# Analysis of daylight factors and energy saving allowed by windows under overcast sky conditions

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## Abstract

The aim of this research is to quantify the daylight factors produced inside a room for different models of windows, and to conduct an analysis of the results obtained. All trials were performed under overcast sky conditions, as these represent the worst case scenario for calculation. The shape, size and position of the window are variable, as is the reflectance of the inner surfaces of the room. A total of 28 simulations are provided by the lighting simulation program Daylight Visualizer 2.6, validated by the CIE test cases. After trials it was concluded that square windows produce daylight factors slightly higher than those obtained with horizontal windows and noticeably higher than those measured with vertical windows, considering the same surface of openings. It is confirmed that the daylight factors are directly proportional to the glass surface, except in the area near the window. It is also concluded that the windows in the upper position allow higher luminance at the back of the room than those in centered locations. Finally, the energy savings produced by the different models of windows is calculated.

*Keywords:* window, daylight factor, daylighting, overcast sky, lighting simulation program, energy saving.

## 1. Introduction and objectives

### 1.1. State of the art

Windows are a key element in architecture, as they represent the most basic resource for allowing natural light inside buildings [1]. The proper design of windows also improves thermal comfort and brings about a notable energy saving in artificial lighting [2].

Daylight factor is the simplest and most common measure to quantify the daylight allowed by a window, as they express the potential illuminance inside a room in the worst possible scenario, under overcast sky conditions when there is less exterior daylight. At present, the daylight factors represent the most widely used metric in the evaluation of daylighting. Moreover, this definition is recognized by the CIE as one of the key metrics in lighting [3]. Since daylight factors are assessed under overcast conditions, the sun's position is not relevant, so the calculation is independent of the location of the room. Therefore, the measurement of daylight factors does not depend on time, window orientation or location of the room, they are only affected by the geometry of the model.

According to the definition of daylight factor, the calculation of the illuminance at an interior point is immediate as long as the external illuminance is known.

Nevertheless, it is important to mention other methods for daylight evaluation, such as daylight autonomy [4], developed by Reinhart et al., which is one of many currently existing metrics that consider the dynamic aspects of daylight and is usually applied for annual calculations.

Daylight factors produced by windows have been studied since the early modern treatises on daylight [5]. In order to simplify its calculation this metric is seen as the sum of three components [3]: the sky component, the internally reflected component and the externally reflected component. The methods of calculation provided more than half a century ago are still valid nowadays. Currently, most treatises [6,7] solve the sky component using analytical formulas and the reflected components using empirical methods.

Empirical methods do not give reliable results, as can be observed from the daylight factor method [8], based on very limited calculation conditions and defined as a low accuracy method [9]. Other empirical calculation methods obtain results with similar accuracy [10,11].

However, at present, lighting simulation programs allow the calculation of daylight factors with greater accuracy than empirical methods [12,13], making them extremely useful tools in the field of natural lighting.

Furthermore, lighting simulation programs have allowed the development of new methods for calculating daylight factors, whose accuracy has been supported by computer simulations. An example of this is the study by Ghisi et al. [14], who developed a calculation method, contrasted with VisualDOE, which determines the ideal window area for maximum efficiency considering the use of natural and artificial lighting. The authors conclude that smaller or wide rooms result in greater energy savings in lighting and the ideal window area tends to be higher in low thermal load orientations. Another notable example can be found in the research of Li et al. [15], who developed a calculation procedure relying on the daylight coefficient concept and confirming the results using the Radiance program. In this study, the authors create a method based on multiple tables and charts for establishing illuminance.

In addition, lighting simulation programs have been used to establish the design conditions of windows and rooms. A noteworthy example is that of the research by Munoz et al. [16], where the authors analyze different metrics in an office illuminated through windows. This study allows the authors to quantify the loss of performance of windows depending on external obstructions.

Currently, most research supported by computer simulations studies daylight factors produced by windows with blinds or shading devices. One of the most interesting articles in this field is that by Alzoubi et al. [17], who analyze the performance of windows with vertical and horizontal shading devices. The authors conclude that there is an optimal orientation for shading devices that keeps the internal illuminance level within the acceptable range with minimum amount of solar heat gain. In this research, the authors also determine the energy saving produced by different shading devices.

The research by Sanati et al. [18] is also worth noting; it concludes that window blinds are not properly used by the occupants and that the use of slat systems allows higher energy savings in artificial lighting. Some interesting research can be observed in the study by Villalba et al. [19] on the permeability of urban trees in daylighting of windows using models based on blinds.

The study on window design is not only based on daylighting conditions. Another approach focuses on thermal comfort, as shown in some research [20,21]. In any case, it is a fact that the study of windows is an endless source of research results.

### 1.2. Aim and objectives

The aim of this research is to quantify the daylight factors inside a room for different models of windows, conducting an analysis of the results obtained. All trials were performed under overcast sky conditions, as these represent the worst case scenario for calculation. The shape, size and position of the window are variable, as is the reflectance of the inner surfaces of the room.

Accordingly, this research is based on three main objectives:

1. To represent the quantification of daylight factors in more conventional calculation models, so that it serves as a reference for window design in architecture.
2. To conduct an analysis of the resulting daylight factors and obtain criteria for shape, size and position of windows.
3. To determine the energy saving produced by different models of windows.

## 2. Description of Methodology for Calculation

### 2.1. Choosing the calculation model

The calculation model for the analysis of daylight factors is defined as a room 3.00 m wide by 6.00 m deep by 3.00 m high. The ceiling, walls and floor of the room have a thickness of 0.25 m. A window of variable shape, size and position is located in the 3.00 m wide façade. The double-leaf window has 0.05 m thick joinery and double glazing which produces a solar factor of 0.7. The reflectance of the inner surfaces of the calculation model is variable, accordingly two basic room models –with light or dark surfaces– are defined. The inner surfaces of the room are diffuse reflectors and the Lambertian reflection of daylight is therefore directly proportional to the cosine of the angle between the observer's line of sight and the surface normal. All variables of the calculation model are shown in Figure 1:

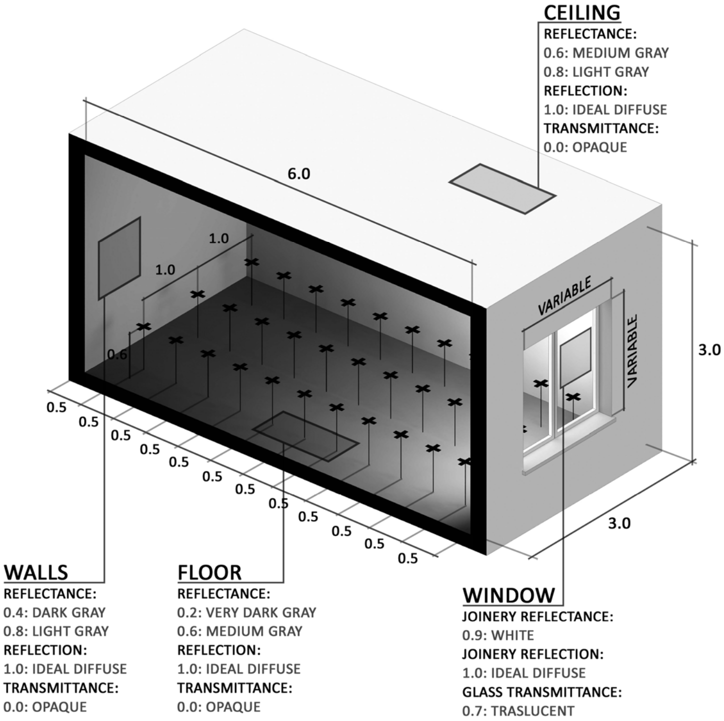


*Figure 1: Calculation model.*

The measurement of daylight factors is performed on the axis of symmetry of the calculation model and on two equidistant axes at 1.00 m. Therefore, the study points are located on these axes with a spacing of 0.50 m and a height above ground of 0.60 m. The study points are represented in Figure 1. A total of 36 study points are used in each model.

The calculation model is defined according to the following variables:

Window shape:

S: Square shape, length/height ratio of 1·1.
H: Horizontal shape, length/height ratio of 2·1.
V: Vertical shape, length/height ratio 1·2.

Window size:

10: Window surface/Façade surface ratio equal to 10%, equivalent to 0.90 m$^2$.
20: Window surface/Façade surface ratio equal to 20%, equivalent to 1.80 m$^2$.
30: Window surface/Façade surface ratio equal to 30%, equivalent to 2.70 m$^2$.
40: Window surface/Façade surface ratio equal to 40%, equivalent to 3.60 m$^2$.
60: Window surface/Façade surface ratio equal to 60%, equivalent to 5.40 m$^2$.
80: Window surface/Façade surface ratio equal to 80%, equivalent to 7.20 m$^2$.

Window position:

C: Window in centered position on the façade.
U: Window in upper position on the façade, with the sill at 1.50 m above room floor level.

Room reflectance:

B: Bright room: Room surfaces with high reflectance.
D: Dark room: Room surfaces with low reflectance.

A total of 28 simulations are established, as shown in Table 1:

| Model | Length/ Height | Window surface | Window dimensions | Window/ Façade | Window position | Glass surface | Glass solar factor | Walls reflectance | Floor reflectance | Ceiling reflectance | Average reflectance |
|---|---|---|---|---|---|---|---|---|---|---|---|
| S.10.C.B | 1 · 1 | 0.90 m² | 0.95·0.95 m | 10.00% | Centered | 0.64 m² | 0.7 | 0.8 | 0.6 | 0.8 | 0.75 |
| S.10.C.D | 1 · 1 | 0.90 m² | 0.95·0.95 m | 10.00% | Centered | 0.64 m² | 0.7 | 0.4 | 0.2 | 0.6 | 0.40 |
| S.10.U.B | 1 · 1 | 0.90 m² | 0.95·0.95 m | 10.00% | Upper | 0.64 m² | 0.7 | 0.8 | 0.6 | 0.8 | 0.75 |
| S.10.U.D | 1 · 1 | 0.90 m² | 0.95·0.95 m | 10.00% | Upper | 0.64 m² | 0.7 | 0.4 | 0.2 | 0.6 | 0.40 |
| S.20.C.B | 1 · 1 | 1.80 m² | 1.34·1.34 m | 20.00% | Centered | 1.41 m² | 0.7 | 0.8 | 0.6 | 0.8 | 0.74 |
| S.20.C.D | 1 · 1 | 1.80 m² | 1.34·1.34 m | 20.00% | Centered | 1.41 m² | 0.7 | 0.4 | 0.2 | 0.6 | 0.39 |
| S.20.U.B | 1 · 1 | 1.80 m² | 1.34·1.34 m | 20.00% | Upper | 1.41 m² | 0.7 | 0.8 | 0.6 | 0.8 | 0.74 |
| S.20.U.D | 1 · 1 | 1.80 m² | 1.34·1.34 m | 20.00% | Upper | 1.41 m² | 0.7 | 0.4 | 0.2 | 0.6 | 0.39 |
| S.30.C.B | 1 · 1 | 2.70 m² | 1.64·1.64 m | 30.00% | Centered | 2.22 m² | 0.7 | 0.8 | 0.6 | 0.8 | 0.74 |
| S.30.C.D | 1 · 1 | 2.70 m² | 1.64·1.64 m | 30.00% | Centered | 2.22 m² | 0.7 | 0.4 | 0.2 | 0.6 | 0.39 |
| S.40.C.B | 1 · 1 | 3.60 m² | 1.90·1.90 m | 40.00% | Centered | 3.06 m² | 0.7 | 0.8 | 0.6 | 0.8 | 0.73 |
| S.40.C.D | 1 · 1 | 3.60 m² | 1.90·1.90 m | 40.00% | Centered | 3.06 m² | 0.7 | 0.4 | 0.2 | 0.6 | 0.38 |
| S.60.C.B | 1 · 1 | 5.40 m² | 2.32·2.32 m | 60.00% | Centered | 4.71 m² | 0.7 | 0.8 | 0.6 | 0.8 | 0.71 |
| S.60.C.D | 1 · 1 | 5.40 m² | 2.32·2.32 m | 60.00% | Centered | 4.71 m² | 0.7 | 0.4 | 0.2 | 0.6 | 0.38 |
| S.80.C.B | 1 · 1 | 7.20 m² | 2.68·2.68 m | 80.00% | Centered | 6.40 m² | 0.7 | 0.8 | 0.6 | 0.8 | 0.70 |
| S.80.C.D | 1 · 1 | 7.20 m² | 2.68·2.68 m | 80.00% | Centered | 6.40 m² | 0.7 | 0.4 | 0.2 | 0.6 | 0.37 |
| H.10.C.B | 2 · 1 | 0.90 m² | 1.34·0.67 m | 10.00% | Centered | 0.65 m² | 0.7 | 0.8 | 0.6 | 0.8 | 0.75 |
| H.10.C.D | 2 · 1 | 0.90 m² | 1.34·0.67 m | 10.00% | Centered | 0.65 m² | 0.7 | 0.4 | 0.2 | 0.6 | 0.40 |
| H.10.U.B | 2 · 1 | 0.90 m² | 1.34·0.67 m | 10.00% | Upper | 0.65 m² | 0.7 | 0.8 | 0.6 | 0.8 | 0.75 |
| H.10.U.D | 2 · 1 | 0.90 m² | 1.34·0.67 m | 10.00% | Upper | 0.65 m² | 0.7 | 0.4 | 0.2 | 0.6 | 0.40 |
| H.20.C.B | 2 · 1 | 1.80 m² | 1.90·0.95 m | 20.00% | Centered | 1.45 m² | 0.7 | 0.8 | 0.6 | 0.8 | 0.74 |
| H.20.C.D | 2 · 1 | 1.80 m² | 1.90·0.95 m | 20.00% | Centered | 1.45 m² | 0.7 | 0.4 | 0.2 | 0.6 | 0.39 |
| H.20.U.B | 2 · 1 | 1.80 m² | 1.90·0.95 m | 20.00% | Upper | 1.45 m² | 0.7 | 0.8 | 0.6 | 0.8 | 0.74 |
| H.20.U.D | 2 · 1 | 1.80 m² | 1.90·0.95 m | 20.00% | Upper | 1.45 m² | 0.7 | 0.4 | 0.2 | 0.6 | 0.39 |
| V.10.C.B | 1 · 2 | 0.90 m² | 0.67·1.34 m | 10.00% | Centered | 0.58 m² | 0.7 | 0.8 | 0.6 | 0.8 | 0.75 |
| V.10.C.D | 1 · 2 | 0.90 m² | 0.67·1.34 m | 10.00% | Centered | 0.58 m² | 0.7 | 0.4 | 0.2 | 0.6 | 0.40 |
| V.20.C.B | 1 · 2 | 1.80 m² | 0.95·1.90 m | 20.00% | Centered | 1.35 m² | 0.7 | 0.8 | 0.6 | 0.8 | 0.74 |
| V.20.C.D | 1 · 2 | 1.80 m² | 0.95·1.90 m | 20.00% | Centered | 1.35 m² | 0.7 | 0.4 | 0.2 | 0.6 | 0.39 |

***Table 1: Calculation models according to defined variables.***

The variables of the calculation models have been established according to the most common parameters of shape, size and position of the window of a conventional room. Obviously, this study sample does not cover all possible hypotheses, but aims to show the most frequent cases study.

## 2.2. Choosing the calculation program

The analysis of the daylight factors was carried out using simulation program Daylight Visualizer 2.6, which calculates luminous distribution using the ray-tracing process. Several studies have confirmed the correct behavior of this calculation program [22,23], determining their accuracy by applying the CIE test cases [12]. Currently, several research related to daylighting are based in this simulation program [24,25]. The calculation parameters used by this program in this research are shown in table 2.

| Calculation | Ray-tracing | Calculation system |
|---|---|---|
| Sky Conditions | Standard Overcast Sky | Perez et al. sky model |
| Ambient | On | Activation of indirect illumination |
| Trace level | 8 | Number of bounces of all types of lighting |
| Ambient trace level | 8 | Number of bounces of indirect lighting |
| Ambient precision | 1 | Relates to the image based sampling used |
| Ambient complexity | 10 | Lighting complexity |
| Ambient feature size | 1 | Relates to the image interpolation quality |

***Table 2: Parameters of the calculation program.***

The trial methodology does not include a comparison of daylight factors for a physical model under an artificial sky, as this can lead to a high margin of error with a real model, and a relative divergence of around 30%, as established by Thanachareonkit et al. [26].

## 2.3. Choosing the calculation conditions

By definition, the calculation of daylight factor components is carried out considering an unobstructed sky of assumed or known illuminance distribution, excluding direct sunlight. The definition of Standard Overcast Sky is used to calculate the sky component.

The Standard Overcast Sky model, used by Daylight Visualizer 2.6, is that developed by Perez et al. [27], where the ratio of the luminance, $L_a$, of an arbitrary sky element to the zenith luminance, $L_z$, is:

$$\frac{L_a}{L_z} = \frac{f(\chi) \cdot \varphi(Z)}{f(Z_s) \cdot \varphi(0)}$$

where:

$$f(\chi) = 1$$

$$f(Z_s) = 1$$

$$\varphi(Z) = 1 + 4 \cdot \exp\left(\frac{-0.7}{\cos Z}\right)$$

$$\varphi(0) = 1 + 4 \cdot \exp(-0.7)$$

$$Z = \frac{\pi}{2} - \gamma$$

where $\gamma$ is the angle of elevation of the sky element. The formulation established by Perez et al. corresponds to the definition of overcast sky accepted by the CIE [28], also known as Sky type 1.

All trials were performed under overcast sky conditions, as these represent the worst case scenario for calculation.

# 3. Calculation

## 3.1. Quantification of daylight factors with square window

Table 3 shows the daylight factors measured at the study points in rooms with square windows, under the conditions established in the methodology.

The square windows in upper position with a surface equal or higher than 30% of the façade are ignored in the calculation models, as the opening would be outside the surface of the façade.

A total of 16 calculation models with square windows are considered, depending on the window surface, the opening position and the reflectance of the inner surfaces of the room.

| Model | Study Point | Distance from study point to window | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 6.0 m | 5.5 m | 5.0 m | 4.5 m | 4.0 m | 3.5 m | 3.0 m | 2.5 m | 2.0 m | 1.5 m | 1.0 m | 0.5 m |
| S.10.C.B | Central axis | 0.17% | 0.19% | 0.21% | 0.24% | 0.28% | 0.34% | 0.42% | 0.58% | 0.85% | 1.40% | 2.45% | 3.90% |
| | Side axis | 0.12% | 0.14% | 0.15% | 0.17% | 0.20% | 0.24% | 0.32% | 0.42% | 0.55% | 0.75% | 1.10% | 0.80% |
| S.10.C.D | Central axis | 0.08% | 0.10% | 0.12% | 0.13% | 0.15% | 0.20% | 0.30% | 0.40% | 0.60% | 1.20% | 2.45% | 3.70% |
| | Side axis | 0.02% | 0.04% | 0.06% | 0.07% | 0.08% | 0.12% | 0.20% | 0.28% | 0.47% | 0.70% | 0.95% | 0.60% |
| S.10.U.B | Central axis | 0.20% | 0.22% | 0.25% | 0.28% | 0.33% | 0.40% | 0.50% | 0.67% | 0.94% | 1.50% | 1.82% | 1.40% |
| | Side axis | 0.16% | 0.18% | 0.20% | 0.23% | 0.28% | 0.35% | 0.42% | 0.53% | 0.72% | 0.95% | 1.00% | 0.60% |
| S.10.U.D | Central axis | 0.09% | 0.11% | 0.14% | 0.16% | 0.20% | 0.30% | 0.38% | 0.52% | 0.70% | 1.30% | 1.65% | 1.10% |
| | Side axis | 0.08% | 0.09% | 0.09% | 0.10% | 0.14% | 0.22% | 0.28% | 0.40% | 0.56% | 0.72% | 0.88% | 0.50% |
| S.20.C.B | Central axis | 0.35% | 0.38% | 0.42% | 0.48% | 0.56% | 0.68% | 0.87% | 1.18% | 1.75% | 3.00% | 5.60% | 9.60% |
| | Side axis | 0.28% | 0.30% | 0.34% | 0.40% | 0.46% | 0.52% | 0.60% | 0.85% | 1.25% | 1.90% | 2.90% | 3.00% |
| S.20.C.D | Central axis | 0.16% | 0.18% | 0.21% | 0.28% | 0.34% | 0.42% | 0.55% | 0.75% | 1.30% | 2.40% | 5.60% | 9.50% |
| | Side axis | 0.14% | 0.16% | 0.18% | 0.24% | 0.30% | 0.38% | 0.48% | 0.67% | 1.05% | 1.65% | 2.30% | 2.20% |
| S.20.U.B | Central axis | 0.42% | 0.46% | 0.48% | 0.53% | 0.68% | 0.85% | 1.20% | 1.60% | 2.20% | 3.05% | 3.90% | 2.90% |
| | Side axis | 0.40% | 0.43% | 0.44% | 0.48% | 0.60% | 0.72% | 1.05% | 1.40% | 1.80% | 2.30% | 2.60% | 1.75% |
| S.20.U.D | Central axis | 0.24% | 0.27% | 0.31% | 0.40% | 0.48% | 0.62% | 0.88% | 1.20% | 1.85% | 2.70% | 3.40% | 2.55% |
| | Side axis | 0.22% | 0.24% | 0.28% | 0.36% | 0.43% | 0.55% | 0.80% | 1.10% | 1.50% | 1.95% | 2.10% | 1.40% |
| S.30.C.B | Central axis | 0.55% | 0.60% | 0.65% | 0.74% | 0.85% | 1.05% | 1.30% | 1.80% | 2.70% | 4.25% | 6.95% | 12.20% |
| | Side axis | 0.52% | 0.57% | 0.61% | 0.70% | 0.78% | 0.95% | 1.18% | 1.67% | 2.20% | 3.42% | 4.70% | 5.70% |
| S.30.C.D | Central axis | 0.27% | 0.31% | 0.36% | 0.40% | 0.48% | 0.67% | 0.93% | 1.36% | 2.10% | 3.70% | 6.18% | 11.60% |
| | Side axis | 0.25% | 0.28% | 0.33% | 0.36% | 0.44% | 0.62% | 0.82% | 1.15% | 1.68% | 2.65% | 3.80% | 5.08% |
| S.40.C.B | Central axis | 0.82% | 0.84% | 0.88% | 0.98% | 1.15% | 1.42% | 1.78% | 2.45% | 3.45% | 5.30% | 8.50% | 14.50% |
| | Side axis | 0.77% | 0.79% | 0.82% | 0.90% | 1.05% | 1.30% | 1.60% | 2.26% | 3.10% | 4.50% | 6.10% | 8.05% |
| S.40.C.D | Central axis | 0.38% | 0.40% | 0.44% | 0.52% | 0.65% | 0.94% | 1.25% | 1.80% | 2.75% | 4.60% | 7.60% | 13.50% |
| | Side axis | 0.36% | 0.38% | 0.41% | 0.48% | 0.60% | 0.82% | 1.05% | 1.55% | 2.30% | 3.45% | 5.10% | 7.50% |
| S.60.C.B | Central axis | 1.20% | 1.28% | 1.38% | 1.58% | 1.85% | 2.25% | 2.82% | 3.85% | 5.20% | 7.50% | 11.25% | 17.45% |
| | Side axis | 1.15% | 1.20% | 1.28% | 1.42% | 1.68% | 2.08% | 2.60% | 3.60% | 4.80% | 6.90% | 9.10% | 12.70% |
| S.60.C.D | Central axis | 0.55% | 0.65% | 0.75% | 0.86% | 1.02% | 1.40% | 1.90% | 2.65% | 4.35% | 6.55% | 10.05% | 15.95% |
| | Side axis | 0.50% | 0.58% | 0.66% | 0.76% | 0.90% | 1.23% | 1.70% | 2.42% | 3.50% | 5.05% | 7.50% | 11.25% |
| S.80.C.B | Central axis | 1.60% | 1.75% | 1.90% | 2.15% | 2.50% | 3.05% | 3.75% | 5.10% | 6.95% | 9.55% | 13.70% | 19.60% |
| | Side axis | 1.52% | 1.65% | 1.80% | 2.00% | 2.35% | 2.85% | 3.40% | 4.80% | 6.45% | 8.80% | 11.80% | 16.80% |
| S.80.C.D | Central axis | 0.75% | 0.85% | 0.95% | 1.15% | 1.45% | 1.90% | 2.55% | 3.55% | 5.30% | 7.65% | 11.90% | 17.90% |
| | Side axis | 0.68% | 0.78% | 0.88% | 1.05% | 1.35% | 1.75% | 2.35% | 3.25% | 4.80% | 6.80% | 9.90% | 13.90% |

***Table 3: Daylight factors measured in the calculation models with square window.***

As can be deduced from Table 3, the measurement of the factors in the study daylight points shows very variable results. As expected, higher daylight factors are observed in all cases at the study points closest to the window, gradually descending towards the back of the room.

The daylight factors observed in the side axis are much lower than those measured on the central axis. However, this difference diminishes as the end of the room is approached. From this observation it is concluded that the illumination is lower in the back of the room, although it is distributed more evenly.

Obviously, the windows with a greater surface allow higher daylight factors. However, as can be deduced from the results obtained, there is no direct proportionality between the glazed area and the daylight factors produced, except at the study points near the back of the room.

It is worth noting that upper windows produce lower daylight factors than centered windows at the study points next to the window. However, it also can be seen that upper windows allow higher daylight factors at the back of the room.

As can be deduced from Table 3, the reflectance of the inner surfaces of the room affects daylight factors. However, this condition is higher at the back of the room and less noticeable in the points near the window. Analysis results will be used to determine the ratio of daylight factors and reflectance of inner surfaces.

## 3.2. Quantification of daylight factors with horizontal window

Table 4 shows the daylight factors measured at the study points in rooms with horizontal windows, under the conditions established in the methodology.

The horizontal windows with a surface equal or higher than 30% of the façade are ignored in the calculation models because according to the height/width ratio of the opening they would be disproportionate to the façade.

A total of 8 calculation models with horizontal windows is considered, depending on the window surface, the opening position and the reflectance of the inner surfaces of the room.

| Model | Study Point | Distance from study point to window | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 6.0 m | 5.5 m | 5.0 m | 4.5 m | 4.0 m | 3.5 m | 3.0 m | 2.5 m | 2.0 m | 1.5 m | 1.0 m | 0.5 m |
| H.10.C.B | Central axis | 0.15% | 0.18% | 0.20% | 0.23% | 0.27% | 0.32% | 0.38% | 0.50% | 0.79% | 1.28% | 2.10% | 2.75% |
| | Side axis | 0.13% | 0.16% | 0.17% | 0.20% | 0.23% | 0.29% | 0.36% | 0.45% | 0.58% | 0.92% | 1.20% | 1.00% |
| H.10.C.D | Central axis | 0.04% | 0.06% | 0.08% | 0.10% | 0.12% | 0.21% | 0.30% | 0.40% | 0.60% | 1.15% | 2.00% | 2.60% |
| | Side axis | 0.04% | 0.05% | 0.06% | 0.07% | 0.08% | 0.18% | 0.26% | 0.35% | 0.48% | 0.80% | 1.05% | 0.90% |
| H.10.U.B | Central axis | 0.16% | 0.19% | 0.22% | 0.26% | 0.29% | 0.37% | 0.44% | 0.58% | 0.91% | 1.38% | 1.75% | 1.00% |
| | Side axis | 0.14% | 0.17% | 0.21% | 0.23% | 0.27% | 0.34% | 0.41% | 0.52% | 0.75% | 0.97% | 1.18% | 0.55% |
| H.10.U.D | Central axis | 0.04% | 0.06% | 0.08% | 0.10% | 0.17% | 0.28% | 0.37% | 0.50% | 0.82% | 1.28% | 1.50% | 0.70% |
| | Side axis | 0.04% | 0.05% | 0.07% | 0.09% | 0.14% | 0.23% | 0.33% | 0.42% | 0.57% | 0.86% | 0.95% | 0.45% |
| H.20.C.B | Central axis | 0.32% | 0.36% | 0.38% | 0.44% | 0.50% | 0.61% | 0.75% | 1.10% | 1.70% | 2.80% | 4.90% | 6.90% |
| | Side axis | 0.30% | 0.34% | 0.36% | 0.42% | 0.48% | 0.57% | 0.64% | 0.95% | 1.40% | 2.20% | 3.35% | 4.30% |
| H.20.C.D | Central axis | 0.21% | 0.23% | 0.26% | 0.28% | 0.34% | 0.43% | 0.56% | 0.87% | 1.40% | 2.40% | 4.40% | 6.70% |
| | Side axis | 0.17% | 0.20% | 0.23% | 0.26% | 0.32% | 0.39% | 0.50% | 0.73% | 1.20% | 1.80% | 2.90% | 4.10% |
| H.20.U.B | Central axis | 0.40% | 0.44% | 0.48% | 0.52% | 0.62% | 0.75% | 1.10% | 1.55% | 2.15% | 3.05% | 3.85% | 2.80% |
| | Side axis | 0.34% | 0.38% | 0.44% | 0.48% | 0.57% | 0.65% | 0.95% | 1.35% | 1.90% | 2.45% | 2.85% | 2.00% |
| H.20.U.D | Central axis | 0.22% | 0.26% | 0.32% | 0.37% | 0.44% | 0.57% | 0.85% | 1.15% | 1.80% | 2.70% | 3.40% | 2.40% |
| | Side axis | 0.18% | 0.24% | 0.28% | 0.34% | 0.41% | 0.53% | 0.72% | 1.00% | 1.50% | 2.20% | 2.50% | 1.70% |

***Table 4: Daylight factors measured in the calculation models with horizontal window.***

As can be seen in Table 4, the daylight factors measured at the study points of the calculation models with horizontal windows show a similar tendency to those of analogous models with square windows: higher daylight factors are observed near the window, while lower ones are found at the back of the room.

Furthermore, the daylight factors obtained in the central axis with horizontal windows are slightly lower than those produced by square windows of equal area. However, in this study, the difference between the daylight factors measured in the central and side axes is smaller than that in the calculation models with a square window, converging at the back of the room. Therefore, it is concluded that horizontal windows produce less illuminance than square windows in the central axis, although they allow more illuminance in the side axis. As in the previous study, it is concluded that the illuminance in the back of the room tends to be homogenized.

As expected, and as is also the case with the previous study, the windows with greater surface allow higher daylight factors. However, in the case of horizontal windows there is no direct proportionality between the glazed area and the daylight factors produced, except at the study points near the back of the room.

As in the previous study, the upper windows produce lower daylight factors than the centered windows at the study points next to the window, although they result in higher daylight factors at the back of the room.

Finally it is observed that the variation of the daylight factors produced by the reflectance of the inner surfaces of the room is similar to that observed for models with square windows: variation is higher at the back of the room and lower at the study points next to the window.

### 3.3. Quantification of daylight factors with vertical window

Table 5 shows the daylight factors measured at the study points in rooms with vertical windows, under the conditions established in the methodology.

The vertical windows with a surface equal or higher than 30% of the façade are ignored in the calculation models because, according to the height/width ratio of the opening, they would be disproportionate to the façade.

The vertical windows in the upper position have also been ignored in this study, as the opening would be outside the façade.

A total of 4 calculation models with horizontal windows are considered, depending on the window surface and the reflectance of the inner surfaces of the room.

| Model | Study Point | Distance from study point to window | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 6.0 m | 5.5 m | 5.0 m | 4.5 m | 4.0 m | 3.5 m | 3.0 m | 2.5 m | 2.0 m | 1.5 m | 1.0 m | 0.5 m |
| V.10.C.B | Central axis | 0.10% | 0.12% | 0.15% | 0.18% | 0.21% | 0.26% | 0.32% | 0.44% | 0.65% | 1.10% | 2.35% | 4.10% |
| | Side axis | 0.04% | 0.05% | 0.07% | 0.10% | 0.15% | 0.23% | 0.30% | 0.36% | 0.46% | 0.58% | 0.70% | 0.38% |
| V.10.C.D | Central axis | 0.04% | 0.05% | 0.06% | 0.07% | 0.09% | 0.15% | 0.25% | 0.37% | 0.52% | 1.00% | 2.05% | 4.05% |
| | Side axis | 0.03% | 0.04% | 0.05% | 0.06% | 0.08% | 0.10% | 0.20% | 0.30% | 0.38% | 0.50% | 0.55% | 0.30% |
| V.20.C.B | Central axis | 0.22% | 0.25% | 0.32% | 0.40% | 0.46% | 0.56% | 0.72% | 0.98% | 1.40% | 2.45% | 4.90% | 9.80% |
| | Side axis | 0.20% | 0.24% | 0.28% | 0.34% | 0.43% | 0.53% | 0.70% | 0.92% | 1.25% | 1.65% | 2.05% | 1.50% |
| V.20.C.D | Central axis | 0.14% | 0.18% | 0.24% | 0.27% | 0.33% | 0.40% | 0.52% | 0.82% | 1.20% | 2.15% | 3.85% | 7.60% |
| | Side axis | 0.12% | 0.16% | 0.22% | 0.25% | 0.30% | 0.37% | 0.47% | 0.65% | 0.92% | 1.35% | 1.70% | 1.30% |

***Table 5: Daylight factors measured in the calculation models with vertical window.***

As can be deduced from Table 5, the daylight factors measured at the study points of the calculation models with vertical windows show a similar tendency to the analogous models with different window shapes. As expected, the daylight factors are higher near the window and lower at the back of the room.

It is also noted that daylight factors produced by vertical windows in the central axis are lower than those obtained by other shapes of windows with similar opening surfaces. This is due to the smaller glass surface of vertical windows compared with other opening forms, as can be seen in Table 1. In addition, according to calculation models with vertical windows, daylight factors measured at the side axis are considerably lower than those measured at the central axis, which implies that this window shape does not produce homogeneous light distribution.

As follows from the ratio of the daylight factors measured at the central and side axes, it is confirmed that the light tends to be more homogeneous at the back of the room, regardless of window shape.

As noted in previous studies, the windows with greater surfaces allow higher daylight factors. However, the proportionality between the glazed area and the daylight factors is observed exclusively at the study points at the back of the room.

As in previous studies, it is concluded that the variation of daylight factors produced by the reflectance of the inner surfaces of the room is higher at the back of the room and lower at the points next to the window.

## 4. Analysis of results

### 4.1. Analysis of window shape

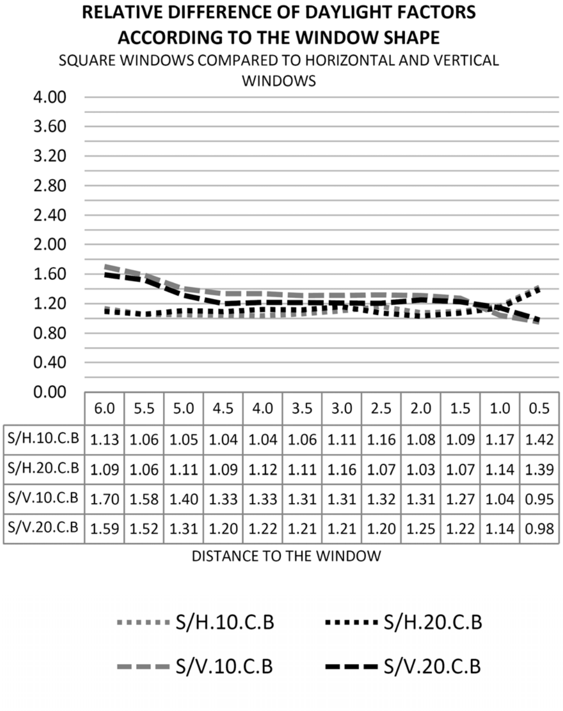
After performing the trials and determining the quantification of daylight factors, an analysis of results of the model calculation is carried out under the conditions established in the methodology, according to the different variables.

The first trial corresponds to the variation of the window shape, considering the reflectance of the inner surfaces of the room and the fact that the position of the openings is invariable.

The study sample for this analysis considers centered windows with an area between 10 and 20% of the façade. A room with highly reflective surfaces is considered and the shape of the aperture is variable.

In order to establish conclusions based on this analysis, the relative difference of the daylight factors is calculated according to the window shape. This relative difference is calculated using the ratio of the daylight factors produced by square windows and those obtained by horizontal or vertical windows. The daylight factors evaluated correspond to those measured at the central axis.

The relative difference of the daylight factors according to the window shape is shown in Figure 2:



| | 6.0 | 5.5 | 5.0 | 4.5 | 4.0 | 3.5 | 3.0 | 2.5 | 2.0 | 1.5 | 1.0 | 0.5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S/H.10.C.B | 1.13 | 1.06 | 1.05 | 1.04 | 1.04 | 1.06 | 1.11 | 1.16 | 1.08 | 1.09 | 1.17 | 1.42 |
| S/H.20.C.B | 1.09 | 1.06 | 1.11 | 1.09 | 1.12 | 1.11 | 1.16 | 1.07 | 1.03 | 1.07 | 1.14 | 1.39 |
| S/V.10.C.B | 1.70 | 1.58 | 1.40 | 1.33 | 1.33 | 1.31 | 1.31 | 1.32 | 1.31 | 1.27 | 1.04 | 0.95 |
| S/V.20.C.B | 1.59 | 1.52 | 1.31 | 1.20 | 1.22 | 1.21 | 1.21 | 1.20 | 1.25 | 1.22 | 1.14 | 0.98 |

***Figure 2: Relative difference of daylight factors according to the window shape.***

As can be deduced from Figure 2, the square window produces daylight factors slightly higher than those obtained with the horizontal window at the central axis. This difference is approximately between 5 and 15%. The higher difference is observed at the nearest point to the window.

Furthermore, as can be deduced from Table 4, the horizontal window allows higher illuminance at the side axes, although its performance in the central axis is lower.

It is observed that the vertical shape has the worst performance: the square window produces noticeably higher daylight factors than the vertical one, quantifying a relative difference of between 20 and 40% approximately. Unlike the previous case, the higher difference is observed at the farthest point to the window.

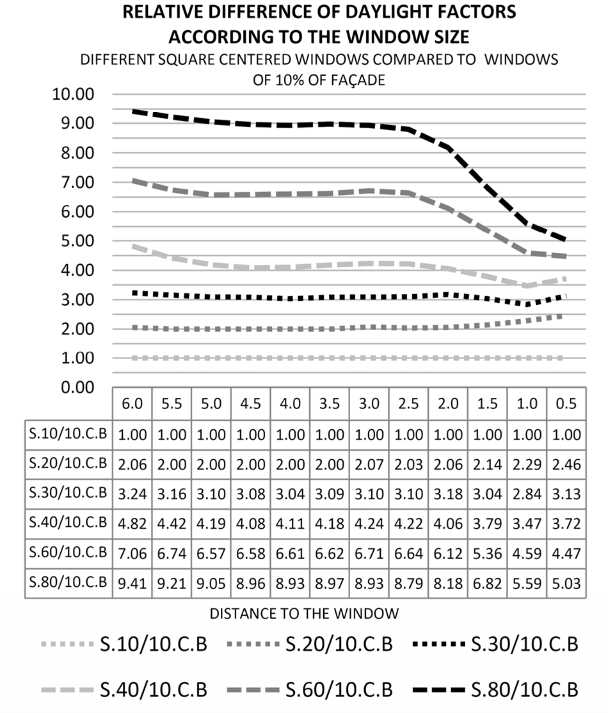
## 4.2. Analysis of window size

The second analysis studies the variation of the window size, considering that the shape and position of the openings and the reflectance of the inner surfaces of the room are invariable.

The study sample for this analysis considers centered square windows. A room with highly reflective surfaces is considered with the surface of the opening between 10 and 80% of the façade.

Just as with the analysis detailed above, the relative difference of the daylight factors is calculated according to window size. This relative difference is calculated using the ratio of the daylight factors produced by variable sized windows and those obtained by windows with areas equal to 10% of the façade. The daylight factors evaluated correspond to those measured at the central axis.

The relative difference of the daylight factors according to window size is shown in Figure 3:



| | 6.0 | 5.5 | 5.0 | 4.5 | 4.0 | 3.5 | 3.0 | 2.5 | 2.0 | 1.5 | 1.0 | 0.5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S.10/10.C.B | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| S.20/10.C.B | 2.06 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.07 | 2.03 | 2.06 | 2.14 | 2.29 | 2.46 |
| S.30/10.C.B | 3.24 | 3.16 | 3.10 | 3.08 | 3.04 | 3.09 | 3.10 | 3.10 | 3.18 | 3.04 | 2.84 | 3.13 |
| S.40/10.C.B | 4.82 | 4.42 | 4.19 | 4.08 | 4.11 | 4.18 | 4.24 | 4.22 | 4.06 | 3.79 | 3.47 | 3.72 |
| S.60/10.C.B | 7.06 | 6.74 | 6.57 | 6.58 | 6.61 | 6.62 | 6.71 | 6.64 | 6.12 | 5.36 | 4.59 | 4.47 |
| S.80/10.C.B | 9.41 | 9.21 | 9.05 | 8.96 | 8.93 | 8.97 | 8.93 | 8.79 | 8.18 | 6.82 | 5.59 | 5.03 |

*Figure 3: Relative difference of daylight factors according to the window size.*

As shown in Figure 3, the daylight factors produced by variable sized openings are directly proportional to the glazed surface, except in the area next to the window area. This is because larger windows allow proportionately higher daylight factors, but also produce a larger light scattering through the glazed surface of the window. This light scattering occurs mainly in the area near the opening.

In accordance to the conducted analysis, the daylight factors allowed by the different window sizes tend to converge towards the façade from a distance of 3 meters, measure equivalent to the height of the room. From that distance to the back of the room, the daylight factors are directly proportional to the glass surface. This observation diverges from the use of many predictive methods for calculating daylight factors produced by windows [8,10,11].

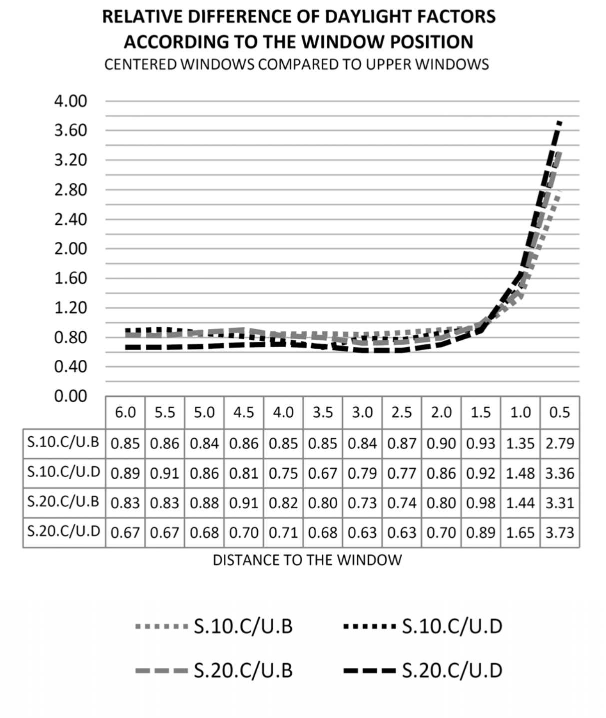
## 4.3. Analysis of window position

The third analysis studies the relative difference of the daylight factors, depending on the window position. In this case, the window shape is considered invariable.

The study sample for this analysis considers square windows with an area between 10 and 20% of the façade. The position of the opening and the reflectance of the inner surfaces of the room are variable.

As in previous studies, the relative difference of the daylight factors is calculated according to the window position. This relative difference is calculated using the ratio of the daylight factors produced by centered windows and those obtained by upper windows. The daylight factors evaluated correspond to those measured at the central axis.

The relative difference of the daylight factors according to window position is shown in Figure 4:



| | 6.0 | 5.5 | 5.0 | 4.5 | 4.0 | 3.5 | 3.0 | 2.5 | 2.0 | 1.5 | 1.0 | 0.5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S.10.C/U.B | 0.85 | 0.86 | 0.84 | 0.86 | 0.85 | 0.85 | 0.84 | 0.87 | 0.90 | 0.93 | 1.35 | 2.79 |
| S.10.C/U.D | 0.89 | 0.91 | 0.86 | 0.81 | 0.75 | 0.67 | 0.79 | 0.77 | 0.86 | 0.92 | 1.48 | 3.36 |
| S.20.C/U.B | 0.83 | 0.83 | 0.88 | 0.91 | 0.82 | 0.80 | 0.73 | 0.74 | 0.80 | 0.98 | 1.44 | 3.31 |
| S.20.C/U.D | 0.67 | 0.67 | 0.68 | 0.70 | 0.71 | 0.68 | 0.63 | 0.63 | 0.70 | 0.89 | 1.65 | 3.73 |

***Figure 4: Relative difference of daylight factors according to the window position.***

As is apparent from Figure 8, the centered openings produce higher daylight factors than those in upper position in the area next to the window. However, the upper openings allow more illuminance in the rest of the room.

Specifically, the windows in upper position produce an increase of daylight factors of close to 20% over the centered windows, except in the area near the window, where the openings in centered position produce far more light.

According to the results, the centered openings allow higher daylight factors from the façade to a distance of 1,5 meters, measure equivalent to the half the height of the room.

## 4.4. Analysis of room reflectance

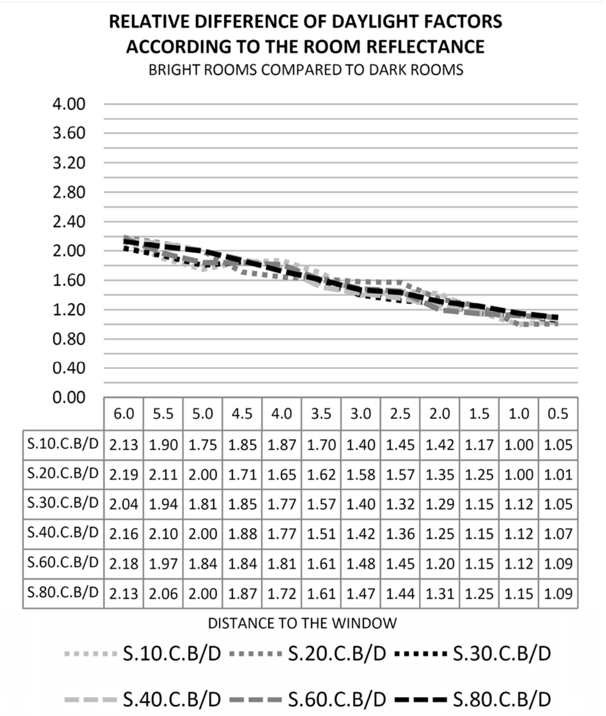
The fourth analysis studies the variation of daylight factors depending on the reflectance of the room, considering that the shape and position of the window are invariable.

The study sample for this analysis considers centered square windows with an area between 10 and 80% of the façade. The reflectance of the inner surfaces of the room is variable.

As in previous analyses, the relative difference of the daylight factors is calculated according to the reflectance of the inner surfaces of the room. This relative difference is calculated using the ratio of the daylight factors produced by high reflectance surfaces and those obtained by low reflectance surfaces. The daylight factors evaluated correspond to those measured at the central axis.

As seen in Table 1, the average reflectance value of the bright rooms is between 0.70 and 0.75, while in the dark rooms this value falls between 0.37 and 0.40, depending on the area occupied by the window. Consequently, the ratio of the average reflectance of the bright and dark rooms is approximately 1.90.

The relative difference of the daylight factors according to the reflectance of the surfaces of the room is shown in Figure 5:



| | 6.0 | 5.5 | 5.0 | 4.5 | 4.0 | 3.5 | 3.0 | 2.5 | 2.0 | 1.5 | 1.0 | 0.5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S.10.C.B/D | 2.13 | 1.90 | 1.75 | 1.85 | 1.87 | 1.70 | 1.40 | 1.45 | 1.42 | 1.17 | 1.00 | 1.05 |
| S.20.C.B/D | 2.19 | 2.11 | 2.00 | 1.71 | 1.65 | 1.62 | 1.58 | 1.57 | 1.35 | 1.25 | 1.00 | 1.01 |
| S.30.C.B/D | 2.04 | 1.94 | 1.81 | 1.85 | 1.77 | 1.57 | 1.40 | 1.32 | 1.29 | 1.15 | 1.12 | 1.05 |
| S.40.C.B/D | 2.16 | 2.10 | 2.00 | 1.88 | 1.77 | 1.51 | 1.42 | 1.36 | 1.25 | 1.15 | 1.12 | 1.07 |
| S.60.C.B/D | 2.18 | 1.97 | 1.84 | 1.84 | 1.81 | 1.61 | 1.48 | 1.45 | 1.20 | 1.15 | 1.12 | 1.09 |
| S.80.C.B/D | 2.13 | 2.06 | 2.00 | 1.87 | 1.72 | 1.61 | 1.47 | 1.44 | 1.31 | 1.25 | 1.15 | 1.09 |

***Figure 5: Relative difference of daylight factors according to the room reflectance.***

As can be deduced in Figure 5, the relative difference between the daylight factors of bright and dark rooms have a linear tendency, reaching maximum values at the back of the room and minimum values in the area close to the window. It follows that surfaces with higher reflectance allow more illuminance at the back of the room, while its effect in the area near the opening is virtually nil.

Quantifying this analysis, it can be argued that the increase of daylight factors at the back of the room is almost directly proportional to the increase of the reflectance of the surfaces of the room, as is apparent from Figure 5 and the ratio of the average reflectances. Consequently, it can be stated that the daylight factors measured in the interior of a room are not directly proportional to the reflectance of the inner surfaces of the room, except in the back of the venue. This statement differs from some methods of calculating the reflected component [5].

## 4.5. Analysis of energy saving

The final analysis examines the energy consumption in artificial lighting of the room, considering different window models and a minimum threshold of illuminance. According to the recommendations of the IESNA [9], two minimum thresholds of illuminance are considered: 250 and 500 lx.

Moreover, it is considered an efficiency of artificial lighting close to the limit established by several technical building codes [29]. Consequently it is defined a value of energy efficiency of the installation of 5 w/m$^2$·100lx.

The interior illuminance measured at each study point is calculated according to the exterior illuminance and the daylight factors shown in Tables 3 to 5:

$$Ei = Ee \cdot DF$$

where *Ei* is the interior illuminance, *Ee* the exterior illuminance and *DF* the daylight factor measured at each study point.

According to Gillete et al. [30], the exterior illuminance can be calculated for an overcast sky, considering the elevation of the Sun:

$$Ee = 300 + 21{,}000 \cdot sin\varphi$$

where $\varphi$ is the elevation of the Sun. The room location and the schedule determine the solar elevation angle, which allows the calculation of the exterior illuminance.

The difference between the minimum threshold of illuminance and that measured at each study point determines the contribution of artificial lighting. Considering a value of energy efficiency of the installation of 5 w/m$^2$·100lx, it is concluded that the energy consumption in artificial lighting according to a threshold of illuminance of 250 lx is shown in Table 6:

| Latitude | 0.00 º | | 10.00 º | | 20.00 º | | 30.00 º | | 40.00 º | | 50.00 º | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Schedule | 8:00<br>16:00 | 10:00<br>14:00 | 8:00<br>16:00 | 10:00<br>14:00 | 8:00<br>16:00 | 10:00<br>14:00 | 8:00<br>16:00 | 10:00<br>14:00 | 8:00<br>16:00 | 10:00<br>14:00 | 8:00<br>16:00 | 10:00<br>14:00 |
| Sun elevation | 30.00 º | 60.00 º | 29.70 º | 58.80 º | 28.30 º | 54.80 º | 26.00 º | 48.90 º | 22.80 º | 41.90 º | 19.10 º | 34.20 º |
| Exterior illuminance | 10800 lx | 18487 lx | 10705 lx | 18263 lx | 10256 lx | 17460 lx | 9506 lx | 16125 lx | 8438 lx | 14324 lx | 7172 lx | 12104 lx |
| S.10.C.B | 10.49 | 8.80 | 10.51 | 8.85 | 10.61 | 9.02 | 10.80 | 9.31 | 11.08 | 9.71 | 11.40 | 10.20 |
| S.10.C.D | 11.17 | 9.95 | 11.18 | 9.98 | 11.25 | 10.11 | 11.40 | 10.32 | 11.61 | 10.61 | 11.85 | 10.96 |
| S.10.U.B | 10.40 | 8.29 | 10.43 | 8.34 | 10.57 | 8.53 | 10.79 | 8.88 | 11.11 | 9.37 | 11.49 | 10.01 |
| S.10.U.D | 11.22 | 9.58 | 11.24 | 9.63 | 11.34 | 9.79 | 11.51 | 10.05 | 11.75 | 10.43 | 12.03 | 10.93 |
| S.20.C.B | 7.64 | 5.67 | 7.66 | 5.72 | 7.80 | 5.90 | 8.04 | 6.20 | 8.38 | 6.61 | 9.05 | 7.23 |
| S.20.C.D | 8.62 | 7.04 | 8.66 | 7.08 | 8.82 | 7.21 | 9.12 | 7.44 | 9.54 | 7.80 | 10.04 | 8.29 |
| S.20.U.B | 6.64 | 4.35 | 6.69 | 4.40 | 6.90 | 4.57 | 7.26 | 4.89 | 7.86 | 5.34 | 8.66 | 6.14 |
| S.20.U.D | 7.90 | 5.63 | 7.94 | 5.67 | 8.13 | 5.84 | 8.46 | 6.17 | 8.99 | 6.66 | 9.64 | 7.36 |
| S.30.C.B | 5.61 | 3.37 | 5.65 | 3.43 | 5.82 | 3.63 | 6.12 | 3.96 | 6.57 | 4.44 | 7.13 | 5.15 |
| S.30.C.D | 7.16 | 5.37 | 7.19 | 5.42 | 7.32 | 5.58 | 7.53 | 5.85 | 7.91 | 6.24 | 8.37 | 6.80 |
| S.40.C.B | 4.32 | 1.98 | 4.36 | 2.03 | 4.54 | 2.23 | 4.87 | 2.58 | 5.35 | 3.12 | 5.99 | 3.86 |
| S.40.C.D | 6.20 | 4.37 | 6.23 | 4.42 | 6.39 | 4.57 | 6.64 | 4.83 | 7.03 | 5.27 | 7.52 | 5.85 |
| S.60.C.B | 2.37 | 0.30 | 2.41 | 0.34 | 2.60 | 0.47 | 2.92 | 0.76 | 3.46 | 1.20 | 4.13 | 1.88 |
| S.60.C.D | 4.72 | 2.77 | 4.74 | 2.82 | 4.88 | 2.98 | 5.16 | 3.28 | 5.60 | 3.69 | 6.13 | 4.33 |
| S.80.C.B | 1.05 | 0.00 | 1.08 | 0.00 | 1.26 | 0.00 | 1.57 | 0.01 | 2.06 | 0.17 | 2.78 | 0.65 |
| S.80.C.D | 3.54 | 1.61 | 3.57 | 1.66 | 3.73 | 1.82 | 4.03 | 2.11 | 4.47 | 2.51 | 5.04 | 3.14 |
| H.10.C.B | 10.35 | 8.49 | 10.37 | 8.54 | 10.49 | 8.73 | 10.70 | 9.05 | 11.01 | 9.48 | 11.41 | 10.00 |
| H.10.C.D | 11.02 | 9.60 | 11.04 | 9.64 | 11.13 | 9.78 | 11.29 | 10.02 | 11.55 | 10.34 | 11.87 | 10.75 |
| H.10.U.B | 10.52 | 8.43 | 10.55 | 8.48 | 10.68 | 8.69 | 10.90 | 9.04 | 11.20 | 9.51 | 11.57 | 10.15 |
| H.10.U.D | 11.30 | 9.67 | 11.32 | 9.72 | 11.41 | 9.87 | 11.58 | 10.14 | 11.81 | 10.53 | 12.08 | 11.01 |
| H.20.C.B | 7.47 | 5.57 | 7.50 | 5.61 | 7.65 | 5.78 | 7.89 | 6.09 | 8.26 | 6.52 | 8.75 | 7.09 |
| H.20.C.D | 8.34 | 6.72 | 8.36 | 6.75 | 8.48 | 6.90 | 8.69 | 7.15 | 9.00 | 7.50 | 9.47 | 8.02 |
| H.20.U.B | 6.71 | 4.61 | 6.75 | 4.66 | 6.92 | 4.84 | 7.27 | 5.14 | 7.83 | 5.58 | 8.63 | 6.21 |
| H.20.U.D | 7.79 | 5.85 | 7.82 | 5.89 | 7.99 | 6.03 | 8.33 | 6.29 | 8.88 | 6.70 | 9.54 | 7.36 |
| V.10.C.B | 11.18 | 9.97 | 11.20 | 10.01 | 11.28 | 10.14 | 11.43 | 10.35 | 11.63 | 10.63 | 11.88 | 10.98 |
| V.10.C.D | 11.65 | 10.70 | 11.66 | 10.73 | 11.73 | 10.82 | 11.84 | 10.98 | 12.00 | 11.19 | 12.19 | 11.45 |
| V.20.C.B | 8.33 | 6.01 | 8.37 | 6.06 | 8.54 | 6.24 | 8.85 | 6.57 | 9.31 | 7.10 | 9.84 | 7.83 |
| V.20.C.D | 9.30 | 7.17 | 9.33 | 7.23 | 9.48 | 7.43 | 9.73 | 7.76 | 10.08 | 8.22 | 10.50 | 8.88 |

***Table 6: Energy consumption, measured in w/m$^2$, in artificial lighting according to a minimum illuminance of 250 lx.***

As deduced from Table 6, the horizontal windows allow a minimum increase of energy saving close to 2% compared with square windows. This value increases to about 8% when horizontal windows are compared with those of vertical shape.

Despite the openings in upper position allow higher illuminance at the back of the room, the energy saving produced by this window model is very similar to that obtained with centered openings.

As apparent from the results, the bright rooms require lower energy consumption than those with dark surfaces. Specifically, bright rooms allow a minimum energy saving of 7% in the case of windows with surface equal to 10% of the façade. This energy saving is increased in the case of windows of larger surface.

Moreover, the energy consumption in artificial lighting according to a threshold of illuminance of 500 lx is shown in Table 7:

| Latitude | 0.00 º | | 10.00 º | | 20.00 º | | 30.00 º | | 40.00 º | | 50.00 º | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Schedule | 8:00<br>16:00 | 10:00<br>14:00 | 8:00<br>16:00 | 10:00<br>14:00 | 8:00<br>16:00 | 10:00<br>14:00 | 8:00<br>16:00 | 10:00<br>14:00 | 8:00<br>16:00 | 10:00<br>14:00 | 8:00<br>16:00 | 10:00<br>14:00 |
| Sun elevation | 30.00 º | 60.00 º | 29.70 º | 58.80 º | 28.30 º | 54.80 º | 26.00 º | 48.90 º | 22.80 º | 41.90 º | 19.10 º | 34.20 º |
| Exterior illuminance | 10800 lx | 18487 lx | 10705 lx | 18263 lx | 10256 lx | 17460 lx | 9506 lx | 16125 lx | 8438 lx | 14324 lx | 7172 lx | 12104 lx |
| S.10.C.B | 23.84 | 21.74 | 23.87 | 21.80 | 24.02 | 22.00 | 24.26 | 22.35 | 24.59 | 22.81 | 25.00 | 23.43 |
| S.10.C.D | 24.55 | 22.90 | 24.58 | 22.94 | 24.69 | 23.10 | 24.88 | 23.36 | 25.15 | 23.71 | 25.47 | 24.23 |
| S.10.U.B | 24.04 | 21.74 | 24.07 | 21.81 | 24.20 | 22.05 | 24.43 | 22.45 | 24.75 | 22.99 | 25.13 | 23.65 |
| S.10.U.D | 24.86 | 23.14 | 24.88 | 23.19 | 24.98 | 23.37 | 25.15 | 23.66 | 25.38 | 24.07 | 25.67 | 24.56 |
| S.20.C.B | 19.99 | 16.24 | 20.04 | 16.31 | 20.28 | 16.55 | 20.68 | 17.14 | 21.29 | 18.10 | 22.07 | 19.29 |
| S.20.C.D | 21.49 | 18.45 | 21.53 | 18.54 | 21.70 | 18.86 | 22.00 | 19.38 | 22.46 | 20.10 | 23.07 | 20.97 |
| S.20.U.B | 19.71 | 14.82 | 19.78 | 14.94 | 20.09 | 15.38 | 20.62 | 16.18 | 21.36 | 17.33 | 22.25 | 18.80 |
| S.20.U.D | 21.26 | 17.17 | 21.31 | 17.28 | 21.56 | 17.69 | 21.98 | 18.36 | 22.57 | 19.29 | 23.28 | 20.53 |
| S.30.C.B | 16.23 | 12.44 | 16.29 | 12.54 | 16.61 | 12.89 | 17.17 | 13.47 | 18.02 | 14.28 | 19.19 | 15.47 |
| S.30.C.D | 18.46 | 15.24 | 18.51 | 15.32 | 18.75 | 15.61 | 19.20 | 16.10 | 19.94 | 16.75 | 20.90 | 17.76 |
| S.40.C.B | 14.12 | 9.97 | 14.19 | 10.07 | 14.52 | 10.43 | 15.06 | 11.02 | 15.92 | 12.00 | 17.13 | 13.31 |
| S.40.C.D | 16.75 | 13.46 | 16.80 | 13.53 | 17.05 | 13.83 | 17.51 | 14.34 | 18.27 | 15.04 | 19.16 | 16.11 |
| S.60.C.B | 10.62 | 6.09 | 10.68 | 6.20 | 11.02 | 6.60 | 11.66 | 7.31 | 12.65 | 8.27 | 13.84 | 9.70 |
| S.60.C.D | 14.13 | 10.54 | 14.19 | 10.63 | 14.45 | 10.97 | 14.95 | 11.52 | 15.74 | 12.26 | 16.72 | 13.41 |
| S.80.C.B | 8.08 | 3.37 | 8.15 | 3.47 | 8.50 | 3.82 | 9.17 | 4.53 | 10.19 | 5.58 | 11.50 | 7.14 |
| S.80.C.D | 12.07 | 8.27 | 12.13 | 8.36 | 12.40 | 8.69 | 12.94 | 9.24 | 13.78 | 10.09 | 14.82 | 11.34 |
| H.10.C.B | 23.91 | 21.53 | 23.94 | 21.60 | 24.08 | 21.84 | 24.32 | 22.26 | 24.65 | 22.82 | 25.04 | 23.51 |
| H.10.C.D | 24.61 | 22.71 | 24.63 | 22.76 | 24.74 | 22.96 | 24.93 | 23.29 | 25.19 | 23.74 | 25.50 | 24.28 |
| H.10.U.B | 24.16 | 21.94 | 24.19 | 22.01 | 24.32 | 22.24 | 24.53 | 22.62 | 24.84 | 23.14 | 25.20 | 23.78 |
| H.10.U.D | 24.93 | 23.27 | 24.95 | 23.32 | 25.05 | 23.49 | 25.21 | 23.78 | 25.44 | 24.17 | 25.72 | 24.65 |
| H.20.C.B | 19.28 | 15.95 | 19.34 | 16.03 | 19.61 | 16.30 | 20.11 | 16.80 | 20.83 | 17.52 | 21.69 | 18.56 |
| H.20.C.D | 20.46 | 17.52 | 20.52 | 17.59 | 20.77 | 17.81 | 21.19 | 18.29 | 21.79 | 18.95 | 22.53 | 19.78 |
| H.20.U.B | 19.68 | 14.79 | 19.74 | 14.90 | 20.06 | 15.30 | 20.59 | 16.11 | 21.34 | 17.27 | 22.23 | 18.76 |
| H.20.U.D | 21.11 | 16.91 | 21.16 | 17.03 | 21.42 | 17.45 | 21.85 | 18.14 | 22.46 | 19.09 | 23.18 | 20.36 |
| V.10.C.B | 24.52 | 22.95 | 24.54 | 23.00 | 24.66 | 23.15 | 24.85 | 23.41 | 25.12 | 23.75 | 25.45 | 24.19 |
| V.10.C.D | 25.00 | 23.76 | 25.02 | 23.80 | 25.12 | 23.91 | 25.27 | 24.11 | 25.50 | 24.38 | 25.76 | 24.73 |
| V.20.C.B | 21.19 | 17.93 | 21.23 | 18.03 | 21.42 | 18.37 | 21.79 | 18.93 | 22.32 | 19.69 | 22.95 | 20.63 |
| V.20.C.D | 22.31 | 19.63 | 22.34 | 19.71 | 22.52 | 19.97 | 22.81 | 20.41 | 23.23 | 21.01 | 23.72 | 21.80 |

***Table 7: Energy consumption, measured in w/$m^2$, in artificial lighting according to a minimum illuminance of 500 lx.***

In the case of a minimum threshold of illuminance of 500 lx, as is apparent from Table 7, the energy saving produced by horizontal windows is very similar to that obtained by square openings. However, the energy saving increases as the window size is larger.

Similarly to the previous study, the window position barely affects the energy saving, although upper windows allow higher illuminance at the back of the room than those in centered position.

As noted above, the bright rooms allow an increase in energy saving compared with those of dark surfaces. However, in the case of a higher threshold of illuminance, the minimum energy saving is reduced to 3%. As in the previous study, the energy saving is increased when the surface of the window is larger.

## 5. Conclusions

The analysis of results has assessed the variation of the daylight factors depending on the shape, size and position of the opening, reaching several conclusions that can be applied to window design. Additionally, the study of the variation of the reflectance of the inner surfaces of the room allows to determine the daylight factors based on this variable.

The quantification of the daylight factors serves as a basis for the analysis of results. However, it also offers a database of the natural illumination produced by a window within a room. Accordingly, the most representative calculation models of current architecture have been chosen for simulation, using the most common window designs. Obviously, this research does not cover all possible hypotheses, but aims to show the most frequent cases study under the most adverse sky conditions.

The study of quantification provides results in one of the first conclusions: for models with square windows, the daylight produced by a window is unevenly distributed in the room, as shown in Table 3. In this particular case, the daylight factors at the back of the room are about ten times lower than those measured in the area next to the opening.

Another conclusion of this study can be seen in Table 4, which shows that the horizontal window allows higher illuminance in the side axes than the square window, although its performance in the central axis is poorer. In contrast, as Table 5 clearly shows, the vertical window produces a greater contrast of illumination. These findings are derived from the relative difference between the daylight factors measured at the central and side axes.

Initial analysis shows the third conclusion concerning the variation of the window shape. As can be observed from Figure 2, the daylight factors obtained by square windows are slightly higher than those produced by horizontal windows. This increase is between 5 and 15% approximately. Furthermore, the vertical window shows the worst performance, with a reduction of daylight factors of between 20 and 40% approximately.

Regarding the variation of the window size, it is concluded that the daylight factors produced by variable size openings are directly proportional to the glazed surface except in the area next to the window. This statement is deduced from Figure 3, which shows that larger openings allow proportionately higher daylight factors, but also produce a greater scattering of the inner light through the glazed surface. Therefore, the daylight factors allowed by the different window sizes tend to converge towards the façade from a distance of 3 meters, measure equivalent to the height of the room.

The third trial is based on the variation of the window position. As is deduced from Figure 4, the centered openings produce higher daylight factors in the area next to the window than those obtained with upper windows. As can be observed, the centered openings allow higher daylight factors from the façade to a distance of 1,5 meters, measure equivalent to the half the height of the room. However, the openings in upper position allow more illumination in the rest of the room, producing an increase of the daylight factors of close to 20% at the back of the room.

The fourth analysis studies the variation of the daylight factors according to the reflectance of the inner surfaces of the room. This is studied in Figure 5, where it is concluded that the relative difference between the daylight factors of bright and dark rooms have a linear tendency, reaching maximum values at the back of the room and minimum values in the area close to the window. In fact, it can be argued that the increase in daylight factors at the back of the room is almost directly proportional to the increase in the reflectance of the surfaces.

Finally, the last analysis determines the energy consumption in artificial lighting of the room, considering different window models and a minimum threshold of illuminance. As can be seen from Tables 6 and 7, the horizontal windows provide higher energy saving than those of square or vertical shape. Moreover, the bright rooms allow an increase in energy saving compared with those of dark surfaces. Specifically, bright rooms allow a minimum energy saving of 3% in the case of windows with surface equal to 10% of the façade, considering a minimum threshold of illuminance of 500 lx. This saving increases to 7% considering a threshold illuminance of 250 lx.

All these findings, as well as the quantification of daylight factors, provide a better understanding of window design, a key element of architecture both in terms of lighting comfort and energy savings.

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