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Linking wide-ranging geometrical and non-geometrical glazing options for daylight effectiveness estimation at an early design stage

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Abstract

This paper consists a first numerical approach to evaluate the main geometrical and non-geometrical characteristics of glazed areas and evaluate their influence on the daylight conditions and the visual comfort in the adjoining spaces. Since visual comfort is the main factor of well-being and also influences the occupant to produce measurable, long term improvements in his professional performance providing higher quality services, we decided to focus our case study on an office room prototype (*3m x 3m x 5.40m*) where openings exist only in the one side. Hence, the present work is a case study where a numerical approach limited on daylight calculation is presented. As literature reveals, the transparency and the roughness of the glazed area as well as the length and the height are important parameters in the daylighting design of office buildings. So, the present paper presents a singular case study where a simplified methodology on the basis of a classic composite DOE method is employed, to predict the daylight factor for different simulation scenarios applied to a given 3D geometry. The entire numerical analysis is developed through computer simulation using DIALux 4.5© as a tool. Then a parametric study has been conducted, where the influence of each investigated parameter that concerns the main geometrical and non-geometrical glazed area's characteristics (length, height, transparency and roughness of the glazing area) is investigated and expressed in the form of adjoining coefficient values, while the mean daylight factor in the working plane is evaluated in detail. As a conclusion, the main aim of this paper is to define and evaluate the influence of each investigated parameter linking selected geometrical and non-geometrical characteristics through statistical modeling via a polynomial function, in order to provide essential information for daylight effectiveness assessment at early design stages to maximize occupant's visual comfort in office buildings according to the international standards.

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Keywords: daylight factor; glazing options; DIALux; parametric study; visual comfort

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1. Introduction and general context

Contemporary research on visual psychophysics has clearly established recently the physiological importance of daylight for the human biological rhythms [1-5]. Furthermore, normative texts accurately regulate in a strict institutional framework the minimum and the maximum needed daylight thresholds in workplaces for enhancing productivity and comfort [1-5]. Thus, last fifteen years, there is a global recognition in a scholar level regarding specific effects of natural sunlight on biological rhythms, comfort and vigilance in workplaces [1-5]. Additionally, many research works based on long-term measurements proved that conventional artificial lightning, even if it is well designed and adapted, does not replace daylight effects on human psychology, biological rhythms and metabolism [2-4].

More precisely it has been reported that a deficient bright light or glare cause mood disorders and discomfort: two essential factors of a human being's adaptation to work. Nevertheless, it has been proved that when daylight is properly distributed in an optimal manner, a person can better concentrate, her/his gestures are more accurate and visual fatigue occurs more slowly [1]. Moreover, many research works underline that natural daylight significantly improves the synchronization of biological rhythms: this knowledge now opens up very new perspectives that might help us to improve comfort at office buildings [1-5]. Hence, we understand that comfort, performance and especially biological rhythm synchronization are the main reasons for proper distribution of daylight at the workplaces.

At this stage, let's try to define comfort and explain how this indicator could be used to optimize daylight in office buildings. In building physics, the feeling of comfort is explained as a synthesis of many elements, such as thermal comfort, acoustic comfort, air comfort and light comfort that characterize a given space in a given time. The latter comes from the balance between the locally defined activity, the amount of daylight and the quality of the daylight that penetrates the glazing surfaces: color, variation, more or less strong contrasts that it creates, etc. Given this multiplicity factor, we understand that we cannot directly measure comfort. Nevertheless, since we focus here on light comfort we identified some globally accepted artificial indicators reported in literature on scale that have been created to guide architects, engineers and glazing industries to optimize the amount of natural light and avoid phenomena such as glare, over lighting or inefficient lighting [1-8]. Thus, there exist two objective theoretical concepts that are scientifically established to define the amount of light (daylight + artificial light):

- The illuminance, which characterizes the quantity of light received by a surface. It is measured in lux (*lx*).
- The daylight factor (*DF*), which is the ratio between the illuminance received at a reference point within the room and a point outside in an open area under overcast sky. It is an indicator dedicated to daylight. It is expressed in *%*. In an existing building, a simple measure of indoor and outdoor lighting is enough for assessing this factor. Therefore in the framework of a new project or a sustainable renovation its evaluation requires the development of a numerical model for estimating it.

Technically, according to past research and international institutional standards the lighting in an office room must provide a minimum of 250 lux and be raised to 500 lux as needed; specifically, 200 to 300 lux are needed for screen work and 500 lux for writing [1-8]. Additionally, it has been reported that in an office building *DF* should be between 2 - 4 to enhance productivity and provide visual comfort [1-8].

1.1. Aims and scope

In a process of sustainable renovation, the use of daylight instead of artificial lighting is preferred for energy consumption minimization purposes. Quality and equilibrated spectral daylight and its variability offer optimal perception of shapes and colors, enhancing productivity and significantly affecting the human biological rhythms providing in the same time minimization of energy consumption due to artificial lightning, since artificial lightning should therefore be considered only as a supplement to daylight according to international normative standards.

Thus, we understand that for glazing industries, the biggest challenge will be to ensure that their products provide a sufficient level of daylight during the year avoiding overexposure and glare. The main non-geometrical properties of a glazing surface that affect the penetration of daylight are reported to be the transparency and the roughness [6-8]. Hence in order to optimize daylight availability in a workplace suffices it to identify the optimum combination of the above-mentioned glazing properties in relation to the dimension of the opening (length + height) and the floor's distance from the ground, since the optimum combination of geometrical and non-geometrical glazing options varies in relation to the distance from the ground. Hence, in the present paper we aim to develop an empirical polynomial equation on the basis of numerical simulations to link geometrical and non-geometrical characteristics of glazing areas with the potential floor's distance from the ground of an office room prototype.

1.2. Materials and Methods

In order to evaluate in a general manner the daylight effectiveness in a typical office prototype of dimensions *3m x 3m x 5.40m* we worked on the development of a simple polynomial model for an accurate estimation of the mean daylight factor on the working plane. Following the CIE (Commission on Illumination) recommendations we decided to conduct our research on the classic hypothesis that the illuminance from natural sources is objectively determined in terms of daylight factor (*DF*) under overcast sky [8-15]. In this approximation the sky luminance distribution is considered symmetrical about the zenith and changes with the elevation above the horizon such that the vertical outdoor illuminance would be the same for all orientations [1-15]. This orientation and direct sunlight independence make daylight factor a very important objective reference-tool. This was the reason that we preferred the concept of daylight factor to the concept of *DC* (daylight coefficient) that considers the changes in the luminance of sky elements, even if this last model offers a more effective way for calculating indoor daylight illuminance under various sky conditions and solar locations [14-15].

On the other side, a derived statistical model had been constructed to understand the effect of the length of the glazing area, the height of the glazing area, the transparency of the glazing area, the roughness of the glazing area and the floor's distance from the ground, on the daylight factor on the working plane in a typical office prototype. The analysis of this derived statistical model enabled the identification of major trends and can help us to predict, on the one hand, the optimum geometrical and non-geometrical glazing options combinations, on the other, the influence of each parameter on the mean daylight factor on the working plane reducing the cost, time and effort associated with numerous experimental sequences [13]. It is important to underline here that the composite factorial design approach used in this study can be applied easily to other geometries in order to enrich and modify the statistical models of this paper.

1.3. Numerical model

A numerical approach concerning the determination of the daylight factor for a variety of simulation scenarios has been conducted. The daylight factor regression model development is based on numerical simulations using the open source well-known software DIALux 4.5©. DIALux 4.5© uses the CIE 110-1994 model [9] for clear and overcast sky. Furthermore, in our case the zenith luminance of Krochmann [10] according to the DIN 5034 [11] is applied because we limit our study on overcast sky and *DF* is calculated only under overcast sky conditions, thus we don't have to conduct our simulations in a precise geographical context. All DIALux 4.5© building models employed in this study, are compliant with general requirements of European Directive on the daylight simulation of buildings and for this reason we chose the abovementionned software to conduct daylight simulations. Furthermore, according to the published validated results [9, 13] for DIALux 4.5© the value for the measuring tolerance of the medium illuminance amounts to ±3.8% and for the global error tolerance of the medium illuminance ±6.3% while the error estimations have been based on the estimations of CIE TC 3.33 [12-13].

1.4. Regression Analysis

In the present paper we used a simple prediction model that can approximate with accuracy the results from the model to the data obtained from simulations in order to find a compromise between simple and complex methods of evaluating the daylight factor [13]. Regression analysis is a statistical technique for investigating and modeling the relationship between variables [16-21]. In fact, since the regression analysis is the most widely used statistical technique [13,18, 20, 21] we developed here a composite regression model with 5 independent variables *x* (length of the glazing area, height of the glazing area, transparency of the glazing area, roughness of the glazing area and floor's distance from the ground) to statistically assess the relationship with a response variable *y* that is the daylight factor. To achieve this we developed a composite DOE simulation plan.

DOE methods and composite factorial design plans have been mainly used in the past related to energy consumption issues on building applications [16-21]. Since our last attempt to use them for energy consumption forecasting purposes and parameter optimization [19-21] was successful we decided to employ this approach for the development of a polynomial system to predict rapidly the daylight factor for each simulation scenario. Thus, the objective of the composite regression analysis conducted in the framework of this study is to predict the single dependent variable (daylight factor) by a set of independent variables which vary inside a defined simulation domain (length of the glazing area [*0.6m-3m*], height of the glazing area [*0.6m-3m*], transparency of the glazing area [*10%-100%*], roughness of the glazing area [*10%-100%*] and floor's distance from the ground [*0-20m*]).

1.5. Case study: Geometrical data and introduced calculation points in the working plan level

We selected to focus on an office prototype (dimensions: *3m x 3m x 5.4m*) that has openings only on the one side. Additionally, in order to approximate the windows' dimensions we have been based on the notion of the centered glazing surface [13]. The centered glazing surface hypothesizes that the opening is placed in the middle of the side where a window is placed. On the working plane level (*0.80m* from the floor and *1.20m* from the window) we have introduced *28* calculation points in a grid of *20cm x 20cm*. The average value of these points gave us the mean daylight factor value (*DF mean*). Finally, since the present study focuses on geometrical and non-geometrical glazing characteristics, potential shading masks haven't been taken into consideration here.

1.6. Case study: Construction of different simulation scenarios

In order to enable the quantification of the prediction of the responses (mean *DF* on the working plane), a classic composite simulation plan composed from *28* different simulation scenarios has been conducted, where the response could be modeled in a quadratic manner [22]. So, for the office prototype that is considered to have an opening only on the one side the investigated parameters and so the inputs for the regression model are the following: length of the glazing area, height of the glazing area, transparency of the glazing area, roughness of the glazing area and floor's distance from the ground. Thus, the originality of the present study, rests on the fact that the determination of mean daylight factor (*DF*) is based on a numerical approach that was investigated after multivariate optimization using composite factorial design in order to allow a quick extensive study of the process variables with a minimum of simulations (*28* in total).

2. Simulation results and discussion

To conduct our study, we chose a priori a mathematical function that relates the response daylight factor on the working plane to the following investigated parameters: transparency of the glazing surface (x_1), roughness of the glazing surface (x_2), floor's distance from the ground (x_3), length (x_4) and height (x_5) of the glazing surface. Then we took a limited development of the classic Taylor-Mac Laurin series [13]. According to the problem's characteristics, the variance function of the response mean *DF* in the composite simulation domain follows the following pattern [13]:

$$\left| DFmean\left(Y/x\right) \right| = b_0 + \sum_{i=1}^{5} b_i x_i + \sum_{i=1}^{5} b_{i-i} x_i^{\,2} + \sum_{i,j=1}^{5} b_{i,j} x_i x_j \tag{1}$$

The residuals for each scenario are illustrated in Fig. 1. The goodness-of-fit results of the polynomial regression model are illustrated in Fig. 2. We can see that the regression model presents a very good fit to numerical model's data trends and a very good fit to absolute location. In this study 98% Confidence Intervals (*98% CIs*) have been used as the error bar of choice in order to take into account the variability of the data (Fig. 2a) [13]. Furthermore, we obtained a very high R^2 value equal to 0.9979 (Fig. 2b). Finally, the polynomial coefficients are summarized in Fig. 3. The regression model is developed according to equation (1), where we should incorporate the coefficients of the Fig. 3. However in order to use this regression model, it is necessary to codify the values in the (-1, +1) scale. Information regarding how we can codify the values are provided elsewhere [13].

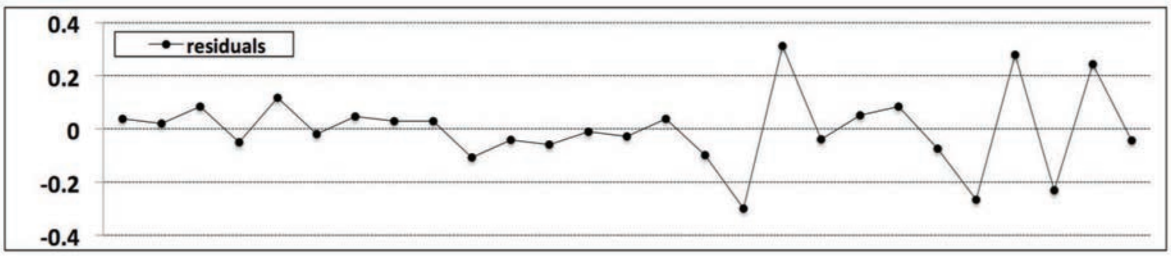

Fig. 1. Residuals for composite simulation scenarios in order to evaluate the regression model's accuracy.

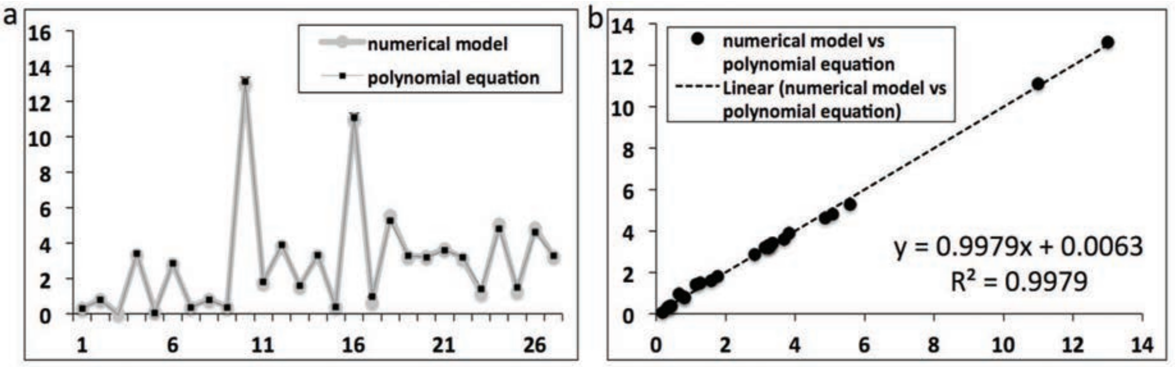

Fig. 2. a) Regression model's very good fit to numerical model's data trends and good fit to absolute location for the composite simulation scenarios. In this study 98% Confidence Intervals (98%CIs) have been used as the error bar of choice; b) Numerical simulation and polynomial simulated data comparison; least square line equation and the square of the linear correlation coefficient are also shown.

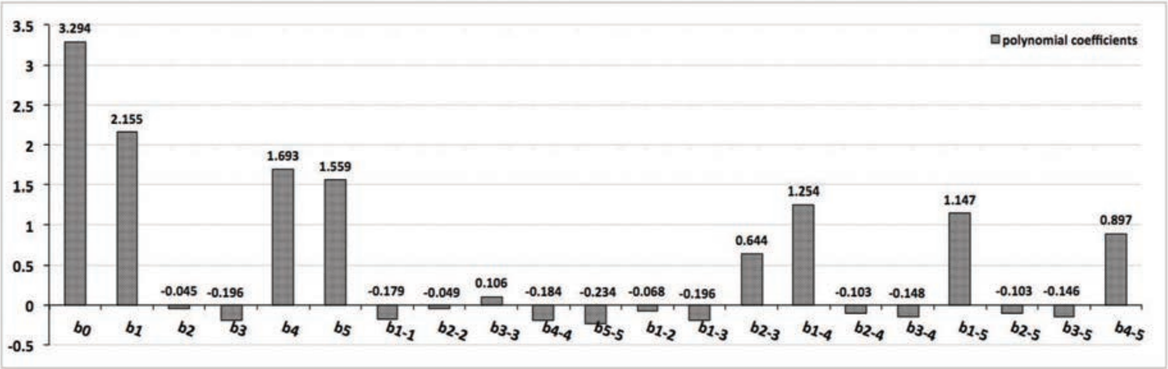

Fig. 3. Final polynomial coefficients in terms of actual factor for constant b_0 (*equation 1*) value equal to 3.294 (codified values).

According to the literature, all the plots are inside the suggested thresholds [13] providing a validated model.

4. Conclusions and Perspectives

In this paper we focus on a numerical approach for mean daylight factor estimation on the working plane for a typical office prototype. The research presented here helped us to obtain an empirical statistical function that links geometrical and non-geometrical glazing characteristics. More precisely, the main aim of the present paper is to present the basic points of a heterogeneous parameter investigation that focus on the mean daylight factor for a considered typical fundamental volume. For this reason classic composite simulation designs have been developed from scratch resulting in a simplified regression model on the basis of 28 different simulation scenarios. The simulations have been performed using the DIALux 4.5© validated software. The confrontation of the statistical and the numerical calculated data revealed that the developed polynomial functions can be used to estimate with accuracy the daylight potential on the working plane in a distance of *1.20m* from the glazing area. In the future, the aim is to further validate and generalize this study with sophisticated environmental setups in order to extend its applicability in the development of sensitive geometry regression models including more influent parameters such as shading masks, etc. Finally, as an alternative, the present regression model will be coupled to a sophisticated genetic algorithm in order to evaluate in depth the present results and develop an accurate hybrid optimization machine for daylight effectiveness optimization.

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