the mean daylight autonomy (DAmean, 300lx), representing the arithmetic average of values for daylight autonomy, considering all grid points in the analysis area. The third indicator was the median daylight autonomy (DAmedian, 300lx) characterized by the daylight autonomy value which divides the set of results in half. In this case, the set of results corresponds to the entire grid analysis area.

Results and discussion

A total of 100 annual daylight simulations of the adopted indoor space were carried out. This section reports the results and presents a discussion of the data analysis.

Figure 3 – **Correlation between latitude and lighting energy consumption**



The annual lighting energy consumption and the latitude

The study observed cities of similar latitudes with different lighting energy consumption values and cities of very distant latitudes with similar lighting energy consumption values. It was also noticed that all the cities located south of 19ºS presented lighting consumption values higher than 1,200kWh. From those cities with latitudes north of 19ºS, only the results for Recife, Salvador, and Bom Jesus da Lapa were higher than this value. The correlation between latitude and lighting consumption resulted in a determination coefficient of 0.42 (p-value 5%), as seen in Figure 3. The inclination of the trend line presented in this graph shows the predominance of higher consumption values for the more southern latitudes.

The graph in Figure 4 shows the correlation between lighting consumption and latitude, individualized by orientation. Facades south-oriented (Figure 4a) had the highest coefficient of determination (0.69), and thus the consumption most strongly influenced by the latitude was observed at this orientation. The following most affected consumption was for the west orientation (Figure 4b), with a coefficient of determination of 0.67. The consumptions for the east (Figure 4c) and north (Figure 4d) directions showed the weakest correlations with latitude, and, for the north orientation, the relation between the consumption and this variable was null. It should be observed that the period of occupation adopted (08:00 – 18:00) resulted in an asymmetry of the solar trajectory of the east and west-facing façades. These results highlighted that the effect of latitude differs for each direction. Except for the north orientation, the consumption tends to increase moving from the equator in a southern direction, which indicates that there is another parameter that has a more relevant effect than the daylight penetration associated with the incidence angle of the direct solar radiation.

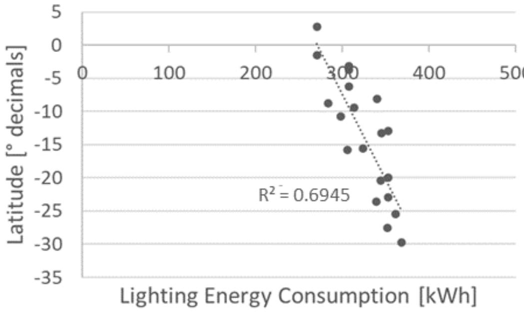
The graph in Figure 5 shows the correlation between lighting consumption and latitude for each of the three latitude groups. The coefficient of determination was higher for Group 1, followed by Group 2 and then Group 3, with values of 0.71, 0.41, and 0.02, respectively. These results show that the latitude presents a stronger correlation with consumption for locations closer to the equator. However, as the coordinates move away from the equator, the correlation between the two variables weakens, as seen by the decreasing coefficient of determination obtained for the three groups. Thus, latitude has less influence on the variation in consumption. The coefficient of determination for Group 2 (0.41) was the closest to the coefficient obtained for the overall data set (0.42), as shown in Figure 3. These results indicate that climatic zoning based on latitude is more appropriate for intertropical latitudes than for subtropical locations.

The variation in the annual lighting consumption for the 20 cities analysed was 20.24% for the global evaluation, considering the four orientations. Considering them individually, the variations were 21.70% for the north, 27.59% for the east, 26.42% for the south, and 25.73% for the west. The variation between the lowest and highest consumption considering the entire data set was 42%. The lowest consumption of 223 kWh/year was that of Boa Vista, west-facing, and the highest consumption of 386 kWh/year was observed for Campo Grande, east-facing.

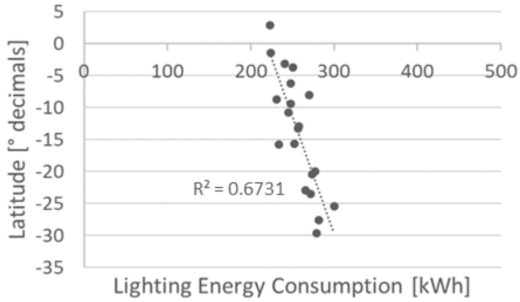
Survey on the frequency of clear sky conditions

The survey to determine the annual frequency of occurrence of clear sky conditions showed that this type of sky is predominant in all of the cities analysed, as shown in Figure 6. Except for Belém, Manaus, and Jacareacanga, all cities presented a clear sky frequency higher than 40% considering hourly data for a whole year. The three cities which are exceptions are located in the northern region of Brazil, which is characterized by a high degree of cloudiness due to the presence of the Amazon basin. They belong to the tropical zone of the Köppen classification (ALVARES *et al.*, 2013), in which Belém and Jacareacanga have a monsoon climate and Manaus has a humid tropical or equatorial climate. Manaus was the only city where the values for the frequency of clear sky and partly cloudy sky conditions were practically the same (21.00% and 21.42%, respectively).

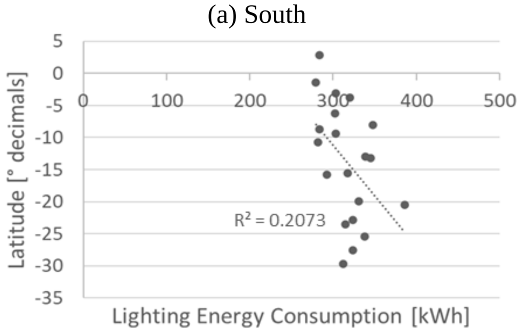
Figure 4 - **Correlation between latitude and lighting energy consumption - orientation**



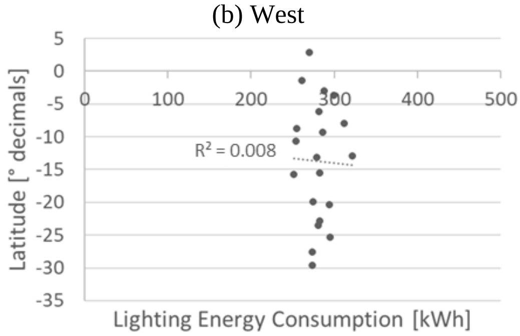
(a) South



(b) West

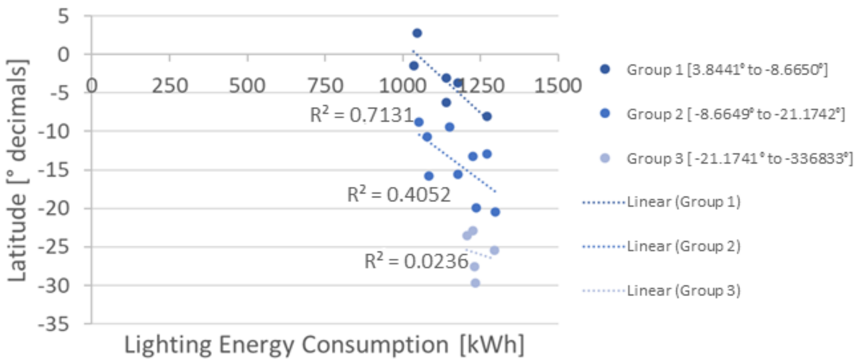


(c) East



(d) North

Figure 5 - **Correlation between latitude and lighting energy consumption - bands of latitude**



The analysis of the correlation between the clear sky frequency and latitude indicated that there is no relationship between these two variables as the coefficient of determination was 0.089. The correlation between the frequency of occurrence of the three types of sky and the lighting energy consumption indicated a positive correlation for the clear sky and a negative for the partly cloudy and overcast sky, although the correlations were weak for the three cases, as shown in Figure 7. This result highlights the limitation of assuming that in places with a high frequency of clear sky, the latitude would be expressive for determining the depth of the daylit zone in the characterization of lighting consumption.

Analysis of the relationship between the three variables

Figure 8 shows the values for the lighting power used percentage (LPUP) for each hour throughout the year when there is direct incident radiation on the façade according to the latitude, the sky type ISO 15469 (INTERNATIONAL..., 2004), and the angle of incidence of direct solar radiation. The latitude values correspond to the latitude of each of the 20 cities. In total, 109,715 points were considered. The most prevalent colour in the graph is dark blue, corresponding to LPUP in the range of 20 - 30%. It should be noted that the depth of the simulated indoor space barely exceeds the depth of daylit area established by traditional rules of thumb for windows without shading devices (i.e., 2.8 times versus 2.5 times the window head height, respectively) (CHARTERED..., 1999; REINHART; LOVERSO, 2007).

Figure 6 – **CIEs sky types occurrence**

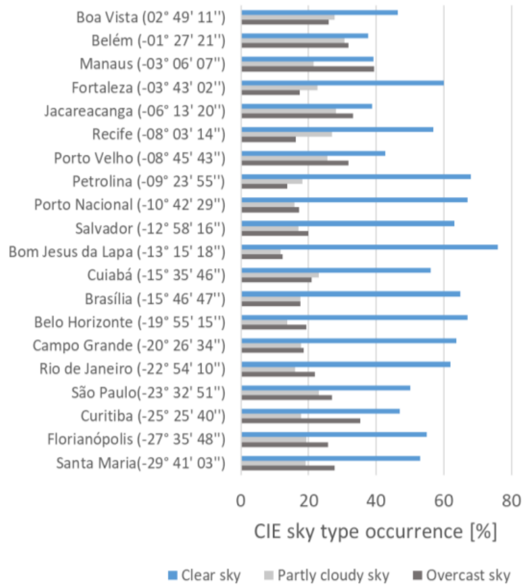


Figure 7 – **Correlation between lighting energy consumption and sky type occurrence**

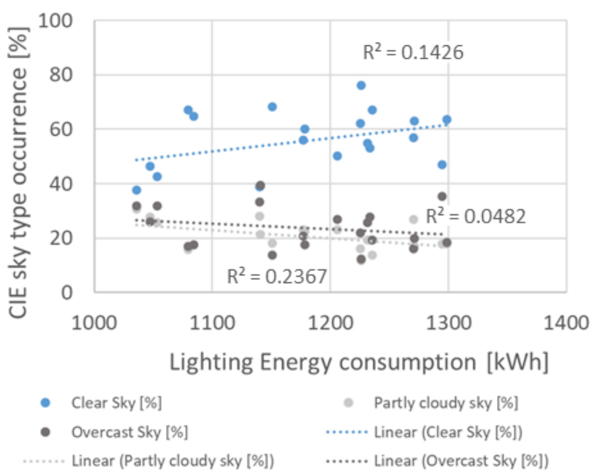


Figure 8 – **LPUL according to latitude, ISO 15469 (INTERNATIONAL…, 2004) sky type, and direct solar radiation incidence angle**

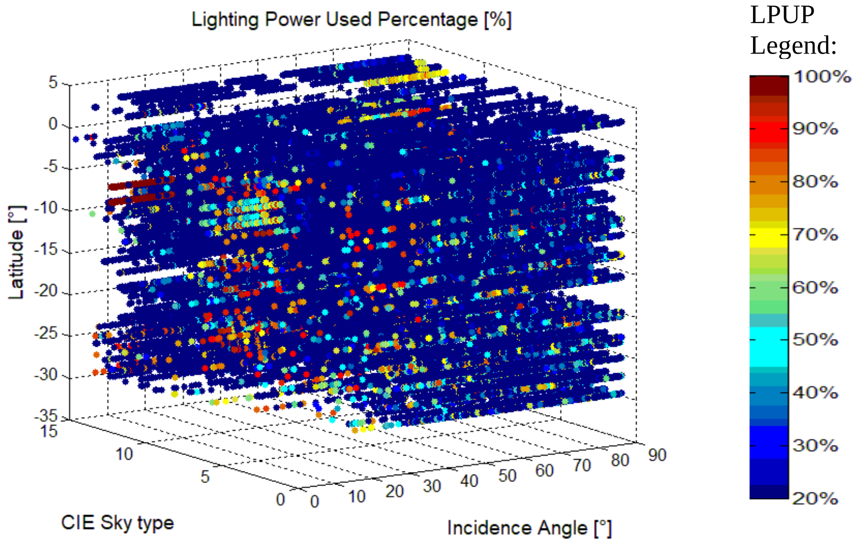


Figure 9 shows the same cases as Figure 8, excluding the null cases of LPUP. A value of 20% for the LPUP was considered a null value as it corresponds only to ballast loss. It can be noted that there are points with different LPUP magnitudes scattered across the graph. Although in a small volume given the sample size, LPUP values above 90% were observed for clear sky conditions (ISO 15469 between 10 and 15) with angles of incidence lower than 20° and higher than 80° for latitudes between 5°S and 10°S. Additionally, the graph in Figure 9 is a flattened version of the 3D graph. As we move away from the equator line toward the south, there is a greater diversity of LPUP values for all angles of incidence. Between the latitudes 0° and 20°S, this diversity is concentrated between angles of incidence of 0º and 50º. For angles above 50º, LPUP values are predominantly lower than 40% for the same latitude interval. These results highlight the effect of location in the different hemispheres on solar geometry. The only city located in the northern hemisphere, Boa Vista (2.82°N), presented very different trends compared with the other cities. For this location, it was noted that angles of incidence higher than 50° were associated with the predominance of LPUP values higher than 60%. In general, a variety of LPUP values are observed for the same angle of incidence and sky condition ISO 15469 (INTERNATIONAL…, 2004). One reason for this is that the same angle of incidence can result from different combinations of orientation, latitude, and solar position. The sky domes resulting from these combinations present distinct characteristics of luminance magnitude and distribution. The variation of the solar position acts together with different patterns of cloudiness and turbidity of the sky dome.

The results for the relation between the angle of incidence and ISO 15469 (INTERNATIONAL…, 2004) sky type seen in Figure 9 indicate that the grouping of the sky conditions (overcast, partly cloudy, and clear) to observe their influence on lighting consumption may not be appropriate. It is because the light use patterns for sky types 4, 9, and 12 differed considerably from that of their groups.

The results of the individual evaluations considering each of the independent variables and the LPUP were particularly useful for associating a variable with the maximum LPUP values. Regarding the ISO 15469 (INTERNATIONAL…, 2004) sky type, only 8 and 13 were associated with an LPUP of 100%, as shown in Figure 10. The former belongs to the partly cloudy group and the latter to the clear sky group. The lowest LPUP maximum was presented by sky 10 (approximately 80%), while sky types 3, 5, 11, 14, and 15 were limited to 90% of LPUP. It was noticed that none of the five ISO 15469 (INTERNATIONAL…, 2004) overcast sky types reached 100% LPUP, highlighting the role of the diffuse luminance of the sky dome in characterising lighting consumption.

Figure 9 – **Flattened version of the 3D graph in Figure 8**

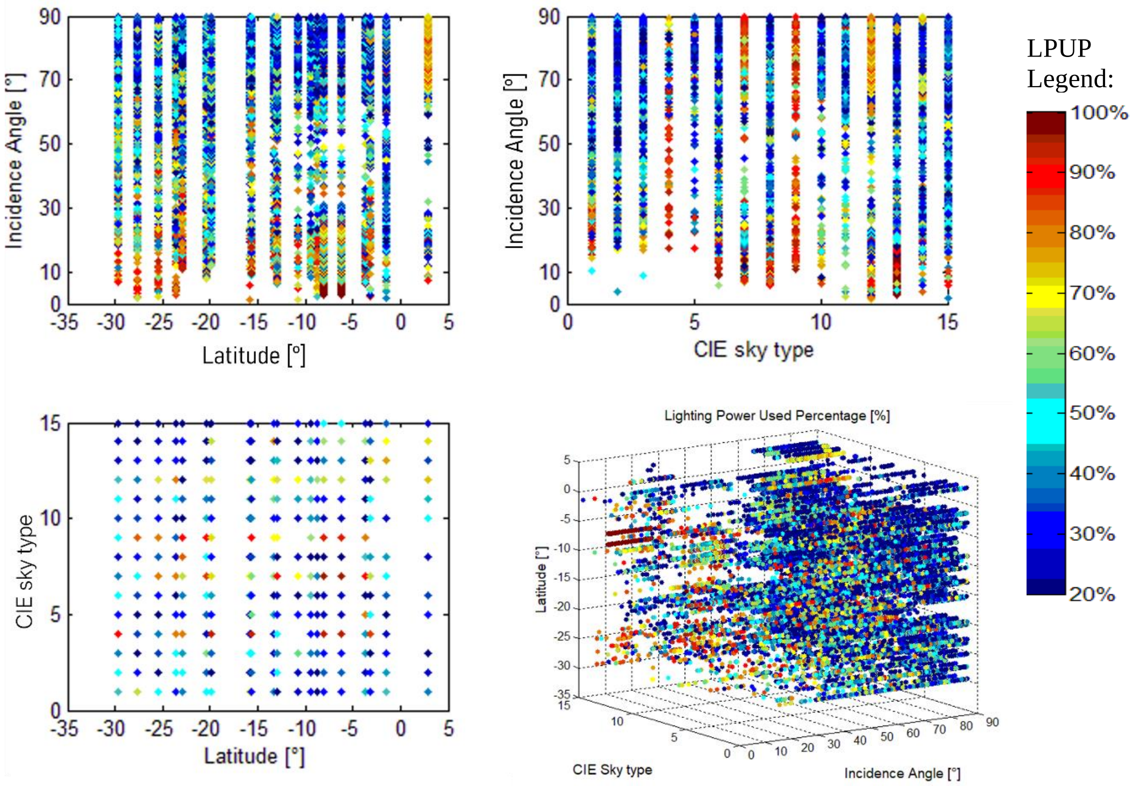
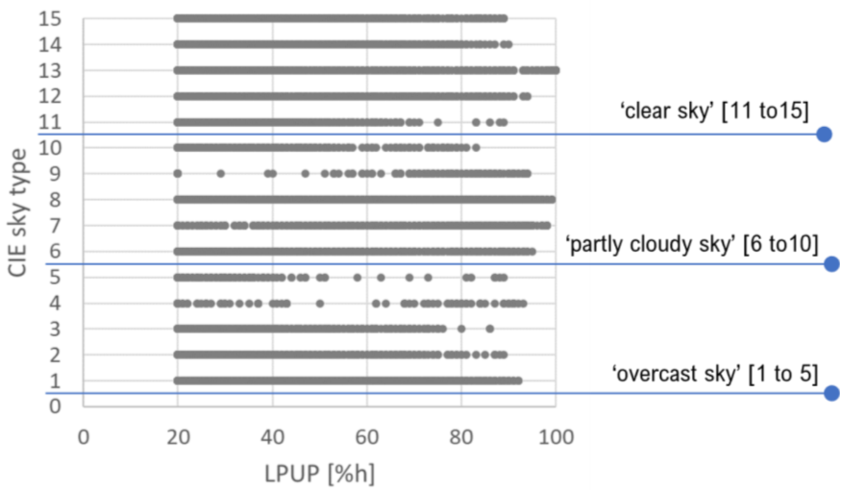


Figure 10 – **LPUP vs. ISO 15469 (INTERNATIONAL..., 2004) sky type**



Legend of ISO 15469 (INTERNATIONAL..., 2004) sky type:

1 - CIE Standard Overcast Sky, Steep luminance gradation towards the zenith, azimuthal uniformity.
2 - Overcast, with steep luminance gradation and slight brightening towards the sun.
3 - Overcast, moderately graded with azimuthal uniformity.
4 - Overcast, moderately graded, and slightly brightening towards the sun.
5 - Sky of uniform luminance.
6 - Partly cloudy sky, no gradation towards the zenith, slight brightening towards the sun.
7 - Partly cloudy sky, no gradation towards the zenith, brighter circumsolar region.
8 - Partly cloudy sky, no gradation towards the zenith, the distinct solar corona.
9 - Partly cloudy, with the obscured sun.
10 - Partly cloudy, with a brighter circumsolar region.
11 - White-blue sky with distinct solar corona.
12 - CIE Standard Clear Sky, low luminance turbidity.
13 - CIE Standard Clear Sky, polluted atmosphere.
14 - Cloudless turbid sky with broad solar corona.
15 - White-blue turbid sky with broad solar corona.

Concerning the latitude, as shown in Figure 11, it was observed that only Jacareacanga (6.22°S) and Recife (8.05°S) had an LPUP value of 100%. These cities show distinct sky conditions as the clear sky frequency in Jacareacanga is only 38.74%, while in Recife it is 56.85%, as seen in Figure 6. Located at close latitudes, both cities present the same maximum value for LPUP (100%), despite Recife's much higher frequency of clear sky conditions. On the other hand, when the results for Recife are compared to those for Florianópolis, a city with a similar frequency of clear sky conditions (54.90%) but located in the south of Brazil at a latitude of 27.5967°S, the influence of the latitude is evident. The highest LPUP value obtained for Florianópolis was approximately 90%. This result indicates that the effect of latitude can only be perceived when cities with similar sky conditions are compared. It was also observed that the maximum LPUP values tend to decrease on moving southward. This tendency contrasts with the data in Figure 3, where the consumption tends to increase moving southward. It is due to the difference between the point-in-time and annual cumulative analyses. The values in Figure 11 are individualised based on the hour of the day, orientation, latitude, and sky type.

The evaluation of the relationship between the angle of solar incidence and the LPUP is presented in Figure 12. The cloud of points in the graph shows that LPUP never reaches 100% for angles of incidence between 25° and 65°. This interval is apparently symmetric, in which the axle of symmetry is at 45°. The lowest maximum LPUP values (approximately 85%) occurred for angles of 35° and 55°. The graph also shows an area with fewer points related to angles of incidence smaller than 15°, particularly for LPUP values below 70%.

The graph in Figure 13 shows LPUP values plotted along the Z axis and are repeated on the colour scale to facilitate the tridimensional view of the cloud of points. These graphs verify the previous observation that, in general, LPUP values greater than 90% are associated with clear sky (ISO 15469:2004 sky 11-15) and partly cloudy (ISO 15469:2004 sky 6-10) conditions when the angle of incidence is smaller than 25º and greater than 65º, as shown in Figure 13(a). However, extreme LPUP values (close to zero and greater than 90%) were observed for similar combinations of sky type ISO 15469 (INTERNATIONAL…, 2004) and angle of incidence. It shows that the effects of each sky type ISO 15469 (INTERNATIONAL…, 2004) on the lighting consumption vary considerably, even within the same category of cloudiness conditions (clear, partly cloudy, and overcast sky). The first part of the graph, where the overcast sky data are plotted (ISO 15469:2004 sky 1-5), shows lower maximum values than the rest of the graph. It highlights the importance of daylight distribution in the sky dome and the sky brightness when the sky is overcast.

Figure 11 – **LPUP vs. Latitude**

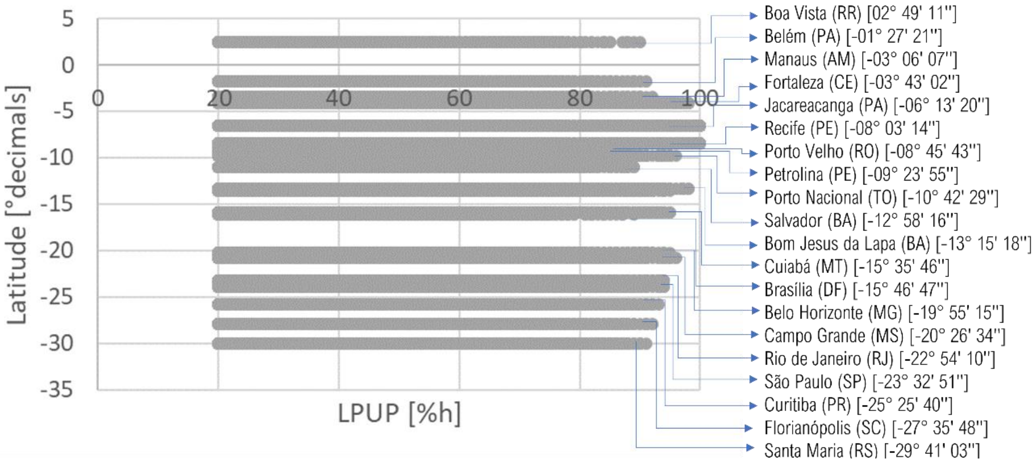


Figure 12 – **LPUP vs. incidence angle**

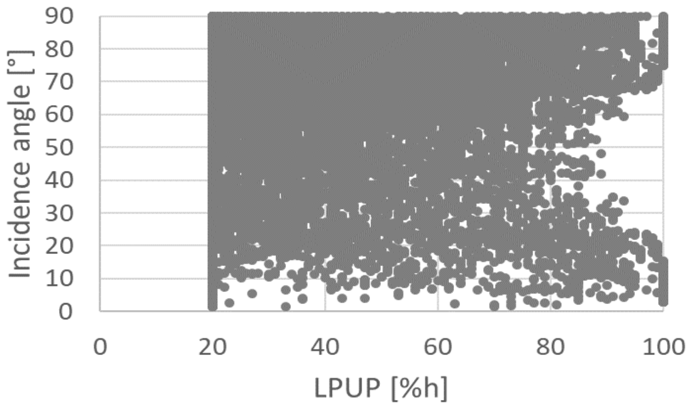
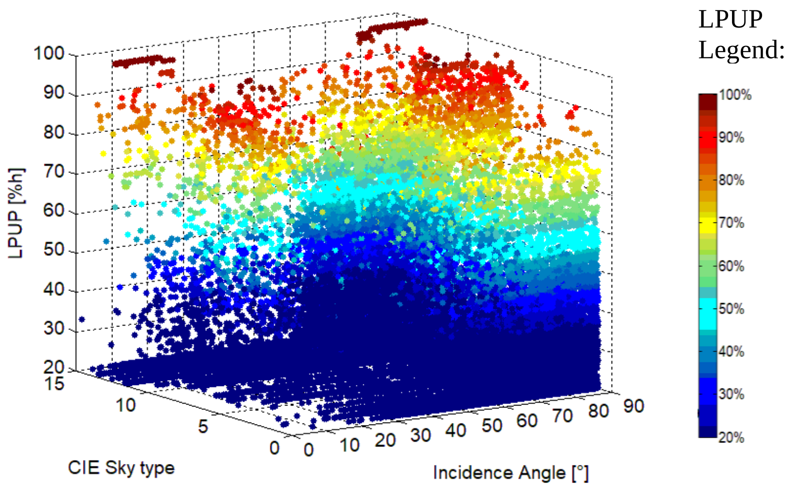


Figure 13 – **LPUL according to ISO 15469 (INTERNATIONAL..., 2004) sky type and direct solar radiation incidence angle - complete data set**



Relation between the annual lighting energy consumption, geographic location variables, sky conditions, and daylighting sufficiency performance variables

The graph of the correlation between the annual lighting consumption, the clear sky frequency, and the latitude shows a tendency for the lighting consumption to increase southward as the frequency of clear sky conditions increases, according to Figure 14. The differences observed for cities at close latitudes are due to variations in the proportions of the different sky conditions (INTERNATIONAL..., 2004) in each of the three groups of sky types. The time when different sky conditions occur for each orientation must be considered because this influences the solar radiation incidence. It was noted that the variation in the annual lighting consumption values for the 20 cities was only around 20%, but on considering the four orientations individually, it increased to approximately 40%.

To discuss the climatic zoning, we identified the cities belonging to the climatic zones of Brazil based on diffuse daylight illuminance (PEREIRA; SCHMITT; MORAES, 2015) in Figure 14. The coefficients of determination for the relationship between consumption and latitude for Zones I and II of this zoning were 0.1292 and 0.0734, respectively (Figure 1a). The correlation for Zone II was much weaker than that reported in Section The annual lighting energy consumption and the latitude for latitude Group 1, that is, 0.7131 (Figure 5), in which only two cities were exchanged between these groups, Recife and Porto Velho. We emphasise that the main limitation of this verification was the sample size, which was restricted by the data available in the SWERA weather files.

The results for the multiple regression analysis applied to the two datasets one based on an hourly evaluation of the lighting consumption; and the other on an annual evaluation, shown in Table 4. The number of cases used in the two hourly-based multivariate regressions was 109,715, and there were 20 and 80 cases for the annual-based multivariate regressions, considering the global and individual orientation approaches, respectively. The variation in the number of cases was one of the factors responsible for the large difference between the residual sum of the squares (RSS) in the multiple regressions, considering the hourly and annual evaluations. For the hourly evaluation, the exponential regression presented better performance than the linear regression, with R^2 values of 0.94 and 0.75, respectively. For the annual evaluations, the coefficient of determination was practically the same for the two models, but RSS was different. On evaluating the relationship between the independent variables and the dependent variable through the F test, it can be concluded that all of the models proposed are suitable to describe the phenomenon with a level of confidence of 95%.

About the relationship between the annual lighting consumption and the three daylighting performance variables, the analysis indicated that the strongest correlation was between the consumption and DA_{mean}, followed by DA_{median} and then sDA, with coefficients of determination of 0.95, 0.73, and 0.65, respectively. The stronger correlations between the consumption and DA_{mean} and DA_{median} can be attributed to the fact that these variables are sensitive to every illuminance level across the space, while sDA only computes the points that hit the targets.

Figure 14 - **Annual lighting energy consumption as a function of latitude and clear sky frequency**

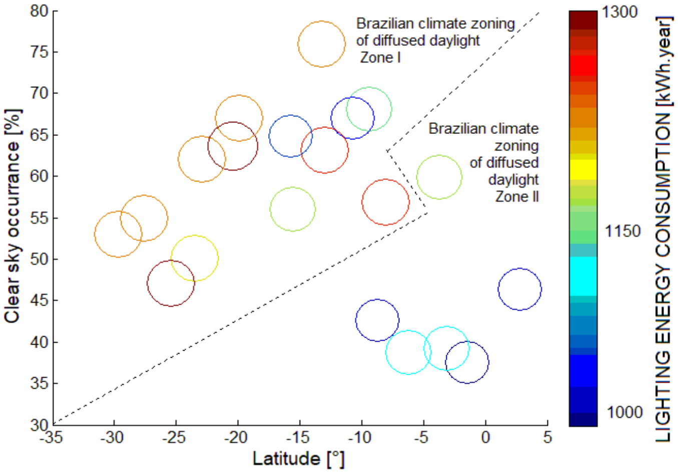


Table 4 - **Results of the multivariate linear regression and multivariate logarithmic regression**

Case	R^2	RSS
Hourly evaluation		
Multiple linear regression	0.75	21,120,015.95
Multiple exponential regression	0.94	63,348.49
Annual assessment - global approach		
Multiple linear regression	0.97	829,015.40
Multiple exponential regression	0.97	34.98
Annual assessment - individual orientations		
Multiple linear regression	0.96	279,161.30
Multiple exponential regression	0.97	80.39

Conclusions

In this study, the relationship between the angle of solar incidence, the annual occurrence of clear sky conditions, and the annual lighting energy consumption was investigated regarding daylight harvesting. The results obtained did not support the hypothesis that places, where the incidence of direct solar radiation allows greater daylight penetration into indoor environments, will be associated with lower lighting energy consumption, for similar clear sky frequency. It was concluded that variables mainly based on direct sunlight, such as the clear sky frequency or the daily average insolation, as used in the Brazilian climatic zoning based on daylight availability by Fonseca, Fernandes, and Pereira (2017), are not representative of the annual lighting consumption. The hypothesis is only valid for a point-in-time analysis, adopting sky conditions with similar characteristics.

The results show that the influence of the brightness of diffuse light in the sky predominates over that of direct sunlight associated with clear sky conditions in the annual analysis. Thus, for locations with similar annual sky characteristics, particularly the brightness, the influence of latitude on the lighting energy consumption can be perceived. However, when the difference in the sky brightness conditions is significant, it is not possible to establish a relationship between the variables. Therefore, climatic zoning based on daylight should involve first characterising the light and brightness distribution of the sky dome and later combining this information with the latitude. A way to characterise the local sky conditions in a simplified way, in a clustering process, would be to include more information on the climate, geography, and local vegetation in the analysis. The frequency of occurrence of cloudiness will vary according to the combination of the predominant climate and the terrestrial or maritime conditions, or even the vegetation, due to the evapotranspiration of plants (ANSELMO; MARDALJEVIC, 2013). In this regard, the Köppen climate classification (ALVARES *et at*., 2013) offers some progress in this direction.

The proposal of daylighting zoning is of interest as the variation in the global lighting consumption was approximately 20%, and considering the different orientations, it was over 40%. The global consumption results led to the conclusion that the discretisation of daylighting zoning, based on latitude, is only appropriate for locations close to the equator and up to the Tropic of Capricorn. A zoning approach based on lighting energy consumption could be extended to the DA_{mean} predictions. However, it was not possible to verify the possibility of extension to the other sufficiency performance variables. Lastly, the grouping of 15 CIE sky types into three groups (overcast sky, partly cloudy sky, and clear sky) for lighting consumption analysis is not recommended as there are significant differences between the lighting use patterns of sky types within the same group.

Concerning future studies, we recommend investigations with more extensive databases, such as the US NOAA[14] Integrated Surface Database (ISD), with data originating from land-based stations, or the Surface Meteorology and Solar Energy (SSE) database and the Prediction of Worldwide Energy Resources (POWER) project, sourced from NASA[15] satellite data. Currently, more extensive databases of Brazilian weather files are available, compared with the time this study was carried out, and this could also be exploited in further research (CLIMATE.ONEBUILDING.ORG., 2020).

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