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Assessment of the thermal and visual efficiency of solar shades

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ABSTRACT

Solar shades are efficient architectural elements in order to reduce the thermal loads inside buildings. In one way, they can reduce significantly the energy needs of cooling systems. But in other way, they can decrease the visual comfort and increase the energy consumption of artificial lighting. Actually, the sizing of shading devices is mainly a thermal optimization process. The efficacy of solar shades must be assess taking into account both thermal and visual point of view.

In this paper simple indices were proposed to compare the thermal and visual efficacy of different types of solar shadings in non-residential buildings. These indices can be derived from the results of numerical simulations that include thermal and daylighting analysis such as the EnergyPlus software. A typical office is studied in order to assess the efficacy of different types of solar protections. The use of the proposed indices made obvious the choice and the sizing of the most efficient solar shade for the case study.

1. Introduction

The design of low energy buildings in tropical climates and in warm climates normally focuses first on the quality of solar shading. Solar shading is the over-riding design feature needed to avoid overheating inside the building and thus decrease the cooling capacity of air conditioning. The capital cost of installation and the operating time of air conditioning systems can be reduced or avoided if solar shading is combined with architectural design features such as cross natural ventilation.

As reduction of the energy consumption of the building sector constitutes now a priority objective, consideration of natural lighting also is essential. This because lighting is a significant proportion of total energy use in many buildings, so replacing it with "free" light from a renewable source such as the sun brings about significant reduction in purchased energy loads. However, with natural light there is a second bonus. In spite of all technological advances in electric light in the past decade, the sun is still the coolest source of light available in buildings.[1] The problem is one of intensity: a 1.2 m long fluorescent lamp on the ceiling of a room will produce approximately 4500 lm [1]; whilst a one square meter skylight will have approximately 100,000 lm impacting it in bright sun, and 20–30,000 lm on a cloudy day. When one is aiming for 200–500 lm per square meter (lux) on the working surfaces in a room, the problem of daylight is how to control the amount of this cooler source of light to the degree that is required.

Few building projects in tropic make the design of natural lighting a primary focus. The impact of solar protections on natural lighting has apparently not been widely studied. Only a few relevant references exist [2,3]. In certain buildings were care has been taken in design of solar protection, it is even possible that artificial lighting is required almost every day because the solar protection is too efficient. This results in increased energy use even though it had been thought during design that the optimum energy design had already been created with the solar protections to reduce cooling load of the air conditioning system. Good solar shade typically excludes all direct sun and much of the indirect light from the sky as well. An optimum design will be a compromise between effective solar protection and a suitable level of natural lighting. The ideal combination of both objectives in terms of reducing the overall building consumption is not obvious.

This paper presents a preliminary study of the simultaneous taking into account of solar shading and natural lighting in a typical room. The goal is to explore whether simple design guidance can be provided to designers that will assist them to balance solar protection and natural light. The room studied is an air conditioned office with a floor area of 12 m^2 and a single window.

After a brief review of typical indices used to evaluate the quality of natural light such as Daylight Factor, a simplified index

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[1] The efficacy of the sun has been reported as 100–130 lm W^{-1} [EERE 2009]; while the current best efficacy of a fluorescent lamp is 70–90 lm W^{-1}.

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combining solar shading efficacy and natural light effectiveness is presented. Then, the index is applied to the visual and thermal behaviors of a simple office. The utility of the index is evaluated by comparing the effect of solar shades size for two orientations that are sun exposed all the year in the south hemisphere: a north and a west-facing window.

2. Evaluation of the quality of solar protections

Some publications examine the dependence of the thermal loads reduction on the size of solar shading systems [4–6]. The solar shading coefficient C_m, presented in the following section, is developed for this purpose. But only a few articles present a coupling approach that integrates the visual comfort and solar protection [1] [3].

In high latitude countries, satisfactory illumination of office activities is often defined according to a particular "Daylight Factor" [7–9]. Daylight Factor in its simplest form is a ratio between two illuminances: that measured at a point inside, typically on a work plane such as a desk divided by that measured under an unobstructed sky outside. It is normally defined for overcast (cloudy) skies. Then it can be a theoretical value calculated for idealized overcast skies, or a measured value, calculated from two simultaneous measurements made inside and outside a building. It is assumed that a 'typical' overcast sky will have a standardised distribution of sky brightness that does not vary from season to season or from one to another window orientation.

Daylight Factor is not normally defined for sunny skies because it is very hard to generalize the sun position. The amount of light entering a window is dependent on the sun's position in the sky; the amount of cloud in the sky, and its distribution; the time of day, and the time of year. No single Daylight Factor will suffice to summarize this.

The Daylight Factor is a simplified design index that assumes that a room designed to achieve a minimum Daylight Factor will have adequate light on those days when the illumination outdoors is higher due to the sun. It is also assumed that the direct sun is excluded entirely from a room. And finally, it is often assumed that the cloudy sky outside condition is typical of conditions on many workdays. But these requirements are established for temperate climates and they are not suitable for other latitudes. In order to evaluate the quality of solar protection and daylight new indices need to be set up – combining concerns for beam radiation protection as well as the need for supplementary artificial lighting to meet standards for work plane illuminance.

3. Indexes used

3.1. Solar shading coefficient C_m

A method to assess the solar shading coefficient was proposed by Garde [10]. This index allows determination of the performance of the solar protection at glazing. This index is linked to the solar radiation load inside the room. The solar shading coefficient is merely the fraction of the beam solar irradiation (I_b) that impacts the glazing with and without the use of solar shadings (Eq. (1)). In order to elaborate the solar shading coefficient only the direct beam solar radiation is used because the solar ray is normally the principal concerns of solar protection design (Fig. 1). The closer the solar shading coefficient is to 0, the more effective the solar protection is.

3.2. Cooling energy demand

Solar protection influences overheating due to the penetration of solar radiation through windows and the amount of artificial lighting needed to deal with the shadows inside caused by the shades. If the one tends to decrease the cooling load, the other increases the internal loads. The cooling demand permits the evaluation of the thermal performance of the solar shading including both these two aspects. It is calculated for a typical meteorological year using a dynamic simulation tools that solve a thermal balance.

3.3. Daylight autonomy (DA)

As it was defined previously, the reference daylight factors used in northern countries are not adapted to tropical climates. The use of a parameter such as the daylight autonomy [11] turns out to be more suitable. Indeed, this coefficient quantifies for a typical period, the percentage of time when the required illumination is available on the work plane in terms of working requirements. Daylight autonomy is the amount of time that you can expect to reach a certain light level through the use of just daylight. In contrast to the more commonly used daylight factor, the daylight autonomy considers all sky conditions throughout the year. The daylight autonomy depends on the illuminance requirements of the user and the schedule of occupancy.

On the other hand, even if the daylight autonomy is independent of the installed electric lighting power and lighting control, the Daylight autonomy is directly linked with the energy consumption of the artificial lighting. The electric demand of the lighting decreases when the daylight autonomy rises.

The French Institute for Care and Health recommends a minimum level of illuminance of 300 lux for an office work. In this study, the daylight autonomy is calculated for this required illuminance of 300 lux.

3.4. Sun patch index on work plane (SP)

Glare is of necessity normally defined for a particular viewing angle. When calculating glare from ceiling lamps in an office for example, the lamp that is the potential glare source must be visible from the normal sitting position for people at their work desks. Similarly, for glare from large area glare sources, such as daylight windows, the angle of view facing the window is taken into account

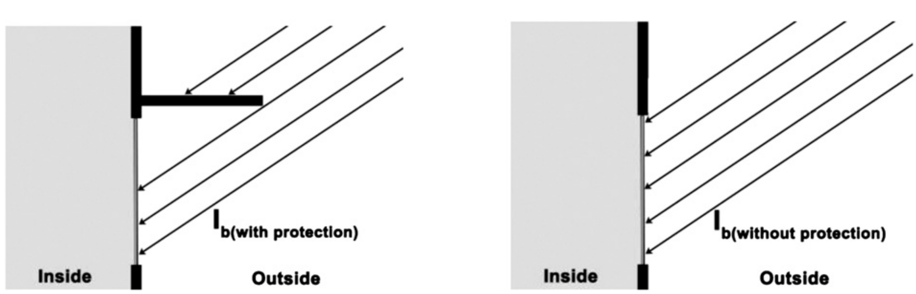

Fig. 1. Solar radiation on the window and calculation of solar shading coefficient.

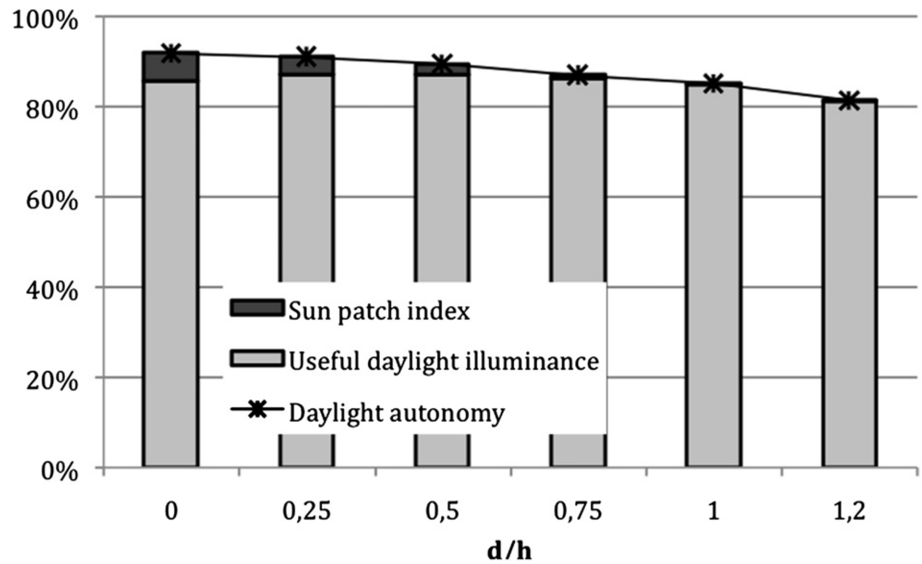

Fig. 2. Daylight visual comfort indices for different sizes of a simple overhang.

[12]. In normal office work, for this study it is assumed that a person would not normally look in the direction of the window but rather would focus on the work plane – the desk or computer screen.

Therefore, we propose to characterize glare potential as the likelihood of discomfort caused by the presence of a sun patch on the working plane. It is clear that sun shining into the eyes of an occupant is far more debilitating than sun reflecting off a desk or other work surface. However, neither are desirable in an office. This definition of a glare index based upon the presence of beam solar illuminance on the working area should also ensure that any person sitting in that working area also does not experience glare when they look up from their work task to relax their eyes looking out at the view – this latter 'function' being the other major human purpose of windows in buildings [13].

In order to evaluate the efficiency of the solar shading to prevent direct solar illuminance, this new index is calculated in the following manner: it is the ratio of the surface of the working area where the level of illuminance is higher than 8000 lux. This level of illuminance corresponds to a value which is too high to only diffuse illuminance and too small to correspond to direct solar illuminance. This limit permits to detect a surface of the work plane affected by direct solar illuminance. A value closed to 0% for the sun patch index is needed in order to attest of the efficiency of solar shading.

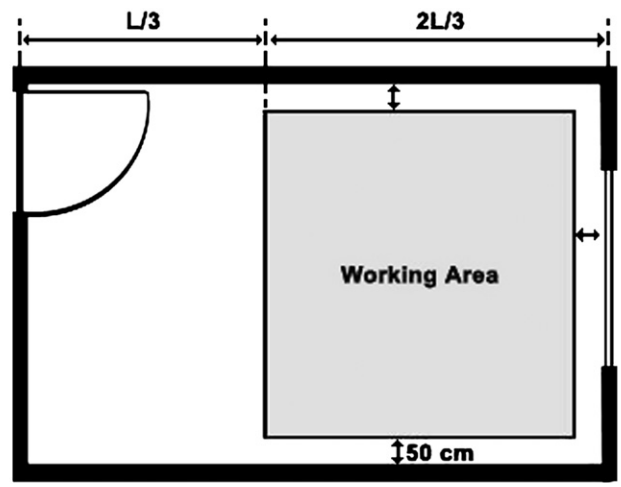

Fig. 4. Ergonomic place of the working area for the case study.

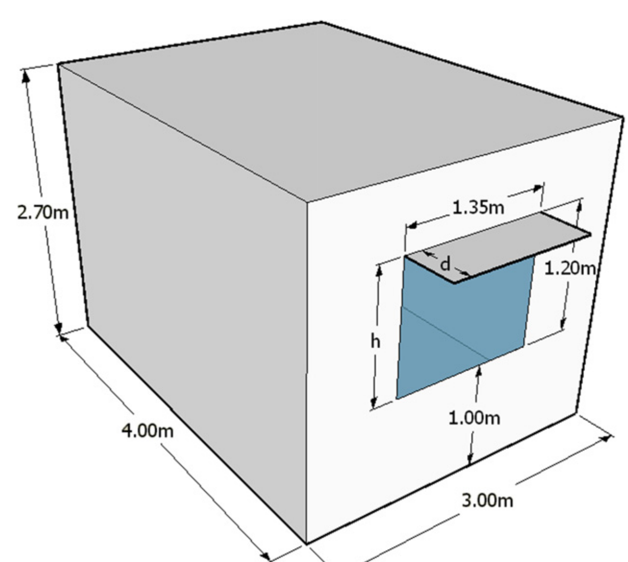

Fig. 3. Geometry of the case study.

3.5. Modified useful daylight index (UDI)

Proposed by Mardaljevic and Nabil in 2005, the useful daylight index is a dynamic daylight performance measure that is based on work plane illuminances [14,15]. As its name suggests, it aims to determine when daylight levels are 'useful' for the occupant, i.e. neither too dark (<100 lux) nor too bright (>2000 lux). The useful

Table 1
Annual weather statistics of the airport of Gillot (Reunion Island).

Mean dry bulb temperature	Mean relative humidity	Amount of solar irradiation	Mean wind speed	Amount of rain
23.9 °C	75.5%	1978 kWh m^{-2}	5.94 m s^{-1}	1476 mm

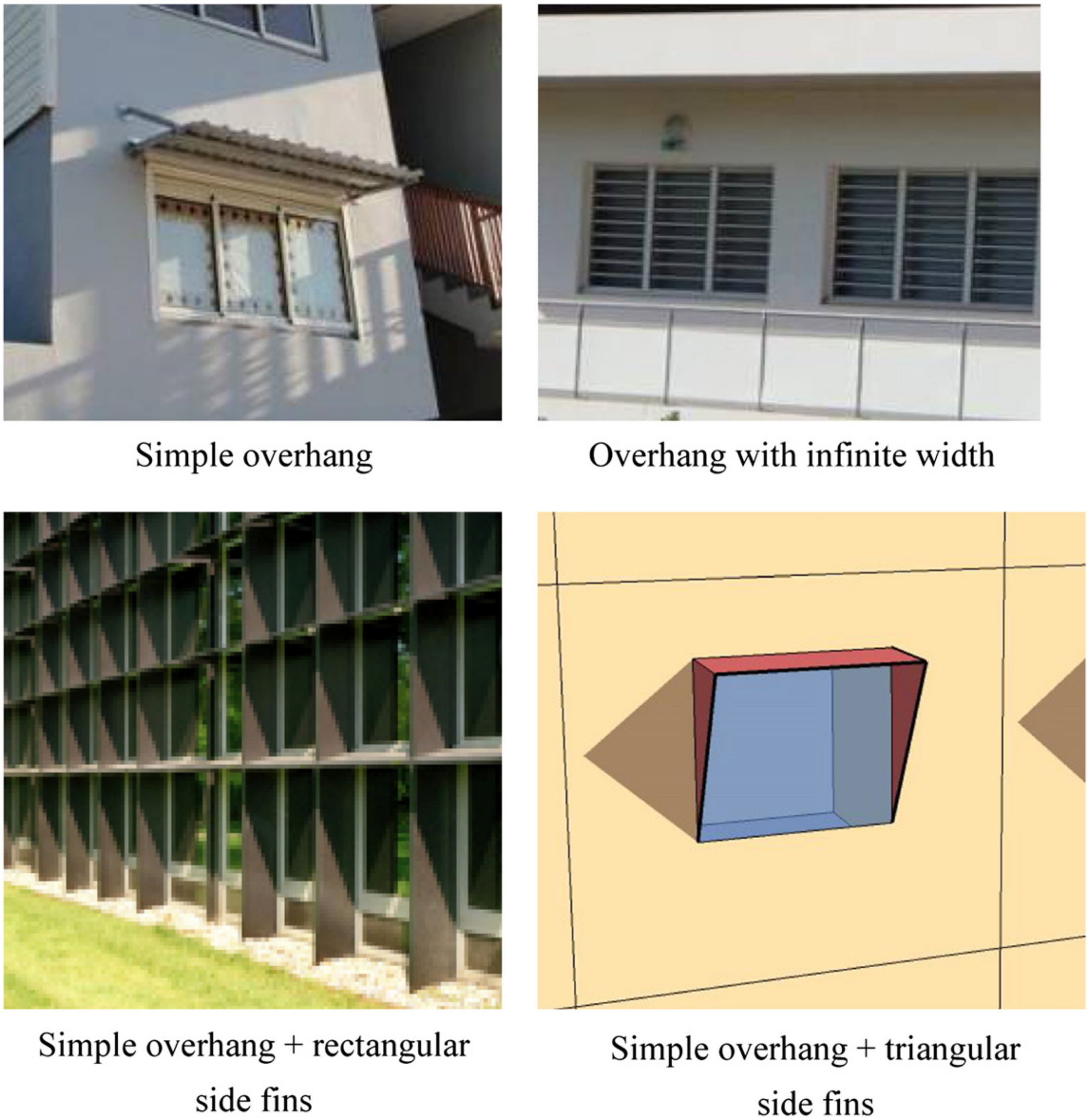

Fig. 5. Four types of solar shadings.

daylight index is calculated with the same process as the daylight autonomy. The UDI corresponds to the ratio of time when the illuminance observed on the work place is ranging between the two extreme values.

In order to link this index with the daylight autonomy and with the sun patch index on the work plane, we propose to use new extremes values to derive the useful daylight illuminance. The minimum level required for an office work is taken for the lower

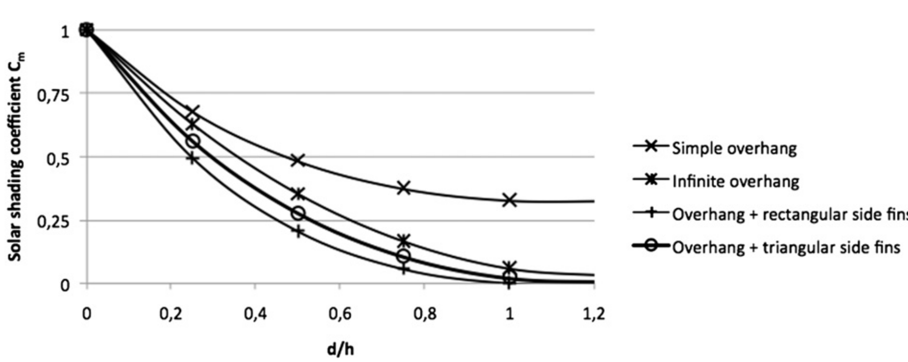

Fig. 6. Solar shading coefficient for different lengths of the solar shades.

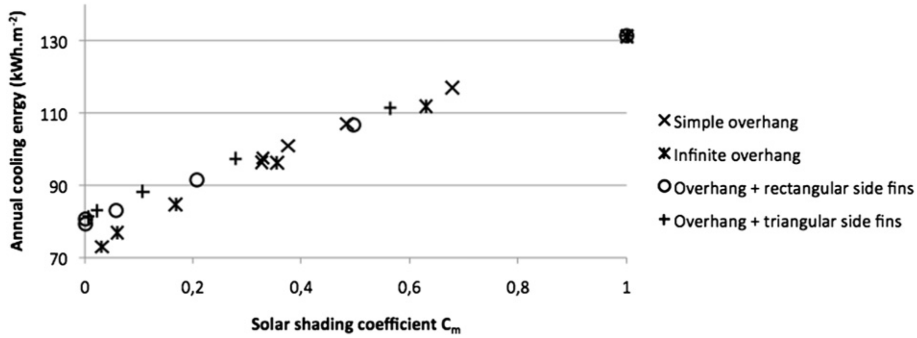

Fig. 7. Annual cooling energy as a function of the solar shading coefficient.

value of this interval, according to the calculation of the daylight autonomy. As defined previously, a level of 300 lux will be used. The upper limit corresponds 8000 lux which is taken from the sun patch index definition. This level of illuminance corresponds to direct beam solar irradiation on the work place.

Then the daylight autonomy is the sum of the useful daylight index and the sun patch index on the work plane (Fig. 2 and Eq. (2)):

4. Simulations

Thanks to the combination of the radiation models, the thermal algorithm [16,17] and the lighting ray tracing method Radiance [18], the EnergyPlus software allows study of the solar efficiency of the solar shading, the illuminance level at different points as well as the thermal loads of the room [19]. The sky radiance distribution is based on an empirical model based on radiance measurements of real skies, as described by Perez [20]. Even if EnergyPlus uses a zonal model to solve the thermal balance, the solar radiation distribution on the building is spatially defined. The shadow of a solar protection is accurately taken into account for evaluating the solar gains through windows and the illuminance inside a room. An ideal load air system is set up in order to evaluate the cooling load. This object of the EnergyPlus program permits to assess the theorical thermal loads needed to achieve the thermal balance at any time step of the simulation. A grid of 100 points is used to determine the illuminance on the working plane.

The case study (Fig. 3) is a typical office of 12 m^2 design for one person. This room stands inside an office building and only the wall with the window is exposed to the exterior environment. The window-to-wall ratio (WWR) is 20%. This ratio corresponds to the recommend opening area for office buildings in the coastal part of Reunion Island [10]. The glass is a single clear sheet, 6 mm thick. The walls, floor and ceiling are in reinforced concrete of 20 cm. One person, a computer with a power of 150 W and the lights are the internal loads. The sizing of the artificial lighting is sized at 10 W m^{-2}. The office schedule is from 8 h AM until 18 h PM with a break of 1 h for the lunch. The lighting has simple on/off control and is switched on when the illuminance in the center of the work plane is less than 300 lux.

Study of the whole area of the room is not suitable for an analysis of visual comfort. Inside a room some places are never dedicated to be working areas (e.g. behind the door and closed to the walls). For this study, we assume that the working area is defined for a good ergonomic situation of the office furniture (Fig. 4). So the area of study of the natural daylighting corresponds to the first two thirds of the room back from the window minus a dead band of 50 cm from the wall. The height of the work plane is 0.8 m. The interior light reflection off the wall and ceiling is 0.6 roughly equivalent to the lighting engineer's standards 0.7 to 0.8 for ceiling, and 0.5 to 0.6 for the wall. The floor has a reflectivity of 0.3.

To assess the level of illuminance at each point of the working area, a grid of 10 $\times$ 10 points is defined inside the EnergyPlus software. Each point is the center of a square surface and represents the mean level of illuminance of this elementary surface. In order to propose easy to use indices to compare the efficiency of different solar protection, the calculated daylight autonomy, sun patch index and useful daylight illuminance correspond to averages across these surfaces. These averages are derived from the yearly values of the indices calculated at each point on the grid.

The simulation site is the airport of Gillot, in the coastal part of Reunion Island. It is situated close to the tropic of Capricorn (20°53′ south and 55°31′ east). The climate is tropical with a high relative humidity (see Table 1). The design of the green buildings must take into account the warm weather and the great amount of solar irradiation of the site. The weather file used for the simulation is a Typical Meteorological Year generated for the PERENE project [10].

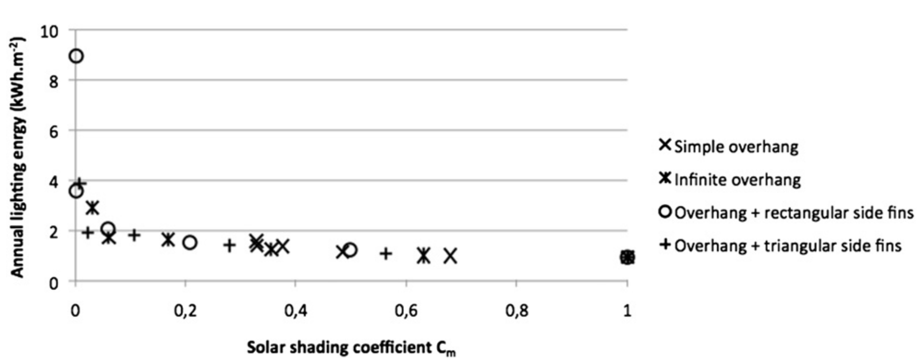

Fig. 8. Annual lighting energy as a function of the solar shading coefficient.

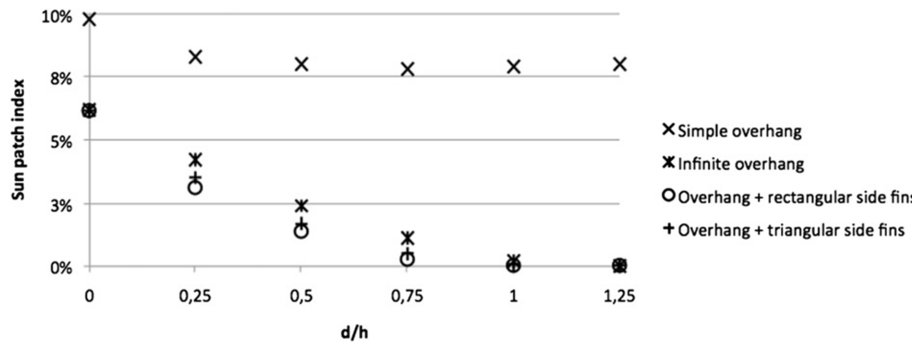

Fig. 9. Sun patch index for different lengths of the solar shades.

5. Comparison of solar shades for a north window

For this first case, four types of solar shading are considered (Fig. 5). All these protections are based on a simple overhang attached at the top of the window. The length *d* (Fig. 3) of the 4 shades is the unique geometric size parameter. To compare their capacity to reach both thermal and visual comfort, a variable length (*d*) of the solar protections is considered.

The objective of the simulations is to compare the efficacy of the four solar shades described in the last subsection. Energy consumption, thermal comfort and visual comfort are taken into account. A north-facing window is considered.

The reduction of the thermal gain of the office depends on the size of the solar protection. The greater the length of the solar protection is important the more the share of direct beam irradiation that passes through the window decreases (Fig. 6). The thermal behavior of the case study office is influenced by the amount of solar irradiation that enters the room. In our case, the annual cooling energy is almost proportional to the solar shading coefficient (Fig. 7). The length of the solar shades corresponds to design parameter used by the architects. The solar shading coefficient index could be taken to be the index that represents the thermal efficacy of the solar shades. For the following curves, the relative length (d/h) and the solar shading coefficient will be used as references (abscises). Using a geometric parameter such as the relative length, this comparison is intended to be of use to architects. Using the solar shading coefficient, which is link to the internal gains, the comparison is focused on a civil engineer audience.

The simple overhang has a lower capacity to reduce the thermal gains from the beam solar irradiation (Fig. 6). It exhibits a minimum solar shading coefficient of 30%. The other types of solar shades are more efficient. They may permit reaching a solar shading coefficient close to 0%.

In the case study, the increase in lighting energy demand does not influence significantly the thermal loads. Cooling energy needs are 20 times higher than the energy consumption of the lights (Fig. 8). For the four types of solar shades the link between the solar shading coefficient and the electric needs for the lights are quite similar. However, this information on the energy consumption of the lights is important for energy needs calculation, it does not inform the designers about daylight visual comfort.

Analysis of the sun patch index shows that the simple overhang is unable to remove discomfort due to direct beam irradiation on the work plane (Fig. 9). Analysis of the modified useful daylight illuminance demonstrates that the rectangular side fins reduce significantly the level of luminance of the room in comparison to the triangular side fins (Figs. 10 and 11). The best solar protection for the case study is clearly the overhang with an infinite width and a relative length equal to 1 (the length of the solar shading is equal to the height of the window). For this sizing, the solar shading coefficient and the sun patch index are around 0%. The modified useful daylight illuminance is 85%, only 2% less than the maximum useful daylight illuminance experienced for the any of the solar shades examined.

6. Sizing of louvers for a west window

For this second case, louvers with a different number of blades are considered (Fig. 12). The zenith angle of the solar rays that could enter through a west-facing window is high and louvers are considered as efficient solar shades for this orientation. The sizing of louvers mainly depends on the number of blades. For the case study, the height, the width and the angle of the blades are fixed (Fig. 12). The distance δ between two slats corresponds to the ratio of the height of the window to the number of blades. The aim of the analysis is to choose the optimal number of blades considering both thermal and visual behaviors.

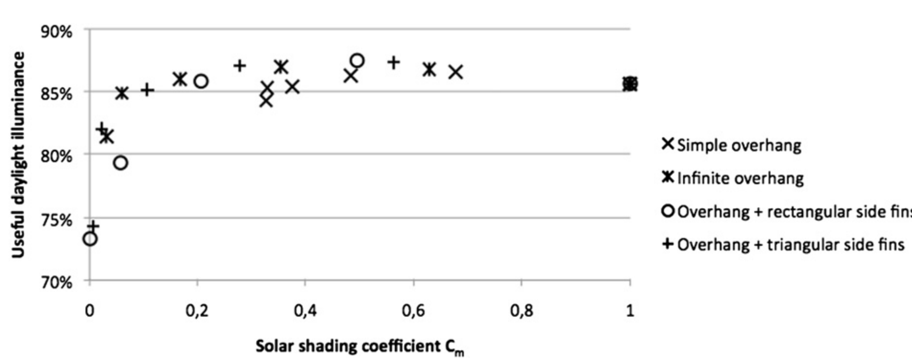

Fig. 10. Modified useful daylight luminance as a function of the solar shading coefficient.

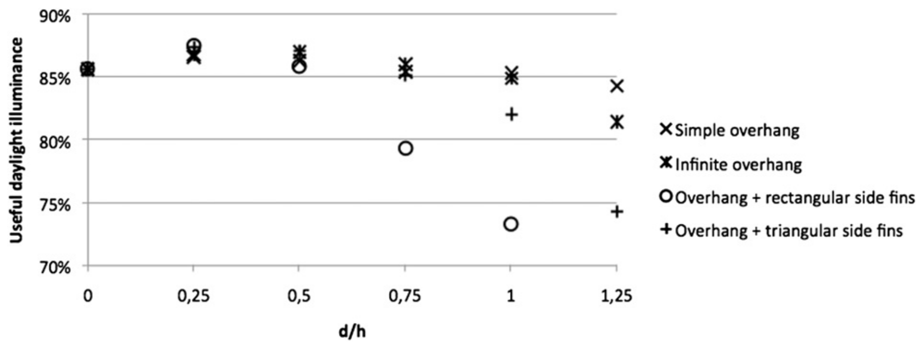

Fig. 11. Modified useful daylight illuminance for different lengths of the solar protections.

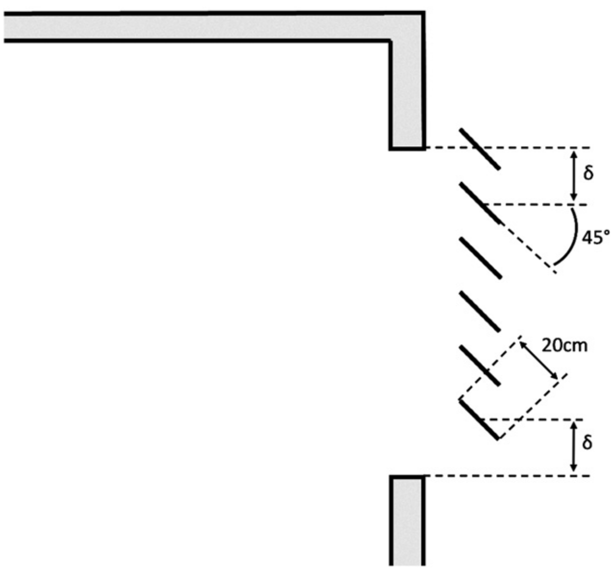

Fig. 12. Louvers dimensional characteristics.

Fig. 13 shows the useful daylight illuminance as a function of the solar shading coefficient and the number of blades. The curve presents three steps. From 0 to 3 blades, the useful daylight illuminance is greater than 80%. Between four and five blades, the useful daylight illuminance is near to 40%. Until five blades the solar shading coefficient decreases significantly while the number of slats increases. And finally, for more than 5 blades, the useful daylight illuminance is below 20% and the solar shade does not permit to reduce the amount of beam solar irradiation that enters through the windows. So, it is not necessary to overprotect the window with a louver that experiences more than 5 blades. It would reduce significantly the visual comfort from daylighting without improving the efficacy of the solar protection.

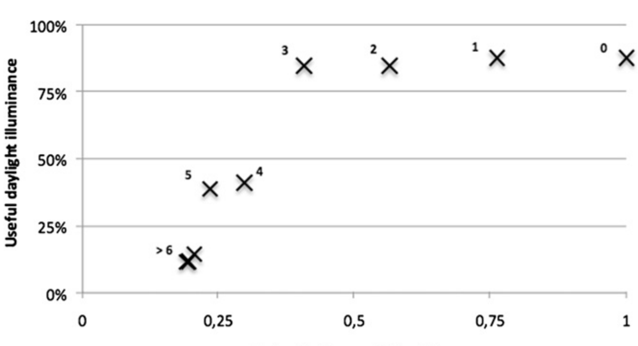

Fig. 13. Modified useful daylight illuminance as a function of the solar shading coefficient.

7. Conclusion

In order to set up a method to assess the efficacy of solar shades in terms of energy demand, thermal comfort and visual comfort, indices need to be developed. Few easy to understand indices, have been proposed that help design teams achieve this goal. The proposed solar shading coefficient reports the thermal efficacy of the solar protection. The visual comfort from daylighting is assessed by a modified useful daylight illuminance. These simple indices have been shown to permit the comparison of the energy and the visual behavior of the case study under different sizing regimes of four types of solar shades. The comparison made obvious the choice and the sizing of specific solar shading.

Using annual meteorological files such as TMYs, a building simulation generates hourly maps of illuminance. The analysis of dayligting provided by these maps can represent a long work. The proposed indices can be automatically generated from these maps. Timesaving could be obtained using these indices in order to optimize the sizing of solar shades.

Designers of green buildings must reach a numerous goals. Sometimes, targets seem to be opposite. This is the case of thermal comfort and visual comfort from daylighting when using solar shading. Even if more and more sophisticated tools permit all the phenomena inside buildings to be known, the proposed easy to use indices improve the dialog between the architects and the civil engineers. This allows the conversation about pro and cons of solar shades design ideas to be considered quickly and easily during the early stages of design.

Equations

$$C_m = \frac{I_{b(\text{with protection})}}{I_{b(\text{without protection})}} \qquad (1)$$

$$\text{Daylight Autonomy} = \text{Modified Useful Daylight Index} + \text{Sun Patch Index} \qquad (2)$$

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