EVALDRC: A TOOL FOR ANNUAL CHARACTERISATION OF DAYLIGHT REDIRECTING COMPONENTS WITH PHOTON MAPPING

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ABSTRACT

Annual simulation is a significant indicator of a daylight redirecting component's performance, since it accounts for seasonal variations in daylight availability as well as the system's response under such conditions.

This study details the simulation of a representative redirecting component using a 3D forward raytracing technique to assess its annual daylighting performance. We streamline and largely automate this workflow with the EvalDRC tool, a Python script which implements a simulation frontend based on the Radiance photon map, coupled to a postprocessing and evaluation backend.

The redirecting component selected for our case study combines retroreflection with redirection and is designed for optimal daylight availability over the entire year without the need for adjustment. The lamella profile can be mounted in a forward and reversed configuration to combine retroreflection with redirection in the lower resp. upper portions of the fenestration.

We evaluate our simulations visually and numerically as high dynamic range (HDR) renderings and a spatial daylight autonomy (sDA) metric based on climate based sky distributions for Geneva, Switzerland. Our case study satisfies the sDA requirement that 55% of the workplane receives an illuminance exceeding 300 lux during 50% or more of the occupancy hours for a whole year. In addition, we propose the msDA, a detailed monthly breakdown of the sDA, for which the criteria are specifically met in the months March–September, while a minimum of 32% is predicted for December.

Our results demonstrate the effectiveness of photon mapping for this application, and that the simulation accurately predicts the redirecting component's expected seasonal behaviour for multiple solar angles and sky configurations. This applies in particular to complex redirecting systems which cannot be reliably simulated with a backward raytracer at reasonable computational cost.

Keywords: raytracing, photon mapping, redirection, spatial daylight autonomy

INTRODUCTION

The accurate simulation of daylit interiors is essential in assessing a building's performance in the context of energy saving potential through daylight autonomy. Raytracing techniques have proven to be expedient in this application as they accurately model the propagation of light within a typical office environment.

Forward raytracing from the light sources is particularly effective at modelling redirecting components for sun shading and glare reduction, which can dramatically affect daylight availability. To this end, a photon mapping implementation has recently been integrated into the RADIANCE lighting simulation system [1].

Analyses are typically performed for an entire year (or half-year, due to symmetry) to account for temporal variations in solar irradiance and sky distribution, and can be reduced to a scalar metric such as the spatial daylight autonomy (sDA) [2].

The ability to quantify the contribution of each light source (i.e. solar altitude or sky patch) to the interior irradiance is essential to annual daylight simulation. RADIANCE's *rcontrib* tool computes and tabulates these contributions in a single raytracing pass for all sources [3], thus establishing an elegant and efficient workflow. This functionality is now also supported by the RADIANCE photon map via *contribution photons* to efficiently quantify the behaviour of specular redirecting components under seasonal variations.

METHOD

Contribution Photon Map

Photon mapping implements a Monte Carlo simulation of light "particle" transport and its interaction with the simulated geometry. Light source contributions are deposited on the geometry via the photons, which are emitted from the sources (combined annual sun positions and Tregenza sky patches) and then probabilistically scattered or absorbed by surfaces based on their material characteristics (see figure 1). This efficiently accounts for the specular reflections (caustics) fundamental to a redirecting component's behaviour.

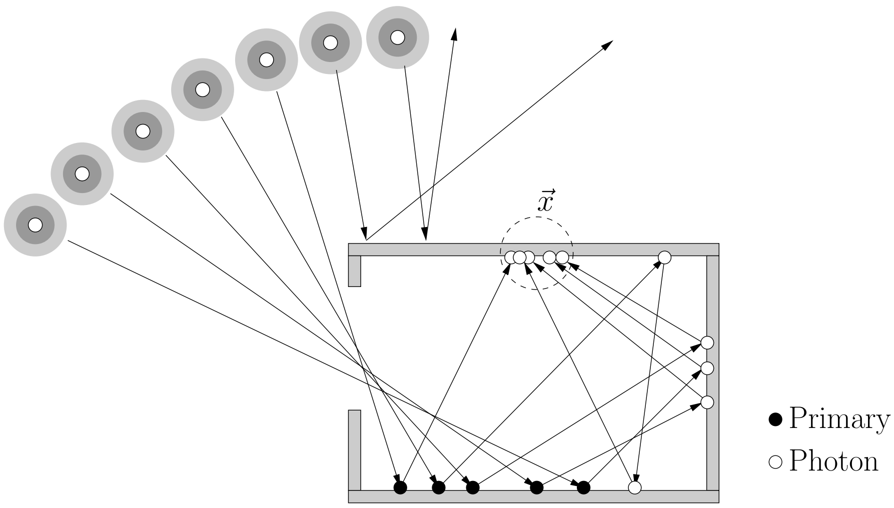

Figure 1: Photons along a path emitted from a light source reference their corresponding primary hitpoint, which in turn refers to its emitting light source. The contribution from each source to the irradiance at point $\vec{x}$ is then evaluated by a modified density estimate for a number of nearby photons around $\vec{x}$.

Each photon is characterised by its position $\vec{x}_p$ (hitpoint during forward raytracing), flux ϕ_p (energy in watts), and an index to its primary hitpoint (not stored as a photon) which identifies the emitting light source l_p. Note that a primary is multiply referenced by all photons it spawns along its path.

The contributions of each light source to the irradiance at a point $\vec{x}$ are then evaluated by a modified photon density estimate [4]. We first locate the N nearest photons around $\vec{x}$, then collect the flux ϕ_p of each photon into a "bin" corresponding to its emitting light source l. This accumulated flux is then divided by the area defined by the search radius r containing the found photons, to obtain the irradiance E_l contributed by source l:

$$E_l(\vec{x}) \approx \sum_{i=1}^{N} K(\|\vec{x}, \vec{x}_{p,i}\|) \frac{\phi_{p,i}}{\pi r^2} \qquad \forall i : l_{p,i} = l,\ \|\vec{x}, \vec{x}_{p,i}\| \leq r, \tag{1}$$

where K is a normalised weighting function based on the photon's distance to $\vec{x}$.

Spatial Daylight Autonomy

The EvalDRC tool implements the spatial daylight autonomy (sDA) metric, which quantifies the daylight availability in both spatial and temporal dimensions [2]. The sDA specifies the percentage of a workplane area receiving sufficient daylight over the course of one year, assuming occupancy hours from 8 am to 6 pm. In addition, we also evaluate the daylight autonomy on a monthly basis for our case study, which we refer to as the msDA.

In typical illuminance calculations on a sensor point grid, a point is considered to be sufficiently illuminated if it receives 300 lux during at least 50% of the given time period. sDA values >55% represent a *nominal*, values >75% a *preferred* daylight sufficiency.

Annual Simulation Workflow with EvalDRC

Annual daylight simulations are traditionally performed with a daylight coefficient method [5]. A coefficient can be a rendering of the scene, illuminated by only one sky patch with normalised radiance, or an irradiance value for a sensor point. Coefficient accumulation, weighted by sky patch radiances, then produces the final result. Descriptions of these simulations with Radiance can be found in [6] and [7]. The sky patch radiances can be determined from actual weather data using the Perez sky model.

The direct sunlight contribution can be integrated by distributing the solar radiance among several neighbouring sky patches, but this is not appropriate for the simulation of redirecting systems which exhibit highly localised peaks, thus being very sensitive to the incoming light direction. Further subdividing the 146 Tregenza sky patches by small powers of 2 (usually 2^2 or 2^4) does not effectively eliminate this accuracy loss. McNeil [8] therefore proposed an extension which introduces a separate, also matrix based, calculation with a new solar vector derived from an extremely fine sky patch subdivision.

In contrast, the EvalDRC frontend uses the Tregenza model only for the hemispherical sky radiance distribution. Direct sunlight is simulated via separate 0.5° Radiance source primitives (see figure 2). The tool handles the addition of cumulative sun primitives automatically dependent on the chosen time and location settings.

A simulation with EvalDRC consists of the following steps:

1. *Sky configuration:* Setting up cumulative sun primitives and determining sky patch and solar radiance distributions for the chosen location and time interval settings
2. *Calculation:* Generating the photon maps and determining the separate sky patch and sun contribution coefficients
3. *Accumulation:* Superposition of the coefficients scaled by the corresponding sky patch and solar radiances to produce final results (sensor point irradiance values or

Figure 2: Sky model used in common annual RADIANCE *simulations using subdivided Tregenza patches (left); the solar radiance is distributed over the three nearest patches. The* EVALDRC *sky model (right) uses the pure Tregenza patches for the sky hemisphere, and an additional accurate 0.5° angle source primitive for the sun.*

HDR renderings) for each timestamp

4. *Reduction:* Applying daylight metrics to the results to derive characteristic parameters describing the daylight perfomance of the simulated scene

The new frontend follows a modular concept, making it suitable for a wide variety of tasks, e.g. automated annual runs or the analysis of individually chosen time periods. Coefficients may be repeatedly evaluated with different sky and solar radiance distributions without additional photon tracing. Several sky models are offered, either based on generic CIE formula or weather-data driven Perez skies. Both HDR renderings and workplane irradiance values including graphical representations can be generated.

The drawback of the method is a higher calculation effort and a somewhat reduced flexibility for repeated coefficient evaluation. Due to the use of exact sun primitives, the generated coefficients are fixed to the chosen time and interval settings.

Case Study

Our case study is performed in a standard 6×6m room located in Basel, Switzerland. The redirecting component is mounted in a single south-facing window which spans the entire width of the room. All room surfaces have a reflectance of 30%.

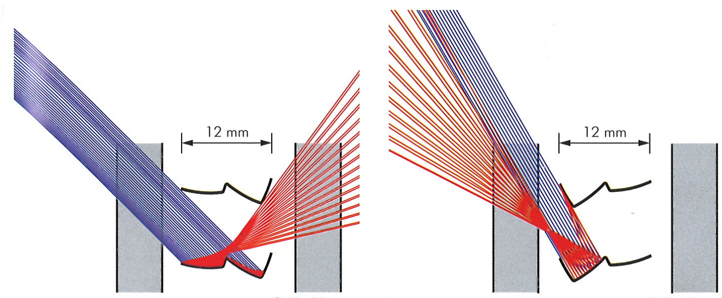

Figure 3: RETROLuxTherm retroreflecting blinds, patented by Helmut Köster. The upper portion of the fenestration redirects light towards the ceiling (left), while the lower portion retroreflects (right). Note the lamella is simply reversed. Reprinted with permission from [9].

The redirecting component for our case study is shown in figure 3. Lamellae are mounted within a double glazing in a forward and reversed configuration to effect retroreflection in the lower fenestration (1-1.75m height) and redirection in the upper fenestration (1.75-2.75m height) via an integrated lightshelf [9].

RESULTS

Figure 4 shows an excerpt from a series of 26 HDR renderings of a half-annual simulation of our case study scripted with EvalDRC using 100M photons. The sky radiance corresponds to a CIE clear sky model for consistency. Forward raytracing and accumulation of contributions for 26×600×400 pixels took 40 resp. 260 minutes on 10 cores.

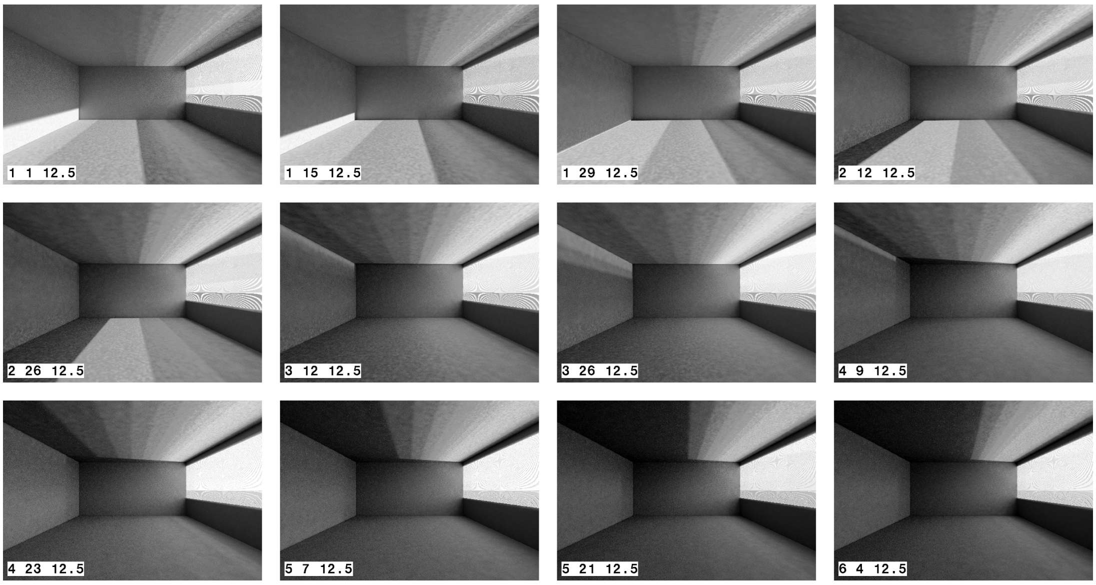

Figure 4: Renderings of our case study for a half year (January to June) at biweekly intervals for midday (12:30pm). Timestamps are in month-day-hour notation.

The redirecting component's behaviour as a function of solar angle is readily apparent. Redirection towards the ceiling can be observed at all times, thus maintaining a high degree of daylight penetration. Transmission, on the other hand, occurs at low solar angles until March, before transitioning into retroreflection at high solar angles.

Table 1 lists the sDA as predicted by EvalDRC with a Perez sky model based on weather data for Geneva, CH, together with the monthly values. The latter yield a more detailed analysis to identify problematic intervals which are subsumed under the annual value. Note that by definition, the annual sDA is not the average of the monthly values.

	Month												**Year**
	1	2	3	4	5	6	7	8	9	10	11	12	
(m)sDA [%]	61	85	100	100	100	100	100	100	100	98	69	32	100

Table 1: Monthly and annual spatial daylight autonomy for our case study.

Our case study predicts that the system performs well throughout the year in providing sufficient daylight on the workplane. Even during winter, the msDA is still above the minimum recommendation of 55% (except for December, for which unseasonably low solar radiation was recorded). Glare evaluation was deliberately excluded, as it demands a more detailed analysis also in terms of applicability of the corresponding annual sunlight exposure (ASE) metric [2] and its various parameters.

CONCLUSION

We have presented a method to efficiently simulate and evaluate the annual performance of redirecting components using our photon mapping implementation embedded in the EvalDRC scripting environment. The combination of visual and numeric analysis in the form of renderings, irradiance graphs, and our proposed monthly sDA metric provides an efficient and powerful planning tool to aid in optimising a redirecting system's annual daylighting performance.

We will continue developing EvalDRC to include the annual sunlight exposure (ASE) as an additional metric. Once in routine use, we shall extend the tool's application spectrum to compare various DRCs for their performance in different locations and urban settings.

ACKNOWLEDGEMENTS

This research was supported by the Swiss National Science Foundation as part of the project "Simulation-based assessment of daylight redirecting components for energy savings in office buildings" (SNSF #147053). We also thank our colleague, Andreas Noback, for beta testing of EvalDRC and for modelling the case study geometry.

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