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Rapid response surface creation method to optimize window geometry using dynamic daylighting simulation and energy simulation

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ABSTRACT

Window geometries have significant impacts on building performance. Thus, simulation-based decision support during the early stages of building design is in high demand. Building designs are multi-objective optimization processes in which unquantified values, such as the design preferences of architects or clients, are included as objective functions along with building performance. In this context, showing architects the response surface between window geometries and building performance is useful for their decision making. This study proposes a procedure for creating a response surface in a feasible manner. In the procedure, the number of dynamic daylighting simulations is reduced by creating a link between the daylight factor (DF) and daylight autonomy (DA). In addition, the procedure allows for the estimation of electric lighting energy savings with high resolution by integrating dynamic daylighting simulation tools into energy simulation tools. In the case studies, DAYSIM and EnergyPlus are used to create the response surfaces. The impact of COPs for the cooling and heating systems on the features of the response surface can be easily analyzed. Higher COP results in a narrower selectable design range in cases where the same percentage of acceptable ranges for building performance degradation is employed (from 30–100% to 60–100%). The method was validated with detailed simulation outputs. The error caused by the proposed procedure (below 1%) was negligible compared with the error caused by the selection of the daylight simulation algorithm (approximately 5%).

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1. Introduction

The design of a building has a significant impact on its energy usage [1–4]. Building performance characteristics, such as daylighting and cooling/heating loads, are influenced by building parameters, such as glazing type, shading device and construction details. The performance characteristics are particularly sensitive to the window geometry, including the window-to-wall ratio (WWR) [5]. Generally, outlines of the building shape, including window geometries, are discussed during the early stages of building design, such as the concept design phase or schematic design phase. Therefore, it is important to perform building performance simulations to show links between building design and building performance as early as possible in the design process [6,7]. The American Institute of Architects (AIA) published an architect's guide to integrating energy modeling in the design process [8]. In this guide, design performance modeling (DPM) is defined as energy/performance modeling during the early stages of design. DPM is mainly used for design decisions. Therefore, it is important that DPM not be complex or time consuming because decisions during early design phases should be made in a feasible and timely manner. Whereas building energy modeling (BEM) during the phases of design development and contract documents demands highly accurate numerical information to compare the performance with standard baselines, DPM is aimed at determining the sensitivities of wide-ranging design parameters rather than their actual building performance values. This information helps architects explore design variables to improve building performance in their designs.

To obtain information about links between building shapes and building performance, many studies on optimization have been conducted [4,9,10]. One difficulty in this type of study is how to address multiple objectives in a real building design process. In addition, design preferences of architects and clients should be included in the objectives, which increases the difficulty of

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multi-objective optimizations because it is difficult to quantify design preferences. Moreover, design preferences tend to be weighted more heavily than building performance in real design processes. In this context, it is somewhat ineffective to show architects a single optimal solution based on a building performance simulation alone to help their decision making. Energy modelers who perform energy simulations should offer multiple and various design alternatives to architects and clients to find "an optimal solution" with consideration of both the design preference and building performance. At the same time, information on the sensitivity of each design parameter should be provided to evaluate the robustness of the design candidates offered by the energy modelers.

In these contexts, showing the response surfaces between building shapes and building performance is an effective means to offer information on multiple design candidates and the parameter sensitivities [11]. However, the creation of response surfaces tends to be time consuming because an enormous number of calculations are necessary to explore the surface features. With this background, the authors are developing methods that can create response surfaces between building shapes and building performance in a feasible and timely manner. This paper describes one of the methods for creating a response surface between window geometry and energy consumption.

Architects should understand which parameters have high sensitivities toward building performance [12]. The response surface helps architects understand to what extent they can widen or narrow the window size without significantly decreasing the building performance. In the assumed design process in this study, the building geometry is studied first because most architects attach importance to the visual design. Then, the surface properties will be discussed to optimize the building performance. In terms of fenestration, the WWR is studied first, followed by the glazing properties [13].

2. Methods

Window geometry is a significant factor in daylighting performance and cooling/heating loads. Moreover, electric lighting energies affected by daylight illuminance change the internal heat load in energy simulations. Therefore, in cases where window geometries, including the WWR, are treated as design parameters, energy simulations to calculate cooling/heating loads should be integrated with daylighting simulations. EnergyPlus [14], an energy simulation tool, allows the energy simulation and daylighting simulation to be integrated [15]. Two sensors in each zone can be set to measure the daylight illuminances and control the electric lighting outputs. However, EnergyPlus does not address cases in which higher resolutions of daylight calculation with more sensor locations are demanded. In such cases, another daylighting simulation tool is necessary. In this study, DAYSIM [16] is used as a dynamic simulation tool to calculate daylight with high resolution. The response surface in this study is created by combining outputs from EnergyPlus and DAYSIM. This method is not limited to these two simulation software applications; any energy simulation tool and daylighting simulation tool can replace them.

2.1. Dynamic daylighting simulation

DAYSIM is a validated RADIANCE-based [17] daylighting analysis software application that models the annual amount of daylight in and around a building. It has various outputs, including continuous daylight autonomy (cDA) [18]. cDA is an index that can relate energy savings to electric lighting. Electric lighting energy is easily estimated with cDA, given a target illuminance and an energy coefficient for electric lighting. DAYSIM was developed for use in real design processes. For this purpose, the calculation time appears to be sufficiently feasible for building designs [19]. However, an enormous number of calculations are necessary to create a response surface. The problem then becomes how to reduce the number of calculations with regard to proposing a method that can be used in the decision-making process. In this study, the number of calculations for cDA using DAYSIM is limited to one. In this calculation, the link between the daylight factor (DF) and cDA is obtained. To create a response surface, the variation of the DF is calculated according to the variation of the window geometry. The variation in the cDA is estimated using the DF and the link between cDA and the DF. Electric lighting energy consumption is then calculated using the estimated cDA. The calculation time is largely reduced in this procedure.

2.2. Energy simulation

EnergyPlus is used to calculate the variation of heat flow through a window according to the variation of the window geometry. In this process, the calculation does not include lighting control. The variation in window geometry is represented by the WWR because the impact of the location, height and spacing interval of the window on the cooling/heating load is negligible compared with the impact on electric lighting energy savings due to daylight. The number of calculations using EnergyPlus depends on the resolution of the WWR. In the case study referenced hereafter, nine calculations using EnergyPlus are performed.

2.3. Electric energy consumption

The total energy consumption including cooling, heating and electric lighting is calculated from Eq. (1). The impact of energy savings on electric lighting due to daylight on the cooling/heating load is estimated using cDA and outputs from EnergyPlus; L_c, L_h, L'_c and L'_h. In this equation, the first term describes the annual electric usage for the lighting system. The second term describes the annual electric usage for the cooling system. During the cooling period, the electric lighting usage is equal to the internal heat load and it becomes the cooling load. Daylighting can reduce the load by reducing the electric lighting usage. The effect of daylighting is roughly estimated with L'_c and cDA. The third term describes the annual electric usage for the heating system. During the heating period, the electric lighting usage can alternate with the heat supply from the heating system and can contribute to reducing the heating load. The effect of the heat supply is roughly estimated with L'_h and cDA. The validity of this rough estimation is evaluated in later sections.

$$Q = (100 - \mathrm{cDA})/100 \times E \times I \times 365 \times 5/7 \times P + \left(L_c - L'_c \times \mathrm{cDA}/100\right)/\mathrm{COP}_c + \left(L_h + L'_h \times \mathrm{cDA}/100\right)/\mathrm{COP}_h \tag{1}$$

where E is the lighting energy to obtain the unit illuminance (W/(m^2 lx)); I is the target illuminance for artificial lighting design (lx); P is the working period (period during which sufficient illuminance is required) (h); L_c is the annual cooling load (W h/m^2); L_h is the annual heating load (W h/m^2); L'_c is the sum of the cooling load results from electric lighting usage (W h/m^2); L'_h is the sum of the electric lighting energy consumption during the heating period (W h/m^2); COP$_c$ is the coefficient of performance for the cooling system (–); COP$_h$ is the coefficient of performance for the heating system (–).

The simulation method is summarized in the following flow chart (Fig. 1).

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