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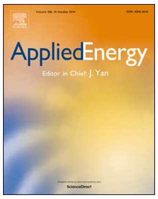

Energy efficiency and lighting design in courtyards and atriums: A predictive method for daylight factors

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HIGHLIGHTS

- Two procedures are proposed to define the daylight factors in courtyards.
- Calculation of the sky component is obtained for three points inside a courtyard.
- The reflected component is obtained following the results of the procedures.
- The method is contrasted with the procedures proposed and its accuracy confirmed.
- The energy saving is quantified according to the method proposed.

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ABSTRACT

The proper design of courtyards and atriums is key in providing sufficient daylight inside buildings as well as major energy savings in electric lighting. Although a suitable design requires calculations using lighting simulation software or complex algorithms, architects lack a quick and precise procedure to determine proper design. The aim of this research is therefore to offer a fast accurate method for determining the daylight factor for different points on a rectangular courtyard or the central space of an atrium, based on the variable geometry and reflectance of the inner surfaces. Firstly, daylight factors are defined using measurements in scale models in an artificial sky and values obtained in real courtyards under real overcast skies. The sky component is subsequently defined based on earlier studies and Tregenza algorithms in order to quantify the reflected component. Following the curve fitting process, a predictive method of daylight factors is defined and compared with the previous measures. The comparison demonstrates that the predictive method offers an average accuracy of over 90% based on a quick and easy calculation. Finally, the energy saving in electric lighting is quantified following the predictive method established.

1. Introductionand objectives

1.1. State of the art

The proper design of courtyards and atriums is essential for the provision of sufficient daylight inside buildings, producing a noticeable reduction in energy consumption in electric lighting [1]. Accordingly, many researchers have tried to determine the implications of geometry and qualities of these architectural resources in the energy performance of buildings [2–4], establishing new design principles and metrics to assess the use of natural light.

Moreover, daylighting improves visual perception [5] and promotes the synchronization of the circadian stimulus [6], resulting in improved comfort and health conditions for occupants [7] while good courtyard or atrium design also provides improved thermal comfort [8,9] and passive ventilation for the entire building [10].

The study of daylight in courtyards and atriums has extended from the procedures proposed in classic treatises [11] right up to the most current research based on computer simulations [12,13]. Early papers on this subject analyzed solar radiation in courtyards and atriums and its influence on daylight illuminance, ignoring any other implications in building design. For example, Mohsen's research [14] developed a mathematical procedure that simulates the interaction of solar incidence on courtyard floors. However, due to its importance in lighting and thermal comfort as well as its impact in energy savings the literature about courtyard design has increased significantly in the last 10 years. In subsequent studies [15–17] the research focused on the energy efficiency provided by proper courtyard design, analyzing the

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lighting and thermal behavior of the building according to the variables established. Several authors have analyzed the daylight distribution on floors and walls in atriums [18–20] in an attempt to establish a proper design according to different variables. However, most of this research was based on specific climate conditions or geometric limitations, making it difficult to find a universal method which helps to determine the illuminance in courtyards or atriums [21].

Daylight illuminance can be determined using two main metrics: daylight factor and daylight autonomy. The daylight factor (DF) corresponds to the ratio of daylight illumination at a given point to that of the light received on a horizontal plane from an unobstructed overcast sky [22]. Nowadays, this is the most widespread metric in the study of daylighting [23–25]. The daylight factor is considered a static metric, that is to say, it depends only on the geometry and qualities of the architecture, since location and orientation are irrelevant in relation to an ideal cloudy sky [26]. Therefore, the daylight factor represents the potential illuminance at a given point for the worst case scenario under overcast sky conditions. Moreover, daylight autonomy (DA), proposed in 1989 [27] and redefined by Reinhart et al. [28], is defined as the percentage of the year when a minimum illuminance threshold is met by daylight alone. Therefore, the higher the daylight autonomy, the lower the energy consumption in electric lighting. Unlike static metrics, daylight autonomy depends on the weather conditions and location of the space, as well as occupancy hours and blind control by occupants. Although daylight autonomy can almost certainly define energy savings more accurately than metrics based on static climate conditions [29], the greater complexity of this metric, supported by a high number of variables, makes the definition of a predictive method almost impossible. It is for this reason that most of the predictive methods developed are based on the daylight factor metric [21].

As seen in the definition established by the CIE [22], daylight factors can be determined as the sum of three components: the sky component (SC), which represents the daylight provided directly from the sky; the externally reflected component (ERC) produced by the reflection of the sky component on the exterior surfaces; and the internally reflected component (IRC) generated by the reflection of the sky light on the interior surfaces of the space.

The sky component (SC) at a point can be obtained following the analytical formulation that considers the luminance generated by the visible fraction of an overcast sky. Tregenza [30] determined the algorithms to calculate the sky component through vertical and horizontal openings. The Tregenza equations are currently used to assess the accuracy of lighting computer programs [31], and in the specific case of courtyards and atriums, the equations were simplified by Acosta et al. [32] to produce a simple calculation procedure with an average margin of error lower than 2%.

Usually, the externally reflected component (ERC) is defined as a fraction of the sky component [33], depending on the distance from the exterior geometry and its reflectance. In the case of courtyards and atriums, the ERC is negligible, as there are usually no obstructions from the zenithal daylight.

The quantification of the internally reflected component (IRC) depends on the endless reflection of daylight on the inner surfaces of the courtyard or atrium, considering the reflectance (how much light is reflected) and the reflection (how light is reflected) in each light bounce [22]. Therefore, given this complex definition, the IRC cannot be based on analytical calculations. Accordingly, initial predictive methods for quantifying the IRC [34,35] are based on light reflection hypotheses, principally on the theory of the integrating sphere [36]. However, this theory was supported by simple geometries which are not applicable to complex architecture. A few decades later, the predictive methods to calculate the IRC were based on curve fitting procedures, usually on mathematical functions fitted to the data obtained from lighting simulation programs, building monitoring, or scale models [19,25,37,38]. One of the specific predictive methods to determine the IRC in courtyards was developed by Acosta et al. [39]. However, this method is based on a curve fitting process argued from the data collected from lighting simulation programs, avoiding comparison with real or scale models. The simulation programs are limited by a maximum number of reflections (in the case of ray-tracing programs) or by a Lambertian reflection (in the case of radiosity programs) [40,41], and as a result their ability to render the real behavior of light is limited.

Moreover, most of the studies on predictive methods mentioned and supported by building monitoring do not describe the luminance conditions of the real sky [25,38]. This is confirmed by the research on this procedure based on scale models [19,42]. As deduced from previous statements, there is no sole valid way to establish a predictive method to calculate daylight factors given the inaccuracy of the individual analysis of the procedures mentioned. Therefore, a solid predictive method must be based on the results obtained from the comparison of different procedures for data collection.

1.2. Aim and objectives

The aim of this research is to determine a predictive method for the calculation of daylight factors for different points of a courtyard or a central space of an atrium, based on the geometry of the architecture and on the reflectance of the interior surfaces. As a result, the proper design of these architectural resources could be defined according to the daylight factors obtained, which represent the lighting comfort and energy efficiency produced by daylight.

This study aims to define the predictive method using the curve fitting process and the results obtained by means of scale models in an artificial sky and real models under a real overcast sky. Accordingly, unlike previous research, this method is reasoned on two different procedures for data collection in order to establish a reliable formulation.

Following previous papers on this research [32,39], the method described determines the daylight factors for different given points on a courtyard or atrium and calculates the sky and reflected components independently, defining the contribution of each component at each study point. One of the novel aspects of this method is that the quantification of the different components is carried out separately, providing information about the influence of the geometry of the architecture and the reflectance of the inner surfaces. In addition, this new method allows the calculation of daylight factors at nine different points of the floor and walls of the courtyard or atrium, helping to determine the illuminance distribution inside these architectural resources.

As already stated, unlike previous studies, this new method is based on real measurements to achieve more accurate calculations. According to the methodology described below, the sky conditions were determined using luminance raw files calibrated with a luminance meter, achieving highly precise measurements for daylight factors under real conditions.

2. Description of methodology for calculation

2.1. Scale model procedure

The first procedure for data collection consists in measuring the daylight factors on the floor of a courtyard scale model in an artificial sky. The scale model was made of medium-density fiberboard using a laser cutter and 3D printer following the recommendations of Thanachareonkit et al. [42] in order to minimize any imperfections affecting the measurements taken. The floor of the courtyard is a square of 30 cm by 30 cm. The stackable scale model allows the assessment of daylight factors on the floor of the courtyard considering a variable height from 30 to 120 cm, that is to say, a variable height to length ratio of 1:4, as seen in Fig. 1.

The base of the scale model has small gates on the corners and midpoints of the perimeter of the courtyard, so that the position of the