TSINGHUA UNIVERSITY

Thesis Project

Multi-Objective Optimization Model for Daylighting Design in Self-Study Classrooms

Department: School of Architecture

Major: Architecture

Name: Jingwen Zhang

Supervisor: Associate Professor Xin Zhang

06, 2023

Instructions on Thesis Usage Authorization

I fully understand the relevant regulations of Tsinghua University regarding the retention and usage of theses, namely: The university has the right to retain a copy of the thesis, and the thesis may be accessed and borrowed. The university may publish all or part of the content of the thesis and may preserve the thesis through photocopying, microfilming, or other means of reproduction.

(Confidential theses must comply with this regulation after being declassified.)

Signature：________Supervisor's Signature:______________Date：______

ABSTRACT

Classrooms, the primary environment for pupils and junior high school students, have a significant impact on them. Among various factors, the lighting environment has a considerable influence on learning efficiency and health. In existing lighting standards in China, the evaluation is mostly conducted based on the overall lighting conditions in whole classrooms. However, there exist individual variations in lighting environments as different positions are scattered within the same classroom, which cannot be generalized.

Building upon previous studies on individual lighting environments evaluation, this paper simulates lighting conditions in standard classrooms model under the climate data set of Linyi, Shandong Province, using the architectural environmental analysis plugin, Climate Studio. Different analysis methods and standards are employed to analyze the data obtained from the simulations.

The research yields two main contributions. Firstly, a new evaluation standard for classroom lighting environment is established. Secondly, the positive impact of the lighting environment on individuals is quantified through mathematical modelling. In addition, the obtained simulation data is used as an example to evaluate and demonstrate shading solutions.

By focusing on individual lighting environments and considering local climatic conditions, this research provides insights into the assessment and improvement of classroom lighting. The proposed evaluation standard and quantitative analysis contribute to creating healthier and more conducive learning environments for students.

Keywords: School classroom lighting environment; Daylighting standards; Daylighting simulation; Climate Studio;

Content

1 Introduction

1.1 Research Background

Primary and middle school students spend the majority of their time in school classrooms, which are complex indoor environments composed of various factors. Existing research shows that physical layout, space dimensions (length, width, and height)[1] , furniture arrangement, lighting environment, humidity, and thermal environment are all factors that influence environmental quality [2][6] . Additionally, research on shared offices suggests that people have preferences for their office environments, and their performance and cognition are affected by the position within the same space and the activities they are engaged in [3][4]

Among these factors, research led by Peter Barrett on the impact of classroom design elements on elementary school students' academic progress indicates that the lighting environment accounts for the largest percentage of factors influencing student progress, approximately 21% [2] . Moreover, if a building meets green certification standards, adequate illumination can also benefit students' eye health [5] Therefore, it can be inferred that different individuals in the same space may experience variations in cognitive efficiency and progress rate due to differences in the lighting environment.

However, lighting solutions in classrooms are not fixed, and individuals have varying preferences for lighting, meaning that different positions within the environment are affected differently by uniform changes in lighting conditions. Additionally, different people may have different comfort needs in the same lighting environment. This has been confirmed by experimental data, which shows that students in different positions within the same classroom lighting environment indeed have different subjective evaluations, cognitive performances, and neurophysiological responses [7] . On the other hand, investigations into the daylighting and lighting conditions of classrooms in 80 primary and middle schools in Laoling, Shandong, revealed that different areas within the same classroom are indeed affected by the objective environmental arrangement, leading to localized lighting differences [8] . Therefore, this paper proposes a more flexible classroom lighting solution that shifts from designing lighting environments based on the classroom as a whole to a more detailed design focused on individual desks, allowing for a higher degree of user adjustability.

1.2 State of the Art

In China, existing standards have already established some regulations for classroom lighting environments. Currently, the lighting design of most primary and middle school classrooms adheres to national standards that primarily evaluate the classroom as a whole, translating lighting requirements into specific design methods to achieve “no less than 2 hours of full-window sunlight on the winter solstice” [9] . These standards are also formulated based on the building's orientation, typically towards the south or southeast [10] . Additionally, industry standards further specify more detailed requirements according to the time of use and the different types of classrooms [11]

Existing standards control classroom lighting environments by stipulating requirements for factors such as average illuminance on desktops, illuminance uniformity, and the duration of full-window sunlight on the winter solstice. Separate standards are set for daylighting and artificial lighting [18] The evaluation process is generally conducted at the classroom level. In addition to the typical scenario of writing on desks, standards may also account for the various activities students engage in within the classroom, thus providing different regulations. Standards guiding the design of classroom shapes also dictate the window-to-floor ratio. More detailed standards require consideration of furniture placement within classrooms to avoid reflective glare [9].

While these standards ensure that most desks meet the lighting requirements, desks in different areas of the classroom may still experience either excessive or insufficient light, potentially straining students’ eyes. Existing research has identified areas for improvement in these standards, and daylighting strategies for desks arranged by rows have already been explored [12]. By treating each individual desk as a unit, and considering the effects of position on cognitive performance in different lighting conditions, researchers have achieved more ideal integrated illuminance data [7].

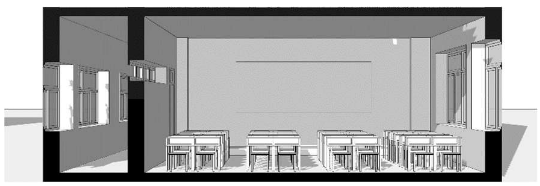
Current technology already allows for the adjustment of lighting at individual desk areas [13] Furthermore, smart lighting systems that adjust based on monitoring classroom conditions to achieve energy savings have been implemented [4][15]

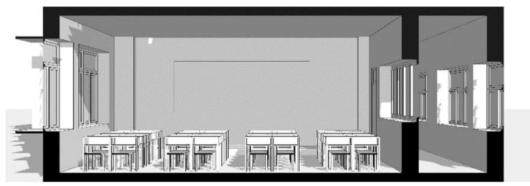
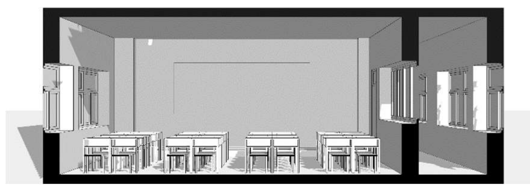
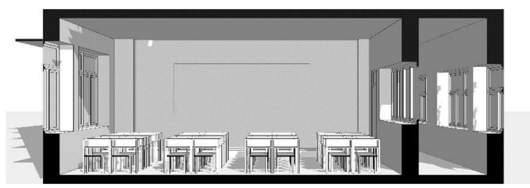
Research has proposed evaluation criteria for lighting environments, with different studies incorporating the impact of seating positions into their analyses. Standards have also been theoretically optimized. Technological advancements suggest that current technology can theoretically meet the requirements of these optimized standards. However, there is still no clear application plan to guide the use of these technologies, and further theoretical refinement is needed to combine different conclusions at the individual desk level.

Building on existing standards and research outcomes, this paper seeks to simulate daylighting solutions at the individual desk level. Additionally, it aims to adjust the lighting environment to create conditions that are visually and psychologically comfortable for individuals. On the technological side, environmental adjustments should not only prioritize energy conservation. Moeiz Miraoui's research suggests that classrooms should form intelligent systems that adjust conditions based on human behavioral patterns [14]. Therefore, this paper proposes to regulate usage methods and design plans that prioritize individual needs for lighting adjustment.

In recent years, school buildings have commonly employed double-sided daylighting strategies, where 2-3 windows are placed on the primary daylighting side of the classroom, and windows are also installed on the corridor-facing side to allow daylight into the hallways. Shading measures include dynamic shading devices like curtains or blinds, as well as structural external shading measures like sunshades. Based on the research by Xin Zhang et al. on individual lighting environments, several shading solutions used in recent school buildings were reviewed, including horizontal shading, mixed shading, and light-guiding panels. These solutions, combined with window height variations, resulted in eight different configurations. Adding two north-facing daylighting solutions and two unshaded south-facing configurations for comparison, a total of eleven solutions were studied [12]. This paper will reference the eleven solutions from this study for further research, as listed in Table 1.1 所示。

Table 1.1 11 Shading Settings

Scheme No.	Classroom Section Diagram	Parameter Settings
1		South - Internal and External Light Guide Panels Window height: 1.50 m Light Guide Panel: Internal 400 mm, External 600 mm
2		North - Reduced South-facing Window South window height: 450 mm Main daylighting window height: 2 m
3		South - Mixed Shading Window height: 1.50 m Shading Panel Depth: 600 mm
4		South - Internal Light Guide Panel Window height: 1.50 m Light Guide Panel: Internal 400 mm
5		South - Horizontal Shading Window height: 1.50 m Shading Panel Depth: 600 mm
6		North Main daylighting window height: 2 m

7		South - Internal and External Light Guide Panels Window height: 2 m Light Guide Panel: Internal 400 mm, External 600 mm
8		South - Mixed Shading Window height: 2 m Shading Panel Depth: 600 mm
9		South Main daylighting window height: 1.50 m
10		South - Horizontal Shading Window height: 1.50 m Shading Panel Depth: 600 mm
11		South Main daylighting window height: 2 m

1.3 Research Content and Technical Path

Based on the aforementioned requirements, the lighting and shading system for classrooms needs to be refined to an individual level within the existing standard frameworks. This refinement aims to optimize the classroom lighting environment and have a positive impact on students' eye health and cognitive learning progress.

In current standards, classroom lighting is often controlled as a whole unit, and there are no clear selection criteria for shading systems in schools. These are often selected through market research rather than based on the results of lighting environment assessments. Existing research has progressed to evaluating lighting at a column-by-column level but further division is still needed.

This paper analyzes that the problem with existing research results might stem from the fact that their evaluation systems are modifications of past standards. These past standards were often based on assessments conducted on groups of people, and most statistical methods, such as averaging, are used to describe data for multiple people, representing the overall lighting effects.

Thus, this paper will attempt to propose a new evaluation standard tailored for individuals. This new standard will evaluate each individual's lighting conditions and determine if each seat in the classroom meets the standard. The final shading evaluation standard will be based on the solution that results in the most individuals meeting the requirements.

This research will combine existing studies and investigate a more reasonable daylighting scheme. The study uses Climate Studio software to evaluate lighting strategies. Starting with the conclusions drawn from dividing seating into columns, the research will proceed to divide seating into rows for further simulation. This will identify the best shading scheme based on the combined effects of rows and columns.

Based on these conclusions, further advancements will be made on the existing school building standards. By combining relevant research with local construction experiences in Linyi and through surveys and simulations, improved standards for the lighting environment in local schools will be developed. The technical route of this paper is illustrated in Figure 1.1.

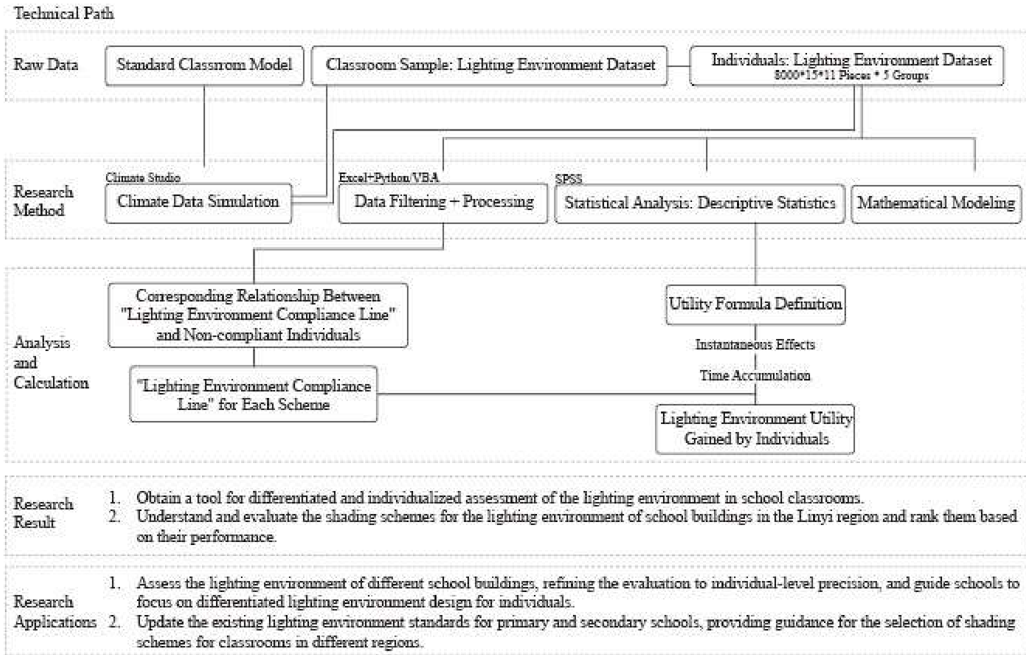


Figure 1.1 Technical Path

2 Research Model Setup

2.1 Simulation Parameters

To simulate classroom lighting, Climate Studio was used to determine various parameters, dimensions, and data required for the model. The model used in this paper is based on the study by Zhang Xin and colleagues[12], which employed a reverse-engineered standard classroom size. The classroom dimensions used in the simulation were 7800mm (depth) by 9300mm (width). The layout of the classroom was modeled according to common designs seen in most primary and secondary school buildings, typically a single corridor on one side. The school consists of three classrooms per floor, and five floors per building, with three buildings arranged side by side.

Inside the classroom, the desks are arranged in four groups, with two rows per group and six desks per row. The dimensions of each desk were 0.60m by 0.40m. To simulate individual lighting conditions, sample points were set for each desk on the horizontal plane, as shown in Figure 2.1. To avoid simulation errors due to overlapping with the desk surface (height of 750mm), the sample points were set 760mm above the ground or 10mm above the desk surface.

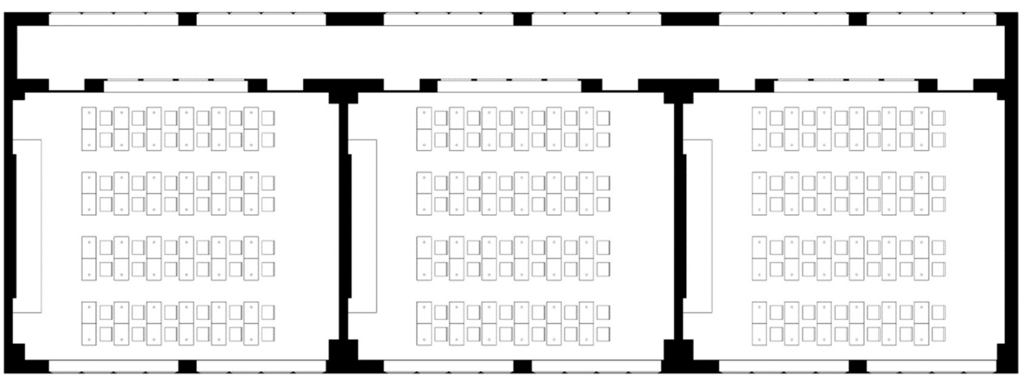


Figure 2.1 Classroom Layout Plan and Sampling Point Location Diagram

In some cases, primary and secondary schools adopt designs where the three classroom buildings are connected by corridors. Therefore, this study initially considered six building layout patterns, including having the main lighting surface of the three buildings facing south and north, and with or without corridors on the east or west sides.

The simulation software used in this study is Climate Studio, an environmental performance analysis plugin for Rhino. The plugin simulates the daylight illuminance on the classroom desks, and the data obtained are used to analyze and calculate subsequent metrics, enabling the formulation of appropriate lighting standards.

In this study, the TMYx climate file for Linyi was selected. This file, derived from NOAA's Integrated Surface Database, contains hourly meteorological data for typical years. The version used in this simulation covers data from 2004-2018 and represents the most recent dataset available for climate analysis.

After setting up the climate data, the material properties of the classroom model were defined. Common classroom materials were selected, and the reflectance and visible transmittance values were assigned to different surfaces. The material properties and values are summarized in Table 2.1.

Table 2.1 Material Setting

Model Component	Material	Reflectance	Visible Light Transmittance TVIS
External Ground	Concrete Grey Exterior floor Tiles	18.38%	
Classroom Floor	Grey Ceramic Tile Floor	53.82%	
Exterior Wall	Exterior Concrete wall	71.10%	
Interior Wall Panels	White Painted Walls	83.99%	
Corridor Wall	White exterior corridor wall	78.61%	
Ceiling	White Painted Ceiling	88.42%	
Window Frame	Aluminum Brown Window Mullion	7.66%	
Window Glass	dear - Clear (Krypton)		0.774
Columns	Column E14 526	82.13%	
Classroom Door	Beige wooden door	78.95%	

Door Frame	Door Frame 7 3014	74.94%
Desk and Chair Surface	Wood Laminate Table Top	50.92%
Metal Desk and Chair Legs	Table Leg E14 526	35.46%
Blackboard	Blackboard	3.89%
Podium	Wooden Floor Planks	10.71%
Shading Panels	Opaque Roller Shade	43.24%
Reflective Layer of Light Guides Panels	Exterior White wall	80.55%

When using the Daylight Availability function in Climate Studio to simulate classroom lighting, the time period selected is from 8:00 a.m. to 4:00 p.m., which corresponds to the duration when most primary and secondary school students spend significant time at their desks for learning. After completing the simulation, data files for each sample point, along with hourly illuminance data throughout the year and relevant visualized images (Figure 2.2).

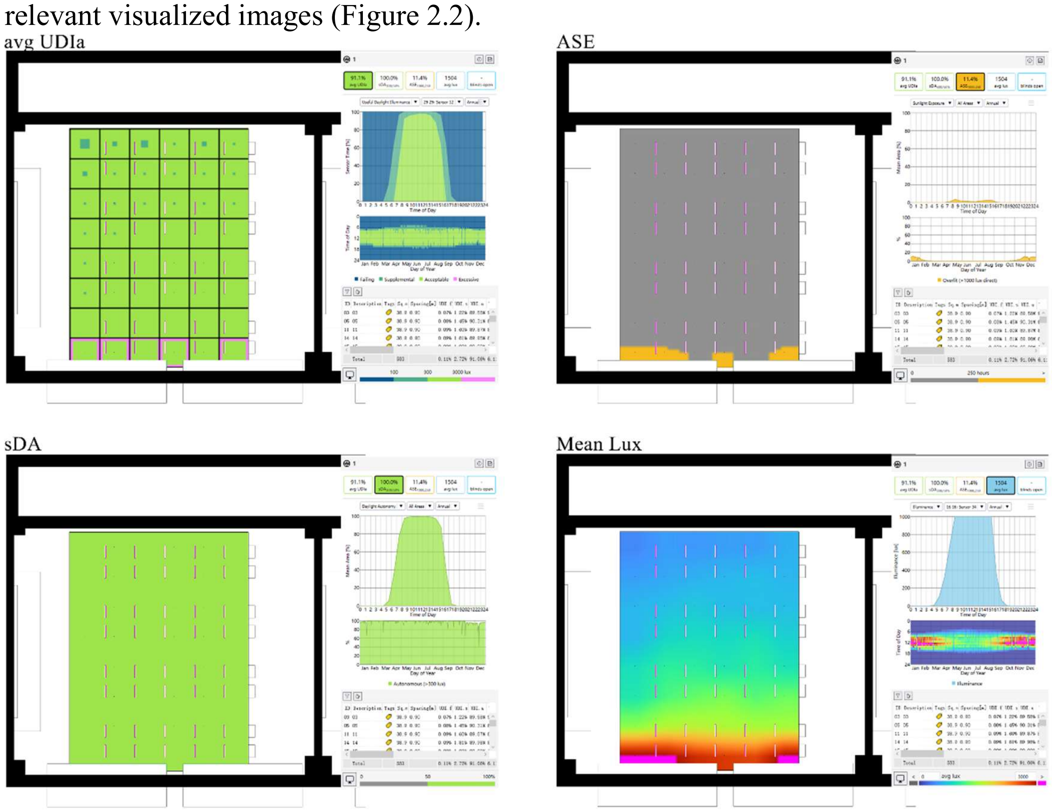


Figure 2.2 Software Simulation Interface and Available Visualization Data

2.2 Simulation Results

Before conducting large-scale simulations, a simulation was carried out for 45 classrooms across three buildings. Sample points were evenly distributed on the windows of the main lighting surfaces in these classrooms to gather results and perform classroom sampling. In this section, we discuss the cases where corridors are located on the east side, west side, and cases without corridors, applied to both east- and west-facing classrooms. A total of six cases were simulated, as shown in Figure 2.3. After conducting simulations for the layout of the six classroom buildings, the results showed that the presence or absence of corridors and the location of the corridor greatly influenced daylight performance. To purely focus on the impact of desk position on lighting conditions, this paper primarily discusses the case without corridors.

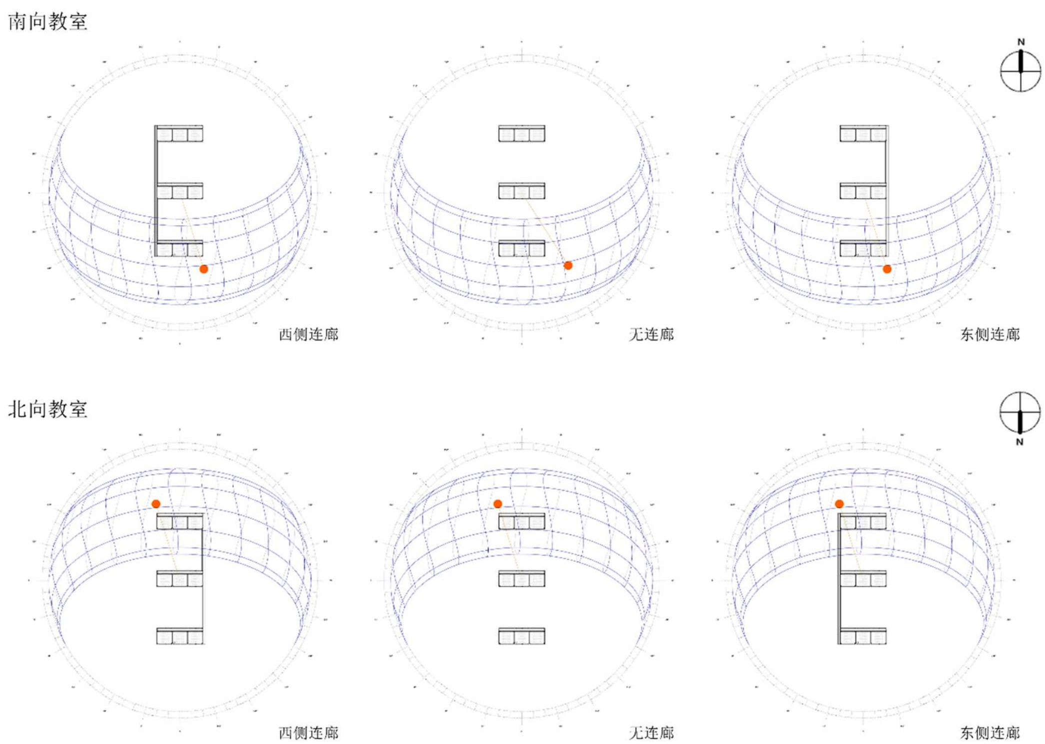


Figure 2.3 Connection Methods and Orientation Layout of Classroom Buildings

The position of a classroom within a building also has a significant impact on its daylight performance. To ensure that classrooms with varying levels of daylighting are considered, this phase selected the best-lit and worst-lit classrooms from each building, as well as a moderately-lit classroom. The numbering of the classrooms used for comparison is shown in Figure 2.4.

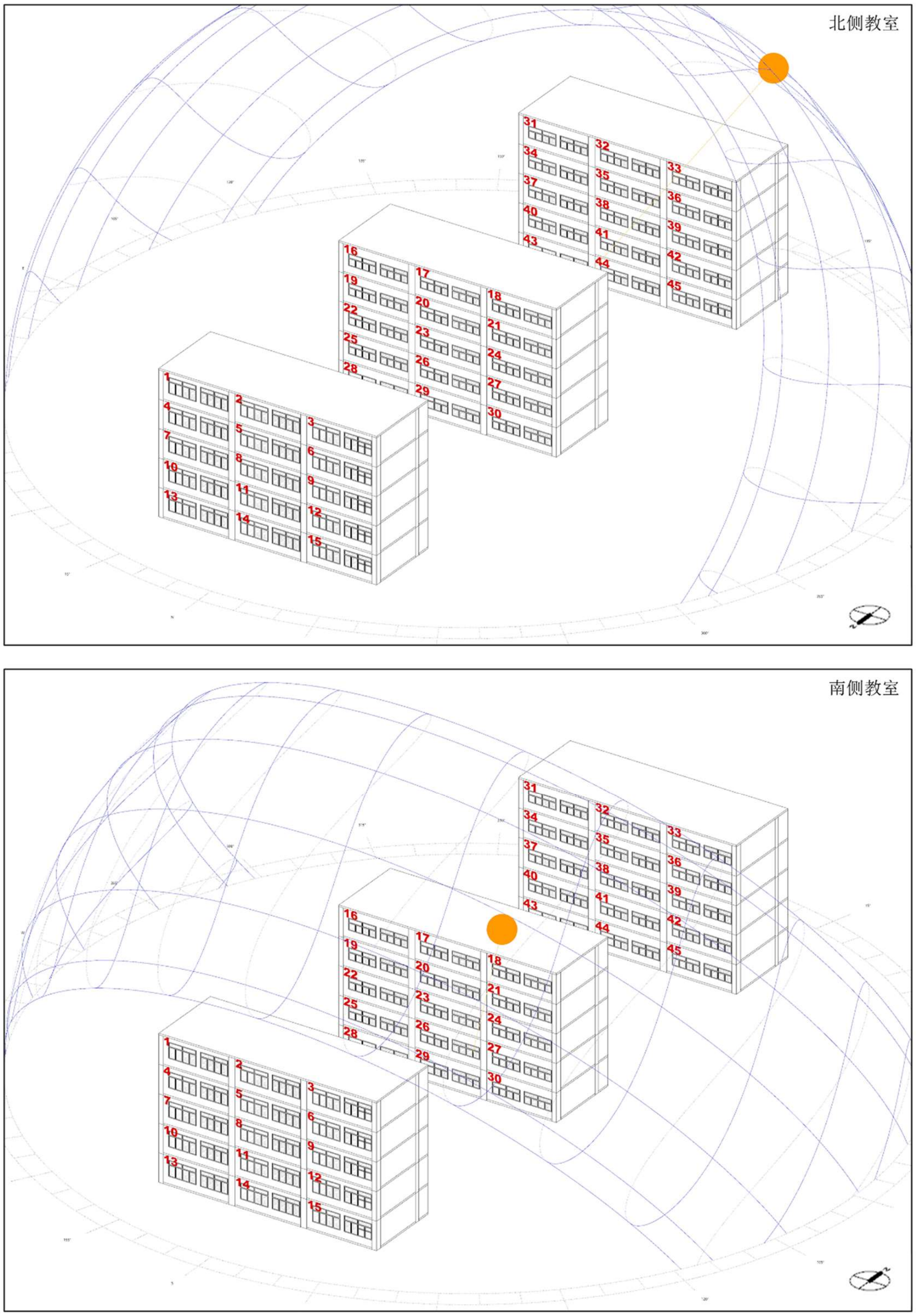


Figure 2.4　　Numbering of Classrooms for Comparison

The simulation was conducted using the parameters set out in Section 2.1 . The results of the simulation are shown in Figure 2.5. The upper part of the figure compares the average illuminance of the windows in each classroom layout, while the lower part shows the comparison of average illuminance across the three buildings for each layout.

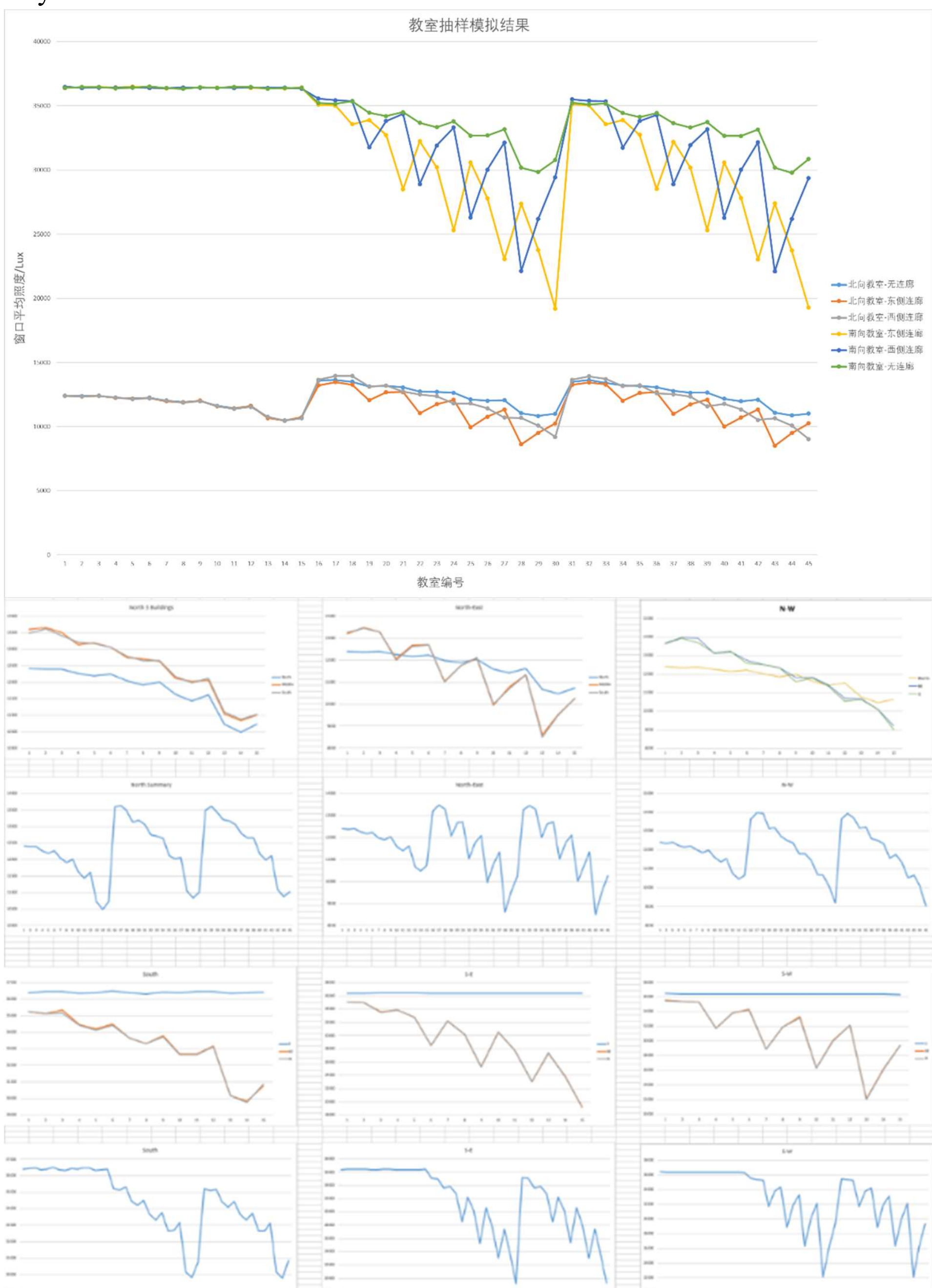


Figure 2.5　Classroom Samples Simulation Results

Since this study focuses on the case without corridors, the north- and south-facing classrooms are the main layouts discussed. A comparison of the average illuminance between classrooms, along with the classification of the classrooms as having optimal, moderate, or poor daylighting conditions, is summarized inTable 2.2.

Table 2.2 Summary of Classroom Sampling Results

Classroom Direction	Classroom Number	Lighting Conditions
South	3,11,16,18,31,33	Excellent
	5,22,37	Average
	14,15,28,29,43,44	Poor
North	1,3,16,17,31,32	Excellent
	9,23,39	Average
	13,14,29,30,44,45	Poor

2.3 Validation of Existing Research

In order to compare the differences between different software and regions from previous research, the simulation method used in prior studies was replicated, and the results were analyzed using the previous standards.

In a study by Zhang Xin et al. in 2020, a survey of existing shading solutions in different primary and secondary schools summarized 11 shading schemes based on window height, orientation, and shading measures. These were then modeled and simulated.[12]。

The scope of the simulation selected the innermost and outermost columns of desks and chairs in each sampled classroom as sampling units. DA_{300lx}[50%] and ASE_{1000lx}[250] calculations were performed to obtain the data for each shading scheme, followed by further analysis. This study also used the new Climate Studio software and local climate data from Linyi for simulations under the same standards.

Previous studies selected the closest and farthest rows of desks from the main daylighting surface and focused on the poor daylighting times for these two rows. The standard used the proportion of time when the natural light on the desk surface exceeded 3000lx to evaluate the poor daylighting utilization time of the row closest to the main daylighting surface. For the row of desks farthest from the daylighting surface, the proportion of time when natural light on the desk surface was less than 300lx was used to evaluate poor daylighting. The sum of these two different daylighting utilization times was defined as the average poor daylighting utilization time of each row. The simulation results are shown in Figure 2.6. Scheme 1 (south-facing classrooms with daylighting and shading by light guides) performed best in terms of poor daylighting utilization time ratio, aside from the north-facing lighting schemes, which aligns with the results of existing research.

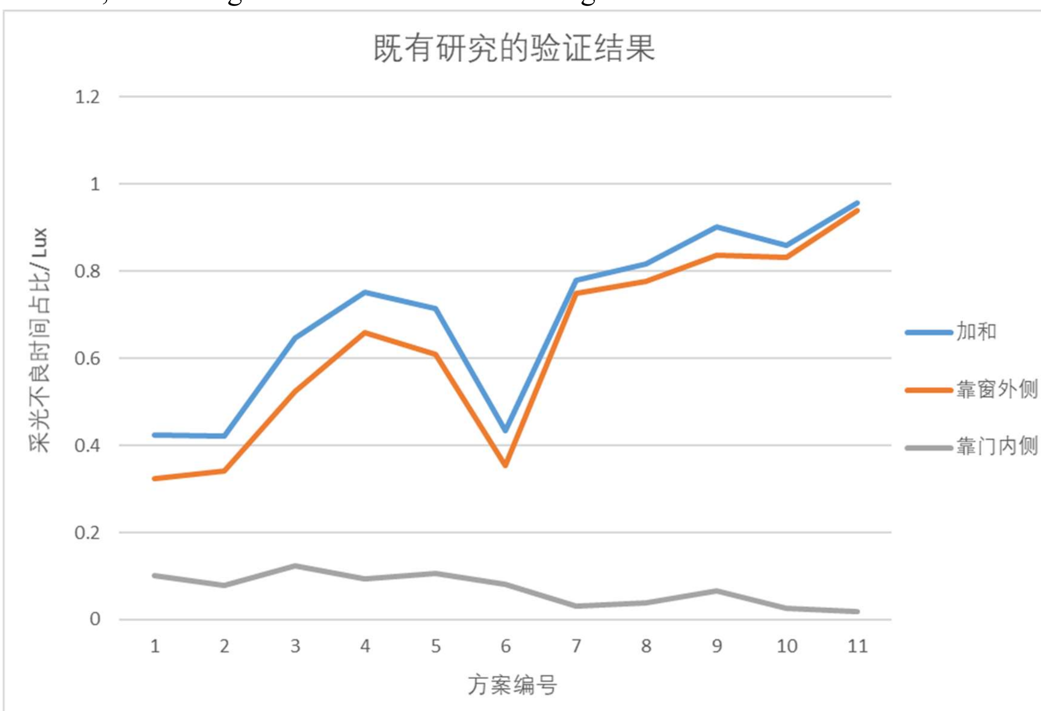


Figure 2.6 Validation Results of Existing Research

3 Research on Shading Scheme Evaluation Standards

3.1 Key Issues to Be Addressed

For existing studies, the method of data processing often uses column averages. In this data processing method, the differences between individual data points are often significantly diminished. However, if individual experiences are the focus, the use of averages is not the best way to evaluate standards. For individuals who are either overexposed to light or suffer from insufficient lighting, using averages cannot accurately reflect their experience.

In this paper, new standards are initially proposed to simulate UDI (Useful Daylight Illuminance) values for each seat. For an individual, UDI_f (illuminance less than 300lx), UDI_s (illuminance between 300lx and 3000lx), and UDI_e (illuminance greater than 3000lx) are added together to calculate the time ratio of poor daylight utilization. This "poor daylight utilization time ratio" is then compared with a newly defined "lighting environment compliance line." If the result exceeds this standard value, the individual is defined as having poor daylight conditions.

This new standard will be used to evaluate different shading schemes. The primary challenge with the new standard lies in determining the threshold value. If the threshold is set higher, fewer individuals will pass, but the daylight quality for those who do will be of a higher standard. Conversely, lowering the standard will allow more individuals to pass, but most will experience mediocre daylight conditions. Thus, the main problem is how to find a critical point that allows more individuals to meet the standard without excessively relaxing the criteria.

3.2 Observation of Non-compliant Individuals and Evaluation

Under the new standard, the study needs to determine the scope of the subjects under evaluation. Based on previous research, only the two rows closest and farthest from the main daylighting surface were discussed for poor lighting conditions. In this study, two simulations were conducted: one compared the "overexposure time ratio" of the row closest to the window and the "underexposure time ratio" of the row farthest from the window. The second simulation summed both time ratios for both rows and compared them with different "lighting environment compliance lines." The results are shown in Figure 3.1.

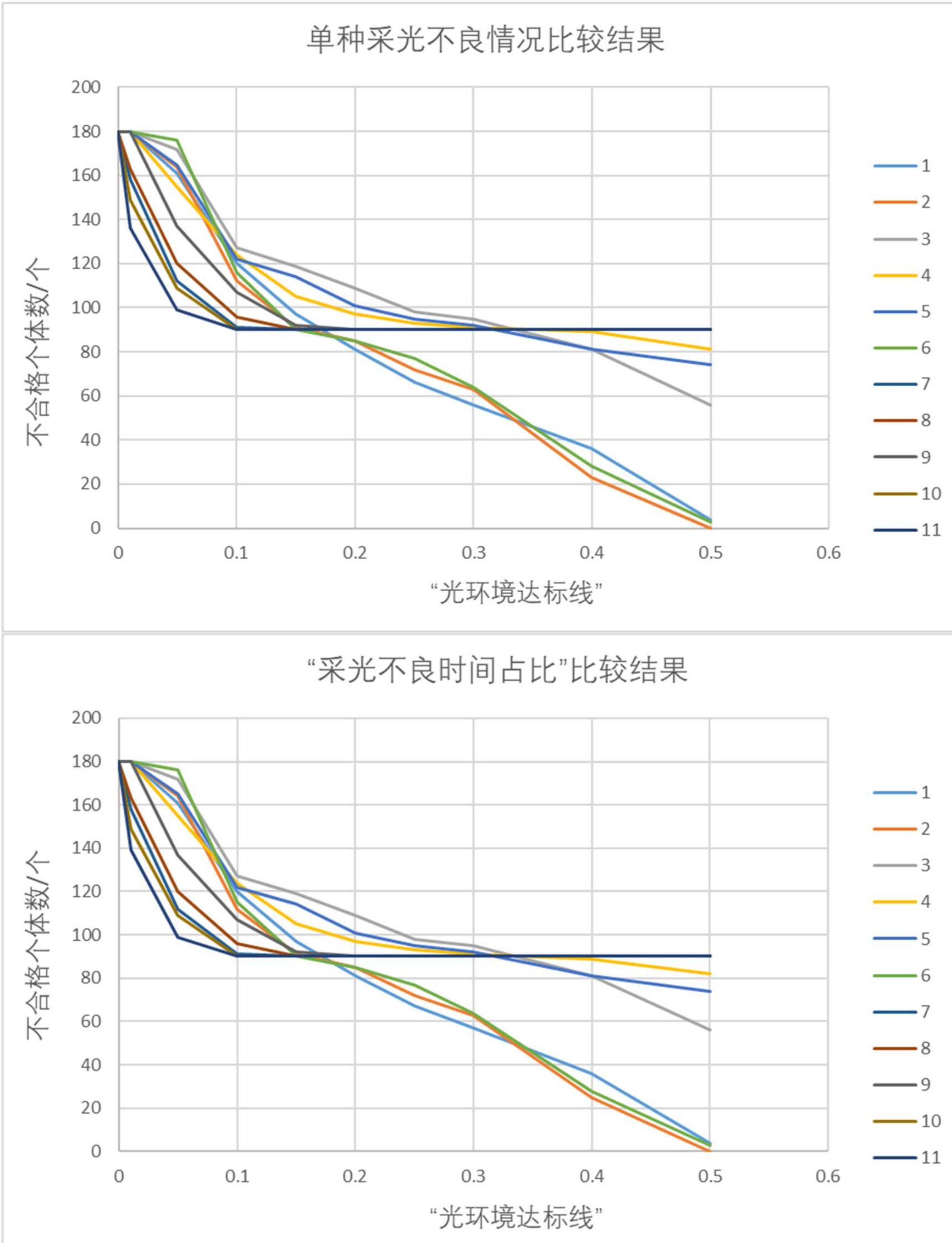


Figure 3.1 Simulation Results of Non-compliant Individuals Judged on a Column-by-column Basis

As the "lighting environment compliance line" is relaxed, the number of non-compliant individuals in some shading schemes stabilizes. This is because, in some shading schemes, the individuals closest to the main daylighting surface have a higher "overexposure time ratio." Therefore, if only these two rows are studied, the number of non-compliant individuals cannot fluctuate much. Thus, the scope of the study was expanded to include all individuals in the sampled classrooms.

Another comparison was made using the same shading scheme but with different conditions. In one set of comparisons, dynamic shading was added and compared with the case where no dynamic shading was used, both during the same time period (8 am to 6 pm). In the second set of comparisons, with no dynamic shading used, different time periods (8 am to 6 pm and 8 am to 4 pm) were compared. The results are shown in Figure 3.2.

As shown in Figure 3.2, even within the same shading scheme, different usage habits and time periods can lead to different daylighting simulation results, which in turn affect the relationship between the "lighting environment compliance line" and the number of non-compliant individuals. This also demonstrates that varying climate conditions create different objective limitations, and a fixed standard value cannot be used for absolute judgment. Instead, the standards must be dynamically adjusted based on local climatic conditions for evaluation.

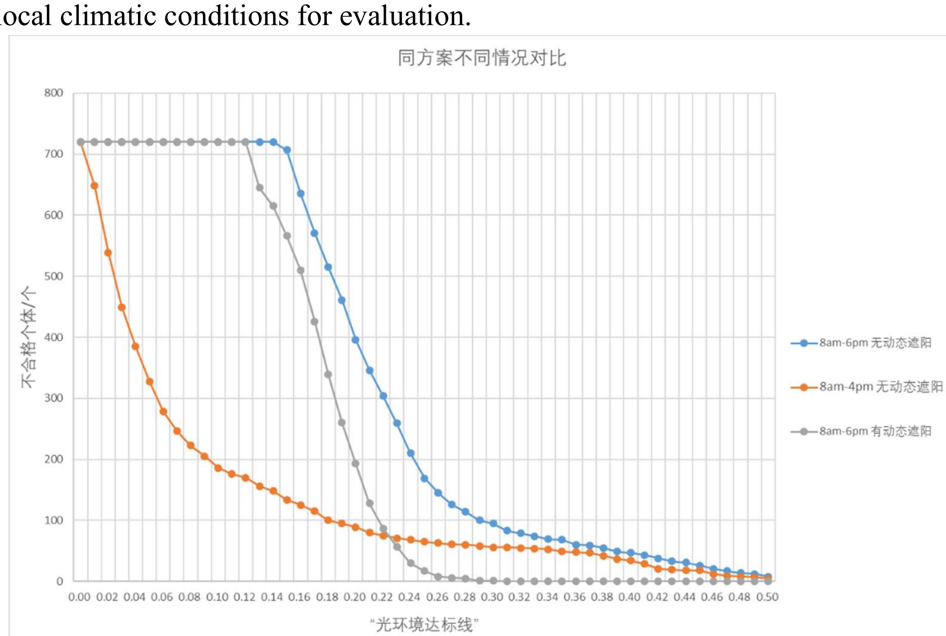


Figure 3.2 Comparison of Results for Different Time Ranges and the Inclusion of Dynamic Shading

3.3 Establishment of the "Lighting Environment Compliance Line"

In this study, the "lighting environment compliance line" was determined by simulating the lighting conditions for all individuals within the sampled classrooms across all shading schemes. A total of 48 seats were sampled, with the sample points aligned with the desk positions. The sample points were set at 760mm above the ground, which is 10mm above the desk surface, to avoid errors caused by overlapping with the desk surface (height of 750mm).

The UDI (Useful Daylight Illuminance) values were analyzed in detail. The time ratio of insufficient daylight (less than 300lx), the time ratio of adequate daylight (between 300lx and 3000lx), and the time ratio of overexposure (greater than 3000lx) were summed to calculate the "poor daylight utilization time ratio." This ratio was then compared with different standard values to establish the "lighting environment compliance line." The analysis aimed to observe the trends in the number of non-compliant individuals under different compliance lines and to find a critical threshold.

Through rough estimations, the smallest standard line was set at 0%, and the highest at 50%. Specific ranges with significant changes in non-compliant individuals were identified, such as 0%-5%, 10%-25%, and so on. A rough count of non-compliant individuals was performed for these ranges.

The results, shown in Figure 3.3, demonstrate the relationship between non-compliant individuals and the "lighting environment compliance line" across the 11 different shading schemes. When the compliance line is set more strictly, the north-facing lighting schemes, Scheme 2 and Scheme 6, have significant advantages. This may be because, for these schemes, the "excessive daylight time ratio" accounts for a large portion of the overall "poor daylight utilization time ratio."

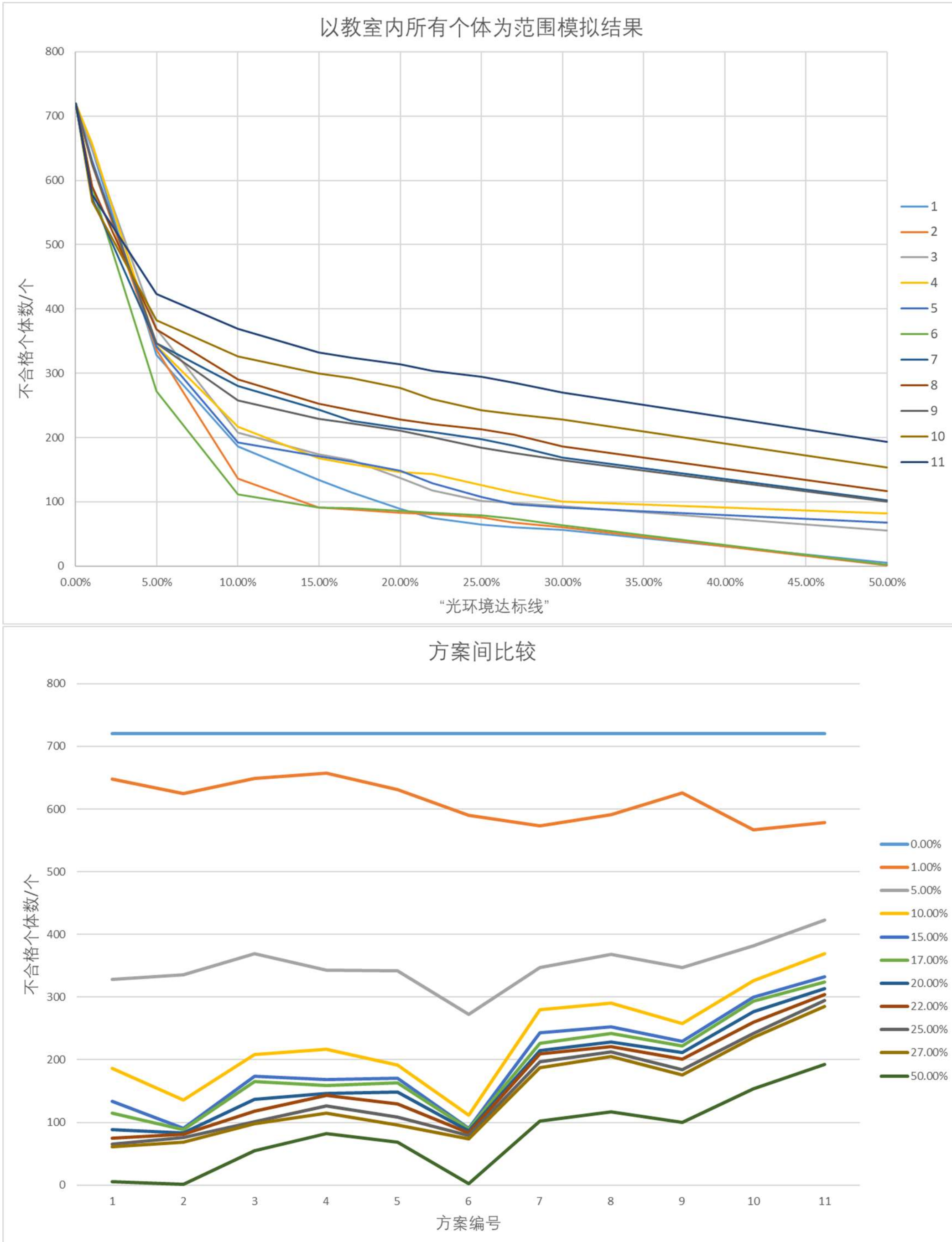
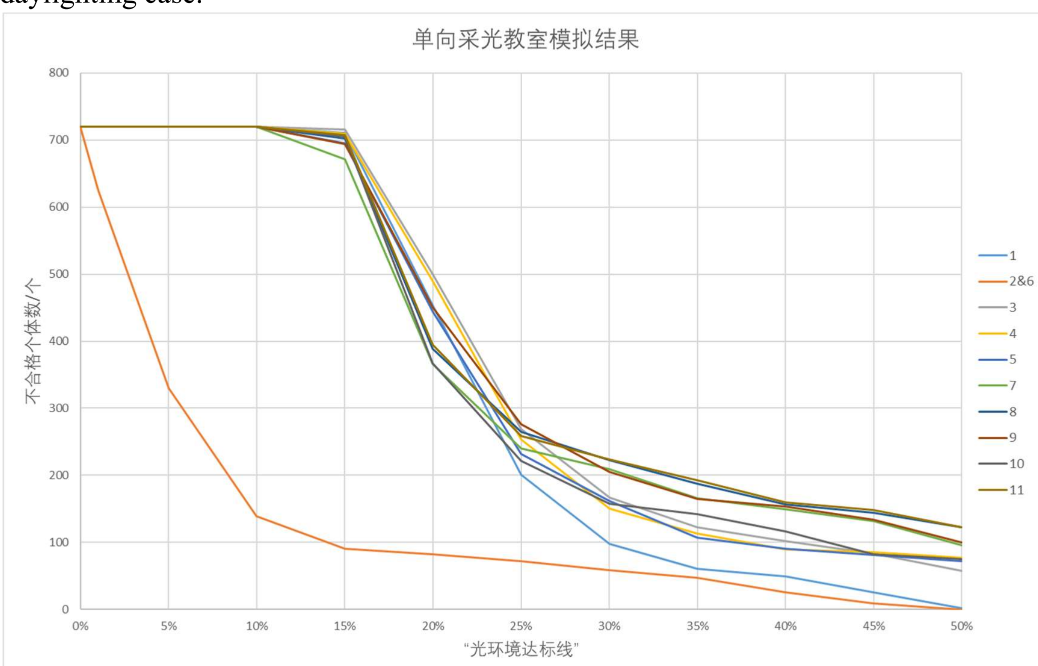


Figure 3.3 Simulation Results for All Individuals in the Classroom

For this simulation, a preliminary comparison of different shading schemes showed that, aside from the two north-facing lighting schemes, Scheme 1 (the double-sided light guide shading scheme) performed the best, aligning closely with the findings from column-based studies. During the process of testing different "lighting environment compliance lines," it was observed that the number of non-compliant individuals significantly dropped when transitioning from a 1% to a 5% compliance line. This suggests that lowering the compliance standard slightly can allow more individuals to meet the requirements, and therefore, it is recommended that the "lighting environment compliance line" be set within this range.

In addition, to compare daylighting conditions in school buildings under different scenarios, the same shading schemes were applied in simulations for single-sided daylighting school buildings. The scope of the study for these simulations was consistent with the dual-sided daylighting conditions discussed in this section, with all desks in the sampled classrooms being evaluated. The results are shown in Figure 3.4. The advantages of the two north-facing schemes became even clearer. Aside from these two schemes, Scheme 1 (the double-sided light guide shading scheme) still demonstrated significant advantages. However, the range within which the number of non-compliant individuals significantly decreased differed slightly in the dual-sided daylighting case.



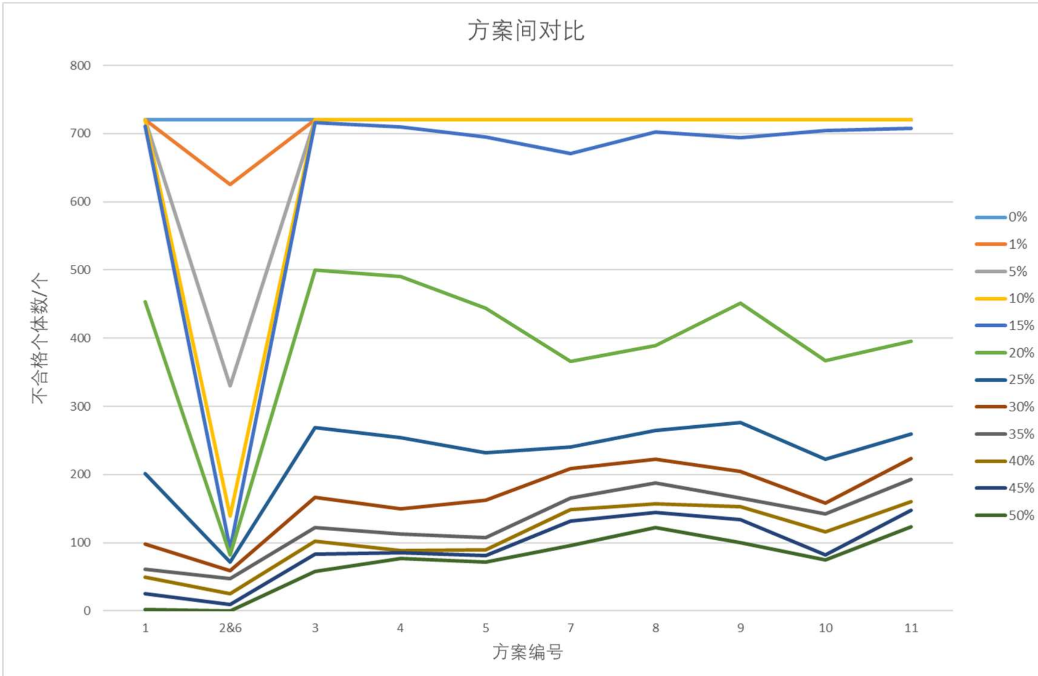


Figure 3.4 Simulation Results for Single-sided Daylighting Classroom

To determine the "lighting environment compliance line," more detailed research was conducted using the simulation results from Figure 3.3 , which included 48 sample points for the entire classroom under the dual-sided daylighting scenario. The range for testing the "lighting environment compliance line" was further refined. Specifically, within the 0%-50% range, a 1% increment was applied to evaluate all sampled individuals in each scheme. The resulting curve, which shows the relationship between the "lighting environment compliance line" and the number of non-compliant individuals, is presented in Figure 3.5.

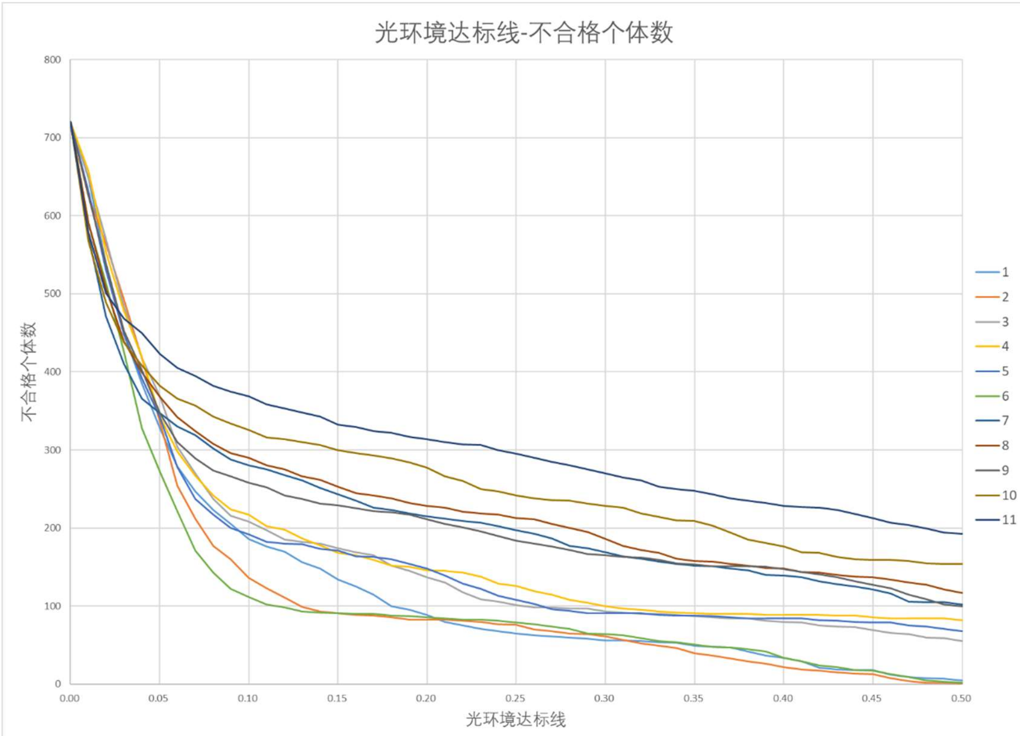


Figure 3.5 Compliance Line vs. Non-compliant Individual Curve (1% Precision)

By calculating the slope for each 0.01 interval on the curve, the point at which the number of non-compliant individuals decreases most sharply for each shading scheme can be identified. The point of the greatest change is defined as the "lighting environment compliance line." The "lighting environment compliance line" for each scheme is shown in Table 3.1.

Table 3.1 "Lighting Environment Compliance Line" for Each Scheme

Scheme	1	2	3	4	5	6	7	8	9	10	11
Compliance Line	2%	1%	3%	2%	2%	1%	1%	1%	1%	1%	1%

In the interim conclusion, an objective relationship can be established between the "lighting environment compliance line" and the number of non-compliant individuals across the 11 shading schemes. In Chapter 3, various simulations using different ranges and models determined the most appropriate evaluation range under the newly established standards. Additionally, by calculating the slope, the "lighting environment compliance line" for each shading scheme was determined.

However, for individuals using the classroom, different lighting conditions cannot be generalized solely based on the relationship between the "lighting environment compliance line" and the number of non-compliant individuals. It is also necessary to consider the impact of different levels of illuminance within the appropriate range. Additionally, it must be evaluated whether different poor lighting conditions produce the same adverse effects and whether the effects of lighting change non-linearly over time as they accumulate.

Therefore, a more detailed discussion and calculation are needed regarding individuals' experiences in the classroom lighting environment.

4 Establishment of the Utility Model

From the above, aside from the objective correlation between the "lighting environment compliance line" and the number of non-compliant individuals, other factors should also be considered. This study will further refine the impact of lighting on individuals and also consider how to calculate a more accurate "lighting environment compliance line" rather than relying on rough estimates. A more detailed mathematical model needs to be established.

The main issue to be addressed is how to quantify the positive impact of the lighting environment on individuals in a visible and comparable numerical form, while incorporating other relevant factors into the result.

4.1 Theoretical Model

As discussed at the end of Chapter 3, the relationship between the "lighting environment compliance line" and the number of non-compliant individuals is inverse. However, using just a single "lighting environment compliance line" for evaluation may not be detailed enough. With stable data regarding the lighting environment, an overall evaluation of each individual's experience can be performed using existing data. This is where the concept of utility from economics comes in handy, representing the degree to which a consumer's needs are satisfied when consuming goods or services.

To calculate the utility that an individual derives from the lighting environment in the classroom, a stepwise logical mathematical model must be developed. First, it is essential to extract the variables that affect the utility of the lighting environment and establish relationships between them. Next, based on different dynamic dimming preferences, it is known that people have different preferences for various illuminance ranges, and these preferences must be considered. Furthermore, the time factor must be accounted for since long durations of poor lighting conditions may lead to a nonlinear increase in negative effects. Lastly, a determination of whether an individual meets the "compliance" criteria should be factored into the utility calculation.

Once a utility model is established, the lighting conditions at each seat can be evaluated, and the total utility of the classroom's shading solutions can be calculated, allowing for comparison between different shading schemes. This method ensures that both individual and overall classroom effects are considered, without neglecting outliers due to statistical averaging.

4.2 Classroom Lighting Environment Utility Model for Individuals

4.2.1 Descriptive Statistics

For all individuals in the classroom, simulated data were collected, and the average illuminance (Mean Lux) was chosen as a key metric to describe the lighting conditions for each seat. The aim is to provide an estimate of lighting conditions across all scenarios and shading schemes. Data were collected from 15 sampled classrooms, each with 48 seats, and the average value for each seat was calculated to represent the lighting conditions for a “standard” classoom. The SPSS statistical software was used to perform descriptive statistical analysis on the dataset, including calculating the mean, extreme values, and standard deviation, and visualizing the data through histograms. The results are presented in .

Table 4.1 Descriptive Statistical Data Results

Project	Mean Value	Std. Err	Min	Max	Std. Dev	Range
1	1513.263	166.7412	578.04	4848.34	1155.217	4270.3
2	1235.272	92.61007	655.05	2842.88	641.6214	2187.83
3	1884.018	27.79933	1405.63	2119.21	192.5994	713.58
4	2026.018	335.72	580.88	8866.51	2325.937	8285.63
5	2001.733	330.5804	546.56	8606.32	2290.328	8059.76
6	1323.9777	89.72612	680.68	2889.11	621.64078	2208.43
7	2533.35	341.4178	771.55	9117.19	2365.412	8345.64
8	2975.064	417.2299	785.49	10547.56	2890.653	9762.07
9	2848.292	470.3912	657.53	11694.73	3258.966	11037.2
10	3276.458	431.6849	807.74	10771.13	2990.801	9963.4

Project	Mean Value	Std. Err	Min	Max	Std. Dev	Range
11	4160.4048	597.71494	922.84	14564.79	4141.09059	13641.95

Based on the results shown in Table 4.1, there are significant differences between the 11 shading schemes. Scheme 11 has the highest average illuminance value, while the two north-facing schemes (Scheme 2 and Scheme 6) have relatively lower average values. In all schemes, the minimum illuminance values exceed 300lx, indicating that most of the seating positions meet the basic lighting requirements for reading and writing. However, in most cases, except for Schemes 2, 3, and 6, the maximum values exceed 3000lx, suggesting that over-illumination is quite common.

Additionally, there are noticeable variations between individuals in all shading schemes. The wide range of illuminance values reflects uneven distribution across the desk surfaces in the classrooms, and this variability is further highlighted by the large standard deviations. Only Scheme 3 appears relatively stable compared to the others. This individual variation is also clearly demonstrated in Figure 4.1 , where the distribution of illuminance levels is plotted on a histogram. The x-axis represents different illuminance intervals (in 1000lx units), and the y-axis indicates the frequency of results falling within each interval for a "standard" classroom. It can be seen that the distribution patterns of the 11 schemes differ significantly, and none of them follow a normal distribution. There is no strong correlation or clear pattern among the data, and the distribution is rather dispersed. This further emphasizes the importance of building evaluation models based on individual circumstances.

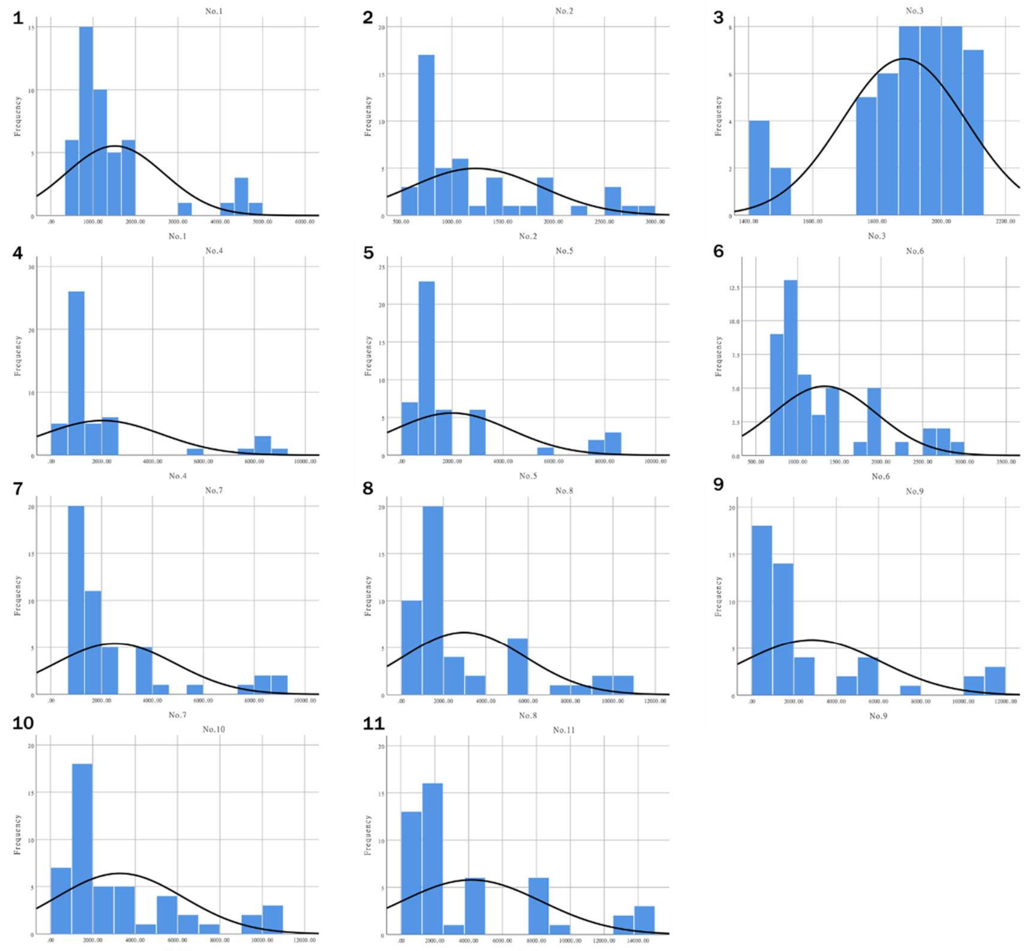


Figure 4.1　　Histogram of a "Standard" Classroom in 11 Shading Schemes

4.2.2 Model Establishment

The comparison and ranking of different shading schemes are determined by the utility derived from the lighting environment experienced by individuals. This section focuses on a more detailed study of illuminance, so the first variable extracted is the average illuminance (E) Since students spend extended periods in classrooms, another key factor to consider is the autonomy time ratio of Useful Daylight Illuminance (UDI_a), which reflects the proportion of time when daylight conditions meet the preferred illuminance range. Using these two variables, the utility U_i for each individual can be defined as (4-1)：

$$U_i = W_E \times |E - E_0| + W_{UDI} \times UDI \tag{4-1}$$

Where:

- W_E and W_{UDI} represent the respective weights of illuminance (E) and UDI,
- E_i is the average illuminance for individual *i*,

For each individual in each shading scheme, the desk illuminance parameters Eand UDI_a can be used to calculate the corresponding weights based on the coefficient of variation method.。

The UDI_a is the proportion of time that daylight conditions fall within the optimal illuminance range (300lx to 3000lx). This indicator is positively correlated with the utility value, meaning that a higher UDI_a leads to a better lighting environment. On the other hand, E represents the average illuminance, and the optimal value for natural daylight in a classroom E_0 is set at 500lx according to the standards. In the formula, the deviation from this optimal value, $|E-E_0|$, is minimized, so the closer E is to 500lx, the better the utility. To standardize $|E-E_0|$, the following formula is applied to transform the deviation into a positive measure:

$$E_i^{'} = \frac{1}{\max|E - E_0| + |E - E_0|_i} \tag{4-2}$$

Where Ei′ represents the transformed illuminance value for individual *i*. This positive transformation ensures that smaller deviations from the optimal value correspond to higher utility. The equation can be iterated into(4-3), also use $E_i^{'}$ for the coefficient calculation:

$$U_i = W_E \times E_i^{'} + W_{UDI} \times UDI \tag{4-3}$$

By calculating the utility for all 48 seating positions in a classroom, a utility score can be generated for each individual. Table 4.2 illustrates an example of how these weights are calculated using the coefficient of variation method for the 0th seat in Scheme 1.

Table 4.2 Coefficient of Variation Method Weights for E and UDI_a (Example: Seat 0 in Scheme 1)

Seat Number		Standard Deviation (σ)	Mean Value (μ)	Information content ((K=σ/μ)	Weight (Wi=Ki/ΣK)
0	E	0.000002656	0.000238218	0.011149044	0.122841306

Seat Number	Standard Deviation (σ)	Mean Value (μ)	Information content ((K=σ/μ)	Weight (Wi=Ki/ΣK)
UDI_a	0.057662856	0.7243105	0.079610686	0.877158694

Additionally, two effects should be considered when calculating the utility for individuals besides UDI and E: instantaneous effects and cumulative effects. Instantaneous effects arise from an individual's preference for specific illuminance levels, while cumulative effects result from prolonged exposure to poor lighting conditions, which can lead to visual fatigue. Both effects must be factored into the overall utility calculation.

1) Instantaneous Effects

According to the dynamic dimming preference experiment, people's preferences for different illuminance levels show a certain degree of clustering, offering more detailed insights compared to the UDI standard. Based on Boyce's [17] dynamic dimming preference experiment, displays the range of illuminance selected by different participants throughout the day and the corresponding proportions. The findings are shown in Table 4.3. From this table, it can be concluded that when the desk illuminance in a workspace falls between 100lx and 1200lx, there is a certain distribution of preference proportions.

Table 4.3 Distribution of People's Preferences for Desk Illuminance Based on Boyce's Experiment

Illuminance Range (lx)	100-200	200-300	300-400	400-500	500-600	600-700	700-800	800-900	900-1000	1000-1100	1100-1200
Preference Proportion	0.0%	9.1%	51.5%	12.1%	6.1%	9.1%	3.0%	6.1%	0.0%	0.0%	3.0%

In this experiment, due to the limitations of the selected dimming range, the calculated preference dynamic dimming range needs to be extended to below 100lx and above 3000lx. The preference distribution of 33 participants for different illuminance intervals from the referenced study is visually represented in Figure 4.2 as scatter points. To predict the preference proportions for illuminance levels outside the 100lx-1200lx range, a segmented nonlinear regression was applied to the scatter plot, resulting in the curve shown in the figure.

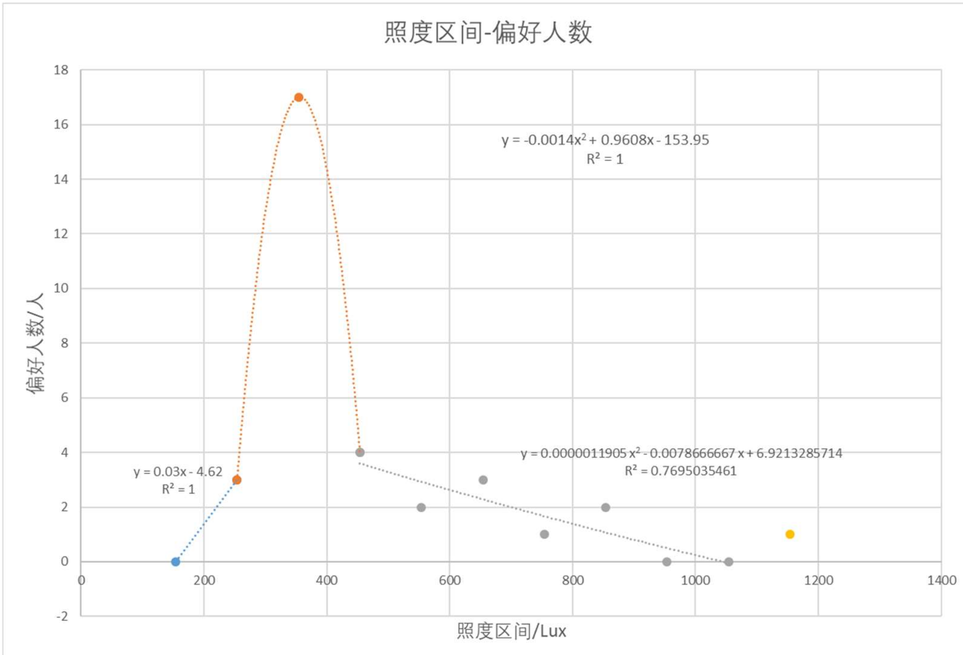


Figure 4.2 Scatter Plot of Illuminance Range vs. Preference Proportion

In Boyce's experiment, due to limitations in the lighting fixtures and controllers, the illuminance range varied approximately between 100lx and 1200lx. For this range, which has actual data, the illuminance was binned in increments of 100lx. For other ranges, they were roughly divided into >3000lx, <100lx, and 1200lx-3000lx. Using the fitted function from the chart, the preference proportions for the other ranges can be estimated. At this point, the sum of all the proportions will not equal 1, so the proportions need to be recalculated to ensure they sum to 1. The complete table of desk illuminance and preference proportions is shown in the corresponding table.

Table 4.4 Desk Illuminance and Preference Proportion Table

Illuminance Range (lx)	<100	100-200	200-300	300-400	400-500	500-600	600-700

Preference Proportion (%)	-17.00%	0.00%	16.35%	92.63%	21.79%	15.96%	12.45%

Illuminance Range (lx)	700-800	800-900	900-1000	1000-1100	1100-1200	1200-3000	>3000
Preference Proportion (%)	9.08%	5.84%	2.72%	-0.26%	-3.11%	-23.76%	-32.69%

Based on different individual preferences, the UDI can be weighted accordingly for different illuminance levels with a corresponding weight P. The value of P is derived from the preference proportions of participants in the desk lamp dimming preference experiment. Based on this, the UDI-related formula is rewritten as follows, resulting in:

$$UDI_i = \sum P_i UDI_i \tag{4-4}$$

2) Cumulative Effects

In cases where the lighting is insufficient, visual fatigue tends to worsen over time. UDI is divided into two parts: one for normal lighting conditions (100lx-3000lx) and one for poor lighting conditions (outside this range). Considering that the issue of "insufficient lighting" can be addressed through individual lighting design adjustments, while using dynamic shading to mitigate "over-illumination" may negatively affect other individuals in the classroom, the accumulated negative effects of insufficient lighting are relatively smaller. The preference ratios for illuminance levels below 100lx and above 3000lx discussed earlier in the section on instantaneous effects also support this assumption. This study adopts this assumption and uses the preference ratios from the previous discussion.

To further refine the analysis of poor lighting conditions, the study categorizes different illuminance intervals with poor lighting. The cumulative duration of exposure to poor lighting and individual preferences for different poor lighting conditions are the variables that influence the results. Here, a constant T is introduced, representing the critical time for the accumulation of visual fatigue. The study attempts to compare two independent variables against the constant T, specifically UDI, and the objective duration of poor lighting conditions.

Using the formula related to UDI_i in Equation (4-4) for iteration, and after unifying the dimensions for comparison with the UDI value, a mathematical model is constructed as follows:

$$UDI_i = \sum P_{正常} t_{正常} + \sum P_{<100lx}(t_{<100lx} - T) + \sum P_{>3000lx}(t_{>3000lx} - T) \quad (4\text{-}5)$$

Referring to Rui Dang's research experiment on visual fatigue [13], participants reported experiencing visual fatigue after 15 minutes. Thus, the constant T is set at 15 minutes. In this mathematical model, the values of, $P_{<100lx}$and $P_{>3000lx}$ are negative. When the duration of poor lighting does not exceed 15 minutes, the utility derived from poor lighting conditions remains positive, but the longer the duration, the smaller the utility becomes. If the cumulative time exceeds 15 minutes, the utility turns negative, leading to adverse effects.

Considering all the above-influencing factors, based on Equation(4-5), the utility impact of UDI for each scheme is shown in Table 4.5.

Table 4.5 UDI Utility Results for Each Scheme Based on Equation(4-5)

Shading Scheme	1	2	3	4	5	6
UDI Utility	46.0003	73.04037	10.31859	-56.5515	-21.061	47.00467

Shading Scheme	7	8	9	10	11
UDI Utility	-211.202	-234.297	-191.729	-320.974	-447.439

If UDI and the constant T are used for comparison and discussion, the mathematical model is constructed as follows:

$$UDI_i = \sum P_{正常} UDI_{正常} + \sum P_{<100lx}(UDI_{<100lx} - T) + \sum P_{>3000lx}(UDI_{>3000lx} - T) \quad (4\text{-}6)$$

According to Equation(4-6), under this model, the utility for each scheme is discussed and shown in Table 4.6.

Table 4.6 Utility Results for Each Scheme Based on Equation (4-6)

Shading Scheme	1	2	3	4	5	6
UDI Utility	69.63045	63.09129	78.14285	57.27329	69.25283	42.91193

Shading Scheme	7	8	9	10	11
UDI Utility	0.276167	0.100673	22.07739	-17.9603	-41.4911

4.3 Utility Calculation Model

4.3.1 Overall Utility Gained by Individuals

Based on the results from Table 4.5 and Table 4.6, we can derive the stage utility results after applying the two-layer progressive logic of UDI. These two sets of results are substituted into Equation (4-3), which gives the utility of each individual before applying the compliance standard. The total utility for each scheme is calculated by summing the utilities of all individuals, providing a quantifiable utility value U for the lighting environment. The calculation formula is as follows (4-7):

$$U = \sum U_i \tag{4-7}$$

The total utility for the sampled individuals in the 11 shading schemes is shown in Table 4.7 and Table 4.8 corresponding to the two scenarios discussed in Section 4.2.2 . The comparison of scheme data is illustrated in Figure 4.3.

Table 4.7 Total Utility Results for Each Scheme Based on Equation (4-3) (Corresponding to Table 4.5)

Shading Scheme	1	2	3	4	5	6
Total Utility Value	30.29758	0.357465	-2.40758	-59.3812	-34.2882	-18.6746

Shading Scheme	7	8	9	10	11
Total Utility Value	-194.989	-210.549	-183.131	-293.718	-407.628

Table 4.8 Total Utility Results for Each Scheme Based on Equation (4-3) (Corresponding to Table 4.6)

Shading Scheme	1	2	3	4	5	6	7	8	9	10	11
Total Utility Value	44.98388	21.26815	54.21828	35.37166	45.42548	10.11923	-12.1593	-11.1319	7.393726	-26.7529	-43.848

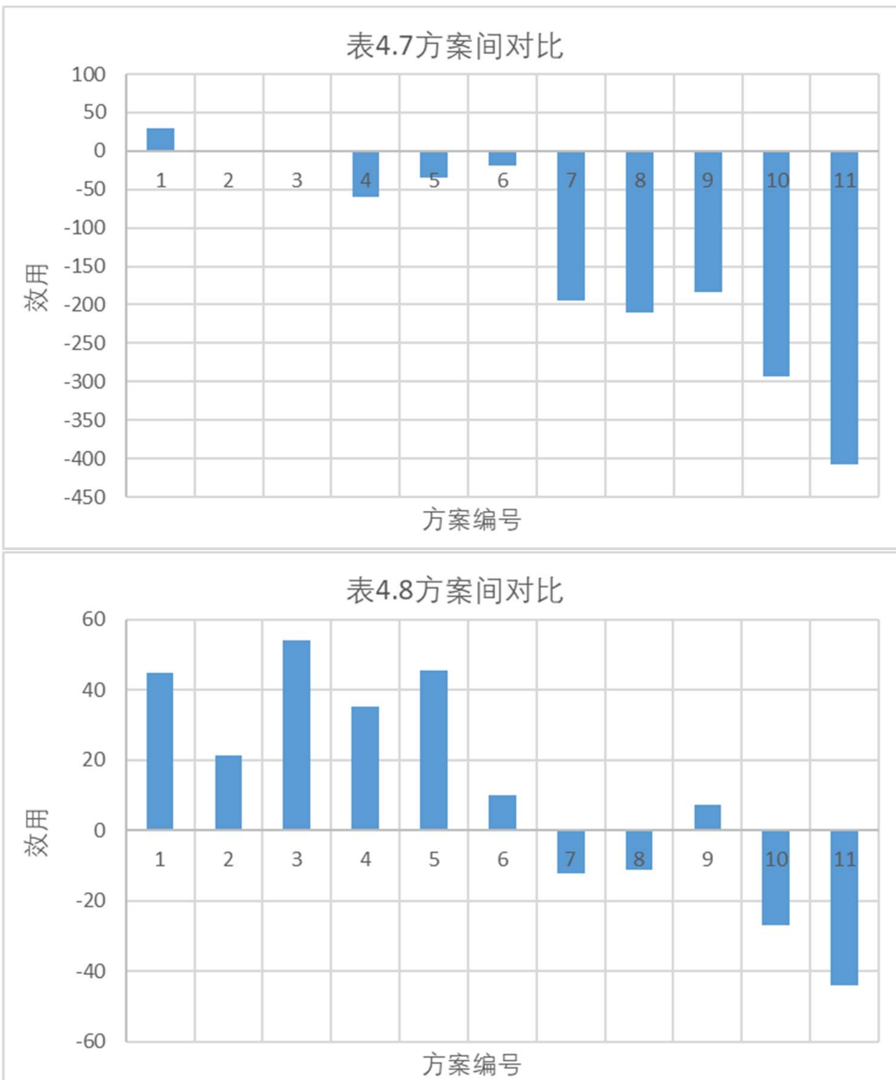


Figure 4.3 Comparison of Total Utility Values for Each Shading Scheme

4.3.2 Utility Model After Compliance Judgment

In Section 4.3.1 , the process of calculating the utility of the dataset obtained from the simulation was demonstrated. This approach allows the utility for each individual to be calculated. However, to describe the overall characteristics of the shading schemes while focusing on individuals, we need to include the compliance judgment discussed in Section 2.3 . The following mathematical model (Equation 4-8) is established to solve this issue:

$$U = \sum (k \times U_i) \tag{4-8}$$

In this formula, k is a compliance judgment coefficient that quantifies whether individual iii is a "non-compliant individual." If the individual passes the "lighting environment compliance line" judgment, k=1; if not, k=0.8. This method introduces the compliance judgment results into the utility calculation, allowing a comprehensive evaluation of the scheme. The results of the calculations based on Equation (4-8) are shown in Table 4.9 and 0, with the comparison of utility values between schemes shown in Figure 4.4.

Table 4.9 Total Utility Results for Each Scheme Based on Equation (4-8) (Corresponding to Table 4.5)

Shading Scheme	1	2	3	4	5	6
Total Utility Value	27.47339	0.789057	2.939035	-43.8036	-23.8106	-14.1614

Shading Scheme	7	8	9	10	11
Total Utility Value	-154.203	-166.449	-144.964	-232.851	-323.731

Table 4.10 Total Utility Results for Each Scheme Based on Equation(4-8) (Corresponding to Table 4.6)

Shading Scheme	1	2	3	4	5	6
Total Utility Value	37.47544	17.07571	45.9532	30.13211	38.18901	8.249921

Shading Scheme	7	8	9	10	11
Total Utility Value	-9.04515	-8.09969	6.514692	-20.574	-34.1802

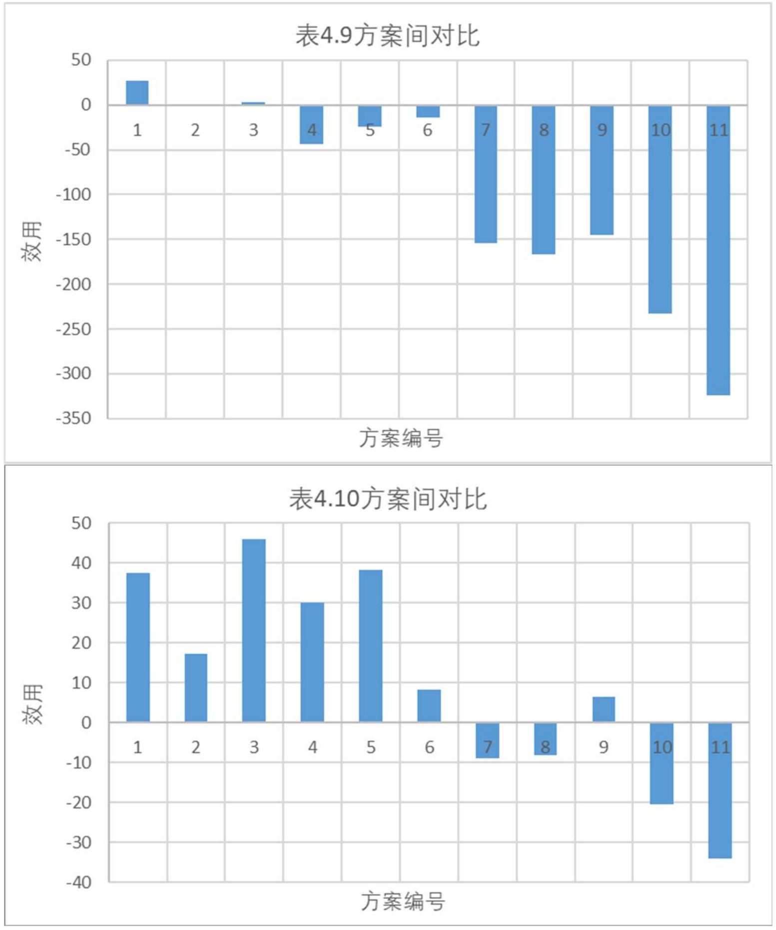


Figure 4.4 Comparison of Individual Utility After "Lighting Environment Compliance Line" Judgment for Different Shading Schemes

5 Conclusion and Outlook

5.1 Conclusion

5.1.1 Model Function Summary

This study establishes a new strategy standard to address the issue of how to select classroom lighting environment strategies based on individual lighting environment assessments. It also discusses how to further quantify the positive impact of classroom lighting on users.

The evaluation standard proposed in Section 2.3 can provide a reference for lighting environment standard setters. By using sampled daylighting data from standard school buildings, a “lighting environment compliance line” suitable for the region can be calculated and applied to classrooms in other school buildings within the same area. Compared to existing standards, this new standard focuses more on individual differences in lighting conditions within the same classroom, evaluating the overall performance based on individual assessments.

In Chapter 4 , the concept of utility from economics was introduced to describe and quantify the positive effects of the lighting environment on individuals. Two-step logic (instantaneous effects and cumulative effects over time) was used to discuss the potential impact of various factors. A mathematical model was established, allowing utility to be calculated for each individual in 48 positions across 15 sampled classrooms for each scheme. This can be used for analysis, statistics, or comparison of individual lighting conditions in real-world applications (e.g., focusing on individuals with poorer lighting conditions or identifying overall distributions of individual lighting utility).

By combining the results of Section 2.3 and Chapter 4 in mathematical modeling, it is possible to integrate individual-focused standards into utility calculations when describing the overall lighting environment for a particular shading scheme. The results provide an overall lighting utility for each scheme, particularly focused on individuals, which can serve as a new reference standard for selecting shading solutions in classrooms.

5.1.2 Shading Scheme Evaluation

Using Climate Studio, the daylighting conditions for a standard classroom building under the climate of Linyi were simulated. These results were then applied to the model established in this study, yielding the following outcomes:

1) The “lighting environment compliance line” varies among the different daylighting schemes. The compliance line-individual non-compliance curve suggests that Schemes 1, 2, 3, 5, and 6 provide better lighting conditions;

2) Without applying the newly proposed individual evaluation standard from Section 2.3 , two sets of results were obtained for the individual lighting utility calculations. The top five shading schemes in the two results are ranked as: 1>2>3>6>5 and 3>5>1>4>2;
3) After applying the new standard for individual assessment and incorporating the assessment results into the utility calculation, the top five shading schemes are ranked as: 1>3>2>6>5 and 3>5>1>4>2;

5.2 Research Limitations

5.2.1 Simulation Error Analysis

This study is based on data obtained from software simulations to develop the model. Due to geographical limitations, actual field measurements were not conducted. The simulation results may differ from real-world measurements, possibly because factors like tree density or nearby buildings might block more light than the simulation accounted for. As a result, the simulated results tend to show brighter conditions, which led to stricter "lighting environment compliance lines" compared to what may be observed under actual conditions.

In addition, Climate Studio, as a building performance analysis software, uses the Radiance engine to simulate light through a progressive path tracing method. In each calculation, an initial estimated value is collected, and then the tracked light paths are accumulated to reduce noise. This dynamic process leads to slight variations in data between simulations, even when the same model and parameters are used. When comparing different models, there may be small discrepancies due to this variability.

5.2.2 Time and Sampling Error Analysis

Due to limitations in time and technology, this study only simulated classroom lighting under the climate conditions of Linyi. Therefore, the conclusions may not be applicable to the assessment of school building lighting conditions in other cities. Additionally, only illuminance and UDI variables were considered in this study, without taking into account other factors such as the uniformity of illuminance. Furthermore, the simulation used hourly illuminance data, which is relatively coarse.

Higher resolution data, such as minute-level data, could make the model more precise and reflective of real-world conditions.

Due to time constraints, the model was not tested in practical scenarios, such as providing guidance for lighting design. This results in certain theoretical limitations of the model. In the future, practical applications and comparisons with other research findings will be needed to validate the model and ensure its broad applicability.

The above limitations can be further improved through continued discussion and research.

5.3 Future Application of the Model

The study proposes a new method for evaluating classroom lighting environments and establishes a model for this purpose. The model can be used to update existing school building lighting evaluation standards by refining them to assess individual lighting conditions.

For example, in the standard "T/CIES 030-2020 Health Lighting Design Specifications for Primary and Secondary School Classrooms," although it is one of the relatively new, detailed, and targeted standards, there is still a lack of detailed guidance on the selection of shading schemes. In Section 4.3.1 , the recommendation "when the natural daylight illuminance on the desk surfaces near the windows exceeds 3000lx, a shading system should be used to reduce the illuminance" could be updated to: "when the natural daylight illuminance on the desk surfaces near the windows exceeds 3000lx, refer to Section 6.1.3 for shading design guidance and choose the lighting scheme that offers the best results according to the local climate conditions and usage habits."

In Section 5.1.2 on shading design, the recommendation could be updated to: "For south-facing classrooms, it is recommended to calculate the 'lighting environment compliance line' based on local climate data. Schools in the area can use this 'lighting environment compliance line' in the classroom lighting utility model to calculate the total lighting utility for each scheme and compare them to determine the optimal scheme."

Although the comparison between shading schemes in this study has certain limitations due to data discrepancies, it provides a feasible evaluation tool. Shading schemes can be selected based on local climate conditions and data, rather than directly opting for the most widely used shading methods on the market.

On the other hand, the conclusions and the modeling approach in this study can guide future classroom lighting design. Each individual's lighting environment can be reassessed using the integrated illuminance data. This model can be used to calculate the lighting utility experienced by each person in the post-lighting environment, aiming to optimize utility to the greatest extent possible.

Illustration Index

Table Index

Reference

[1] LLORENS-GÁMEZ M,HIGUERA-TRUJILLO J L, OMARREMENTERIA C S,et al.The impact of the design of learning spaces on attention and memory from a neuroarchitectural approach: A systematic review[J].Frontiers of Architectural Research,2022,11(3):542-560.

[2] Barrett, Peter & Davies, Fay & Zhang, Yufan & Barrett, Lucinda. (2015). The impact of classroom design on pupils' learning: Final results of a holistic, multi-level analysis. Building and Environment. 59. 10.1016/j.buildenv.2015.02.013.

[3] Galasiu A D, Veitch J A. Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review[J]. Energy and buildings, 2006, 38(7): 728-742.

[4] Villa C, Labayrade R. A suitable and energy-efficient luminous environment for a shared office[J]. Lighting Research & Technology, 2016, 48(6): 755-770.

[5] Singh P, Arora R. Classroom illuminance: Its impact on students' health exposure & concentration performance[C]//Proceedings of the International Ergonomics Conference HWWE. 2014.

[6] Castilla N, Llinares C, Bravo J M, et al. Subjective assessment of university classroom environment[J]. Building and Environment, 2017, 122: 72-81.

[7] 崔思瑶,张昕.位置如何影响大学生自习行为的认知和评价——一项基于神经建筑学视角的自然实验世界建筑,2022(11):114-115.DOI:10.16414/j.wa.2022.11.015.

[8] 潘翠萍,邓胜芝.山东省乐陵市 80 所中小学校教室采光照明检测结果[J].河南预防医学杂志,2022,33(08):616-618+626.DOI:10.13515/j.cnki.hnjpm.1006-8414.2022.08.015.

[9] 中华人民共和国住房和城乡建设部. GB50099-2011 中小学校设计规范[S]//中华人民共和国国家标准. 北京: 中国建筑工业出版社, 2010.

[10] 中华人民共和国住房和城乡建设部. GB 50033-2013 建筑采光设计标准[S]//中华人民共和国国家标准. 北京: 中国建筑工业出版社, 2012.

[11] 中国照明学会. T/CIES 030-2020 中小学教室健康照明设计规范[S]

[12] 张昕,周昕怡,陈晓东.从“教室采光”到“课桌采光”——基于不良利用时间占比的中小学教室采光标准重评估[J].世界建筑,2021(03):36-41+126.DOI:10.16414/j.wa.2021.03.008.

[13] Sun B, Zhang Q, Cao S. Development and implementation of a self-optimizable smart lighting system based on learning context in classroom[J]. International journal of environmental research and public health, 2020, 17(4): 1217.

[14] Miraoui M. A context-aware smart classroom for enhanced learning environment[J]. International Journal on Smart Sensing and Intelligent Systems, 2018, 11(1): 1-8.

[15] Yuan B, Li J, Liu Z, et al. Research on Classroom Lighting Energy Saving System Based on YOLOv3[C]//Journal of Physics: Conference Series. IOP Publishing, 2021, 1871(1): 012007.

[16] Rui Dang, Yuxing Liu, Suo Chang, The impact patterns of classroom lighting parameters on visual fatigue and a mathematical model, Building and Environment, Volume 234, 2023, 110193, ISSN 0360-1323.

[17] Boyce PR. Veitch JA, Newsham GR, Jones CC,Heerwagen J,Myer M,Hunter CM. Occupantuse of switching and dimming controls in offices. Lighting Research and Technology 2006:38:358-378.

[18] GB7793-2010 中小学校教室采光和照明卫生标准