A novel data-driven BSDF model to assess the performance of a day- light redirecting ceiling panel at Calgary Airport Expansion


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Published in
Proceedings PLDC 5th Global Lighting Design Convention,
VIA Verlag, Gütersloh, ISBN 978-3-9811940-3-6 (2015)

A novel data-driven BSDF model to assess the performance of a daylight redirecting ceiling panel at Calgary Airport Expansion

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OBJECTIVES

The design of the Calgary Airport Expansion shall be optimized for the utilization of daylight [1]. Daylighting is improved within the building by illuminating the perimeter zones via the facades (figure 1) and the central zones using skylights (figure 2). As part of the expansion the Transborder Departures Level is presented exemplarily.

The skylights shall reduce glare and control solar gains. Daylight performance is evaluated applying *Daylight Autonomy (DA)* as an annual daylight metrics based on *Climate Based Daylight Modeling (CBDM)* [2]. For the required annual simulations an accurate model of the skylight glazing assembly shall be developed.

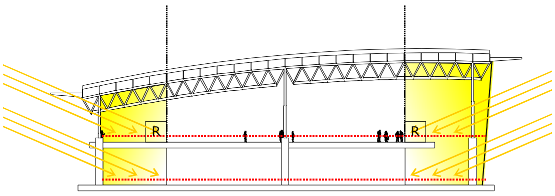

Figure 1: Daylight for perimeter zones via facades.

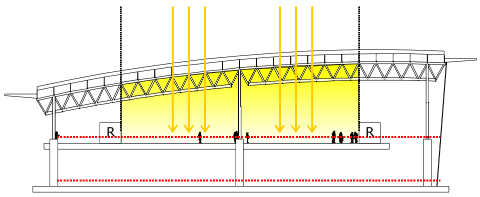

Figure 2: Daylight for central areas via skylights.

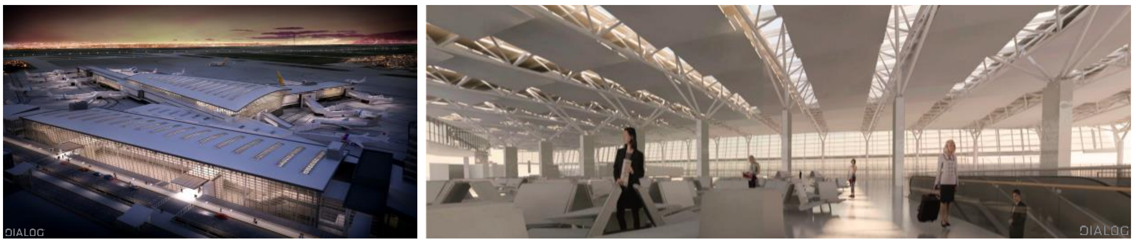

Figure 3: Calgary Airport Expansion: visualization, interior view of the central areas with the optimized skylights.

SKYLIGHTS WITH EMBEDDED MICRO LOUVERS

At an early stage of the design process external shading techniques were excluded from consideration in order to minimize maintenance. Instead, the concept suggests a ceiling panel consisting of an embedded micro louver (figure 4) within a triple glazing assembly [3]. The micro louver is a highly reflective rectangular grid which creates small light shafts with parabolically formed walls.

Oriented correctly according to the building's location and the inclination of its roof, direct sunlight is blocked while a maximum of diffuse light can pass (figures 4, 5). This principle allows occupants to experience a naturally lit room while a comfortable climate is maintained and artificial lighting can be reduced.

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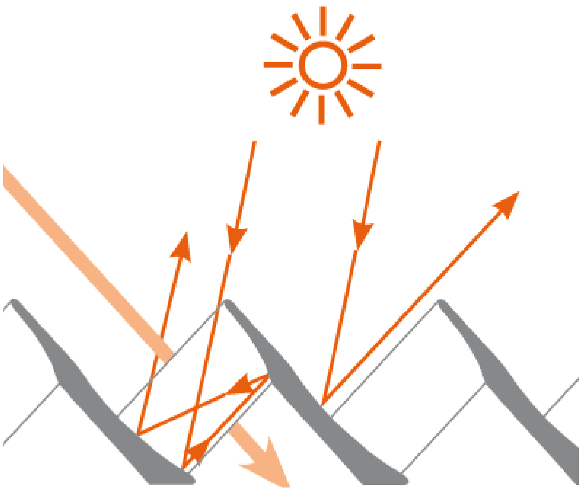

Figure 4: Embedded micro louver: principle of selective transmission.

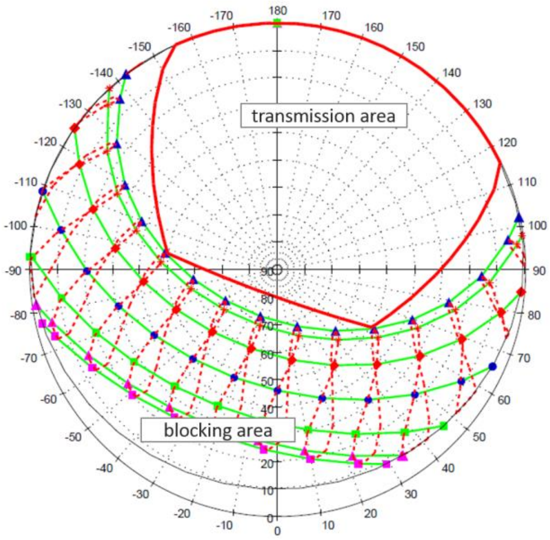

Figure 5: Sunpath with overlaid directions where sunlight is blocked (South) or transmitted (North).

METHOD

Development of a data-driven model of the skylights

Complex Fenestration Systems (CFS) such as the embedded micro louvers are challenging in daylight simulation due to their irregular transmission characteristics. The *Bidirectional Scattering Distribution Function (BSDF)* describes these characteristics as a function of incident and outgoing light directions. It is an angle-dependent matrix of the light transport through a CFS. The *Differential Scattering Function (DSF)* is equivalent and suppresses instabilities of the BSDF at directions close to grazing angles [4].

The application of the BSDF to replace the detailed geometry of the CFS in the simulation allows reducing model complexity. As no analytical models are available that can be fitted to the complex BSDF of the ceiling panel, a data-driven model is developed using the recently added support for such models in the lighting simulation software Radiance [5,6].

The BSDF of the panel is measured for a sparse set of incident directions using a goniophotometer (figure 6). Only transmission is considered, while the impact of reflection from the inner surface of the panel is assumed not to be significant. Leveraging symmetry, the incident azimuth angle ϕ_i is regularly increased from 0° to 180° in increments of 30°. The incident elevation angle θ_i is incremented from 0° to 80° in steps of 10°. For each of the 49 incident directions, the distribution of scattered light is recorded at approx. 150,000 to 250,000 directions. This high resolution is required due to the particular, irregular features in the BSDF located at multiple off-specular directions.

A set of interpolants is built by approximating the measured distributions by sets of Gaussian lobes. A complete BSDF model, representing the transmission for any combination of incident and outgoing directions, is then constructed by interpolation of the lobes using mass-transport algorithms [7]. The resulting dataset of four dimensions (incident and outgoing elevation and azimuth angles) is reduced by 98% so that important features of the BSDF are maintained, while areas where little variance is observed get merged. This step is essential, when one or multiple BSDF models have to be loaded into memory by the simulation software.

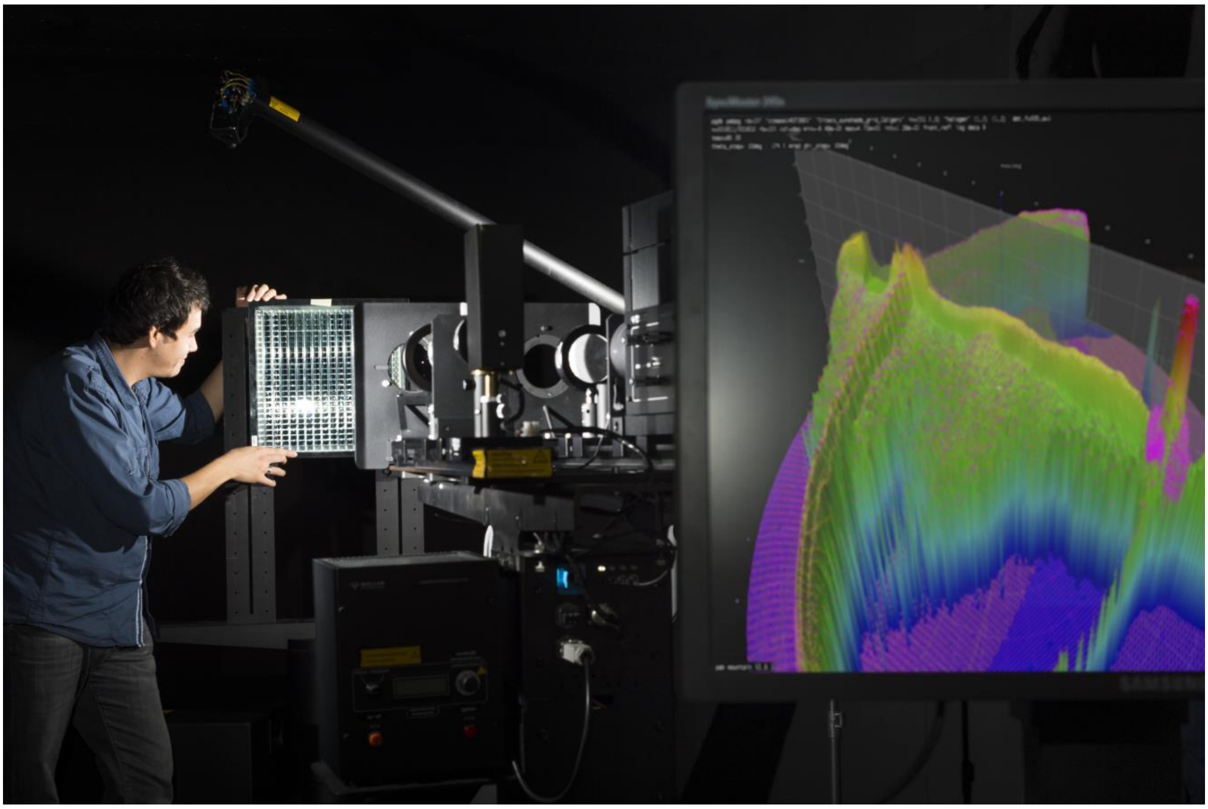

Figure 6: Daylight redirecting panel mounted on the scanning goniophotometer.

Daylight simulation model of the Calgary Airport Expansion

A model of the airport terminal including geometry and optical properties is developed. The data driven BSDF model of the ceiling panel is applied to the skylights as a uniform surface property. To focus on the contribution of the micro louver, all glazed areas but the skylights are modeled opaque.

Climate-based simulation and application of daylight performance metrics

Daylight Autonomy DA is used as a metric to verify that the daylight targets are met by the design. DA is defined as the percentage of occupied hours per year, when the minimum required illuminance can be maintained by daylight alone. The term *Daytime Daylight Autonomy DDA* describes a modification of DA, considering only hours between sunrise and sunset. During daylight autonomous hours, no artificial lighting is required. The occupied hours in the Calgary Airport Expansion are from 4 am to 12 pm, and the minimum illuminace level for the zone of interest is 200 lux.

Assessments based on DA require an annual evaluation of hourly illuminance levels for a grid of sensor points based on representative meteorological years. *The Daylight Coefficient (DC)* method is applied for the efficient computation of hourly illuminance values. DC are normalized solar quantities contributed to virtual sensors by the segments of a discretized sky dome. Folding these

DCs against luminance efficacy and distribution models allows estimating illuminance levels for any time of the year [8].

RESULTS

Transmission measurement

The DSFs for the incident elevation angle θ = 50° are visualized for two incident azimuth angles ϕ = 0° (North) and 180° (South) in projections of the transmission hemisphere (figures 7,8). Profiles of the DSFs in the scatter plane are plotted in figure 9. A logarithmic scale is applied to cover the wide dynamic range of the observed distributions. Direct transmission for incident directions in ϕ = 0° (red curve in figure 9) is reflected by the appearance of a distinct peak at θ = 130°, which is not present in the distribution for incident directions in the South (green curve).

Transmission model of the ceiling panel

The interpolants with their corresponding peak directions indicated by spheres, are shown in figures 10 and 12. The result of the subsequent interpolation and data-reduction step, leading to a full four-dimensional data-driven BSDF model with variable resolution, is shown for these directions in figures 11 and 13.

Daylight Autonomy based on climate based simulation

Simulation results with the data-driven BSDF model applied as a material definition for the skylights are shown for one level in the central area in figure 14. The average DA is 54%. This low number is caused by operation during day- and nighttime hours. A better indicator for the impact of the skylights is DDA, with an average 90% (figure 15).

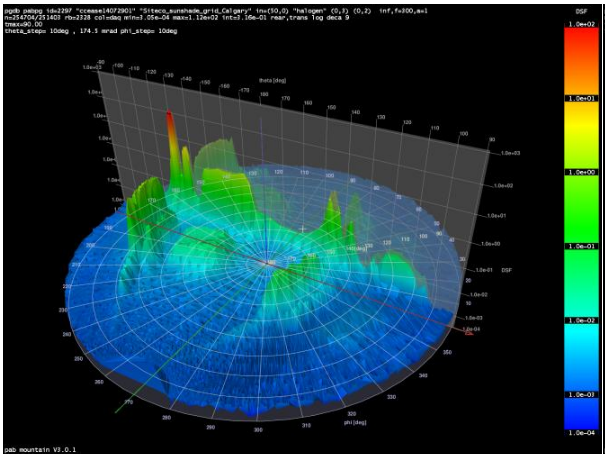

Figure 7: DSF, incident direction θ = 50°, ϕ = 0° (North).

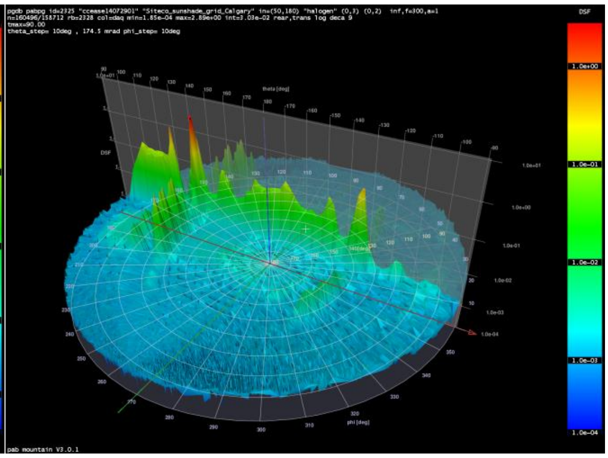

Figure 8: DSF, incident direction θ = 50°, ϕ = 180° (South).

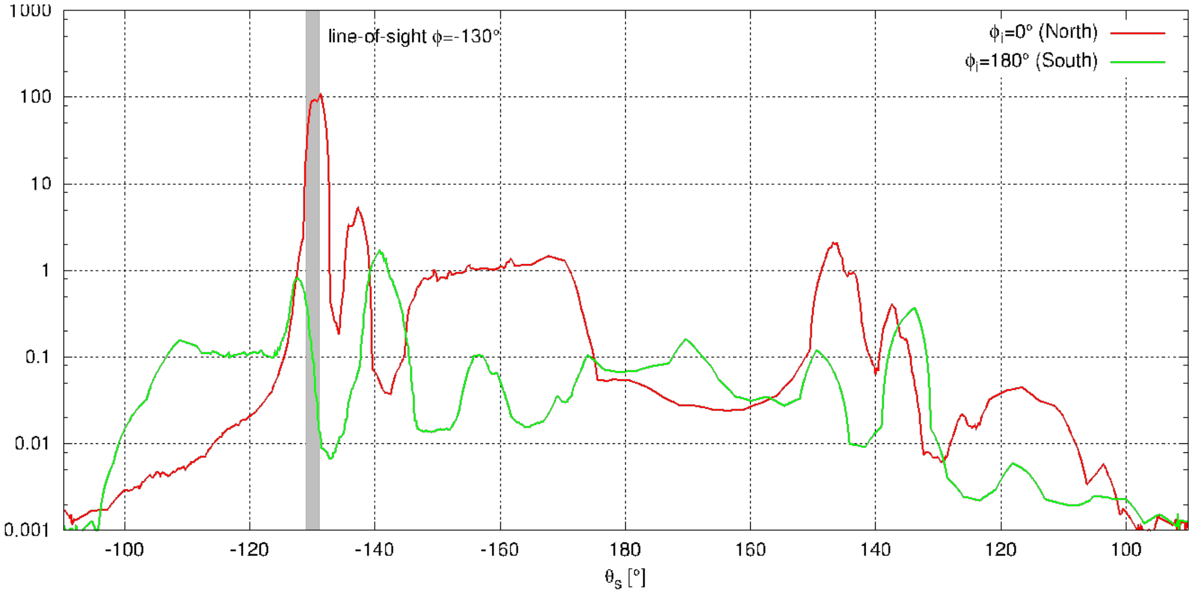

Figure 9: Profiles through distributions for incident direction θ = 50°, ϕ = 0° (North, red) and 180° (South, green).

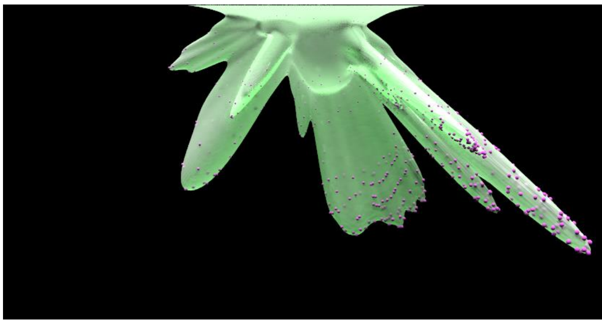

Figure 10: BSDF interpolant for θ = 50°, ϕ = 0°.

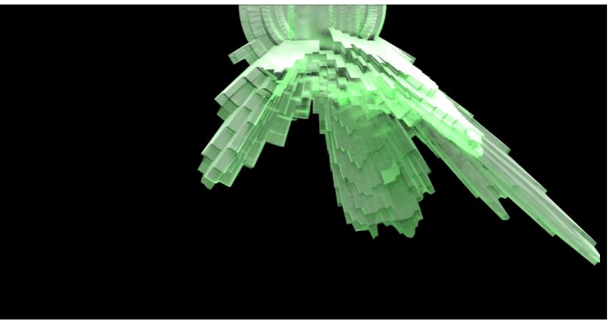

Figure 11: Variable resolution BSDF for θ = 50°, ϕ = 0°, after data reduction.

Figure 12: BSDF interpolant for θ = 50°, ϕ = 180°.

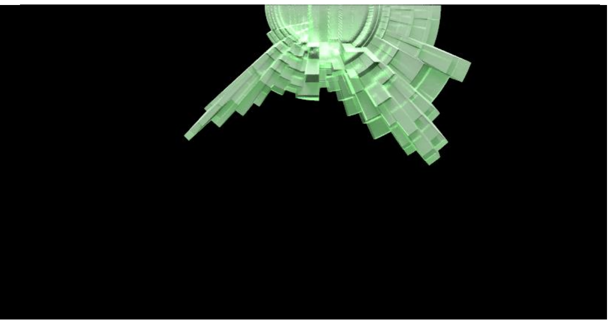

Figure 13: Variable resolution BSDF for θ = 50°, ϕ = 180° after data reduction.

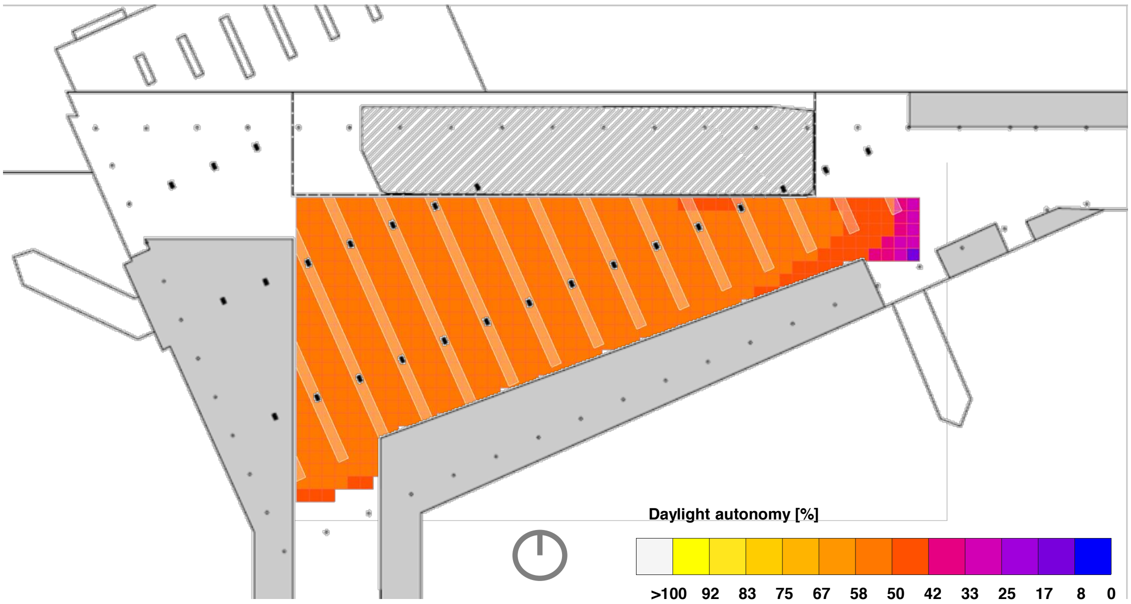

Figure 14: Daylight Autonomy DA for the Transborder Departures Level.

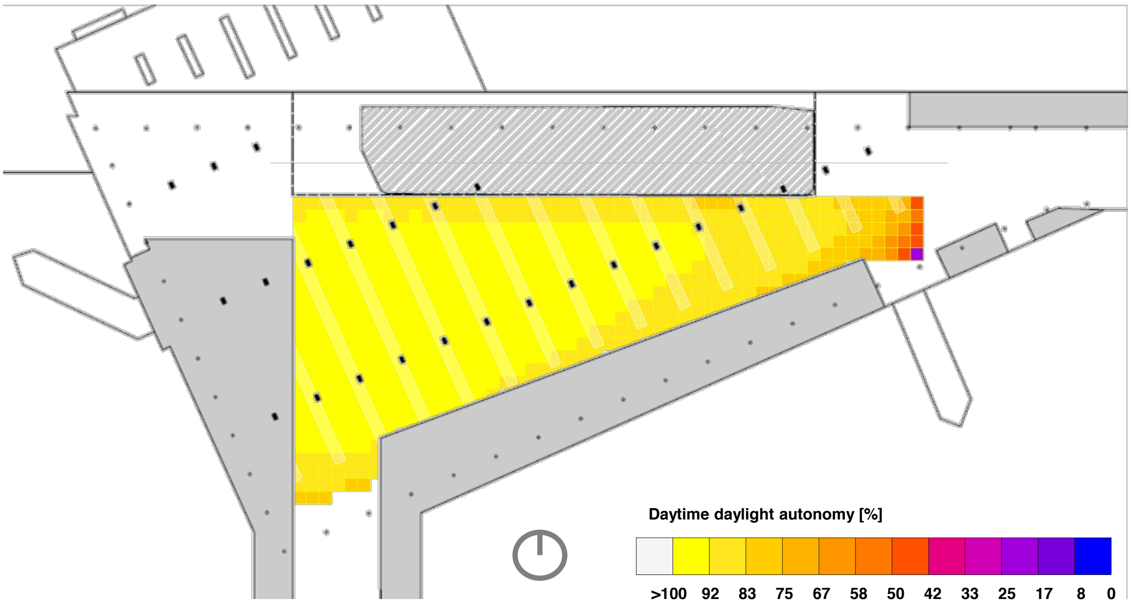

Figure 15: Daytime Daylight Autonomy DDA.

CONCLUSION

The data-driven BSDF model in Radiance allows to predict daylight performance of CFS in the early design phase.

Other than simulation-based or numerically generated BSDF models, the application of measured BSDF data includes the entire glazing setup as well as unexpected impacts of e.g. manufacturing tolerances. Besides its direct application in daylight simulation it can be used for the verification of computationally generated BSDF models.

According to the simulation, the skylights can be expected to provide an average daytime daylight autonomy of 90%. They supplement artificial lighting to a large extent and promise energy savings for electrical lighting.

ACKNOWLEDGEMENTS

This research was supported by the Swiss National Science Foundation #147053 as part of the project “Simulation-based assessment of daylight redirecting components for energy savings in office buildings”.

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