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# Experimental study on the effectiveness of internal shading devices

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ABSTRACT

These days, many studies are about the performance of some shading devices. Many engineers think the performance of internal shading systems is inferior to external systems. Because when using internal shades, the solar heat has already entered the internal spaces and has become trapped. However, in real applications, external shading is difficult to use, easily damaged and prone to dirt buildup. Internal shading is more flexible, cheaper and easier to repair. Some engineers doubt the validity of this traditional thinking and believe internal shading may be effective and useful to some extent because many occupants use internal blinds to minimize air conditioning costs. In this paper, the possibility of substituting the external shades with an internal ones using high reflectivity materials was studied through experimental tests and simulation validations. The results indicate that an internal shading system may be as effective as an external system if proper materials are used. Such substitution can reduce the overall cost of a shading system and can provide flexibility to the design of building facades. A grey relational analysis of the internal shade optimization is further presented so that the significant factors influencing the internal shading device performance are better understood. These factors should be taken into consideration during the design.

## 1. Introduction

Energy efficient and good daylighting design is receiving increasing attention as environmentally friendly buildings are becoming more popular. Using suitable shading devices can reduce the energy consumption, and meanwhile, daylighting requirements that illumination levels in buildings be kept within an acceptable range with no or little glare. Therefore, shading devices are well suited to provide protection against excessive solar radiation and decrease a building's cooling load during summer.

In traditional view, the energy-saving effect of internal shading device is far lower than that of external one [1]. But if internal shading devices can get the similar energy-saving effect to external ones, and be used instead of external ones, the designers can be free to design the appearance of buildings, can be more convenient to change the devices, and can reduce the expense of construction. Many studies have compared the influence of different types of shading devices on the energy needs and cooling or heating demands in buildings [2,3]. The effect of external vertical and horizontal shading devices was examined by Alzoubi and Al-zoubi [4], who addressed the quality of daylight in buildings and the associated energy savings for three common positionings. Kim [5] developed a series of simulations and measurements to verify the energy savings provided by external shading devices. The effect of different shading devices and shading control strategies for visual and thermal comfort combined with energy use has been analysed in several studies [6–9]. Frontini and Kuhn [10] investigated the effect of coatings with various internal blinds on the operative room temperature in an office space. Some simulation studies have concluded that the amount of energy that can be saved using internal shading devices is lower than using external ones by just moving the blinds from the outside to the inside. Thus, they advised using only external shading systems. However, this can be incorrect and is expanded upon in the latter part of this paper. At the same time, some researchers have focused on the assessment methods used to determine shading device performance. Gugliermetti and Bisegna [11] proposed simplified algorithms to assess the indoor natural illumination at a prefixed point with external fixed shading devices. A ray-tracing method was developed to describe the global solar transmittance of louver shading devices by Saelens et al. [12], who integrated using TRNSYS to assess the cooling demands and required cooling power in an individual office facing south. The results showed that both the cooling demand and peak cooling power can be estimated within an accuracy of 3%. These studies demonstrated that detailed simulations can capture the performance of both external and internal shades correctly. However, few studies have been done to compare the energy efficiency between internal and external shading devices. Even if the

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comparison has been done, there are still some shortages in these studies. EnergyPlus has been used by Atzeri et al. [13] to compare the performance of outdoor and indoor shading devices, and to examine the thermal and visual comfort and the overall primary energy use. PMV used in their study is a way to evaluate the effect by testers. Due to the subjective evaluations instead of objective judgements, some errors may occur. Thus, more exact ways need to be taken to eliminate the influence from the testers.

In this paper, air-conditioning cooling loads are analysed through experiments and simulations to compare the energy performance of external and internal shading devices. The comparative experiments were performed in Shanghai (China) for two rooms of the same size, orientation and cooling equipment. Hourly cooling loads were recorded to compare the energy performance of the two enclosed spaces installed with external and internal shading systems, respectively. The errors due to feeling deviation of testers usually occur in some experiments of subjective evaluations. Because the experiments and simulations in this paper are all objective, the errors have been ruled out. Thus, the results from the experiments and simulations can eliminate errors due to feeling deviation of testers, and can judge whether internal shading devices can get the same energy-saving effect to external ones when some parameters of internal shading devices are optimized. Because internal shading devices are more convenient and cheaper than external ones, and can provide more freedom to building designers, internal shading devices can replace external ones if these two kinds of devices can save the similar quantity of energy.

Moreover, the energy performance of shading systems depends on multi-factor and multi-variable inputs. Thus, a shading device can be regarded as a grey system, which is a system with many parameters—these parameters can affect the performance of the system, but the correlated degree between these parameters and the performance is unknown. The grey relational analysis can be applied to assess the factors influencing the energy-saving effect. Grey relational analysis (GRA), proposed by Deng [14] in 1982, is an important component of grey system theory (GST) [15]. GRA is a mathematical method suitable for solving problems with complicated interrelationships between multiple factors and is used for capturing their dynamic characteristics. GRA has been successfully applied in many fields, such as solving many multiple attribute decision making problems [16–19], assessing and optimizing boilers [20], flat-plate collectors [21], predicting software project efforts [22,23], forecasting the performance of ejector refrigeration systems [24], etc. Lee and Lin [25] proposed a perspective of multiple objective outputs to evaluate the energy performance of buildings and then used the GRA to rank the evaluated buildings. The grey correlation coefficients between ECEI (Elasticity Coefficient of Environmental Investment), ECEC (Elasticity Coefficient of Energy Consumption) and EEF (Energy Ecological Footprint) in Shanghai (China) were calculated by Liu [26] to demonstrate the interaction between an ecosystem and a behaviour system.

In this paper, we used a grey relational analysis (GRA) to study the main factors affecting an internal shading device. EnergyPlus [27] enabled the simulations of both external and internal shadings to compare the shading effect for various input matrices. The results of the factor analysis are helpful for designers and engineers to choose the right materials and specify installation methods if an internal shading system is to be built.

## 2. Theoretical analysis and methodology

### 2.1. Energy performance of internal and external shadings

The distribution of solar heat radiation through a window without any shading is shown in Fig. 1. The sunlight hits the glass, which absorbs some heat and then delivers it to both the indoor and outdoor environments via convection and radiation. Due to the limited heat capacity of ordinary clear glass, heat can only be stored for a short time in the glass before being transferred directly to both sides. Because the outdoor air temperature is higher and the direction of radiation is from outdoor to indoor, the overall trend is a continuous flow of heat from the outside to the inside, which could increase the indoor air temperature. In addition, a portion of the daylight penetrates the glass and heats indoor objects directly, which then heats the indoor air via convection and radiation.

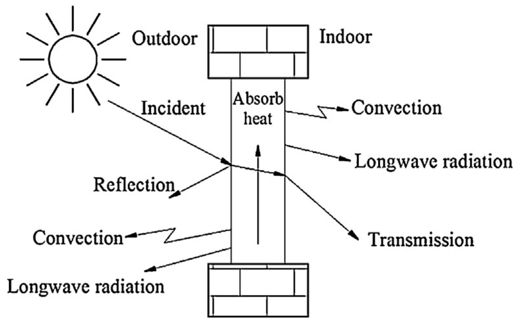


**Fig. 1.** Distribution of solar heat radiation through a window.

Fig. 2b shows that an external shading system will prevent most of the outside heat from entering a room, whereas an internal shading system (Fig. 2a) redistributes heat that has already entered the room. Therefore, the performance of internal shadings is generally inferior to external shadings.

From the comparison shown in Fig. 2, indoor heat gains are mainly obtained through radiation and convection, presented as:

$$q_{\text{total}} = q_{\text{rad}} + q_{\text{conv}} \tag{1}$$

The terms on the right side of Eq. (1) are difficult to calculate, but it is not necessary to determine $q_{\text{total}}$ in part for this study. It is important to know the differences associated with external and internal shading devices, which can be expressed as follows:

$$\Delta q_{\text{total}} = q_{\text{total,int}} - q_{\text{total,ext}} = q_{\text{abs}} + q_{\text{ref}} \times a \tag{2}$$

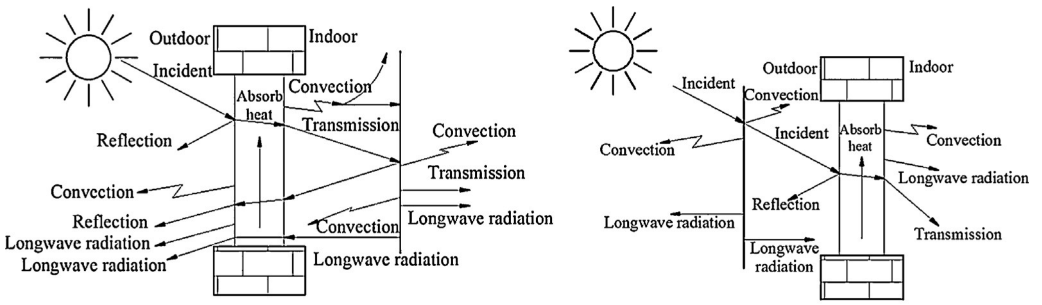
where $q_{\text{toatal,int}}$ is all the heat components associated with internal shading, $q_{\text{toatal,ext}}$ is all the heat components associated with external shading, $q_{\text{abd}}$ represents the heat absorbed by the internal shading device, $q_{\text{ref}}$ represents the heat reflected by the internal shading device, and $a$ is the radiation heat reflected by the internal shades, but blocked by the window glass. The radiation parameters are defined as:

$$\alpha + \beta + \tau = 1 \tag{3}$$

where $\alpha$ is the absorptivity of the internal shading device, $\beta$ is the reflectivity of the internal shading device, and $\tau$ is the transmissivity of the internal shading device.

Based on Eq. (3), when $\beta$ is large, $\alpha$ and $\tau$ are correspondingly small. According to Eq. (2), if $\alpha$ is lower and $\beta$ is higher, $q_{\text{abs}}$ will be lower and $q_{\text{ref}}$ will be higher. The variation of $q_{\text{abs}}$ will be higher than that of $q_{\text{abs}} \times a$. Therefore, the total heat can be small if a highly reflective material is used for the internal shading.

In addition, convection occurs between the shading device and glass inside the room if internal shadings are used, whereas convection occurs outside the room if external ones are used. With an internal shading system, a portion of the radiative heat is reflected outside. However, some portion of this heat is reflected back from glass, increasing the indoor load. Other radiative heat is transferred into the room through gaps and another portion will heat the shading device, which will deliver heat to both sides through radiation and convection. However, if an internal blind is positioned



a. Internal shading devices b. External shading devices

**Fig. 2.** Impact of internal and external shading devices on solar radiation. (a) Internal shading devices and (b) external shading devices.

very close to the external glass, the value of $q_{\text{ref}} \times a$ can be smaller. This way can lower the total heat trapped inside.

When an outdoor shading system is placed in front of a window, only a small portion of the radiative heat will pass through the gaps. External shading devices are heated up and normally have a higher temperature than the outdoor air. However, such heat is mostly carried away by the outdoor air and only a small portion is transferred inside through convection. The reflectivity of external shades has little impact on its performance.

The comparison of heat flow between internal and external shading gives the impression that external shading devices are always better than internal shading devices. This impression may not be always true because it depends highly on the reflectivity of the shading materials, gap size, and the distance from the shading device to the glass. To minimize or even eliminate this part of heat, the distance between a shade and the glass should be shortened and the reflection coefficient of the interior side of glass should be as small as possible. Besides, shading materials with a high reflectivity should be selected to minimize the heat absorbed by the internal shading device, which will reduce the heat through convection between the shading device and the glass, and will lower the cooling load from the heat gained through radiation.

Due to economical and convenient demands, internal shading devices are better choices than external ones. If internal shading devices can get the same effect to the external ones by changing some parameters, it is better to use internal shading devices instead of external ones. Thus, it is important whether internal shading devices can get the same energy-saving effect to external ones, or even better than external ones. In the first part of the presented paper, related experiments and simulations are used to solve the concerned problems.

### 2.2. Grey relational analysis

Grey System Theory (GST), proposed by Deng [14] in 1982, is a recently developed system engineering theory based on the uncertainty of small samples. Grey relational analysis (GRA) is one important method used in GST. It may be used to determine the correlations between the reference factor and other comparative factors of a system [28]. It makes use of relatively small data sets and does not demand strict compliance to certain statistical laws, simple or linear relationships among the observable variables [24]. The effects of the design and operation parameters on the energy performance of the internal shading system involve multiple factors. Thus, this can be regarded as a grey system, and the GRA can be applied to assess the factors influencing the energy savings to gain more comprehensive information about their distribution and contributions. These data will lead to better designs and operations of internal shading systems.

The grey relational coefficient expresses the relationship between the expected and actual experimental results. The degree of influence, which is referred to as the grey relational grade (GRG), is simultaneously calculated corresponding to each factor. The degree of influence may be represented by the distance in an imaging grey space without making prior assumptions about the distribution type, which reveals the relative variations between two factors, and indicating magnitude and gradient in a given system. One sequence of data is assigned to be the reference series $X_0 = \left\{x_0(1), x_0(2), \ldots, x_0(n)\right\}$, and the other is the comparative series $X_i = \left\{x_i(1), x_i(2), \ldots, x_i(n)\right\}$. Generally, the GRA procedure is:

*Step 1:* Dimensionless processing to remove anomalies associated with different measurement units and scales, which is also called grey relational generating. In this paper, the initial-value processing is applied to transform the data sequences into dimensionless forms. In the initial-value processing, the elements in each series are divided by the first component, such as:

$$x_0' = \frac{x_0(m)}{x_0(1)} \quad \text{and} \quad x_i' = \frac{x_i(m)}{x_i(1)} \tag{4}$$

*Step 2:* Calculation of the grey relational coefficient between $X_0$ and $X_i$ at point $k$, which expresses the relative distance between two factors:

$$\xi_i(k) = \frac{\min_i \min_k \left|x_0'(k) - x_i'(k)\right| + \rho \max_i \max_k \left|x_0'(k) - x_i'(k)\right|}{\left|x_0'(k) - x_i'(k)\right| + \rho \max_i \max_k \left|x_0'(k) - x_i'(k)\right|} \tag{5}$$

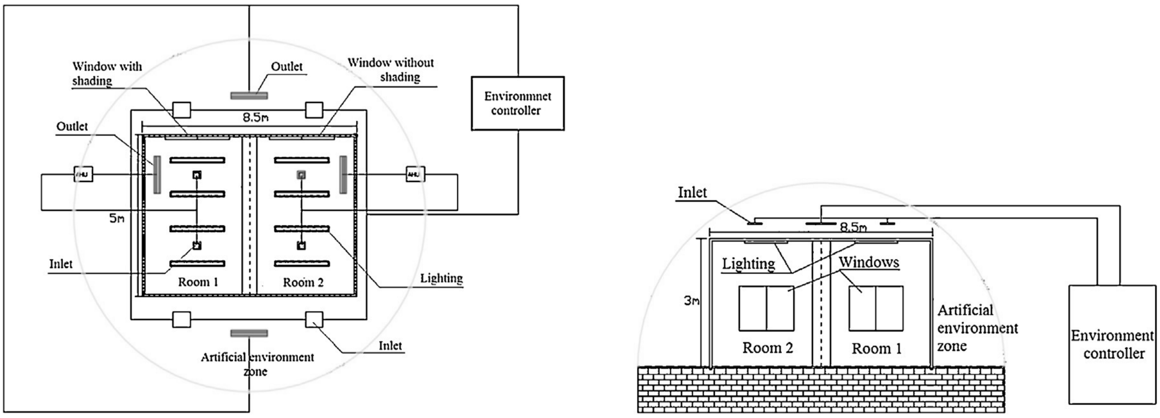
where $\left|x_0'(k) - x_i'(k)\right|$ is the absolute value of the difference between $X_0$ and $X_i$ at point $k$, $\min_i \min_k \left|x_0'(k) - x_i'(k)\right|$ is the smallest value of $\left|x_0'(k) - x_i'(k)\right|$ and $\min_i \min_k \left|x_0'(k) - x_i'(k)\right|$ is the largest value of $\left|x_0'(k) - x_i'(k)\right|$. The variable $\rho \in (0, 1)$ is the distinguishing coefficient used to adjust the range of the comparison environment and to control the level of differences in the relational coefficients, which is set as 0.5 in this paper.

*Step 3:* Calculation of the grey relational grade. There are too many relational coefficients to be compared directly, so further data reduction makes use of average-value processing to convert each series' grey relational coefficients at all points into its mean, which is known as the grey relational grade (GRG). Assuming each point in a sequence of equal weight, the mean values of each factor may be calculated using Eq. (6), the result of which is the correlation between different factors and total cooling load for this study:

$$R_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k) \tag{6}$$

where $n$ is the number of simulation groups.

The GRG indicates the degree of similarity between the comparative sequence and the reference sequence. For each attribute,



a. Vertical view b. Front view

**Fig. 3.** The experimental platform used in this work. (a) Vertical view and (b) front view.

the reference sequence represents the best performance that could be obtained by any of the comparative sequences. Therefore, for a comparative sequence transformed from an alternative that has the highest GRG between the reference sequence and itself, such an alternative will be determined to be the best choice. The values of the variable $R_i$ are between 0 and 1 in this work. The examined factor, along with a higher value of $R_i$, will affect the energy consumption more significantly. Therefore, the main factors affecting the behaviour of an internal shading system can be obtained in this way.

If internal shading devices are superior to external ones in terms of the energy-saving effect, how to optimize the internal shading devices is necessary to be considered. The GRA is a good way to evaluate which parameters are more important to the shading effect of internal shading devices. In the second part of the presented paper, simulated data by EnergyPlus are analysed, and the most important factor can be obtained using GRA.

## 3. Experimental tests

### 3.1. Introduction of experiments

The experiments in this work were carried out to analyse the differences in performances of external and internal shadings to assess if well-designed internal shading devices are viable replacements for external shading devices in actual projects. Internal shading can result in not only convenient installation and lower costs but also more flexible building facade designs.

The experimental platform was established in Shanghai (China), and the test chamber configuration and size are shown in Fig. 3. The platform consists of two identical full-scale rooms (4.25 m by 5 m) equipped with an air handling unit (AHU), which can perform comparative experiments on the cooling load. The left room is equipped with a shading device and the right has no shading devices. The windows are facing south for each room.

The internal shading device was a curtain with a high reflectivity coating on the side facing the windows. The coating was specifically designed for shading. The external shading device is a roller blind. The experiments were carried out for three working conditions (no shading systems, external and internal shading systems) during the period when the outdoor environmental parameters are similar. AHUs ensured that the rooms remained at the same temperature. The hourly cooling rate was recorded through a BTU-meter. The cumulative cooling load for each working condition from 9:00 a.m. to 2:00 p.m. was calculated. After 2:00 p.m., no direct sun hit the shading devices. If the condition with no shading is treated as the baseline case, the cumulative energy-saving rate of the external and internal shading systems can be obtained from:

$$\Delta = \frac{q_{\text{cum,no shad}} - q_{\text{cum,shad}}}{q_{\text{cum,no shad}}} \times 100\% \tag{7}$$

Through the comparison of energy-saving rates, the difference in the actual energy performance of external and internal shading systems may be analysed to determine if it is appropriate to substitute external shading with internal shading.

### 3.2. Experimental results and discussions

Two identical rooms were tested for comparison of the three working conditions, including:

- No shading test. Two rooms with no shading systems;
- External shading test. One room with external shading and one room without shading;
- Internal shading test. One room with internal shading and one room without shading.

The first experiment with no shadings was conducted to verify that the two rooms were comparable to each other and have nearly the same independent variables. After utilizing the shading, the energy-saving rate can be calculated via comparison of the two rooms. Each working condition was tested from 9:00 a.m. to 2:00 p.m., and the experimental results for similar outdoor environmental parameters were selected for analysis.

#### 3.2.1. Environmental parameters

The outdoor environmental parameters are plotted in Figs. 4 and 5 for the three-day experiments, including the outdoor dry-bulb temperature and direct solar radiation intensity. It was necessary to ensure that clear sky conditions were prevalent during the experiments. On the first day the no shading test was performed to confirm that the two rooms are similar to each other. On the second day the internal shading test was carried out, in which one room was installed with an internal shading device. On the final day the external shading test was conducted. The energy-saving rates from the two rooms on the same day were compared with each other, so that the difference in outdoor dry-bulb temperatures and direct solar radiation intensities, as shown in Figs. 4 and 5, have little influence on the results.

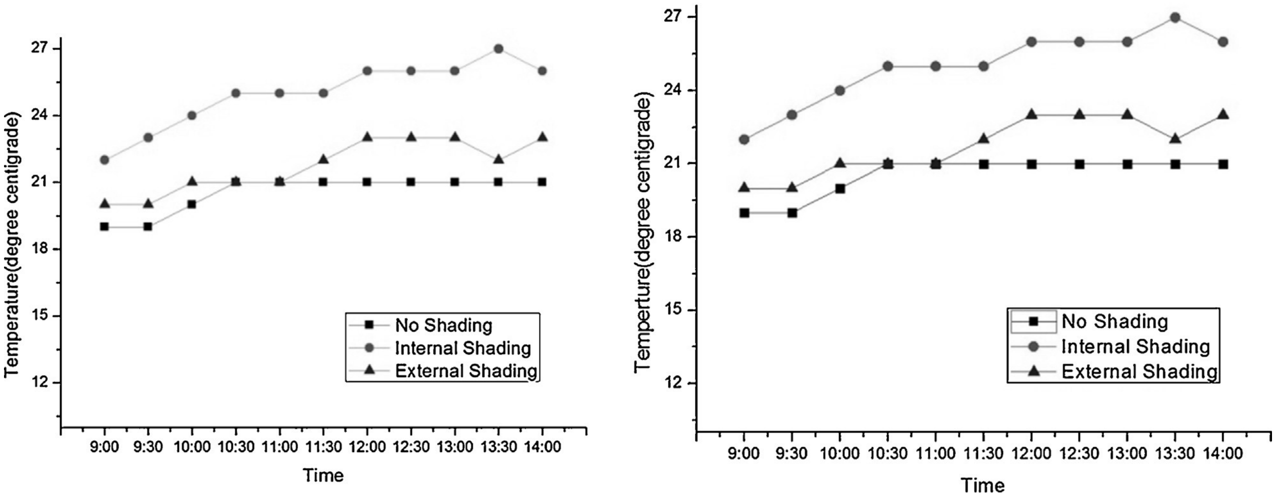


**Fig. 4.** Outdoor dry-bulb temperature.

### 3.2.2. Data analysis

The analyses of energy-saving effect are shown in Figs. 6–8. In the experiment, the working condition with no shading in the two rooms was first investigated to ensure the two rooms have approximately the same independent variables. Then, the cooling capacities for the room with shading and the other without shading are used to calculate the energy-saving rates.

In Fig. 6a, each scattering point represents the cooling capacity of the two rooms at a three-minute interval. It was found from the comparison that the cooling demands of the two rooms are essentially identical at each interval. Fig. 6b also shows that the cumulative cooling demands of the two rooms are close to each other. The cumulative cooling demands of Room 1 are approximately 9% higher than those of Room 2. The difference may arise from the sensors' inherent errors or slight differences in construction of the two rooms. When the two rooms are equipped with no shadings, a slight imbalance in the cooling capacity still exists. Although the rooms were designed the same and heavy insulation was installed in the east and west walls, the two rooms may still possess slight differences in construction, resulting in a small

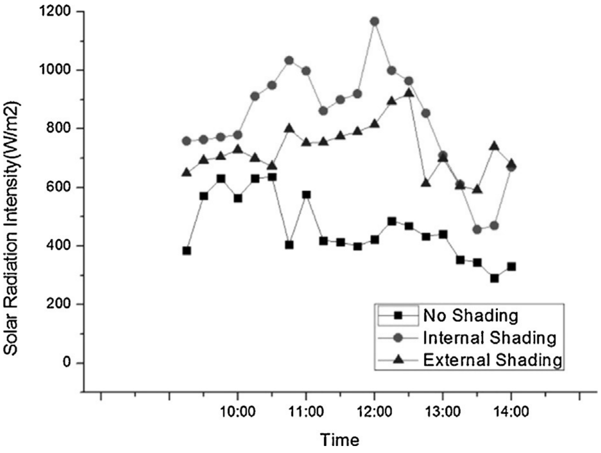
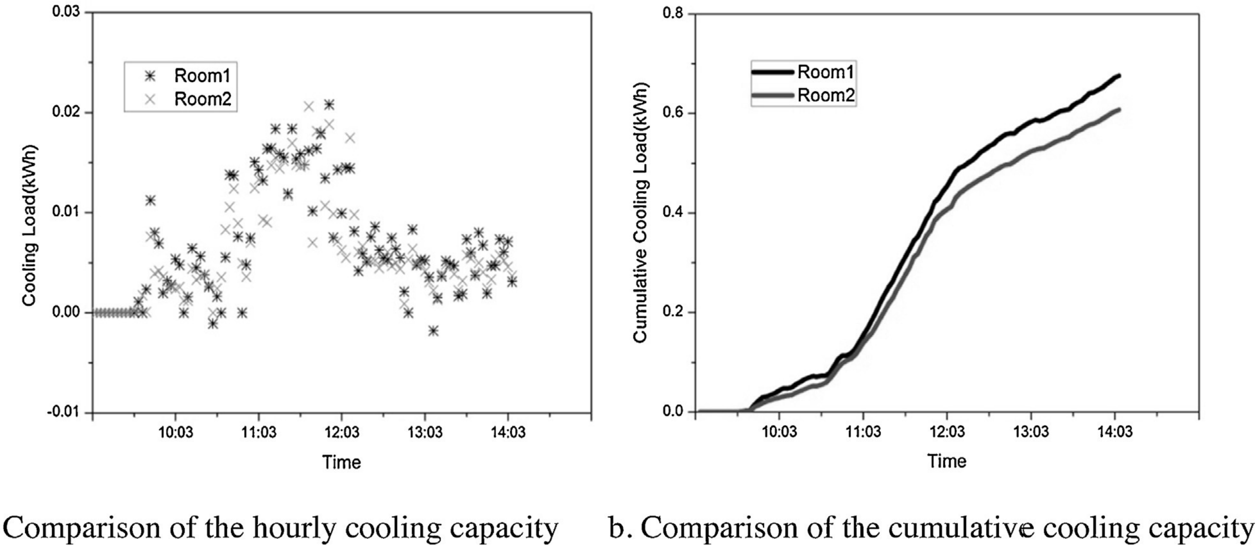
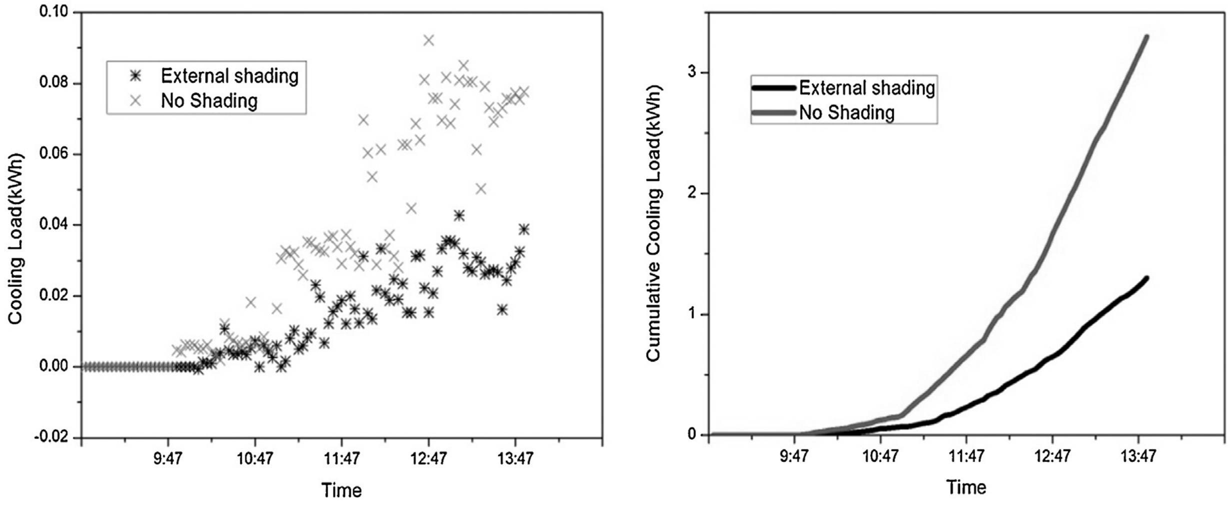


**Fig. 5.** Direct solar radiation intensity.



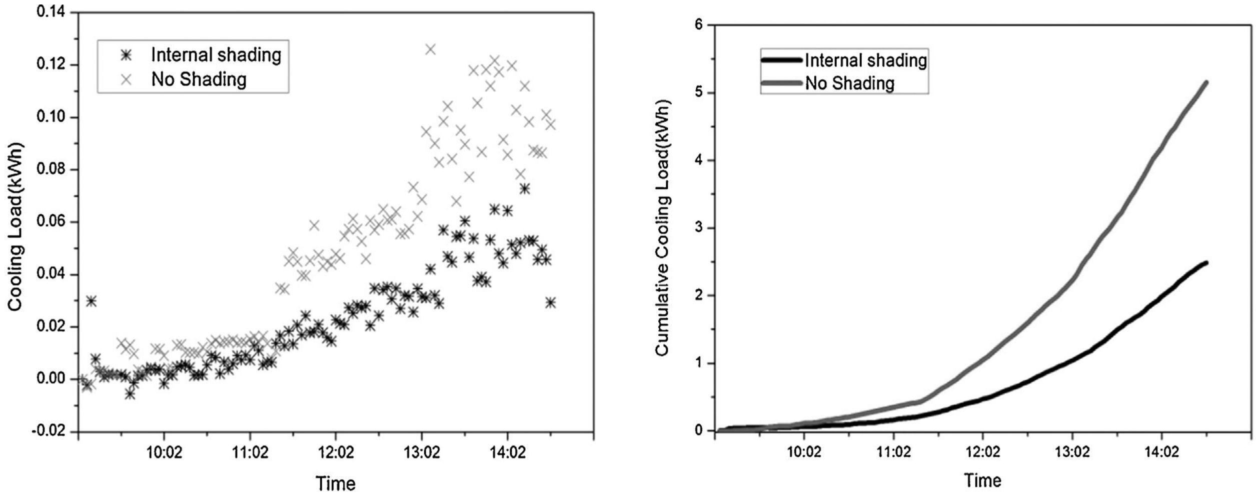
a. Comparison of the hourly cooling capacity b. Comparison of the cumulative cooling capacity

**Fig. 6.** Comparison of the hourly and cumulative cooling capacity in the two rooms with no shading systems. (a) Comparison of the hourly cooling capacity and (b) comparison of the cumulative cooling capacity.



a. Comparison of the hourly cooling capacity b. Comparison of the cumulative cooling capacity

**Fig. 7.** Comparison of the hourly and cumulative cooling capacity in the two rooms with external and no shading systems, respectively. (a) Comparison of the hourly cooling capacity and (b) comparison of the cumulative cooling capacity.



a. Comparison of the hourly cooling capacity b. Comparison of the cumulative cooling capacity

**Fig. 8.** Comparison of the hourly and cumulative cooling capacity in the two rooms with internal and no shading systems, respectively. (a) Comparison of the hourly cooling capacity and (b) comparison of the cumulative cooling capacity.

discrepancy in cooling load. This difference is considered in the later study to adjust the cooling load measured from the two rooms.

When one room uses a shading device and the other does not, the differences in the cooling capacities of the two rooms are approximately the energy savings. The ratio of such difference and the cooling capacity of the room with no shadings is the energy-saving rate when shading is used.

Figs. 7 and 8 show the cooling capacities of the two rooms during the experiments on the second and third day. As seen in Fig. 7a, the hourly cooling load of the room with external shading is much lower than that without external shading. The energy-saving effect is significant when the outdoor air temperature is high and the solar radiation is intense. The overall energy-saving rate is 64.1% (adjusted) from 9:00 a.m. to 2:00 p.m.

As seen in Fig. 8a, the hourly cooling capacity decreases with the use of internal shadings, and the energy-saving effect is also significant when the outdoor air temperature is high and the solar radiation is intense. The overall energy-saving rate is 56.2% (adjusted) from 9:00 a.m. to 2:00 p.m.

Because the room is not large and only office level illumination is maintained inside with no occupants, the cooling load comes mainly from the outdoor heat and solar radiation. In this experiment, the total lighting load is approximately 40 W, and most of the heat exists in the recessed ceiling space. Therefore, the cooling load from the lighting can be neglected. The experimental results indicate good performance from both the external and internal shadings. The internal shading system can replace the external shading system of suitable materials are used and installed properly.

## 4. Simulation validations

From the experimental results, we can see that the shading effects and the effects in terms of cooling load reduction from

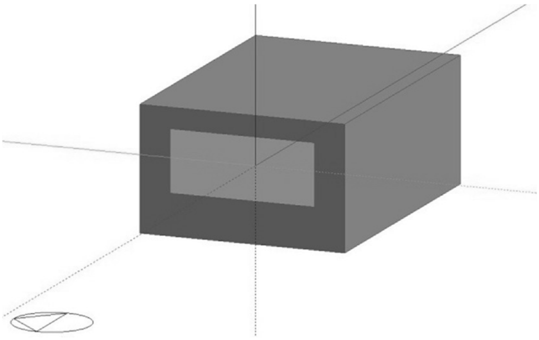


**Fig. 9.** Simulation model.

**Table 1**
Parameters of the reference shading materials.

| | |
|---|---|
| Solar transmittance | 0.3 |
| Solar reflectivity | 0.5 |
| Transmittance of visible light | 0.2 |
| Reflectivity of visible light | 0.7 |
| Total emissivity of infrared light | 0.9 |
| Transmittance of infrared light | 0.05 |
| Material thickness [m] | 0.005 |
| Thermal conductivity [W/(m K)] | 0.06 |

**Table 2**
Performance evaluation of the external and internal shadings composed of the same materials for the summer design day.

| Cooling capacity throughout the day with no shadings (kW h) | Cooling capacity throughout the day with internal shadings (kW h) | Cooling capacity throughout the day with external shadings (kW h) |
|---|---|---|
| 14.92 | 14.27 | 12.86 |
| | Energy-saving rate with internal shadings (%) | Energy-saving rate with external shadings (%) |
| | 4.36 | 13.81 |

**Table 3**
Performance evaluation of the external and internal shadings composed of the same materials for the entire year.

| Capacity throughout the year with no shadings (kW h) | Capacity throughout the year with internal shadings (kW h) | Capacity throughout the year with external shadings(kWh) |
|---|---|---|
| 3565.39 | 3499.62 | 3285.79 |
| | Energy-saving rate with internal shadings (%) | Energy-saving rate with external shadings (%) |
| | 1.84 | 7.84 |

internal shading are similar to those from external shading. Thus, in actual projects, some internal shading measures should not be excluded from consideration. EnergyPlus was used to further verify the experimental results.

### 4.1. Model establishment

Shanghai (China) was selected as the location for simulations because high-rise buildings in Shanghai all have problems related with external shadings. A model room of 7 m in length, 5 m in width and 3 m in height was established. The room is lit by a window in the wide side, which is 1.2 m high and 3 m wide and is composed of 3 mm thick single-pane glass. A lighting system was also placed in the room. The building model and its size parameters are shown in Figs. 9 and 10. The parameters of the reference shading materials are shown in Table 1.

Moreover, there is no occupancy in the rooms in a whole day, and the material of envelop is color plate. Also, the thickness of wall is 0.24 m, and the heat transfer coefficient of wall is 0.2 W/(m$^2$ K). For controlling the environment conveniently, the two rooms are covered by glass that can isolate the controlled environment and real setting.

### 4.2. Simulation results and discussions

The cooling capacities and the energy-saving rates throughout the summer design day compared with those with no shadings are shown in Table 2. The same materials were used for the external and internal shading devices. The cooling load throughout the entire year was also calculated, as listed in Table 3.

From the simulation results, it was found that by just moving the external shading to an internal location, the shading performance will decrease to some extent. Therefore, it is necessary to change the solar reflectivity and the solar transmittance of the internal shading system, as shown in Fig. 11.

It can be seen from Fig. 11 that the energy-saving rate of internal shadings rises as the solar reflectivity increases and the solar transmittance decreases. When the solar transmittance and reflectivity are 0.1 and 0.8, respectively, the energy-saving rate will be approximately 8.5% over the summer design day and approximately 4.5% over the entire year. Although such effect is still inferior to that of external shading, the results prove that the energy performance of the internal shading device can be notably improved if the solar reflectivity and transmittance are adjusted.

In addition, the energy-saving effect of the internal shading system is related to the distance between the shading device and window. The evaluation of shading performance for different distances between the shade and window is shown in Fig. 12, when the solar transmittance and reflectivity are maintained at 0.3 and 0.4, respectively. It may be concluded that reducing the distance can also increase the energy-saving rate for the internal shading system. Therefore, in actual projects, the distance between the shade and window should be minimized to maximize the performance of the internal shading system.

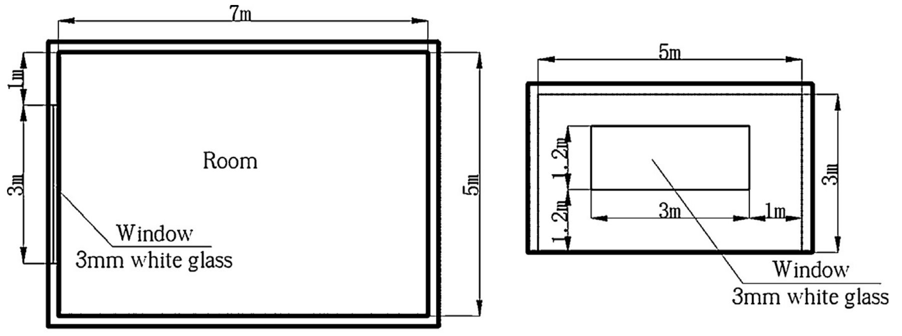
According to the simulations, the solar reflectivity, solar transmittance, and the distance between the shading device and the window are the factors that most change the performance of internal shading devices. If these factors are all adjusted to optimized values (the solar transmittance and reflectivity are 0.1 and 0.8, respectively, and the distance between shading device and window is 0.01 m), the results are shown in Table 4.

After the adjustment, the energy-saving rate for the internal shading is higher than with external shading. From Table 4, it is obvious that internal shading devices have the potential to achieve a good energy-saving performance, sometimes even better than the external shading devices if designed properly.

It can be concluded from the simulations that both the external and internal shading measures exhibit an energy-saving effect to some extent, and that internal shading devices can exhibit similar effects as external shading devices through appropriate adjustment of some parameters.

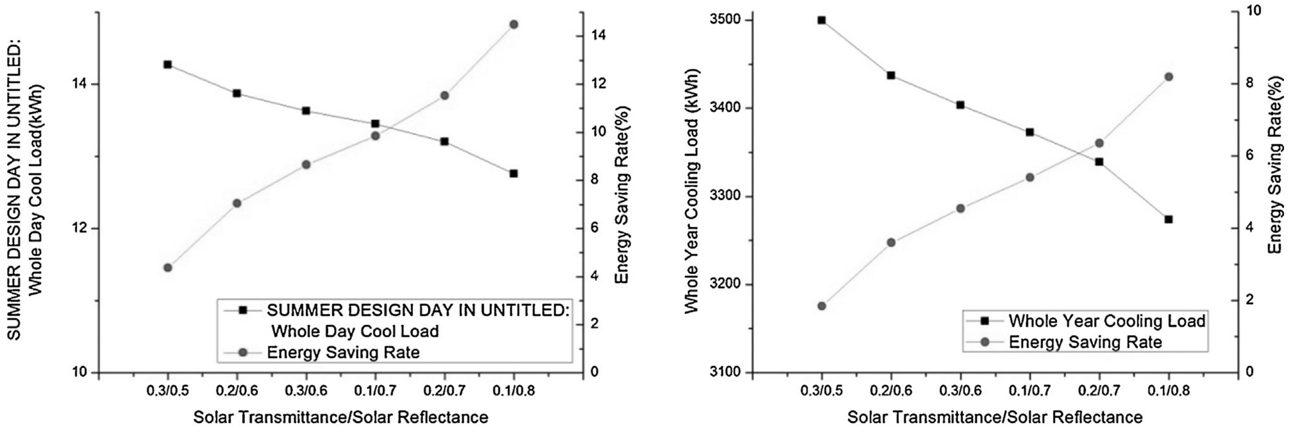
## 5. Optimization of internal shading system by GRA

According to the analysis in Section 4.2, we can conclude that the amount of energy savings can be improved if some factors of the internal shading system are adjusted. In addition to the solar transmittance, solar reflectivity, and distance between shading device and window, there are some other factors that affect the performance of internal shading. If these factors are suitably adjusted,



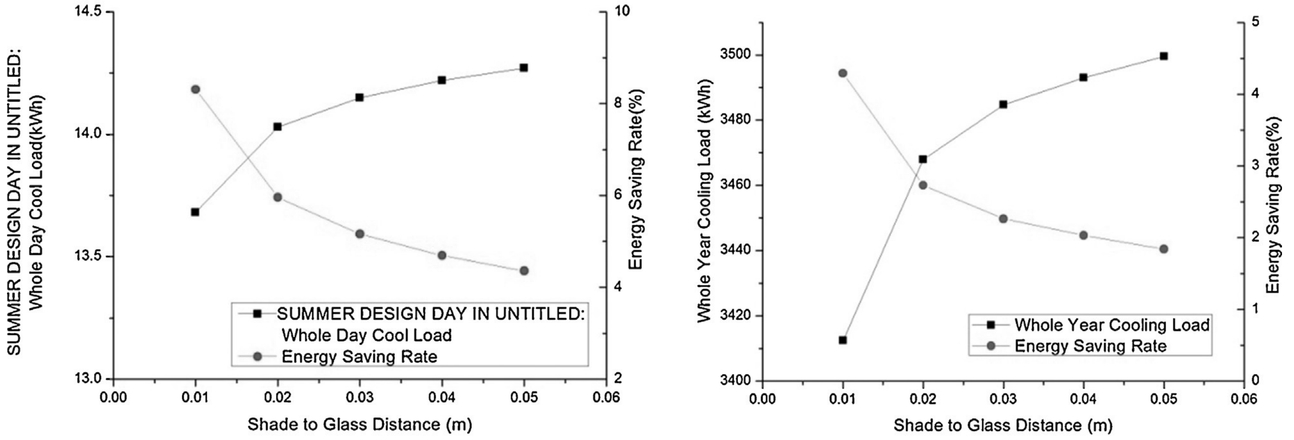
a. Plan view of the model. b. Vertical view of the model.

**Fig. 10.** Size parameters of the simulation model. (a) Plan view of the model and (b) vertical view of the model.



a. The summer design day b. The entire year

**Fig. 11.** Performance evaluation of the internal shading system for different solar reflectivity and transmittance values over the summer design day and the entire year. (a) The summer design day and (b) the entire year.



a. The summer design day b. The entire year

**Fig. 12.** Performance evaluation of the internal shading system for different shading device and window distances over the summer design day and the entire year. (a) The summer design day and (b) the entire year.

**Table 4**
Performance evaluation of the optimized internal shading.

| Adjusted parameters of internal shadings | | Cooling load with internal shadings(kW h) | Energy-saving rate with internal shadings (%) |
|---|---|---|---|
| Solar transmittance/Solar reflectivity | 0.1/0.8 | In the summer design day | |
| | | 12.39 | 16.96 |
| Distance between shade and window [m] | 0.01 | In the whole year | |
| | | 3214.62 | 9.84 |

**Table 5**
The results of the grey relational analysis.

| Group number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Solar transmittance | 0.3 | 0.2 | 0.3 | 0.2 | 0.2 | 0.3 | 0.3 | 0.2 | 0.1 |
| Solar reflectivity | 0.5 | 0.6 | 0.5 | 0.6 | 0.7 | 0.6 | 0.5 | 0.6 | 0.8 |
| Visible transmittance | 0.3 | 0.2 | 0.3 | 0.2 | 0.2 | 0.3 | 0.2 | 0.2 | 0.2 |
| Visible reflectivity | 0.5 | 0.6 | 0.5 | 0.6 | 0.7 | 0.6 | 0.7 | 0.7 | 0.7 |
| Infrared hemispherical emissivity | 0.9 | 0.9 | 0.8 | 0.9 | 0.9 | 0.8 | 0.9 | 0.8 | 0.8 |
| Infrared transmittance | 0.05 | 0.05 | 0.1 | 0.05 | 0.05 | 0.05 | 0.05 | 0.1 | 0.1 |
| Thickness [m] | 0.003 | 0.004 | 0.003 | 0.005 | 0.005 | 0.004 | 0.005 | 0.005 | 0.005 |
| Conductivity [W/(m K)] | 0.1 | 0.08 | 0.05 | 0.05 | 0.08 | 0.05 | 0.06 | 0.07 | 0.06 |
| Dis. between shade and glass [m] | 0.01 | 0.05 | 0.03 | 0.03 | 0.05 | 0.05 | 0.05 | 0.04 | 0.03 |
| Total cooling load in summer design day [kW h] | 13.67 | 13.86 | 14.18 | 13.73 | 13.20 | 13.64 | 14.27 | 13.85 | 12.74 |
| Cooling load in whole year [kW h] | 3412.62 | 3437.39 | 3490.12 | 3422.90 | 3339.64 | 3406.78 | 3500.77 | 3435.93 | 3269.89 |

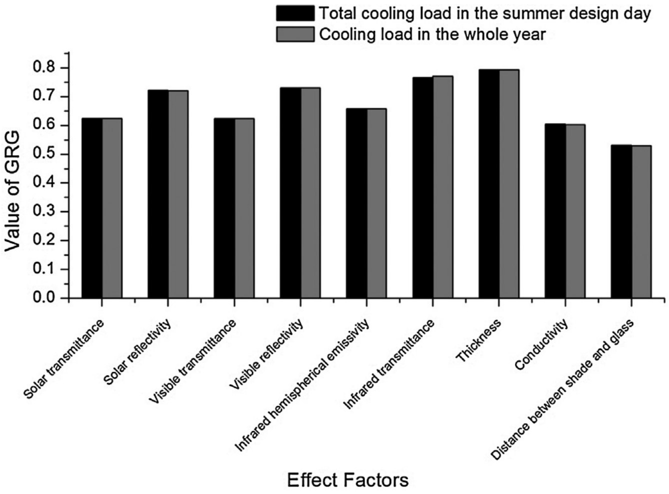


**Fig. 13.** The correlation between the effect factors and the total cooling load.

the performance of internal shading system can be as good as that of the external shading system, or even better.

From Table 5, there are nine main factors affecting energy saving. These factors are the characteristics of shading materials and geometric parameters, which changes the shading effect substantially. Using EnergyPlus, we designed and conducted nine individual groups of simulations with different values for the factors. The same types of internal and external shadings are used in these simulations. The different values for the factors in the nine groups and total cooling load are listed in Table 5.

To obtain the main factors of the internal shading device's energy performance, the grey relational analysis (GRA) is used according to Table 5. First, the nine main factors and total cooling load during the summer design day are transformed into dimensionless values through initial-value processing and are defined as $x_i$ $(i = 1, 2, \ldots, 9)$ and $x_0$. The group number is set as $k$ $(k = 1, 2, \ldots, 9)$. Then, $\xi$ and $R_i$ are calculated according to Eqs. (5) and (6), respectively. If $x_0$ is the cooling load over the entire year, the method should was used over the summer design day. The results from the GRA are shown in Fig. 13.

From Fig. 13, we summarize that the thickness, infrared transmittance, visible reflectivity, and solar reflectivity are the most important factors in determining the internal shading performance. When the materials are selected for internal shading devices, these factors need to be paid the most attention.

Additionally, other considerations should be taken:

(1) The reflectivity at the interior side of the window should be as low as possible. Ordinary glass is better than low-e windows in this respect. Some special windows, such as double-layer low-e windows, can block the heat reflection of the internal shading to outside. In such case, the energy-saving performance using internal shading device may be reduced.
(2) The distance between the shading device and the window should be shortened to reduce the heat transferred via convection, which has been mentioned in Section 4.2. This factor is the least important, as shown in Fig. 13. However, it is a zero cost factor and a convenient method to reduce heat into rooms.
(3) The space between the shading device and the window should be well sealed to reduce the hot air infiltration through the gaps.
(4) A shading material with high solar reflectivity and low transmittance should be selected. This is an important and effective way to improve the performance of internal shadings.
(5) If it is allowed, the thickness of shading blinds should be increased. This is the factor that exhibits the highest correlation with the effect factors and the total cooling load. Thus, the shading device should be as thick as possible within an allowable range.

## 6. Conclusions

Shading is one of the most effective means to reduce the cooling load for buildings. The common wisdom holds that external shading is better than internal shading. However, external shading has many limitations, especially in high-rise buildings. External shading is difficult to install and expensive to maintain and repair.

If properly designed, good internal shadings can be as effective as external shadings. This study proves through both simulations and experiments that by using highly reflective material, internal shading can reduce the cooling load significantly. The cooling load reduction from internal shading can even match external shading if used properly.

If external and internal shading devices use the same material and have the same geometric dimensions, the effectiveness of the internal shading is inferior to the external ones. However, by adjusting the solar transmittance, solar reflectivity and distance between shading device and window, internal shadings can achieve good energy performances, sometimes even better than some external ones. Thus, engineers may consider using internal shading to substitute for external shading to save costs. Additionally, building codes should not exclude internal shading as an alternative way to provide shade in code compliance calculation.

By using grey relational analysis (GRA), we find that thickness, infrared hemispherical emissivity, visible reflectivity, and solar reflectivity are the most important factors in determining the performance of internal shading system. Therefore, engineers should pay more attention to these factors than any others.

In summary, a properly designed internal shading system can work as well as an external shading system. When designing buildings, architects and engineers should consider internal shading as a viable option for improving the overall building facade energy efficiency.

## References

[1] China Architecture & Building Press, Sunshade and Energy Efficiency in Buildings, China Architecture & Building Press, 2009 (in Chinese).
[2] A. Tzempelikos, A.K. Athienitis, The impact of shading design and control on building cooling and lighting demand, Sol. Energy 81 (3) (2007) 369–382.
[3] V. Corrado, M. Filippi, V. Serra, A detailed analysis of the effects of external shading systems on window solar gain, in: Chima 2000/Napoli 2001, The Seventh REHVA World Congress, 15–18 September, 2001, Napoli, 2001.
[4] Hussain H. Alzoubi, H. Al-zoubi Amneh, Assessment of building façade performance in terms of daylighting and the associated energy consumption in architectural spaces: Vertical and horizontal shading devices for southern exposure facades, Energy Convers. Manage. 51 (2010) 1592–1599.
[5] G. Kim, H.S. Lim, T.S. Lim, L. Schaefer, J.T. Kim, Comparative advantage of an exterior shading device in thermal performance for residential buildings, Energy Build. 46 (2012) 105–111.
[6] N.H. Wong, A.D. Istiadji, Effect of external shading devices on daylighting penetration in residential buildings, Light. Res. Technol. 36 (4) (2004) 317–333.
[7] S. Grynning, B. Time, B. Matusiak, Solar shading control strategies in cold climates—heating, cooling demand and daylight availability in office spaces, Sol. Energy 107 (2014) 182–194.
[8] C. Aghemo, A. Pellegrino, V.R.M. LoVerso, The approach to daylighting by scale models and sun and sky simulators: a case study for different shading systems, Build. Environ. 43 (2008) 917–927.
[9] Pedro Correia da Silva, Vítor Leal, Marilyne Andersen, Influence of shading control patterns on the energy assessment of office spaces, Energy Build. 50 (2012) 35–48.
[10] F. Frontini, T.E. Kuhn, The influence of various internal blinds on thermal comfort: a new method for calculating the mean radiant temperature in office spaces, Energy Build. 54 (2012) 527–533.
[11] F. Gugliermetti, F. Bisegna, Daylighting with external shading devices: design and simulation algorithms, Build. Environ. 41 (2006) 136–149.
[12] D. Saelens, W. Parys, J. Roofthooft, A. Tablada de la Torre, Assessment of approaches for modeling louver shading devices in building energy simulation programs, Energy Build. 60 (2013) 286–297.
[13] A. Atzeri, F. Cappelletti, A. Gasparella, Internal versus external shading devices performance in office buildings, Energy Procedia 45 (2014) 463–472.
[14] J.L. Deng, Control problems of grey system, Syst. Control Lett. 1 (1982) 288–294.
[15] J.L. Deng, The introduction of Grey system, J. Grey Syst. 1 (1989) 1–24.
[16] W.H. Chen, Distribution system restoration using the hybrid fuzzy-grey method, IEEE Trans. Power Syst. 20 (2005) 199–205.
[17] D.L. Olson, D. Wu, Simulation of fuzzy multiattribute models for grey relationships, Eur. J. Oper. Res. 175 (2006) 111–120.
[18] Y. Kuo, T. Yang, G.-W. Huang, The use of grey relational analysis in solving multiple attribute decision-making problems, Comput. Ind. Eng. 55 (2008) 80–93.
[19] Y. Xie, Z. Mao, Evaluation of residential energy-saving buildings based on grey relational analysis method, Procedia Eng. 29 (2012) 3149–3153.
[20] J. Morán, E. Granada, J.L. Míguez, J. Porteiro, Use of grey relational analysis to assess and optimize small biomass boilers, Fuel Process. Technol. (87) (2006) 123–127.
[21] C-F.J. Kuo, T.-L. Su, P.-R. Jhang, C.-Y. Huang, C.-H. Chiu, Using the Taguchi method and grey relational analysis to optimize the flat-plate collector process with multiple quality characteristics in solar energy collector manufacturing, Energy 36 (2011) 3554–3562.
[22] S.J. Huang, N.H. Chiu, L.W. Chen, Integration of the grey relational analysis with genetic algorithm for software effort estimation, Eur. J. Oper. Res. 188 (2008) 898–909.
[23] Q. Song, M. Shepperd, Predicting software project effort: a grey relational analysis based method, Expert Syst. Appl. 38 (2011) 7302–7316.
[24] S. He, Y. Li, R.Z. Wang, A new approach to performance analysis of ejector refrigeration system using grey system theory, Appl. Therm. Eng. 29 (2009) 1592–1597.
[25] W.-S. Lee, Y.-C. Lin, Evaluating and ranking energy performance of office buildings using Grey relational analysis, Energy 36 (2011) 2551–2556.
[26] H. Liu, The impact of human behavior on ecological threshold: Positive or negative?—Grey relational analysis of ecological footprint, energy consumption and environmental protection, Energy Policy 56 (2013) 711–719.
[27] U.S. Department of Energy, EnergyPlus Energy Simulation Software.
[28] J.L. Deng, Properties of relational space for grey system, in: J.L. Deng (Ed.), Essential Topics on Grey System Theory and Applications, China Ocean, Beijing, 1988, pp. 1–13.