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Daylighting Performance of CdTe Semi-Transparent Photovoltaic Skylights with Different Shapes for University Gymnasium Buildings

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Abstract: The daylighting environment in university gymnasiums affects daily teaching and sports training. However, direct sunlight, glare, and indoor overheating in summer are common problems. Semi-transparent photovoltaic glass can solve these issues by replacing shading facilities, blocking solar radiation, and generating electricity. This study examines the influence of different types of CdTe semi-transparent film photovoltaic glass on the daylighting environment of six typical university gymnasium skylights. The optimal types of CdTe semi-transparent film photovoltaic glass are determined by dynamic daylighting performance metrics DA, DAcon, DAmax, and UDI. The results show that, for instance, centralized rectangular skylights benefit from the 50–60% transmittance type, while centralized X-shaped skylights require the 70–80% transmittance type to enhance indoor daylighting. The research results offer specific recommendations based on skylight shapes and photovoltaic glass types and can provide a reference for the daylighting design of university gymnasium buildings with different forms of photovoltaic skylights in the future.

Keywords: university gymnasium; daylighting; dynamic daylighting performance; skylights; BIPV

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1. Introduction

According to statistics, by 2021, there will be a total of 3012 higher education institutions in China, including 2756 universities (1270 universities, 1486 junior colleges) and 256 adult education institutions. To meet the daily physical education and training needs, most colleges and universities build gymnasiums according to national standards. The daylighting environment in the gymnasium is an important factor influencing people's activities [1]. Some studies show that 80% of the information obtained by the sports crowd comes from the visual information caused by the daylighting environment [2]. At the same time, the university gymnasiums not only provide the venue for physical education activities in colleges and universities but also sometimes host some international competitions. For example, some of the venues for the 2008 Beijing Olympic Games are set in several university gymnasiums in Beijing, which has higher demands on the quality of the daylighting environment in the gymnasium. The university gymnasium is a tall space building with a large depth. In order to meet the daylighting requirements, it is necessary to set up openings for daylighting. The main daylighting methods include side window daylighting, skylight daylighting, and side window skylight co-daylighting [3,4]. Although the window structure improves the indoor illumination level, it will bring problems such as direct sunlight and glare. Also, it can cause indoor overheating in summer and increase building energy consumption [5–7].

Most of the studies on the light environment aspects of gymnasium buildings mainly use a single window form and mainly consider the impact on the indoor environmental objectives by changing parameters such as building shape, shading parameters, window sizes and materials, and lack of studies on the light environment aspects of gymnasiums with different shapes of skylights [1,8–10], and there is a lack of research on different shapes of skylight gymnasiums in terms of the light environment.

Flat skylight is the most commonly used skylight in university gymnasiums, with high lighting efficiency, uniform illumination distribution, flexible layout, and low glare probability. The layout is mainly divided into centralized and uniform distributed skylights; centralized skylights include centralized rectangular skylights, centralized ribbon skylights, and centralized X-shaped skylights; uniform distributed skylights include distributed rectangular skylights, distributed vertical strip skylights, and distributed horizontal strip skylights, as shown in Figure 1 [3]. For the above different types of skylights, it is necessary to study their impact on the lighting performance of gymnasium buildings so as to make up for the deficiency in the study of the gymnasium light environment.

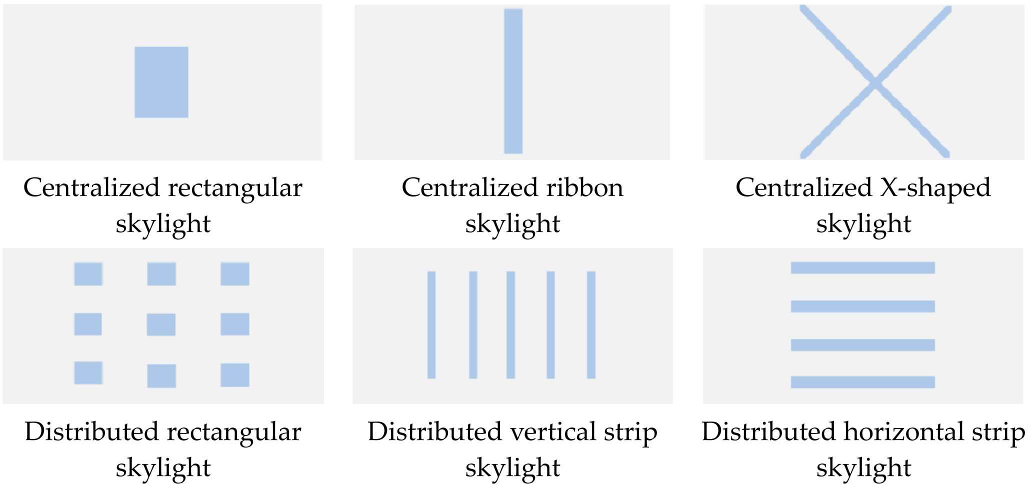

Figure 1. Skylight layout.

Building integrated photovoltaic (BIPV) is a technology that integrates solar power generation products into buildings [11–13]. As a part of the external structure of the building, BIPV not only has the function of generating electricity, but also has the function of building components and materials. It can also improve the beauty of the building and form a perfect unity with the building. As a form of BIPV, solar photovoltaic glass can replace sunshade facilities to solve the problem of indoor glare caused by direct sunlight. Its semi-transparency also blocks a certain amount of solar radiation into the room, alleviates the phenomenon of indoor overheating in summer, and reduces summer cooling power consumption; the electricity generated can be used for the building itself or the use of the grid, with great energy saving potential. For instance, in the China National Stadium, one of the three main venues for the 2008 Beijing Olympics, 24 solar photovoltaic glass panels are installed on its roof, with a rated output of 100 kW per day, reducing CO_2 emissions by about 94 tons per year. With the progress of photovoltaic technology and the promotion of building energy conservation, solar photovoltaic glass is very likely to be applied to the skylight and glass curtain wall structure of the university gymnasium. However, the existing research on photovoltaic glass modules is mainly focused on energy conservation [14–22], and the research on indoor daylighting environments of buildings rarely involves university gymnasiums [23–27]. It is not known whether the actual illumination level of solar photovoltaic skylights applied in university gymnasiums can meet indoor daylighting requirements.

In the past 20 years, research has mainly focused on glare and illuminance to establish reliable indicators for assessing visual comfort [28–31]. Currently, the daylight factor (DF) static index is widely used in China's architectural daylighting design field to evaluate indoor daylighting under ideal CIE cloudy conditions [32]. However, this type of lighting assessment presents static characteristics, merely reflecting the illumination levels of a specific day. It fails to capture the variations occurring at different times and seasons, thereby limiting the evaluation of building illumination [33]. Based on the development of Climate-Based Daylight Modeling (CBDM) [34], dynamic daylight metrics have been introduced to assess the annual daylighting performance and are widely adopted worldwide. Daylight Autonomy (DA) and Useful Daylight Illuminance (UDI) have been proposed as dynamic metrics to quantify the amount of daylight [29]. However, due to issues such as insufficient lighting and excessive glare, two dynamic daylight metrics, Continuous Daylight Autonomy (DAcon) and Maximum Daylight Autonomy (DAmax), are also introduced for comprehensive analysis of indoor lighting conditions.

DA measures the proportion of time that a point in the building meets the minimum illumination requirement throughout the year. DAcon quantifies the degree of insufficient lighting below the minimum requirement. DAmax describes the possibility of glare generation with 10 times the minimum daylighting illumination as a reference value [35]. UDI measures the proportion of time that a point in the building is in the effective utilization range during the operating period of the year. Nabil [35] studied building daylighting environments and categorized indoor illuminance levels into three intervals using 100 lx and 2000 lx as thresholds. Illumination below 100 lx is considered too low for visual activities, while illumination between 100 lx and 2000 lx is considered moderate. Illumination exceeding 2000 lx may cause visual discomfort.

Based on the above four dynamic daylighting evaluation indexes, this paper conducts dynamic daylighting simulation for six skylight forms common in university gymnasiums, explores the influence of different types of CdTe thin film photovoltaic glass on building daylighting, and makes the optimal selection. The noteworthy contributions of this study extend beyond the elucidation of optimal photovoltaic glass types. By placing emphasis on skylight shapes and their specific requirements, our research provides architects and researchers with concrete recommendations for informing the daylighting design of university gymnasium structures.

2. Methodology

Firstly, the typical university gymnasium and skylight with different shapes are modeled, and the material and boundary conditions of the envelope structure are set. Secondly, the simulation software is used to simulate the dynamic daylighting of CdTe thin film photovoltaic glass of different transmittance types, and the indoor daylighting environment is analyzed by obtaining the dynamic daylighting index value. Finally, the most optimal type of CdTe thin film photovoltaic glass for skylights with six shapes is summarized. The methodology is presented in Figure 2.

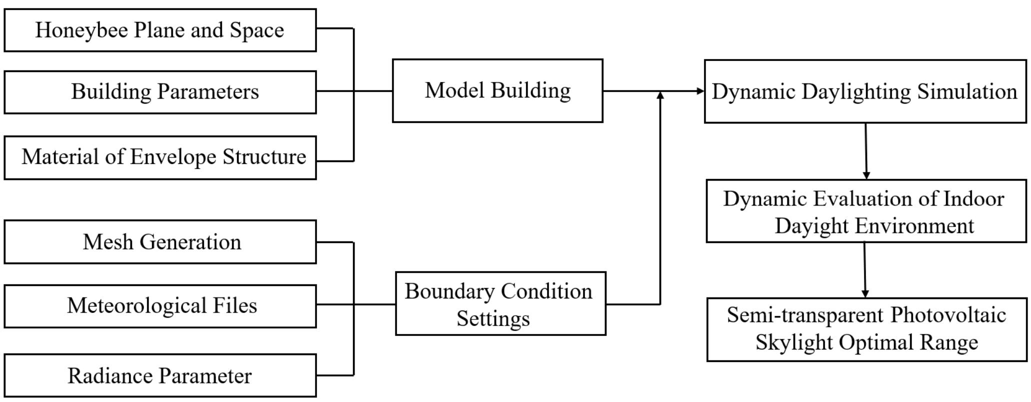

Figure 2. Steps involved in the methodology.

The basic building is modeled using Rhinoceros 3D software (version 7.4) [36] and imported to Ladybug and Honeybee plug-in [37] for Grasshopper for dynamic daylighting simulation and assessment for the actual design. Parameters such as the geometry, size, and location of the skylight are taken into account in the gymnasium model building, and accurate material properties are set in the model to ensure that the simulated results match the actual environment. The Grasshopper parametric tool [38] has been used to model the skylight and provide multiple variations for the skylight shape.

After completing the creation of the parametric model, we use the Honeybee plug-in to perform detailed model property settings, which include the precise definition of the materials for the building envelope and skylight. In this process, we pay special attention to the optical properties, reflectance, and glazing transmittance of the building envelope and skylight materials. We further proceed with the detailed setup of the simulation boundary conditions. This step covers the generation of the simulation mesh, the setting of the simulation parameters, and the use of the meteorological file. Ladybug reads imported meteorological files, correlates Radiance with a parameterized platform through the Honeybee interface plug-in, generates the simulation mesh and inputs set parameters into simulation analysis software, and gets visualization data results after calculation.

Dynamic daylighting simulations for different scenarios are carried out using Ladybug and Honeybee plug-ins. The aim of this phase of the simulation is to evaluate the dynamic daylighting performance of CdTe thin film photovoltaic glass in different skylight forms with different transmittance types and to analyze its impact on the indoor daylighting environment. Through this process, we obtain key data, such as the dynamic daylighting indexes, which are used to quantitatively evaluate the practical effectiveness of different transmittance types of CdTe thin film photovoltaic glass in a typical university gymnasium. This provides an important basis for our subsequent summary of the optimal CdTe thin film photovoltaic glass types.

Finally, a comprehensive assessment of the indoor daylighting environment is carried out using dynamic daylighting metrics. This dynamic assessment involves comparing the performance of CdTe thin-film photovoltaic glass under six different skylight forms to determine the optimal type of CdTe thin-film photovoltaic glass.

2.1. *Software Introduction*

In this study, the building was modeled parametrically in the Rhino and Grasshopper. Grasshopper is a visual programming plugin and one of the leading software tools in the field of parametric design. We carried out the dynamic daylighting simulation of the university gymnasium by the Ladybug and Honeybee component, a free and open-source simulation plugin based on Grasshopper. The core of daylight simulation in Honeybee is primarily based on the Radiance. Radiance is a validated daylighting simulation engine that employs a backward raytracing algorithm created by Greg Ward at Lawrence Berkeley National Laboratory [39]. The accuracy of building performance simulation software has been verified in detail by predecessors [40].

2.2. *Photovoltaic Glass Properties*

Solar photovoltaic glass mainly includes crystalline silicon photovoltaic glass [41] and thin film photovoltaic glass. Crystalline silicon photovoltaic glass is composed of photovoltaic cells and tempered glass; the internal photovoltaic cell is not transparent; by controlling the cell gap and edge gap between the double-sided glass to control the sunlight transmittance, crystalline silicon photovoltaic glass is easy to cause indoor illumination uneven. Thin film photovoltaic glass includes silicon thin film type [42], compound semiconductor thin film type [43], new material thin film type battery [44], etc. A nano Cadmium telluride solar cell (CdTe) is a thin-film solar cell based on the heterogeneous combination of P-type CdTe and N-type CdS. Compared with traditional solar products, CdTe has better low-light performance and higher conversion efficiency. Products with different light transmittance can be made by laser etching, and the structure is shown in Figure 3.

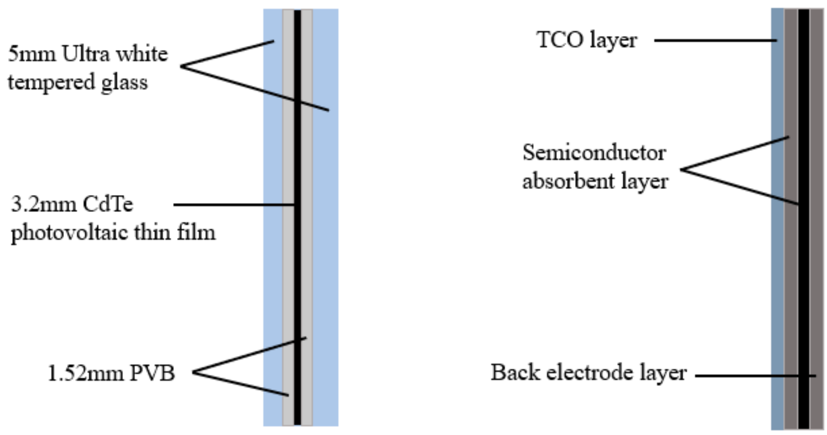

Figure 3. Structure of CdTe power generation glass and CdTe power generation film.

In this paper, CdTe thin film photovoltaic glass is taken as the research object to explore the influence of different types of thin film photovoltaic glass on indoor daylighting in the university gymnasium. The CdTe thin film photovoltaic glass of 10–80% transmittance type is set, and the step size is 10%, corresponding to a 90–20% power generation thin film coverage area ratio, respectively. The minimum coverage ratio of power generation film is set at 20% because the photovoltaic glass with lower film coverage has too low revenue. In the following content, 10–80% CT is used to represent the CdTe thin film photovoltaic glass of 10–80% transmittance type, respectively. Based on the hypothesis of Miyazaki [45] on thin film photovoltaic cells, the transmittance, thickness, and other parameters of front and rear panel glass are input into the software Window 7.7, and the photothermal properties parameters of CdTe thin film photovoltaic glass of different transmittance types are obtained, as shown in Table 1.

Table 1. Photothermal properties parameters.

Photovoltaic Glass Type	Subsequent Name	Visible Transmittance	Shading Coefficient	Solar Heat Gain Coefficient
10% transmittance type	10% CT	0.091	0.418	0.363
20% transmittance type	20% CT	0.181	0.48	0.417
30% transmittance type	30% CT	0.272	0.541	0.471
40% transmittance type	40% CT	0.363	0.603	0.524
50% transmittance type	50% CT	0.454	0.664	0.577
60% transmittance type	60% CT	0.546	0.725	0.631
70% transmittance type	70% CT	0.637	0.786	0.684
80% transmittance type	80% CT	0.729	0.848	0.738

2.3. Model Parameter

According to the field survey and data analysis of 29 university gymnasiums in China by predecessors [3] and the Gymnasium Design Standard (JGJ31-2003) [46], the simulated building, oriented with its long side facing east-west and short side facing north-south, has a plane size of a 46 m $\times$ 70 m rectangle. The competition area within this rectangle measures 38 m $\times$ 44 m, and the building has a height of 18m with fixed stands on both sides. No side windows were considered, and a gymnasium with an integrated skylight was modeled to accurately represent the daylighting conditions. The simulation location is set in Beijing, located in the Chinese daylighting climate zone III. Table 2 shows the natural light utilization hours and design illuminance in different daylighting climate zones.

According to China National Standard for Daylighting Design of Buildings (GB50033-2013) [47], for daylighting in class III climate zones and buildings with daylighting grade IV, the skylight ratio of glazing to floor area is set at 1/13, to calculate the area covered by the glazing, this ratio is multiplied by the floor area. In our case, the floor area is 3220 square meters, and the calculated glass area for each of the six skylight shapes is approximately 248 m^2. The indoor interface reflectance is also set according to the real utilization condition, as shown in Table 3.

Table 2. Hours of natural light utilization in different climatic zones.

Daylighting Climate Zones	Number of Stations (lx)	Annual Average Total Illuminance (lx)	Design Illuminance of Exterior Daylight (lx)	The Number of Hours of Natural Light Utilization for Design Illuminance (h)	Critical Illuminance of Exterior Daylight (lx)	The Number of Hours of Natural Light Utilization for Critical Illuminance (h)
I	29	48,781	18,000	3356	6000	3975
II	40	42,279	16,500	3234	5500	3921
III	71	37,427	15,000	3154	5000	3909
IV	102	32,886	13,500	3055	4500	3857
V	31	27,138	12,000	2791	4000	3689

Table 3. Indoor interface reflectance.

Type	Material	Reflectance
Ceiling	Concrete and steel construction	0.2
Wall	White paint	0.75
Floor	Light color wood floors	0.58

2.4. Simulation Parameter Settings

Based on the China National Standard for Daylighting Design of Buildings (GB50033-2013), the minimum illuminance level of the gymnasium in the form of top lighting is set at 150 lx. The height of the calculating plane is set as 1.5 m above the ground to be closer to the real illumination of the human eye, and a 1 m × 1 m grid is set on the calculating plane, resulting in a total of 1748 grids, the 3D image of the reference plane grid is shown in Figure 4. Other relative simulation parameters for RADIANCE are set in Table 4. Ambient bounces represent the number of reflections between the surfaces. Ambient divisions and super-samples set the number of samples sent. Ambient resolution deals with the maximum error, scene dimension, and the sampling cutoff point. The ambient accuracy (-aa) is usually set to 0.1 to 1, and lower numbers result in better accuracy. The daylight simulation quality defined in Honeybee is set to a value of 1, which corresponds to medium quality.

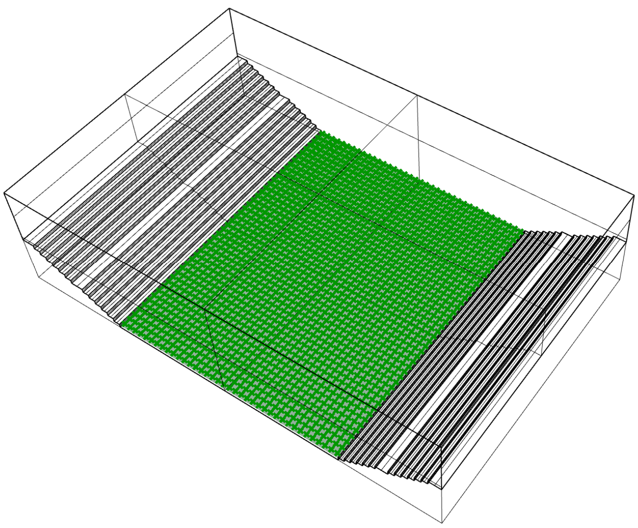

Figure 4. Plane grid diagram (green area represents the plane grid).

Table 4. Environment parameter settings.

Parameter	Setting Value
Quality	1
Ambient bounces	5
Ambient divisions	2048
Ambient super-samples	512
Ambient resolution	512
Ambient accuracy	0.08

Table 5 presents the primary analysis options for the simulations. Based on the above-mentioned preset simulation conditions, a comprehensive simulation analysis study was conducted on the indoor lighting environment with different application scenarios of CdTe thin film photovoltaic glass.

Table 5. Analysis settings in RADIANCE.

Parameter	Setting Value
Occupancy schedule	8:00–18:00
Minimum illumination	150 lx
Grid size	1 m × 1 m
Number of grids	1748

3. Results and Discussions

3.1. DA Analysis of Six Shapes of Skylights

The average DA variation curves and varying ranges of DA of six shapes of skylights under the condition of 10–80% CT photovoltaic glass are shown in Figure 5. The average DA is obtained by calculating the average of all measuring points on the calculating plane. A higher average DA in the upper part of the range suggests that there are more measuring points with adequate daylighting, while a lower average DA in the lower part of the range indicates that there are more measuring points with inadequate daylighting. Moreover, the average DA of the six skylight shapes increases as the transmittance of the CT photovoltaic glass increases.

During the working period from 8 am to 6 pm, when the measured DA is less than 25%, daylighting is considered very poor; when the measured DA is between 25% and 55%, daylighting is considered insufficient; when the measured DA is between 55% and 75%, daylighting is considered acceptable; when the measured DA is above 75%, daylighting is considered ideal [48].

From Figure 5, it can be seen that for the centralized rectangular skylight, distributed horizontal strip skylight, and distributed vertical strip skylight, when the photovoltaic glass is 80% CT, all of the measured DA value is above 75%; for the distributed rectangular skylight and centralized ribbon skylight, when the photovoltaic glass is 70–80% CT, all of the measured DA value is above 75%; for the centralized X-shaped skylight, there is no such situation where the DA value of all the measuring points is above 75%. Compared with distributed skylights, the DA value of centralized skylights has a wider range. The reason is that some areas are far from directly under the skylight, and the lighting quality in these areas differs greatly from that directly under the skylight.

To better analyze the indoor daylighting situation of the gymnasium, the detailed DA values of the six kinds of skylights are shown in Tables 6–11. DA $\geq$ 75%, 55% $\leq$ DA < 75%, 25% $\leq$ DA < 55%, and DA < 25% represent the proportion of measuring points that meet the requirements of their respective DA to all measuring points.

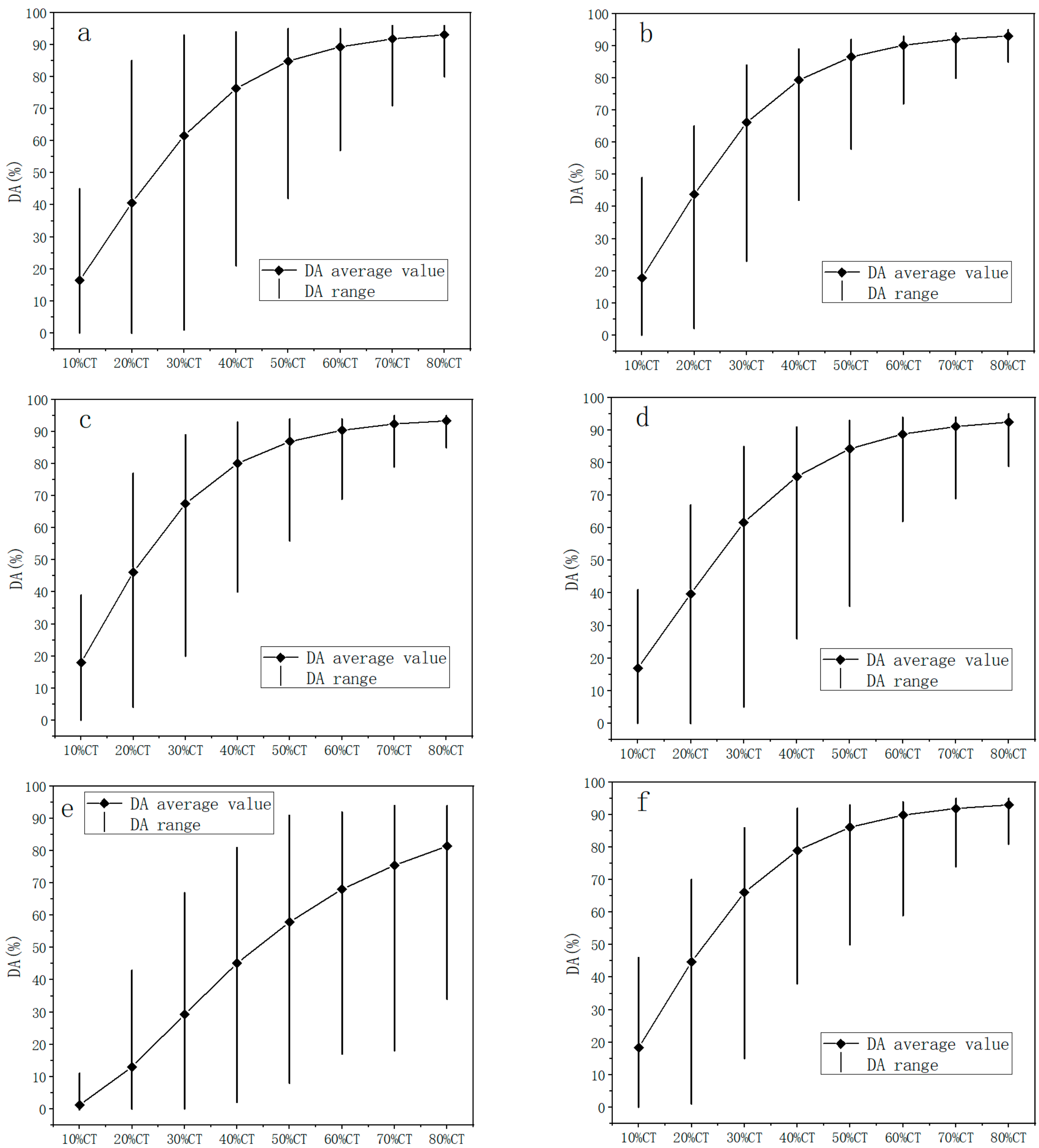

Figure 5. DA curves of six kinds of skylight: (**a**) centralized rectangular skylight; (**b**) distributed rectangular skylight; (**c**) centralized ribbon skylight; (**d**) distributed vertical strip skylight; (**e**) centralized X-shaped skylight; (**f**) distributed horizontal strip skylight.

Table 6. Detailed data of DA for a centralized rectangular skylight.

Type	Centralized Rectangular Skylight			
	DA ≥ 75%	**55% ≤ DA < 75%**	**25% ≤ DA < 55%**	**DA < 25%**
10% CT	0%	0%	30.55%	69.45%
20% CT	9.55%	21.4%	42.91%	26.14%
30% CT	34.5%	31.35%	25.57%	8.58%
40% CT	61.04%	27.8%	10.87%	0.29%
50% CT	83.06%	14.82%	2.12%	0%
60% CT	95.54%	4.46%	0%	0%
70% CT	99.6%	0.4%	0%	0%
80% CT	100%	0%	0%	0%

Table 7. Detailed data of DA for a distributed rectangular skylight.

Type	Distributed Rectangular Skylight			
	DA ≥ 75%	55% ≤ DA < 75%	25% ≤ DA < 55%	DA < 25%
10% CT	0%	0%	28.66%	71.34%
20% CT	0%	25.34%	64.87%	9.97%
30% CT	32.44%	49.03%	18.53%	0%
40% CT	73.68%	24.54%	1.78%	0%
50% CT	94.45%	5.55%	0%	0%
60% CT	99.66%	0.34%	0%	0%
70% CT	100%	0%	0%	0%
80% CT	100%	0%	0%	0%

Table 8. Detailed data of DA for a centralized ribbon skylight.

Type	Centralized Ribbon Skylight			
	DA ≥ 75%	55% ≤ DA < 75%	25% ≤ DA < 55%	DA < 25%
10% CT	0%	0%	30.43%	69.57%
20% CT	2.29%	34.1%	51.37%	12.24%
30% CT	41.93%	33.3%	24.43%	0.34%
40% CT	69.5%	26.6%	3.9%	0%
50% CT	89.47%	10.53%	0%	0%
60% CT	99.03%	0.97%	0%	0%
70% CT	100%	0%	0%	0%
80% CT	100%	0%	0%	0%

Table 9. Detailed data of DA for a distributed vertical strip skylight.

Type	Distributed Vertical Strip Skylight			
	DA ≥ 75%	55% ≤ DA < 75%	25% ≤ DA < 55%	DA < 25%
10% CT	0%	0%	32.44%	67.56%
20% CT	0%	23.51%	55.21%	21.28%
30% CT	26.95%	45.54%	24.03%	3.48%
40% CT	63.5%	28.49%	8.01%	0%
50% CT	87.87%	10.98%	1.15%	0%
60% CT	97.71%	2.29%	0%	0%
70% CT	99.54%	0.46%	0%	0%
80% CT	100%	0%	0%	0%

Table 10. Detailed data of DA for a centralized X-shaped skylight.

Type	Centralized X-Shaped Skylight			
	DA ≥ 75%	55% ≤ DA < 75%	25% ≤ DA < 55%	DA < 25%
10% CT	0%	0%	0%	100%
20% CT	0%	0%	16.65%	83.35%
30% CT	0%	4.46%	56.58%	38.96%
40% CT	3.66%	29.12%	52.06%	15.16%
50% CT	22.2%	37.64%	36.27%	3.89%
60% CT	43.25%	33.81%	22.48%	0.46%
70% CT	60.07%	30.38%	9.44%	0.11%
80% CT	76.66%	19.22%	4.12%	0%

Table 11. Detailed data of DA for a distributed horizontal strip skylight.

Type	Distributed Horizontal Strip Skylight			
	DA ≥ 75%	**55% ≤ DA < 75%**	**25% ≤ DA < 55%**	**DA < 25%**
10% CT	0%	0%	30.43%	69.57%
20% CT	0%	29.4%	60.93%	9.67%
30% CT	35.58%	41.82%	22.31%	0.29%
40% CT	69.62%	26.72%	3.66%	0%
50% CT	91.65%	8.06%	0.29%	0%
60% CT	98.34%	1.66%	0%	0%
70% CT	100%	0%	0%	0%
80% CT	100%	0%	0%	0%

3.1.1. DA Analysis for Centralized Rectangular Skylight

Detailed data on the DA of centralized rectangular skylights are shown in Table 6. For 10–30% CT photovoltaic glass, the measured DA is mostly less than 75%, indicating a poor indoor daylighting environment; for 40–80% CT photovoltaic glass, the DA of more than half of the measurement points is greater than 75%, indicating that the daylighting environment of most of the space is better in the gymnasium. Although the DA of more than half of the 40% CT photovoltaic glass measurement points is greater than 75%, the DA of more than 10% of the measurement points is less than 55%. To create a better daylighting environment, 50–80% CT photovoltaic glass is a better choice.

3.1.2. DA Analysis for Distributed Rectangular Skylight

Detailed data of DA of distributed rectangular skylights are shown in Table 7. For 10–20% CT photovoltaic glass, the DA of all measurement points is below 75%, implying a very poor indoor daylighting environment; for the 40–80% CT photovoltaic glass, the DA of more than half of the measuring points is greater than 75%, indicating that the daylighting environment of most of the space is better in the gymnasium. The DA of 30% CT photovoltaic glass measuring points over 80% is greater than 55%, which belongs to the acceptable daylighting environment, but the proportion of measuring points with DA less than 55% is more than 10%. To create a better daylighting environment, 40–80% CT photovoltaic glass is a better choice.

3.1.3. DA Analysis for Centralized Ribbon Skylight

Detailed data on the DA of centralized ribbon skylights are shown in Table 8. For 10–30% CT photovoltaic glass, the measured DA is mostly less than 75% and shows a poor daylighting level; for the 40–80% CT photovoltaic glass, the DA of more than half of the measuring points is greater than 75%, indicating that the daylighting environment of most of the space is better in the gymnasium. The DA of more than half of the 40% CT photovoltaic glass measuring points is greater than 75%, and the proportion of measuring points with DA less than 55% is very small. Therefore, 40–80% CT photovoltaic glass is a better choice for a centralized ribbon skylight.

3.1.4. DA Analysis for Distributed Vertical Strip Skylight

Detailed data on the DA of distributed vertical strip skylights are shown in Table 9. For 10–20% CT photovoltaic glass, the DA of all measurement points is less than 75%, implying a very poor indoor daylighting environment; for 30% CT photovoltaic glass, the DA of more than 70% measurement points is greater than 55%, but the DA of less than 55% is relatively high; for the 40–80% CT photovoltaic glass, the DA of more than half of the measuring points is greater than 75%, indicating that the daylighting environment of most of the space is better in the gymnasium. Therefore, 40–80% CT photovoltaic glass is a better choice for a distributed vertical strip skylight.

3.1.5. DA Analysis for Centralized X-Shaped Skylight

Detailed data on the DA of centralized X-shaped skylights are shown in Table 10. For 10–30% CT photovoltaic glass, the DA of all measurement points is below 75%, indicating a very poor indoor daylighting environment; for 30–60% CT photovoltaic glass, only a few measuring points of the DA is greater than 75%, the daylighting environment is still not ideal; for the 70–80% CT photovoltaic glass, the DA of more than half of the measuring points is greater than 75%, implying that most of the indoor space has ideal daylighting. Therefore, 70–80% CT photovoltaic glass is a better choice for a centralized X-shaped skylight.

3.1.6. DA Analysis for Distributed Horizontal Strip Skylight

Detailed data on the DA of distributed horizontal strip skylights are shown in Table 11. For 10–20% CT photovoltaic glass, the DA of all measurement points is less than 75%, implying a very poor indoor daylighting environment; for 30% CT photovoltaic glass, the DA of more than 70% measurement points is greater than 55%, but the DA of less than 55% is relatively high. Therefore, 40–80% CT photovoltaic glass is a better choice for a distributed horizontal strip skylight.

3.2. DAcon and DAmax Analysis of Six Shapes of Skylights

Compared with DA, DAcon is a more comprehensive evaluation index for the daylighting of buildings. When the DAcon of indoor measuring points is greater than 80%, the daylighting environment can be considered acceptable even if the indoor illuminance cannot meet the design requirements. When the proportion of measuring points greater than 5% of DAmax is relatively high, indoor glare is more likely to occur.

The variation curves of DAcon and DAmax of six shapes of skylights under the condition of 10–80% CT photovoltaic glass are shown in Figure 6. It can be observed that the six types of skylights exhibit a similar trend in terms of the variations of the DAmax and DAcon. According to the variation curves of DAcon and DAmax, the daylighting of the six shapes of skylights is best as follows: centralized rectangular skylight: 50–60% CT; distributed rectangular skylight: 40–60% CT; centralized ribbon skylight: 50–60% CT; distributed vertical strip skylight: 40–50% CT; centralized X-shaped skylight: 70–80% CT; distributed horizontal strip skylight: 40–50% CT. However, all of them have the potential to cause glare.

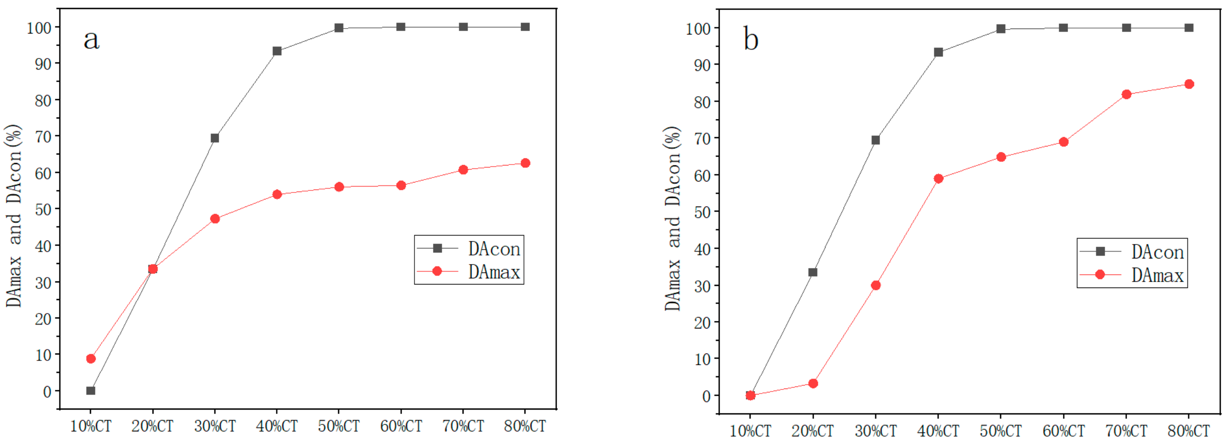

Figure 6. *Cont.*

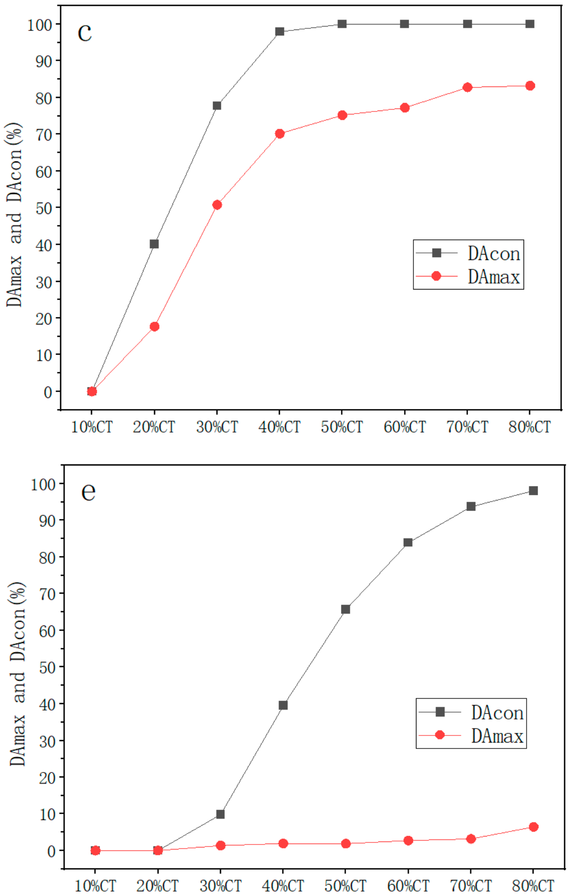

Figure 6. DAcon and DAmax curves of six kinds of skylight: (**a**) centralized rectangular skylight; (**b**) distributed rectangular skylight; (**c**) centralized ribbon skylight; (**d**) distributed vertical strip skylight; (**e**) centralized X-shaped skylight; (**f**) distributed horizontal strip skylight.

3.3. UDI Analysis of Six Shapes of Skylights

The variation curves of UDI of six shapes of skylights under the condition of 10–80% CT photovoltaic glass are shown in Figure 7. It can be seen that with the increase of the transmittance of CT photovoltaic glass, the proportion of UDI < 100 lx decreases rapidly; the proportion of 100 lx < UDI < 2000 lx first increased and then decreased except for the centralized X-shaped skylight, the reason is that the daylighting of the centralized X-shaped skylight is poor, and the illumination of few indoor measuring points exceeds 2000 lx; the proportion of UDI > 2000 lx increased slowly.

For centralized rectangular skylight, the best indoor daylighting environment is 50–80% CT; distributed rectangular skylight: 40–80% CT; Centralized ribbon skylight: 40–80% CT; distributed vertical strip skylight: 50–80% CT; Centralized X-shaped skylight: 70–80% CT; distributed horizontal strip: 40–70% CT.

From the simulated results of various daylighting metrics above, it can be observed that under different skylight forms, there are variations in the degree of change in dynamic daylighting metrics with the increase in the transmittance of photovoltaic glass. However, overall, they exhibit similar changing trends. According to a similar study [27], this trend is also noticeable under different photovoltaic glass conditions in different climatic regions. Given the diverse skylight forms in this study, when compared to the aforementioned similar study, variations in the numerical values and degrees of change in each daylighting metric differ due to differences in building types, skylight glass, and other relevant design parameters.

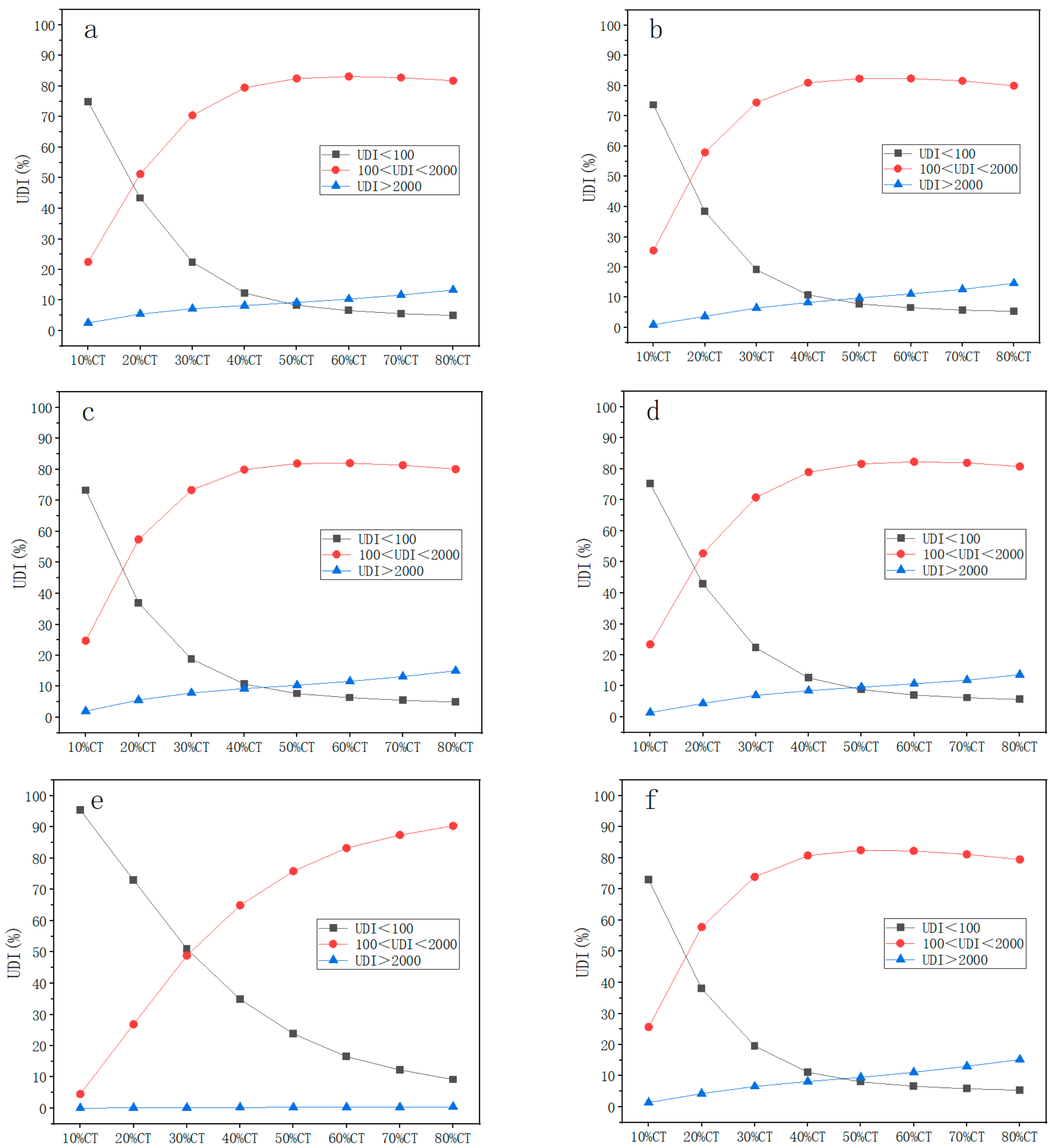

Figure 7. UDI curves of six kinds of skylight: (**a**) centralized rectangular skylight; (**b**) distributed rectangular skylight; (**c**) centralized ribbon skylight; (**d**) distributed vertical strip skylight; (**e**) centralized X-shaped skylight; (**f**) distributed horizontal strip skylight.

In terms of research on different skylight distributions, a similar study [49] is also present. Focusing on railway stations, this study selected two cities and two different skylight distribution patterns. From this, it can be observed that each city, under different skylight distribution patterns, exhibits similar forms of variation in daylighting metrics. This finding aligns with the discoveries made in our study.

3.4. Optimal Type of Photovoltaic Glass for Six Kinds of Skylight

The actual layout of skylights in university gymnasiums is varied, and the area is also different. This study simulates six typical shapes of skylight in a typical university gymnasium. The results cannot be applied to all university gymnasiums. DA, DAcon, DAmax, and UDI are used to analyze indoor daylighting and select the optimal scheme.

The optimal CT photovoltaic glass types of centralized rectangular skylight are shown in Table 12. It can be seen from Table 12 that 50–60% CT photovoltaic glass is the optimal type to create a good indoor daylighting environment, which can ensure that the indoor illumination level meets the minimum requirements for a long time. However, there is the possibility of glare, and certain shading facilities are needed in the period of intense sunlight.

Table 12. Optimal type of CT photovoltaic glass for a centralized rectangular skylight.

Daylighting Index	Evaluation Methodology	Optimal Type
DA	Proportion of measuring points with value $\geq$ 55%	50–80% CT
DAcon	Proportion of measuring points with value > 80%	50–80% CT
DAmax	Proportion of measuring points with value > 5%	10–60% CT
UDI	Average value within 100–2000 lx	50–80% CT

The optimal CT photovoltaic glass types of distributed rectangular skylights are shown in Table 13. It can be seen from Table 13 that 40–60% CT photovoltaic glass is the optimal type to create a good indoor daylighting environment. Shading facilities are needed in the period of intense sunlight.

Table 13. Optimal type of CT photovoltaic glass for a distributed rectangular skylight.

Daylighting Index	Evaluation Methodology	Optimal Type
DA	Proportion of measuring points with value $\geq$ 55%	40–80% CT
DAcon	Proportion of measuring points with value > 80%	40–80% CT
DAmax	Proportion of measuring points with value > 5%	10–60% CT
UDI	Average value within 100–2000 lx	40–80% CT

The optimal CT photovoltaic glass types of centralized ribbon skylight are shown in Table 14. It can be seen from Table 14 that 50–60% CT photovoltaic glass is the optimal type to create a good indoor daylighting environment. Shading facilities are needed in the period of intense sunlight.

Table 14. Optimal type of CT photovoltaic glass for a centralized ribbon skylight.

Daylighting Index	Evaluation Methodology	Optimal Type
DA	Proportion of measuring points with value $\geq$ 55%	40–80% CT
DAcon	Proportion of measuring points with value > 80%	40–80% CT
DAmax	Proportion of measuring points with value > 5%	10–60% CT
UDI	Average value within 100–2000 lx	50–80% CT

The optimal CT photovoltaic glass types of distributed vertical strip skylights are shown in Table 15. It can be seen from Table 15 that 40–50% CT photovoltaic glass is the optimal type to create a better indoor daylighting environment. Shading facilities are needed in the period of intense sunlight.

Table 15. Optimal type of CT photovoltaic glass for a distributed vertical strip skylight.

Daylighting Index	Evaluation Methodology	Optimal Type
DA	Proportion of measuring points with value ≥ 55%	40–80% CT
DAcon	Proportion of measuring points with value > 80%	40–80% CT
DAmax	Proportion of measuring points with value > 5%	10–50% CT
UDI	Average value within 100–2000 lx	50–80% CT

The optimal CT photovoltaic glass types of centralized X-shaped skylight are shown in Table 16. It can be seen from Table 16 that 70–80% CT photovoltaic glass is the optimal type to create a good indoor daylighting environment. However, the possibility of glare from the centralized X-shaped skylight is very small.

Table 16. Optimal type of CT photovoltaic glass for a centralized X-shaped skylight.

Daylighting Index	Evaluation Methodology	Optimal Type
DA	Proportion of measuring points with value ≥ 55%	70–80% CT
DAcon	Proportion of measuring points with value > 80%	70–80% CT
DAmax	Proportion of measuring points with value > 5%	10–80% CT
UDI	Average value within 100–2000 lx	70–80% CT

The optimal CT photovoltaic glass types of distributed horizontal strip skylights are shown in Table 17. It can be seen from Table 17 that 40–50% CT photovoltaic glass is the optimal type to create a good indoor daylighting environment. Shading facilities are needed in the period of intense sunlight.

Table 17. Optimal type of CT photovoltaic glass for a distributed horizontal strip skylight.

Daylighting Index	Evaluation Methodology	Optimal Type
DA	Proportion of measuring points with value ≥ 55%	40–80% CT
DAcon	Proportion of measuring points with value > 80%	40–80% CT
DAmax	Proportion of measuring points with value > 5%	10–50% CT
UDI	Average value within 100–2000 lx	40–70% CT

3.5. Verification

In order to verify the accuracy of the results, the gymnasium model is established in Rhino according to the original scale and compared with the measured results. The gymnasium is Zhuoer Gymnasium of Wuhan University. The skylight shape is a centralized ribbon skylight, the ceiling is whitewashed, the wall material is gray sound-absorbing board, and the floor is wooden. The reflection ratio of the enclosure structure is set according to the China National Standard for Daylighting Design of Buildings (GB50033-2013) [48]. The pollution reduction coefficient of the window glass is set as 0.6, and the light-blocking reduction coefficient of the interior component is set as 0.65. The location distribution of measuring points is shown in Figure 8.

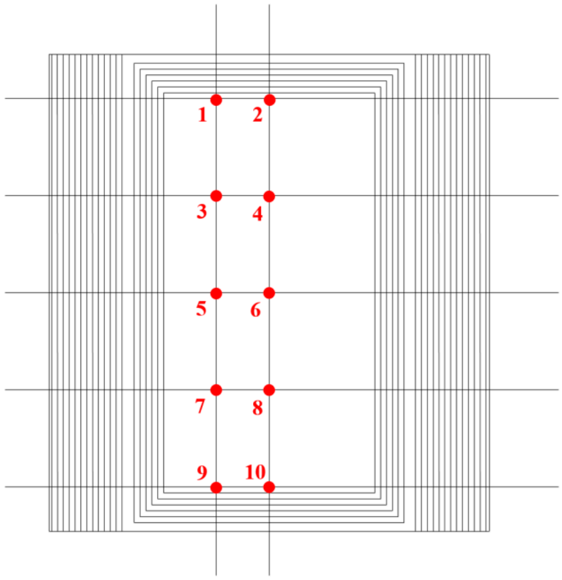

Figure 8. Distribution of measuring points for indoor illuminance (Points 1–10).

The measured data are from the literature [3]. The sky condition is rainy, and the outdoor illumination is 5384 lx. The comparison between measured illumination and simulated illumination is shown in Figure 9. It can be seen that the measured value is almost consistent with the simulated value, and the simulated illuminance is slightly larger than the measured illuminance because of the plane simplification of the seat in the modeling process.

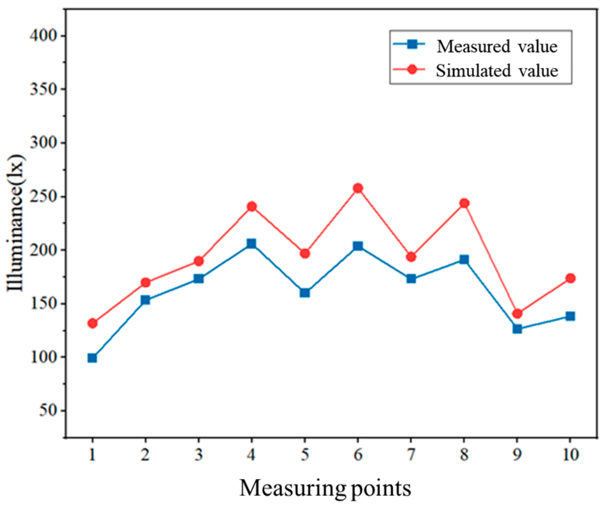

Figure 9. Comparison of illuminance measurement values with simulation.

3.6. Summary

The optimal types of six different shapes of skylights with CT photovoltaic glass for the gymnasium are summarized in Table 18. It can be seen that the daylighting environment of a centralized X-shaped skylight is relatively poor, and CT photovoltaic glass with high transmittance is needed to ensure indoor daylighting. Different shapes of skylights have a certain impact on the daylighting of the gymnasium. The optimal type of CT photovoltaic glass varies with the skylight shape.

Table 18. Optimal type of CT photovoltaic glass for shapes of skylights.

Skylight Shape	Optimal Type
Centralized rectangular skylight	50–60% CT
Distributed rectangular skylight	40–60% CT
Centralized ribbon skylight	50–60% CT
Distributed vertical strip skylight	40–50% CT
Centralized X-shaped skylight	70–80% CT
Distributed horizontal strip skylight	40–50% CT

4. Conclusions

In this paper, Rhino software (version 7.4) is used to model a typical university gymnasium to explore the impact of six different shapes of CdTe thin film photovoltaic skylights on the indoor daylighting environment of the university gymnasium. The indoor daylighting environment of the university gymnasium varies greatly due to the different shapes of the skylight. Based on the dynamic daylighting evaluation indexes DA, DAcon, DAmax, and UDI, the optimal types of CT photovoltaic glass suitable for skylights with different shapes are summarized.

The mean DA of the six shapes of skylight increases with the increase of transmittance of CT photovoltaic glass. For the centralized rectangular skylight, distributed horizontal strip skylight, and distributed vertical strip skylight, when the photovoltaic glass is 80% CT, DA of the competition area is all above 75%; for the distributed rectangular skylight and centralized ribbon skylight, when the photovoltaic glass is 70–80% CT, the DA of the competition area is above 75%; for the centralized X-shaped skylight, all types of CT photovoltaic glass contain areas with DA below 75%. Compared with distributed skylights, the DA of centralized skylights has a wider distribution range.

With the increase of transmittance of CT photovoltaic glass, DAcon and DAmax gradually increased. All skylights are prone to glare except the centralized X-shaped skylights. Therefore, certain shading facilities should be set up during periods of strong sunlight. The results show that for the centralized rectangular skylight, The optimal type of CT photovoltaic glass is 50–60% CT, the optimal type of distributed rectangular skylight is 40–60% CT, the optimal type of centralized ribbon skylight is 50–60% CT, the optimal type of distributed vertical strip skylight is 40–50% CT, the best type of centralized X-shaped skylight is 70–80% CT, and the optimal type of distributed horizontal strip skylight is 40–50% CT.

At present, there are still few studies on the influence of semi-transparent photovoltaic skylights on university gymnasium daylighting. The results of this work focus on the coupled consideration of six different skylight shapes and different types of CT photovoltaic glass only for the city of Beijing, which is located in the Chinese III lighting climate zone, and the conclusions drawn may not be applicable to the rest of the lighting climate zones locations, while the skylight shapes and glass types considered are limited. In the future, the influence of skylight area, geographical location, building orientation, and other factors on university gymnasium daylighting should be studied.

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