SIMULATION OF REFLECTED DAYLIGHT FROM BUILDING ENVELOPES

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ABSTRACT

With more frequent problems of reflected daylight from building envelopes, it is important to assess the influence of a building envelope design in terms of reflected daylight at early stage. This could reduce the risk of environmental problems and minimize the consequences cost after construction.

The objective of this study is development of procedures for the assessment. A tool chain has been implemented on parametric design platform RHINO and GRASSHOPPER. With the form of the building envelopes analyzed, the critical areas around the assessed building including roads, pavements and façades of neighboring buildings could be examined for reflected daylight distribution. Rich information is recorded for the critical areas: annual irradiance values contributed from the assessed envelope, period with irradiance value above a threshold, origin of the reflected daylight on the assessed building envelope, etc. This information could help designers to optimize the form and material selection of the building envelope.

INTRODUCTION

Buildings could influence surrounding microclimate with their envelope designs. Reflective surfaces on the building envelopes could reflect daylight to the neighborhood and cause problems such as glare and overheating. For the drivers, pedestrians and building occupants in the area, the reflected sunlight from the building envelope becomes the bright spot in their view which may result visual discomfort or impairment. With the development of new glazing technologies, glass is increasingly being used on building envelopes. Additionally, in order to achieve the goal of energy conservation and lower the cooling load, glazing with high reflectance is preferred by façade designers. Both of these contributed to the more frequently encountered problems of reflected daylight from building envelopes. Another issue may lead to the problem of reflected daylight is the design of free formed or curved envelopes. Without careful analysis, reflective materials on the curved surface could magnify sunlight in the same way as solar concentrators and cause problems more than annoyance to immediate neighbors. In extreme cases, scorched people's hair or even melted plastic cups are reported (Whitely, 2010).

In literature, many approaches to evaluate and prevent the hazard from reflected daylight can be found. In several countries, planning authorities have enacted regulations to eliminate the problem of reflected daylight from building façades, mainly by controlling the use of building materials based on their reflectivity alone (Building and Construction Authority of Singapore, 2010; California Natural Resources Agency, 2007; City Council of Busselton, 2010). In practice, problems may rise because of such regulations. The policy may be possibly too restrictive with material selection, particularly in cases where proper architecture design can offset the additional reflected daylight from the envelope.

In academia, researchers have developed several methods to evaluate the effect of reflected daylight from building envelopes. A research from 2001 presents a computer-aided visualization of the influence of reflected sunbeams from glass curtain wall buildings (Shih and Huang, 2001). Reflected sun light from building envelops is projected to the horizontal plan and the boundary of reflection area (BRA) is proposed as a performance index to evaluate the effect of the reflected daylight. The limitation of this method is that reflectivity of façade material is not considered in the calculation and only simple massing geometry could be analyzed. In 2005, a research project in California quantified the reflected daylight from the Walt Disney Concert Hall (Schiler and Valmont, 2005). The assessment method developed in this project has two steps: in the first step, a computer simulation is launched to find excessive luminance values from critical viewpoints around the analyzed building. In the second step, the views with extreme luminance values on the respective dates and times are photographed and processed for glare evaluation. This method could only analyze a limited number of viewpoints in the simulation step and as a result, it is possible that viewpoints with severe glare problem in the neighboring area are overlooked.

Building professionals have established methods to assess potential solar hazard from the proposed development in response to the requirement in building regulations. The methodology of David N.H. Hassall is widely adopted by Australia building consultants (Hassall, 1991). Using the method, photographs are taken at critical viewpoints around a constructed building for each main aspect of the façade. With the path of the virtual or reflected sun and a plan view of the assessed building, the areas in the neighborhood which are influenced by the reflected sunlight are located. The application of this method is limited to constructed buildings and thus could not predict potential problems from reflected daylight in the design stage. Another limitation of this approach is that it ignores the duration of time over which reflections occur to the neighboring buildings.

With the aim of overcoming most of the drawbacks explained above, a new software tool for the evaluation of the reflected daylight from building envelopes has been developed. Each building envelope design could be evaluated in the design stage. It allows detailed description of the assessed building envelope and the neighboring buildings with material reflection property. Positions in the neighborhood where reflected daylight is concentrated could be identified by the algorithm. With selected positions as viewpoints, using annual weather data in the simulation, each time period when reflection occurs could be detected. The tool could also record the origin of the reflected daylight from the assessed building envelope and display it on the 3D model.

The tool presented may help architects to have a better understanding of the environmental impact of the building envelopes at design stage. Additionally, it also provides information for designers to modify the form of the envelope and make material selection.

SIMULATION METHOD

For the task to assess reflected daylight from building envelopes, the two most commonly used lighting simulation methods: forward ray tracing and backward ray tracing were examined.

Daylight varies in intensity, color and direction over time. After intersection with building envelopes, the reflected daylight distribution in the neighborhood becomes more complicated to predict. Forward ray tracing method is more efficient in this situation to identify the areas which are affected by the reflected daylight. It could trace the whole transmission process of daylight: emission from the sun - reflection on the assessed building envelopes – terminates on the neighboring buildings.

The distribution of the reflected daylight from building envelopes follows angle of incident as well as ambient weather conditions and seasonal differences. Therefore, it is necessary to evaluate the distribution using annual weather condition rather than selected situations. RADIANCE and its backward ray tracer provide an efficient way for time-series simulations with daylight coefficient method (Reinhart and Walkenhorst, 2001). It could avoid redundant computations and improve the overall speed of annual simulations by a large factor.

In order to combine the advantages of both simulation methods, the working procedure could be divided into four steps (see figure 1). In the first step, the assessed building envelope and the neighborhood models are required with their material reflection property. The next step is to localize reflected daylight distribution in the neighborhood using forward ray tracing method. The critical positions which are affected the most could be identified. This step works as a pre-selection step for the following backward ray tracing procedures. The third step is to quantify the reflected daylight received at the critical positions with annual simulations. In the last step, the annual simulation result from previous step is further processed to extract information of the origin of the reflected daylight on the assessed building envelope. With all the information from the above evaluation process, designers could modify the envelope design accordingly by changing the form, materials, orientation, etc. The design-evaluation process could be repeated until the design target is achieved.

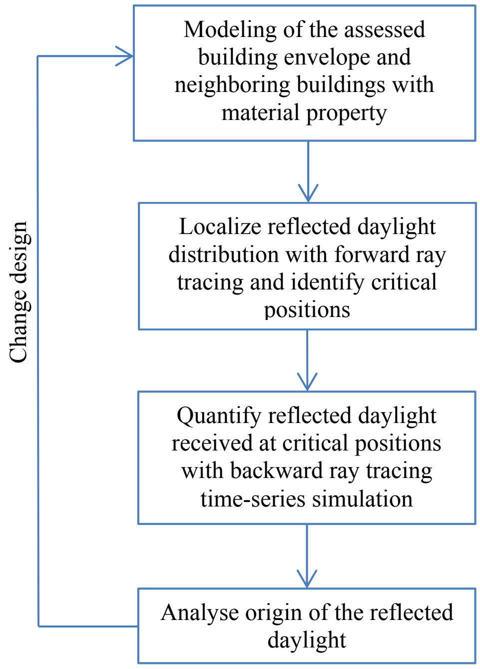


Figure 1 Flowchart of the reflected daylight evaluation procedure.

Modeling of the assessed building envelope and the neighborhood

For the presented evaluation method, detailed models could be used instead of simple massing models in some of the current evaluation methods. Therefore, more details of the assessed building envelope could be presented. Some of the details such as the curvature of the façade could affect the reflected daylight significantly.

Another important aspect of the models which is neglected in the current approaches is the reflection properties of the materials used on building envelopes. It plays an important role in changing the distribution of the reflected daylight if not the most important one. Figure 2 shows the distribution of the reflected daylight from two identical building envelopes with different materials. The distribution is identified with reflected ray intersection density in the neighborhood which is introduced in the later section. The simulation is based on sun positions in June at Zurich. The blocks in grey show the assessed building envelope. The reflected daylight on the neighborhood is color coded based on the intensity. It is obvious that the reflected daylight from the glazing façade is concentrated in a small area compared to the distribution from the diffuse envelope which covers a much larger area with less intensity.

In the evaluation method presented in this paper, all buildings including the assessed building and the neighborhood are modeled in RHINO. Materials reflection properties are defined in RADIANCE material description format and attached to the models accordingly with a newly developed tool running on RHINO's plugin GRASSHOPPER.

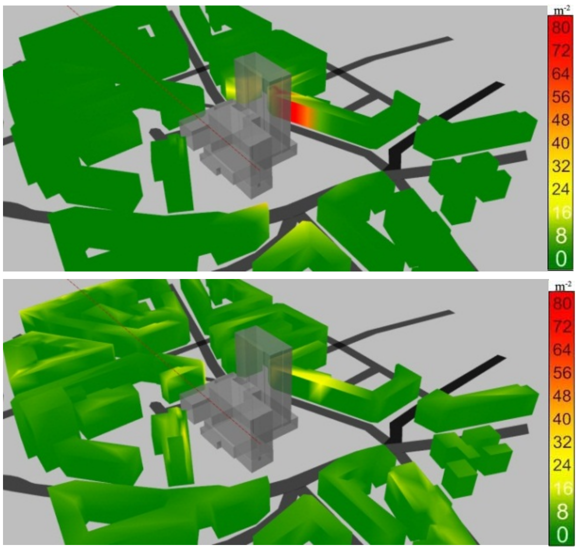


Figure 2 Color coded intersection density (number of intersection per unit area) in the neighborhood with the assessed building envelope (the gray blocks) using different materials. Top: double glazing. Bottom: 35% diffuse concrete.

Localize reflected daylight distribution and identify critical positions

Reflected daylight from building envelope is affected by many variables: sun position, solar radiation intensity, materials on envelopes, etc. Compared to the backward ray tracing algorithms which requires view positions, forward ray tracing algorithm is more efficient to find distribution of reflected daylight. RADIANCE does not have native forward ray tracing capability. Therefore, the normal simulation procedure is changed to fit this situation (Steve, 2012).

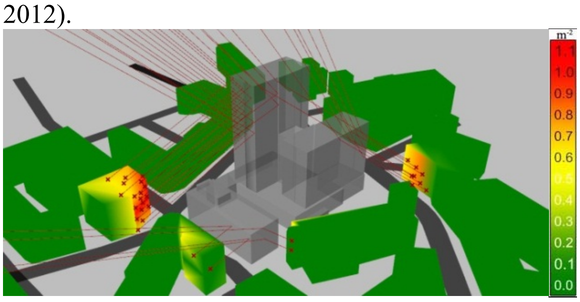


Figure 3 Forward ray tracing to locate reflected daylight from assessed building envelop on neighboring buildings with color coded intersection density.

Using RADIANCE tool *rtrace*, an array of parallel rays is sent along the solar direction vector. The rays terminate after the first reflection and those terminate on the assessed building envelope are extracted for further process. According to the reflection property of the material on the assessed building envelope, the selected rays are redirected and continue the tracing process for one more reflection. The rays which intersect with the neighborhood are selected with the intersection positions recorded (see figure 3). As a result of the above procedure, for a given sun position, distribution of reflected daylight on the neighboring buildings is identified. This process is repeated half-hour step throughout one year to get cumulated annual reflected daylight distribution. It is presented with intersection density on the neighboring buildings. The intersection density is calculated for each mesh face:

$$\text{Intersection Density} = \frac{N}{A} (1)$$

where N is the number of intersections in one mesh face and A is the corresponding mesh face area. After analyzing the annual simulation data, the critical positions with the highest intersection density are identified (see figure 4). These positions may suffer from excess reflected daylight and further investigation is necessary to quantify the received daylight.

The forward ray tracing process is implemented using RADIANCE *rtrace* tool with an interface developed in GRASSHOPPER. The interface packages the information of the 3D models such as geometry and materials and then sends it to a Linux server together with RADIANCE commands. After the simulation is finished, the interface receives the result from the server and displays it on the 3D model for a visual presentation of the distributed reflected daylight.

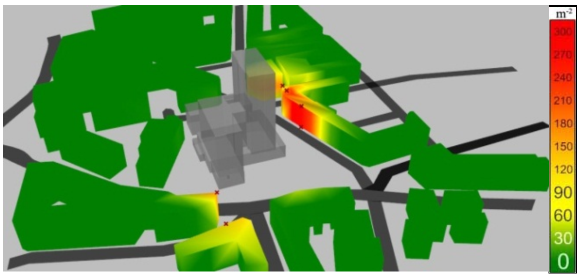


Figure 4 Color coded intersection density in the neighborhood with critical positions marked with red crosses.

One drawback of the previous reflected daylight evaluation methods is that selected viewpoints for the assessment may not cover all the positions where reflected daylight could become hazardous. Due to the limited computational capacity, only a few viewpoints around the assessed building could be selected for the assessment. The viewpoints are normally selected at the critical locations such as crossroads and other positions where reflected daylight may cause serious problems. However, it is difficult to predict the affected area by studying the drawings even for experienced professionals. Especially for the case of free formed façade, it is impossible to predict where the reflected daylight may concentrate without time-series simulations.

Using the forward ray tracing method described above as a pre-processing step, all positions in the neighborhood where daylight is concentrated could be identified. This ensures a comprehensive evaluation of the distribution of the reflected daylight.

The rays in this step carry the information of direction of sunlight while information of light intensity is lost. In order to quantify the influence of the reflected daylight and compare it to standards, the critical positions identified are used as viewpoints in the next step.

Quantify reflected daylight at critical positions

Reflected daylight follows ambient weather conditions and seasonal differences. Therefore, it is necessary for the evaluation to use climate based simulation method. In this project, daylight coefficient method is used for the annual simulation. Daylight coefficients are normalized contributions from discretized sky or ground segments, or preset solar positions, to solar quantities calculated for sensor points. With sky distribution models, it can calculate instance time series of irradiance value for sensors. In the presented method, rays are used instead of sensor points and radiance values are calculated accordingly.

EnergyPlus Weather data (Crawley et al., 1999) is used in the presented method. The global irradiance and direct irradiance from the weather file are converted to complete sky distributions using Perez All Weather Sky model (Perez et al., 1993). The resulting continuous sky distribution is segmented into a discrete description of a sky consisting of patches of uniform luminance. The direct sun is included in the patch-based sky model by distributing its luminance over the three patches close to the solar position.

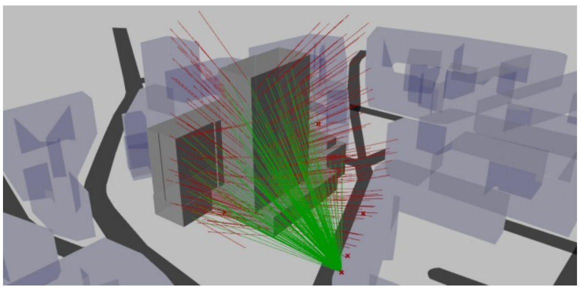


Figure 5 Random rays generated from one critical position and reflected on assessed building envelope. Green lines represent the initial rays before reflection. Red lines represent the rays reflected from the building envelope.

To evaluate the reflected daylight at critical positions which are identified in the previous step, random rays are sent from each critical position toward the section of the assessed building envelope which is visible from the position (see figure 5). Each ray is traced using RADIANCE tool *Rtcontrib* and daylight coefficients DC_α are generated for each sky patch α. For a discretized sky distribution with the same number of patches, the radiance associated with each ray L_i can be written as sum of the radiance value for sky patch $L_{SKY,\alpha}$multiplied with corresponding daylight coefficient DC_α:

$$L_i = \sum_{\alpha=1}^{m} DC_{i,\alpha} * L_{SKY,i,\alpha} \quad (2)$$

where m is the total number of sky patches plus the patch covering the lower hemisphere to account for ground reflection. The irradiance received at each critical position from the assessed building envelope equals to the sum of the radiance for each ray multiplied by its solid angle:

$$E = \sum_{i=1}^{n} L_i * \Omega_i * \cos(\theta_i) \quad (3)$$

where n is the total number of random rays generated from the critical position and θ_i is the angle between view direction and the corresponding ray.

Similar to the previous step, the simulation process using daylight coefficient method is implemented on a Linux server. With RADIANCE tool *Rtcontrib* and *dctimestep*, irradiance received at each critical position is calculated at hourly time-step. An interface was developed in GRASSHOPPER which sent information of the geometry and material properties to the server and collect simulation results for further analysis.

The irradiance calculated for hourly time-step at each critical position is plot as heat maps. The horizontal axis shows the date of the year and the vertical axis represents the hour of each day. Irradiance values for each hour is converted to illuminance using RADIANCE default constant 179 lx/W·m^{-2} and then color coded according to the scale.

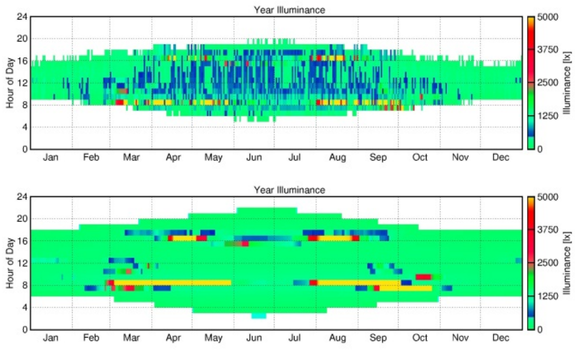


Figure 6 Heat map of illuminance received at one critical position with different weather condition. Top: weather data for Geneva. Bottom: CIE clear sky.

Both weather data and CIE clear sky model could be used in simulation. The result with sky model assumes sunny sky over the whole year which represents the worst case scenario for reflected daylight from the assessed building envelope (see figure 6 lower). The simulation using weather data addresses the influence of weather condition for the location of the building and therefore it could be used to predict the reflected daylight in a local context (see figure 6 upper).

The sensory effect of the reflected daylight was studied by analyzing the correlation between the illuminance value received at the critical positions and Daylight Glare Probability (DGP) values at the same points. DGP is a glare index designed to evaluate visual comfort for daylight spaces (Wienold et al., 2006). A standard office room facing the assessed building was modeled inside the neighboring buildings at each critical position. With a view set up in each testing room, DGP was calculated at hourly time-step under the same weather condition for the reflected illuminance simulation. The preliminary result shows a very strong correlation between the reflected illuminance and DGP.

Analyze origin of the reflected daylight

The simulation result carries information of radiance from each ray generated from critical positions to the assessed building envelope. Other than accumulating the values at each time step to generate irradiance values for each position, an alternative method to process the data is to add up radiance values for each ray throughout one year which results cumulative radiance L_c:

$$L_C = \sum_{t=1}^{8760} L_t \quad (4)$$

where radiance from one ray L_t is cumulated for hourly time step over one year.

Considering that the rays are generated from critical positions toward the assessed building envelope, the radiance value for each ray represents the radiance at the intersection point on the building envelope. Therefore, the cumulative radiance value could be attched onto the building envelope. With this information displayed on the 3D model, origins of the reflected daylight are presented. Figure 7 shows the color coded cumulative radiance displayed on the assessed building envelope.

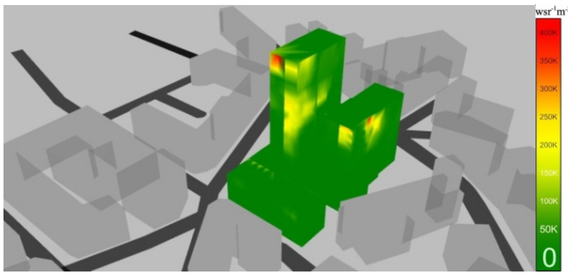


Figure 7 Color coded cumulative radiance on the assessed building envelope.

The radiance value at each time step could also be filtered to count the number of time steps above a certain threshold. Figure 8 shows the hour count of luminance with a threshold of 10000 cd/m^2. For each ray, the number of hours with radiance over the threshold is counted througout one year. This plot identifies the areas on the assessed building envelope which may generate excess reflected daylight.

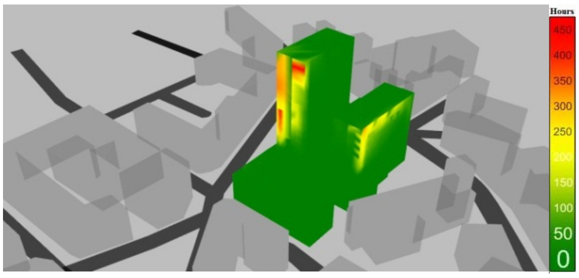
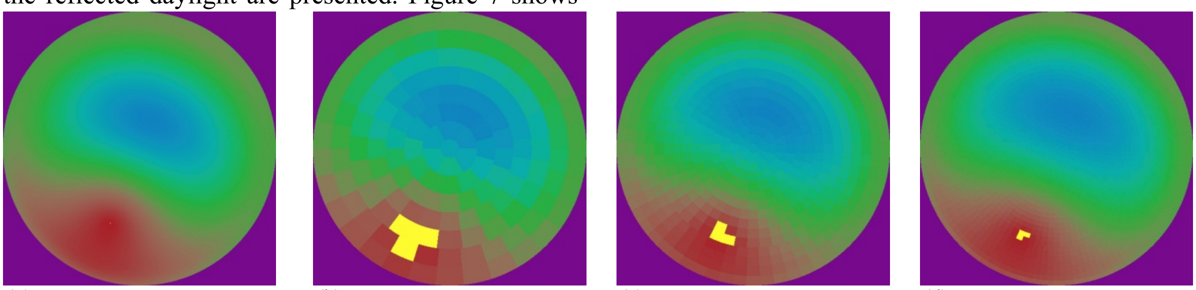


Figure 8 Hour count of luminance above threshold of 10000 cd/m^2 displayed on the assessed building envelope.

With previous steps focusing on the influence of reflected daylight in the neighborhood, results from this step provides understandings of the origins where reflected daylight is generated. It provides an insight into the relationship between the form of the building envelope and the its effect on the reflected daylight. This information could help architects targeting the modification of the form or materials on the identified areas of the assessed building envelope which cause problems.

Sky patch resolution

In order to use the tool presented above for the evaluation of reflected daylight from building envelopes, settings for some of the parameters are



(a) (b) (c) (d)

Figure 9 Visualizations of a continuous sky model (a) and (b) Tregenza sky with 145 patches, (c) Reinhart's sky with 1297 patches and (d) Reinhart's sky with 2305 patches (McNeil, 2009).

crucial for delivering accurate results. Number of the sky patches for daylight coefficient method is one of the important parameters. The original proposed method to calculate daylight coefficient divides the sky hemisphere into 145 patches (Tregenza, 1987). Some extensions of Tregenza sky subdivide the skypatches further for a higher resolution. When continuous sky distribution is segmented into a discrete sky patches, the direct sun distributes its luminance over the three patches closed to the solar position. For Tregenza sky, 0.5° apex angle sun is spread into three 13.5° apex angle patches. With larger number of subdivisions, the sun is spread into smaller area with higher luminance value (Figure 9).

The sky patch resolution could affect the simulated irradiance at critical positions to a large extent. Figure 10 shows the heat maps of illuminance values received at critical positions with differnet sky patches resolutions. With larger number of sky patches, the time period with extreme values decreaes while the absolute value increases. This could be explained by the fact that using higher sky patch resolution, the luminance from the sun is concentrated to a smaller area. The probability for a ray to hit a sun patch is lower and the radiance received is higher once a hit occured. Therefore, with the original Treganza sky, the frequency of reflected daylight is overestimiated and the intensity is underestimated. Therefore, althrough simulation is faster with small number of sky patches, considering the significent differences in the result, high sky patch resolution is prefered.

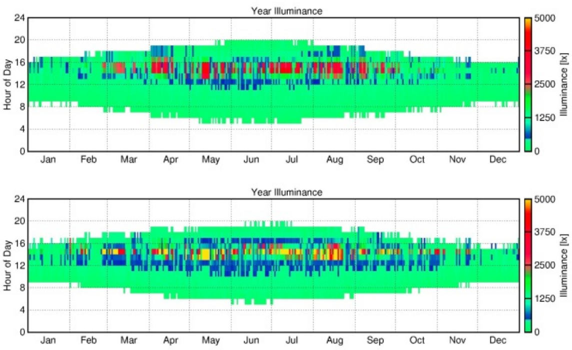


Figure 10 Heat maps of illuminance contributed from the reflected daylight received at critical positions with different number of sky patches. Top: Tregenza sky. Bottom: Reinhart sky with 2305 patches.

CASE STUDY

The presented reflected daylight evaluation tool is applied to analyze performance of a building with a curtain wall façade. The assessed building is located in Zurich and covered with a full glazing envelope. The model was created in RHINO together with the neighbourhood. The assessed building envelope was modelled with Double Pane Low-e glazing assuming reflectance of 29.3%. The neighboring buildings are 35% diffuse reflectors and the reflectance of the ground was set to 20% (Figure 11).

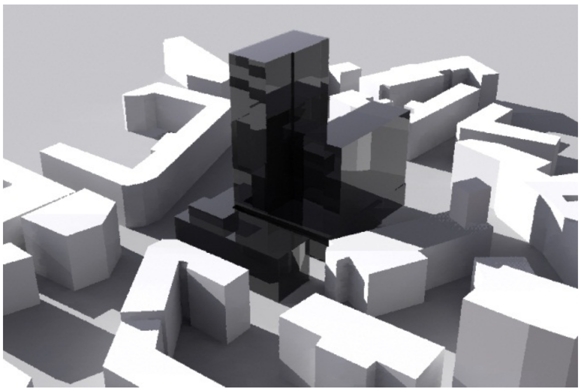


Figure 11 The assessed building with glazing envelope and neighboring buildings.

With Zurich's sun path, forward ray tracing was carried out using half-hour time step throughout one year. The distribution of reflected daylight from the assessed building is located and 7 critical positions which have the highest density of ray intersections are identified (see figure 12). Position 2 and 5 are located on the roof of the neighboring buildings while the other positions are on the façades.

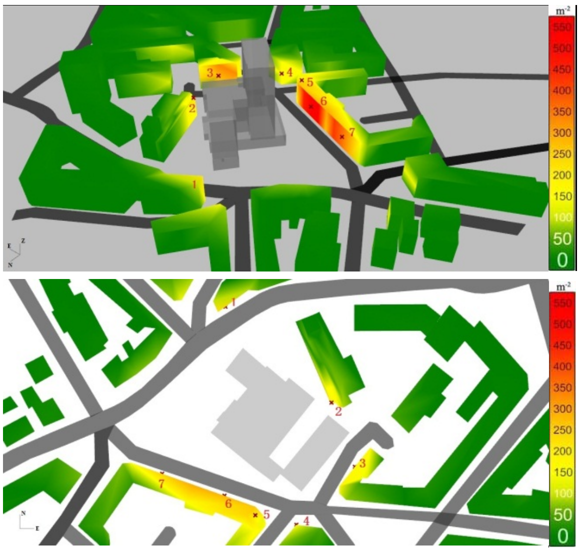


Figure 12 Color coded intersection density with critical positions numbered and marked with red crosses. Top: perspective view. Bottom: top view.

With critical positions identified, the climate based simulation was carried out with luminance distribution of the sky set according to measured data in Zurich. Some of the results are presented in Figure 13. Position 2 receives the highest intensity of reflected daylight among all the tested positions because it is located the closest to the assessed building which constitutes a large part of the view at position 2. Position 3 only receives excess reflected daylight in the early morning. The reason consists in the fact that this position locates opposite southeast facing façade of the assessed envelope. Reflected daylight could only reach position 3 when the sun is to the east of the façade. Position 6 receive large amount of reflected daylight throughout the year around 3pm. This explained the high intersection density at position 6 in figure 12. In the afternoon, intensive daylight is reflected by the southwest facing tower block toward the façade where position 6 is located.

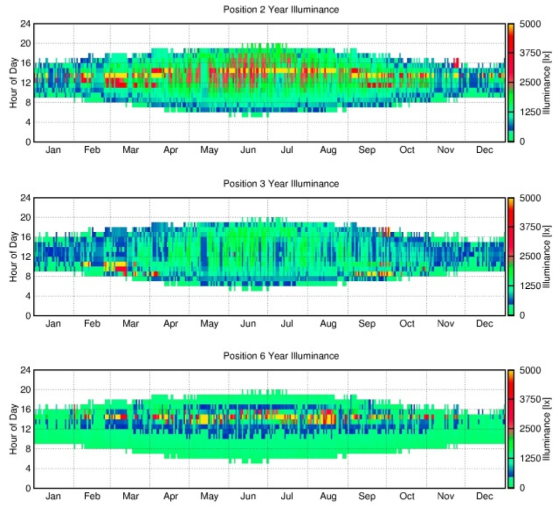


Figure 13 Heat maps of illuminance contributed from the reflected daylight received at critical positions.

After further processing of the time-series simulation results, the cumulative radiance of the reflected daylight from the assessed building envelope is calculated and displayed on the model (see figure 14). The southwest facing façade of the tower block reflects intensive daylight and the extreme values occur at the highest levels of the southeast facing façade. The effect of the daylight reflection is also evaluated by counting hours when luminance is above threshold of 10000 cd/m^2 (see figure 15). The color coded pattern is very close to the radiance distribution pattern in figure 14. The difference is that highest values are located around the medium height on the building rather than the highest levels.

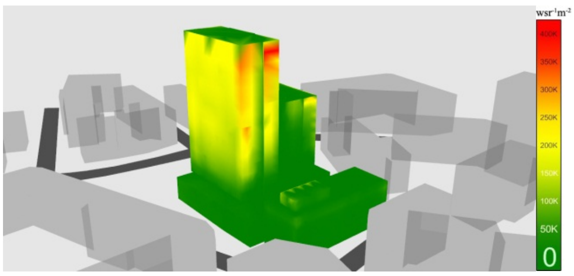


Figure 14 Color coded cumulative radiance on the assessed building envelope.

Designers could focus the optimization work on the identified areas with extreme values in figure 14 and figure 15. Whether to choose results from cumulative radiance assessment or luminance above the threshold depends on the function of the neighboring buildings and the potential effect of the reflected daylight.

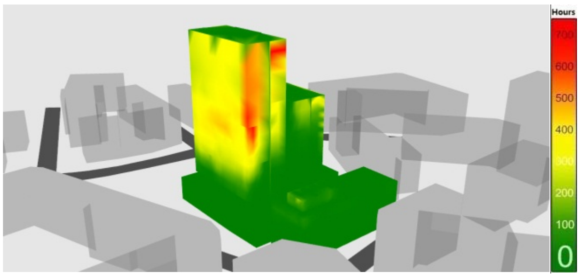


Figure 15 Hour count of luminance above threshold of 10000 cd/m^2 displayed on the assessed building envelope.

CONCLUSION

A software tool for the assessment of the reflected daylight from building envelopes has been developed. It overcomes the drawbacks of the existing assessment methods (see table 1). Detailed models for the assessed building envelope and the neighboring buildings are accepted. Material reflection property is emphasized for the building models which should be based on verified or measured material models. Forward ray tracing is introduced to the evaluation procedure as a pre-processing step for the following annual simulation. It could identify all critical positions in the neighborhood where daylight is concentrated and make the later steps more efficient. Both weather data and CIE weather model could be used for the time-series simulation. For all viewpoints assessed in the neighborhood, rich information could be recorded including annual irradiance values contributed from the assessed envelope, period with irradiance value above a threshold, origin of the reflected daylight on the assessed building envelope, etc. With the assessment results displayed on the 3D model using color scale, designers could identify the critical areas on the envelope quickly and adjust the envelope design accordingly.

Further improvements of the presented method are planned. The assessment result could be linked to algorithms for mesh modification. With this feature, the whole design-assessment process could be repeated automatically. Ideally, the improved method could suggest optimized envelope design in which minimal modification is involved. Validation of the assessment results by comparing to measured results of constructed buildings is also an interesting task for the future.

Table 1 Comparison of approaches to assess reflected daylight from building envelope

Feature/Approaches	**Shih**	**Schiler**	**Hassall**	**New**
Light source	Sun	Sun	Sun	Sun and Sky
Stage	Planning	Built	Built	Design
Material properties	No	Yes	Yes	Yes
Viewpoints	Ground	Set	Set	Auto Detected
Building geometry	Simple Mass	NA	NA	Detailed Mesh Model

NOMENCLATURE

A	=	area of mesh face (m^2)
DC	=	daylight coefficient (-)
E	=	irradiance (W/m^2)
L	=	radiance ($W/(m^2sr)$)
L_c	=	cumulated radiance ($W/(m^2sr)$)
L_{SKY}	=	radiance of a sky patch ($W/(m^2sr)$)
N	=	number of ray intersections
Ω	=	solid angle (sr)
θ	=	angle between view direction and one ray (degree)

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