A radiosity-based methodology considering urban environments for assessing daylighting

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Abstract. Daylight computation requires the use of climate-based data as well as the correct treatment of lighting exchange, both in the interior and exterior environments, which is frequently not considered or roughly approximated. We present an efficient method for computing daylighting that considers the exterior components accurately. We analyze the influence of the exterior components depending on the number of light bounces, which may benefit early stage projects by providing a useful analysis for understanding the different daylight contribution sources.

1. Introduction
Daylighting plays a very important role in sustainable building design. The daylight performance of an interior space is computed by calculating the annual hourly illuminance values over sensors, typically placed on a working plane at 0.75m height. Therefore, accurate daylight computation requires the use of climate-based data as well as the correct treatment of the lighting exchange, both in the interior and exterior environment. The exterior component depends on the urban model context of the building, which is frequently roughly approximated, not accounting for the full reflectance component.

In this paper, we propose an efficient method for computing daylight accessibility that fully integrates the urban context, that is suitable for analyzing the exterior component contribution. We used the Useful Daylight Illuminance (UDI) [1] metric. The method is based on the pinhole radiosity method and the sparsity of the form factor matrix in urban environments [2, 3]. Fast daylighting computations for full global illumination solutions are provided.

Our main contribution is the proposition of an alternative to the most frequently used methodologies, which works on ray-based techniques, such as Radiance packages [4]. In this work, we particularly analyze the influence of the exterior environment component depending on the number of bounces of light taken into account. Relating daylighting calculation to the number of bounces an urban configuration may require provide a useful analysis that could be used in an early stage project for understanding the different daylight contribution sources. We believe that, in addition to the fast daylight computation, our methodology can help urban planners, allowing them to analyze a whole district for daylighting assessment before designing the interior spaces.
2. Daylighting computation

The analysis and treatment of daylighting involves several factors as climate-based data and daylight metrics. One of the most used daylight metric is the UDI [1], which categorizes the illumination values into 3 ranges: $0 - 100$ lx, $100 - 2000$ lx, and over $2000$ lx. The UDI accounts for the number of hours in the year where the illuminance values fall into the middle range. This metric is incorporated in lighting analysis and design software packages [5] for its use to assess decision making. The daylight performance of interior spaces is computed by calculating the annual hourly illuminance values over a number of sensors typically located at 0.75m height, representing a work plane. The total illuminance reaching a sensor can be split into three components: the sky component (SC), which is the direct light entering the room, the exterior reflected component (ERC), which is the incoming light arriving after reflection on other buildings, and the interior reflected component (IRC), which is the light reaching the sensor after internal reflections [6]. Radiance based packages use the three-phase simulation method, which integrates SC and ERC to measure the influence of the exterior elements of the model.

Regarding daylighting computation, several methods are based on the Daylight Coefficient (DC) approach, originally proposed by Tregenza [7]. Most of the architecture and energy analysis community works on the Radiance [4] and DAYSIM platforms [5]. The concept of DC begins by dividing the sky dome into a set of sky tiles. Then, the contribution of each sky tile to the total illuminance at various sensors is calculated. The sensors are characterized by their position and orientation, and their total illuminance is obtained by a linear superposition of each DC. Working with DCs is a two-step process: first calculating the DCs, and then folding them against time-varying luminances. The approach is very efficient for static scenes, but the DCs should be re-computed whenever the geometry is modified. For this reason they are not an attractive approach for optimization problems, where thousands of configuration should be evaluated.

2.1. A radiosity-based approach

Our method is based on the urban context approach of the pinhole-based method [2, 3]. The method is radiosity-based, assuming all surfaces as perfect diffuse and limiting the accuracy for non-lambertian materials. The pinhole method follows a two-steps strategy. First, an approximated urban radiosity solution $B_{c(s)}$ is calculated for each tile $s$ of the discretized sky. Then, a compact representation that relates the interior sensors with the opening elements and the sky dome is computed using the pinhole based method (see Fig. 1). In the pinhole method, an opening is replaced by a set of pinholes. Each pinhole can be easily added (or removed), allowing to shape the opening. The inputs of the process are: a sky model, hourly-year daylight data, the urban model with a selected objective building, and an interior room model where the opening is already configured. The Tregenza’s 145 sky tile discretization [7] is used. For the algorithm details and the mathematical formulation of the method we refer the reader to corresponding reference [3].

3. Results

Figs. 2 and 3 show the exterior and interior models used, respectively, for our tests. In the first test we analyze the number of required exterior light bounces. We relate this number with the reflectivity index of the buildings in the city and with the Sky View Factor (SVF), which denotes the ratio between radiation received by a planar surface to that received from the entire hemispheric radiating environment. The simulations were conducted on a desktop computer, with Intel quad-core i7 processor, 8 Gbytes RAM, and a NVIDIA GeForce-780 GPU processor. The urban model (Fig. 2) is composed of 142k patches. The climate-based data correspond to Gatwick, London-UK. They are derived from the direct normal and diffuse horizontal irradiation...
Figure 1. Pinhole based method and its components [8].

Figure 2. Whole urban model (left) and the selected building in orange (right). The yellow points at the building facade show the location of the top and bottom south views.

Figure 3. Office model with 24 sensors, distributed in three rows.

data, extracted from Test Reference Year data [9]. For the interior model, we take the same office room as Nabil and Mardaljevic [1] (Fig. 3). The office is a box composed by 1260 patches, where 640 of them correspond to the opening surface, located in one of its walls. The window glass has a transmittance of 0.76, whereas the reflectivities of the walls, ceiling, and floor are 0.7, 0.8, and 0.2, respectively. There are 24 sensors of illuminance, which are distributed uniformly in three horizontal rows, at a height of 0.75m [8].

In ray-based techniques, an increment in the number of bounces is related to a considerable increment in the computational cost. Therefore, searching the minimum number of bounces for obtaining valid results becomes important when the evaluation of different design options is
needed. On the other hand, underestimating the number of external light bounces required may be an important source for controlling the error in the interior illuminance and UDI calculations. To estimate this parameter, we conducted experiments relating the number of light bounces to the illuminance error for a given set of reflectivity coefficients. After that, a similar set of experiments were realized to calculate the UDI values, for different number of bounces and reflection values, for each different view of Fig. 4. See Tables 1 and 2.

Theoretically, an exact radiosity vector for each patch of the scene, \( B_{c}^{(\infty)} \), can be calculated after an infinite number of Jacobi iterations. But in practice, the iterative process stops after a finite number of steps, because usually \( \| B_{c}^{(i+1)} - B_{c}^{(i)} \| = 0 \) after some iterations due to floating point representation issues. To simplify the calculation of \( B_{c} \) with \( n \) bounces and for any sky, we calculate \( 145 B_{c(s)} \) where the emitter of each one is a different sky tile \( s \). Those \( B_{c(s)} \) are linearly combined to calculate the \( B_{c} \) for a particular sky. The calculation of each bounce (or iteration of Jacobi) for the 145 \( B_{c(s)} \) took us about 28s. Therefore, computing all \( B_{c(s)} \) considering 10 or more reflections only takes a few minutes. Once \( B_{c(s)}^{(\infty)} \) is obtained for all sky tiles \( s \), it is possible to find the minimum number of iterations such that the relative error of \( B_{c(s)} \), for all sky tiles, is lower than a given upper bound \( \varepsilon \) (see Table 1).

\[
\frac{\| B_{c(s)}^{(\infty)} - B_{c(s)}^{(i)} \|}{\| B_{c(s)}^{(\infty)} \|} < \varepsilon, \quad \forall \text{sky tile } s
\]

| \( R \) | \( \varepsilon = 0 \) | \( \varepsilon = 0.01 \) | \( \varepsilon = 0.05 \) |
|---|---|---|---|
| 0.1 | 14 | 6 | 5 |
| 0.3 | 26 | 9 | 8 |
| 0.5 | 45 | 15 | 12 |
| 0.7 | 86 | 26 | 20 |
| 0.9 | 280 | 75 | 57 |

Table 1. Number of iterations (bounces) needed to obtain the exact luminous exitance \( B_{c}^{(\infty)} \), when \( \varepsilon = 0 \), and to obtain bounded values of the relative error of \( B_{c} \) (\( \varepsilon < 0.01 \) & \( 0.05 \)).

Table 1 shows the relation between the reflectivity index \( (R) \) of the scene and the required number of bounces needed to achieve a given error. It can be observed that, when \( R \) grows, the number of bounces also increases, and that this resulting number of bounces is larger than the numbers usually considered in practice [4] (typically up to 5). This is just an observation for a particular urban model, and it should be interesting to carry out a further analysis also for different configurations.

Regarding the error study, another interesting aspect is the analysis of the configuration of patches that are more sensitive to the number of light bounces. Fig. 5 shows four views of the city, where each patch is colored with the mean of the relative error of its luminous exitance, for different reflectivity indexes \( (R=0.3 \text{ and } R=0.7) \) and number of bounces \( (3 \text{ and } 9) \). The mean of the relative error is measured as the mean of all the relative errors produced when the light is emitted for each one of the 145 sky tiles. Besides that less bounces and greater \( R \) imply greater error, it can be appreciated that those patches with large SVF, such as the roofs of the buildings, have lower relative error. Also, patches with small SVF, like those surrounded by buildings, have larger relative error. These errors can be reduced using more iterations. Therefore, it can be
Figure 4. Fisheye views from the 4 selected locations in the building.

Figure 5. Relative errors for the city patches, when $R = \{0.3, 0.7\}$, and for $\{3, 9\}$ bounces.

We concluded that a smaller SVF leads to a larger number of bounces, when the relative error is constrained.

We also provide results relating the UDI to the number of bounces and the SVF (see Table 2). The four locations for the office window were analyzed (see Fig. 4), and each one tested with $R=0.3$ and $R=0.7$. We compute the UDI for the configured room at different heights (top and bottom) of the same facade of the building and also for different orientations (North and South). Fig. 2 shows the locations of the offices in the city, and Fig. 4 shows the fisheye external views for their respective locations. It can be appreciated that the orientation and environment of each office opening has a significant difference in the portion of visible sky, which may have an influence in the amount of daylight illuminance received. As a general conclusion of this experiment, 3 bounces seem to be enough for almost all studied UDI values. The error is below 5% in most cases. The test where more light bounces are needed is the bottom north view when $R=0.7$. Here, the difference between 3 and 9 bounces of light is of about 15% $\approx (1337 - 1166)/1166$ for the UDI achieved, and $-24\%$ and $125\%$ for the number of hours where Illuminance$>2k$ and Illuminance$<100$, respectively. This situation may be due to the very small SVF and the large $R$ associated with this particular view. This kind of situation is interesting to analyze, because in many cases indirect illumination reflected from an exterior surface is the main source of light.

4. Conclusion and future work

We have presented a daylighting method using climate-based data able to deal with a full urban context. The correct treatment of the external component is the major contribution of our work. We analyze this component in terms of the number of bounces required to achieve a given accuracy, showing its possible influence on the UDI results. The correlation between SVF and number of bounces is explored. We emphasize the importance of accurately computing the urban
influence in daylighting assessment. The proposed method can deal efficiently in processing time and memory requirements with huge data.

Another conclusion of our work is related to the specific techniques used in our method. Our results show an interest of recovering the classic radiosity method for computing daylighting parameters, particularly, the possibility of computing directly an arbitrary or “infinite” number of reflections with considerably short processing time. However, one of the reasons why the radiosity method was somehow discarded by the illumination community is that, in the original form, it only considers perfect diffuse reflections. Works on extended form-factor, like the one presented by Sillion and Puech [10], show that specular reflection can be included within radiosity. Further work should analyze if these extensions could also be integrated in the presented method in order to manage, for example, urban areas with highly glazed buildings. Then, radiosity could arise as a complement or an alternative to the ray-based methods usually used in architectural applications, where mirror and glossy surfaces that have a non-negligible specular component are frequently used.

Finally, the studies conducted in this work can take profit of other benefits of the pinhole method, such as allowing opening shape optimization where multiple configurations should be analyzed.

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Table 2. Results in the format UDI Illuminance > 2000lx
            Illuminance < 100lx varying reflectivity bounces

| Location   | SVF | R   | 0 bounces | 3 bounces | 9 bounces | ∞ bounces |
|------------|-----|-----|-----------|-----------|-----------|-----------|
| Top south  | 0.49| 0.3 | 463 2423  | 479 2453  | 479 2453  | 479 2453  |
|            |     | 0.7 | 463 2423  | 467 2508  | 470 2511  | 470 2511  |
| Bottom south| 0.13| 0.3 | 35 1137   | 343 1421  | 354 1424  | 354 1424  |
|            |     | 0.7 | 35 1137   | 720 1901  | 730 1908  | 730 1908  |
| Top north  | 0.24| 0.3 | 1 1237    | 376 1794  | 378 1797  | 378 1797  |
|            |     | 0.7 | 1 1237    | 497 2239  | 515 2280  | 515 2280  |
| Bottom north| 0.02| 0.3 | 0.9 3650  | 171 3437  | 173 3477  | 173 3477  |
|            |     | 0.7 | 0.9 3650  | 0.9 3479  | 0.9 3477  | 0.9 3477  |

| Location   | SVF | R   | 0 bounces | 3 bounces | 9 bounces | ∞ bounces |
|------------|-----|-----|-----------|-----------|-----------|-----------|
| Bottom north| 0.02| 0.3 | 0.9 3650  | 1166 2686 | 1337 2643 | 1342 2657 |
|            |     | 0.7 | 0.9 3650  | 0.9 3479  | 0.9 3477  | 0.9 3477  |