

Article

Evaluation of Daylight and Cooling Performance of Shading Devices in Residential Buildings in South Korea

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Abstract: Accounting for more than half of buildings in South Korea, the energy consumed by residential buildings has become a main concern and the cooling demand has rapidly increased. To reduce energy consumption, several passive and active design strategies have generally been applied. However, there has been an increasing demand for high window-to-wall ratios in residential buildings, it is imperative to block sunlight into a building effectively. Focusing on the reduction of cooling energy consumption in a residential building, the present study assessed the daylight and energy performance of shading devices. Among various types of shading devices, the Venetian blind, horizontal louver, light shelf, and egg-crate were selected. The illuminance levels in three different areas in a building were measured. In addition, the annual cooling energy consumption by these shading devices was investigated. As a result, both daylight and energy performance varied with different design options of these shading devices. Because of the slight performance difference among shading devices, the artificial loads of two best shading devices were compared. In sum, the egg-crate shading was the most proper shading device to block sunlight as well as reduce the cooling energy consumption effectively.

Keywords: daylight; cooling energy; shading device; residential building

1. Introduction

Accounting for more than half of buildings in South Korea (hereafter Korea), residential buildings have consumed a significant amount of energy and it has rapidly increased [1]. Specifically, more than half of the total building energy consumption was used by residential buildings, which was about 60% [2,3]. Focusing on energy consumption by the residential sector, many studies have been conducted to improve energy efficiency and develop energy conservation measures [4–7]. Considering the effort to reduce greenhouse gas emissions, it is necessary to find ways of reducing energy consumption by residential buildings.

Generally, most of the energy in the residential building has been used for heating and cooling to maintain thermal comfort. Thus, it is necessary to reduce the heating and cooling demand in residential buildings in that the total energy consumption in buildings can be reduced. To reduce the energy for heating and cooling, building envelope-enhancement is initially considered. In general, advanced materials have been used to improve thermal resistance in building envelopes such as phase change materials, vacuum insulation panels, various types of double pane glazing, etc. [8–12]. In addition, the use of shading devices and airtightness improvement can be also effective strategies to reduce heating or cooling in buildings [13,14].

Among components of building envelopes, window systems are the main contributor to the heat loss and their energy performance generally depends on thermal properties of glazing and frames [15]. Even though the use of advanced glazing can improve the thermal performance of window systems, there are still issues about the poor thermal performance of window systems compared to other components of building envelopes [16,17]. As mentioned above, another way of reducing heating and cooling demand is the use of internal and external shading devices that can control sunlight through window systems [13]. According to the study of Cho et al. [18], external shading devices for high-rise residential buildings reduced cooling energy demand effectively by minimizing solar heat gain during the summer. Similar studies about the energy-saving potential by using external shadings were performed [19–22]. By absorbing or reflecting the sun's radiation, shading devices play a significant role to maintain thermal comfort in buildings.

Since daylighting highly influences not only the energy performance of buildings but also occupant satisfaction, productivity, and health, it is one of the most important factors that need to be considered from the architectural design stage. In addition, daylighting should be well-controlled and appropriately used to avoid a further increase in heat gains including internal heat gains such as from artificial lighting and home appliances. Regarding the recent design trend of residential buildings, the demand for high window-to-wall ratios in residential buildings in Korea is rapidly increasing. Moreover, the cooling demand has been consistently increasing [18,23,24]. While most studies have focused on the energy performance of in buildings, the present study assesses the daylighting and cooling energy performance of both internal and external shading devices. In addition, the relationship between the daylighting of shading devices with cooling energy demand was also investigated.

2. The Control of Building Energy Consumption by Shading Devices

As essential factors influencing thermal conditions in a building via thermal gains/losses, solar radiation has been controlled with shading devices [25]. Since the solar shadings were initially introduced, the interest of this area has been growing rapidly. Researchers are focusing on diverse methods that can maximize the performance of shading devices. Marrero and Oliviera [26] showed that the installation of louver shading devices in buildings can lead to more comfortable indoor thermal conditions for the residents as well as significant savings in building energy consumption. A similar result was also obtained by Lim et al. [27]. Their result showed that window glazing coupled with shading devices enhanced tropical daylighting quantity as well as visual comfort. Solar shading devices can also provide an energy saving of 8% and 20% during the winter and summer, respectively [28].

Many types of shading devices have been developed by designers and building scientists over the years. They vary in several aspects such as shape, size, and overall performance. Several shading types were investigated by Nedhal and Fadzil [29]. Among various types, the egg-crate shading had the most significant impact on the indoor air temperature decrease in high-rise residential buildings. In addition, locations, size, and color of the internal blinds can significantly influence building energy consumption and the proper design of internal blinds can save energy about 14% of total building cooling consumption during the summer season [30]. According to the study of Uribe [31], the optimum design of shading devices can influence annual energy consumption in buildings and the design variables of the shading devices should consider the time of day and seasonal differences. Focusing on the design of shading devices, window glass types, seasonal and daily temperature change, and the operation of mechanical systems for heating and cooling should be also considered [32]. Previous studies have revealed that the use of shading devices play an important role in reducing electric lighting, while it provides a required amount of light for visual tasks.

According to the study of Datta [33], externally fixed horizontal louvers with different slat lengths and tilts on buildings have a different impact on thermal conditions in buildings. Therefore, shading strategies were developed to control daylight quantities. One of the strategies brought by Tzempelikos and Athienitis [34] was the control of building cooling and lighting demand by exterior roller shades. As a result, the shading devices reduced the energy demand for cooling and lighting by limiting 20% of

solar transmittance. Horizontally installed shading devices in buildings in tropical regions controlled solar heat gains as well as reduced HVAC (Heating, Ventilation, and Air Conditioning) loads [35]. In the case of the internal blinds, the automated Venetian blind was used to limit direct sunlight while admitting diffused sunlight for visual comfort [36]. Similarly, absorptive blinds in an office building can also reduce the indoor air temperature by 1 °C during the summer [37].

3. Methodology

3.1. Building Description

To evaluate the daylighting and energy performance of a residential building with shading devices, a typical apartment building in Seoul in Korea was chosen, in which the latitude and longitude are 37.5665° N and 126.9780° E, respectively. The annual mean air temperature in Seoul is 12.5 °C, and the highest and lowest mean air temperatures are −2 °C and 26 °C, respectively [38]. In addition, the mean annual insolation is 4125 MJ/m² [39]. The total area of the unit space was 145 m² with a ceiling height of 2.3 m and located on the eighth floor of an apartment building with 17 floors. All bedrooms and the living room were headed to the south (Figure 1). Due to a high WWR of 90% of the southern wall, a large quantity of solar radiation was expected. Thermal properties and other conditions for the energy simulation were presented in Table 1. In addition, the energy model was created by SketchUp.

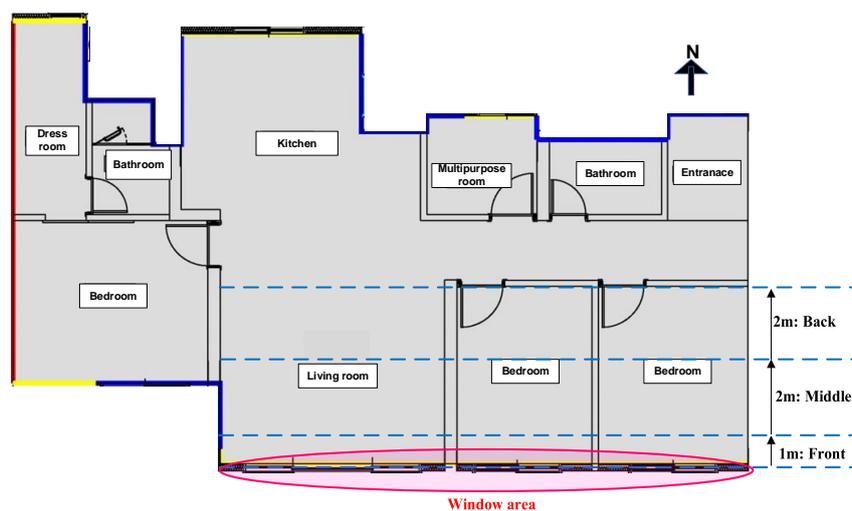


Figure 1. The plan of the selected unit of the reference residential building.

Table 1. The specification for the energy simulation.

Building System	Design Value
Walls	0.397 W/m ² K
Window systems	1.46 W/m ² K
Shading coefficient	0.6
Air infiltration	2.1 cm ² /m ² (3.5 ACH @ 50 PA)
Internal heat gain	4 occupants Lighting: 5.4 W/m ² Equipment: 7.0 W/m ²
HVAC system setpoint temperature	26 °C for cooling and 20 °C for heating

3.2. The Selection of Shading Devices

The main role of a shading device is to block direct sunlight as well as diffuse sunlight and reflective sunlight. Direct sunlight can be controlled simply with external shading devices, while diffuse sunlight is usually controlled with internal shading devices. For the present study, 4 different

shading devices were selected as shown in Figure 2 the design variables of these shading devices were presented in Table 2.

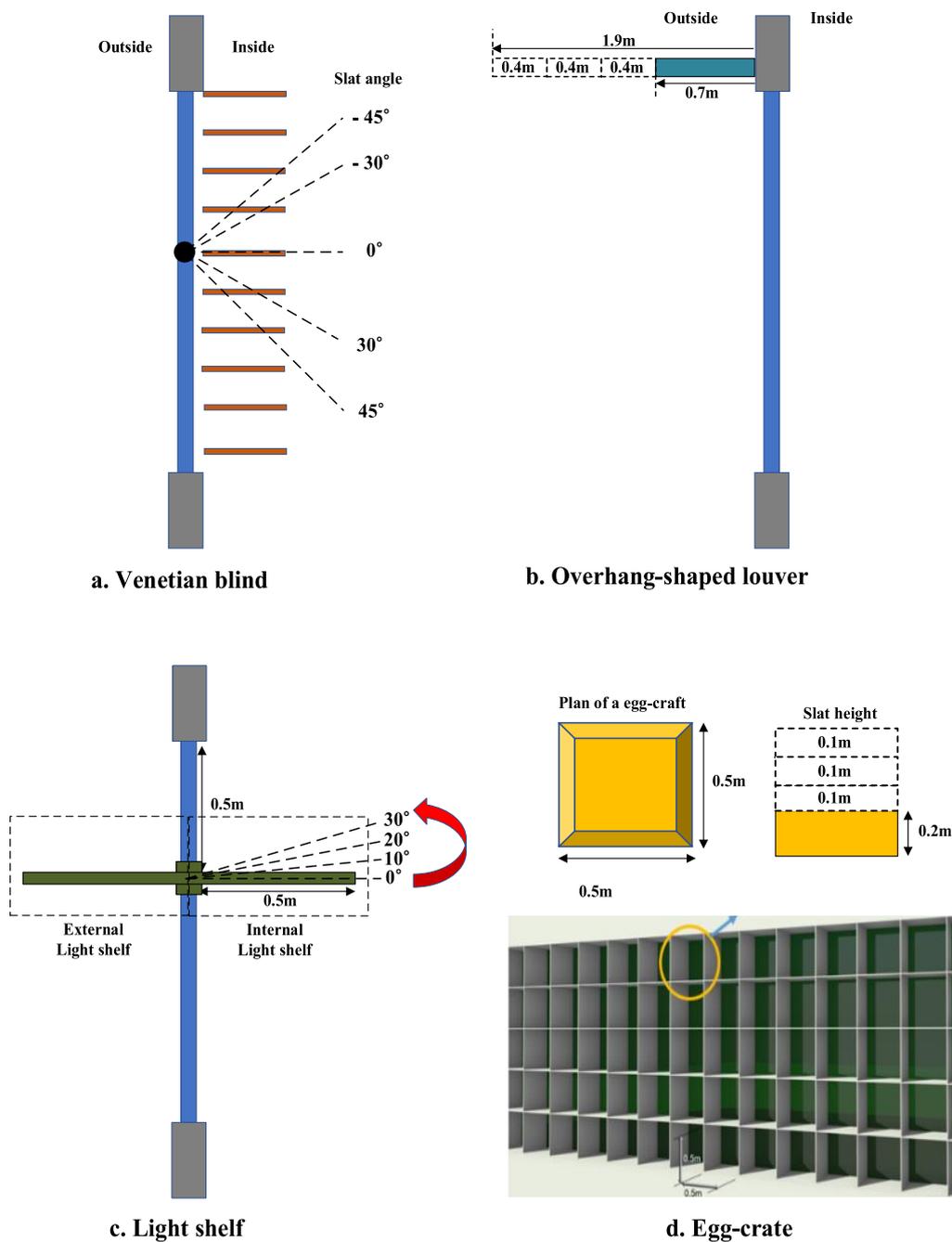


Figure 2. Design variables of the shading devices.

Table 2. The design variables of shading devices.

Shading Device	Design Variable
Venetian blind	Slat angles: -45° , -30° , 0° , 30° , and 45° .
Overhang-shaped louver	Projection length: 0.7 m, 1.1 m, 1.5 m, and 1.9 m.
Light shelf	Internal shelf angles: 0° , 10° , 20° , and 30° .
Egg-crate	Vertical and horizontal slat height: 0.2 m, 0.3 m, 0.4 m, and 0.5 m.

The first shading device is the Venetian blind. The Venetian blind is generally used to control both direct and diffuse sunlight. Slat angle adjustment is the most important variable and these slats are adjusted negatively or positively when there is a need to reduce incoming light. To assess the daylighting and cooling energy performance of the Venetian blind, 5 different slat angles were set. The second shading device was an overhang-shaped horizontal louver. Since the admitted sunlight quantity can be highly influenced by the projection lengths of the louver [26], 4 different projection lengths with 0.4 m intervals were created for the present study. The third shading device was the light-shelf modeled based on the design guideline provided by BRE [40]. To figure out the daylighting and energy performance of an angle of the internal shelf, 4 different angles were considered. The last shading device was an egg-crate shading device that refers to a shape formed by combining the vertical and horizontal shading types. The horizontal shade functions to control direct solar radiation depending on the solar altitude, while the vertical shade functions to block or control side light depending on the change of azimuth. The plan size of each egg-crate was 0.5 m by 0.5 m. For the present study, 4 different heights of a vertical and horizontal slat were considered for the assessment since the solar radiation differs by the heights of the egg-crate.

3.3. Simulation for the Assessment of Daylighting and Cooling Energy

To evaluate the daylighting and energy performance of a residential building with various types of shading devices, two simulation tools were used. For the analysis of daylighting through shading devices, the Radiance was used, which was developed by the lighting research team of the LBNL (Lawrence Berkeley National Laboratory) in the US [41]. By verifying and visualizing light rays from the light source, illuminance through shading devices was calculated. The simulation conditions were based on IES (Illuminating Engineering Society) guidelines as presented in Table 3 [42].

Table 3. Input parameters for the Radiance.

Input Parameters	Value
Orientation	South-facing window
Time	June and December 21 (noon)
Sky condition	CIE Clear sky for direct sunlight
Glazing visual Transmittance	70%: Glazing double pane Low E 20%: A standard floor made by an opaque material
Material properties (Reflectance)	70%: A standard ceiling 50%: A standard wall 50%: A standard external shadings and curtain wall frames

Based on the building description above and the specifications of the building envelopes (Table 1), the energy simulation was performed. In addition, hot water and space heating was assumed to be provided by the central heating systems fueled by natural gas. Compact Fluorescent lamps were mainly used as a lighting system. For the weather condition, the “Seoul” EPW (Energy Plus Weather format) file in South Korea was used. The energy model was created by using the SketchUp program (Figure 3). The design variables of shading devices were also modeled by using SketchUp for energy simulation. For the evaluation of the cooling energy, IES VE was selected as a building energy simulation program [43].

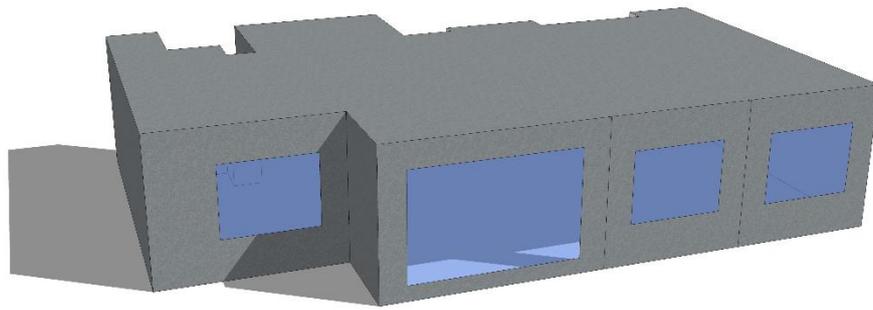


Figure 3. The energy model created by SketchUp.

Since the energy performance of shading devices in a building can be varied by the degree of indoor temperature in the space, the design temperature in the cooling season was set to 20 °C. For the energy consumption comparison, the annual energy consumption operated by each shading device was compared. By using the coefficient of variation of the root mean squared error ($CV(RMSE)$) provided by ASHRAE Guideline 14, the monthly energy consumption of the reference residential building without any shading devices was compared with the energy simulation [44]. The models will be declared to be calibrated if they produce $CV(RMSE)$ s within $\pm 15\%$ with monthly energy data

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (M_i - S_i)^2}{n}} \quad (1)$$

$$C_V(RMSE) = \frac{RMSE}{M_{avg}} \times 100 \quad (2)$$

where M_i is the energy consumption of the residential building, while S_i is the monthly energy consumption by energy simulation. N is the period and M_{avg} is the average for the energy consumption of the residential building.

4. Result

4.1. Daylighting Performance

Since the solar azimuth changes depending on the changes of time and seasons, to evaluate by season, the daylighting performance in the front, middle, and back areas were assessed for the standard time of noon during the spring and autumn equinoxes, the summer solstice, and the winter solstice.

4.1.1. The Venetian Blind

As shown in Figure 4, the illuminance was decreased when the slats of the blind were parallel to the X-axis of the window (0°) about 90% in the front area during the summer. When the slat angles were set to -30° and -45° , the illuminance was also significantly decreased in the front area, while the positive slat angles of the blind exceeded 12,000 lux during the summer. According to the lighting handbook of IESNA, the recommended light level ranges 200–300 lux for residential buildings [45]. The observed illuminance levels in the front area during the summer through the slat angles of -30° and -45° were satisfied with the recommendation of IESNA. While the illuminance with the slat angle of 0° was somewhat higher than the recommendation of IESNA, this slat angle can be applied to the summer season because the illuminance level was decreased in the middle and back areas. The other two positive slat angles may cause discomfort such as glare. During the winter, the positive angles of the blind admitted more illuminance than the negative angles of the blind in the middle area of the space. Considering the obtained results, it can be seen that the illuminance level can be highly influenced by the slat angles of the blind.

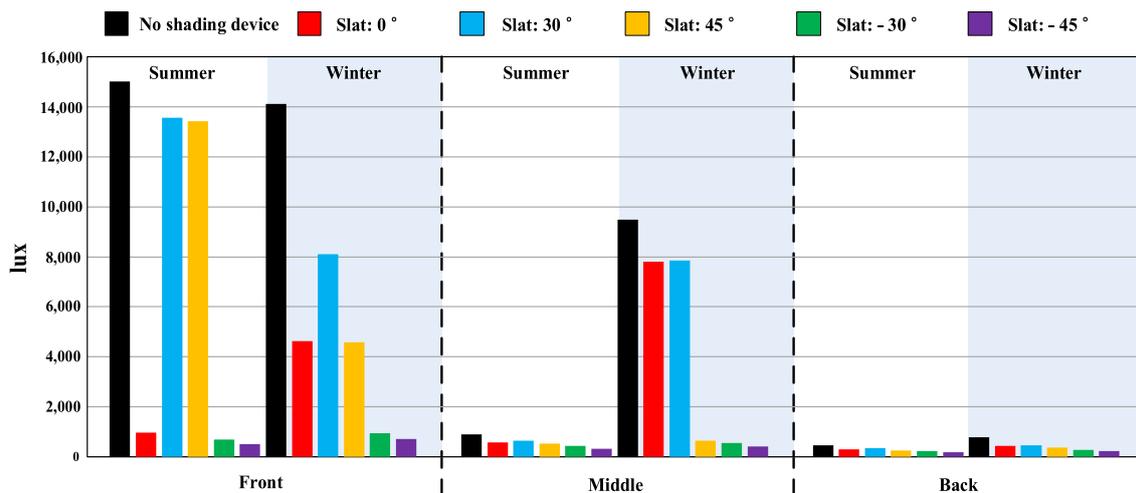


Figure 4. Daylighting performance through the Venetian blind.

4.1.2. The Overhang-Shaped Louver

When the projection length was ranged from 0.7 m to 1.1 m, about 50% of the illuminance was reduced compared to the building without a shading device in the front area during the summer as shown in Figure 5. As the projection length was increased from 1.1 m to 1.9 m, the illuminance was significantly reduced to below 1000 lux. Even though this illuminance level was somewhat higher than the IESNA recommendation, the projection length from 1.1 m to 1.9 m can be applied because the illuminance level in the middle and back areas was close to the recommendation. During the winter, there was a slight illuminance difference among the cases with various projection lengths in the front area.

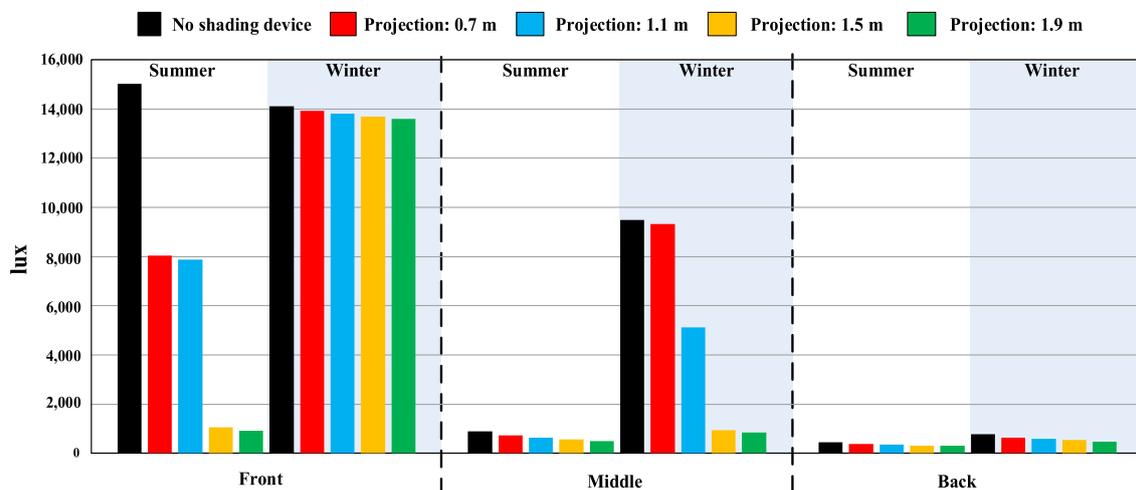


Figure 5. Daylighting performance through the overhang-shaped louver.

4.1.3. The Light Shelf

In the case of the light shelf, the illuminance level was measured when applying four different internal shelf angles in a building (Figure 6). Comparing the illuminance in the reference building without a shading device, the illuminance of all the cases was significantly reduced to below 1000 lux in the front area during the summer. In addition, there was a little illuminance difference among the cases with the angles of the internal shelf from 0° to 30°. A similar trend was also observed in the front area during the winter. Thus, it can be seen that the angle of the internal shelf had little impact on the illuminance in a building.

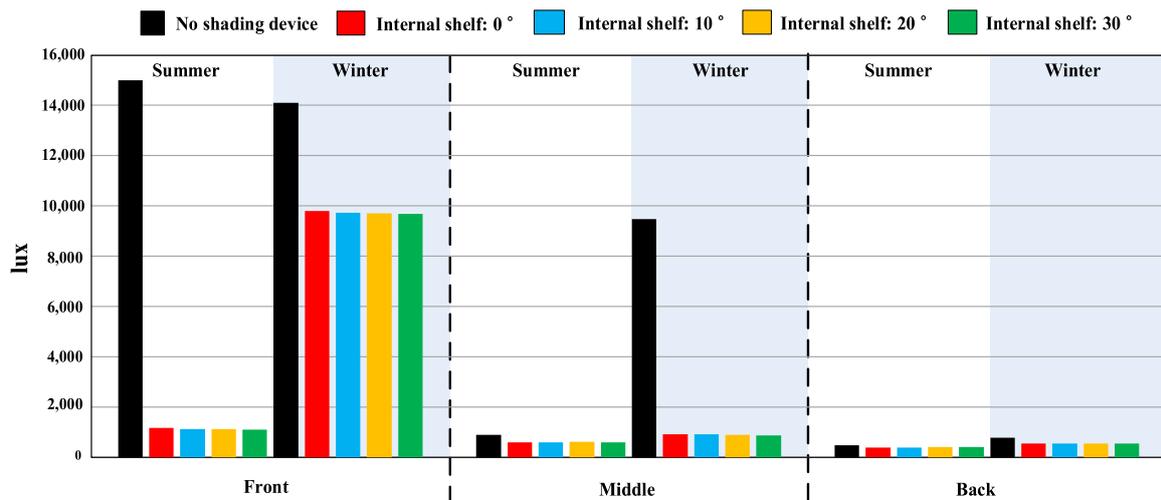


Figure 6. Daylighting performance through the light shelf.

4.1.4. The Egg-Crate

During the summer, the illuminance was reduced to below 2000 lux in the front area when the egg-crate shading was applied (Shown in Figure 7). While there was a little illuminance increase about 10% from with the vertical and horizontal slat height increase from 0.2 m to 0.3 m, the illuminance was significantly reduced as with the increase in the vertical and horizontal slat height during the summer in the front area. During the winter, 30% of the illuminance was reduced from the building without a shading device to the cases with the vertical and horizontal slat heights of 0.2 m ~0.3 m in the front area. As the vertical and horizontal slat height was increased, about 45% of the illuminance was additionally decreased. Based on the result, the use of the egg-crate shading can effectively reduce the illuminance in a building during the summer while admitting sunlight during the winter.

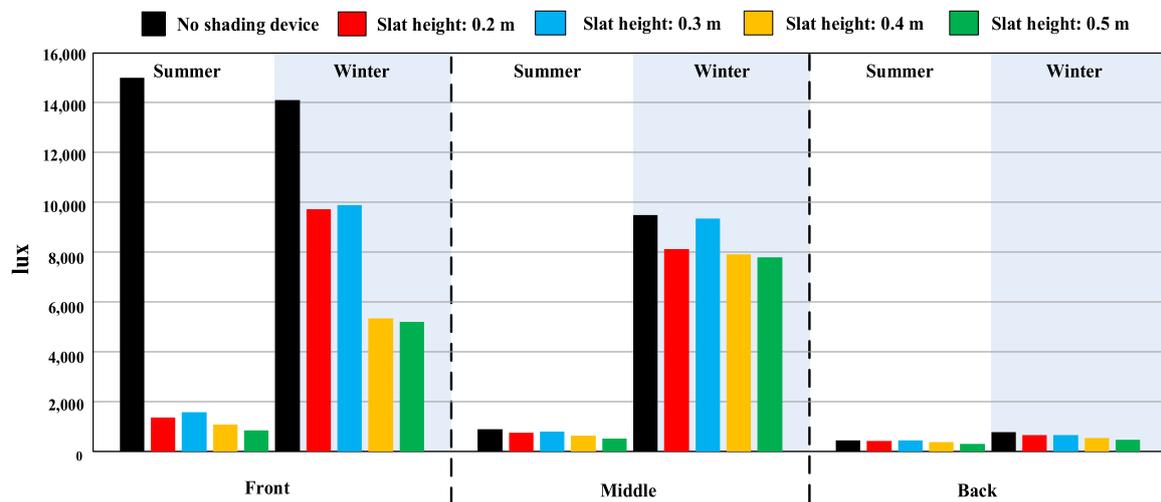


Figure 7. Daylighting performance through the egg-crate.

4.2. The Analysis of Annual Cooling Energy Consumption by Shading Devices

4.2.1. The Comparison between Energy Simulation and the Monthly Energy Consumption

To validate the energy simulation, the monthly energy consumption of the reference residential building was compared with the energy prediction by the simulation. The total energy consumption of the residential building was about 76.4 MWh, while there was a 5% decrease for the energy use predicted by the energy simulation. As shown in Figure 8, the largest difference was observed in

April, which about 30%. Specifically, the root-mean-squared errors (CV(RMSEs) were calculated and these were ranged from 0.16 to 3.5 (Table 4). Since these results were within the acceptable range, the predicted results by the simulation met the requirement by ASHRAE Guideline 14 [44].

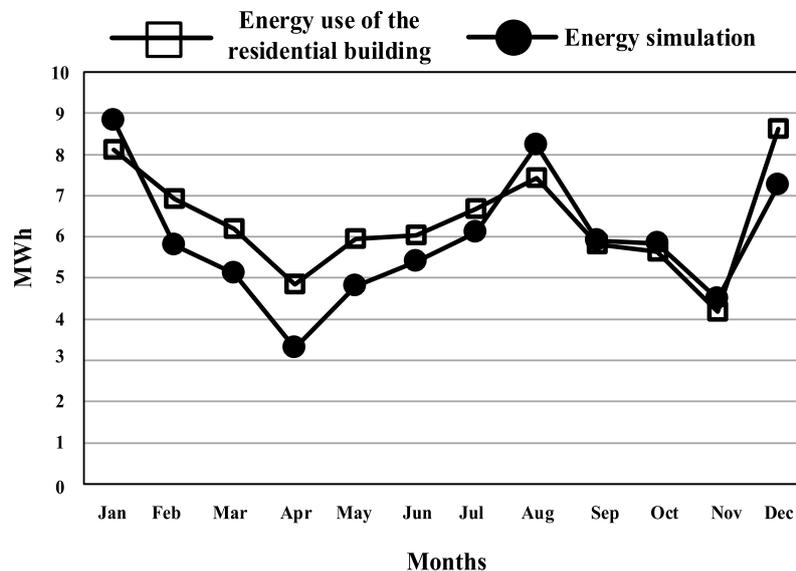


Figure 8. Energy consumption comparison between the reference residential building and the energy simulation.

Table 4. The monthly energy consumption comparison for the reference case.

Month	Energy Consumption (MWh)			CV(RMSE) (%)
	The Reference Residential Building, 2017	Energy Simulation	Difference	
January	8.1	8.8	−0.7	1.59
February	6.9	5.8	1.1	2.54
March	6.2	5.1	1.1	2.46
April	4.8	3.3	1.5	3.50
May	5.9	4.8	1.1	2.61
June	6.0	5.4	0.6	1.46
July	6.7	6.1	0.6	1.34
August	7.4	8.2	−0.8	1.85
September	5.8	5.9	−0.1	0.16
October	5.6	5.8	−0.2	0.48
November	4.2	4.5	−0.3	0.72
December	8.6	7.3	1.4	3.10

4.2.2. The Cooling Energy Comparison by Shading Devices

To find the most effective shading device for reducing cooling demand in a residential building, the annual cooling energy consumption by four shading devices was compared (Figure 9). When applying the Venetian blind in a building, about 14% of the annual cooling energy was reduced. Among five different slat angles, the largest cooling energy was reduced by about 18%, when the slat angle was set to 45°. Conversely, the smallest amount of cooling energy was reduced, which was about 8%, when a slat angle was set to −45°. It can be seen that the reduction of cooling energy consumption was varied with the different slat angles of the blind. In the case of the overhang-shaped louver, the annual

cooling energy was reduced as the projection length was increased. When the projection length was 1.9 m, the largest energy consumption reduction was observed, which was about 51% of the total annual cooling energy consumption. The average cooling energy reduction was about 32% with the louver. When the projection length was 0.7 m, only 6% of the cooling energy was reduced. As can be shown, the cooling energy in a building with the overhang-shaped louver was highly influenced by the projection lengths of the louver. Moreover, about 30% of annual cooling energy saving was made when the light shelf was used. However, there was little difference in the cooling energy consumption reduction among the cases with different angles of the internal shelf. Therefore, the angles of the internal shelf have a less impact on cooling energy consumption in a building. Lastly, about 50% of the annual cooling energy consumption was reduced with the egg-crate shading in a building. As the length of vertical and horizontal slats was increased, the cooling energy consumption reduction was also increased. The largest energy-saving was obtained, when the vertical and horizontal slats were 0.5 m, which was about 54%.

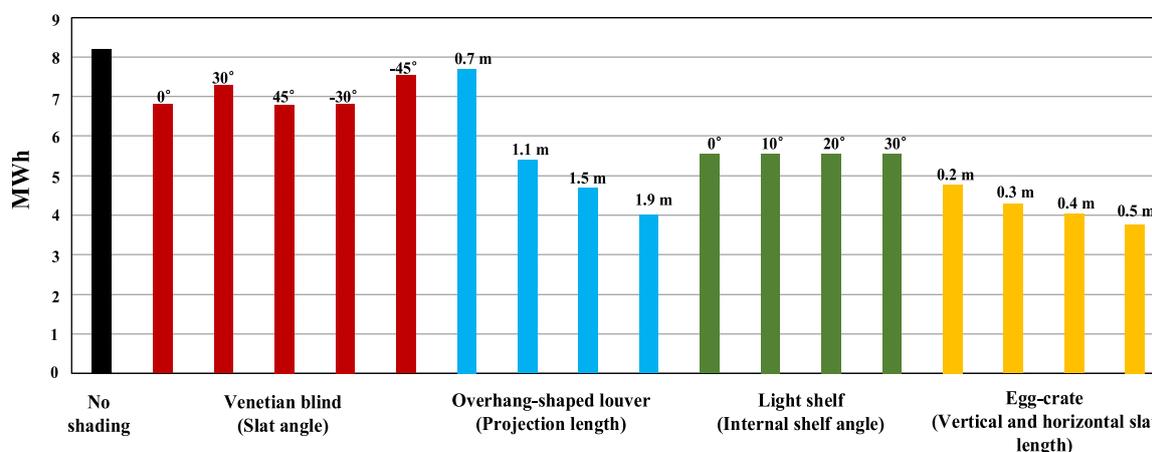


Figure 9. The reduction of annual cooling energy consumption by shading devices.

In sum, the use of an overhang-shaped louver with a projection length of 1.9 m and the egg-crate shading with a vertical and horizontal slat height of 0.5 m can effectively reduce the annual cooling energy consumption in a residential building among various shading devices.

5. Discussion

For the present study, the daylighting and energy performance of shading devices in a residential building was assessed. As can be shown above, each design variable had a different impact on the illuminance level and cooling energy demand in the building. Considering the daylighting performance, the light shelf, and the egg-crate effectively blocked sunlight in the front area during the summer more effectively than the others, while the overhang-shaped louver and the egg-crate shading had more impact on reducing the cooling energy consumption than the others. A similar result was obtained through the study of Alhuwayil et al. [20]. According to their result, the energy-saving was increased as the fin widths and the projection lengths of the overhang were increased. This was also mentioned in the present study. In addition, Alzoubi and Al-Zoubi [46] have investigated the energy performance of three types of external shadings including vertical, horizontal, and horizontal 45°. They concluded that the most effective shading for the reduction of energy consumption was the vertical shading device. This showed a similar result to the present study. Even though the egg-crate in the present study is not the vertical shading device, it showed the best overall performance among other shading devices by blocking the sun both horizontally and vertically.

In the present study, the annual energy consumption was calculated for the IES VE simulation. However, the time and date for the Radiance simulation program were set on only two days such as June and December 21st at noon to find the most effective shading devices during the summer and

winter as well as reduce the computational resources, while other studies have considered the annual daylighting performance [20,47–49]. Considering the outcome of the present study, the obtained illuminance levels can be overestimated or underestimated. Thus, it is necessary to consider annual daylighting performance for further study.

Moreover, it can be seen that the performance difference between daylighting and cooling energy consumption was caused by the illuminance in the middle and back areas. This can influence other loads in buildings. Thus, it is necessary to evaluate other building energy use such as artificial lighting. As mentioned previously, the best shading device for reducing the cooling energy consumption was the egg-crate shading with a vertical and horizontal slat height of 0.5 m, and the second one was the overhang-shaped louver with a projection length of 1.9 m. However, there was only a 3% difference in annual cooling energy consumption between the two strategies. To find out the shading device with the best overall performance, the artificial lighting loads by these strategies were compared. As can be shown in Figure 10, about 15% of energy saving for the artificial load was obtained by using the egg-crate shading with a vertical and horizontal slat height of 0.5 m, while 5% of artificial lighting energy was reduced by the overhang-shaped louver. Therefore, the use of the egg-crate was a more effective shading device for blocking sunlight as well as reducing cooling energy demand in a residential building than the overhang-shaped louver.

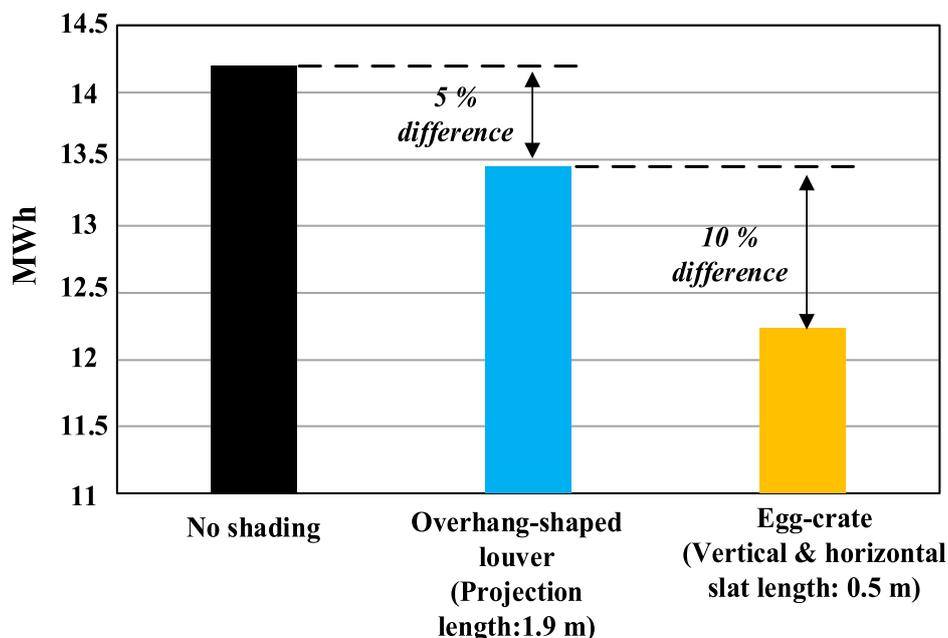


Figure 10. The reduction of artificial lighting energy consumption by two shading devices.

6. Conclusions

As one of the main contributors to energy consumption in South Korea, the number of residential building has gradually increased and the energy consumed by residential buildings has become the main concern. Thus, many studies have been conducted to reduce energy consumption in residential buildings by applying passive and active design solutions. In addition, several renewable energy systems were used to improve energy efficiency in residential buildings. In South Korea, the energy demand for cooling in residential buildings has been increasing rapidly. Focusing on possible passive design strategies, the present study investigated the daylight and cooling performance of several shading devices in a residential building.

Among various types of shading devices, four shading devices were selected including the Venetian blind, horizontal louver, light shelf, and egg-crate. Using two different simulations, the illuminance level and annual cooling energy reduction by various design variables of these shading devices were

analyzed. For both assessments, the illuminance and cooling energy performance were varied by the design options of shading devices. For the daylight assessment, all the shading devices blocked the sunlight effectively. Specifically, the light shelf and egg-crate were able to block a significant amount of sunlight in a building during the summer, while admitting sunlight during the winter. Regarding the cooling energy consumption, the overhang-shaped louver and egg-crate were able to reduce the cooling demand more effectively than the other shading devices. Among various design options of these two devices, the overhang-shaped louver with a projection length of 1.9 m and the egg-crate shading with a vertical and horizontal slat height of 0.5 m reduced about 51% to 54% of the annual cooling energy consumption. Because of only a 3% difference in the cooling energy consumption, the artificial lighting loads of these two design options were compared. As a result, about 15% of the artificial lighting load was reduced by the use of the egg-crate shading with a vertical and horizontal slat height of 0.5 m, while the overhang-shaped louver only reduced 5% of the load. Therefore, it is necessary to consider both daylight and energy performance for developing energy reduction strategies by using shading devices.

Considering the outcome of the present study, the proper use of shading devices has the potential for energy saving by reducing the cooling and artificial lighting loads in a building. Moreover, the obtained result can be used for the development of energy-efficient building design. Finally, it can reduce greenhouse gas emissions. For further study, more various design options and shading devices will be included in the analysis of energy efficiency and daylighting performance. In addition, it is necessary to consider the annual daylighting performance for more accurate analysis.

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