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Determination of appropriate metrics for indicating indoor daylight availability and lighting energy demand using genetic algorithm

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ABSTRACT

Design optimisation problems of window size in buildings with regard to energy saving and comfort criteria have been investigated many times. To indicate daylight availability and energy consumption in indoor spaces, a number of metrics have been proposed, but so far there is no convention on which daylight and energy metrics are preferred. Meanwhile, evolutionary techniques such like genetic algorithm have long been used to optimise parameters in building design. In the optimisation process, however, different metrics or objectives normally lead to different degrees of uncertainty of the obtained results. This article presents a study to determine the most appropriate metrics for the case of daylight optimisation in a reference office space, by comparing various daylight metrics and lighting energy demand indicators, using genetic algorithm to optimise the window-to-wall ratio (WWR) and the room interior reflectance. To determine the appropriate metrics, the optimisation results were classified based on their computational precision. It is found that maximising spatial useful daylight illuminance $(\mathrm{sUDI})_{100\sim2000\mathrm{lx},50\%} - \mathrm{sUDI}_{>2000\mathrm{lx},50\%}$ leads to objective function values with the highest precision, while minimising annual lighting energy demand + $\mathrm{sUDI}_{>2000\mathrm{lx},50\%}$ gives the most robust input variables. Therefore, these two pairs of metrics are suggested as the most appropriate for optimising daylight in the particular space.

1. Introduction

In the context of building design, windows are regarded as one of the most important components. It has been known and proven that windows give somewhat positive influence on the health and well-being of building occupants. Moreover, windows are important not only since they provide daylight and view (e.g. Kaplan, 1993; Tennessen and Cimprich, 1995; Kim and Wineman, 2005; Aries et al., 2010), but also since they can necessarily shape the overall energy demand in buildings (e.g. Bodart and de Herde, 2002; Li and Lam, 2003; Li and Wong, 2007; Li, 2010). In the design phase, problems often occur in finding the balance between daylight availability from the window and its impact on energy demand. Maximising the window area will normally yield larger daylight penetration and better view to outside, however this will at the same time increase the artificial lighting, heating, and cooling energy demands. Having known that, a single objective optimisation approach is more often not applicable, since most objectives in building design normally possess a conflicting nature. Therefore, a multi-objective optimisation approach is required to solve the problem (e.g. Alanne et al., 2007; Capeluto and Perez, 2009; De Antonellis et al., 2010; Alwaer and Clements-Croome, 2010).

Investigations to find the optimum window size and configuration with regard to the building energy performance have been conducted by many researchers since long time ago (e.g. Arimi, 1977; Johnson et al. 1984). The influence of material of the glazing or fenestration systems (e.g. Klainsek, 1991; Kontoleon and Bikas, 2002; Inanici and Demirbilek, 2000) and the integration of energy-generating elements such as photovoltaic panels on building façades (e.g. Vartiainen et al., 2000; Davidsson et al., 2010; Didoné and Wagner, 2013; Skandalos and Karamanis, 2015; Han et al., 2010) has also been investigated by many researchers.

In the nowadays context of building design, it is generally realised that integration and better use of daylight is important in achieving energy savings in buildings, while still maintaining sufficient daylight in the space (Ghisi and Tinker, 2005; Goia et al., 2013; Ochoa et al., 2012). Since daylight is a constantly changing stimulus, appropriate metrics that can indicate its availability in indoor spaces are necessary. It is the aim of this study to determine these metrics in a systematic way.

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1.1. Daylight metrics

1.1.1. Rules of thumb

A number of metrics have been proposed in the past to indicate indoor daylight availability. The simplest approach is perhaps the use of rules of thumb applicable for a sidelit space, commonly known as the window-head-height (h) rule. This rule relates the effective daylight penetration depth with the height of the window from the floor (Reinhart, 2005). For unobstructed facades of a typical sidelit space equipped with shading devices (e.g. venetian blinds), the effective daylight penetration (or limiting) depth (d_{eff}) usually lies between 1 and 2 times the window-head height, i.e. between h and $2h$, but can be as large as $2.5h$ for spaces without any movable shading devices.

Other rules of thumb that can be applied to estimate limiting depth in diffuse daylighting situations are also available, for instance as proposed by Lynes (1979). The constraints in each rule of thumb normally lead to various calculated values of d_{eff}. To anticipate the worst case situation, designers are advised to choose the minimum values, so that:

$$d_{eff} = \min \begin{cases} \dfrac{2/(1-R)}{\frac{1}{w}+\frac{1}{h}} \\ (h-h_{wp})\tan\theta \\ 2h \text{ ; if there is a shading device} \\ 2.5h \text{ ; if there is no shading device} \end{cases} \tag{1}$$

where R is the area-weighted mean surface reflectance of the room, w is the room width, h is the window-head height, h_{wp} is the height of workplane, and θ is the sky angle (Otis and Reinhart, 2009; Reinhart and LoVerso, 2010).

1.1.2. Daylight factor

The assumption of diffuse daylighting (or sky) condition also leads to another metric commonly known as the daylight factor (DF) (Moon and Spencer, 1942; Hopkinson et al.; 1966), which is the ratio of indoor (E_{in}) and unobstructed outdoor (E_{out}) illuminances under the standard CIE overcast sky. Due to the simplified sky model, given a certain daylight opening configuration, the DF at a given point will stay approximately constant, regardless the orientation, geographical location, and climate variation. Many national standards still adopt this concept (e.g. BSI, 2008), most probably due to its simplicity. For design purpose, the so-called split-flux method (Tregenza, 1989) assumes that DF consists of three separate components: the sky, externally reflected, and internally reflected components (SC, ERC, and IRC), so that:

$$\mathrm{DF} = \mathrm{SC} + \mathrm{ERC} + \mathrm{IRC} \tag{2}$$

For cases in which the calculation points are close enough to the daylight opening, the SC, which is the proportion of daylight illuminance contributed from the visible sky only ($E_{i,sky}$), can be thought as the most dominant component among the three. This tendency leads to the suggestion of calculating only the SC, rather than the DF, to assess indoor daylight availability (e.g. BSN, 2001). Knowing that the luminance L_θ distribution for the standard CIE overcast sky at an elevation angle θ and azimuth angle ψ is as follows:

$$L_\theta = L_z \frac{1 + 2\sin\theta}{3} \tag{3}$$

in which L_z is the zenith luminance, the SC is now a purely geometrical variable depending on the relative width and height of the effective (entirely unobstructed) daylight opening as seen from the calculation point. For the case of a vertical, effective daylight opening ABCD at a distance D from a horizontal calculation point U (Fig. 1), where A is the projection of U on the plane of ABCD, the SC at U can be determined analytically (Seshadri, 1960):

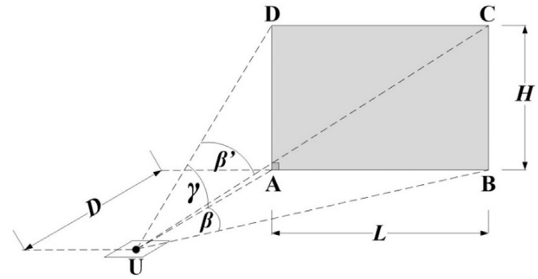

Fig. 1. Illustration of a horizontal calculation point U at a distance D from a vertical, effective daylight opening ABCD, taken from Mangkuto and Siregar (2018).

$$\mathrm{SC} = \frac{E_{i,sky}}{E_o} = \frac{\frac{L_z}{3}\int_0^{\theta'}\int_0^{\beta}(1+2\sin\theta)\sin\theta\cos\theta d\theta d\psi}{\frac{L_z}{3}\int_0^{2\pi}\int_0^{\pi/2}(1+2\sin\theta)\sin\theta\cos\theta d\theta d\psi} = \frac{3}{14\pi}(\beta-\beta'\cos\gamma) + \frac{2}{7\pi}\arcsin(\sin\beta\sin\gamma) - \frac{1}{7\pi}(\sin 2\gamma\sin\beta') \tag{4}$$

knowing that:

$$\tan\theta' = \tan\gamma\cos\psi \tag{5}$$

$$\tan\beta = \frac{L}{D} \tag{6}$$

$$\tan\gamma = \frac{H}{D} \tag{7}$$

$$\tan\beta' = \tan\beta\cos\gamma = \frac{L}{\sqrt{H^2+D^2}} = \frac{L/D}{\sqrt{(H/D)^2+1}} \tag{8}$$

referring to Fig. 1.

For a detailed design calculation, the ERC can be determined based on the 'sky component' contributed from the external obstructions (SC_{obs}, i.e. as if the obstructions were an area of visible sky) multiplied with the reflectance of the obstruction (R_{obs}), which can be roughly taken as 0.2 (Chan, 2008).

$$\mathrm{ERC} = \mathrm{SC}_{obs} \times R_{obs} \tag{9}$$

The IRC can be determined as follows (Chan, 2008):

$$\mathrm{IRC} = \frac{\tau_j A_j}{A(1-R)}(CR_{fw} + 5R_{cw}) \tag{10}$$

where τ_j is the glazing transmittance (normally taken as 0.85 for clear glass), A_j is the window area, A is the total room surface area (including windows), R is the area-weighted mean surface reflectance of the room, R_{fw} is the area-weighted mean reflectance of the floor and walls below the mid-height of the window excluding the window wall, R_{cw} is the area-weighted mean reflectance of the ceiling and walls above the mid-height of the window excluding the window wall, and C is a coefficient depending on the obstruction angle. For an obstruction angle of 0°, C can be taken as 39.

To allow a somewhat more realistic estimation, additional corrections are suggested, taking into account the maintenance factor (M), glass factor (G), and bars or framing factor (B). For a vertical opening in a relatively clean room at a non-industrial area, M is taken as 0.90; for a clear glass, G is 1.00; and B is generally the ratio between net glass area and overall window area, or can be roughly taken as 0.85 at the most. A complete table of these factors is available, for instance in Szokolay (2008). The final estimated DF is therefore:

$$\mathrm{DF} = (\mathrm{SC} + \mathrm{ERC} + \mathrm{IRC}) \times M \times G \times B \tag{11}$$

1.1.3. Climate-based daylight metrics

Since DF is arguably insensitive to temporal and spatial constraints,