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Window design in architecture: Analysis of energy savings for lighting and visual comfort in residential spaces

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HIGHLIGHTS

- The window geometry and position are analyzed to quantify the energy saving.
- Dynamic metrics show a database of energy saving allowed by different windows.
- Horizontal openings produce higher energy saving than other window shapes.
- Energy saving is directly proportional to reflectance in the back of the room.
- Energy saving according to window orientation and location is quantified.

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ABSTRACT

Window design is decisive in providing appropriate visual comfort for occupants and sufficient energy savings in electric lighting. In daylighting, visual comfort is dependent on the maximum daylight autonomy. Moreover, energy consumption in electric lighting relies on daylight autonomy. The aim of this research is to quantify these metrics in a residential room for different window models and analyze the results obtained. The surface reflectance and the geometry of the window are variable. DaySim 3.2 lighting program provides the simulations of the room model according to different orientations and weather conditions. Following the trials, it was concluded that daylight autonomy is proportional to the glass surface and reflectance of surfaces at the back of the room, while its influence near the façade is negligible. However, energy consumption does not depend on window shape. It is also concluded that windows located higher up result in higher illuminance at the back of the room than those in centered locations. The conclusions of this research are contrasted with the analysis of daylight metrics for different locations and orientations of the window.

1. Introduction and objectives

1.1. State of the art

At present, energy saving is one of the most important variables in building design. Proper use of daylighting is essential in reducing energy consumption in electric lighting while maximizing visual comfort for occupants. As can be seen from previous research, daylighting improves visual perception [1] and synchronization of the circadian stimulus [2]. Accordingly, windows are the greatest resource to allow daylight into buildings [3]. A proper window design also improves the thermal comfort and produces a significant energy savings in electric lighting [4,5].

The most common metric for quantifying daylighting in architecture is the daylight factor, as it defines the ratio of the illuminance inside a room to that observed outside under overcast sky conditions [6]. Currently, the daylight factor is the most used metric in the analysis of daylighting [7,8]. Since daylight factors are evaluated under overcast conditions, the position of the sun is irrelevant, hence the room location and the window orientation do not affect to the calculation results. Therefore, the measurement of daylight factors is only conditioned by the geometry of the architecture. According to this definition, the illuminance at an interior point is obtained knowing the external illuminance.

However, the daylight factor is not a completely reliable metric when defining the energy savings in electric lighting, given that it ignores daylight produced under clear sky conditions [9]. Therefore, as stated in current research, it is increasingly common to use dynamic metrics in daylighting studies, defining the energy savings according to the orientation of the window, location of

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the room and sky conditions. One of the most extended dynamic metrics is daylight autonomy, proposed in 1989 by the Association Suisse des Electriciens [10] and redefined by Reinhart et al. [11]. Daylight autonomy is defined as the percentage of the year when a minimum illuminance threshold is met by daylight alone. According to this definition, the higher the daylight autonomy, the lower the energy consumption in electric lighting.

Window design has been widely studied in the analysis of daylight factors. Most current treatises on lighting in architecture [12,13] study the proper sizes and shapes for windows. Studies on window design are usually based on empirical methods and lighting simulation programs. The results obtained from empirical methods are not accurate, as can be deduced from the daylight factor method [14], which is defined as a calculation procedure with limited calculation variables. However, current lighting simulation programs provide a better accuracy than empirical procedures [15,16], making them useful tools for the study of daylighting and energy savings in architecture.

There is an abundance of studies of window design using static metrics from lighting simulation software [17]. An example of this is the calculation method developed by Ghisi and Tinker [18], which defines the ideal window area considering the combination of electric and natural lighting. The authors conclude that the ideal window area should be larger in low thermal load orientations. Another interesting research can be observed in the studies of Li et al. [19], who determined a calculation method which relies on the daylight coefficient concept. In this study, the authors determine a procedure based on multiple charts and tables for defining the illuminance values. Following this methodology, the study by Acosta et al. [20] determines the rules of thumb for window design based on the analysis of daylight factors under overcast sky conditions. When examining the study of static metrics, it is worth noting the research of Fasi and Budaiwi [21], which analyzes the energy savings when daylight and electric light are integrated while maintaining visual comfort.

Although dynamic metrics are not applied in most of the current studies on daylighting, an important example of their use can be observed in the study by Munoz et al. [22], where the authors determine different dynamic metrics in an office room illuminated by openings located in the Spain. Another interesting paper regarding this issue was written by Mangkuto et al. [23], who determined the suitable window-to-wall ratio according to the tropic latitude and the corresponding weather conditions. In other cases, the window-to-façade ratio has been analyzed in order to determine the thermal requirement of buildings according to the thermal transmittance of the envelope in US locations [24]. Following this issue, another noticeable research is the study of Vanhoutteghem et al. [25], who analyses the impact of façade window design on energy, daylighting and thermal comfort in nearly zero-energy houses located in Denmark.

Studies on window design are not based solely on daylighting conditions. Another approach focuses on thermal comfort, as can be seen in some research [26,27], where the window design is essential to provide a passive heating and ventilation in buildings. Equally, new metrics such as the circadian stimulus are defined according to window design [28]. Overall it becomes patent that the study of windows is an endless source of research results.

The originality of the presented research is argued in the analysis of the relative difference of the daylight autonomy values according to the geometry of the window, room reflectance, façade orientation and weather conditions. All articles studied in the field of daylight dynamic metrics compare the absolute values obtained from the assessed study sample. However, the comparison of the relative difference of such results can determine the impact of window design with a higher accuracy, providing a criteria for designers and architects.

Moreover, this study presents for the first time the relative impact of the window design in energy savings in accordance with the results obtained from different latitudes and weather conditions. The findings can serve to adjust the window design depending on the dwelling location.

1.2. Aim and objectives

The aim of this research is to quantify the daylight dynamic metrics in a residential room for different models of windows, in order to analyze the results obtained. The shape, size and position of the window are variable, as is the reflectance of the inner surfaces of the room. Therefore, daylight autonomy is defined in more conventional residential rooms, serving as a reference for window design in architecture in order to reduce the energy consumption in electric lighting.

Subsequently, the analysis of the resulting daylight autonomy values defines criteria for shape, size and position of the window, according to the orientation and location of the residential room. The design guidelines defined in this research also consider other dynamic metrics such as maximum daylight autonomy, which establishes visual comfort in relation to a maximum illuminance threshold.

2. Description of methodology for calculation

2.1. Characteristics of the room model

A virtual room measuring 3.0 m wide × 6.0 m deep × 3.0 m high, the size of a typical living room in the studied locations, was used to analyze the daylight dynamic metrics and the energy savings provided by windows. The room ceiling, walls and floor had a thickness of 0.25 m. A window of variable shape, size and position is located in the 3.00 m wide façade. The double pane window was 0.05 m thick with a visible transmission of 0.75. Daylight simulations were conducted using the window sizes listed in Table 1 with two room surface average reflectances, also listed in Table 1. The inner surfaces of the room were assumed to display Lambertian reflectances. The luminous intensity of reflected light was therefore directly proportional to the cosine of the angle between the observer's line of sight and the surface normal. All variables of the calculation model are shown in Fig. 1.

The daylight dynamic metrics are measured on five equidistant axes at 0.75 m, considering a symmetry axis respect to the window position. As can be observed in Fig. 1, the study points are located on these axes with a spacing of 0.30 m from each other and at 0.60 m above floor level. 100 study points in total are used in each model.

The room model is defined according to window shape (square, horizontal and vertical), size (window-to-façade ratios of 10–80%) and position (centered or upper). The reflectance of the inner surfaces is also variable depending on the values represented in Fig. 1. 28 room models are established following the variables defined, as shown in Table 1.

The variables of the calculation models were established following the most common values of shape, size and position of the window of a typical residential room. Although this study sample obviously cannot cover all possible hypotheses, it does aim to show the most usual case studies.

2.2. Parameters of the calculation program

DaySim 3.2 is a validated radiance-based daylighting analysis tool that uses a daylight coefficient approach combined with the Perez all-weather sky model [29] to predict the amount of daylight in buildings, based on direct normal and diffuse horizontal irradi-