DEVELOPMENT OF A DAYLIGHTING INDEX FOR WINDOW ENERGY LABELLING AND RATING SYSTEM FOR RESIDENTIAL BUILDINGS IN BRAZIL

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ABSTRACT

The purpose of this paper is to develop an index to evaluate the fenestration efficiency regarding the daylighting scene. In this study, three different types of frames and twelve different types of glass where evaluated. The models were based on Brazilian building characteristics and were simulated according to three Brazilian climate zones. The program adopted for the daylighting simulation was Daysim, and for energy simulations EnergyPlus. As a result, an index that combines the percentage of the environment area presenting more than 50% of UDI with glazing and floor area was obtained. This index allowed the development of a labeling system that classifies the windows from A to E. One expects to show the relevance of considering daylighting in any attempt to evaluate the contribution of windows to building energy efficiency.

INTRODUCTION

Daylighting presents a number of qualities that has proven its value in the architectural design. It is well know that the contribution of daylight in the living environment has positive effects in human health, considering the sleep-wake cycles, productivity (HESCHONG, 2002), and quality color reproduction, among other aspects. In addition, it has a recognized potential for energy saving when replacing or supplementing artificial lighting. However, the use of daylighting must be regulated in order to avoid excess in the illuminance levels, which may cause visual discomfort and greater solar gain, increasing cooling loads in buildings (MARDALJEVIC et al, 2011). Fenestration quality has a fundamental role in its performance; technological advances such as spectrally selective low-emissivity coatings have significantly enhanced the energy efficiency of windows over the last years. Lower transmittances across the visible spectrum will promote a reduction in the solar heat gain and probably make the glass appear darker (APTE et al., 2002). Several countries are in the process of developing and implementing Window Energy Rating Systems (WERS), that indicate the potential amount of savings a high performance window can provide, when compared to a standard window (Karlsson and Roos, 2004; Singh and Garg, 2009). Most current WERS do not consider an index to measure the fenestration capability of transmitting and controlling daylight and its influence in the built environment. According to Mardaljevic et al. (2011), the formulation of the daylighting metrics is in continuous development, and it is not yet evident if a single metric would be applicable to both non-domestic and residential buildings, since they present very different characteristics. The daylighting metric adopted for this paper was Useful Daylighting Illuminance (UDI), with a band ranging from 300lux to 2000lux, to evaluate the spectrally selective glazing and attempt a balance among the window features that allow daylight admission, avoiding excessive illuminance levels. UDI is defined as the annual occurrence across the work plane of iluminances within a useful range for the occupants, being subdivided into two ranges: daylight illuminances from 100 to 500 lux are considered as UDI supplementary, presumed sufficient independently or combined with artificial lighting, and daylight illuminances from 500 to 2500 lux, called UDI autonomous, where additional artificial lighting probably will not be required (MARDALJEVIC et al, 2011). The assessment of the energy efficiency considering the use of daylight in buildings was carried out through thermodynamic simulation software, which combines local weather data and the Daylight Coefficients concept in the simulation process. The software chosen for this study was EnergyPlus, which also calculates the interior illuminance based on the split-flux and radiosity method. Since the EnergyPlus program has shown a tendency to overestimate daylighting in the building's interior, the software Daysim is employed, calculating the interior illuminance based on the ray-tracing method (YUN and KIM, 2013). This integrated simulation method compensates the limitation of the program EnergyPlus by considering in the calculations a report of the artificial lighting control produced by Daysim, estimating the total energy consumption of the studied environment. (PEREIRA and DIDONÉ, 2010; VERSAGE *et. al* , 2010).

In a study to evaluate the predictive accuracy of lighting energy consumption by the EnergyPlus program and by the integrated simulation method, Yun and Kim (2013) obtained the lighting schedule from Daysim to complete an accurate calculation of lighting energy consumption with EnergyPlus. The results of their study showed that the ISM (integrated simulation method) is more accurate than the EnergyPlus simulation, since the modified lighting schedule is similar to the actual situation.

The proposal of this paper consists in using the daylighting index as a complementation of a thermal labeling system, enabling a broader assessment of the window's performance. The main contribution of this study is to emphasize the importance of daylight in fenestration evaluation. For this, the method adopted was structured in three parts. The first part consists in comparing two energy consumption simulation models, one with the entire lighting potential activated and one that possesses lighting systems with dimming controls, for harnessing the potential of daylighting. This comparison was possible with the integration of the programs Daysim and Energy Plus. The second part deals with the application of a selectivity index that considers the balance between the visible transmittance (VT) and the Solar Heat Gain Coefficient (SHGC). The third part has to do with the evaluation of the area considered as daylit. It is expected that the window evaluation system provides these three pieces of information, allowing a better assessment of the fenestration system.

It is important to highlight that a reference model was created in order to compare the performance of the windows types. With the intention of comparing the fenestration combination, it was decided to maintain the architectural geometry unchanged throughout the simulations, allowing the observance of different windows when subjected to the same test environment.

Residential buildings were chosen for this study because the window energy rating systems (WERS) proposed for Brazilian case for residential edifications does not consider daylighting in the window evaluation. This paper intends to demonstrate that daylighting can be a relevant part of window labeling systems. The same methodology can be applied for commercial edifications, as long as the reference model has been replaced by a new one based on commercial buildings architectural features.

SIMULATION

To ensure a balanced well-lit environment, the window should allow the transmission of light while controlling excesses, therefore avoiding glare that frequently induces the use of devices such as curtains, which may significantly reduce the entrance of light.

In this context, it is proposed to complement the window's thermal performance with luminous performance data, providing more information regarding energy.

Reference models

Climate data

As climate data, EPW files for Porto Alegre, São Paulo and Salvador were used. The territory was divided into three climate zones, represented by the selected cities, as illustrated in Figure 1.

Figure 1: Division of the territory into three zones.

Thermo-energetic simulation parameters

The model used for the thermal energy simulation consists of a one-story single family dwelling, with four thermal zones. It consists in a generic home to serve as a baseline for the fenestration comparison. The reference model incorporates architectural features common in Brazilian dwellings. In Brazil is not common use any type of insulation.

Envelope

The building has fenestrations of 1.2m x 1.6m, distributed on the four façades. It has two windows in each façade for the orientations South, East and West and four windows in the North façade, as illustrated in Figure 2.

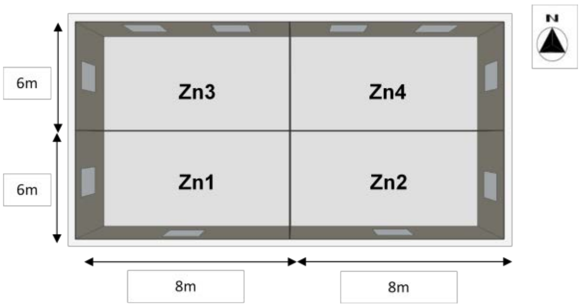

Figure 2: Zoning of the model.

The walls are made of brickwork, with a transmittance of 2.5 W/m². K. The floor and ceiling are composed by 12cm slabs and considered as adiabatic.

Internal loads

The building has a simplified occupation, maintaining a heat load of 100 Watts per zone, which is equivalent to the heat emitted by a person in light activity.

The equipment load is 50 Watts per zone. The lighting is also considered invariable in the simulation. The installed power density is 2.75 W/m^2 in all zones and remains activated from 7am to 11pm, on a daily basis.

Table 1: Glazing properties.

NOMEN-CLATURE	SHGC	VT (Tn)	U-Factor	Tdaysim (tn)
#1 (single)	0.454	0.421	5.674	0.46
#2 (single)	0.425	0.479	5.678	0.52
#3 (double)	0.374	0.643	3.238	0.70
#4 (single)	0.65	0.478	5.834	0.52
#5 (single)	0.573	0.728	5.799	0.79
#6 (single)	0.827	0.885	5.799	0.96
#7 (double)	0.339	0.384	2.676	0.42
#8 (double)	0.321	0.44	2.689	0.48
#9 (double)	0.305	0.581	1.672	0.63
#10 (double)	0.539	0.442	2.722	0.48
#11 (double)	0.458	0.659	2.714	0.72
#12 (double)	0.744	0.807	2.72	0.88

Frames

Four different materials were simulated: Steel, Aluminum, Wood and PVC. The U-factors adopted were as follows: Steel 5 W/m^{2}K; Aluminum 3 W/m^{2}K; Wood 2.5 W/m^{2}K and PVC 2 W/m^{2}K.

Depending on the material, the windows present different proportions of glass and frame. The structure of window frames made of wood or PVC is thicker than the ones made of steel or aluminum. For this reason, a 70% glass/frame ratio was adopted for the simulations with wood and PVC frames and for steel and aluminum frames a proportion of 80% was adopted.

Glazing

The glazings used in the simulations were selected primarily by parameters such as SHGC, VT and U-Factor, which covered theoretic minimum and maximum values that can be found in the market.

With the WINDOW 6.3 program and the IGDB (International Glazing Database approved by the NFRC), that provides data of specific glazing producers and also of generic products, the glasses were selected with parameters similar to those previously defined. The values of the generic glazings are an average of at least two samples, in accordance with the NFRC THERM5.2/WINDOW5.2 Simulation Manual (2006).

For the simple glazing values were selected samples of producers listed by IGDB that are present in the Brazilian market, with values close to those proposed in Table 1.1. The program WINDOW 6.3 provides the U-factor, which is determined by IGDB, and automatically calculates the VT and the SHGC of the glazing, according to NFRC standards.

The double glazing were calculated with WINDOW 6.3, based on the selected single glazings and adding an air filled layer of 12mm in addition to a clear generic glass of 4mm. The results are found in table 1.

Daylighting simulation parameter

Unlike the thermal simulation, where it was constructed a model with four different thermal zones, the daylight modeling is performed separately, each zone corresponding to one natural lighting model.

The characteristics were equivalent to the ones applied in the thermal model.

For the surfaces average reflectance the adopted values were: ceiling 70%, wall 50% and floor 20%.

The Daysim program establishes as glazing property input the transmissivity (Radiance, 2010), which is obtained through its light transmittance by the following equation:

$$tn = (sqrt(0.8402528435+0.0072522239*Tn*Tn)-09166530661)/0.0036261119/Tn \qquad (1)$$

Internal Loads

The power density adopted was 2.75W/m^2 and the control system is dimmable. The consumption of the automatic shutdown presence sensor and the dimmers used in the Daysim simulations is of 0.2W/m^2.

The occupation period considered was from 7 am to 11 pm.

Useful Daylighting Index

In order to emphasize the ability of the window to transmit light and following recent recommendations, the usual minimum UDI was increased from 100lux to 300lux. Thus, the boundaries of UDI for this study are the illuminances located between 300lux and 2000lux, during the occupation period of the building.

Labeling evaluation system

In order to complement the window's thermal label, the assessment of the light performance is composed of three parts: integrated simulation, selectivity index and daylighting area. These three parts are independent from each other and aim to provide more daylight information in the labeling system.

Integrated simulation

The integrated simulation aimed to highlight the glass/frame sets that presented better thermal and luminous performance. To this end, the data file (*. Intgain.csv) generated by the program Daysim was imported as lighting schedule for EnergyPlus, informing when the artificial lighting system should be activated and in what proportion. A dimming sensor was located in the center of each zone. For the integrated simulation the glazings from 1 to 12 were simulated with aluminum, PVC and wood frames.

Selectivity index

Based on the "Coolness" Index of Arasteh, Johnson and Selkowitz (1986), this index seeks to relate the glazing solar factor with its light transmittance, benefiting the glass that transmits more light with less heat.

The solar radiation (electromagnetic radiation emitted by the sun) that passes through the atmosphere and reaches the earth's surface comprises a spectrum with approximately the following composition:

a. 1% to 5% of ultraviolet (UV)
b. 41% to 45% of visible light (VL)
c. 52% to 60% of infrared (IR)

It was adopted a visible light percentage of 41%. Then, if the glass transmitted only visible light, the calculation of the maximum selectivity index (k) value for the theoretic glass with VT = 1, Tsolar = 0 and solar absorptance = 0.41, resulting in SHGC = 0.41, would result in 2,44, as shown in Eq. 2.

$$k = \frac{VT}{SF} = \frac{1}{0.41} = 2.44 \qquad (2)$$

The k values were normalized in this study, so their values lie between 0 and 1(k'). Therefore, the higher the value of k', the most suitable is the glazing balance between heat gain and light transmission.

Daylighting area

To evaluate the glass/frame set that provides a better daylighting condition it was adopted a method based on Useful Daylight Illuminance (UDI). The simulations of the program Daysim were used to obtain the UDI values. A total of 288 simulations were performed, one for each building zone, considering 12 types of glass, two glass/frame ratios and 3 cities. Each illumination zone was simulated with a grid of 96 points spaced at 0.50 m.

Three steps were followed to achieve the window rating:

1st step: For each point it was obtained a value of UDI, being the percentage of periods of the year that, for determined point, the illuminance was between 300 and 2000lux.

2nd step: The environment area where the daylight was within the useful illumination range was obtained.

3th step: The windows were classified in a range from A to E, where A is the most efficient and E the least efficient. For the determination of the intervals, the lowest value obtained by the 2nd step was subtracted from the higher value obtained from 2nd step. Than this result was divided by 5, obtaining a constant x1 (equation 3). The constant obtained was added to the lowest value found in 2nd step, and the values below this result were classified as level E. The values above level E limit and bellow the lowest value found in 2nd step added (2*x1) were classified as level D, and so on, as seen on the Table 2.

$$x1 = \frac{(Higher\ environment\ \%\ UDI - Lower\ environment\ \%\ UDI)}{5} \qquad (3)$$

For each city analysis, it was used a different range due to the respective weather files used in the simulations. This difference was preserved in order to reveal the benefits of each window in distinct climates.

In order to provide a simplified method for classification of windows in regard of the daylighting, distinct equations were developed for each city. To generate the equations it was adopted two methods of multivariate regression, a linear and an exponential. The Excel spreadsheet was used as a tool.

Table 2: Ranges indicating the percentage of the area that is within the UDI interval.

		A	>	% of UDI area min+4*x1
% of UDI area min+4*x1		B	>	% of UDI area min+3*x1
% of UDI area min+3*x1	≥	C	>	% de UDI area min+2*x1
% of UDI area min+2*x1	≥	D	>	% UDI area min+x1
		E	≤	% oUDI area min+x1

DISCUSSION AND RESULTS ANALYSIS

These three procedures were performed for all combinations of windows and frames in order to provide a complete label, with luminous and thermal information.

Integrated Simulation

The results presented in this article correspond to the simulations of the glazing from 1 to 11 with aluminum, PVC and wood frames, in the city of São Paulo. Observing the figures 3 and 4 one can see a decrease of 75% in final consumption. A significant reduction related to lighting can be noticed, followed by the cooling loads. On the other hand the heating loads arise, though this consumption does not exceed 100kWh/year/m ^{2}. Despite the fact that the dimmer is an unusual device in Brazilian residential buildings, it is important to emphasize the potential of energy savings for environments that are well daylit. The models presented in figure 3 show the artificial lighting activated throughout the occupation period. Figure 4, shows the energy consumption considering the daylighting harnessing, since these are environments with small dimensions the natural light is enough to illuminate the spaces during most of the day.

Regarding the glazing performance, glass 3 presents one of the best performance, since it has reduced consumption compared to other glazings and presents the best light/heat balance, being single glazed. The double glazings 7 and 8 also show reduced consumption even with low VT. Reduction in cooling loads outweighs the increased lighting consumption. Meanwhile, glass 9 (two panes of glass 3) had the lowest consumption, though it is more elaborate, being double glazed.

Models with aluminum frame showed superior consumption due to higher heat loads coming from the glass area.

Selectivity index

The selectivity index was calculated for the 12 kinds of glazings, as shown in Table 3. Through this index it can be noticed a better performance of the double glazings. This difference is due to a greater reduction of the solar heat gain coefficient (SHGC) compared to the visible transmission (VT).

Table 3: Selectivity index (k') for the 12 types of glazings.

Nomenclaure	SF	VT (Tn)	K'
#1 (single)	0.454	0.421	0.381
#2 (single)	0.425	0.479	0.463
#3 (single)	0.374	0.643	0.705
#4 (single)	0.65	0.478	0.303
#5 (single)	0.573	0.728	0.520
#6 (single)	0.827	0.885	0.439
#7 (double)	0.339	0.384	0.463
#8 (double)	0.321	0.44	0.561
#9 (double)	0.305	0.581	0.779
#10 (double)	0.539	0.442	0.336
#11 (double)	0.458	0.659	0.590
#12 (double)	0.744	0.807	0.443

Daylighting area

According to the described method, the following limits have been obtained for the three cities studied (Table 4, 5 and 6):

Table 4: Limits to the city of Salvador.

SALVADOR				
		A	>	54.28
54.28	≥	B	>	46.19
46.19	≥	C	>	38.09
38.09	≥	D	>	30.00
		E	≤	30.00

The differences among the cities are due to daylight availability in every region.

Table 7 shows the classification results of the respective windows for different combinations of glass/frame for every city. There was an improvement of one level when using thinner frames, such as steel and aluminum.

Figure 5 illustrates the comparison of the two glass/frame ratio performances and the visible transmission multiplied by 100. In general, the aluminum and steel frames indicate a higher performance, except for the glass 6, which possesses a visible transmittance of 0.88.

For glass 6, the thicker frame (lower glass area) provides a higher UDI area. This occurs because of an illuminance excess, due to a high visible transmittance and opening area. This performance was repeated for the three cities.

Table 5: Limits to the city of São Paulo.

SÃO PAULO				
		A	>	51.13
51.13	≥	B	>	43.51
43.51	≥	C	>	35.88
35.88	≥	D	>	28.25
		E	≤	28.25

Table 6: Limits to the city of Porto Alegre.

PORTO ALEGRE				
		A	>	49.48
49.48	≥	B	>	43.56
43.56	≥	C	>	37.63
37.63	≥	D	>	31.70
		E	≤	31.70

Based on the simulations results two equations were produced for each city using multivariate regression. One of the equations is linear while the other is exponential. The purpose of testing the two equations was to verify if a non linear approach could present better results than the linear approach.

Equations 4, 6 and 8 are the linear equations to Salvador, Sao Paulo and Porto Alegre and equations 5, 7 and 9 are the exponential equations to the same cities.

Salvador:

Linear

$$A_{UDI} = 55{,}329 \times T_n + 15{,}6381 \times \%glass \qquad (4)$$

Exponential

$$A_{UDI} = \mathrm{EXP}\ (\ln(4{,}9857) \times T_n + \ln(41{,}9039) \times \%glass) \qquad (5)$$

São Paulo:

Linear

$$A_{UDI} = 54{,}8494 \times T_n + 11{,}7487 \times \%glass \qquad (6)$$

Exponential

$$A_{UDI} = \mathrm{EXP}\ (\ln(5{,}3453) \times T_n + \ln(35{,}8117) \times \%glass) \qquad (7)$$

Porto Alegre:

Linear

$$A_{UDI} = 51{,}0684 \times T_n + 19{,}6117 \times \%glass \qquad (8)$$

Exponential

$$A_{UDI} = \mathrm{EXP}\ (\ln(4{,}2746) \times T_n + \ln(48{,}7216) \times \%glass) \qquad (9)$$

The coefficient of determination (r²) and residual sum of squared (SSresid) for every equation are shown on Table 8, in order to enable the comparison.

Table 7: classification of Windows for the three cities.

		CITY					
	GLASS	**SALVADOR**	**CLASSIF.**	**SÃO PAULO**	**CLASSIF.**	**PORTO ALEGRE**	**CLASSIF.**
FRAME 70%	#1 (simple)	28.09278	E	23.96907216	E	30.67010309	E
	#2 (simple)	35.05155	D	32.98969072	D	37.37113402	D
	#3 (simple)	49.2268	B	44.32989691	B	47.93814433	B
	#4 (simple)	34.27835	D	25.77319588	E	35.30927835	D
	#5 (simple)	52.57732	B	50.77319588	B	55.41237113	A
	#6 (simple)	53.35052	B	51.03092784	B	54.12371134	A
	#7 (double)	21.90722	E	20.6185567	E	25.77319588	E
	#8 (double)	30.41237	D	32.21649485	D	37.88659794	C
	#9 (double)	53.35052	B	47.93814433	B	53.60824742	A
	#10 (double)	31.18557	D	29.63917526	D	33.50515464	D
	#11 (double)	49.2268	B	44.07216495	B	47.93814433	B
	#12 (double)	52.57732	B	51.80412371	A	54.3814433	A
FRAME 80%	#1 (simple)(13)	34.79381	D	32.73195876	D	36.34020619	D
	#2(simple)(14)	40.72165	C	38.40206186	C	40.97938144	C
	#3 (simple)(15)	56.70103	A	50	B	52.31958763	A
	#4 (simple)(16)	40.72165	C	37.62886598	C	40.46391753	C
	#5 (simple)(17)	62.37113	A	58.7628866	A	54.12371134	A
	#6(simple)(18)	51.80412	B	49.48453608	B	54.12371134	A
	#7 (double)(19)	28.60825	E	26.03092784	E	31.95876289	D
	#8 (double)(20)	37.62887	D	34.53608247	D	39.17525773	C
	#9 (double)(21)	58.50515	A	53.09278351	A	54.12371134	A
	#10 (double)(22)	37.37113	D	34.27835052	D	38.1443299	C
	#11 (double)(23)	53.60825	B	50.25773196	B	52.31958763	A
	#12 (double)(24)	53.09278	B	50.77319588	B	53.86597938	A

Table 8: Values of r^2 e SSresid for the equations for each city.

			r^2	SSresid
SAL	linear	equation 1	0.9816	6.375292
	exponential	equation 2	0.9974	0.197914
SP	linear	equation 3	0.9831	5.677116
	exponential	equation 4	0.9976	0.189225
POA	linear	equation 5	0.9915	4.357508
	exponential	equation 6	0.9974	0.201313

The six equations were applied to 24 combinations of windows. Figure 6 shows the results of computer simulation compared with the equations results**.** Similar results were found, when comparing the results of linear and exponential equations for Salvador, Sao Paulo and Porto Alegre. The first part of the graph presents the windows that possess glazed area of 70%, while the second part presents the windows with 80% of glass area. This graphic analysis indicates a limitation of the equations overestimating the UDI area for models 6, 18 and 24. The main feature of this window is that it is composed by a glass with high Tn and presents a reduced UDI area, due to the excessive illumination. The equations cannot represent properly this excessive illumination limitation.

However the equated results for models 3, 9, 15 and 21 showed results below the simulated ones. Apart from this, the study shows that from Tn 65% the UDI area is almost constant.

CONCLUSION

This study brings a discussion about the importance of considering daylighting in windows evaluation. Knowing the benefits of using daylighting either related to comfort or to energy efficiency, stresses the importance of considering this parameter on a label that assesses windows performance.

It is recommended that the windows thermal performance labeling system should be based on integrated simulations in order to provide more energetically efficient fenestrations in terms of daylighting. Furthermore, it is shown that the selectivity index and the classification of daylighting evaluation using the parameter "percentage of the area lying within the UDI range" can be an important complement in order to better inform consumers about the window quality.

As a recommendation on the classification by "percentage of the area lying within the UDI range" it was observed better results through computer simulation, since the equations do not succeed in reproducing the phenomenon that UDI limits low and excessive illuminances. These equation types must represent more appropriately indexes based on measures like Daylight Autonomy, which do not have an upper limit for illuminance.

Regarding the mathematical expressions, the exponential equations presented a smaller residual sum of squared, while linear equations also presented good results and the implementation is less complex.

The purpose of the equations is to evaluate any type of glass without having to run simulations. Since the reference model was build based on common Brazilian architectural typology, this method could be replicated for the whole country, trough the creation of one equation for each bioclimatic zone. In this study, the equations were generated for each bioclimatic zone, although further research could attempt to join climate features in a single equation, appropriate for the entire country.

The advantage of the use of this combined index instead of VT and SHGC is that the information provided for the consumer is more comprehensive when using data such as daylight autonomy. Also the integrated simulations emphasize the potential of harnessing daylight in the built environment and its benefits in energy savings.

NOMENCLATURE

tn = transmissivity
Tn = transmittance
AUDI = percentageof the area lying within the UDI range 300lux-2000lux
%glass = percentage od the aperture area that is glazed.

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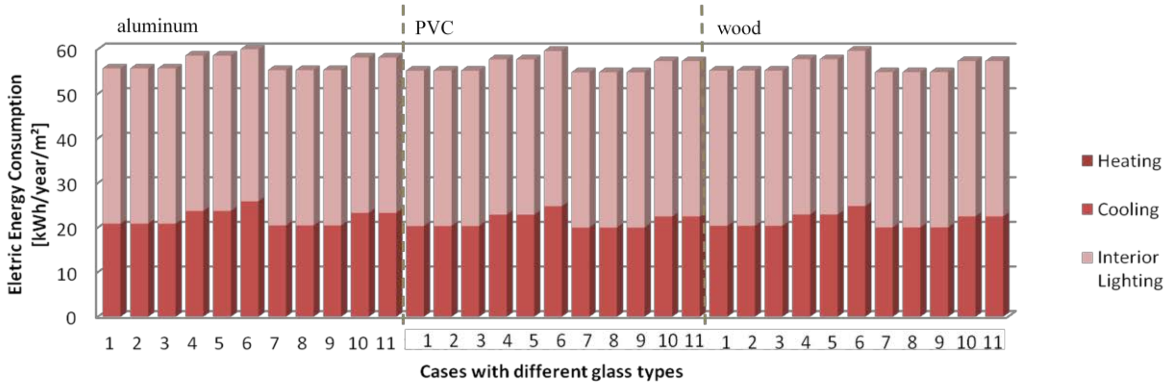

Figure 3: Electric energy consumption without considering daylighting for São Paulo.

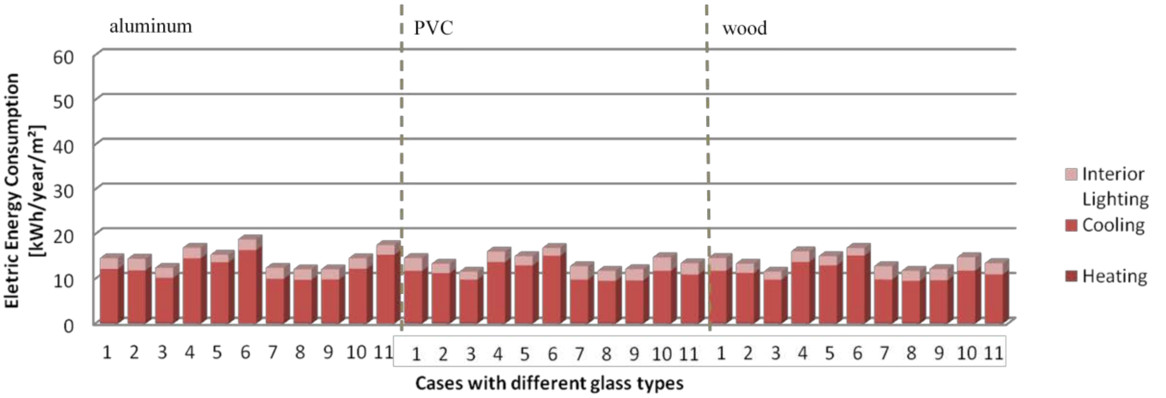

Figure 4: Electric energy consumption considering daylighting for São Paulo.

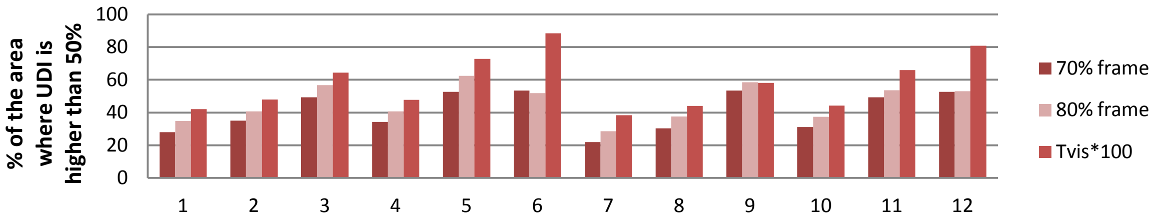

Figure5: Performance of different types of glass and different types of frame for the city of Salvador.

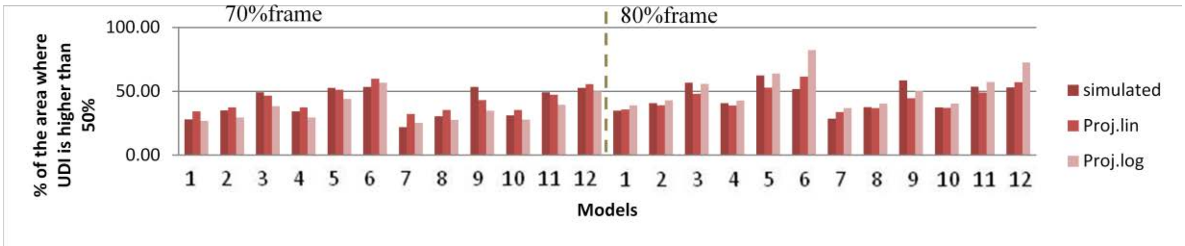

Figure6: Results obtained by computer simulation, linear and exponential equations for the city of Salvador