

306: Sustainable Daylighting Design in Southern Europe

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Abstract

Daylighting is one of the most important and conditioning factors of the indoor environmental quality in buildings. In the context of sustainability and rational use of energy in buildings, it is important to demonstrate clearly how daylighting can contribute to energy efficiency and also to make available reliable methods of evaluation that allows the designer to guarantee the referred energy efficiency without impairing the daylighting conditions. Therefore, it is important to develop an effective methodology that allows for the quantification of the energetic impacts of daylighting. A reliable and effective methodology should incorporate the prevailing climatic conditions in the region, the effect of shading and artificial lighting systems and controls and the attitudes and motivations of occupants towards those systems. In the present communication the results of a study, which have the aim to develop a methodology of quantification of real energy savings in buildings due to the conscious use of daylighting, are presented. The results include "on site" evaluations of selected case studies, the development of a mathematical model and the study of occupants' opinions and attitudes towards daylighting.

Keywords: daylight in buildings; energy efficiency, visual comfort

1. Introduction

The main function of daylight in buildings is to provide an adequate indoor visual environment that ensures the most adequate lighting conditions for the performance of visual tasks. These conditions include: i) adequate lighting levels and distribution, ii) the guarantee of visual comfort for the occupants and iii) the more subjective benefits related to the use of natural light instead of artificial light and the contact with the outer environment through windows.

Daylighting can also contribute to the energy efficiency provided that its energy impacts are correctly assessed during the design phase of buildings. The energy-related aspects of daylighting are particularly important in regions with long hot cooling seasons where non-overcast skies conditions prevail, which is the case of most of the regions in Southern Europe and in particular in Portugal. However, in the design process of buildings, the assessment of the energy-related impacts of daylighting are often dissociated from the daylighting aspects themselves and linked to other domains of the building design, such as the artificial lighting design, envelope and HVAC design or the verification of compliance with thermal regulations. This dispersion can harm the final daylighting conditions, in particular in what refers to the visual comfort requirements of the occupants and their preferences regarding the indoor visual environment.

Several studies that deal with the problem of assessing the energy-related impacts of

daylighting have been published (section 2.2), but all of them have limitations in their application, in particular when taking into account the effect of occupants motivations and attitudes towards the visual indoor environment and the control systems (lighting and shading) in regions with prevailing clear or quasi-clear sky conditions.

In this document the description and the first results of a new methodology for the prediction of real energy savings in buildings due to the conscious use of daylighting is presented. The method takes into consideration the climatic characteristics of Southern European regions, the visual comfort needs of the occupants, the influence of shading and artificial lighting systems and respective controls and the attitudes and motivations of occupants towards those systems and to the lit environment in general.

2. Background

2.1 The Problem and its Context

When using daylight to illuminate the interior spaces of buildings, two major energy-related consequences can be distinguished: i) potentially positive (reducing the energy use for artificial lighting and for mechanical heating and cooling of interior spaces and allowing for the use of thermal solar gains through windows in colder periods) and ii) potentially negative, related to eventual overheating (during the Summer and mid season periods) or excessive heat losses (during the colder winter periods), both of these

with implications at the comfort and/or energy use levels (Fig.1). These potential energy-related consequences of daylighting derive from the daylighting and fenestration design (prevailing climate conditions, glazing visible transmission and area, required lighting levels, minimization of visual discomfort, etc.) from the characteristics of the lighting and shading systems and respective control strategies and from the attitudes of the occupants towards those control systems and the interior environment.

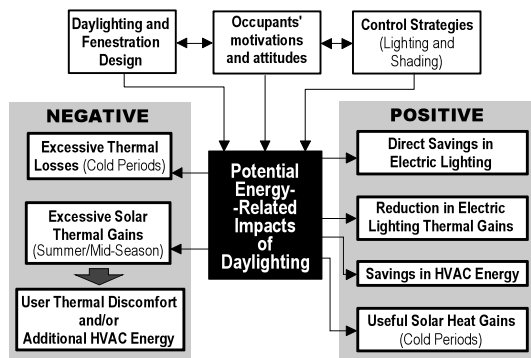


Fig. 1 Schematic illustration of the major potential energy-related impacts of daylighting

The majority of studies that have demonstrated the virtues of daylighting as an energy saving technology have their origin in climates with prevailing cloudy conditions. In these regions, the daylighting design strategies are directly associated with generous glazing areas with obvious benefits to the occupant's visual comfort without, usually, severe overheating problems.

However, in regions with long and hot cooling seasons, one of the main priorities in the design of buildings is the effective control of solar heat gains during mid-season and summer periods. In these regions, despite the high daylight availability throughout the whole year, daylighting haven't always confirmed its attributes a technology that promotes the energy efficiency. There are several reasons that explain this fact. One of the main causes is the inadequate articulation among the different control strategies (daylighting, solar protection, glare attenuation and artificial lighting) that often leads to potentially avoidable excessive energy use (in heating, cooling and lighting) and/or visual and thermal discomfort issues for the occupants. Other reasons include the incorrect choice of shading devices and the lack of knowledge on occupants' typical behavioural patterns towards the indoor environmental control systems (and in particular shading and electric lighting control) in sunny climates.

Consequently, in order to guarantee that the most adequate daylighting strategies are effectively implemented, it is essential to address the energy-related aspects of daylighting, at early stages of the building design process, so that the final daylighting conditions are not harmed by other aspects of the building design. Particular attention should be paid to the main aspects of the visual comfort of the occupants.

2.2 Previous Research

The characterization of the energy impacts of daylighting in buildings have been addressed in different ways by different authors [1-9]. The first consistent studies were concerned with the savings in energy for lighting due to the use of daylight in buildings. The first models were developed by *Crisp* [1] and *Hunt* [2,3]. The proposed methodologies take into consideration the effect of daylight-linked controls in savings in electric lighting energy and also incorporated a behavioural model translated into a probability of switching the lights on (P_{switch}) as function of the time of the day and of the minimum daylight factor in the work plane (equation 1):

$$P_{switch} = a + c / \{1 + \exp[-b(\log_{10} E_{min_wp} - m)]\} \quad (1)$$

Where: a , b , c and m are constants and E_{min_wp} is the minimum illuminance in the working plane.

Despite of the in-depth work and of the detailed techniques of evaluation, the results of the authors have not been widely used in the current practice of the design of buildings, although they established the foundation for future research on the rational use of lighting energy [4-9]. The main reasons for this rely in the fact that the model needs the detailed knowledge of point-by-point illuminances along the working planes, for the whole building, which may be unfeasible at the early building design stages, since the fenestration details may not yet be decided.

Lynes and *Littlefair* [4] addressed some of the difficulties of Hunt's model and proposed a new method for the quantification of lighting energy savings due to the use of daylight. The method is relatively simple and particularly useful in the early design stages. It is based on the definition of a two-zone daylight model and on the concept of Average Daylight Factor. It also incorporates an adapted version of Hunt's probability of switching consistent with the Average Daylight Factor method. Although reliable and valuable, the usefulness of the method under non-overcast dominated climates is rather limited.

The *LT Method* [10,11] is one of the most widely used simplified methods for the assessment of energy impacts in buildings. The LT Method provides the means to estimate the relative energy performance of different building design alternatives by allowing the separated prediction of energy use for heating, cooling and lighting. Based on a set of charts with the total and segregated heating, cooling and lighting energy use, the numerical details of the models that originate those charts are not known, limiting its applicability to specific climatic, constructive and functional conditions. Additionally, the method relies merely on the transparent fraction of the façade to account for daylighting.

More recent methodologies [9,18,19] take into consideration the effect of occupants in the lighting use in buildings through the incorporation of behavioural models. The extent of the results is still limited to office buildings but important aspects for further research have been identified.

3. Development of a New Model

3.1 General Aspects and Methodology

A new model for the quantification of the energy-related impacts of daylighting is proposed. The model addresses some of the problems identified in the previous section. It takes into consideration the prevailing average climatic conditions, the assurance of the lighting needs (daylighting levels, absence of glare, psychological benefits of daylight and contact with the exterior) in an energy efficient way and the attitudes and motivations of building users towards indoor visual comfort and control systems. The incorporation of these aspects in a global energy building design strategy is often the real challenge in any successful daylighting design process.

The new model has four linked modules which permit to quantify the energy daylighting impacts in the conditions described in the previous paragraph. The four modules are designated as: *i)* exterior module; *ii)* transmission module; *iii)* interior module and *iv)* behavioural module.

3.1.1. The Exterior Module

The *Exterior Module* allows for the characterization and representation of the luminous climate in Southern European regions. It uses the data collected for Lisbon under the IDMP Programme [12,13] and additional information from the Satel-light Project [14]. The implementation of the module was based on the methodology used in the representation of the luminous climate incorporated in the *Daylighting-Hours Indicators* model [15,16].

3.1.2. The Transmission Module

The *Transmission Module* quantifies the effects of the glazing/shading system using a Daylight Transmission Factor (DTF) and a Solar Thermal Transmission Factor (STF). DTF and STF are being measured in a test cell for different types of shading devices, and compared with a numerical model, in development [17], and reference computational applications (WIS, WINDOW 6, etc.). The complete set of daylight measurements in the test cell is illustrated in Fig. 2. Irradiances are also measured for the corresponding solar/thermal characterization.

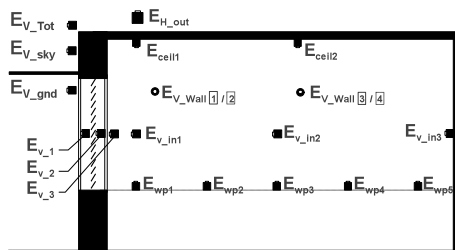


Fig. 2 – Illustration of the complete set of illuminances measured at LNEC's test cell

The measurements are carried out under overcast and clear sky conditions for four different shading system configurations: no

shading, shading completely closed, shading with slats at 45° and slats horizontal (0°).

3.1.3. The Interior Module

The *Interior Module* quantifies the influence of daylighting conditions (work plane illuminances, uniformity and glare) and the impact of the electric lighting and shading systems (types, zoning, controls and patterns of use) in the energy use for lighting. It uses information from the exterior and transmission modules and incorporates information resultant from the behavioural module (typical patterns of use). The interior module is based on an improved version of the *Daylighting-Hours Indicators* model [15,16], briefly described in the following paragraphs.

The *Daylighting-Hours Indicators* model characterizes the daylighting availability in interior spaces in climates where clear skies and sunlight effects prevail. The indicator and the corresponding method of calculation are intended to be used in southern European countries and, more generally, in regions where sunlight is important to daylighting performance. The indicator is called *daylighting-hours indicator* and may be used to compute the electric lighting use and to estimate energy savings due to daylighting. Daylight data are presented as illuminance charts (Fig.3).

The *Daylighting-hours indicators* are represented by the term *H_{ref}*, where *ref* indicates an illuminance value, and they are applied to a zone of a space. Daylighting-Hours can be defined as the *average number of hours of the period of use of the space, during which daylighting illuminance levels at a point and plan, representative of the zone, exceed the reference level ref and simultaneously visual comfort requirements are accomplished*. If appropriate, mean illuminance values on several representative points can be considered. For instance, H300=1000 hours means that during the period of use, the representative daylighting illuminances exceed 300 lx, during 1000 hours in average, per year, maintaining the visual comfort requirements.

The calculation method uses a model of representation of the daylight climate based on the following assumptions: *i)* external daylight conditions can be represented by sequences of periods without sunshine, and of periods with sunshine; *ii)* The mean frequency of occurrence of periods with sunshine is given by the relative sunshine duration.

The calculation of *daylighting-hours indicators* is first performed separately for the periods with and without sunshine. The annual value is then computed weighting the results obtained for each type of periods according to the relative sunshine duration data for the location.

The model also assumes that the ratio between the internal illuminances from a vertical glazing and the illuminances on the external surface of that glazing is constant and equal to the value established for a standard CIE overcast sky. The minimum vertical illuminance (E_{V_min}) on the external face of a window required to produce an internal illuminance E_{in} at a point and plane with a

daylight factor DF (%) due to daylight coming from that glazing is then given by:

$$E_{V_min} = (E_{in} \cdot 40\%) / DF\% \quad (2)$$

Using the previous expression the average number of hours during which the internal illuminances exceed E_{in} can be determined, by estimating the number of hours during which illuminances on the external face of the glazing exceed E_{V_min} . *Illuminance charts* (Fig. 3) can be used to perform these estimates. *Illuminance charts* are the representation, on a solar chart, of the average illuminances on different surfaces produced by skylight and sunlight for a grid of positions of the sun. In order to be able to consider separately periods with and without sunshine there are different charts for each type of these periods. For periods with sunshine there are also charts for global illuminances (skylight + sunlight) and for diffuse illuminances (in order to estimate the effect of external obstructions).

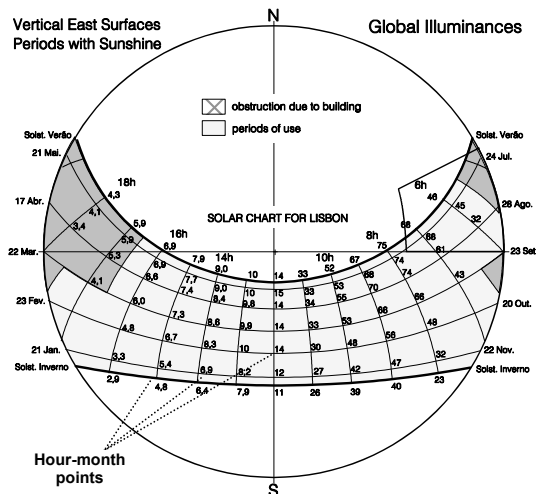


Fig. 3 Global illuminance chart for East vertical surfaces, for periods with sunshine with the hour-month points. The periods of use and the obstructions can also be taken into consideration

The calculation procedure for a *daylighting-hours indicator* (H_{ref}) is the following:

- Determination of the parameters that relate the interior illuminance E_{in} with the known exterior illuminances;
- Estimation of the daylight factor DF(%) at the point and plane under consideration;
- Determination of E_{V_min} (using equation 2) considering $E_{in} = ref$;
- Definition of a characteristic pattern of use for the shading devices (bearing in mind the maintenance of the visual comfort conditions, the necessary solar protection and the occupants' behavioural patterns of control);
- Use of the appropriate illuminance charts, to estimate, separately for periods with sunshine and without sunshine, the number of hours per year during which the illuminances at the glazing surface exceed E_{V_min} ;
- Scoring the number of hour-month points (Fig. 3) for which the above conditions are satisfied;

- Estimation of H_{ref} indicator combining results obtained for each period according to the annual mean relative sunshine duration value. Calculations can be more complex, due to windows with different orientations, to the existence of external obstructions, and the need to take into account the daylight reflected by the ground that reach the different windows. In these situations a computer application is used. For comparison and validation purposes of the *interior module*, systematic on-site daylighting, lighting and energy surveys are being made in several buildings selected as case studies.

3.1.4. The Behavioural Module

Recent studies [9,17,18] have already pointed out the essential influence of the occupants' attitudes towards their indoor environmental controls in the visual, thermal and energy performance of buildings. In fact, in order to anticipate the realistic daylighting and visual comfort conditions inside buildings its essential to have a solid knowledge on the typical patterns of use of shading and electric lighting. These patterns of use are directly related with the occupants' preferences and motivations regarding their indoor visual and thermal environment.

One of the most innovative aspects of the methodology herein presented is the integration of the occupants' motivations and attitudes towards daylighting and control systems in the model, through the definition of typical patterns of behaviour. These patterns have a crucial influence in the final indoor illuminances, and in the visual and thermal comfort and energy use in lighting. The behavioural module is being developed based on on-site observations of behavioural patterns in various buildings and by informal and formal surveys.

4. Results and Analysis

The results and conclusions obtained so far are drawn from on-site daylighting measurements and observations, daylighting and thermal characterization of shading devices in a test cell and on-site behavioural patterns observation and user evaluation through formal and informal post-occupancy surveys.

The characterization of different shading devices in the test cell allowed establishing effective daylight and thermal transmission factors that will be used as input data for the daylighting-hours indicators model. Some of the results already obtained are described in reference [17].

For the on-site observation and measurements different types of buildings (traditional and open-plan offices, schools, mixed-use buildings, etc.) with different daylighting, shading and control strategies, were selected as case studies.

The on-site measurements allowed the quantification of several daylighting systems performance, allowing comparisons with reference models and methodologies. In Figs. 4 to 6 the daylighting results obtained from the measurements in one of the selected buildings are depicted. Figures 4 and 5 illustrate the

Daylight Factor and illuminance profiles (measured under overcast sky and clear sky, respectively, in a horizontal plane 0.80 m from the floor) in a South facing room with and without shading devices (external awning and interior venetian blinds). In Fig. 6 the shading efficiency and direct sunlight penetration analysis is also presented for the same room.

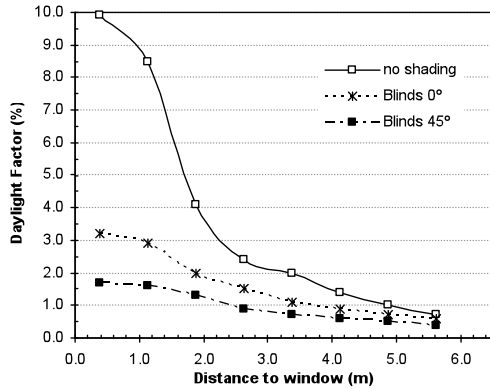


Fig 4. Measured Daylight factor (%) profiles under overcast sky conditions

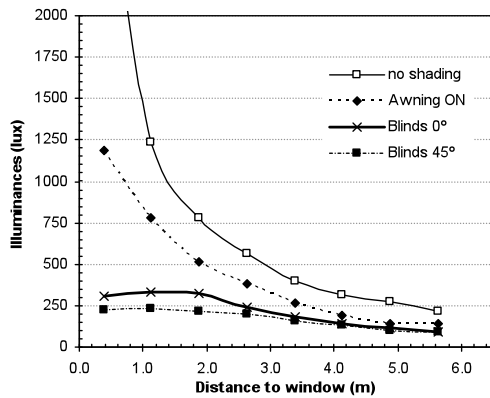


Fig 5. Measured illuminance profiles (in a horizontal plane 0.80 m above the floor) under clear sky at solar noon during the Summer Solstice

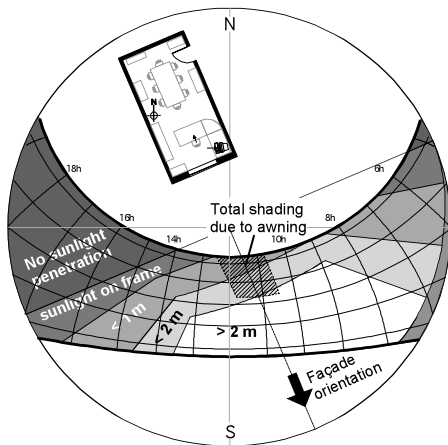


Fig 6.- Shading efficiency and direct sunlight penetration study in a South facing office room

Despite the potential good daylighting conditions, it was observed that during summer roughly 80% of the South-facing rooms had the interior blinds

fully closed (with an average illuminance on the working plane of about 150 lux) and about 75% of them had the artificial lighting on. These results show that the poor solar protection performance of the awnings (fully activated during the cooling season – Fig. 6) led to use of the interior blinds with repercussions in final daylighting levels and in potentially unnecessary electric light usage (if the exterior shading devices had a better combined daylight and solar protection performance). Moreover, it was found that in almost all of the rooms the electric lighting was continuously on during all working day and the position of interior blinds were kept unchanged (closed) during several days. Additionally, 70% of the occupants answered in a written survey that they prefer to work with daylight only. When asked to identify the reasons for activating the interior blinds in the summer, only 20% of them identified excessive summer heat as the reason for having them activated. However, during later individual interviews, almost 90% of them admitted that the reason for closing the blinds was the excessive heat. Surprisingly, in the formal written survey when inquired about the degree of satisfaction with several aspects of their indoor environment, the occupants scored positively all aspects including daylighting and thermal conditions (Fig. 7), revealing an inconsistency with the measurements and observations.



Fig 7. Occupants' degree of satisfaction with their indoor environment (results from a formal written survey issued to 90 occupants of the building)

5. Conclusions and Further Work

In this paper, a methodology for the evaluation of the energy impacts of daylight in buildings is presented. The proposed methodology is considered particularly adequate for climates where the non-overcast sky conditions prevail. From the preliminary analysis of the results obtained up to now, the following conclusions can be drawn:

- The poor shading performance (basically due to the wrong choice of the shading system) combined with inadequate shading control and electric lighting strategies was found in several of the buildings monitored, being two of the major constraints to the visual comfort and energy efficiency in buildings located in regions dominated by clear-sky conditions.
- Occupants' opinions are valuable when optimizing existing control systems. In general

most of them are aware of the problems and have strong opinions about what they dislike about their comfort conditions, even if their attitudes towards the improvement of those conditions are not always the most adequate (the lack of change in the state of activation of lighting and shading systems, for instance was identified in most of the monitored buildings);

- Formal written surveys are powerful, useful and fundamental techniques to infer patterns of behaviour from the occupants' attitudes and motivations. However, they should be complemented by informal questionnaires and objective observations, in order to avoid inconsistencies in the final models for the patterns of behaviour. Better questionnaires and unbiased techniques of analysis should be used in order to draw the correct conclusions. Individual informal interviews proved to be fundamental in the assessment/validation of occupants' real attitudes and motivations associated with indoor comfort issues and patterns of behaviour.
- In average, occupants tend to highly appreciate the presence of daylight and the existence of views out, but they tend to "forget" to change the activation state of lighting and shading systems when the exterior daylighting conditions change.
- "Energy efficiency" in buildings located in regions with long cooling seasons is frequently achieved at the expenses of the visual comfort conditions with the justification for the need of additional summer protection. Actually, the problems often arise due to the lack articulation between several areas of the building design. The results of the monitored buildings confirmed this statement.

Further work should be done in order to complete the solar-optical characterization of different types of shading devices in a test cell under different sky conditions. Additionally, the information resulting from the formal post-occupancy surveys must be analyzed in a more rigorous and consistent way in order to improve the overall accuracy of the model. Comparison and validation against reference models should also be completed. A simplified global model will also be derived from the basic model so that the energy impacts of daylighting can be assessed in an easy way at the early building design stages.

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