Energy and Buildings 65 (2013) 391–397

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Development of a suitable synthetic projection to simultaneously study solar exposure and natural lighting in building windows

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ARTICLE INFO

Article history:
Received 5 January 2013
Received in revised form 17 March 2013
Accepted 1 June 2013

Keywords:
Luminance
Hemispherical projection
Daylight

ABSTRACT

The level of comfort inside buildings is highly related to daylight availability, which is associated with solar access, irradiation on windows as well as solar rights. These mentioned variables are frequently calculated using similar methods.

For the graphic study of these variables, mathematical projections are used which provide a geometric view of the analytical results. However, the existing projections are not suitable for calculating and representing sky vault luminance.

In this paper we present a synthetic projection developed specifically for vertical windows in order to study and determine the main variables associated with solar exposure and natural lighting according to the International Commission on Illumination (CIE) standard overcast sky model recognized in the ISO standard. The proposed projection of the sky vault visible from a window provides insight on the problems related to natural lighting, shading and solar access, while aiding in solar access decision making.

1. Introduction

The daylight availability on building facades and particularly on building openings and windows is associated with desirable effects such as the sensation of psychological or therapeutic well-being provided by sunny rooms. In fact, urban development legislation increasingly requires builders to ensure minimum solar exposure levels of buildings depending on their use as the entry of direct sunlight is considered a determinant of health, and is an element of visual comfort related to natural lighting and the existence of an unobstructed view. In different countries these needs are recognized as “solar rights”. In Europe [1], solar rights are understood as the rights of building occupants to enjoy minimum daily sun exposure in their homes. Littlefair et al. [2] conducted a comprehensive study on the criteria proposed in the literature and established under different standards to ensure adequate levels of insolation in residential buildings.

Graphics methods are a key factor in order to determine the solar envelope. Most of them required geometric characterization, not also for the land but for the adjacent buildings too [3]. Knowles [4] includes a temporal dimension for the geometric characterization of the solar envelope. Papadakis [5] shows the important effect that vegetable roof has on openings and windows solar access even though his geometric description is quite complex.

Compagnon [6] addresses the relationship between urban fabric’s geometry and anisotropic distribution of irradiation and skylight to define iso-solar collection surfaces. He proposes an anisotropic sky model based on defined regions by stereographic diagrams.

Littlefair [7] indicates the utility of diagrams, called indicators, in order to determine sunlight hours and skylight on windows, as well as the use of Waldram diagrams to calculate the solar factor. Waldram developed a useful methodology to determine solar factor in overcast skies relying on cylindrical diagram of the visible vault from a window [8]. Waldram methodology can be applied for CIE-Overcast sky [9].

Hemispheric representations of the sky vault contribute to our understanding of the problems related to shading or solar access and support solar access decision making [10]. Each of the projection permits representing points on a spherical surface in a plane. In our study we highlight the following projections (Fig. 1):

- Stereographic projection: This type of projection preserves the angular distances. The plane representation of 3D circumferences included in the 3D sphere is transformed into 2D circumferences. Pleigel [11] developed the Globoscope; an optical instrument for obtaining stereographic images directly from the reflection of the sky vault in a parabolic mirror.

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http://dx.doi.org/10.1016/j.enbuild.2013.06.006

Nomenclature

A_T	Area of any region of sky vault in the transformation plane
C	Integration constant
I	Illuminance
I_H	Illuminance on horizontal plane
I_V	Illuminance on vertical plane
lx	Lux
L_ϕ	Luminance at zenith angle ϕ
L_z	Luminance at zenith
r	O′P′ vector on the transformation plane
O	Central point of a window
O'	Origin of coordinates in REDUCA-OSLIP transformation plane
P	Generic point of the sky vault
P'	Representation of P in REDUCA-OSLIP transformation plane
R	Integration enclosure domain
SF	Sky factor
α	Angle between the OP vector and the normal vector of the plane or window
φ	Zenith angle (angle relative to the zenith)
χ	Angle between OP vector and horizontal axis in the transformation plane
Ω	Solid angle

- Gnomonic projection: In this type of projection, lines in three dimensional space are represented as 2D lines. The representation of sun paths correspond to the lines of a planar sun dial.
- Orthogonal projection: Nusselt's analogy shows that the view factor of a 3D surface coincides with the 2D surface of the orthogonal projection [12].
- Lambert projection or equal-area hemispherical: In this projection, the solid angles are proportional to the projected surfaces; a property which permits the sky opening indicator to be determined from a given vantage point.
- Polar projection: In polar projections, the distance from the 2D point to the center of the image is proportional to the zenith angle of the 3D point represented. Ideally, fisheye lenses produce polar (equiangular) projections [13]. However, most fisheye lenses have been found to distort the images [14], [15], making it necessary to calibrate the lenses before they can be used for measurement purposes.
- Cylindrical projection: Several authors have used cylindrical representations in studies on solar exposure. This type of representation is intuitive and simple to do with the aid of goniometers.

The advantages and drawbacks to each type of projection have been extensively studied by different authors. There is general consensus on the usefulness of the different hemispheric representations since, as mentioned above; they permit a better understanding of the problems of shading or solar access and support solar access decision making. For this reason, the above diagrams are a fundamental tool in determining variables such as hours of direct solar exposure or access to direct solar radiation. However, these diagrams have significant limitations for studying access to natural lighting. The specific aim of this work was, therefore, to overcome these limitations and enable the existing graphic projections to be applied to the study of access to natural lighting. To do so, we develop a new projection to represent half of the sky vault that is visible from a window. The metric characteristics of this projection are directly related to Eq. (2) on natural lighting. Moreover, like the classic projections, this projection allows studying variables related to solar access.

Studies on the availability of natural light in the hollows and windows of buildings focus on the diffuse fraction of radiation and illuminance. Indeed, direct sunlight usually produces undesirable effects such as visual discomfort glare. In 1955, the CIE adopted the formula proposed by Moon and Spencer [16] on the spatial distribution of luminance in the sky vault of overcast skies.

$$\frac{L_\varphi}{L_Z} = \frac{1 + 2\cos\varphi}{3} \tag{1}$$

The CIE method continues to be widely used today by architects in their preliminary calculations. The sky pattern described by this model corresponds to an overcast sky with stratus clouds distributed in multiple layers or cloudy skies with nimbostratus clouds covering the entire sky vault [17]. While there are models based on more complicated equations to determine sky luminance under the assumption of a fully overcast sky, the results vary only slightly from the values given by Eq. (2). In this formula, the zenith luminance values are provided in tables or estimated by the CIE models [18].

It is quite complicated to calculate CIE overcast illuminance in the plane of a window in the presence of large obstructions. To approach this problem mathematically, Eq. (2) must be solved. In practice, the greatest difficulty lies in determining the boundaries of the integration enclosure domain R.

$$E = \iint_R L_\xi \cdot \cos\varphi \cdot d\Omega = \iint_R L_\varphi \cdot \cos\alpha \cdot d\Omega \tag{2}$$

Drif et al. [19] describe a method for obtaining this enclosure domain based on topographic observation. In the event that the obstructions are due to non-compact vegetation, the mathematical calculation is impractical.

The REDUCA-Oslip transformation permits Eq. (2) to be solved in an easy manner, even in the most complex cases of obstructions due to non-compact vegetation.

2. Method. development of a new hemispheric projection for studies on natural lighting

The transformation developed aims to obtain an image in which the area of visible sky in the projected image is equal to the luminance of the standard CIE overcast sky. For this technical reason, and due to the scope of this work, we have decided to call the projection the REDUCA–Overcast Sky Linearized Illuminance Projection (REDUCA-OSLIP). Mathematically, a transformation is developed that satisfies condition (3) for the entire R region of the sky vault.

$$I = \iint_R L_\varphi \cdot \cos\alpha \cdot d\Omega = A_T \tag{3}$$

2.1. Mathematical calculation of the REDUCA–OSLIP projection

In order to perform the mathematical calculation, a vertical rectangular window included in the OXY plane is considered. The origin of the coordinates is the central point of the window, which we assume is representative of the window. With the chosen system, points P of the visual sky vault are bounded by the conditions:

$$-\pi/2 \le \theta \le \pi/2 \tag{4}$$

and

$$0 \le \alpha \le \pi/2 \tag{5}$$