Daylighting design with lightscoop skylights: towards an optimization of proportion and spacing under overcast sky conditions

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Abstract

The main aim of this article is to determine suitable proportions for lightscoop skylights, whose main characteristic is a vertical opening oriented in the opposite direction to the solar trajectory, with a view to ensuring maximum illuminance on the area under study within a room. Lightscape 3.2 software was used to carry out the simulations, comparing the results with those obtained using Daysim 3.1. It was finally concluded that for this type of skylight a height/width ratio of approximately 4/3 is the most suitable for ensuring the highest daylight levels in a room in overcast sky conditions.

Keywords: Skylight, Lightscoop, daylighting, Architectural environment, Overcast Sky, Lighting software.

1 Introduction and objectives

The use of skylights is frequent in modern architecture since they allow access to natural light in rooms lacking façades, while providing homogeneous lighting over the horizontal plane. Most researchers in this field have based their methodology on classic treatises on daylighting [1] and computer simulation.

Treado et al., among other authors, offered in-depth research on open skylights [2], analyzing their advantages and drawbacks. Among their conclusions they highlighted the fact that skylights are the most efficient openings in terms of daylighting, as an entire room can be adequately illuminated using 2% of the ceiling surface. They also concluded that lighting through skylights is more efficient than through windows, both for levels of illuminance and for uniformity. Subsequently, McCluney [3], basing his research on the analytical formulation developed by the IESNA [4] and on statistical data on the behaviour of skylights, created SKYSIZE, the first program for calculating daylighting and implemented in programmable calculators.

More recently Tsangrassoulis [5], using the method for flow transfer developed by Bouchet and Fontoynont [6], studied the efficiency of circular skylights and the amount of light these skylights allowed into a room. In 2003, the National Research Council of Canada developed SkyVision, a simulation program devoted exclusively to open or focal skylights [7]. This program is based on four description factors: optical characteristics of the glass panes, type of glazing assembly, calculation of daylighting using ray-tracing, and sky conditions as established by the CIE [8]. Despite the limitations in terms of types of skylight, since it only covers open skylights, the program obtains very precise results, as shown by Laouadi and Arsenault [9]. These results demonstrated the efficiency of this type of skylight, even in overcast sky conditions, while in clear sky conditions it is possible to obtain considerable thermal gains within the room. As a result, Laouadi [10] concluded that this type of skylight was ideal for cold climates with low solar radiation.

Lightscoops, with their characteristic vertical opening oriented in opposition to the solar trajectory, are frequently used in museum exhibition rooms, library reading rooms, etc. The term lightscoop should be further clarified, since this type of skylight has been described using a variety of architectural terms. Treado et al. define them as clerestories [11], and the CIBSE as monitors [12]. One of the most widely-used definitions is provided by Lam [13], who terms them lightscoops if the opening is oriented towards the open sky, or sunscoops if oriented towards the solar trajectory.

Despite the fact that lightscoops are highly representative of contemporary architecture, few studies have been carried out on the luminous distribution they generate. Lam is one of the few authors to carry out in-depth studies on their behaviour for daylighting [14], concluding that lightscoops provide the lowest and steadiest light levels with minimum annual heat gain.

Among recent studies on lightscoops and sunscoops it is worth highlighting research carried out by García-Hansen et al. [15]. Using models on a 1:20 scale, with different models of skylight, the authors used nine photometers to study luminous distribution within the rooms. Using the level of illuminance measurements within the rooms, the authors deduced the thermal gains produced and consequently the Solar Saving Factor, which demonstrates the thermal behaviour of the skylight. The value of this factor shows the correct operation of this type of skylight, particularly for high latitudes.

Despite the fact that numerous studies have shown the efficiency of this type of skylight, little attention appears to have been paid to the efficiency of the design in making the most of daylight.

The main aim of this study was to determine the most suitable height/width ratio in lightscoops in order to obtain higher illuminance levels within the spaces they light. Subsequently, a study was carried out on the most suitable distance required between lightscoops to ensure homogeneous lighting of the plan under study. This study followed preliminary research included in a published lecture presented at the 4th International Congress on Energy and Environment Engineering and Management [16].

2 Calculation Methodology

2.1 Choosing the calculation conditions

Given that in this context a high number of variables preventing universal conclusions were introduced, the use of the clear sky hypothesis was ruled out. Analyses in overcast sky conditions are more advisable for comparing time variations as in these conditions uniformity coefficients and daylight factors remain invariable. The overcast sky model, used in all the trials, is that defined by Moon-Spencer [17], where the luminance values are distributed in accordance with the following law:

$$L_\theta = L_Z \cdot (1+2\sin\theta)/\ 3$$

Where L_Z is the luminance at the zenith of the sky vault and θ the projection angle. This implies that the lowest luminance value in an overcast sky vault occurs on the horizon, and is equivalent to a third of the maximum luminance at the zenith:

$$L_0 = L_Z/\ 3$$

The formulation established by Moon-Spencer corresponds to the definition of overcast sky accepted by the CIE [18].

Clear sky conditions always provide a greater luminance of the sky vault than overcast sky conditions [19]. As a result, if the calculation model meets expectations for overcast sky conditions, predictably it will also do so under a sky with greater luminance. However, in clear sky conditions the design of the skylight must avoid direct sunlight within the space. Lightscoop models avoid direct sunlight, opposing the opening to the solar trajectory, provided this trajectory follows a predominant orientation. These skylight models are therefore valid for locations north of the Tropic of Cancer and south of the Tropic of Capricorn. Nevertheless, at very high latitudes, lightscoops require vertical shading for shielding from low angle sun.

2.2 Choosing calculation programs

Two daylighting simulation programs were chosen to analyze the different skylight models.

The first of the programs used was Lightscape 3.2, which calculates luminous distribution using radiosity. The second program used was Daysim 3.1, which is based on the RADIANCE backward ray-tracer [20]. Several studies have confirmed the precision of these calculation programs [21,22,23]. Comparing the two provides more information for validating the results.

Table 1 shows the calculation parameters used by each program.

Lightscape 3.2			
Sky Conditions	Overcast sky		
Mesh Spacing		Min	0.1 m
		Máx	0.2 m
Subdivision Contrast Threshold			0.65
Skylight Accuracy			0.60
Source	Direct Source	Min	0.12
		Subdivision Accuracy	0.42
	Indirect Source	Min	0.24
		Subdivision Accuracy	0.42
	Shadow Grid Size		Five
Tolerances	Lenght		0.0005
	Ray Offset		0.001
	Initialization Min Area		0.01
DaySim 3.1			
Sky conditions	Overcast Sky		
Project Climate file	Madrid.wea		
Grid dimensions	X	Start position	0.05
		Grid Size	8.90
		Number of cells	40
	Y	Start position	0.05
		Grid Size	8.90
		Number of cells	40
RADIANCE Simulation Parameters	Ambient Bounces		5
	Ambient Divisions		1000
	Ambient Super-samples		20
	Ambient Resolution		300
	Ambient Accuracy		0.1
	Limit Reflection		6
	Specular Threshold		0.1500
	Specular Jitter		1.0000
	Limit Weight		0.0040
	Direct Jitter		0.0000
	Direct Sampling		0.2000
	Direct Relays		2
	Direct Pretest Density		512

Table 1: Parameters of the calculation programs

2.3 Choosing the calculation model

The initial model used for the trials was a room 9 m wide by 9 m long by 3 m high. A lightscoop, 6 m long and with variable height (Y) and width (X) (fig. 1), was placed in the centre of the roof.

The model represents the typical dimensions of a museum or library room. The low height of the ceiling in relation to the measurements of the space allows a distribution of light that is largely dependent on the Sky Component and is therefore of use in analyzing the efficiency of the skylight proportions under study.

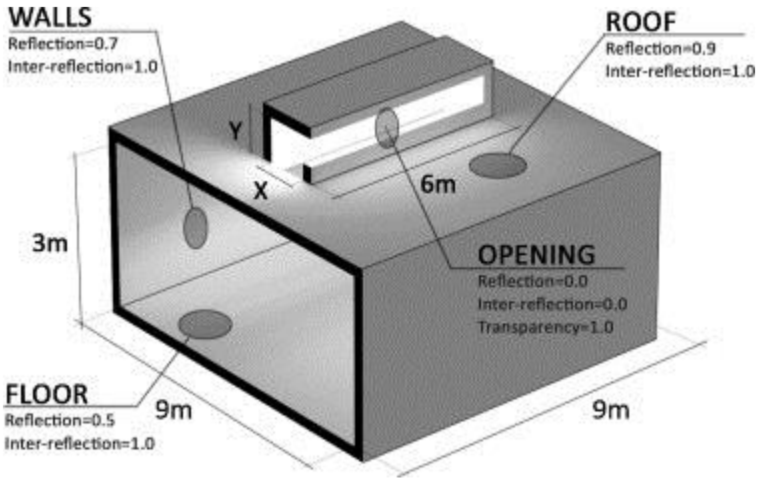

Figure 1: Initial calculation model

To adapt the results to the skylight proportions the qualities of surfaces are considered invariable. The inter-reflection of all the surfaces is completely diffuse, and as a result the light falling on a surface is reflected in all directions. Each surface has a different reflection index: the ceiling has an index of 0.9, the walls 0.7, and the floor 0.5, normal values in the design of interiors.

The maximum, average, and minimum values of the daylight factors observed on the room floor were studied in the calculation model. These values were the result both of the Sky Component and the Internally Reflected Component. All the definitions used in this article are included in the CIE glossary [24] and described in detail by Hopkinson et al. [25].

3 Calculation

3.1 Calculation for different skylight proportions using Lightscape 3.2

The first trial analyzed suitable proportions for the skylight, defining variations in height and width for the lightscoop using the Lightscape 3.2 calculation program. Nine rooms with lightscoops of different proportions were analyzed, considering a length for the variable X of 1 to 5 m, as well as a value for variable Y of 1 to 5 m. The surface at the back and the ceiling of the skylight always add up to the same values, and thus all skylights have the same reflection surface. As a result, the surface of the opening in the ceiling and that of the window of the skylight always add up to the same surface area for all lightscoops (fig. 2).

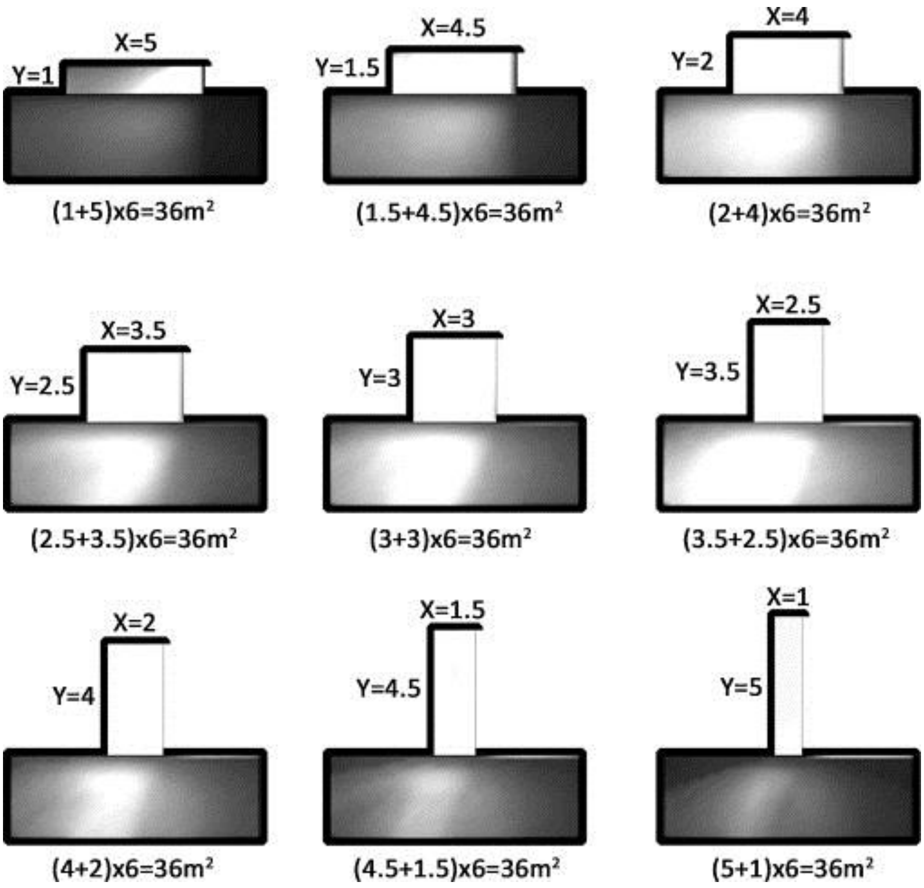

Figure 2: Longitudinal section of trial models

The results of maximum, average, and minimum daylight factors measured on the floor plan of the model are represented in figure 3.

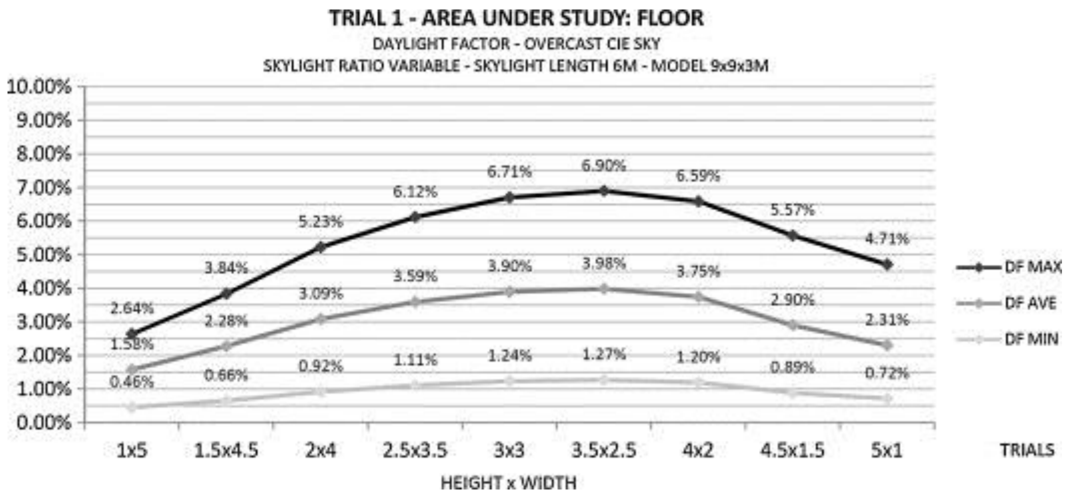

Figure 3: Trial 1. Calculation using Lightscape 3.2. Room 9x9x3 m. Maximum, average, and minimum daylight factors. Lightscoop with variable width and height and a length of 6 m.

Considering an overcast sky, under the calculation conditions of Lightscape 3.2, the lightscoop 3.5 m high and 2.5 m wide produced the best lighting of the floor plan, as can be observed in figure 3.

3.2 Comparing results using DaySim 3.1

To confirm the results observed with Lightscape 3.2 for the suitable proportions of the lightscoops, a second test was carried out using DaySim 3.1. The series of skylights examined in this study was the same as that used in the first trial. All the models were studied in overcast sky conditions.

Comparing results with DaySim 3.1 allows us to observe the behaviour of skylights under a different calculation algorithm.

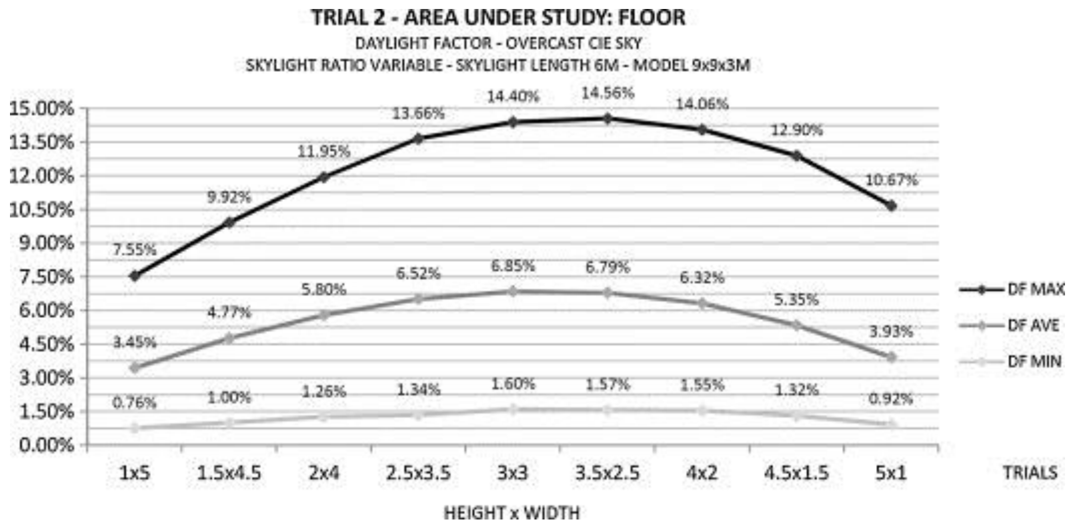

Figure 4: Trial 3. Calculation using DaySim 3.1. Room 9x9x3 m. Maximum, average, and minimum daylight factors. Lightscoop with variable height and width and a length of 6 m.

As can be observed in figure 4, in the calculation carried out using DaySim 3.1 the highest daylight factors are also obtained for the range close to that of a skylight measuring 3.5 m high and 2.5 m wide.

3.3 Study of skylight proportions with variable room measurements

The two previous trials were carried out using an initial room model to establish suitable proportions for the lightscoop and obtain higher levels of lighting in overcast sky conditions. In order to generalize the conclusions obtained for any type of room, we show below the results obtained from a further study carried out with Lightscape 3.2, where the same lightscoop proportions were analyzed for different room models with variable measurements:

- Square room, 9 m wide by 9 m long.
- Rectangular room, 6 m wide by 12 m long.
- Rectangular room, 12 m wide by 6 m long.

Each room was studied considering variable heights of 3, 4.5, and 6 m, thus obtaining a total of nine types of rooms: eight new types in addition to the original model (fig. 5).

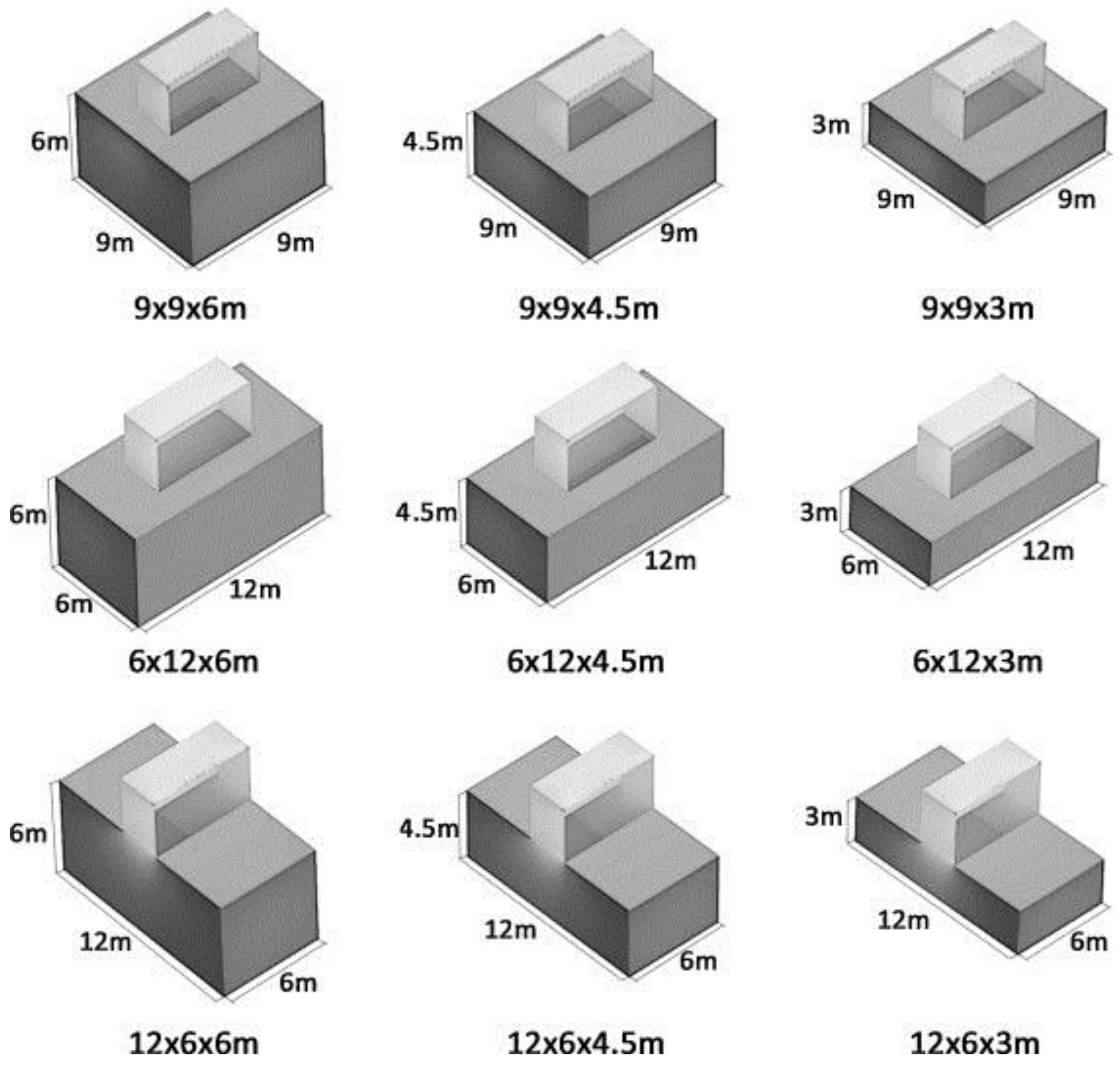

Figure 5: Representation of the measurements of the different models of rooms under study for the 2.5x3.5 m lightscoop.

In short, a total of nine skylights of variable proportions were studied for nine different types of rooms, obtaining a total of eighty-one new tests.

Figure 6 shows the average daylight factors on the square floor plan model, with a length of 9 m and variable heights of 3, 4.5, and 6 m.

Both in the room measuring 4.5 m in height and in the one 6 m high the behaviour of the daylight factors, measured on the floor, was very similar to that observed in the room measuring 3 m high, although logically the daylight factors decreased as the height of the room increased.

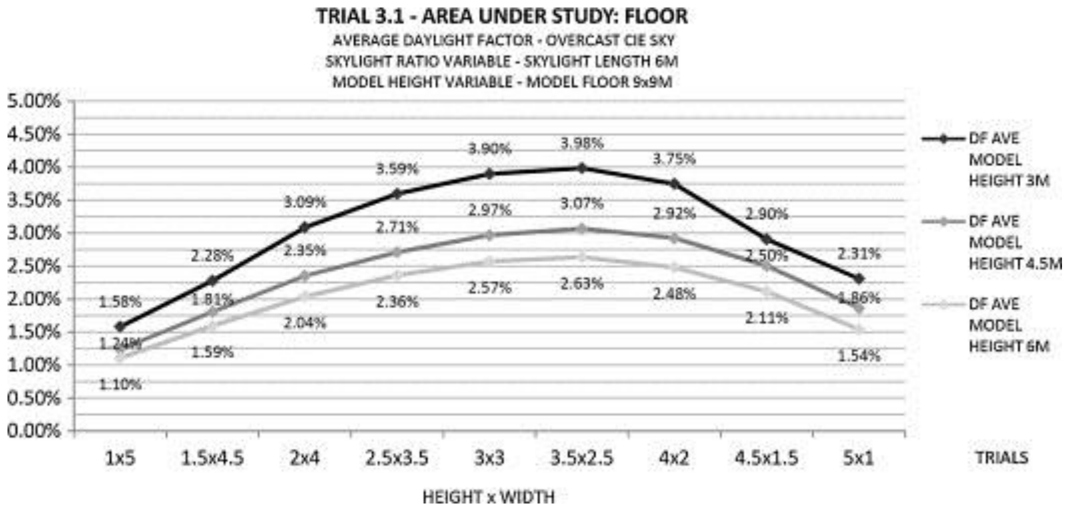

Figure 6: Trial 3.1. Calculation using Lightscape 3.2. Room floor 9x9 m. Room height variable. Average daylight factors. Lightscoop with variable height and width and a length of 6 m.

Therefore, for the square floor plan model the lightscoops with a height/width of approximately 4/3 are those which produce the highest levels of daylight.

The following series of tests was carried out on the rectangular floor plan model, 6 m wide by 12 m long, considering variable heights of 3, 4.5, and 6 m. The average daylight factors of each room are represented in figure 7. As was observed, the behaviour of daylight factors was very similar to that in the square floor plan. The maximum values were observed in the skylight with a height/width proportion of 4/3 (lightscoop 3.5 m high by 2.5 m wide).

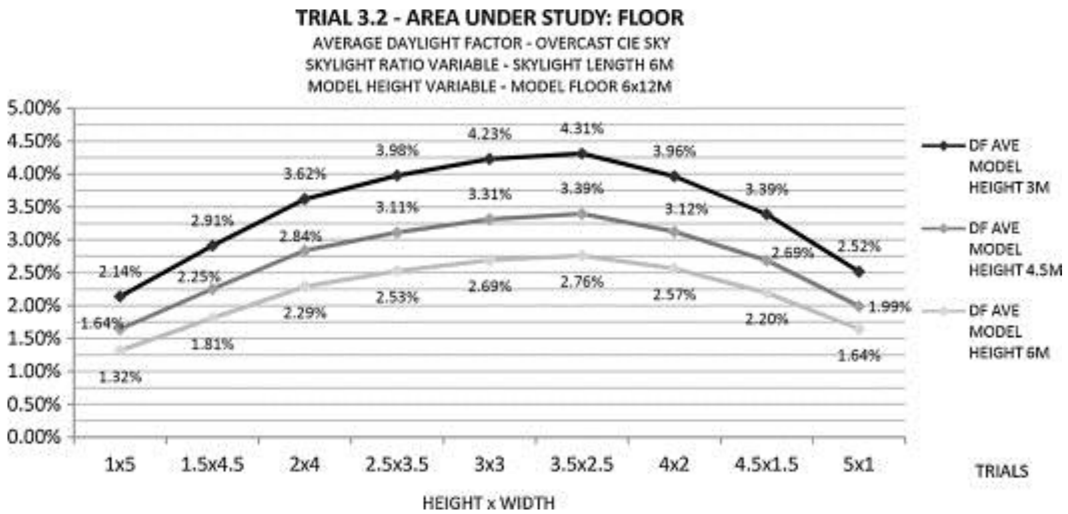

Figure 7: Trial 3.2. Calculation using Lightscape 3.2. Room floor 6x12 m. Room height variable. Average daylight factors. Lightscoop with variable height and width and a length of 6 m.

The last series of tests analyzed the rectangular room, 12 m wide and 6 m long, with variable height at 3, 4.5, and 6 m. The average daylight factors of each room are represented in figure 8. As was observed, the behaviour of the daylight factors on the floor plan of the different rectangular models was similar to that observed in square floor plan models. Consequently, the lightscoops with height/width ratios close to 4/3 allow the highest illuminance levels, independent of the room measurements. As expected, it was also observed that of the three room models analyzed, the highest daylight factor values were obtained in the rectangular floor plan 6 m wide by 12 m long, as reflection is more effective on the walls parallel to the opening than on the perpendicular ones.

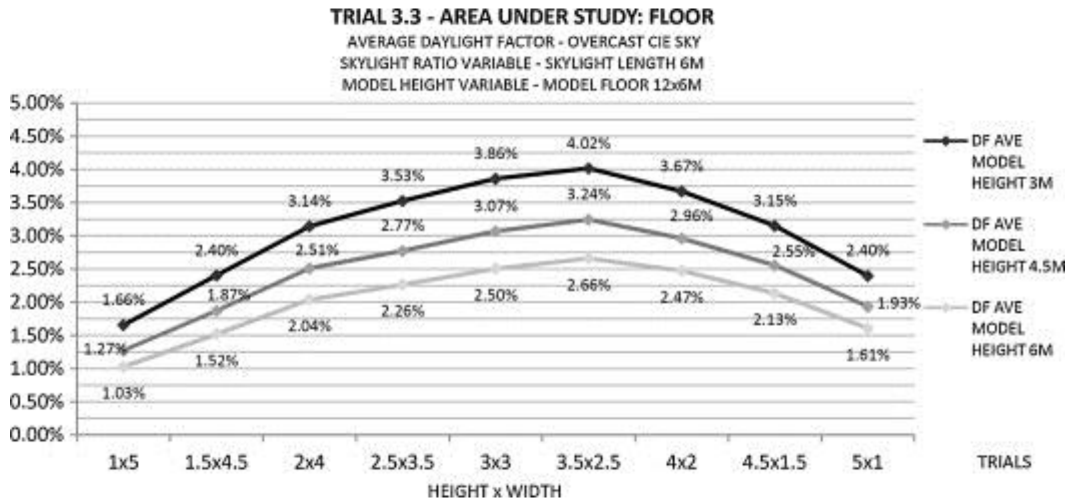

Figure 8: Trial 3.3. Calculation using Lightscape 3.2. Room floor 12x6 m. Room height variable. Average daylight factors. Lightscoop with variable height and width and a length of 6 m.

4 Study of illuminance distribution

4.1 Geometric analysis of the illuminance distribution caused by the Sky Component in skylights

Once the suitable proportions of the lightscoops had been determined, a complementary study was developed to examine the illuminance distribution generated by these skylights in a room in overcast sky conditions.

The aim of the study was to assess the uniformity of lighting within a room, ignoring the quantification of the levels of daylight resulting from the type of skylight. These conclusions are based on the fact that illuminance within a room is highly unstable, due to the high variability of the luminance of the sky vault.

The room model used was the initial one (fig. 1). However, in this case the skylight covered the length of the room and the effect of light on the wall opposite the opening was observed more clearly. The reflection index of all the interior surfaces was considered to be nil and as a result the Internally Reflected Component disappeared, meaning that the luminous distribution inside the room depended solely on the Sky Component. The omission of inter-reflection within the room made it possible to examine the more unfavourable lighting conditions. Nevertheless, it must be noted that if the Internally Reflected Component were to be allowed, a greater spacing would be set between skylights.

Figure 9 displays the illuminance distribution generated by the Sky Component in overcast sky conditions for a lightscoop with a height/width ratio of 4/3.

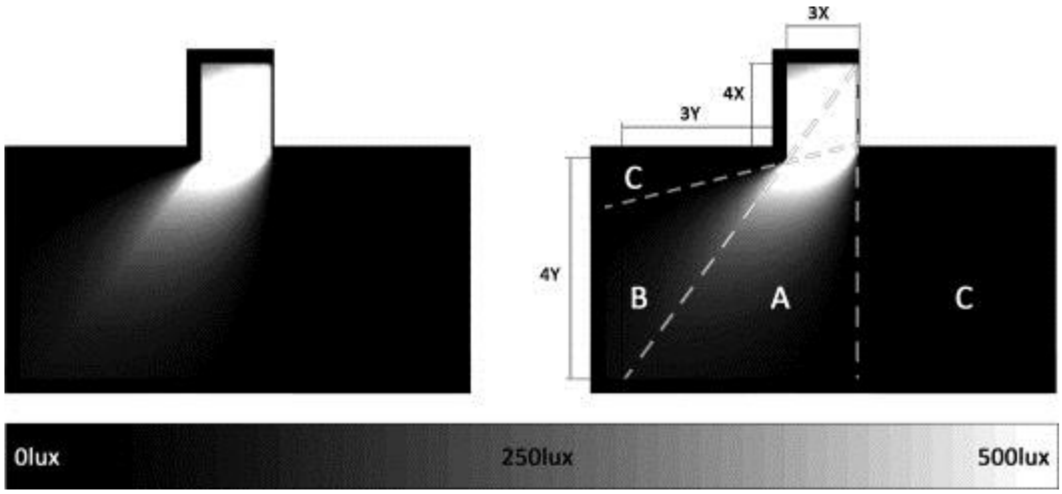

Figure 9: Illuminance distribution of the Sky Component within a room in overcast sky conditions with a lightscoop with a height/width ratio of 4/3.

As can be observed, the illuminance distribution of the Sky Component is completely dependent on the proportions of the lightscoop. It is also possible to observe three areas which are clearly differentiated in terms of the amount of illuminance.

- Area A is that with the greatest illuminance, as the opening of the skylight is completely visible from any point of this area and as a result the effect of the luminance of the sky vault is at a maximum.
- Area B is an area with less illuminance as the opening is not completely visible from any of its points.
- Area C refers to zones that are completely hidden from the opening and therefore, in the absence of an Internally Reflected Component, illuminance in these areas is nil.

The illuminance distribution generated by a series of skylights is different from that observed in a room with a single opening (fig. 10).

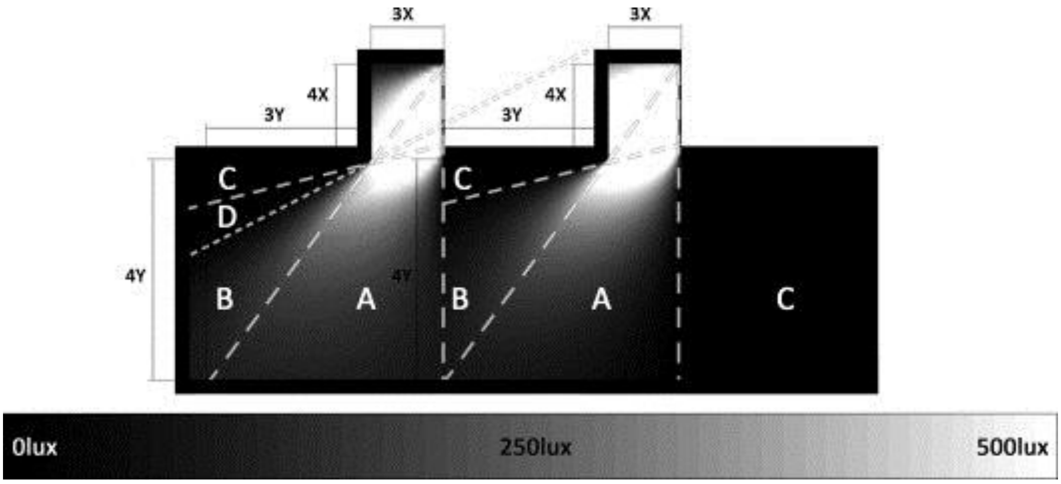

Figure 10: Illuminance distribution of the Sky Component within a room in overcast sky conditions with two lightscoop models with a height/width ratio of 4/3, considering the height of the room as equivalent to 4/3 of the spacing between skylights.

As was observed in the previous figure, in evaluating the different areas in terms of lighting, a new surface -D- appeared, characterized by a different degree of illuminance. The sky vault was not visible from this area, as it was blocked out by the following skylight. As a result, the lighting of this surface depended on the Externally Reflected Component generated by the reflection of the luminance of the sky vault on the outer wall of the next skylight.

4.2 Study of the spacing between skylights

The distribution of the light within a room makes it possible to determine the spacing between skylights to ensure homogeneous illuminance on the plan under study. Accordingly, a new study was carried out, analyzing different layouts for lightscoops in the same room, in order to establish the correct distance at which they should be placed.

The study was carried out in overcast sky conditions, in the same location observed in previous trials. The program used was Lightscape 3.2.

Just as in the previous study, the interior surfaces of the room had zero reflection value, meaning that only the Sky Component was assessed.

Five trials were carried out with different spacings between skylights. The spacing between the lightscoops is proportional to the height of the room (fig. 11). The levels of illuminance were analyzed on the floor plan and represented in the room section.

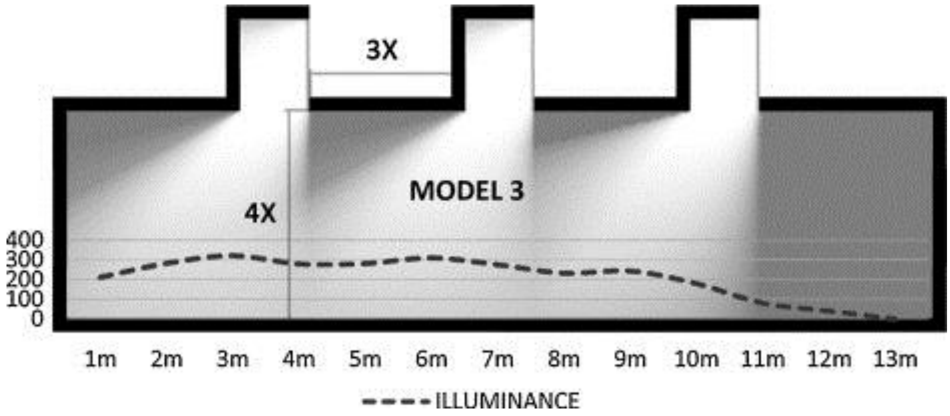

Figure 11: Levels of illuminance within a room in overcast sky conditions with lightscoop models with a height/width ratio of 4/3. The ratio of room height to the distance between skylights is 4/3.

After determining the levels of illuminance resulting from the different spacings between skylights, an assessment was carried out of the uniformity of the illuminance on the floor plan in each trial. To do so, attention was paid to the quotient resulting from the minimum and maximum value of illuminance in the range of influence of the series of skylights. This range considered the levels of illuminance at points located between the 3 and 9 m marks in the length of the room, as the ends of the room fell outside the influence of the skylights.

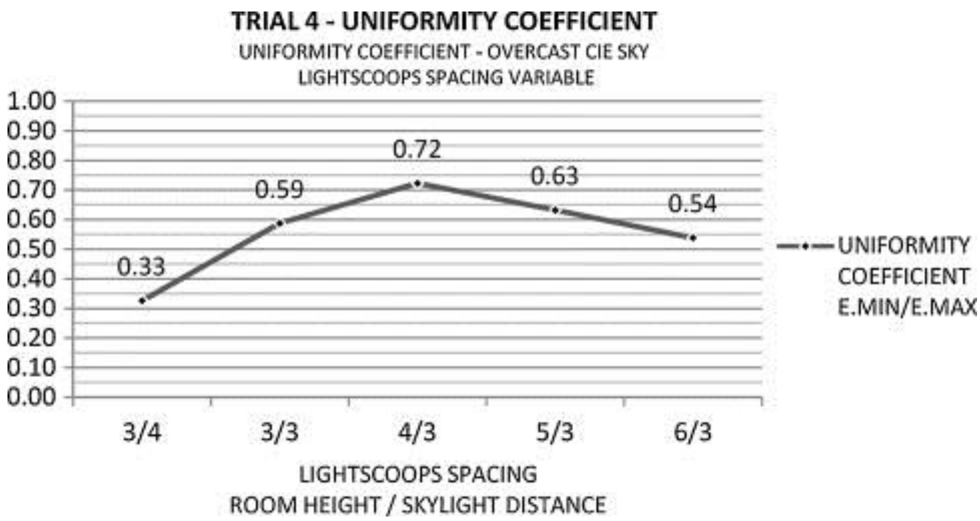

Figure 12: Uniformity coefficient: Quotient of the minimum level of illuminance divided by the maximum on the floor plan, in a range of 3 to 9 m in the length of the room.

As was observed in figure 12, the highest uniformity coefficient corresponded to the spacing between the skylights for a room with a height/spacing ratio of 4/3. It was also observed that the skylights with a greater distance between each other cause a non-uniform distribution while those closer together provide an acceptable distribution of illuminance.

In conclusion, considering a lightscoop with a height/width ratio of 4/3 and considering that the plan studied corresponds to the floor of the room, the distribution of the illuminance determines that the height of the room should be equal to or less than 4/3 of the length of the ceiling separating two skylights.

As pointed out at the start of this study, it must be noted that if inter-reflection were considered, the spacing between lightscoops would be greater.

5 Conclusion

According to the results observed in the trials carried out, in overcast sky conditions lightscoop skylights provide greater levels of illuminance on the floor plan when the height/width ratio of the skylight is close to a 4/3 value, regardless of the size of the room illuminated.

The proposed ratios of approximately 4/3 for the lightscoops are suited to sky conditions of greater luminance than those with an overcast sky, for instance a clear sky, providing direct sunlight is avoided within the room.

As regards the positioning of the skylights in the ceiling, considering a lightscoop model with a height/width ratio close to 4/3, the proportion between the height from the area under study to the ceiling and the separation between the openings of the skylights must be equal to or less than 4/3 to obtain acceptable uniformity of the illuminance within the room.

It was observed that the skylight surface necessary to illuminate a room can be small, as concluded from the average daylight factors from trials 1 to 3, and in agreement with the observations of Treado et al.

One of Lam's conclusions is confirmed: the illuminance produced by a lightscoop on the floor plan is ostensibly homogeneous.

6 6. References

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