AUTOMATIC CALCULATION OF A NEW CHINA GLARE INDEX

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ABSTRACT
Lighting simulation is widely accepted and used to evaluate lighting performance including glare metrics. Digital technologies such as Computer Aided Design (CAD) and Building Information Modeling (BIM) can ideally reduce time consuming manual efforts in glare evaluation workflows and are commonly used to achieve automatic workflows. However, varying BIM standards and information interoperability present challenges when new metrics are introduced and existing tools can no longer achieve automatic workflows. Using a case study of the new China daylighting glare metric, we discuss the gaps in current software tools and present a new prototypical software to automate the calculation of the China Daylight Glare Index (DGI\textsubscript{China}). Besides practical usage in industry, the new software facilitates technical investigations and clarifications for DGI\textsubscript{China} and discussions for future developments in BIM necessary for practical industry usage.

INTRODUCTION
It is widely accepted that glare constitutes an important part of interior lighting quality. A number of glare indices have been proposed and adopted worldwide, including VCP (DiLaura, 1976), UGR (Eble-Hankins and Waters, 2005), DGI (Hopkinson, 1957, 1972). While there are many glare indices—BGI, CGI, DGR, DGP and UDI (Rubíño et al., 1994; Nazzal, 2000; Wienold and Christoffersen, 2006; Reinhart and Walkenhorst, 2001; Nabil and Mardaljevic, 2005; Einhorn, 1969), they invariably involve the same four basic parameters of glare source luminance, size, position, and background luminance or illuminance. While these four parameters are composed differently in various metrics using different exponents and constants, they allow a common computational basis (functions based upon the four parameters). DGI\textsubscript{China} exceeds this computational basis since one of the parameters is now differently defined.

In the China green building effort, local experiments suggested that the climatic conditions would result in glare conditions over 90% of the time if windows are too large (MOHURD, 2012). The prevalent Daylight Glare Index (DGI) originally proposed by Hopkinson (1972) is modified and included in the China national standard “GB50033-2013 Standard for Daylighting Design of Buildings”. This modification results in difficulty in using current software tools to evaluate the new metric.

China Daylight Glare Index (DGI\textsubscript{China})
Specifically, DGI\textsubscript{China} makes two modifications. First, the definition of a glare source includes the entire window brightness rather than sections of windows that have brightness above a certain multitude of adaptation levels. As DGI\textsubscript{China} is meant to evaluate the objective effect of windows, DGI\textsubscript{China} disregards the conventional definition of glare sources as determined by adaptation levels. The formulation of DGI\textsubscript{China} is thus identical to the common Hopkinson DGI except for the definition of $L_s$ in glare constant equation (2) below:

$$DGI_{\text{China}} = 10\log \sum G_n$$

where glare constant for each external window in the room is:

$$G_n = 0.48 \frac{L_s^{1.6} \omega^{0.8}}{L_b + 0.07 \omega^2 L_s}$$

where

$L_s$ = average brightness of window (cd/m²)
$L_b$ = average background luminance, resulting from all visible internal surfaces (cd/m²)
$\omega$ = angular size of window from view position (sr)
$\Omega$ = solid angle subtended by window modified by position index (sr)

The definition of $\Omega$ (solid angle subtended by each window modified by position index) also follows prevalent glare metrics:

$$\Omega = \int \frac{d\omega}{p^2}$$

where $p$ is Guth position index:
\[ \begin{align*}
  p &= \exp \left( \frac{35.2 - 0.31889\alpha - 1.22e^{-2\gamma}}{21 + 0.26667\alpha - 0.002963\alpha^2} \right) 10^{-3}\beta + 10^{-5}\beta^2 \\
  \alpha &= \text{angle from vertical axis to center of window} \\
  \beta &= \text{angle between view axis and center of window}
\end{align*} \] 

where

The second modification in DGI_{China} is the acceptable threshold values, but does not affect computation, which is the focus of this paper. “Daylighting Grade” is a classification used in the China standard and not a concern in this paper. For example, offices and conference rooms have a Grade-III requirement whereas copy rooms have a Grade-IV requirement. While corresponding notional window brightnesses are listed, these values are for reference only since the standard uses calculated DGI_{China} values for evaluation. Equivalent DGI threshold values in UK standards are also listed for reference.

<table>
<thead>
<tr>
<th>DAYLIGHTING GRADE</th>
<th>LEVEL OF GLARE PERCEPTION</th>
<th>WINDOW BRIGHTNESS (CD/M²)</th>
<th>DGI CHINA</th>
<th>DGI UK</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>No glare</td>
<td>2000</td>
<td>20</td>
<td>19</td>
</tr>
<tr>
<td>II</td>
<td>Slight perception</td>
<td>4000</td>
<td>23</td>
<td>22</td>
</tr>
<tr>
<td>III</td>
<td>Acceptable</td>
<td>6000</td>
<td>25</td>
<td>24</td>
</tr>
<tr>
<td>IV</td>
<td>Discomfort</td>
<td>7000</td>
<td>27</td>
<td>26</td>
</tr>
<tr>
<td>V</td>
<td>Tolerable</td>
<td>8000</td>
<td>28</td>
<td>28</td>
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Prevalent Glare metric computation workflow and tools

The typical workflow for evaluating glare, including DGI, includes three stages centered around lighting simulation (Figure 1). In the pre-simulation stage, building geometry and surface information are prepared so that they are suitable for use by lighting simulation software. RADIANCE is the prevalent software used in industry and it utilises an ASCII text-based input representing three-dimensional information of scene geometry and material properties. In the second stage lighting simulation is conducted to predict point luminance values in the scene. RADIANCE conducts stochastic backwards ray-tracing to produce a bitmap image of the specified view with calculated luminance values for pixels (Ward, 1991). In these first two stages the effort and complexity is low. There are numerous tools widely used in industry to automatically convert digital building models to RADIANCE input format, such as Ecotect, Revit, IES, OpenStudio. Likewise, RADIANCE is fairly user-friendly and requires only minimal user-specified parameters to operate and obtain desired glare-view luminance-based images (hereafter referred to as RADIANCE images).

The third and final stage are to calculate glare metrics. In the case of common international glare metrics such as VCP, UGR, and DGI, RADIANCE provides easy-to-use auxiliary programs to obtain the metrics from the simulation results in the form of RADIANCE images. These metrics usually define glare sources as areas within views having brightness several times of background luminance (typically seven times brighter). The RADIANCE images can therefore easily be used in a two-pass method (Ward, 1992). The auxiliary program findglare parses the image to tabulate the average luminance of the image and finds regions that are too bright and considered glare sources (together with view directions, solid angles, and luminance of these glare sources). A second program glarex uses the tabulated results to obtain the desired glare metric. These two programs are similarly easy to use, and have facilitated the inclusion and use of glare metrics in industry.

![Figure 1 Current 3-part process to calculating common glare metrics](image-url)

Challenge Presented by DGI_{China}

Considering the third stage in the workflow described above, the main limitation hitherto not a major concern (since there is no need to correlate the luminance image with geometric information) is how the auxiliary program findglare finds glare sources. As noted by Ward, since the RADIANCE image is a bitmap devoid of geometric information, only pixel-based methods are feasible and thresholding algorithms (comparing each pixel luminance to a threshold luminance) are the most effective method of determining glare sources and requisite attributes.

The challenge presented by DGI_{China} lies in the modified definition of glare source ($L_g$ in equation 2). Since it is possible that a window might contain both sections brighter than threshold as well as sections darker than threshold luminance at the same time, it is no longer simple to use thresholding algorithms. Considering available RADIANCE auxiliary programs, the only workaround is to manually crop a glare-view luminance image to obtain partial images for each window (Figure 2).
Findglare can then be configured (threshold equals zero) to treat the entire image as a glare source to obtain requisite glare-attributes for each window. The individual window results can then be combined to obtain the overall DGI. Unfortunately, this presents a very time-consuming and manual task of preparing image-masks for each window in each space to be evaluated for glare.

The challenge to computing DGI_{China} efficiently can thus be summarized as determining which pixels in RADIANCE images belong to external windows so that necessary values used in the DGI_{China} equations can be obtained. Since a digital building model is typically used (as discussed above) to generate the RADIANCE input files, it follows that we can use the geometric information in this model to process the RADIANCE image to automatically obtain all necessary values and calculate DGI_{China} (Figure 3).

As mentioned, the objective of a new DGI_{China} software is to take advantage of a digital model, such as a building information model (BIM) built with interrelated parametric relationships to automatically determine which pixels in RADIANCE images represent windows such that necessary values for the DGI_{China} equations can be obtained and the equations evaluated. The main considerations for this new software are 1) the platform or environment in which the software is to be developed, 2) the type of BIM schema to be adopted, 3) the ease of software development and implementation, and 4) the modularity and extensibility of the entire system to accommodate future needs and developments. Notionally, the new software will have as input a RADIANCE image and corresponding BIM data, both of which originating from the same CAD model (Figure 4).

**Software Platform Development**

In recent years, there has been much software developed to leverage BIM data for automating various simulations and calculations. There are generally two approaches: either to develop the new application within CAD/BIM tools (such as plug-ins in Revit or SketchUp), or to develop a standalone application that interfaces with the CAD/BIM tools via BIM data exports in particular BIM schema formats. The authors have experienced both approaches in previous research (Author, 2008, 2008a, 2013), and the main findings for the four considerations mentioned above are summarized in Table 2 below.

**Table 2**

<table>
<thead>
<tr>
<th>Considerations in developing new software</th>
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<tr>
<td><strong>APPLICATION WITHIN EXISTING CAD/BIM SOFTWARE (PLUG-INS)</strong></td>
</tr>
<tr>
<td>Platform / Environment</td>
</tr>
<tr>
<td>BIM Schema</td>
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</table>
The new DGI\textsubscript{China} software is developed as a standalone Java application for a general audience and considering ease of development. The CAD building model is anticipated to originate from a multitude of prevalent CAD/BIM software used in China such as Ecotect, Revit, IES, and SketchUp, all of which have BIM data export functions, or allow relatively easy-to-implement custom data export. From the mentioned experience, it is easier and faster to prototype the new software as a standalone application by being able to reuse existing libraries and quickly getting to the main algorithms rather than spending time understanding and dealing with the CAD/BIM tool framework and restrictions. The two approaches can be characterized as top-down when working within existing CAD/BIM environments necessitating careful development planning, and a bottom-up approach when mixing and matching existing modules flexibly to quickly test new ideas. Given the context of this research the latter is deemed more appropriate. The flexibility to choose Java, besides familiarity, allows this research to have direct control over data structures and memory since some ray-tracing is anticipated.

The new DGI\textsubscript{China} software adopts the gbXML schema instead of IFC, both of which are supported by the prevalent CAD/BIM software mentioned above. Authors (2007) presented a comparison between the two schemas showing the former to be more flexible and easier to implement in situations similar to this research. While there are serious limitations to gbXML especially in terms of supported geometric types and data consistency, these limitations do not severely affect the new DGI\textsubscript{China} software, and are generic BIM schema problems not entirely addressed by IFC as well.

**Implementation**

As presented earlier, the new software will assume a well-formed and correct gbXML data file of the building model, as well as a RADIANCE luminance image (*.pic or *.hdr format, Ward, 1991) from successful RADIANCE simulation. In contemporary workflows (as presented in Section 1.2 above), both items can be obtained with relative ease. The RADIANCE image can be any resolution, but must be a hemispherical view as necessary for glare calculations. The algorithm for calculating DGI\textsubscript{China} is as follows:

**Step 1:** import luminance image (pixel luminance) and header (view attributes), import corresponding gbXML for raytracing and surface type checks

**Step 2:** determine background luminance

**Step 3:** for each pixel, spawn and trace ray to determine if external window and cache results

**Step 4:** for each window, based on visible section, determine solid angle, average luminance, and position index

**Step 5:** calculate DGI\textsubscript{China}

As mentioned, this project builds upon previous work and libraries to achieve the steps above (Figure 5). Existing gbXML and raytracing libraries developed in previous research (Author 2008, 2008a) are slightly modified and used to achieve BIM data import. An existing RADIANCE luminance image library provides support to import and view the images, and is extended so that an image pixel position can be mapped to a direction vector in model coordinate-space.

**Figure 5 New and extended modules in new DGI\textsubscript{China} software**

The bulk of the development lies in Step 3, where a scanline method is used to process each pixel in the image. The model coordinate-space direction vector corresponding to each pixel is obtained and raytraced using the kd-tree of model surfaces maintained by the gbXML library. Following Authors et al. (2007) and Author (2008), we are able to distinguish external windows by simple extension of the gbXML surface types enumeration to include “External Windows”. The raytracer checks if the nearest visible external surface intersected is a window, and if so, assigns the pixel to a list of windows accordingly. In essence, the software figures out which pixels represent views of external windows.

The benefit of this pixel-based approach is the relative ease by which the necessary values for DGI\textsubscript{China} can be obtained. Since the image is a hemispherical projection defined as having $2\pi$ steradians, the solid angles of the visible sections of windows are simply a ratio of the number of pixels.
representing the window view and the total number of pixels in the circular image. Likewise, the position index of the window can be obtained in constant time by reversing the model space hemispherical projection on a 2-dimensional image-plane.

**Initial Demonstration**

The new software (Figure 6) makes it easy to calculate DGI\textsubscript{China} without any need for manual image masks or tedious manual calculations. With this automatic workflow, conducting a large number of lighting simulation and DGI\textsubscript{China} evaluation is now feasible. This allows detailed studies on DGI\textsubscript{China}. The China standard “GB50033-2013” only lists the equations 1-4 presented above, but does not include computation protocols, such as sky conditions, room sampling criteria, and view positions, to be used when evaluating DGI\textsubscript{China} for a building.

![Figure 6 New DGI\textsubscript{China} software application](image)

The necessity of studies to understand the new DGI\textsubscript{China} metric is demonstrated by an initial demonstration of the new software. Using an actual building project that is representative of local designs and performs well in other performance metrics especially daylighting, we compute both DGI and DGI\textsubscript{China} for a large set of positions (Figure 7). We observe that DGI\textsubscript{China} is significantly different from the DGI due to the modification in glare luminance $L_s$ to include the entire window. In many cases DGI does not include entire windows that do not cross adaptation thresholds.

Whereas DGI ratings are nominally higher for views diagonally across typical office spaces (representing the view entering an office from a door in the corner) than in the middle of the same space (representing the view of a typical workstation) due to lower luminances within visual fields (a heightened “tunnel” effect), this generalization is no longer the case in DGI\textsubscript{China} with the change in $L_s$. Likewise, previous rule-of-thumbs or anecdotal relationships between DGI and view direction or positions in buildings have been observed to change significantly in DGI\textsubscript{China}.

![Figure 7 Initial tool demonstration and comparison of DGI and DGI\textsubscript{China} in actual building project](image)

**Developing Protocols**

Following our initial observations above, we then use the tool to assist a local standards agency to suggest and review protocols by simulating a large set of glare positions and conditions in reference designs. The study (currently ongoing) initially focuses on glare positions, impact of typical architecture geometric parameters, and an analysis of the DGI\textsubscript{China} stipulated thresholds.

The mentioned China standard for daylighting includes a protocol for sky model to be used in daylighting (but not glare) simulation: a cloudy sky model, with one of five stipulated specific horizontal illuminance according to geographical location. The standard establishes thresholds and the sky model for daylighting based upon actual weather data and simulation analysis. From a standard-implementation perspective, we follow this sky model protocol for consistency.

![Figure 8 Combinatory data set for protocol analysis: 4 dimensions, glass transparency, 4 candidate glare positions](image)

Typical China office spaces have window height ratios of 0.2 to 0.6, window width ratios of 0.5 to 0.9, ceiling heights 2.6m to 3.5m, room depths 7m to 11m, and glass visible transmittance from 0.4 to 0.7 (Figure 8). Together with 4 candidate glare positions,
we generate a total of 432 glare calculations in this protocol study.

As with the initial demonstration, we note that computed DGI and DGI\textsubscript{China} are radically different due to the different definition. More importantly, we note that it is difficult to generalize any trend between the size of windows (as measured by steradians subtended by visible windows) and the severity of DGI\textsubscript{China} (Figure 9).

We then analyze subsets of the initial data (Figure 9) to evaluate the suitability of candidate positions to be included in DGI\textsubscript{China} computation protocols. The objective is to include a minimally sufficient set of positions that would be representative of the performance of the space; the position should yield sufficient DGI\textsubscript{China} range whilst still being close to the median of possible DGI\textsubscript{China} values, and should not be redundant by being directly correlated to the results of another candidate position. In this study we included four candidate positions that initially seem representative of views in spaces (Figure 8): middle of room perpendicular towards the facade, back of room perpendicular towards the facade, diagonally across entire room, and at the side of the room viewing across with the facade parallel.

In Figure 11, the results of the four candidate positions are grouped for analysis. The distribution of DGI\textsubscript{China} results from each candidate position is observed against other positions, and the distance of each group of results from the median value of all positions is ranked. The two positions with perpendicular views towards the facade have very similar characteristics, one should be omitted. Between the two, the position in the middle of room has better representativeness. The DGI\textsubscript{China} results for diagonal and the parallel positions appear on opposite sides of the median DGI\textsubscript{China}, with both positions having similar magnitude of difference from the median. This again suggests redundancy between the two positions, where one is sufficient to quantify the expected DGI\textsubscript{China} range within the room. In other words, the inclusion of just two positions, middle of room towards facade, and diagonally across room, might be sufficient for computation protocols.

We note that the existing sky model protocol does not adversely affect DGI\textsubscript{China} results. There are five sky types in the China standard, Type-1 being the brightest and Type-5 being the darkest. DGI\textsubscript{China} differs by no more than 1.1 across the sky types (Figure 10). Although insignificant, a darker sky results in slightly less glare (DGI\textsubscript{China} < 0.3), which is opposite of the positive correlation between sky brightness and daylighting. This result further supports the case for using existing sky model protocols.

Last, we sort the simulation data by spatial dimension attributes to observe the relationship between DGI\textsubscript{China} and architecture design. While we noted earlier the absence of generalizable trends, there are clear patterns in localized studies. As in Figure 12, we observe that DGI\textsubscript{China} has a quadratic relation to window sizes. Glare becomes worse as windows become larger but only up to a point, and becomes better again as windows continues to be enlarged from that point. The subsets of data show...
very clearly that this point of optimality occurs at different points for different types of spaces.

Figure 12 Subgroups of simulation data sorted by spatial attributes

This finding is interesting in that it at once negates rule-of-thumb generalities but posits clear optimization possibilities in instantiated cases. In other words, the data does not guide design synthesis but clearly helps design optimization.

DISCUSSIONS AND CONCLUSION

With APIs and BIM data export capabilities, CAD and BIM tools are increasingly easy to modify to achieve necessary workflows and tasks for glare evaluation in industry. The new $\text{DGI}_{\text{China}}$ glare metric requires computation not supported by existing glare tools, and this research develops a new software to automate such computation. By leveraging on existing BIM and simulation tools research, this research is able to reuse and extend existing software libraries and achieve a quick development time.

Besides practical ease-of-use in industry, the new $\text{DGI}_{\text{China}}$ software enables future research into better understanding and benchmarking the $\text{DGI}_{\text{China}}$ scale, establishing appropriate protocols for its usage, as well as directing efforts in BIM development for generality and sustainable usage.

Setting Standards

It is imperative when developing standards to thoroughly investigate the protocols and ensure that the standard is feasible, and effects desired design changes or impacts. In the case of glare, thresholds for comfort are well accepted, as is the rule of thumb that a lower ratio between window luminance and adaptation levels lowers glare. While instituting a glare standard in China is commendable, there is yet to be publicly available comprehensive studies to facilitate understanding on the overall implication of standard, especially about the changed glare parameter. With an automatic tool, it is possible to gain more insight and establish succinct protocols. Using large sets of simulations, China climatic data, reference buildings representing typical local designs and construction, the following research areas can be further investigated:

- Reasonable and feasible protocols considering practicality in usage, rule sets to determine the minimally sufficient number of rooms, location of rooms in buildings, and position of views in rooms, to characterize the level of glare quality in an entire building.
- Examining the effectiveness of preferred window locations and sizes in the glare standard.
- Comparing the applicability of $\text{DGI}_{\text{China}}$ for typical China buildings against international metrics and other performance standards within the China green building standard.
- Identifying cost benefits and the anticipated design impact of $\text{DGI}_{\text{China}}$ to the China green building standard.

Departure from Established Glare Definitions

$\text{DGI}_{\text{China}}$ departs significantly from established glare analyzes in two ways: the inclusion of all visual scenarios in the metric scale, and the protocols by which glare is considered.

As mentioned in introduction, $\text{DGI}_{\text{China}}$ disregards the conventional definition of glare sources determined by adaptation levels, and uses the average brightness of windows. This means that windows that are not excessively bright and not considered glare sources in established glare metrics would yield non-zero results in $\text{DGI}_{\text{China}}$. In the experiments above that attempts to consider typical visual experiences in reality, we note that the $\text{findglare}$ program in RADIANCE often omits windows that are included in $\text{DGI}_{\text{China}}$. Given this fundamental difference, it can be confusing and futile trying to draw parallels between DGI and $\text{DGI}_{\text{China}}$.

Although the mean window brightness instead of maxima values is used, underestimating the likelihood of glare is very unlikely insofar as considering typical interior scenes that $\text{DGI}_{\text{China}}$ is designed for and the experiments presented above attempt to consider. Considering the view from interior spaces would typically be near horizon (as indicated by the outer rings in Figure 13), the luminance difference across the window would not be significant.

This consideration highlights the second significant departure from established analyzes: the sky model protocol. Glare analyzes typically assume typical and worst case scenarios. But as discussed earlier, the existing China standard sky model is a cloudy sky. Considering the sky luminance (left side of Figure 13) of typically visible sections to be only around 4000cd/m² and window glass transmittance to be less than 0.7, the indicative brightness of windows would be less than 2800cd/m², below the “Slight Perception” glare threshold in Table 1. This explains the results presented earlier that the thresholds require reexamination. As the established thresholds have empirical origins and $\text{DGI}_{\text{China}}$ is a result of a theoretical sky model that is defined with other policy-related considerations, there is a gap between the two. It is thus necessary to calibrate either the scaling coefficient of $\text{DGI}_{\text{China}}$ (0.48 in equation 2), or the thresholds in the $\text{DGI}_{\text{China}}$ scale (lowering the limits).
Further research could be conducted to identify the most appropriate sky model, which might not significantly affect the conclusions in this paper. Barring protocol changes in view positions and directions, the sky luminance of typically visible sections of two the sky models are similar as shown in Figure 13 above.

**Extensibility andSortable Spatial Topology**

It is obvious that simply examining generic building geometries without parametric interrelationships among them will be computational intensive. For instance, ray casting and intersection tests are very effective way of identifying locations of geometric objects; yet they are very expensive in light of computation and thus less efficient. Alternatively, we can impose a strictly defined hierarchical structure, such as IFC—Industry Foundation Class, to regulate all geometrical objects. In doing so, an ideal BIM model will be acquired and therefore provides advantages to infer useful analytics. However, current schemas, to most extent, recognize merely physical building products and object-level dependencies, which are not sufficient to represent abstract spatial topologies. In our above-mentioned project, we had to extend gbXML to distinguish “external” windows. This albeit provides a very efficient way of identifying objects of interest, yet less sustainable on an ad hoc basis. For the long term, it is envisaged that a hybrid mode of containing both object-level dependencies and space-level correlations is deemed as a necessary step towards sustainable development catering to unforeseen needs and new requirements.

As a general class of problem, we envision new needs and uses for BIM (such as this China standard) would invariably increase and require the BIM standards and protocols to be established. It is envisaged that by extending spatial topological structures, fluid building information exchange can be achieved as needed and appropriate.

**REFERENCES**


