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A fast daylighting method to optimize opening configurations in building design

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ABSTRACT

Daylighting plays a very important role for energy saving in sustainable building, therefore, setting the optimal shapes and positions of the openings is crucial for daylighting availability. On the other hand, computing daylighting for climate-based data is a time-consuming task involving large data set and is not well suited for optimization approaches. In this paper we propose a new and fast daylighting method that allows to perform opening shape optimizations. The base of our method is to model each element of an opening surface as a pinhole and then formulate a compact irradiance-based representation to ease global illumination calculations. We use the UDI metric to evaluate our method, on an office-based model, for different orientations and different geographical locations, showing that optimal windows shapes can be obtained in short times. Our method also provides an efficient way to analyze the impact of climate-based data on the shape of the openings, as they could be modified interactively.

1. Introduction

Configuring the opening shape and position is a crucial element for improving the daylight exploitation, a well known effective means to reduce artificial requirements of buildings. The problem of finding the best opening configuration involves two related tasks: the geometric model optimization and the daylight computation.

Concerning daylight measurements, nowadays there are well established metrics that take into account hourly-data for the whole year, such as the daylight autonomy (DA) [1] or the useful daylight illuminance (UDI) [2]. These metrics replaced successfully the rough approximation of the widely used daylight factor, with more realism. The metrics are known as climate-based, since they consider time-varying daylight illumination for a full year. As output of the computation, they evaluate the percentage in hours that a place can have daylight accessibility. Involving hourly Sun and sky conditions leads to work with a huge dataset, with thousands of skies.

Regarding the problem of finding the optimal geometric model that achieves a given goal, such as maximizing the daylight hours, this problem cannot be solved by standard CAD tools that work on forward-based strategies. This strategy is unsuitable for optimization problems, where thousands of possible configurations should be tested. The problem should be stated as an inverse problem [3] and formulated as an optimization approach [4]. In the case of optimizing the shape for daylighting intentions, an additional difficulty is that we need to evaluate the whole hourly dataset of the year, at each iteration of the optimization.

One of the most used daylighting method is based on the daylight coefficient (DC) approach, originally proposed by Tregenza and Watters [5]. The concept behind this approach is to divide the sky dome into patches and the contribution of each sky tile is computed at each particular sensor position. Then, for a given configuration, it is possible to compute the total illuminance contribution for different sky conditions, for the whole year dataset. However, if the geometry changes, the DCs may also change and should be re-computed at each optimization step. This drawback discourages the DC method for optimization problems.

In this paper, we propose a new daylighting computation method which is suitable for the optimization of opening shapes. The base of the method is to represent each element of a window as a pinhole approximation. The incoming light that passes through each pinhole of the opening is then modeled using a compact radiosity formulation that allows to isolate the window as a single source contributor. In [6], a pinhole-based radiosity method was presented, but only for static sky and environment maps. The new method can deal with a whole-year dataset, providing fast

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daylighting computation and considering full global illumination solutions. An important result obtained in our formulation is that the overall computational cost of the optimization process does not depend on the size of the scene nor on the number of sky tiles. We also show that our approach could work in problems based on the use of daylighting coefficients.

The main contributions of our work is a new formulation of daylighting computation that allows modifying the geometry of the opening. The new formulation enables us to obtain the optimal shape for windows at early stages of the design process. However, here we do not go further with building technological considerations of the result, such as real windows insertions or electric energy requirements, which are out of the scope of this work. Moreover, a complementary contribution is the possibility to analyze the impact of weather data on the geometry at the design phase, a subject not completely addressed before in the literature.

The rest of the paper is divided into six sections. In Section 2 related work for daylighting and inverse lighting problems is reviewed. In Section 3 the pinhole-based radiosity method is reviewed and in Section 4 the extension for computing illuminance from dynamic skies is formulated. Then, our optimization approach is described in Section 5. Our method was tested with a box office (Section 6). Our analysis provides results for different orientations and different geographical locations of this office. Finally, the conclusions and further work are summarized in Section 7.

2. Related work

The main related subject to this work are daylighting and the optimization problem, which are reviewed in this section.

2.1. Daylighting computation

Considering dynamic daylighting simulation, several metrics based on hourly measured data have been developed. These include daylight autonomy (DA) [1], continuous daylight autonomy (CDA) [1], useful daylight illuminance (UDI) [2], and spatial daylight autonomy (sDA) [7]. The daylight performance assessment of an interior space is computed from annual hourly illuminance values calculated over some sensors, typically at 0.75 m height representing a workplane. DA is the percentage of illuminance values above a minimum desired illuminance, without an upper threshold bound for illuminance. For this reason, it does not capture over-illuminated situations that can produce visual discomfort. CDA improves continuity by giving partial credits to values below the minimum desired illuminance. sDA relates the working space by computing the percentage of area that is above a threshold for at least 50% of the annual evaluated hours. These metrics also have the problem of not taking visual comfort into account. Another frequently used metric is the UDI [2], which is the percentage of illuminance values above a desired minimum, typically 100 lx, and below a desired maximum, typically 2000 lx. Unlike other metrics, UDI captures the daylight sufficiency and visual comfort of a design solution because values above the upper threshold are likely to cause visual discomfort/glare. In Section 6 we use UDI as the daylighting metric to optimize.

Regarding the daylighting computation, one of the most used methods is based on the DC approach originally proposed by Tregenza and Watters [5]. The concept of DCs is to divide the skydome into a set of sky tiles and then calculate the contribution of each sky tile to the total illuminance at various sensor points in a building based on each sensors position and orientation. The total sensor illuminance at a given point is obtained by linear superposition of each DC. Time-varying solar and sky tiles luminances can be calculated using direct and diffuse irradiances from weather data-files. Working with DCs is a two-step process: first calculating the DCs, then folding them against time-varying luminances. The approach is very efficient for static scenes, but, when the geometry changes, the DCs should be re-computed. This discourages the use of a DC approach for optimization problems. However, it is computationally possible with time consuming executions. Recent approaches following this strategy, and aiming also to link daylighting to energy performance, can be found in [8,9]. In [8], an example for a particular model optimization using DC is presented, whereas in [9] the problem is addressed by studying a few number of configurations, without an optimization process.

Other daylighting methods are focusing on the efficient calculation of complex fenestration systems. In this case, a bidirectional scattering distribution function (BSDF) is used to represent the optical behavior of the opening. The “three-phase simulation method” [10,11] and the “five-phase method” [12] allow computing annual daylight performance for such systems using the RADIANCE package [13], by condensing the computation into several pre-computed matrices. For instance, in the three-phase method, the matrices account for the relation between sky patches and incident opening direction (**D**: daylight matrix), the relation between the incident opening direction and the exiting directions (**T**: transmission matrix) and the relation between the outgoing opening directions to the desired calculation points (**V**: view matrix). The matrix product **VDT** relates the luminance of the sky tiles with the illuminance of interior points of the scene. This strategy allows obtaining in a few seconds the illuminance at the desired points for any changing sky condition, since no rays are casted. It can be used also to optimize the BSDF (as for example the slat angle) by changing only the **T** matrix. However, this approach cannot be used to optimize the shape of the window, because the full computation of **V** and **D** matrices are required at each step of the optimization process, which is expensive in computational resources.

2.2. Opening optimization and inverse lighting problems

An early approach to inverse opening shape design was presented by Tourre et al. [14]. They considered openings with anisotropic light sources, however, their work did not consider essential global illumination features neither occlusions. A more general solution, where the previous restrictions are overcome, is presented in [15]. This method considers openings composed of a set of small elements as in the present work. It computes the directional incoming light from the sky through parallel projections. Next, at each opening element, a directional and spatial representation is stored by means of anisotropic light sources. These light sources are then used to evaluate their importance for a given indoor lighting intention. The final solution used a ray-based method for global illumination taking several hours to achieve simple shape optimization. No existing lighting coherence was considered to accelerate the computational process.

Global illumination coherence in architectural models can be exploited using a low-rank radiosity (LRR) approach in combination with a meta-heuristic method for optimization [3,16]. In this case, optimal shapes of diffuse skylights can be obtained in minutes. However, the method is restricted to translucent surfaces.

Other related works on opening optimization focus on an integrated energy evaluation, which includes artificial lighting and thermal analysis [17,18]. In [17], they focus on the whole facade for optimization, then, only the window-to-wall ratio is used as a parameter for optimization. In [18], a genetic algorithm is used to optimize the modeling of windows as cells. However, they use