DAYLIGHT GLARE ANALYSIS FOR AN ALL GLASS CATHEDRAL: INTEGRATING SIMULATION WITH COMMON SENSE TO IMPROVE VISUAL COMFORT

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ABSTRACT
Visual comfort in heavily glazed indoor environments is a growing concern in contemporary architecture. Significant progress has been made toward understanding and even quantifying daylight glare using modern software tools. The simulation tools are proficient in their evaluation of daylighting glare conditions. However, the creative design process and the pace at which decisions must be made do not lend themselves to the iterative, simulation-based workflow that practitioners have become accustomed to. The process with which to validate proposals and optimize solutions, therefore, must combine intuition and experience alongside analytical horsepower, and perhaps a traditional sun path diagram.

The Christ Cathedral (formerly known as the “Crystal Cathedral”) is an existing all-glass structure in Orange County, California—an exemplary case study in glare simulation. The building walls and roofs consist almost entirely of curtain wall, so the building energy and daylighting performance was incredibly sensitive to the strength and position and of sun. A glazing replacement was ruled out early on, so the design team developed a system of interior panels to serve not only as aesthetic components to enhance visual diversity, but also as shading devices to reduce the excessive daylight exposure to future occupants. The basic design condition was evaluated using DIVA for Rhino for daylight glare analysis based on geometric information gathered from the architectural 3-D models and local climatic data. The iterations of analysis simulated solar position throughout the day and year, intolerable glare hours using Daylight Glare Probability (DGP) as a main metric, and various RADIANCE simulations to identify specific issues at critical points in time. The simulation helped detect problematic times and areas where glare issues occurred. Focused more on the detected time and area, each shading panel was analyzed in a small scale with 2D Sun angle diagraming, in order to find out how the design could be improved. Several alternatives for the shading panels, which came to be known as “quatrefoils,” and configuration thereof were analyzed and evaluated in order to help inform the ultimate design decisions.

INTRODUCTION
As part of an ongoing indoor environment improvement of the Christ Cathedral, daylight glare analysis was conducted to enhance visual comfort for worshippers and other users of the building. The cathedral is located in Garden Grove, Orange County, CA and the building is symmetrical along the north-south and east-west axes. Philip Johnson’s Crystal Cathedral was completed in 1981 and still serves as the largest glass building in the world. After being purchased by the Arch Diocese of Orange, the new owners decided they would modify more than just the building’s title, and started planning their $55 million renovation. After which, it will continue to hold Catholic masses and ceremonies in half a dozen languages.

Figure 1. Project Location and Orientation

Glare is one of the most frequent and significant factors causing visual discomfort, especially in this kind of glass façade architecture. The architect had proposed interior panels, not only as aesthetic components to enhance visual diversity, but also as shading devices to reduce the excessive daylight exposure to users. There are four kinds of panels and each panel consists of four leaves. Here are images of what they look like below.
This research discovered the sun positions at the intolerable glare hours and investigated various panel options to reduce the hours of intolerable glare. The study options include minor adjustments—rotating panels and adjusting angle of leaves of panels.

Methods and Metrics

A daylighting condition is evaluated from two general aspects; quantity and quality. In the case of this project, the quantity of daylighting was abundant, entering into interior spaces through all glazing facades. The quatrefoil panels muted the illumination to adequate levels, but it was the daylight quality that was of a greater and less understood concern. The analysis workflow described herein was developed in order to focus on that concern, and mitigate it as much as possible within the other constraints of the design. One of the most important issues related to daylight quality and visual comfort is glare. Glare is hard to measure because it depends on how people perceive light. However, metrics have been developed and improved to characterize and assess the perception of subjects involved, as well as physical factors such as source luminance (cd/m²), solid angle of the glare source, background luminance, etc. In this comfort evaluation analysis, we use a glare metric called Daylight Glare Probability (DGP) (Wienold and Christoffersen, 2006).

DGP (Daylight Glare Probability)

Daylight Glare Probability (DGP) is a metric used to predict the appearance of discomfort glare in daylit spaces proposed in 2006 by Jan Wienold and Jens Christoffersen, who were at Fraunhofer Institute for Solar Energy Systems in Germany, and Danish Building Research Institute, respectively, at that time. This metric uses a combination of an existing discomfort glare algorithm and an empirical approach. It considers the overall brightness of the view, position of glare sources and visual contrast. The algorithm also includes user-polling conditions from two independent experiments conducted at the Danish Building Research Institute (SBi, Denmark) and at the Fraunhofer Institute for Solar Energy Systems (ISE, Germany). As a result, DGP showed very careful measurement and a very strong correlation with the user’s response regarding glare perception (Wienold and Christoffersen, 2006).

Climate Data

The TMY3 climate data collected from Los Angeles International Airport was used for this analysis. The weather station is about 30 miles away from the project building. The sky condition was set as “clear sky with sun” in the simulation, assuming the extreme condition for glare.
ANALYSIS AND IMPROVEMENT

The analysis was conducted in four steps. The first step was an annual glare simulation to represent the baseline condition. This was to evaluate the current condition and get a general sense of the space throughout a typical day and year. The second step was Point-in-time glare analysis of selected critical times. Based on the annual glare simulation data, three critical points were selected to be analyzed, where the intolerable glare occurred most frequently. Point-in-time glare evaluations at critical times detected locations of the source of glare. The third step was a design improvement by sun angle study. This was focused on detected sources of glare, and a specific type of shading panel that generates the problem. The small-scale analysis utilized sun angles taken from a 3D sun-path diagram for design development. The final step was re-evaluation of the improved condition. The annual glare metric evaluated the improved condition to compare the proposed options with the baseline condition.

Annual Glare Simulation for baseline

The first step of this analysis was annual glare simulation to see the baseline design condition. The calculation results show DGP for the whole year by using DAYSIM prediction. This simulation produced an annual evaluation of comfort within the space to help understand the glare issues and identify where the next step of analysis should be focused. There are 8,760 hours in a year; approximately 4,400 hours are when the sun is down. The results from this analysis indicated 706 hours of intolerable glare (DGP of 4.5 and higher), which is 8% of a year, and 16% of daytime of a year. This is a drastic improvement over the cathedral modeled without shading or structure, which is 2658 hours. However, we found further improvements.

Critical Point-in-time Analysis

In order to analyze the glare problem closely, three critical points were selected based on the frequency of intolerable glare. First, July, November, and December were selected because these three months generate the most intolerable glare hours.

Each month has a specific time when the high DGP occurs most frequently; 12pm in December, 1pm in November, and 3pm in July. Among the hours, one date with the highest DGP was selected for this analysis. The three points-in-time were July 12th 3pm, November 14th 1pm, and December 12th 12pm.

The annual DGP chart below shows a different pattern between summer, winter, and shoulder seasons. Intolerable DGP hours were concentrated in morning and afternoon during the summer, and mid-day during the winter. Spring and fall seasons have more scattered high DGP hours throughout the daytime and the glare doesn’t last long.

![Annual DGP Summary](image)

![Number of Hours of Intolerable Glare](image)

* 21 days have intolerable glare issue in July at 3pm
* Selected time: July 12th 3pm
• 19 days have intolerable glare issue in November 1pm  
  Selected time: Nov 14th 1pm

• 17 days have intolerable glare issue in December 12pm  
  Selected time: Dec 12th 12pm

For the three selected times, point-in-time glare simulation was conducted, and the sun location was detected from a 3D sun-path diagram. Critical points all indicated the majority of issues were coming from direct solar rays through the two sloped south roof surfaces.

Table 2. Sun Path at the Analysis

• July 12th 3pm  
  Altitude; 46.5°, Azimuth; 267.1°

• November 14th 1pm  
  Altitude; 36.2°, Azimuth; 195.0°

• December 12th 12pm  
  Altitude; 33.0°, Azimuth; 179.9°

Table 3. Sun Location at the Analysis

• July 12th 3pm  
  The direct sun falling on the south roof

• November 14th 1pm  
  The direct sun falling on the south sloped roof

• December 12th 12pm  
  The direct sun falling on the south sloped roof
The analysis was focused on 45-degree panels on the roof because one leaf of the 45-degree panel was flattened (to be parallel to a horizontal plane) in order to accommodate lighting fixtures. The configuration brought in a significant amount of sunlight compared to adjacent panels that had consistently tilted petals. The major research area was on the roof, where the direct sunlight comes into the building during the entire middle of the day. The roof consists of two surfaces; flat roof surface located on south corner, and a big main roof steeply slopped to the south.

**Design Improvement by Diagraming**

**Improvement 01.**

Sun path analysis and Point-in-time glare simulations helped us to find out that two sloped south roofs allow the direct sunlight come into the space, generating most of the source of glare. The first improvement was focused on the south-end sloped roof, which is tilted 10 degree towards the south, and 60% of the area are composed with 45-degree panels.

![45-degree panels](image)

<table>
<thead>
<tr>
<th>Panels</th>
<th># of Panels</th>
<th>% of Panels</th>
</tr>
</thead>
<tbody>
<tr>
<td>45-degree</td>
<td>94</td>
<td>60%</td>
</tr>
<tr>
<td>30-degree</td>
<td>41</td>
<td>26%</td>
</tr>
<tr>
<td>15-degree</td>
<td>22</td>
<td>14%</td>
</tr>
</tbody>
</table>

* Excludes partial panels on the edge

![Figure 9. Shading panels on the south-end sloped roof](image)

The sun angle study in 2D diagraming showed that one 0-degree panel on south side allow the winter sunlight come into the inside space. Since the winter sun angle was low, more perpendicular panels could block more direct sunlight. Especially for the direct sunlight from the south, we suggested to rotate these 45-degree panels with lighting by 180 degrees. The proposed shades had the 0-degree panel on north side. The 45-degree panel located on south side can block the winter sun penetrating and reduce direct low angle sunlight in wintertime.

![Table 4. Diagraming of As-Designed and Proposed Shades](image)

<table>
<thead>
<tr>
<th>AS-DESIGNED SHADES</th>
<th>PROPOSED SHADES</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-degree panel</td>
<td>0-degree panel</td>
</tr>
<tr>
<td>45-degree panel</td>
<td>Winter Sun Angle</td>
</tr>
<tr>
<td>Summer Sun Angle</td>
<td></td>
</tr>
</tbody>
</table>

The annual glare simulation was run to evaluate the improvement. As shown below, the annual DGP summary indicates 627 hours of intolerable glare, which is 7.2% of a year. This is a 0.9% reduction from the baseline. The annual glare analysis pattern shows that the improvement reduced intolerable glare hours during the wintertime.

![Figure 10. Annual DGP Summary - Improvement 1](image)

This improvement significantly reduced hours of intolerable glare during the wintertime. Among three critical points, intolerable hours of November 1pm became half, from 19 hours to 8 hours. In December
12pm, the hours decreased from 17 to 10. This trend is applied in total intolerable hour counts in November (73 → 48), December (73 → 53), and January (59 → 39).

Further improvement could result from using 15 or 0-degree panels. It would need to be balanced with other facades and meeting minimum daylighting targets (in foot-candles).

**Table 5. Diagraming of As-Designed and Proposed Shades**

<table>
<thead>
<tr>
<th>AS-DESIGNED SHADES</th>
<th>PROPOSED SHADES</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-degree panel</td>
<td>30-degree panel</td>
</tr>
<tr>
<td>45-degree panel</td>
<td></td>
</tr>
</tbody>
</table>

The annual DGP summary indicates 605 hours of intolerable glare, which is 6.9% of a year. This is a 1.2% reduction from the baseline. The annual glare analysis pattern shows that the improvement reduced intolerable glare hours during the spring and fall.

**Figure 12. Number of Hours of Intolerable Glare - Improvement 1**

**Improvement 02.**

The south sloped main roof was analyzed as well. The roof was tilted 30 degree towards the south, and 38% of the area was comprised of 45-degree panels.

On this steeply sloped roof, the same change with "Improvement 01" could block the winter sun but it allowed the summer sunlight to come inside more, as the Figure 14 is shown.

In order to control both winter and summer sun, the 45-degree panels were changed to all 30-degree panels.

**Figure 13. Interior shading panels on the south sloped main roof**

| 45-degree Panels | 341 | 38% |
| 30-degree Panels | 366 | 41% |
| 15-degree Panels | 182 | 20% |

* Excludes partial panels on the edge

**Figure 14. Applying "Improvement 01" change to the south sloped main roof panels**

The annual DGP summary indicates 605 hours of intolerable glare, which is 6.9% of a year. This is a 1.2% reduction from the baseline. The annual glare analysis pattern shows that the improvement reduced intolerable glare hours during the spring and fall.
In addition to Improvement 01, Improvement 02 reduced the hours of intolerable glare during shoulder seasons. In March, the intolerable hours decreased from 66 to 61, and it was reduced from 56 hours to 49 hours in September.

**CONCLUSION**

Low Visible Light Transmission (VLT) glazing and designed interior shading devices control DGP within tolerable range most of the time and enhance visual comfort significantly over the baseline condition. However, the annual glare analysis conducted with a selected view (from the Bishop’s seat toward south podium) shows that, with the proposed design, there are still more than 700 hours of intolerable glare per year. Three critical points-in-time with the highest frequency of intolerable glare were analyzed to detect the greatest contributor of glare.

Simulation was used for evaluation and problem detection in this analysis. The simulation tool with its parametric plug-in was not able to optimize solutions in a way that fit the design constraints, especially for this kind of large building with complex geometry and interior shading devices. Developing design alternatives was the area where the creativity of designers and consultants was required. Traditional and simplified diagraming helped create solutions and turn intuition from a common sense into logical analysis.

For the Christ Cathedral, the improvement steps were focused on one type of panel in each sloped roof. The highest and lowest sun angles from the 3D sun-path diagram were drawn in simplified 2D diagram. This allows to create two improvement options to control the direct sun;

1. **Improvement 01 at South Corner Flat Roof**: Rotate 45-degree panels with lighting 180 degrees
2. **Improvement 02 at Main Sloped Roof**: Replace 45-degree panels with 30-degree panels

“Improvement 01: Rotate 45-degree panels with lighting 180 degrees” on the South corner flat roof significantly reduced the hours of intolerable glare during winter time. The annual glare analysis indicates 11% reduction of the hours of intolerable glare.

To improve visual comfort during the summer and shoulder seasons, other options were analyzed on the main sloped roof, on top of the Improvement 01.

“Improvement 02: Replace 45-degree panels with 30-degree panels” reduced shoulder seasons’ intolerable glare hours about 3.5% more from Improvement 01. This shows that the angle of shading panels sensitively effect on daylight glare so treating the angle of panels is one of the keys to improve visual comfort.

With the two improvements, the total intolerable glare decrease from 706 hours to 605 hours.

**REFERENCES**


http://diva4rhino.com/