DYNAMIC DAYLIGHT SIMULATION: NEW TECHNICS AND METRICS TO STUDY STRATEGIES TO REDUCE LIGHTING ENERGY CONSUMPTION

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ABSTRACT

After the energy crisis of 1973, the control of the thermal conditions in buildings has exponentially increased and new technologies have been developed forward greater energy efficiency in buildings, including artificial lighting between them.
As a proper thermal conditioning reduces energy consumption by reducing energy demand, an adequate daylighting will reduce the lighting energy consumption, increasing thereby the energy efficiency by taking advantage of a natural and free CO2 emissions source.
However, while there is a long history to predict the temperature and humidity conditions, the prediction of daylighting conditions is based, for more than 50 years ago, in the calculation of Daylight Factor.
This factor, despite its great international expansion and recognition, for example in LEED or BREEAM accreditation systems, is not considering the light from the Sun, so the only possible real sky conditions where there is no presence of the Sun is under a completely overcast sky, but considering this sky condition, Daylight Factor is insensitive to orientation.
In addition, due to the low frequency of cloudy skies in the sunnier climates in southern Europe, daylighting studies have fallen into disuse, considering the Daylight Factor distribution, at best, as representing the worst daylighting conditions. So, artificial lighting is usually designed independently to daylighting.
However, the recent emergence of Dynamic Daylight Simulation makes possible to obtain daylighting levels throughout the year due to local climatic conditions, considering, therefore, the presence and action of the Sun.
The statistical analysis of these results has led to the birth of new Daylighting Metrics that predict, for example, the amount of hours in which daylight is sufficient or the amount of hours when the use of electric lighting is really needed for visual comfort.
The analysis of these new metrics allows us to obtain a better comprehension of daylighting performance of a space, letting us making certain decisions that directly affect to comfort and energy consumption.
In this paper, the importance of these new daylight metrics is highlighted but also their relationship with lighting energy use. Considering these new metrics, a better lighting system design and a better adequacy of its regulation and control devices can be reached, giving energy savings up to approximately 30%.

Keywords: Dynamic Daylight Simulation, Dynamic Daylight Metrics, Lighting Energy Saving

1.- Introduction

The Energy Performance of Buildings Directive (EPBD) highlights the importance of reducing energy consumption in buildings, given that this represents up to 40% of the total energy consumption in the European Union [1]. In Mediterranean climates, where there are many hours of direct solar radiation, there is a great amount of available daylight but it is not usually used in its entirety [2]. In fact, in Spain, artificial lighting consumption accounts for up to 30% of total electric consumption in office buildings [3].

It's well-known that the amount of daylight that enters a building is fundamental, both as a means of reducing the consumption of electric lighting [4] [5] and in terms of its influence on visual comfort conditions, user moods, solar gains and qualitative aspects of the illuminated space [6]. The goal of making good use of daylight provision however needs to be tempered by the need to prevent the undue occurrence of very high levels of daylight illuminance since these are associated both with visual discomfort and the likelihood of excessive solar gain (i.e. increased cooling loads) [7] [8].

Daylight modelling has traditionally relied on abstract rather than absolute measures of illumination together with qualitative shadow-pattern studies for shading. Traditionally however, the reality of daylight illumination is artificially separated into categories: diffuse from a (sunless) overcast sky and direct from a (sky-less) sun. In this approach, the principal quantitative evaluation metric is the Daylight Factor (DF). The Daylight Factor is insensitive to both the prevailing local climate and the building orientation [9].

However, the development of the Climate-based Daylight Modelling (CBDM) and thus the appearance of dynamic daylight metrics such as Daylight Autonomy (DA) and Useful Daylight Illuminances (UDIs) [10] provide further information on the variable behaviour of daylight throughout the year. This means it is once again possible to take daylight fully into account when making decisions that affect architectural design [11].

Daylighting only saves energy if it temporarily replaces electric lighting. As a consequence, energy savings due to daylight depend not only on the annual daylight available at a work place but also on when and how occupants use their blinds and lighting controls [12].

Climate-based Daylight Modelling and the fundamentals of Dynamic Daylight Metrics are introduced in this work. It is also shown the difference between these metrics and the oldest one, the Daylight Factor, in terms of accuracy and approximation to reality, especially once it is decided to improve the energy efficiency of lighting systems including by means of linking dimming controls and indoors daylight environment.

2.-Daylight prediction

2.1-Daylight factor

Formulated in the UK over sixty years ago, the Daylight Factor is simply the ratio of internal illuminance to unobstructed horizontal illuminance (ec. 1) under standard CIE overcast sky conditions [9] (fig. 1).

$$DF = \frac{E_{int}}{E_{out}} \times 100\ (\%) \quad (1)$$

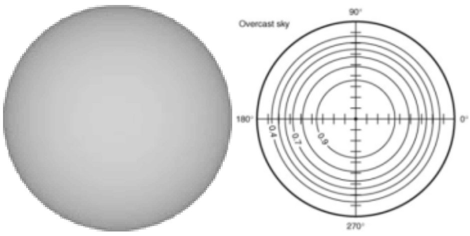

Fig. 12 “Luminance distribution of the CIE standard overcast sky”. Source: Hopckinson [13].

It is usually expressed as a percentage, so there is no consideration of absolute values, and it is usually graphically shown by means of isoDF curves over the workplane (fig.2). The luminance of the CIE standard overcast sky is rotationally symmetrical about the vertical axis, i.e. about the zenith. And, of course, there is no sun. Thus for a given building design, the predicted DF is insensitive to either the building orientation (due to the symmetry of the sky) or the intended locale (since it is simply a ratio) [14]. In other words, the predicted DF value would be the same if the building had North-facing window in Santander or South-facing window in Seville.
The prescription for minimum daylight factor values found in some guidelines inevitably results in a ‘more is better’ perception. Guidelines and recommendations for target daylight factors, as purposed by Standards or by the LEED or BREEAM credits system, often result in over-glazed buildings with excessive solar gain. So, the hoped for daylight benefit is often not achieved because, in over-glazed buildings, the blinds/shades are likely to remain drawn much of the time and electric light switched on.

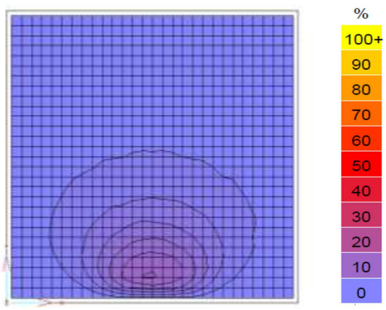

Fig. 13 “Graphical representation of Daylight Factor values distribution on the workplane”. Source: P.M. Esquivias

2.2-Climate-based daylight modelling

Climate-based daylight modelling is the prediction of various radiant or luminous quantities (e.g. irradiance, illuminance, radiance and luminance) using sun and sky conditions that are derived from standard meteorological datasets (e.g. EPW, TMY2 or CIBSE design years) (fig. 3).

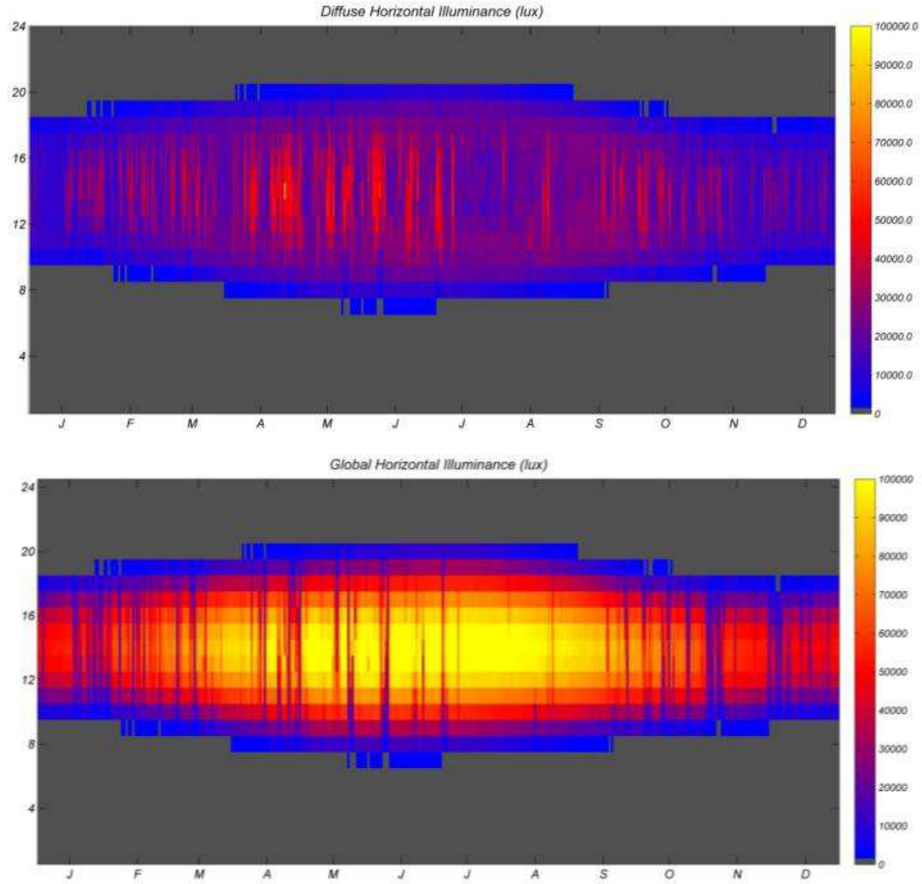

Fig. 14 “Diffuse and Global Horizontal Illuminance taken from the EPW climate file for Seville [15]”. Source: P.M. Esquivias

Besides the simplicity of Daylight Factor calculation, the reasons for moving to Climate-based Daylight Modelling are:

- Climate-based daylight modelling predicts absolute measures of illumination using realistic descriptions for the sky and the sun conditions.
- The evaluation period is usually for a full year to capture all of the naturally occurring variation in meteorological conditions.
- Sun and (variable) sky conditions are evaluated together.

Usually, the overall daylighting potential of the building, the occurrence of excessive illuminances, as inputs to behavioural models for light switching and/or blinds usage, or the assessment of the performance of daylight responsive lighting controls are based on time-series. Time-series analysis involves predicting instantaneous measures (e.g. illuminance) based on all the hourly (or sub-hourly) values in the annual climate dataset.

For every calculation point a time-varying daylight illumination profile can be obtained at the time of the climate data (fig. 4). For most climate files this will be hourly and result in the generation of 4380 illuminance values (i.e. number of daylight hours) for every calculation point [10].

A climate-based daylight analysis is intended to represent the prevailing conditions over a period of time, rather than be simply a “snapshot" of specific conditions at a particular instant.

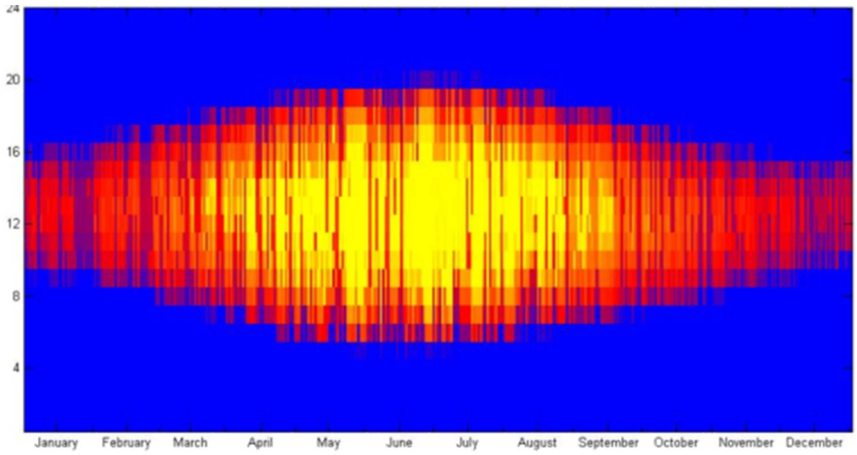

Fig. 15 "Temporal map showing the hourly illuminance values predicted for a point of the workplane". Source: P.M. Esquivias

2.3.-Climate-based daylight metrics

Climate-based daylight evaluation can generate huge amounts of time-varying illuminance data that needs to be processed, reduced and interpreted. Whilst a summary metric might be the end goal, the time-space dynamics of daylight illumination contains much information that can indicate the designer about the prevailing character of daylight illumination in the space [14].

Climate-based daylight metrics allow us to study the annual daylight amount for a given space using hourly or sub-hourly calculations of the illuminance of every sensor point placed usually on the workplane [16].

Both DA and UDI metrics are tools that make it possible to process a large amount of illuminance data for each point of the workplane. Both metrics analyse the illuminance data by establishing a time range and a suitable illumination level for carrying out visual tasks [9] [10] [17]. Daylight autonomy (DA) is a daylight availability metric that corresponds to the percentage of the occupied time when the target illuminance at a point in a space is met by daylight [10].

Achieved Useful Daylight Illuminance (UDI-a) is defined as the annual occurrence of illuminances across the work plane that are within a range considered "useful" by occupants. The range considered "useful" is based on a survey of reports of occupant preferences and behaviour in daylit offices with user operated shading devices.

Daylight illuminances in the range 100 to 500 lux are considered effective either as the sole source of illumination or in conjunction with artificial lighting. Daylight illuminances in the range 500 to 2000 lux are often perceived either as desirable or at least tolerable. Taken 100 lux as the minimum threshold and 2000 lux as the maximum one to carry on visual tasks, UDI-a then is defined as the annual occurrence of daylight illuminances that are between 100 and 2000 lux. But these thresholds may change as more data on user preference are obtained [9] [10] [18].

The UDI scheme is applied by determining at each calculation point the occurrence of daylight illuminances that:

- Are within the range defined as useful (i.e. 100 lux to 2000 lux): UDI-achieved
- Fall short of the useful range (i.e. less than 100 lux): UDI-feel short.
- Exceed the useful range (i.e. greater than 2000 lux): UDI-exceeded.

Thus, only three metrics are needed to provide a compact representation of the hourly-varying daylight illuminances for an entire year at each of the calculation points [18].

Based on occupant preferences, there is reasonable certainty that illuminances in the UDI-a range will not result in a switch on. Accordingly, maximisation of the occurrence of the UDI-a metric should be taken as the most reliable indicator that the overall level of electric lighting usage (for that space) will be low [10].

3.- A case study

Let's see the case we want to know the daylight availability of a small office to link the artificial lighting system performance.
Based on the UDI scheme, it can be said that the percentage of the workplane within the UDI-feel short range will require the lighting system switched on. The percentage within the UDI-exceeded range will probably present glare and thermal discomfort problems, pushing the occupant to close blinds and switch on lights, but experience tell us that once they are closed they will remain in that position even when glary conditions have past [14] [19].
The percentage of the workplane with UDI-a range may require or not supplementary artificial lighting to carry on visual tasks [20]. The question is then what is the illuminance value which is acceptable to consider a space daylit, reducing the electric lighting energy consumption. The other concept to keep in mind when working with time-varying values is the maintenance or the achievement of this value throughout time: daylight sufficiency of a space which can be defined as a minimum daylight illuminance level achieved for certain period of time.
According to the sustainability concept of reducing energy demand to reduce energy consumption, firstly is necessary to provide by architectural design the amount of daylight which is sufficient to achieve visual tasks and later it is necessary to link artificial lighting control to daylight sufficiency to achieve some lighting energy savings.
So at first stage we'll see the differences between considering DF or Climate-based Daylight Metrics to show the daylight illumination prediction of a space; and at second one, we'll show the differences between having lighting systems switched on all working hours and improving the artificial lighting by the implementation of daylight-linked lighting control.

3.1-Reference model

The model under study is simple geometrical space of 3x3x3 m for width, depth and height dimensions. Guidelines recommend a window size up to 10% the façade surface. This recommendation results in a window size of 0'95x0'95 m which is centred at the South-facing façade with a window sill of 1'025 m (fig. 5).
The workplane is found 0'80 m from the floor, with sensor points every 0'20 m. There is a minimum distance of 0'2 m between sensors and walls. The reflectance coefficients for floor, walls and ceiling are 20%, 50% and 80% respectively. The glazing unit is a single clear glazing which visible transmittance is 88'36%. There are no blinds.
The model has a general lighting system based on fluorescent lamps giving an average value of 387 lux with 118 W installed, giving an installed lighting power density of 13'11 W/m^2. This system has a manual lighting control which corresponds to a standard manually controlled electric lighting system with a single on/off switch near the door.

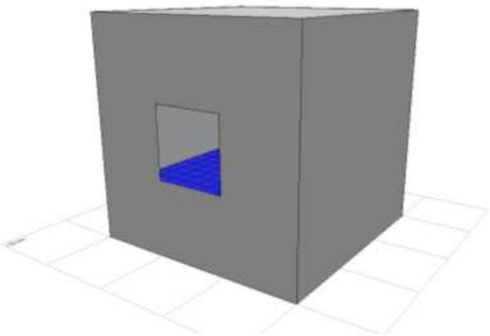

Fig. 16 "Reference model". Source: P.M. Esquivias

3.2-Daylight requirements for a daylight sufficiency of a space

Based on some evidences, 300 lux is defined as the minimum illuminance level to be achieved for the most common visual tasks. This illuminance threshold is in accordance with some standards and recommendations [21].

Once this limit was defined, the question was: "what percentage of the area of the study space needs to be daylit at or above 300 lux at least x percent of the time to be satisfied with the daylight sufficiency of the space?" The IES Daylight Metrics Committee agreed to use the 50 percent time as the temporal threshold to consider a space daylit.

Meanwhile is immediate to obtain the percentage of the workplane which meet 300 lux or more for the 50 percent of the time using the Daylight Autonomy metric, it isn't as direct using the Daylight Factor metric. It has to be noticed that the temporal range used in the calculation of Daylight Autonomy is the working hours, usually from 8'00 to 18'00 h.

Following the Daylight Factor equation (ec.1), 300 lux is the input data for the internal illuminance, but to obtain what is the daylight factor value which represents the 50 percent occurrence within a year we have to pay attention to the external diffuse horizontal illuminance input.

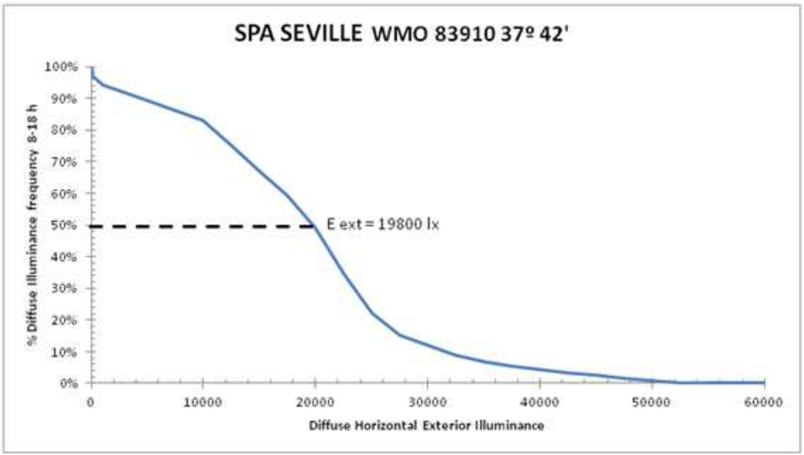

Fig. 17 "Diffuse Horizontal Exterior Illuminance cumulative curve for 8'00 to 18'00h working hours". Source: P.M. Esquivias

Traditionally a design sky value is taken to get daylight factor values, but that concept doesn't match to 50 percent of the time. So it is necessary to analyse the local weather file to know which is the external horizontal diffuse illuminance value occurring 50 percent of working hours. This can be obtained using a cumulative curve (fig. 6).

So, in terms of $DA_{300\ lux}$ a minimum value of 50% is the daylight criteria, and in terms of DF, a value of 1’51% will represent a diffuse illuminance contribution that will sure 300 lux at least half of the time considered.

3.3-Lighting controls

A manual on/off switch is the most widely used and simplest lighting control system (fig. 7). This system cannot improve energy efficiency by itself as it depends on the user behaviour. Lighting control can provide energy savings by adjustments to real-time occupancy [22]. Some authors, as Dubois [5], Galasiu [23], and Newsham [24] between others, coincide in the positive impact of lighting control systems, but there are different opinions about quantifying their energy saving. For example, manual regulation has a range between 7% and 25%, or occupancy sensors can provide a range of energy savings between 20% and 35%.

In this work an occupancy sensor with 5 minutes switch-off delay time has been combined with manual lighting control to evaluate their link and impact in the lighting energy consumption throughout a year (fig. 7).

Thus, the lighting system can only be activated manually through the switch. It is switched off either manually by the user or automatically by the occupancy sensor. The occupancy sensor consumes a standby power of 0’3W when the lighting system is switched on.

Fig. 18 “Manual switch and occupancy sensor”.

Another option is incorporating a photo-sensor-controlled dimming system. This lighting system corresponds to an ideally commissioned, photo sensor-controlled, dimmed lighting system. The photocell dims the activated lighting until the total work plane illuminance (daylight & electric light) reaches the target illuminance. At a minimum lighting output of 1% the system has ballast lost factor of the dimming ballast of 20%. The lighting is manually activated via a single on/off switch near the door. The photocell consumes a standby power of 0’3W.

3.4-Simulation methodology

Based on an assessment of the simulation tools available, it is internationally recognized the working process established by the combination of the software ECOTET with DAYSIM, specific software based on RADIANCE, to perform a dynamic daylight simulation.

ECOTECT Version 5.5 developed by Andrew Marsh of Square One was used to generate the 3D geometry files which are exported to a format file that can be read by the calculation engine RADIANCE.

DAYSIM, which is based on this engine, uses the daylight coefficient method developed by Tregenza in 1983 along with the Perez All-weather Sky Model to calculate the levels of lighting for each of the sensors defined for the work plane for each hour of the year [25]. This allows annual (8760 hrs) simulations of daylighting using an EPW weather file for a location, and hourly reports of illuminance levels at various sensor grids within the space models [12] [25].

By defining an annual schedule and a minimum illuminance on the workplane, DAYSIM calculates the DF, DA and UDIs, as well as other parameters. The

international database of climate records for energy calculations (IWEC) provided the climate data used [15].
DA and energy use for lighting have been calculated considering a time range from 8'00 to 18'00 h during all workdays, an active user model by default and a manual switch on/off lighting control located near to the main door. This implies that a zone is occupied by a single user type who operates the electric lighting and blinds actively, by lack or excessive presence of daylight [26].
The base case that studies the maximum energy use for lighting is simulated without openings, as a way to ensure that lighting will be on all the working hours.

4.-Results
4.1-Daylight sufficiency and architectural design

analysis	criteria	maximum	minimum	median
DF	43.20%	11.41%	0.50%	1.33%
DA	98.22%	91.00%	28.00%	77.00%
UDI<100	-	22.00%	7.00%	12.00%
UDI 100-2000	-	87.00%	25.00%	81.00%
UDI>2000	-	68.00%	0.00%	7.00%

Table 6 "Results for the reference model"

The results obtained for the reference model (table 1) show that only the 43% of the sensor points have a Daylight Factor value higher than 1'51%, but considering global daylight illuminances almost whole the sensor points have 300 lux or more for at least half of the working hours. For sunny climates, there is a big difference from analysing daylight factor values, based on diffuse illuminance, and climate-based daylight metrics (fig. 8). Even the median daylight factor doesn't reach the minimum required value.
Looking at UDI values we'll find that the 50% percent of the sensor points at workplane are within a useful range for 81% of the working hours, but we have to remember that UDI-a considers an illuminance range from 100 to 2000 lux, so the difference with DA value is that there will be sensor points lying between 100 and 300 lux.
Anyway, analysing the statistical data from the three UDI indicators, it can be seen that there are some sensor points at the deeper zone which haven't present glare problems (fig. 9), but they will always require artificial lighting.

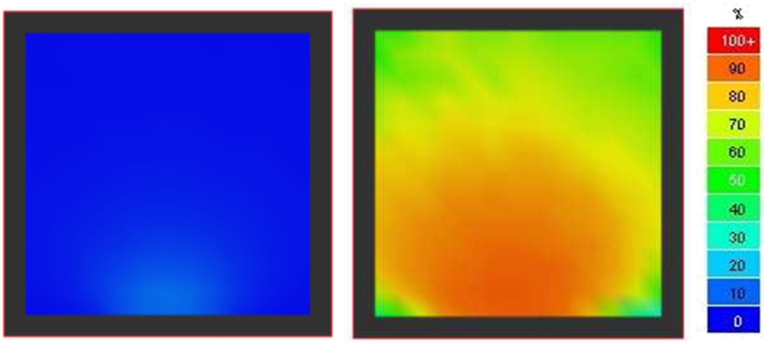

Fig. 19 "Daylight Factor, Daylight Autonomy values distribution". Source: P.M. Esquivias.

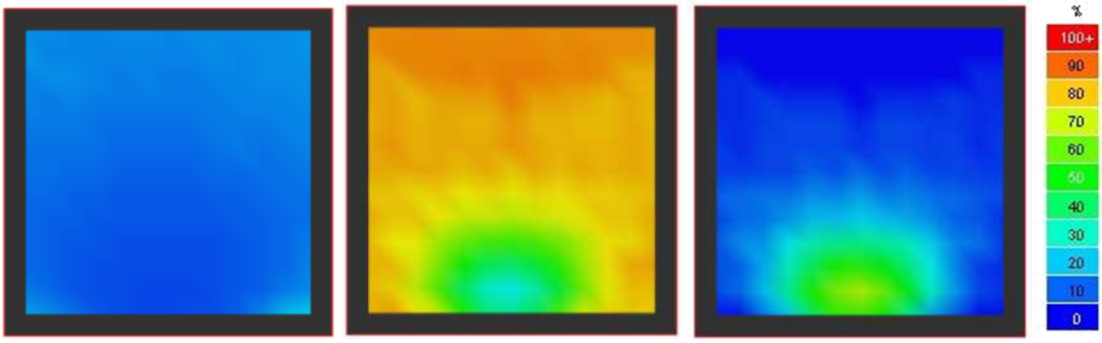

Fig. 20 "UDI feel-short, achieved and excessive values distribution". Source: P.M. Esquivias.

If we were applying for a LEED credit we won't obtained it as only 31% of sensor points are equal or higher than DF 2% and the requirement specifies that the percentage of the workplane getting DF values 2% or more has to be at least 75%. Having this at early design stages, the immediate strategy to solve this would be increasing window size, following an intuition: "higher the window, better the daylighting results".
But, what happens if we follow the nowadays architectural tendency for fully glazed buildings? In the case we decide to move forward to a fully glazed South façade the simulation results would be as follows:

analysis	criteria	maximum	minimum	median
DF	100.00%	24.17%	5.69%	11.11%
DA	100.00%	92.00%	90.00%	91.00%
UDI<100	-	8.00%	7.00%	7.00%
UDI 100-2000	-	28.00%	7.00%	14.00%
UDI>2000	-	86.00%	64.00%	79.00%

Table 2 "Results for fully South façade glazed"

In this situation all sensor points reach the criteria exposed in 3.2 but based on having the major part of the work plane with excessive daylight illuminance, so it's possible to get glare and thermal discomfort problems throughout a year.
Moving forward climate-based daylight metrics will provide us more useful information about the amount of daylight entering in a space depending on the variable meteorological events but also their distribution on different illuminance range that can be found of useful for architectural design and for artificial lighting planning.

4.2-Lighting energy consumption
Now, let's have a look at what happens with lighting controls. Defining an occupancy schedule Monday through Friday from 8'00 to 18'00 h and considering that the occupant leaves the office three times during the day (30 minutes in the morning, 1 hour at midday, and 30 minutes in the afternoon), the total annual hours of occupancy at the work place are 2066.0 hours.
Firstly, let's suppose the case artificial lighting is not linked with daylighting, so it will be switched on throughout the working hours (fig. 10). Having an installed lighting power density of 13.11 W/m^2 this results in a lighting energy consumption of 31'9 $kWh/m^2{}_{year}$.
Going back to the reference model with a manual lighting control, artificial lighting will be switched on and off every time the user has the impression of having insufficient or enough daylight and this will depend on the activeness or passiveness of the

occupant to leave its workplace to adapt the lighting system performance to daylighting. By default, an active user is considered giving an electric lighting consumption of 23.9 kWh/m^2_{year}.

Fig. 10 "Office environment where lighting is switched on all day besides daylight availability in the space". Source: Illuminet

An improvement option is the implementation of occupancy sensors that are able to automatically switch off the lighting system, but not switch on. The lighting system only can be switched on only manually through the switch. In this case, the predicted annual electric lighting energy use is of 13.3 $kWh/\ m^2_{year}$.
Another option is changing the occupancy sensors for a dimming system which is based on an ideally commissioned photosensor-control. In this case, the predicted annual electric lighting use is of 16.4 $kWh/\ m^2_{year}$.
Thus the improvement on lighting control will result in an energy saving around 50%.

5.-Conclusions and discussion

Net Zero Energy Buildings require paying attention not only in the energy performance of active systems of a building but in how that building is designed to improve its passive energy performance. A very low energy demanding building will require lesser energy consumption and it will be closer to a net zero energy building that one which rely it energy efficiency only on the performance of its active systems.
Meanwhile some interior environmental issues can be corrected once the building has been finished, daylighting is specially dependant on building design, and it has long-term energy consequences.
If a space appears to be too dark it will have its lighting system switched on all the time and it also will be an indicator of having higher heating energy demand due to the absence of sunlight entering in that space than a well-balanced daylit space.
If a space appears to be too bright it will probably have glare and overheating problems due to the presence of great amounts of sunlight falling into that space. In this case the energy consequences can be divided in two.
If there are no blinds or shades to block solar radiation entering in the space it will demand higher cooling energy consumption than a well-balance daylit space from the thermal systems to compensate the overheating. If there are blinds the users will put the blinds on and switch lights on. In this case, based on experimental studies, the blinds will remain in that position even when glary conditions have past, so the supposed daylight benefits to save lighting energy will be past over.
A well-balance daylit space requires a great effort and dedication at design stages during the architectural process even when there are no legal requirements for daylighting nowadays. Architects need to be aware of the consequences on the internal environment of their design decisions. They also need to evaluate their

different options using appropriate calculation methods and metrics that would provide more realistic information of what would possibly occur in the space.
Once the building form has been optimised due to internal environmental aspects it's time for planning active systems and their performance control system. Regarding lighting energy saving, it depends not only on the daylight availability of a space but on how users perform blinds and lighting controls.
An environmental awareness user will maintain lights switched on all the time even when there is enough daylight to perform visual tasks. Apart from changing human behaviour that is out of our scope as technicians, we can improve the performance of the most common manual lighting control by adding occupancy sensors or photo-sensor dimming control resulting in important lighting energy savings.

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