CHARACTERIZATION OF DISTINCT SOLAR SHADING DEVICES BY THEIR THERMAL AND LIGHTING PERFORMANCE

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Abstract

The aim of this work is to analyze the impact of adding solar shading devices on the lighting and total energy consumption of office rooms. This analysis was done for the climate of Sao Carlos, a city located in the state of Sao Paulo, in Brazil. Distinct combinations of solar shading, window and room dimensions for each façade orientation were simulated using two complementary programs: Troplux, for the lighting simulation and EnergyPlus, for the thermal/energy simulation. The results show that the total energy consumption always decreases due to added shading. The results are discussed in terms of the most effective solutions to reduce the energy consumption without creating much impact on the natural light availability.

1. Introduction

Solar radiation achieves high intensity in Brazil, due to its low latitudes. Windows then are a vulnerable surface of the buildings located in this country, due to the highest impact of solar gains on the cooling energy consumption and comfort. Commercial buildings are normally the most likely to suffer from the negative influence of windows solar gains, as their window/wall ratio is generally high. This is added to the fact that usually their occupancy occurs during the warmer periods of the day, their internal gains are high and they use air-conditioning full time. In a study that created prototypes based on surveyed data of what is commonly built in Brazil (Carlo and Lamberts, 2008), a prototype of a Brazilian office building corresponds to a building with bronze glasses and no external shading. It is well known in the literature that locating an external shading device on a window does not necessarily reduce the amount of natural light entering a room (Lechner, 2009). This is true if some design considerations are taken into account, like avoiding glare and diffusing and distributing the light over the room. In order to improve the daylighting level and its distribution, some parameters have to be observed, like the room length, the window dimensions and position, the type of glass, the surfaces color, the type of shading device, etc.

External solar shading devices can have a range of geometries, colors and be made of several materials. It is important, though, to analyze the performance of these important architectural elements both from the thermal and lighting point of view. The combined influence of other aspects, like room dimensions, window position and dimensions, among others, also need to be taken into consideration.

2. Objective

The aim of this work is to analyze the impact of adding solar shading devices on the lighting and total energy consumption of office rooms. This analysis was done for the climate of Sao Carlos, a city located in the state of Sao Paulo, in Brazil.

3. Methodology

3.1 Computational simulations with TropLux and EnergyPlus

The methodology is based on computational simulations using two complementary programs: Troplux (Cabús, 2006), for the lighting simulation and EnergyPlus (Department of Energy, 2010), for the thermal/energy simulation.

Distinct office room geometries were considered in the simulations. Each combination of them was first simulated through Troplux. The result was the lighting level at various points along the room, located on the work plan (height of 0.75 m). These data were given for one representative day of each month, from sunrise to sunset.

The Troplux outputs indicated when and where complementary artificial light was required for each model. With this information, a schedule indicating the artificial lighting level (W) for every hour of a representative day of each month was created. This was done for the all EnergyPlus input files. The next step was to run EP for all cases and to obtain their energy consumption.

3.2 Room geometries

The simulations were performed for office rooms, considered as monozone models in EnergyPlus. These rooms had four vertical walls, where only one of them was external and had a window. The other ones, plus the ceiling and the floor, were considered as adiabatic, which means that there was no heat flow through them.

The five geometries analyzed are presented on Table 1. Each one corresponds to a distinct combination of room depth and window size. According to the bibliography, both of these parameters influence the availability of natural light alongside the room. The room depth is characterized by the depth factor (A), and the window size, by the window/floor area (B).

$$A = \frac{room\ depth}{height\ of\ the\ superior\ part\ of\ the\ window} \quad \text{(eq. 1)}$$

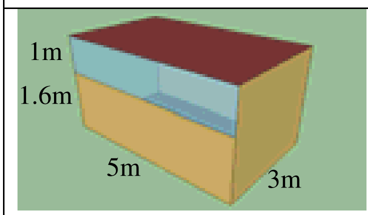
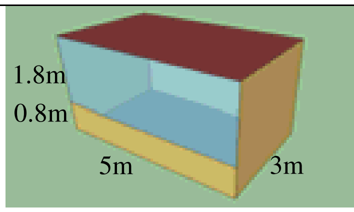
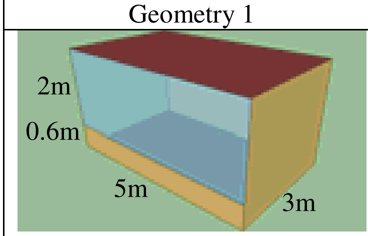
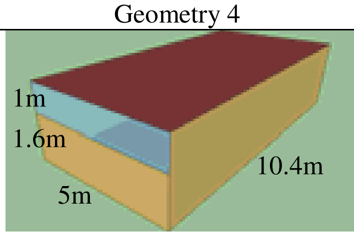
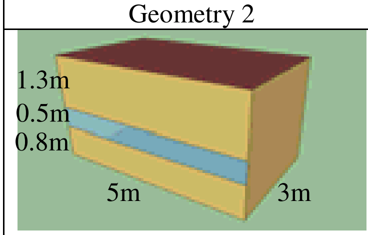
Where:

A: depth factor

$$B = \frac{window\ area}{floor\ area}\ (\%) \quad \text{(eq. 2)}$$

Only the window area 0.80m above the floor is considered.

Tab. 1: Geometries analyzed

Geometry	**Characteristics**		**Geometry**	**Characteristics**	
	A depth factor	**B** window/ floor area		**A** depth factor	**B** window/ floor area
 Geometry 1	1	33%	 Geometry 4	1	60%
 Geometry 2	1.1	60% (1)	 Geometry 5	4	9.6%
 Geometry 3	1.1	16.7%			

3.3 Solar shading devices

Each geometry was simulated both with and without external solar shading and various window orientations were considered in the research. Table 2 presents all solar shading and orientations run for each geometry. Orientations south and southeast were not considered because they did not need a protection, according to the method used.

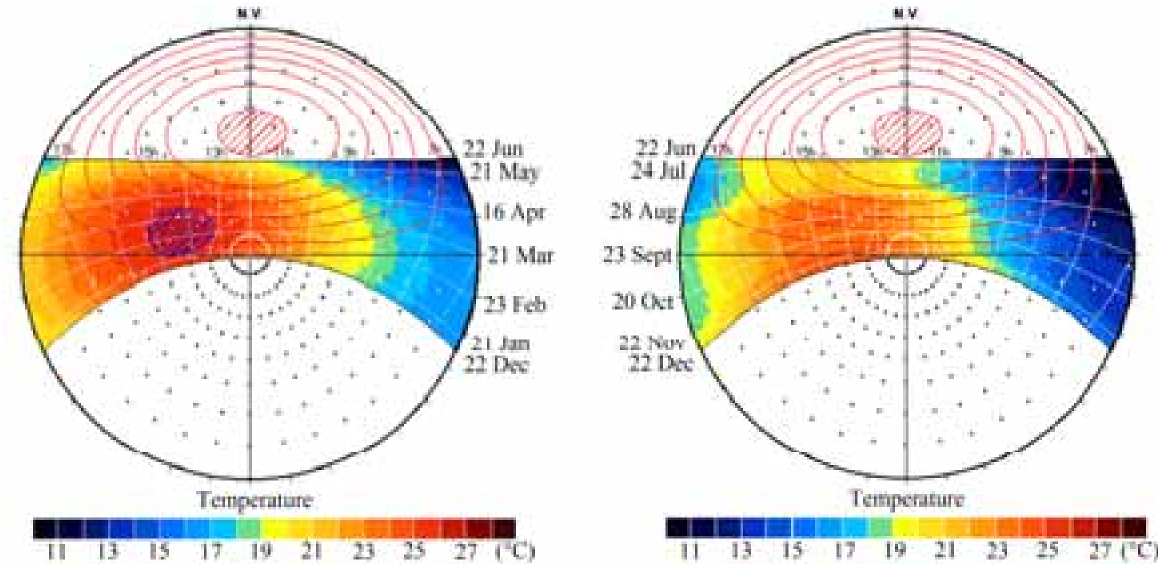
Tab. 2: External solar shading and orientations considered for each geometry

Geometry	Orientation and external solar shading
Geometry 1	North (0°): horizontal and mixed (horizontal + vertical) Northeast (45°): two horizontal models East (90°): horizontal Southwest (225°): horizontal and mixed (horizontal + vertical) West (270°): horizontal Northwest (315°): horizontal and mixed (horizontal + vertical)
Geometry 2	North (0°): horizontal West (270°): horizontal
Geometry 3	North (0°): horizontal
Geometry 4	North (0°): horizontal
Geometry 5	North (0°): horizontal West (270°): horizontal

The method chosen to design the external solar shading devices was an adaptation of the one proposed in the Brazilian Thermal Regulation for dwellings (INMETRO, 2010). This is the unique available method in the Regulations. First of all, it is necessary to have the sun chart for the latitude to be studied. In this case, the studied city was Sao Carlos, located in the state of Sao Paulo, Brazil, at 22°South latitude (Figure 1).

Fig. 1: São Carlos location in Brazil

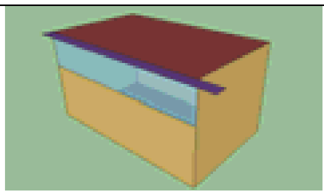
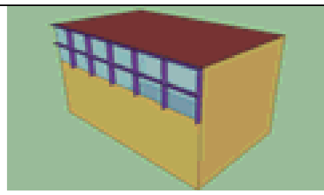
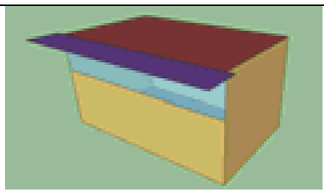
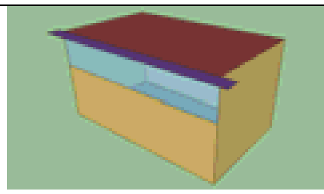
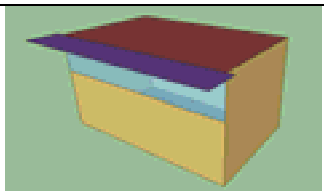
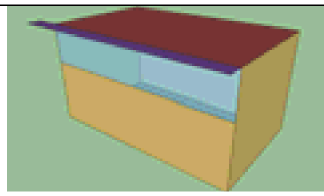
Then, the period when solar shading is needed has to be defined in the solar chart (Figure 2). It is defined considering both the typical hourly mean air temperature for each month and the intensity of solar radiation. There are distinct criteria for small and large openings, and for this work, the instructions for large windows were considered. These criteria were, however, adapted in order to better fit office buildings and as a consequence result in larger shading devices. Figure 2a also shows, as a result, the periods that solar shading is needed, highlighted in blue. The solar shading devices were then designed for each orientation. The result was a shading mask that covered the blue area shown on Figure 2a. Their resulting geometries are shown on Table 3.



(a) (b)

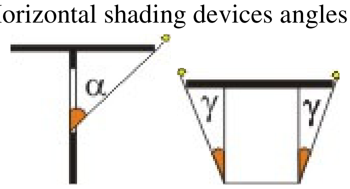
Fig. 2: Sun charts for São Carlos, Brazil (obtained from Roriz and Roriz, 2009). The period when solar shading is needed is highlighted in blue (only in Fig. 2a).

Tab. 3: External solar shading devices

Geometry	**Orientation and Solar shading device**	**Shading angles** [(1)]	**Geometry**	**Orientation and Solar shading device**	**Shading angles**[(1)]
Geometry 1	 north / horizontal	frontal: 15° right.: 0° left.: 30°	Geometry 1	 north / mixed	frontal: 15° right.: 10° left: 10°
Geometry 1	 notheast / horizontal 1	frontal: 40° right: 10° left: 10°	Geometry 1	 northeast / horizontal 2	frontal: 20° right.: 10° left: 20°
Geometry 1	 east / horizontal	frontal: 40° right: 10° left: 10°	Geometry 1	 southwest / horizontal	frontal: 20° right: 30° left: 0°

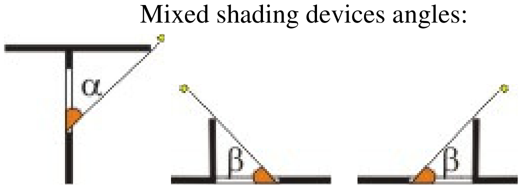
(1) Shading angles:

Horizontal shading devices angles:



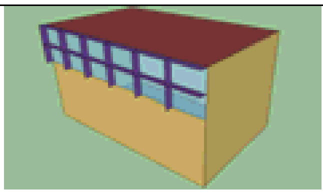
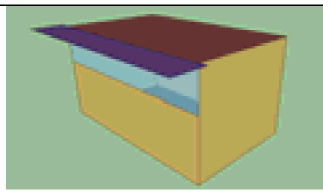
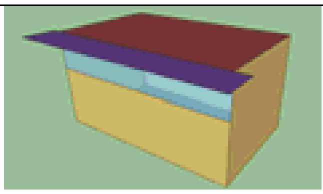
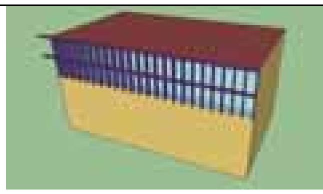
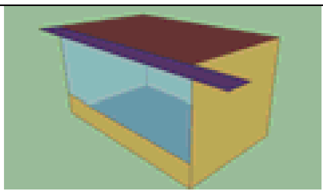
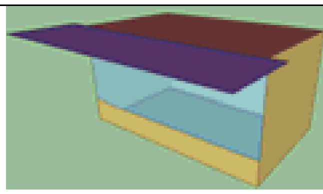
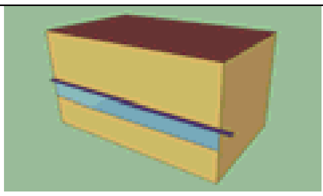
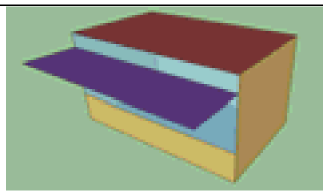
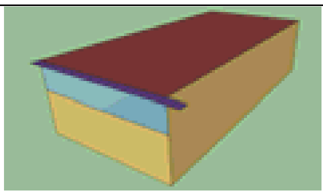
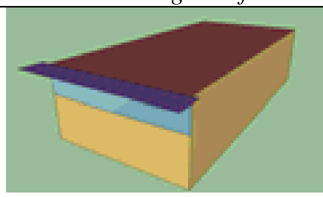
Frontal Right Left

Mixed shading devices angles:



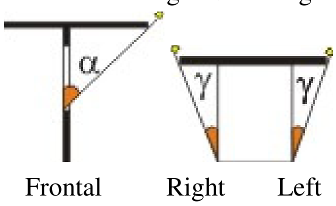
Frontal Left Right

Tab. 3: External solar shading devices (continuation)

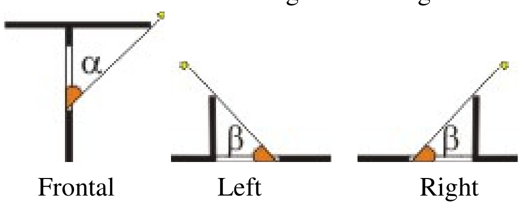
Geometry	Orientation and Solar shading device	Shading angles (1)	Geometry	Orientation and Solar shading device	Shading angles(1)
Geometry 1	 southwest / mixed	frontal: 20° right.: 10° left: 10°	Geometry 1	 west / horizontal	frontal: 40° right: 15° left: 10°
Geometry 1	 nothwest / horizontal	frontal: 40° right: 10° left: 20°	Geometry 1	 northwest / mixed	frontal: 20° right: 15° left: 40°
Geometry 2	 north / horizontal	frontal: 15° right: 0° left: 30°	Geometry 2	 west / horizontal	frontal: 40° right: 15° left: 10°
Geometry 3	 north / horizontal	frontal: 15° right: 0° left: 30°	Geometry 4	 north / *lighshelf*	frontal: 45° right: 0° left: 0°
Geometry 5	 north / horizontal	frontal: 15° right: 0° left: 30°	Geometry 5	 west / horizontal	frontal: 40° right: 15° left: 10°

(1) Shading angles:

Horizontal shading devices angles:



Mixed shading devices angles:



3.4 Artificial lighting

The minimum lighting level for office tasks, according to the current Brazilian Norm is equal to 500 lux. The artificial lighting system was an energy efficient one. It was designed in a way that complementary lighting was automatically turned on only when and where natural light was not enough.

3.5 Other input data

The first simulations were conducted with the Troplux program. Its database contained the climatological data from the city analyzed (Sao Carlos), obtained from the climate normals. The surfaces solar reflectivity were defined as the following: shading device (0.5), ceiling (0.7), walls (0.5) and floor (0.3).

The second step was to perform the simulations using the EnergyPlus program. For all geometries, internal gains due to people and equipment were equal to 24.5 W/m^2. Internal gains due to complementary artificial lighting varied as a function of natural light availability in various points of the room and during various periods of the year. The occupancy occurred during weekdays, from 8:00 to 18:00 hrs. Heating and cooling set points were, respectively, 18°C and 24°C. The infiltration air rate is equal to 0.8 air changes per hour, during 24 hours. There was heat flux only through the windows and external walls, as the other surfaces were considered to be adiabatic. Windows were made of clear glass (3 mm of thickness) and external walls, of concrete blocks (total thickness equal to 41 cm). The external solar absorption coefficient of the walls is 0.35.

4. Results

In all studied cases, heating energy consumption was negligible and therefore is not presented. This result was expected, as this is an office room, only used during the day. Total energy consumption always corresponds to artificial lighting plus cooling consumption.

4.1 Results for the north orientation

Table 4 shows the results for the north orientated window. The first room has good dimensions for natural lighting use (A equal to 1.1). Its window area, equal to 33% of the floor area, is higher than the suggested in the literature (15%). When there is no shading, complementary artificial lighting is necessary only in the end of the day (in some months, in the whole room and in others, only in the back). Due to this, its lighting consumption is very low (3.7% of the total). Adding a horizontal shading device, designed according to the Brazilian Energy Standard, increases the lighting consumption by 14.2%: now, the lamps have to be turned on during the whole year and in the whole room, but still only in the end of the day. The lighting consumption is still very low (4.2 % of the total). On the other hand, the cooling consumption is reduced by 23.3 %, and the total energy consumption has also a decrease of 22.3%. A horizontal plus vertical shading device is a bit more efficient: the hours and places where complementary lighting is necessary remain the same and the positive impact on the cooling consumption is a little higher. The consequence is that the total energy consumption is reduced by 27.1 %.

Tab. 4: Results for the north oriented windows

North orientation										
Room and window sizes[1]	Ext. shading device	Artificial lighting			Cooling [2]			Total [3]	
		Energy consumption (kWh/m²)	Energy consumption increase [3]	Part of the total	Energy consumption (kWh/m²)	Energy consumption decrease[3]	Part of the total	Energy consumption (kWh/m²)	Energy consumption decrease [3]
A: 1.1 B: 33%	Absent	3.7	---	2.7%	132.7	---	97.3%	136.4	---
	Horizontal	4.2	14.2%	3.9%	101.7	23.3%	96.0%	105.9	22.3%
	Mixed	4.2	14.2%	4.2%	95.3	28.2%	95.8%	99.5	27.1%
A: 1.1 B: 60%	Absent	3.7	---	1.8%	195.2	---	98.2%	198.8	---
	Horizontal	4.9	33.3%	3.2%	147.4	24.8%	96.8%	152.3	23.4%
A: 1.1 B: 16.7%	Absent	3.7	---	3.8%	92.5	---	96.2%	96.1	---
	Horizontal	3.7	0.0%	4.5%	77.0	16.7%	95.5%	80.7	16.0%
A: 1.1 B: 60%	Absent	3.7	---	1.9%	184.2	---	98.0%	187.9	---
	Lighshelf	4.9	32.8%	4.3%	108.5	41.1%	95.7%	113.3	39.7%
A: 4 B: 9.6%	Absent	21.8	---	17.6%	101.6	---	82.3%	123.4	---
	Horizontal	23.0	5.5%	20.0%	91.9	9.6%	80.0%	114.9	6.9%

The second room has the same size, but a larger window. Its area is twice as large as the one before (window/floor area, B, does not increase in the same proportion because only the window area 0.80 m above the floor is considered for this calculation). The positive impact of using a horizontal shading device with the same shading mask as before is very similar: reduction of 23.4 % on the total energy consumption. But this option does not actually give any advantage, as the cooling and total energy consumption is much higher. For example, for the case with horizontal shading, its total consumption is 43.8 % higher than the room above.

The third combination presented on Table 4 corresponds to the same room, but with the lowest window/floor area considered in the simulations (equal to 16.7%). This solution proved to be the most efficient: the complementary artificial lighting is still necessary only in the end of the day and its total energy consumption is 24% lower than the one of the first room, considering both with horizontal devices that correspond to the same shading mask. This case has shown the smallest benefit of shading the windows (16%), as solar gains were already low for the case without solar shading devices.

The impact of using a *lighshelf* in this type of room is presented in the fourth case of the Table 4. In this case, there is a small upper window without shading (B= 13.3%). The window below, with a window per floor area equal to 60 %, has horizontal shading like a veranda, which is a traditional element in Brazilian architecture. Its shading mask is bigger than the one adopted before. As a result, this veranda has a positive impact on the cooling consumption of the room, if compared to the case without shading: the reduction is equal to 41.1%, the highest achieved in the situations analyzed. On the other hand, due to the size of the window, even when it has the veranda, the total energy consumption (113.3 kWh/m²) is on the same level as that of the room with 33% of window/floor area and horizontal shading (105.9 kWh/m²).

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[1] A: depth factor. Room depth/height of superior part of the window.
B: window/floor area (%). For lighting purposes, only the window area 0.80m above the floor is considered.
[2] Heating consumption was so low that it could be disregard. Total energy consumption is equal to lighting plus cooling consumption.
[3] Energy consumptin increase or decrease: always related to the case without shading device.

Finally, a deep room was considered (A=4). Besides being a room with poor natural lighting conditions according to the literature, its window/floor area is also lower than the recommended value: 9.6%. As a result, complementary artificial lighting is needed during the whole day. The lighting consumption is higher than the cases presented before. On the other hand, due to the small window, the cooling consumption is the lowest found in the simulations. But even in this case, the contribution of the cooling on the total consumption is much higher than the lighting: 82.3% of the total, for the case without shading. The use of a shading device does not produce much impact on the lighting and cooling consumption (5.5% of increase and 6.9% of decrease, respectively). But even in this situation the total energy consumption is reduced by 6.9% due to the use of a shading device. The total energy consumption of this room (with a horizontal shading device) is equal to 114.9 kWh/m². This consumption is comparable to the ones found for the first and fourth cases (both with horizontal shading devices).

The following can be concluded after analyzing the above results, for the north orientation:

- For no deep rooms (the studied room had A=1.1):
  - there was not much difference between the natural light availability for the various window/floor areas studied, even when they had shading devices
  - On the other hand, the impact of the window size on the total energy consumption was very high. The minimum window/floor area considered was 15%, and it was the most efficient option.
  - Shading devices also had a positive impact. The larger the shading mask, the lower the energy consumption. This impact was higher when the windows were bigger.
  - Bigger windows need larger shading masks. But the biggest impact on the total energy consumption is the use of a smaller window.
- Deep rooms with small windows (the studied room had A=4 and B=9.6%) need to complement the natural lighting many hours during the year. Nevertheless, they can consume little energy, due the energy efficient solution adopted for the complementary artificial lighting. On the other hand, this type of solution is not advisable, due to the benefits of the natural light.

4.2 Results for the west, southwest, northeast, northwest and east orientations

Table 5 presents the results for the west orientation. The first room (A=1.1 and B=33%) has a higher lighting consumption than the cases with the north orientation. The complementary lighting is necessary in longer periods in the end of the day. Adding a horizontal shading device increases the lighting consumption and decreases the cooling (91.5%, against 31.2%, respectively). The overall reduction on the energy consumption is equal to 26.8%. The second situation corresponds to the same room with a larger window. In this case, the energy consumption is also superior. The positive impact of the horizontal shading device (with the same shading mask as before) is higher, equal to 33.2%. But the total energy consumption is 23% higher than the case with a smaller window (both with horizontal shading). The third case is the deep room (A=4) with a small window (B=9.6%). The lighting consumption is much higher, as it was expected. The low impact of the shading device on the cooling and the total energy consumption was also expected (6.4% and 1.9% respectively). The total energy consumption is very low and comparable to the one for the case with twice the window size and area three and half times lower (both cases with horizontal shading devices).

Tab. 5: Results for the west oriented windows

West orientation									
Room and window sizes	**Ext. shading device**	**Artificial lighting**			**Cooling**			**Total**	
		Energy consumption (kWh/m²)	Energy consumption increase	Part of the total	Energy consumption (kWh/m²)	Energy consumption decrease	Part of the total	Energy consumption (kWh/m²)	Energy consumption decrease
A: 1.1 B: 33%	Absent	4.0		3.5%	108.6		96.4%	112.6	
	Horizontal	7.7	91.5%	9.3%	74.7	31.1%	90.7%	82.4	26.8%
A: 1.1 B: 60%	Absent	4.3		2.7%	155.2		97.3%	159.6	
	Horizontal	10.8	148.6%	10.1%	95.8	38.3%	89.9%	106.6	33.2%
A: 4 B: 9.6%	Absent	23.3		19.8%	94.6		80.2%	117.9	
	Horizontal	27.1	16.2%	23.5%	88.5	6.4%	76.5%	115.6	1.9%

The southwest orientated room is presented on the Table 6. The results show that both the horizontal and the mixed (horizontal plus vertical) shading devices do not present an impact on the cooling consumption as it was observed before. The reduction is only 14.6% and 18.8%, respectively. There is also not much difference between (13.2% reduction on the total energy consumption for the horizontal one against 16.8% for the mixed one).

Tab. 6: Results for the southwest oriented windows

Southwest orientation									
Room and window sizes	**Ext. shading device**	**Artificial lighting**			**Cooling**			**Total**	
		Energy consumption (kWh/m²)	Energy consumption increase	Part of the total	Energy consumption (kWh/m²)	Energy consumption decrease	Part of the total	Energy consumption (kWh/m²)	Energy consumption decrease
A: 1.1 B: 33%	Absent	4.2		4.5%	88.0		95.5%	92.2	
	Horizontal	4.9	16.8%	6.1%	75.2	14.6%	93.9%	80.0	13.2%
	Mixed	5.2	25.5%	6.8%	71.5	18.8%	93.2%	76.8	16.8%

Results for northeast orientation are shown on Table 7. The same room and the same window size were considered in three situations: without shading, with shading mask according to the Brazilian Thermal Regulation (horizontal 1, angle of 40°) and with smaller shading mask (horizontal 2, angle of 20°). The biggest impact was due to the largest shading, with no negative impact on the lighting level (reduction of 39.8%). The room with the smallest shading device consumes 24% more energy than the other one.

Tab. 7: Results for the northeast oriented windows

Northeast orientation									
Room and window sizes	Ext. shading device	Artificial lighting			Cooling			Total	
		Energy consumption (kWh/m²)	Energy consumption increase	Part of the total	Energy consumption (kWh/m²)	Energy consumption decrease	Part of the total	Energy consumption (kWh/m²)	Energy consumption decrease
A: 1.1 B: 33%	Absent	3.8		2.6%	144.5		97.4%	148.3	
	Horizontal 1	5.9	55.2%	6.6%	83.4	42.3%	93.4%	89.3	39.8%
	Horizontal 2	4.2	9.4%	3.8%	106.6	26.2%	96.2%	110.8	25.3%

Table 8 presents the results for the northwest orientated windows. The impact of using a shading device on reducing the total energy consumption is significant. There is also a considerable increase in the lighting energy consumption, but this type of behavior does not alter the final results, as lighting consumption corresponds to a small part of the total. On the other hand, there is not much difference between the impact of the horizontal and the mixed (horizontal plus vertical) shading devices (34.7% against 36.5% reduction on the total energy consumption, respectively).

Tab. 8: Results for the northwest oriented windows

Northwest orientation									
Room and window sizes	Ext. shading device	Artificial lighting			Cooling			Total	
		Energy consumption (kWh/m²)	Energy consumption increase	Part of the total	Energy consumption (kWh/m²)	Energy consumption decrease	Part of the total	Energy consumption (kWh/m²)	Energy consumption decrease
A: 1.1 B: 33%	Absent	4.2		3.2%	124.7		96.8%	128.8	
	Horizontal 1	7.8	88.5%	9.3%	76.3	38.8%	90.7%	84.1	34.7%
	Mixed	7.3	75.7%	8.9%	74.5	40.3%	91.1%	81.8	36.5%

Finally, results for the east orientated windows are shown on Table 9. Once more, the positive impact of a shading device on the energy consumption is observed. In this case, the reduction is 32.8%.

Tab. 9: Results for the east oriented windows

East orientation									
Room and window sizes	**Ext. shading device**	**Artificial lighting**			**Cooling**			**Total**	
		Energy consumption (kWh/m²)	Energy consumption increase	Part of the total	Energy consumption (kWh/m²)	Energy consumption decrease	Part of the total	Energy consumption (kWh/m²)	Energy consumption decrease
A: 1.1	Absent	3.8		2.8%	130.1		97.1%	133.9	
B: 33%	Horizontal	6.1	59.7%	6.8%	83.9	35.5%	93.2%	90.0	32.8%

5. Conclusions

The heating energy consumption was so low that it could be disregarded in all studied cases. The results show that the adoption of a shading device decreases the cooling energy consumption. On the other hand, the lighting consumption always increases for the rooms with shaded windows. But as this increase is comparatively very small, the total energy consumption always decreases due to added shading. According to the cases considered in this study, the following could be concluded, for each orientation:

- **North**. In this orientation, the use of shading (horizontal or mixed) presented one of the lowest impacts on the lighting level. The reduction of the window size had also the same effect. On the other hand, the impact of the window size on the total energy consumption was very high. Small windows are recommended (15% of the floor area), in order to reduce the thermal load. Deep rooms are also not advisable, even when they have energy efficient lighting systems, due to the need to complement the natural lighting many hours during the year.
- **West**. The use of horizontal shading presented a higher impact on the lighting level increase than the North orientation. Nevertheless, its impact on decreasing the cooling and consequently the total energy consumption was very high. Small windows and no deep rooms are also advisable.
- **Southeast**. In this orientation, the impact of adopting shading devices (horizontal or mixed) on the reduction of the total energy consumption is the lowest found in the simulations.
- **Northeast**. The biggest impact on the total energy consumption was due to the largest horizontal shading, with no negative impact on the lighting level.
- **Northwest**. The impact of using a shading device on reducing the total energy consumption is significant, but there is not much difference between the impact of the horizontal and the mixed (horizontal plus vertical) shading devices.
- **East**. The use of horizontal shading presented a higher impact on the lighting level increase than the North orientation. Nevertheless, its impact on decreasing the cooling and consequently the total energy consumption was very high.
- **South** and **Southeast**. These orientations did not need solar shading devices, according to the used method.

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7. References

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