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Sensitivity analysis on daylighting and energy performance of perimeter offices with automated shading

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ABSTRACT

This paper presents a comprehensive global uncertainty and sensitivity analysis of daylighting and energy performance for private offices with automated interior roller shades using an advanced integrated thermal and lighting simulation model. The purpose was to identify the more important factors with respect to building thermal and lighting energy performance so as to facilitate decision making in building design stage and simplify further investigation such as optimization analysis. Seven studied parameters were selected: window-to-floor ratio, shading transmittance, shading front and back reflectance, space aspect ratio, insulation thermal resistance and glazing type. The performance metrics include useful daylight illuminance (500–2000 lux), annual lighting, heating and cooling demand per unit floor area and annual source energy consumption per unit floor area. The uncertainty analysis is based on the Monte Carlo method with Latin Hypercube Sampling, showing the possible ranges in these performance indices. The sensitivity analysis uses a variance-based method in the extended FAST implementation. Application of the analysis to perimeter private office spaces for the climate of Philadelphia showed the first order and total order effects of each studied parameter to determine the building parameters that have the most significant impact. Results are presented for different facade orientations.

1. Introduction

Commercial buildings, primarily office buildings, consume a large amount of energy and present a rapid increase in total primary energy consumption. The situation of high energy requirements on one hand and limited energy resources on the other hand has sparked a lot of research activities concentrating on early stage building design as well as on retrofit efforts for energy saving purposes. Conventionally, previous studies used approaches based on evaluation of several alternative design options to identify the best solution [22] or analysis of influence coefficients in terms of a base case to determine the important design parameters [17,38]. In the design procedure, it is beneficial to identify the importance of design parameters correctly in order to efficiently develop design options or reach optimal design solutions. Recently, more advanced sensitivity analysis approaches have been employed in determination of the most important parameters in relation to building performance. Heiselberg et al. [12] used the elementary effects method to investigate which design parameters are the most important among the 21 selected factors to change in order to reduce the primary energy consumption. Their results showed that lighting control is one of the two most important parameters that will have the most significant effect. Mechri et al. [21] employed the Monte Carlo method with Latin Hypercube Sampling (MC-LHS) and the Analysis Of Variance-Fourier Amplitude Sensitivity Test method (ANOVA-FAST) for uncertainty and sensitivity analysis of heating and cooling energy needs. The first order effect of each studied factor was calculated and the envelope transparent surface ratio was distinguished as the most significant factor for both heating and cooling energy needs. In some studies [6,15,43,44], the MC-LHS method was also used to calculate the sensitivity indices such as the Standardized Regression Coefficient (SRC) and the Standardized Rank Regression Coefficient (SRRC) given that the model coefficient of determination is higher than 0.7 [32].

In the above mentioned studies, windows have gained enough importance as an influential envelope element. Usually one or more factors related to windows (including transparent surface ratio, *U*-value and solar heat gain coefficient) were considered in the analysis. However, those thermal parameters were considered only for the concern of heating/cooling load or energy consumption. A series of studies have focused on the glazing optical properties and the resulting effects on lighting, heating and cooling needs. It is well

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known that utilization of daylight in perimeter office spaces introduces opportunities for energy savings [7,18,29]. The daylighting performance is affected by many interfacing factors such as glazing size and properties, shading properties and control [3,25,35,39], room aspect ratio and orientation [8]. These factors also affect the thermal loads and hence the energy performance of space. In order to improve the overall performance via most effective approach in design, a sensitivity analysis should be applied to an integrated building model, especially when dynamic control of lighting systems or shading devices is in use. Furthermore, the different window properties are often correlated and therefore require great carefulness in defining the probability density functions and respective ranges. For example, a window with a high solar heat gain coefficient might also have a high *U*-value. Such properties are not completely independent and the combination between them is not really random.

This paper presents a comprehensive global uncertainty and sensitivity analysis of daylighting and energy performance for private offices with automated interior roller shades using an advanced transient simulation model. Studied performance indices include useful daylight illuminance, annual lighting, heating and cooling demand and annual source energy consumption. The uncertainty analysis is based on MC-LHS method showing the possible ranges in these performance indices. The sensitivity analysis uses a variance-based method in the extended FAST implementation. First order and total order effects of each studied parameter were calculated to determine the building parameters that have the most significant impact on the performance indices.

2. Uncertainty and sensitivity analysis

Mathematical methods for uncertainty and sensitivity analysis are well known [33,34]. In the past few decades, uncertainty and sensitivity analysis have become more and more popular in various engineering fields. In building physics practice, uncertainty analysis provides the expected distribution of possible values for a model response following the variations of the input parameters within their respective distributions and ranges. Building performance uncertainty may result from different groups of sources such as building material properties, design parameters and building functions. A realistic study should be performed with respect to a specific uncertainty type since it is difficult to combine them due to their different nature and significance on building performance [14]. Comparing the model response under uncertainty with monitored real data, uncertainty analysis is used to calibrate building models for better probabilistic predictions in retrofitting existing buildings [13,41]. Uncertainty analysis is also used to assess the feasibility of certain building techniques [27] given various building designs and usage. The top and bottom ranges of the model response usually indicates the necessity for a further sensitivity analysis and then influence the decision making at the building design stage.

The purpose of sensitivity analysis is to apportion the uncertainty in the model response to different sources of uncertainty in the model input. It distinguishes itself as a good practice by revealing which of the input parameters has a significant impact on the output so as to direct research priorities to factors that are responsible of the biggest output variability, and eventually achieve the design aim of energy saving or other purposes. There are many techniques that can be applied in uncertainty analysis. Among those, the Monte Carlo technique is the most popular one. It is based on performing multiple evaluations with randomly sampled points of model inputs according to their corresponding probability density functions, and then using the results of these evaluations to determine the uncertainty in model predictions. If the model is linear or at least monotonic to each of its inputs, these evaluations can also be used to determine the contributions of the inputs to this uncertainty by calculating SRC, SRRC or other indicators. In the meantime, several methods have also been developed for sensitivity analysis. For example, the differential method [19], Factorial method [10], Morris method [23] and variance-based methods are the often used approaches. The differential method is mostly used for local sensitivity analysis. The factorial method and the Morris method are usually employed to isolate the very few dominating factors among a large amount of inputs. In general, for a moderate number of factors (tens) and a model with short execution time (less than one minute), variance-based methods are ideal.

3. Methodology

3.1. Building simulation model

An integrated thermal and lighting building simulation model developed in a previous study [35,40] is used here with two improvements. The model has been validated with experimental measurements [36] and with EnergyPlus for simple facade configuration cases. Fig. 1 shows the flowchart diagram of the model. The model is composed of a daylighting calculation part and a thermal calculation part, which run simultaneously and are coupled by facade design parameters as well as by shading and lighting controls.

The lighting calculation includes four steps: calculation of incident illuminance on facade using the Perez model [28]; calculation of transmitted illuminance into space in terms of the angular glazing-shade system transmittance; calculation of interior surface luminous exitance and illuminance on work plane using the radiosity method [2,11]; and calculation of daylight metrics [24,30] and electric lighting requirements. In its previous version, the model simplified inter-reflections between the interior roller shade and the glazing interior surface. This may introduce small errors and reduce the importance of shade properties in the sensitivity analysis since the interior roller shade will affect the properties of glazing for both short-wave radiation and long-wave radiation. In this study, Eqs. (1)–(4) [9] are used in the current model to calculate some of the effective values of glazing and shading properties at each calculation time step (direct and diffuse components are separated appropriately):

$$\tau_e = \tau_g \cdot \frac{\tau_{sh}}{1 - \rho_g^b \cdot \rho_{sh}^f} \tag{1}$$

$$\alpha_{eg}^{i,f} = \alpha_g^{i,f} + \tau_g \cdot \frac{\rho_{sh}^f}{1 - \rho_g^b \cdot \rho_{sh}^f} \cdot \alpha_g^{i,b} \tag{2}$$

$$\alpha_{eg}^{i,b} = \frac{\tau_{sh}}{1 - \rho_g^b \cdot \rho_{sh}^f} \cdot \alpha_g^{i,b} \tag{3}$$

$$\alpha_{esh} = \tau_g \cdot \frac{\alpha_{sh}}{1 - \rho_g^b \cdot \rho_{sh}^f} \tag{4}$$

where τ_e is the effective system (including glazing and shading) transmittance; $\alpha_{eg}^{i,f}$ is the effective front glazing absorptance for the *i*th glass pane; $\alpha_{eg}^{i,b}$ is the effective back glazing absorptance for the *i*th glass pane; α_{esh} is effective shading absorptance; τ_g is glazing transmittance; ρ_g^b is the back glazing reflectance; $\alpha_g^{i,f}$ is the front glazing absorptance for the *i*th glass pane; and $\alpha_g^{i,b}$ is the back glazing absorptance for the *i*th glass pane.