Solar radiation entering through openings: Coupled assessment of luminous and thermal aspects

Paula M. Esquivias, David Moreno, Jaime Navarro

This is an **Accepted Manuscript** of an article published by **Elsevier**:

Energy and Buildings, Volume 175, 2018, Pages 208-218, ISSN 0378-7788,

https://doi.org/10.1016/j.enbuild.2018.07.021

Authors' names and affiliations:

Paula M. Esquivias [a], David Moreno [a], Jaime Navarro [a]

[a] ARHESUS TEP 130 Research Group, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla

Corresponding Author:

Paula M. Esquivias, ARHESUS TEP 130 Research Group, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla, Spain

Email: pesquivias2@us.es

Telephone number: +34 636 50 99 13

Abstract

Usually the effect of global solar radiation on buildings is evaluated by focusing on the visible part of its spectrum, namely daylight, or on the thermal equivalent of sunlight, solar heat gains through external windows. At present, due to the difficulty of integrating and comparing thermal and daylighting results, approaches considering the integrated effect of global solar radiation are scarce. As a consequence, both approaches separately provide strategies for sustainable buildings – strategies that can, in fact, be contradictory.

In order to evaluate daylighting potential and its correlated solar heat gains, a common framework of calculation is established and a set of metrics are defined. These metrics are based on the Daylight Sufficiency criterion, the recommended illuminance ranges for visual tasks and the trigger irradiance value defined in the Blindswitch-A model.

The results of applying this method to a simple model show the correlation between the luminous and the thermal performances that are simultaneously achieved on the workplane. This method, therefore, allows both aspects of solar radiation entering though windows to be visualised on one graph, thus enabling an integral assessment, so necessary if strategies that consider both aspects at the same time need to be proposed.

Highlights

- Time series annual climate dataset analysis
- Daylight sufficiency metrics
- Relationship between solar heat gains according to blindswitch and excessive illuminance
- Simultaneous assessment of daylighting and solar heat gains

Keywords: Climate-based Daylight Modelling, Building Energy Performance Simulation, Daylighting, Solar Heat Gains, Sunlighting

1 Introduction

Daylighting has numerous positive effects on a building's occupants. It enhances visual performance, productivity, health and well-being, etc., and it is generally preferred over artificial lighting, especially for office environments [1] [2]. Furthermore, the exploitation of daylight, commonly referred to as daylight utilisation or daylight harvesting, is recognised as an effective means of reducing the use of artificial lighting [3] as well as reducing internal lighting, and thus cooling loads [4].

It is well-known that for several reasons, especially for those of health and well-being, sunlighting is essential for any interior space, particularly during winter months. Solar heat gains can contribute positively to the reduction of heating energy consumption. Sunlight and solar heat gains are, however, not so desirable during warmer months – especially during summer – as they are in winter.

A suitably daylit environment is one where the architectural design provides both good daylighting and effective solar protection [5]. This means that the architectural design reduces excessive solar gains, glare and heating and cooling loads derived from excessive daylighting (i.e. including the solar component) [4]. This also implies a reduction in the need for occupants to operate blinds and/or shades and to turn on lighting and HVAC systems, which in turn will reduce the building's energy consumption.

Usually the effect of global solar radiation on buildings is evaluated by focusing on the visible part of its spectrum, namely daylight, or on the thermal equivalent of sunlight, solar heat gains through external windows. At present, due to the difficulty of integrating and comparing thermal and daylighting results, approaches considering the integrated effect of global solar radiation are scarce [6] [7]. As a consequence, both approaches separately provide strategies for sustainable buildings – strategies that can, in fact, be contradictory.

The effective integration of daylighting and its thermal component, solar heat gains, requires daylight performance to be described in such a way that the description can be obtained and combined with the thermal performance. Based on the study of the nature of the climate-based daylight metrics and the solar heat gains, two main problems are highlighted.

The first is that solar heat gains are expressed as hourly or sub-hourly, at a frequency of smaller periods than hours, time series for the whole space, usually visualised as a 2D curve or as a temporal map. Meanwhile, climate-based daylight metrics are expressed as the percentage of the occupied time in which a certain illuminance level is achieved by using daylighting for each sensor on the workplane and which can be visualised as a false colour map.

Climate-based daylight modelling [8] [9] delivers hourly or sub-hourly time series of absolute quantities (i.e. illuminance) for each calculation point using sun and sky conditions that are derived from standard meteorological dataset. Compared to predicting daylight illuminances based on overcast sky condition, this time series is dependent on both the building's location climate – providing usually higher outside illuminance values than the overcast sky condition - and the orientation of its windows, in addition to the building's composition and configuration [10]. Climate-based daylight metrics, such as Daylight Autonomy (DA) [11] or Useful Daylight Illuminance scheme (UDI) [12], are derived from the cumulative analysis of the daylight illuminance profile of each sensor point, based on an illuminance target or ranges and an analysis schedule throughout the year, expressed as spatial or false colour maps.

Another method of analysing the annual climate dataset is by means of time series analysis. This involves predicting instantaneous measurements (e.g. illuminance) based on each of the hourly or sub-hourly values in the annual climate dataset. These predictions are used to evaluate, for example, the overall daylighting potential of the building or the occurrence of excessive illuminances [13]. By performing a time series analysis, a temporal performance graphic is obtained, which can then be coupled with the temporal graph expressing the solar heat gains.

The second problem is that solar heat gains are calculated for the whole year, at hourly or sub-hourly intervals, while climate-based daylight metrics only consider the occupied time, which has to remain constant throughout the year, be it measured hourly or sub-hourly.

Currently there is debate over whether, in order to obtain daylight performance metrics, standardised building occupancy schedules or all of the daylit hours over one year should be used with regard to the annual analysis period of annual climate datasets [13] [14].

An analysis of all daylit hours during the year has the advantage of representing the architectural daylighting potential, something that will never change unless the surrounding urban environment changes [9]. During the building design stages annual daylit hours can contemplate any working day, occupancy pattern or change in the building's usage. Considering the annual daylit hours, the results of daylighting evaluation are valid over a long-term period.

Another question to be taken into account, in order to provide strategies considering daylight and solar heat gains, is how to define illuminance and solar heat gains thresholds with the subsequent aim of defining a suitably daylit environment.

In 2006 the Illumination Engineering Society of North America (IES) created a Daylighting Metrics Sub-Committee (DMsC) which developed the Daylight Metrics Project [15] whose aim was to provide a guide to good daylighting by incorporating climate-based daylight metrics to standards. The project's main objective was to develop a set of daylight performance metrics and criteria that describe a well-daylit space and which can be used in building specifications, efficiency programmes, codes and standards in order to promote daylit buildings more successfully. This would result in greater energy savings and a reduction in energy demand.

One of the concepts the DMsC focused on was daylight sufficiency. The Committee found a 300-lux illuminance threshold to be the best predictor of expert and occupant assessments and it then defined a daylight sufficiency metric. This metric, termed spatial Daylight Autonomy, or $sDA_{300,50\%}$, reports the percentage of an of area in a space or building meeting or exceeding 300 lux of daylight illumination for 50% of the yearly analysis period, i.e. 1825 hours per year [15] [16]. These thresholds are known as the Daylight Sufficiency criterion.

Another metric was proposed considering sunlighting by defining a number of hours of exposure to sunlight, yet it does not take into account the solar heat gains that arise within that space. In a review of the literature regarding the presence of overheating and glare, one of the indicators found was the occupants' need to lower blinds [17].

One criterion to assess the performance of solar heat gains through windows can be the value above which the user perceives a certain discomfort that triggers the closing of blinds. Blinds operation affects the amount and distribution of daylight entering a building, as well as all forms of thermal transfer through windows. Despite the fact that there is a substantial body of research in this area [18] [19] [20] [21] [22] [23], there is no comprehensive consensus on the way people operate blinds or on the motivating factors that influence their decisions [17].

There are several different studies suggesting disparate control values of solar irradiance (11-325 W/m^2) regarding the control trigger for blind engagement [17]. Van Den Wymelenberg, after summarising some different threshold values, proposed a manual control algorithm related to exterior irradiance normal to the sun, called Blindswitch-A [24] [25] [26].

The objective of this research is to establish a common calculation framework for daylighting and insolation in order to obtain comparable results and define a set of metrics based on the Daylight Sufficiency criterion, the recommended illuminance ranges for visual tasks and a proposed solar heat gains criterion, based on the trigger value of the Blindswitch-A model.

The framework and metrics proposed form a decision tool that enables the daylighting potential of a space, also considering its thermal component, to be evaluated.

2 Methodology

In order to provide a better understanding of what is proposed in this work, each procedure is applied to simulation results obtained for reference geometry (Figure 1). The reference geometry corresponds to a simple sidelit residential space (3m high, 3m wide and 3m deep). The space is located in Seville, Spain, (37.42°N, 5.9°W) and has a south-facing façade with a centred, simple clear-glazed aperture with a Window-to-wall ratio of 10% (0.95m high and 0.95m wide), a direct normal visual transmittance of 88.36% and a solar heat gain coefficient of 81.8%. The ceiling, walls, and floor have purely diffuse reflectances of 80%, 50% and 20%, respectively.

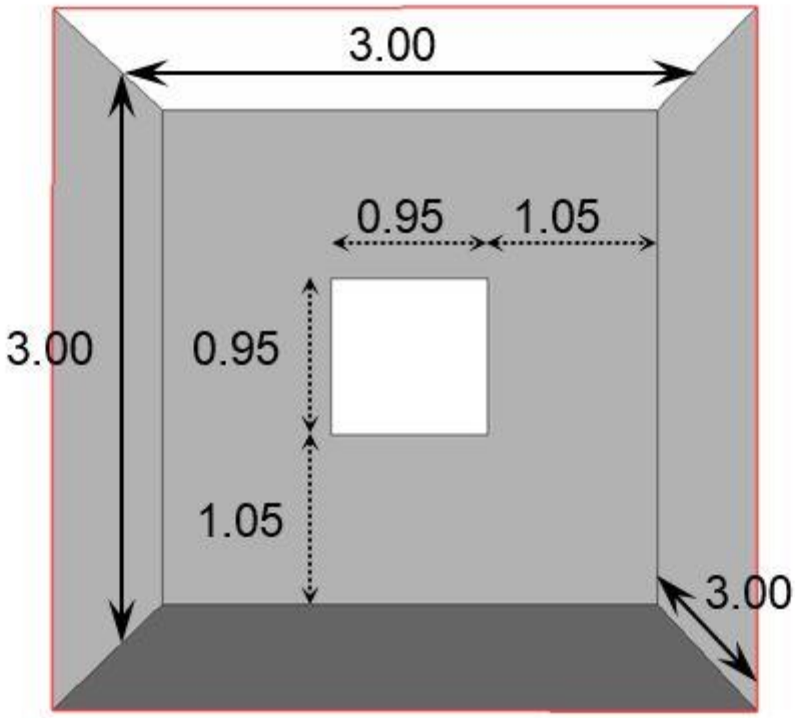

Figure 1: Example sidelit space

Lighting simulation was performed using the validated Radiance-based DAYSIM program version 3.1.e [27]. The annual daylight illuminances and the consequent daylight metrics were calculated over a grid with 0.10m spacing, positioned at the working plane height (0.80m), with a peripheral band of 0.05m from the walls excluded in order to obtain as precise data as possible. The simulation time step was one hour throughout the whole year. Table 1 shows the Radiance simulation parameters that were used for all daylight simulations.

Ambient bounces (ab)	7	Specular threshold (st)	0.1500
Ambient divisions (ad)	1500	Specular jitter (sj)	1.0000
Ambient super-samples (as)	100	Direct jitter (dj)	0.0000
Ambient resolution (ar)	300	Direct sampling (ds)	0.200

Ambient accuracy (aa)	0.1	Direct relays (dr)	2
Limit reflection (lr)	6	Direct pretest density (dp)	512
Limit weight (lw)	0.004000		

Table 1: Utilised Radiance simulation parameters

Solar heat gains through external windows are obtained from energy simulation software such as DesignBuilder [28] which calculates them separately from the other thermal loads in a space. By performing an annual simulation in DesignBuilder, time series data are obtained at a pre-established time step, defined here as hourly.

As only solar heat gains through external windows were of interest, the walls, floor and ceilings were modelled as external surfaces, adjacent to outside conditions. U-values of these external surfaces were established following limit values established in Spanish Energy Saving Code (DB-HE-1) [29]. The space was unconditioned and unoccupied in order to assess the building's passive performance.

In this methodology two types of information are given: descriptive and analytical. The former describes the illuminance and the solar heat gains distribution in the space throughout the year, while the latter is based on applying the Daylight Sufficiency criterion and the information derived from the studies on overheating-related operation of the blinds.

2.1 Describing daylighting and solar heat gains as temporal maps

DAYSIM automatically generates an annual illuminance profile (*.ill) and derives several dynamic, climate-based daylighting metrics (DA files), such as Daylight Autonomy (DA) and the three original subdivisions of Useful Daylight Illuminance scheme (UDI): $UDI_{<100}$, $UDI_{100\text{-}2000}$ and $UDI_{>2000}$. It also generates a file with the extension «*.daylight_factor.DA» which corresponds to RADIANCE-based daylight factor calculations.

The annual illuminance profile (*.ill) is a time series of indoor illuminance at points of interest in a building. The file contains the illuminances for all of the sensors specified in the sensor file and for all of time steps over the year specified in the DAYSIM climate file (Figure 2). Therefore, if the simulation time step is of one hour throughout the whole year, the annual illuminance profile contains 8760 rows.

The format of the file is as follows:

- columns 1-3: month, day, hour
- columns 4-(4+ # of points): illuminances at the individual sensors

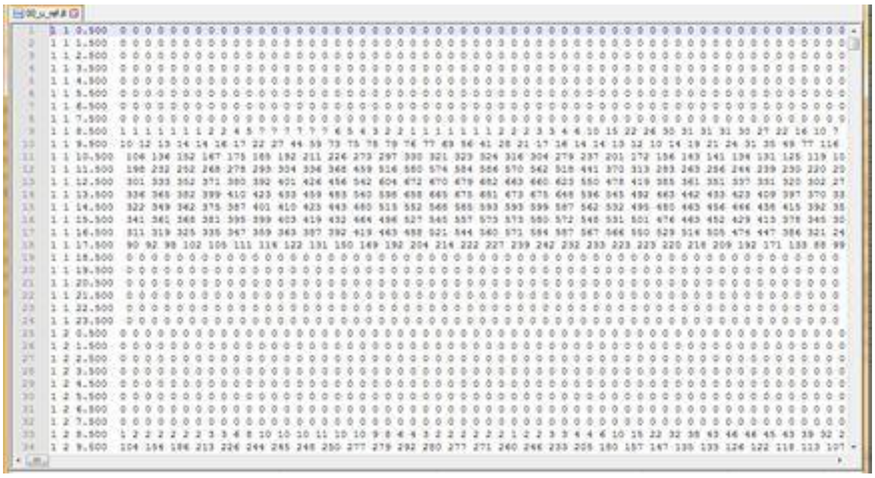

Figure 2: Annual Illuminance profile (.ill)*

In order to obtain the most common climate-based daylight metrics – Daylight Autonomy (DA) and Useful Daylight Illuminance scheme (UDI) – a cumulative analysis of the annual hourly daylight illuminance profile is performed for each column (each sensor point). In order to determine how many hours a sensor reaches an illuminance target, this analysis is based on a daily time period of analysis and a minimum illuminance level or minimum illuminance ranges [15].

A cumulative analysis sums the hourly results for a full year for each sensor and thus allows the number to be plotted on the floor plan as a spatial map. This approach, therefore, preserves geometrical information. The key issue, however, is that the conditions do not occur concurrently. They are, rather, a separate yearly summation for each point [15] [10].

However thermal performance is usually expressed as a temporal graphic as it considers the whole space as one node. In order, therefore, to couple thermal and daylight performances, both have to be expressed as temporal graphs, such as on temporal maps.

Temporal maps present performance over time and therefore lack spatial distribution [15] [30] while spatial maps present performance over space and so lack temporal information. Temporal maps indicate *when* while spatial maps indicate *where*. Temporal maps provide information useful for daylight harvesting and for building design while spatial maps provide information useful for lighting systems control. Ideally, therefore, temporal and spatial maps should be used in combination [31].

A temporal map is characterised by plotting the days of the year along the x-axis and the time of a day (solar time) along the y-axis. Such a map can be created with MATLAB [32] using a 24x365 matrix (for hourly values), which can be obtained by reshaping an 8760x1 matrix. This format enables the user to see at a glance the way that hourly and seasonal changes affect the availability of daylight within or around a particular building design.

Therefore, in order to express daylight performance on a temporal map, a time series analysis (every-hour) is proposed, instead of the commonly used cumulative analysis (every sensor). A time series analysis applied to the annual illuminance profile provides the percentage of the sensors simultaneously receiving a certain illuminance range.

This procedure is applied to obtain the simultaneous achievement of different illuminance ranges, following the Useful Daylight Illuminance scheme (UDI) concept [5]:

- UDI not achieved if the illuminance is less than 100 lux.
- UDI supplementary if the illuminance is greater than 100 lux and less than 300 lux.
- UDI autonomous if the illuminance is greater than 300 lux and less than 3000 lux.
- UDI exceed if the illuminance is greater than 3000 lux, as established in the most recent research [5].

It can be observed that UDI-autonomous illuminance suites range from a minimum illuminance threshold of 300 lux to an upper limit of 3000 lux based on a survey of reports of occupant preferences and behaviour in daylit offices with user-operated shading devices [33].

UDI-supplementary (100-300 lux) mostly corresponds to the illuminance range suitable for performing high-contrast or large-scale visual tasks; UDI-autonomous covers medium-contrast, small-scale (300-500 lux), and low-contrast and very small-scale visual tasks (500-3000 lux). In order, therefore, to correlate the UDI scheme illuminance thresholds with visual tasks, a subdivision of UDI-autonomous is proposed (UDI300-500 and UDI500-3000).

In the example case, having 29x29 sensor points and a time step of one hour, the annual hourly illuminance profile is an 8760x844 matrix. Every row, corresponding with every hour (8760), contains illuminance values at the individual sensors (841).

The application of this procedure provides five 8760x1 matrices that contain the percentage of those sensors reaching every illuminance range each hour. Theses matrices are reshaped to present the data in temporal maps [34]. An example of such maps is shown in Figure 3a to 3d.

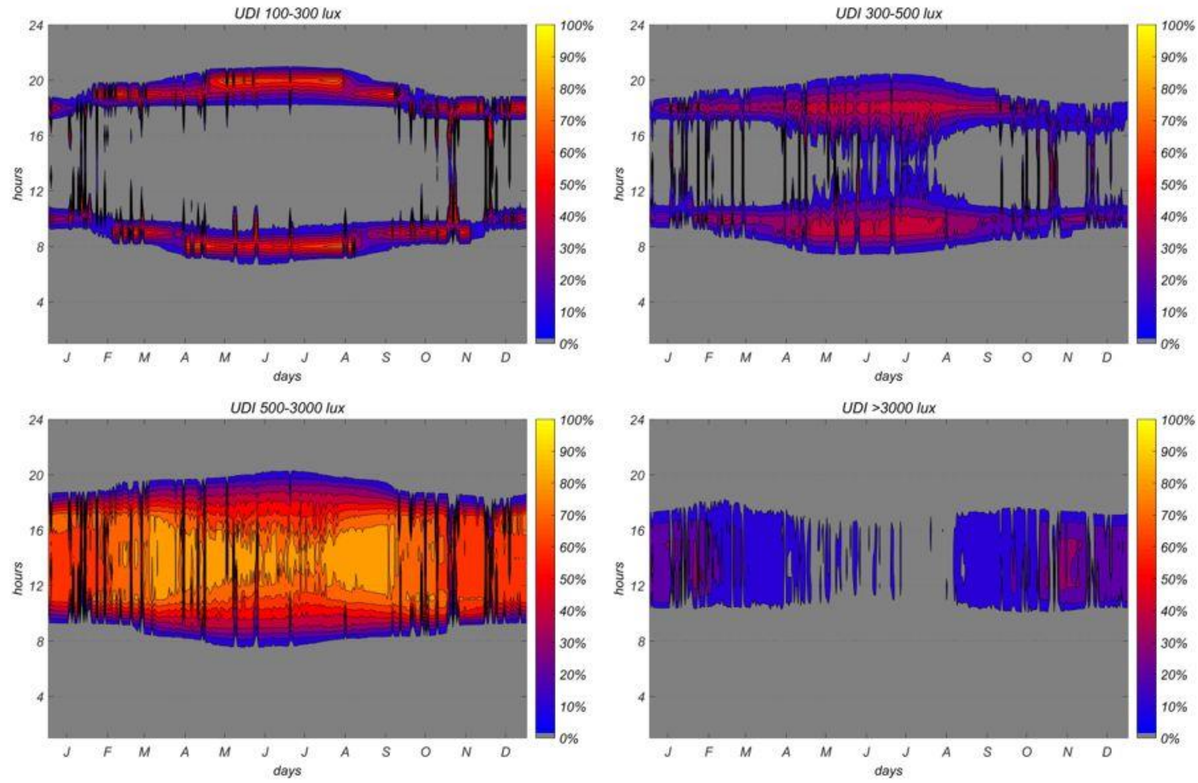

Figure 3: Temporal maps for a south-facing glazing façade in Seville: (a) sUDI100-300 (b) sUDI300-500 (c) sUDI500-3000 (d) sUDI>3000

These temporal maps show that more than 90% of the workplane achieves an illuminance range of 500-3000 lux from mid-March to mid-September (Figure 3c), varying from a maximum time length at both equinoxes and a minimum at summer solstice. Also, a 50% coverage of the workplane within this range is achieved for almost all daylight hours.

If this space was designed to perform high-contrast visual tasks (Figure 3c), this would be adequate, but movable solar protection should be added in order to reduce excessive illuminances during winter time with the aim of avoiding illuminances higher than 3000 lux (Figure 3d). If the space was intended to accommodate medium-contrast visual task activities (Figure 3b), the most meaningful design advice is to reduce the window size, reduce the glazing visible transmittance, and/or install fixed or movable shading devices.

Furthermore, taking the hourly data stored in the standardised weather file for Seville, external daylight availability can be displayed as shown in Figure 4a and 4b, and external weather variations with the indoor fluctuations can be correlated.

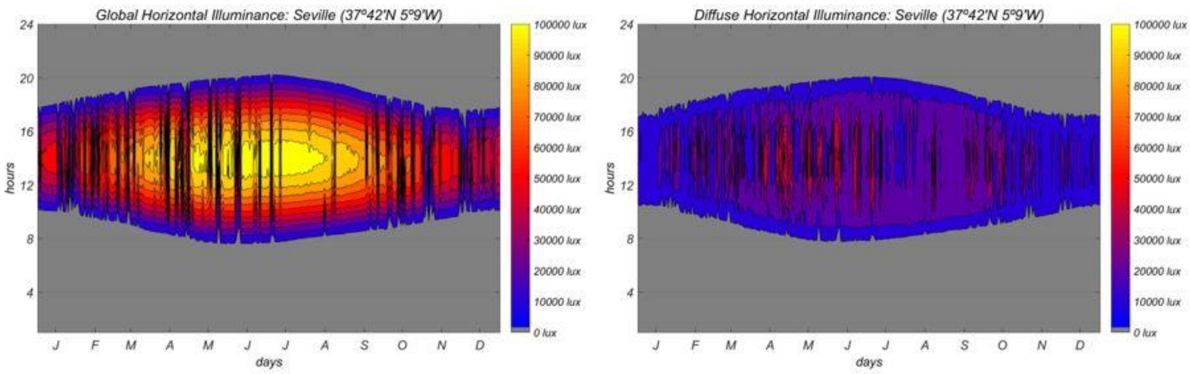

Figure 4: Temporal maps for the data taken from the Energy plus weather data file (.epw) for Seville (Spain): (a) Global horizontal illuminance Eh,g and (b) Diffuse horizontal illuminance Eh,d.

Figure 4 illustrates how the higher daylight availability of global horizontal illuminance corresponds to the higher achievement of simultaneous illuminances between 500 and 3000 lux.

The annual hourly solar heat gain profile obtained by energy simulation is also an 8760x1 matrix. This is also reshaped into a 24x365 matrix and plotted as a temporal map, as shown in Figure 5.

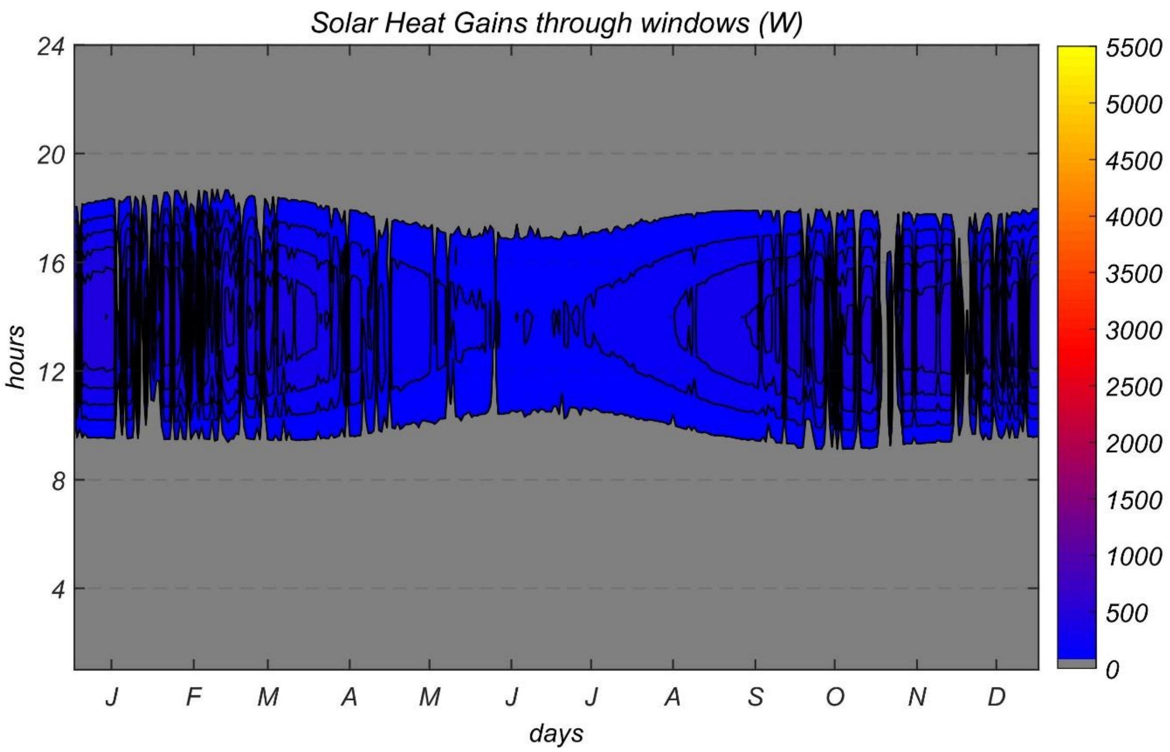

Figure 5: Solar heat gains through windows for the example sidelit space displayed as a temporal map

It can be observed that the admission of solar heat gains is higher during the winter, in agreement with the achievement of illuminances higher than 3000 lux on the workplane.

Therefore, simultaneous daylight illuminances on the workplane are expressed in the same format as solar heat gains, so it is possible to assess the luminous and thermal impact of the solar radiation entering through windows by applying illuminance and solar heat gains criteria.

2.2 Metrics and analysis criteria

2.2.1 Daylight sufficiency criterion

The analysis of daylight metrics performed by Heschong et al. [15] emphasises the fact that a space's daylighting conditions are characterised by certain illuminance values (lux), maintained over a certain time period (%h) and covering a certain portion of the workplane (% wp). The combination of those three parameters composes the Daylight Sufficiency criterion. In order for this criterion to yield a good daylit space, the thresholds are a minimum illuminance target of 300 lux, for 50% of the yearly analysis period during the occupied time or during daylight hours, as well as a 50% minimum workplane coverage.

The achievement of fulfilling this criterion by the cumulative analysis performed on the annual daylight illuminance profile is what is known as spatial Daylight Autonomy (sDA) metric [15] [16].

In this research, a time series analysis is performed in order to obtain the percentage of sensors on the workplane that achieves certain illuminance values each hour. So an 8760x1 matrix is obtained where each value represents the percentage of the sensors of the workplane that achieves simultaneously an illuminance higher than 300 lux each hour.

Having fixed the illuminance target, the application of the Daylight Sufficiency criterion (300 lux, 50%hours, 50%sensor points) results in two different analyses:

- Coverage analysis: the percentage of workplane achieving concurrently 300 lux for a certain percentage of the time (50% hours); or
- Maintenance analysis: given a certain percentage of workplane (50% of sensor points), what percentage of time 300 lux is achieved concurrently.

It must be emphasised that for the current climate-based daylight metrics – Daylight Autonomy, Useful Daylight Illuminance, spatial Daylight Autonomy – the yearly analysis period corresponds to the occupied time of the space. In this research, the daylighting potential is examined in order to consider all or any diurnal occupation of the space so the daylight hours through the year are considered the yearly analysis period [9]. Therefore, the nocturnal values are excluded before the maintenance or coverage analyses.

A time percentage threshold (50% hours) provides the daylighting sufficiency criterion coverage, plotted along the x-axis, termed Global Daylight Sufficiency (DSg). Plotted along the y-axis is the workplane percentage threshold (50% sensor points). This gives the duration of daylighting sufficiency criterion compliance over time and is termed Maintained Daylight Sufficiency (DSm) (Figure 6).

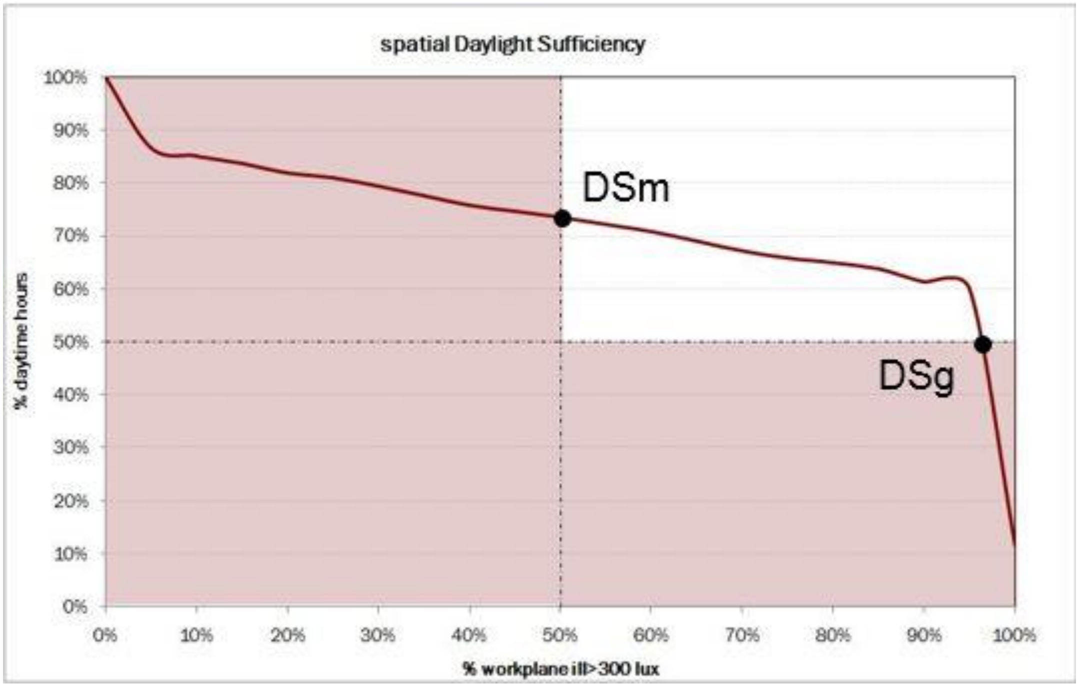

Figure 6: Simultaneous spatio-temporal fulfilment of the Daylight Sufficiency criterion for the example daylit space. Shaded areas imply that maintenance, coverage or both criteria were not met.

Global Daylight Sufficiency (DSg) represents the percentage of the workplane simultaneously meeting or exceeding 300 lux by daylight illuminances for 50% of the annual daylight hours and Maintained Daylight Sufficiency (DSm) represents the percentage of the annual daylight hours simultaneously meeting or exceeding 300 lux by daylight illuminances for a coverage of 50% of the workplane.

It can observed that DSg achieves a value of 97%wp and DSm achieves a value of up to 75%. Auxiliary electric lighting is therefore needed for 25% of annual daylight hours to cover at least 50%wp. However, for half of the annual daylight hours the workplane reaches 300 lux almost completely.

Global Daylight Sufficiency (DSg) and Maintained Daylight Sufficiency (DSm) are based on global horizontal illuminance values on the workplane using realistic sun and sky conditions derived from standardised annual climate data. Currently, however, worldwide design guidelines recommend daylight provision in terms of the long-established daylight factor (DF) [35]. In this context, Mardaljevic and Christoffersen [14] have proposed a method for adapting the Daylight Factor concept to the diffuse daylight availability determined from climate files in order to bridge the gap between climate-based daylight metrics and the daylight factor by defining the Climate-based Daylight Factor (DF_{CB}).

The basis of this adaptation is that by knowing the DF value of each sensor point, which is a fixed value, and the interior illuminance target ($E_{h,t}$ =300 lux), it is possible to connect the Daylight Factor concept to the climate file by determining the External Horizontal Diffuse Illuminance ($E_{h,d}$) with a certain frequency from the data contained in the weather files.

$$DF_{CB} = (E_{h,t} / E_{h,d}) \times 100 = (300 \text{ lux} / E_{h,d}) \times 100 \ (\%) \qquad \text{[Eq. 1]}$$

The frequency of the $E_{h,d}$ corresponds to the yearly analysis period that, in this research, is formed by the diurnal hours through the year, and represents the Median external diffuse horizontal illuminance ($E_{h,d\ med}$). The median external diffuse horizontal illuminance value is obtained by means of a cumulative diffuse illuminance curve extracted from the annual time series of hourly values for diffuse horizontal illuminance in a standardised climate file [36] [14] [37].

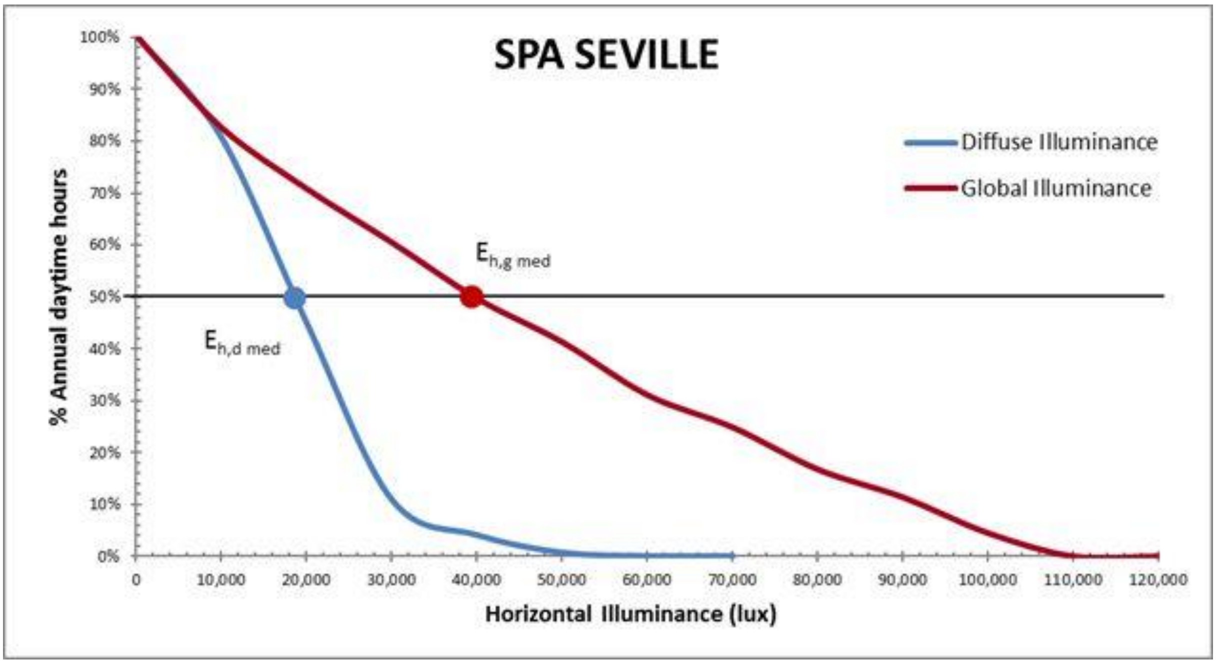

Figure 7: Cumulative diffuse horizontal illuminance curve for Seville (Spain).

Having the $E_{h,d\ med}$ value and 300 lux as the target horizontal daylight illuminance $E_{h,t}$, a climate-based DF (DF_{cb}) value is obtained by Equation 1 [14].

Once this DF_{cb} is defined and established as a threshold, the percentage of sensors on the workplane exceeding this value is calculated. The resulting value is defined as Diffuse Daylight Sufficiency (DSd) and represents the percentage of the workplane simultaneously meeting or exceeding 300 lux of diffuse daylight illuminance for 50% of the annual daylight hours.

2.2.2 Solar Heat Gains trigger value for closing blinds

Sunlight and solar heat gains can be restricted by user-operated, movable, solar shading devices. Among other reasons, blind use by occupants is dictated by demands of visual and thermal comfort. Other possible factors, however, are occupant concerns for privacy, the quality of view or social dynamics [17]. Most solar energy measurements with regard to blind use interactions focus on using irradiance data as a proxy for the presence of direct sunlight [17].

From a robust literature review, Van Den Wymelenberg proposed two manual control algorithms [17]. The first, Blindswitch-A, occludes more windows as solar penetration increases once exterior irradiance normal to the sun exceeds 120 W/m^2. The second algorithm, Blindswitch-B, increases blind engagement once exterior vertical illuminance exceeds 20 klux [24] [25] [26].

In order to correlate the thermal and luminous consequences of solar radiation entering a space, a limit for solar heat gains, or irradiance, is required. Here, a threshold value (I thr) of 120 W/m^2 is proposed in agreement with the trigger value proposed for lowering the blinds in the Blindswitch-A model [17].

At any instant, the net heat gain through a unit area of sunlit window is defined as being equal to the sum of the radiation transmitted through the window, the inward flow of heat from the solar radiation absorbed by the glazing material, and the heat flow (heat loss) due to the outdoor-indoor temperature difference. The relationship between the solar heat gains and the total incident irradiance is shown in the following equation [38].

$$Q = U\,A\,(t_{out} - t_{in}) + (SHGC)A\,I = U\,A\,(t_{out} - t_{in}) + SHG \qquad \text{[Eq. 2]}$$

Where

Q = instantaneous energy flow, W

U = overall heat transfer coefficient (U-factor), W/m^{2}K

A = total projected area of fenestration (the product's rough opening in the wall minus installation clearances), m^2

t_{in} = indoor air temperature, °C

t_{out} = outdoor air temperature, °C

SHGC = solar heat gain coefficient, dimensionless

I = total incident irradiance, W/m^2

SHG = solar heat gain, W

In order to establish an SHGthr which may indicate the lowering of blinds and given a proposed threshold in terms of irradiance (W/m^2) and hourly energy simulation results in terms of solar heat gains (W), the glazed area and solar heat gain coefficient is needed.

In the application example there is a 0.90 m^2 glazing area and 81.80 %glazing SHGC. Therefore, SHGthr is 88.34 W. Thus, the number of daylight hours this value is exceeded can be obtained from the 8760x1 hourly solar heat gain values matrix provided by energy simulation.

The resulting value is defined as the Solar Heat Gain blindswitch (SHGb) and represents the percentage of the annual daylight hours meeting or exceeding Solar Heat Gain through external windows so that irradiance is equal to, or greater than, 120 W/m^2.

3 Results

The time series analysis of the annual daylight illuminance profile provides various 8760x1 matrices, expressing the hourly achievement of some illuminance ranges. However, the Daylight Sufficiency criterion defines a temporal threshold of 50% of the yearly period of analysis. This period in the present research, is the daylight hours.

Applying this threshold to the 8760x1 matrices provides an annual value for each matrix expressing the percentage of the sensors on the workplane that achieves a certain illuminance range for 50% of the diurnal hours. This scheme is termed the simultaneous Useful Daylight Illuminance scheme (sUDI).

The application of the Daylight Sufficiency criterion and the Irradiance threshold also provides annual values called Global Daylight Sufficiency (DSg), Maintained Daylight Sufficiency (DSm), Diffuse Daylight Sufficiency (DSd) and Solar Heat Gains blindswitch (SHGb).

As a single annual value does not describe seasonal variations, we propose calculating monthly values for a complete year. These monthly values are obtained for the diurnal hours for the sUDI, DSg, DSm, DSd and SHGb metrics from their corresponding 8760x1 matrices. Some of them are expressed in workplane sensor percentages (sUDI, DSg, DSd) and some in daylight hour percentages (DSm, SHGb).

Having 50% as the time threshold to achieve certain illuminance values on the workplane the median value is obtained in order to reach this 50% value within a temporal range (diurnal hours), be it annual, seasonal monthly, or even daily. To express seasonal variations, monthly and annual values are chosen to display simulation results. Moreover, annual and monthly values are common time step display values in buildings' energy performance.

A simple graph is thus created, showing monthly values (along the x-axis) for every new daylight sufficiency and insolation performance metric. As sUDI expresses different illuminance ranges, this scheme is shown as cumulative columns while the other metrics are shown as curves.

The left y-axis shows the percentage of workplane sensors and the right y-axis shows the percentage of diurnal hours, as shown in Figure 8.

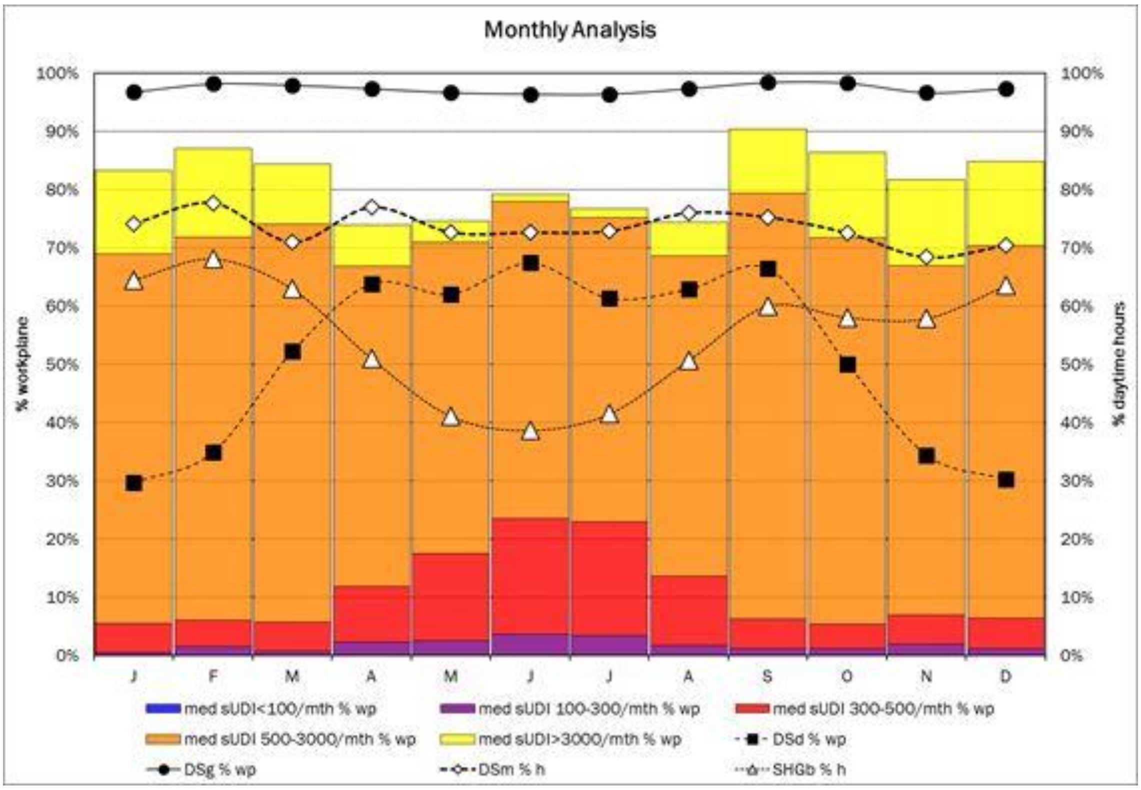

Figure 8: Climate-based daylight metrics for simultaneous illuminance achievement and solar heat gains assessment for the example sidelit space.

Based on the information shown in Figure 8 and Table 2, it can be stated that, with regard to the Daylight Sufficiency criterion, this space has sufficient global daylighting throughout the whole year, the DSg monthly value being around 97%. However, if the focus is the diffuse component, derived from the Daylight Factor, the DSd value only reaches 50%wp from March to October. Taking only the diffuse illuminance values over the workplane into account, continuous artificial lighting would be required for almost 6 months.

The relationship between global and diffuse daylight illuminances and solar heat gains through external windows is also represented in the DSg and DSd curves (Figure 8). For autumn and winter months, except for some occasional climatic incidences, daylighting is based on the direct component, as there are high DSg values contrasting with low DSd values. During spring and summer months the diffuse component increases while SHGb decreases, as does direct solar incidence.

A certain parallel is to be observed between the SHGb and $sUDI_{>3000}$ curves, representing a relationship between insolation and the appearance of overlit areas on the workplane. There also seems to be a certain connection between the decrease in $sUDI_{>3000}$ values and the increase in $sUDI_{300\text{-}500}$ values. The sum of their respective median monthly values reaches around 20% wp coverage (Table 2).

	sUDI med/mth					Daylight Sufficiency			Solar Gains
	<100	100-300	300-500	500-3000	>3000	DSd	DSg	DSm	SHGb
	% wp	% wp	% wp	% wp	% wp	% wp	% wp	% h	% h
January	0.00%	0.48%	4.99%	63.50%	14.39%	29.61%	96.79%	74.19%	64.52%
February	0.00%	1.43%	4.64%	65.76%	15.28%	34.84%	98.22%	77.71%	68.15%
March	0.00%	0.71%	4.99%	68.37%	10.34%	52.20%	97.98%	71.03%	62.97%
April	0.00%	2.26%	9.57%	54.99%	7.13%	63.85%	97.38%	76.98%	50.99%
May	0.00%	2.50%	14.98%	53.51%	3.69%	62.07%	96.67%	72.69%	41.08%
June	0.00%	3.57%	19.92%	54.52%	1.19%	67.42%	96.43%	72.67%	38.67%
July	0.00%	3.33%	19.62%	52.20%	1.55%	61.36%	96.43%	72.90%	41.51%
August	0.00%	1.66%	11.95%	54.99%	5.83%	62.90%	97.38%	76.01%	50.67%
September	0.00%	1.19%	5.11%	73.13%	11.00%	66.47%	98.45%	75.26%	60.05%
October	0.00%	1.13%	4.22%	66.35%	14.74%	50.06%	98.34%	72.58%	58.06%
November	0.00%	1.90%	4.99%	60.05%	14.86%	34.36%	96.67%	68.42%	57.89%
December	0.00%	1.19%	5.23%	63.97%	14.51%	30.20%	97.38%	70.44%	63.52%
Annual	**0.00%**	**2.14%**	**9.51%**	**58.50%**	**6.06%**	**54.93%**	**97.38%**	**73.48%**	**53.64%**

Table 2: Monthly Daylight and insolation metrics values (sUDI, DSd, DSg, DSm, SHGb)

The predominant daylight illuminance range of this space ranges from 500 to 3000 lux, as can be seen in the corresponding temporal map (Figure 3) in which minimum coverage is higher than 50%wp and the maximum is close to 75%wp. For annual diurnal hours, median values do not indicate workplane areas with a daylight illuminance lower than 100 lux, meaning that continuous artificial lighting is not necessary. The scanty presence of areas with a daylight illuminance of between 100 and 300 lux indicates the possibility of not using artificial lighting for diurnal hours when performing medium-precision visual tasks.

Overlit areas, especially during winter and accompanied by high SHGb values will, however, cause the occupants to operate solar shading devices, thus decreasing the daylight illuminance values.

The irradiance threshold has shown the relationship between the presence of solar heat gains in the space and the need of occupants to lower blinds [17]. Moreover, the upper illuminance threshold for the UDI scheme was conceived to indicate the occupants' need to lower blinds due to a high ambient daylight levels, with the concomitant probability of glare within a space [5] [33].

Therefore, knowing the percentage of diurnal hours equal to, or greater than, a vertical irradiance of 120 W/m^2 for each month, a percentile function is applied to diurnal sUDI$_{>3000}$ values to obtain the k-th percentile of values, establishing in this manner a relationship between SHGb (%h/month) and sUDI$_{>3000}$ (%wpe-SHG%/month).

A monthly evolution of insolation conditions and the percentage of the workplane simultaneously meeting a daylight illuminance greater than 3000 lux (representing a certain probability of glare) are therefore obtained from the same percentage of monthly daylight hours.

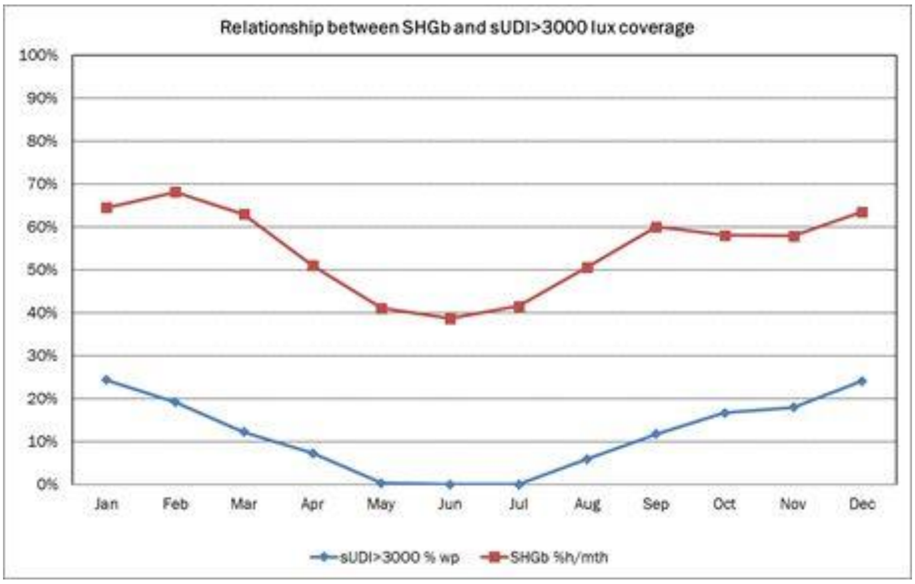

Figure 9: Relationship between SHGb (%h/month) and sUDI>3000 (%wpe-SHG%/month) for the example sidelit space.

It can be observed that for around 40% SHGb, the percentage of monthly diurnal hours reaching or exceeding a calculated solar heat gain limit described earlier –the percentage of workplane simultaneously exceeding 3000 lux – is null. 40% of the monthly diurnal hours might, therefore, represent a threshold – a higher value indicating a certain probability of the blinds being lowered. However, future field research is needed to establish upper thresholds for both solar intensity and time percentage.

It also can be observed that Solar Heat gains through windows are lower in summer than in winter due to the higher solar elevation and lower solar radiation intensity. sUDI$_{>3000}$ values also present a similar performance (Figure 3d). For the sidelit space facing south without any type of solar protection, a minimum value of around 40% of hours per month of solar heat gains greater or equal to 88.34 W is achieved from May to July. The corresponding sUDI$_{>3000}$ percentile values are zero for those three months.

The most meaningful design advice for reducing the probability of glare is to install movable shading devices which will reduce SHGb by as much as 40% in winter and mid-seasons. This action, however, acts negatively by increasing the demand for heating energy, especially in winter. If the shading device is fixed, SHGd in summer will probably be reduced, reducing the demand for cooling energy while $sUDI_{>3000}$ remains zero.

4 Conclusions

This research provides a decision tool for evaluating the simultaneous achievement of illuminance on the workplane and its correlated solar heat gains in order to balance the contribution of daylight when undertaking visual tasks with the illuminances and solar heat gains that can cause discomfort.

This decision tool is based on establishing a common calculation framework and on defining a set of metrics for the coupled assessment of daylighting and insolation. It is based on a data treatment of the primary results obtained by lighting and thermal simulations that can be performed in half an hour, at the most.

The novelty of the present methodology is that of applying a time series analysis of the annual daylight illuminance profile and the establishment of the annual daylight hours as thetemporal range in order to obtain illuminance and solar heat gain values in such way they could be comparable.

Based on the Daylight Sufficiency criterion (300 lux, 50% time, 50% workplane), the recommended illuminance ranges for visual tasks and the irradiance value upon which users close blinds, as established in the Blindswitch-A model, 5 metrics are defined as follows:

Global Daylight Sufficiency (DSg) and Diffuse Daylight Sufficiency (DSd) are based on the Daylight Sufficiency criterion. They evaluate the percentage of the workplane that reaches simultaneously 300 lux for 50% of the time range considered. They also represent the global and diffuse contribution of daylight. In this context, DSd supposes the adaptation of the Daylight Factor to the methodology in order to integrate it and to compare the results with the other metrics.

Maintained Daylight Sufficiency (DSm) assesses the percentage of time when 300 lux is reached simultaneously on at least half of the workplane. This metric, therefore, provides information about the how long of minimum daylighting requirements for a daylit space are maintained over the time range. of the minimum daylighting requirements for a daylit space.

The combination of DSg and DSm is called spatial Daylight Sufficiency and provides on a single graph information about how a space achieves the requirements concerning coverage and maintenance of a minimum illuminance of 300 lux.

Simultaneous Useful Daylight Illuminance (sUDI) divides the simultaneous illuminance achievement in 5 illuminance ranges, according to the recommended illuminance ranges for visual tasks. It assesses the suitability of a space for performing different visual tasks in terms of a workplane percentage within an illuminance range for 50% of the time range. Those percentages with low and excessive illuminance ranges are of especial interest, as they indicate the need to take project decisions in order to correct them.

Using the sUDI values some decisions can, moreover, be taken during building design regarding the suitability of a space for its associated activity, thus leading to modifications in the architectural project; i.e. a better localization of a bedroom in a house plan or modifying building characteristics to increase or decrease the achievement of a certain illuminance range.

Solar Heat Gains blindswitch (SHGb) evaluates the percentage of time in which there is such irradiance that the user needs to operate blinds, according to the Blindswitch-A model. In this sense, this metric illustrates the need to incorporate solar protection devices or to modify the architectural project in order to avoid the presence of excessive irradiance.

In summary, and bearing in mind that every architectural decision has luminous and thermal consequences, this decision tool enables certain decisions concerning building characteristics to be taken, especially during the design stage

However, it has to be taken into account that the thresholds proposed for the metrics are statistical approaches concerning users' preferences. A better understanding and correlation between physical parameters, such as illuminance, irradiance or temperature, and users' actions, such as closing blinds due to glare or overheating, will alter the proposed thresholds. Furthermore, the vagaries of human behaviour are perhaps the greatest difference when comparing a simulation and actual environmental performance.

Acknowledgements

The authors want to express their gratitude to John Mardaljevic and Jens Christoffersen for several interesting conversations regarding the nature of daylight performance metrics.

The authors are grateful for the financial support provided by SUB-UMBRA Project: Tertiary Buildings Energy Refurbishment under Mediterranean climate by means of Optimization of Solar Protection Devices (BIA2014-53949-R) belonging to Plan 2013-2016 Challenges – RDI Projects of the Spanish Ministerial Department for Economy and Competitiveness.

References

[1] W. Bommel and G. Van den Beld, "Lighting for work: A review of visual and biological effects," *Lighting Research & Technology,* vol. 36, no. 4, pp. 255-269, 2004.

[2] A. D. Galasiu and J. A. Veitch, "Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review," *Energy and Buildings,* no. 38, pp. 728-742, 2006.

[3] M.-C. Dubois and A. Blomsterberg, "Energy saving potential and strategies for electric lighting in future North European, low energy office buildings: A literature review," *Energy and Buildings,* no. 43, pp. 2572-2582, 2011.

[4] M. Bodart and A. De Herde, "Global energy savings in offices buildings by the use of daylighting," *Energy and Buildings,* no. 34, pp. 421-429, 2002.

[5] J. Mardaljevic, "Daylight, Indoor Illumination and Human Behaviour," in *Sustainable Built Environments*, V. Loftness and D. Haase, Eds., New York, Springer New York, 2013, pp. 69-111.

[6] M. Q. Li Li y S. Peng, «Performance evaluation of building integrated solar thermal shading system: Building energy consumption and daylight provision,» *Energy and Buildings,* nº 113, p. 189–201, 2016.

[7] D. Chi, D. Moreno y J. Navarro, «Design optimisation of perforated solar façades in order to balance daylighting with thermal performance,» *Building and Environment,* vol. 125, pp. 383-400, 2017.

[8] C. F. Reinhart and S. Herkel, "The simulation of annual daylight illuminance distributions-- a state-of-the-art comparison of six RADIANCE-based methods," *Energy and Buildings,* vol. 32, pp. 167-187, 2000.

[9] C. Reinhart, J. Mardaljevic and Z. Rogers, "Dynamic daylight performance metrics for sustainable building design," *Leukos,* vol. 3, no. 1, pp. 1-25, 2006.

[10] J. Mardaljevic, "Simulation of annual daylighting profiles for internal illuminances," *Lighting Research and Technology,* vol. 32, no. 3, pp. 111-118, 2000.

[11] C. F. Reinhart and O. Walkenhorst, "Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds," *Energy and Buildings,* vol. 33, pp. 683-697, 2001.

[12] A. Nabil and J. Mardaljevic, "Useful daylight illuminance: a new paradigm for assessing daylight in buildings," *Lighting Research and Technology,* vol. 37, no. 1, pp. 41-59, 2005.

[13] J. Mardaljevic, L. Heschong and E. Lee, "Daylight metrics and energy savings," *Lighting Research and Technology,* vol. 41, pp. 261-283, 2009.

[14] J. Mardaljevic y J. Christoffersen, «'Climate connectivity' in the daylight factor basis of building standards,» *Building and Environment,* nº http://dx.doi.org/10.1016/j.buildenv.2016.08.009, 2016.

[15] Heschong Mahone Group, "Daylight metrics: PIER Daylighting Plus Research Program," California Energy Commission, California, 2012.

[16] Illuminating Engineering Society of North America. Daylight Metrics Comittee, "Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)," IESNA, New York, 2013.

[17] K. Van Den Wymelenberg, "Patterns of occupant interaction with window blinds: A literature review," *Energy and Buildings,* vol. 51, pp. 165-176, 2012.

[18] C. Reinhart and K. Voss, "Monitoring manual control of electric lighting and blinds," *Lighting Research and Technology,* vol. 35, no. 3, pp. 243-260, 2003.

[19] M. Foster and T. Oreszczyn, "Occupant control of passive systems: the use of Venetian blinds," *Building and Environment,* vol. 36, pp. 149-155, 2001.

[20] Y. Zhang and P. Barrett, “Factors influencing occupants’ blind-control behaviour in a naturally ventilated office building,” *Building and Environment,* vol. 54, pp. 137-147, 2012.

[21] W. O'Brien, K. Kapsis and A. K. Athienitis, “Manually-operated window shade patterns in office buildings: a critical review,” *Building and environment,* vol. 60, pp. 319-338, 2013.

[22] P. Correia da Silva, V. Leal and M. Andersen, “Influence of shading control patterns on the energy assessment of office spaces,” *Energy and Buildings,* vol. 50, pp. 35-48, 2012.

[23] A. Tzempelikos and A. K. Athienitis, “The impact of shading design and control on building cooling and lighting demand,” *Solar Energy,* no. 81, pp. 369-382, 2007.

[24] C. Dyke, K. Van Den Wymelenberg, E. Djunaedy and J. Steciak, “Comparing Whole Building Energy Implications of Sidelighting Systems with Alternate Manual Blind Control Algorithms,” *Buildings,* vol. 5, pp. 467-496, 2015.

[25] A. Nezamdoost, A. Mahic and K. Van den Wymelenberg, “Annual energy and daylight impacts of three manual blind control algorithms,” in *2014 Illuminating Engineering Society Annual Conference*, Pittsburgh, 2014.

[26] A. Nezamdoost and K. Van Den Wymelenberg, “Blindswitch 2017: Proposing A New Manual Blind Control Algorithm for Daylight and Energy Simulation,” in *2017 IES Annual Conference*, Portland, 2017.

[27] C. F. Reinhart, “Daysim,” [Online]. Available: http://daysim.ning.com/. [Accessed 2011].

[28] DesignBuilder Software Ltd, [Online]. Available: http://www.designbuilder.co.uk/. [Accessed 2013].

[29] Ministerio de Fomento, “Orden FOM/1635/2013, de 10 de septiembre, por la que se actualiza el Documento Básico DB-HE "Ahorro de Energía", del Código Técnico de la Edificación, aprobado por el Real Decreto 314/2006, de 17 de marzo,” Madrid, 2013.

[30] S. Kleindienst, M. Bodart and M. Andersen, “Graphical representation of climate-based daylight performance to support architectural design,” *Leukos,* vol. 5, no. 1, pp. 39-61, 2008.

[31] S. Cammarano, A. Pellegrino, V. R. Lo Verso and C. Aghemo, “Assessment of daylight in rooms with different architectural features,” *Building Research and Information,* vol. 43, no. 2, pp. 222-237, 2015.

[32] The MathWorks, Inc., [Online]. Available: http://www.mathworks.com/products/matlab/.

[33] J. Mardaljevic, M. Andersen, N. Roy and J. Christoffersen, “Daylighting metrics: Is there a relation between useful daylight illuminance and daylight glare probability?,” in *Proceedings of the Building Simulation and Optimization Conference BSO12*, Loughborough, UK, 2012.

[34] M. Andersen, S. Kleindienst, L. Yi, J. Lee, M. Bodart and B. Cutler, “An intuitive daylighting performance analysis and optimization approach,” *Building Research and Information,* vol. 36, no. 6, pp. 593-607, 2008.

[35] R. Hopkinson, P. Petherbrigde and J. Longmore, Daylighting, London: Butterworth-Heinemann Ltd, 1966, p. 640.

[36] J. Mardaljevic and J. Christoffersen, “A roadmap for upgrading national/eu standards for daylight in buildings,” in *Proceedings of CIE Centenary Conference "Towards a New Century of Light"*, Paris, 2013.

[37] C. Munoz, P. Esquivias, D. Moreno, I. Acosta and J. Navarro, “Climate-based daylighting analysis for the effects of location, orientation and obstruction,” *Lighting Research and Technology,* no. 46, pp. 268-280, 2014.

[38] American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., "Chapter 15 Fenestration," in *Ashrae Handbook Fundamentals*, Atlanta, Ashrae, 2009.