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# A PRELIMINARY EXPLORATION OF DAYLIGHTING SIMULATION IN CHINESE TRADITIONAL SIHEYUAN WITH WINDOW PAPER

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## Abstract

Window paper plays an important role in interior daylighting of Chinese traditional architecture. But there's a lack of attention in the conservation practices of historic buildings, and existing studies rarely focus on the combination of architectural space and window paper using simulation methods. Therefore, this study compares Gaoli paper (typically used as window paper in China) with glass on their daylighting features in Siheyuan – a Chinese traditional folk house, using methods of static and climate based dynamic simulation, assisted by optical measurement and a validation experiment. The result shows that the use of Gaoli paper can help increase the overall uniformity of interior daylighting, and improve the shadow areas near the window, with little loss of light in relatively inner areas. Further studies are still required both in the paper's optical properties and different scenes of daylighting in Chinese traditional architecture.

*Keywords*: Gaoli Paper, Daylighting Simulation, Chinese Traditional Siheyuan

## 1 Introduction

Chinese architecture has gone through a long period of development using paper as its light transmissive material. Compared with a long history of glass using in western countries, dating back to the Middle Ages and becoming popular in the late 16$^{th}$ century, Chinese traditional architecture kept using paper on windows from Tang Dynasty (about 7$^{th}$ century). Not until the 20$^{th}$ century did glass begin to replace window paper widely among ordinary people. Obviously, the use of window paper has a great influence on Chinese traditional architecture, especially on interior luminous environment. But there are no related studies on window paper in China at the moment, especially quantitative ones, which might be a limitation on our comprehension of traditional interior space and the way of using it.

From the perspective of conservation and restoration of historic buildings, the Venice Charter proposed the concept of authenticity for the first time, which was strengthened later in the Nara Document on Authenticity. Accordingly, the authenticity of lighting is also an important part of traditional architecture. However, in the modern practice of conservation, physical restoration has become the mainstream and the lighting factor is generally not valued.

Although there are no useful references about window paper in China, there are actually some related studies carried by Japanese researchers. For example, Miyata (1987) studied the relationship between light and Shoji (traditional Japanese paper screens used as doors), where he measured the illuminance in a room with Shoji. Hirai et al. (2003) measured 10 different types of Shoji paper on their reflectance, transmittance and haze value. But there is a lack of studies applying paper on architectural spaces, and providing convincing quantitative analysis using simulation methods. So this paper could be used as a preliminary reference in the Chinese context to other researchers who work on similar topics. Also, it's the base of further studies on daylighting related issues in Chinese traditional buildings.

This study could also be helpful in lighting designs. A successful design case in the Palace Museum used paper-like glass (see **Figure 1**) to create a uniformly scattered lighting condition, which intended to approach the real atmosphere in ancient times (Feng et al., 2017). Some historical themed exhibitions might also get inspiration from this study.

**Figure 1 – "Paper Glass" used in the Palace Museum (Feng et al., 2017)**

# 2 Pre-simulation experiments

## 2.1 Methods of experiments

### 2.1.1 Measurement of the selected paper

Gaoli Paper was the typical choice in ancient China, both in the Forbidden City and in ordinary folk houses. Ancient Gaoli paper was made of mulberry bark, which is also the ingredient of some Japanese Shoji paper. This study has used a single layer of modern Gaoli paper for both measurement and simulation (see **Figure 2**).

**Figure 2 – Photo of Gaoli paper under sunlight**

There are two primary ways of measuring the optical properties of light transmissive material (Sun et al., 2018). The first divides the reflected or transmitted light flux into two parts: specular and diffuse part. The former quantifies the direct flux, and the latter quantifies the remaining flux as a single value by assuming it contains no directional information. This method is usually used when angular information is not important. The second emphasizes the directional qualities of reflected or transmitted flux, such as the method of Bidirectional Scattering Distribution Functions (BSDF), using a goniophotometer to record angular information.

Window paper can be classified into the type of non-redirecting and forward scattering material (Apian-Bennewitz, 2013). The BSDF feature of such materials consists of bell-shaped functions around the forward direction. So we can make the assumption that the Gaoli paper is close to perfectly diffuse both in reflection and transmission, which is also supported by the result of optical measurement. Moreover, there is also a validation experiment showing convincing results for this assumption, and choosing the first measuring method seems to be a good choice at present. However, a BSDF method still deserves consideration in future studies.

The measurement of transmittance and reflectance of a material can be performed using a spectrophotometer and an integrating sphere. The technical requirements and details of their measurement are described in the International Commission on Illumination (CIE) standard. **Table 1** is an example of the measured data, including 8 parameters every 5nm of the visible light whose wavelengths range from 380 nm to 780 nm.

**Table 1 – Sample optical data of Gaoli paper**

| Wavelength | $R_{f\_total}$ | $R_{f\_diffuse}$ | $T_{f\_total}$ | $T_{f\_diffuse}$ | $R_{b\_total}$ | $R_{b\_diffuse}$ | $T_{b\_total}$ | $T_{b\_diffuse}$ |
|---|---|---|---|---|---|---|---|---|
| 520 | 0,558 | 0,555 | 0,478 | 0,461 | 0,543 | 0,540 | 0,484 | 0,467 |

### 2.1.2 Validation of simulation with paper

A validation experiment between measurement and simulation is also performed to ensure the simulation material is convincing enough for the following simulation. The simulation software is DIVA for Rhino 4.0, which uses Radiance as its calculation engine.

In the simulation part, a CIE 171 standard test case, a box of 4 m × 4 m × 3 m with a centred 1 m × 1 m roof opening, is used in the validation (Maamari & Fontoynont, 2003), in which 8 horizontal calculation points are lined from west to east at the middle of the model, numbered from P1 to P8 (see **Figure 3**). A Perez sky model is used and customized by using the Radiance gendaylit program with inputs (-W option) of direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI). Other inputs include time, latitude, longitude and standard meridian.

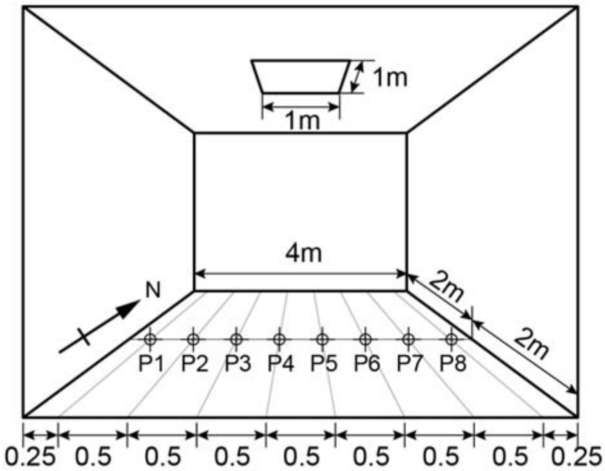



**Figure 3 – Geometry and measurement points of the calculation models**

The measurement was taken on April 18, 2019, in an open square at Tsinghua University, Beijing, China. The measurement used a scale model 1:10 to CIE 171 standard test case, which was made from 5mm thick medium density fiberboards and covered with white cardboard on the interior faces. It was also covered with a shade cloth from outside when measuring, in case light went in through unexpected gaps. The radiation data was measured using a JTTS-01 pyranometer fixed horizontally on a tripod to measure global horizontal irradiance (GHI), as shown in **Figure 4(a)**. And DHI was measured by manually covering the direct sunlight with a shading disc. DNI could be calculated using the equation $GHI = DNI \times \cos\theta + DHI$, where $\theta$ was the solar zenith angle (The National Renewable Energy Laboratory (NREL), 2019). The illuminance inside the model was measured using 8 XY wireless luxmeters, as shown in **Figure 4(b)**. Both radiation and illuminance data were measured every 30 minutes, from 9:30 am to 4:30 pm, obtaining 15 groups of data altogether.

(a) (b)

**Figure 4 – Equipment of measuring radiation (a) and illuminance (b)**

## 2.2 Results of experiments

### 2.2.1 Optical measurement

As shown in **Figure 5**, the diffuse reflectance/transmittance is very close to the total value. All specular reflectance is below 0,01, and all specular transmittance is below 0,02. This result can help to prove our previous assumption that the Gaoli paper is close to perfectly diffuse both in reflection and transmission.

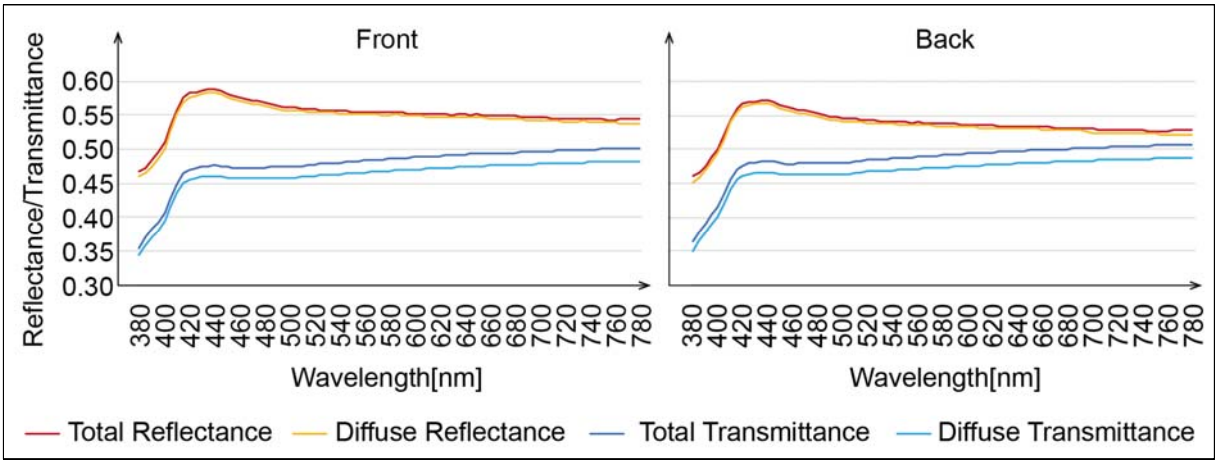



**Figure 5 – Optical measurement results of Gaoli paper**

### 2.2.2 Validation

There were almost half clear and half overcast skies on the day we performed the measurement. It is good evidence to increase the credibility of this validation experiment, in case a single sky type could probably cause significant errors, especially in a dynamic simulation.

To separate the sky model error from the simulation error, a calibration factor is generated by dividing the measured outdoor horizontal illuminance by the simulated outdoor horizontal illuminance (Reinhart & Walkenhorst, 2001). A calibrated illuminance is a result after multiplying with this factor. **Figure 6** compares these 3 values of 8 calculation points during a day. We can see the 2 simulated values are close but both above the measured values. And the calibration factor helps most at 14:30 on values seriously deviating from measured data, but at other times there is no obvious calibration.

Simulation results are considered reliable if the relative mean bias error ($MBE_{\text{rel}}$) is less than 15% and the relative root mean squared error ($RMSE_{\text{rel}}$) is less than 35% (McNeil & Lee, 2013), and in another study these two numbers are 20% and 30% (Reinhart & Breton, 2009). **Table 2** shows the $MBE_{\text{rel}}$ and $RMSE_{\text{rel}}$ between measurement and simulation, with and without calibration. All values of $MBE_{\text{rel}}$ and $RMSE_{\text{rel}}$ are less than 15% and 30%, of which the biggest is 12,4% and 13,9%. There are 7 points holding a lower $MBE_{\text{rel}}$ without calibration, except P3. But there are 6 points holding a lower $RMSE_{\text{rel}}$ with calibration, except P3 and P4. And all $MBE_{\text{rel}}$ is greater than 0, since all simulated values are bigger than measured.

**Table 2 – MBE$_{\text{rel}}$ and RMSE$_{\text{rel}}$ of 8 calculation points**

| | P1 | | P2 | | P3 | | P4 | |
|---|---|---|---|---|---|---|---|---|
| | $MBE_{\text{rel}}$ | $RMSE_{\text{rel}}$ | $MBE_{\text{rel}}$ | $RMSE_{\text{rel}}$ | $MBE_{\text{rel}}$ | $RMSE_{\text{rel}}$ | $MBE_{\text{rel}}$ | $RMSE_{\text{rel}}$ |
| Without Calibration | 5,7 | 10,2 | 10,7 | 13,5 | 9,0 | 12,1 | 5,4 | 13,7 |
| With Calibration | 6,5 | 7,8 | 11,4 | 12,1 | 5,5 | 13,9 | 6.0 | 13,8 |

| | P5 | | P6 | | P7 | | P8 | |
|---|---|---|---|---|---|---|---|---|
| | $MBE_{rel}$ | $RMSE_{rel}$ | $MBE_{rel}$ | $RMSE_{rel}$ | $MBE_{rel}$ | $RMSE_{rel}$ | $MBE_{rel}$ | $RMSE_{rel}$ |
| Without Calibration | 11,6 | 13,8 | 10,7 | 12,3 | 10,4 | 12,2 | 6,3 | 8,9 |
| With Calibration | 12,4 | 12,9 | 11,6 | 12,0 | 11.3 | 11,6 | 7,1 | 7,7 |

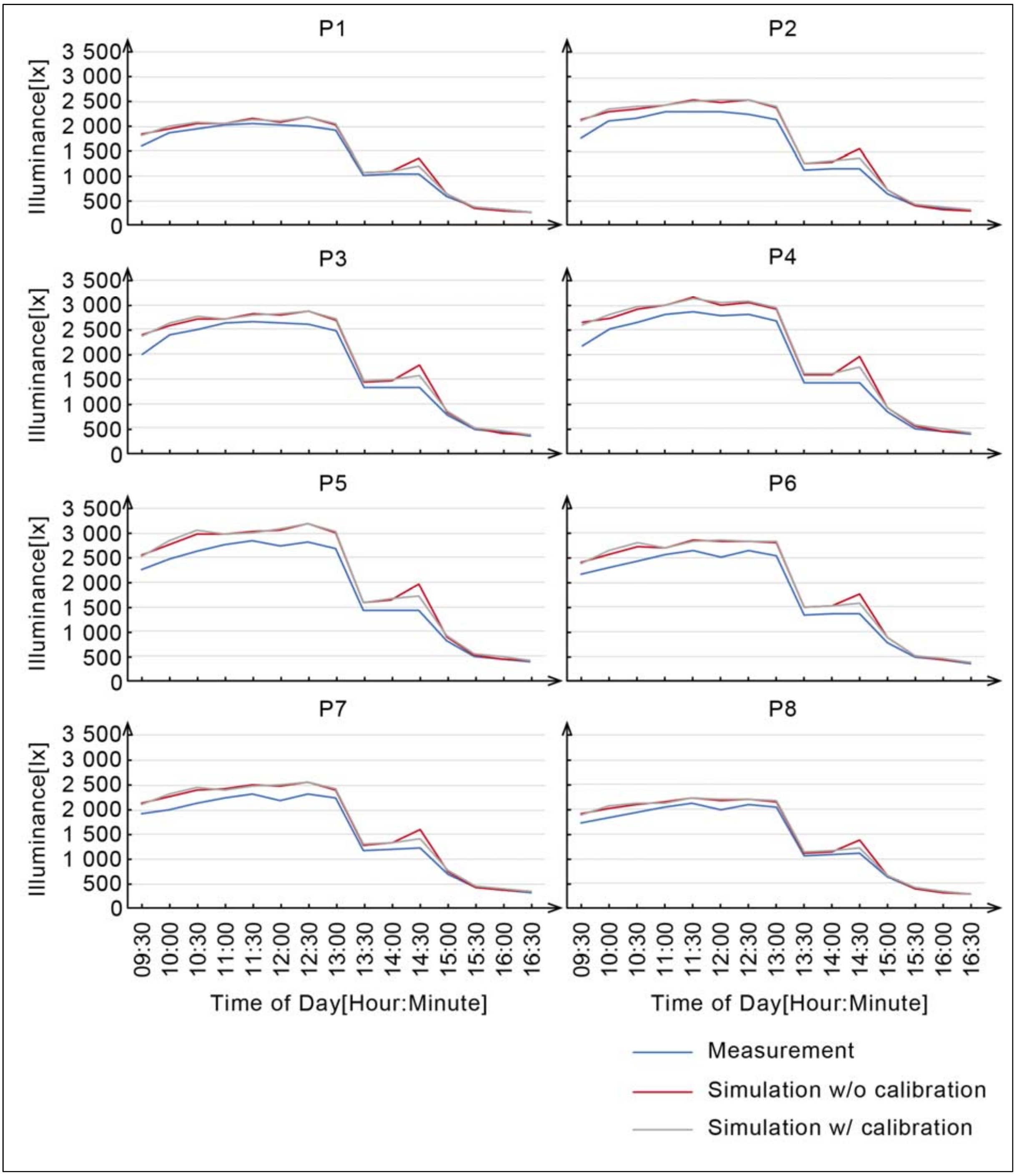



**Figure 6 – Results of the validation experiment**

# 3 Simulation in Siheyuan

## 3.1.1 Model selection

A traditional residential building in Beijing called Siheyuan, meaning a courtyard house, was used in the simulation. The simplest group of Siheyuan contains 4 houses surrounding a central courtyard and facing 4 different directions, of which the main house where the householder lives is usually the one facing south for considerations of lighting, temperature, and Fengshui (Chinese geomancy). A model with a combination of 6 typical courtyards, each 25m × 25m, is used for simulation, of which 1 courtyard and its main room were selected and modeled in detail (see **Figure 7**).

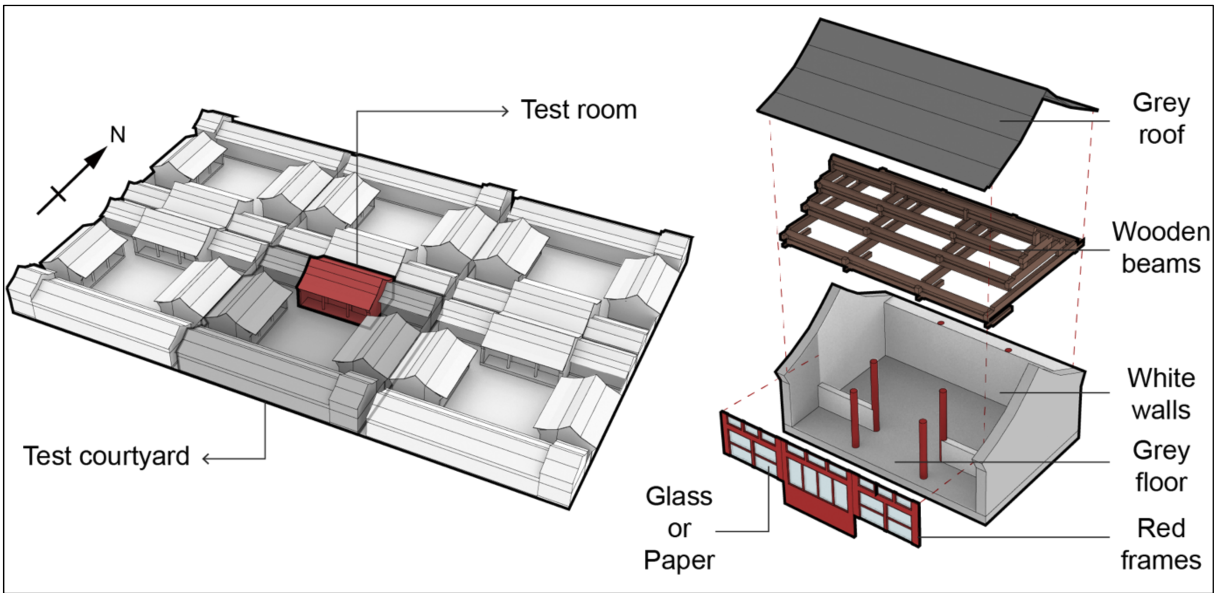



**Figure 7 – Simulation model of test courtyard and test room**

## 3.1.2 Simulation parameters

A Beijing typical year weather data of Chinese Standard Weather Data (CSWD), obtained from EnergyPlus in .epw format, was used in the simulation.

Two light transmissive materials, an 88% transmittance single pane of glass defined using Radiance glass material primitive and a single layer of Gaoli paper defined using Radiance BRTDfunc material primitive, were compared in the simulation. Apart from these two, other interior material of the test room was either measured or estimated by colour to make their reflectance close to materials in a real Siheyuan.

## 3.1.3 Simulation types

A series of static simulations were done under CIE clear sky condition to compare the daylighting features between glass and Gaoli paper on some typical dates and times. The key times selected for the simulations were 9 am, noon and 3 pm on solstice and equinox days. The calculation planes were all 6 interior faces of the test room, of which the sloped ceiling was replaced by a single plane just above the upper windows (see **Figure 8(b)**).

Most importantly, a climate based dynamic simulation was also used to compare the lighting changes over time. Instead of using all faces as calculation planes, 6 horizontal points and 6 vertical points on the north-south axis of the room were used, of which the horizontal points were at the height of 750 mm work plane and the vertical points were at the height of human eyes (see **Figure 8**). In this simulation, the hourly change of the average annual illuminances was calculated for analysis.

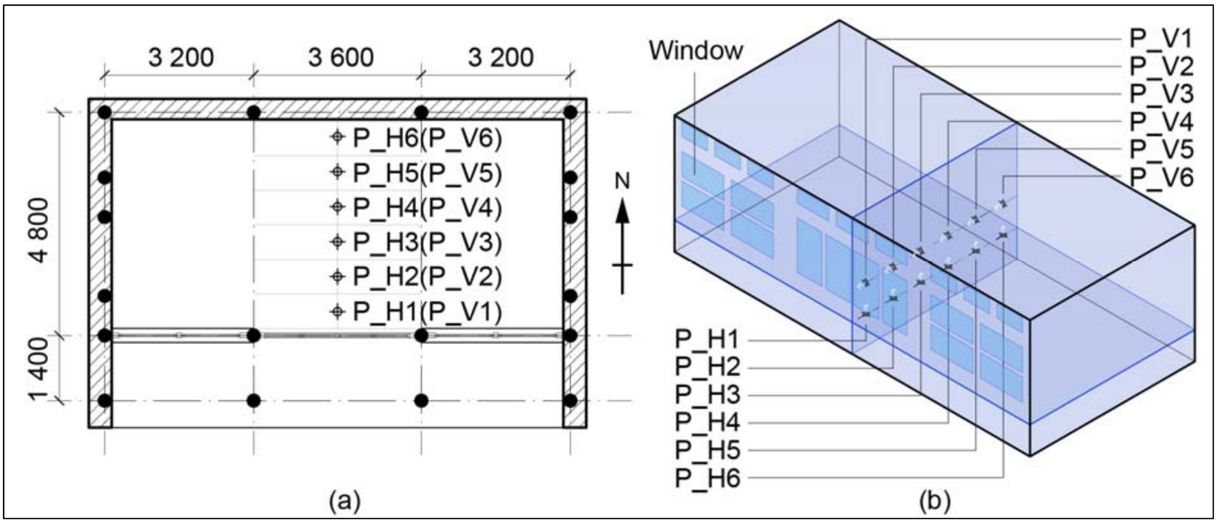
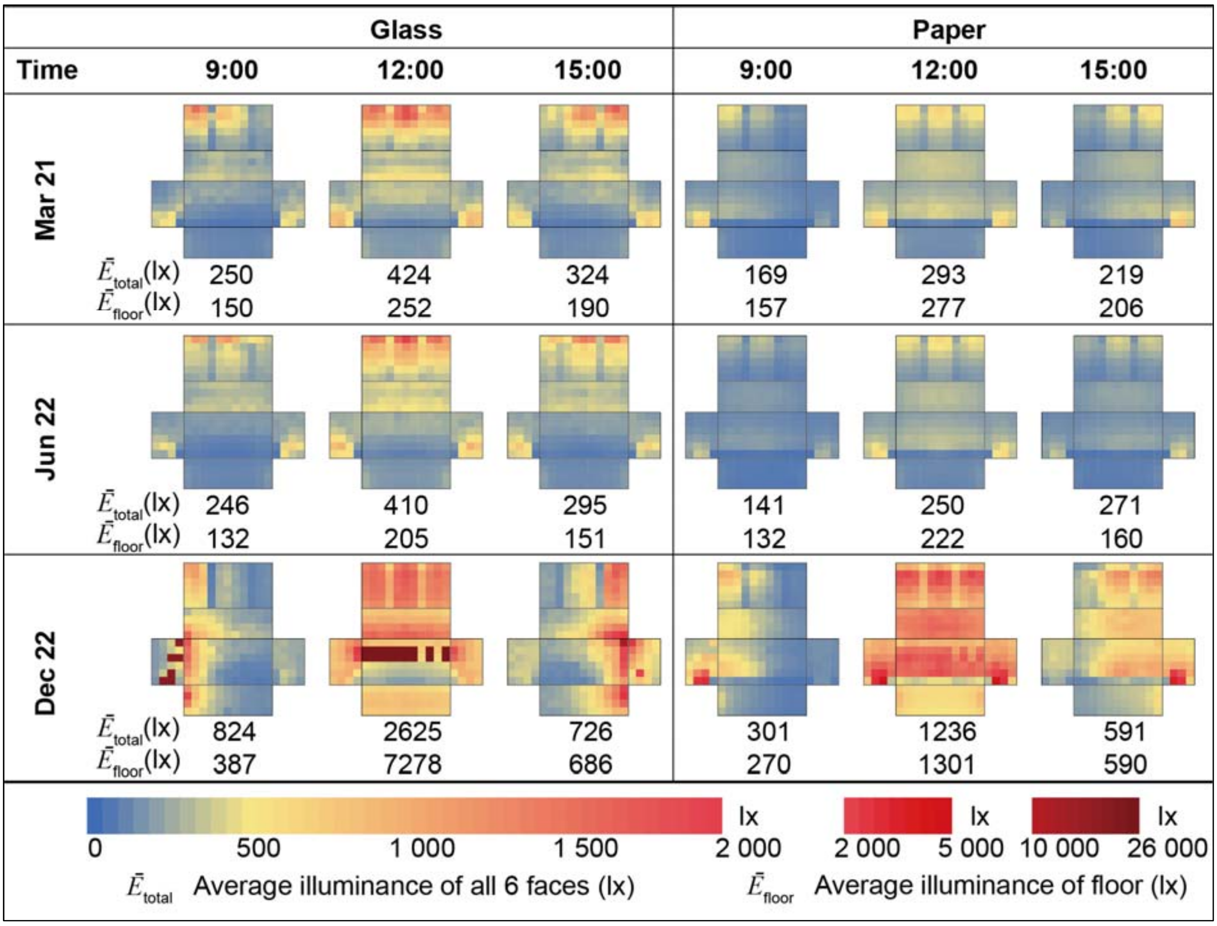



**Figure 8 – Dynamic calculation points and static calculation planes**

## 4 Results

Figure 9 shows the results of static simulations between the use of glass and paper at 9 key times. On March 21 and June 22, the use of paper can obviously increase the illuminance on the floor near the window, but a slight reduction of illuminance also occurs on back walls. The average illuminance of all 6 faces are bigger using glass than using paper, but the average illuminance of the floor reverses. On December 22, paper can help prevent direct sunlight over 10 000 lx from penetrating into the room and improve lighting conditions in areas of floors and back walls which are relatively far from the sun, especially in areas near the window.



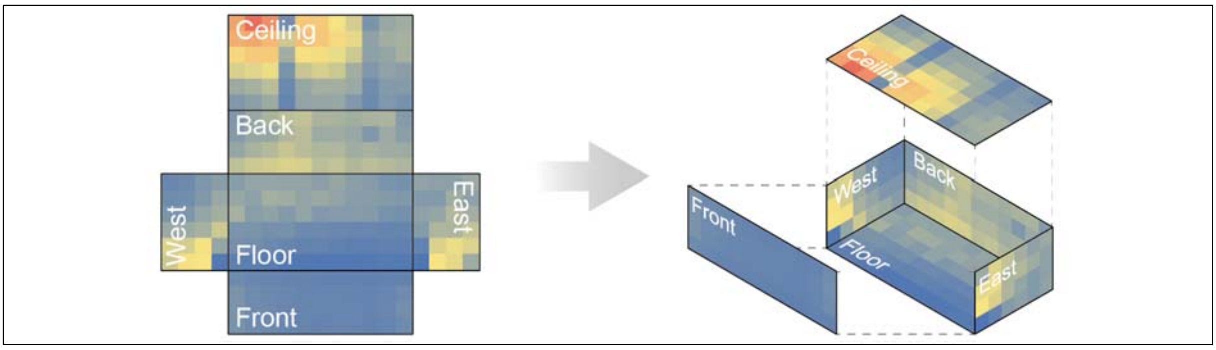



**Figure 9 – Results of static simulations at key times**

**Figure 10** and **Figure 11** show the results of dynamic simulations. We calculated hourly changes of average annual illuminances, by adding all the illuminance values at the same time of a day and dividing them by 365.

From the horizontal points on work plane, we see that P_H2 and P_H3 have illuminances over 2000 lx from 11:00 to 14:00, which could cause visual discomfort as proposed in the Useful Daylight Illuminance (UDI). And there are obvious falls in value at noon of these two points. Of all the points, P_H1 has the lowest value in glass case but has the highest value in paper case. From P_H4 to P_H6, both glass case and paper case have relatively low illuminances, but the differences between them are not significant since the highest illuminances in paper case are all above 300 lx.

As for the vertical points at the height of human eyes, P_V1 and P_V2 in glass case have illuminances over 2 000 lx from 10:00 to 15:00, except 1 value in P_V2 from 11:00 to 12:00, of which the highest is over 10 000 lx. But these values in paper case are relatively low – almost all the illuminances of P_V2 are under 2000 lx, and P_V1 under 4 000 lx. There are also falls in illuminance in glass case at noon, or even longer with P_V2 for 5 hours. As for P_V3 to P_V6, there is much less difference between glass and paper than in horizontal points, even there are times the illuminances of paper case exceed that of glass case in P_V4. But there is more time of illuminance under 100 lx using paper than using glass.

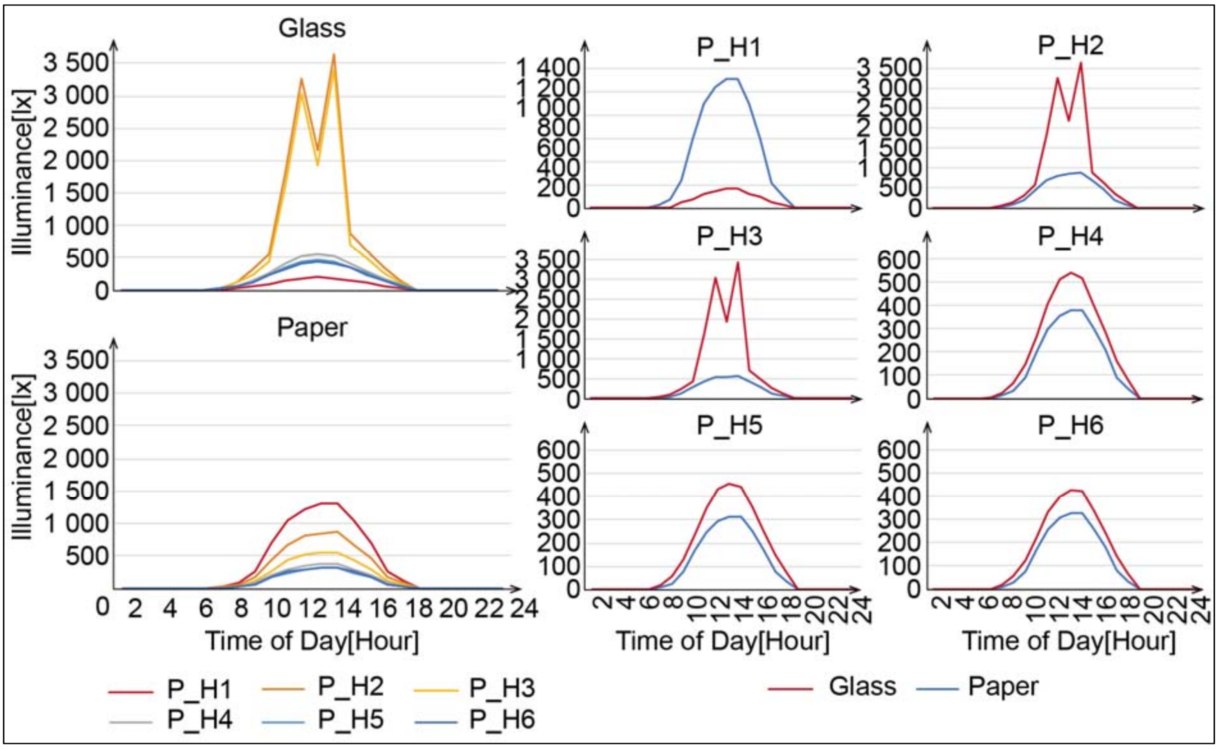



**Figure 10 – Results of dynamic simulation on horizontal work plane**

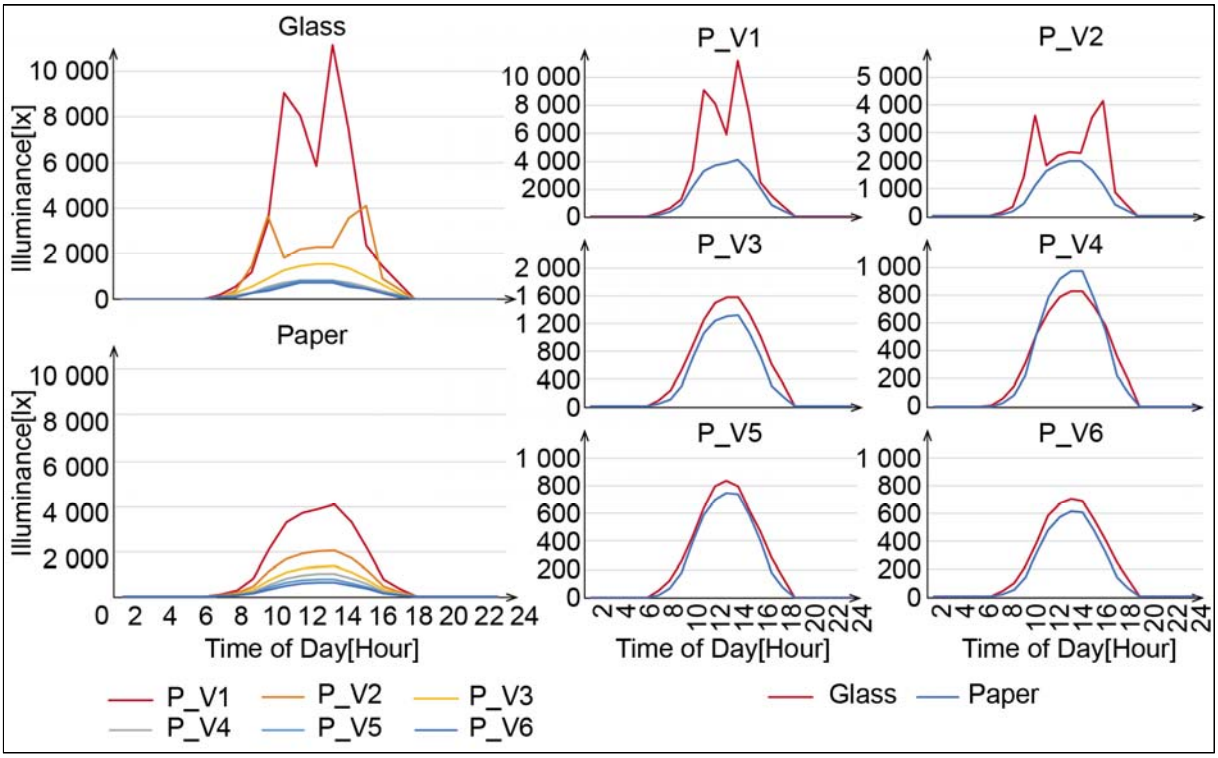



**Figure 11 – Results of dynamic simulation on vertical points of human-eye height**

## 5 Discussions

In the validation experiment, the $MBE$ and $RMSE$ are statistical quantities to characterize the similarity/difference between two data series. The $MBE_{rel}$ indicates the tendency of one data series to be larger or smaller than the other. The $RMSE_{rel}$ indicates how far one data series "fluctuates" around the other (Reinhart & Breton, 2009). Since the $MBE$ and $RMSE$ values of the validation experiment are in the range of the suggested ones, we could consider the results of later simulations in Siheyuan to be reliable. Moreover, $MBE_{rel}$ greater than zero indicates an identical tendency that simulated data is bigger than measured data, from the graph of **Figure 8** we could get the same conclusion. However, this conclusion contradicts with the study of Thanachareonkit et al. (2005) that (measurement in) a scale model shows a general trend of overestimation. This difference may occur for the following reasons: errors occured from measurement of solar radiation especially diffuse radiation; the physical model was too small that the size of the wireless luxmeters could not be ignored; a side window in the model, which was closer to a real condition, was not taken into consideration in the current experiment. Therefore, a follow-up experiment is required for more accurate and convincing results.

The static simulation shows that the use of Gaoli paper can help prevent direct sunlight from penetrating into the room and reduce the highest illuminance to an acceptable level. Also, paper improves the lighting condition in shadow areas such as areas on the floor near the window, which indicates a better lighting uniformity.

From the dynamic simulation on horizontal work plane, using glass could bring about the darkest area near the window while the neighboring areas are brightest, which would cause a big contrast between light and dark, leading to a possible visual discomfort, and bad spatial recognition. The illuminance fall at noon might result from the shading of the eave. By contrast, in paper case, the area near the window is the brightest and light fades going deeper – the shadow area is improved. But even deep into the room, there's a relatively small loss of light compared with glass case. And illuminances of all points are below 1 500 lx, which may bring more visual comfort. Paper can also be free from the shading of the eave, with no illuminance falls at noon. Compared with horizontal results, vertical simulation at human eyes height shows a much smaller difference between glass and paper. There exists an issue of over brightness in the front areas near the window using glass, while paper can reduce these high illuminances to a reasonable degree. The deeper part is still satisfying and even a little better in certain areas to use paper than glass. But what must be pointed is that there are more times like early morning and late afternoon where illuminance is lower than 100 lx using paper.

## 6 Conclusions

This study is a preliminary exploration of daylighting in Chinese traditional Siheyuan with Gaoli paper, compared with that with ordinary clear glass. Firstly, a validation experiment was performed to ensure the material definition used in the later simulation to be reliable. The result turns out pretty good but still needs further study to improve current defects. Secondly, before the dynamic simulation, a static one was performed on all 6 interior faces at 9 key times, including a ceiling plane close to the original sloped ceiling. It finds that paper can help increase the uniformity of interior lighting, and improve low light areas especially those on the floor near the window. A direct sunlight penetration is also sheltered and the highest levels of illuminance are decreased into visually acceptable ones. Finally, the dynamic simulation shows that paper is also useful in improving the work plane’s shadow area near the window, and free from the shading effects of eaves, keeping a continuous change in illuminance during a day both horizontally and vertically. Inner areas could also get a reasonable amount of light using paper, even a slight improvement can be expected in the middle of the room vertically. But still, these findings are at a very preliminary stage of excavating the complete optical features of window paper used in traditional buildings, which may refer to issues of surroundings, details of the window structure and different types of architecture. The follow-up studies may in return help in fields of similar material research, lighting design and conservation of historic buildings.

## 7 Acknowledgements

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