energies

MDPI

Article

Evaluation of External Light Shelf Performance in Relation to the Ceiling Types Used in Indoor Spaces

Su-yeon Jung [1], Min-Goo Lee [2] and Heangwoo Lee [1,]*

[1] College of Design, Sangmyung University, Cheonan-si 31066, Chungcheongnam-do, Republic of Korea; s201920289@gmail.com
[2] Korea Electronics Technology Institute, Seongnam-si 13509, Gyeonggi-do, Republic of Korea; emingoo@keti.re.kr
* Correspondence: 2hw@smu.ac.kr; Tel.: +82-41-550-5215

Abstract: A light shelf is a type of natural daylight system that brings natural light from the outside into an indoor space through a reflector and a ceiling surface. The introduction of light shelves has led to studies evaluating their efficiency. However, past studies on light shelves did not consider the diversity of ceiling types when evaluating their performance. Therefore, this study derives fundamental data involving external light shelf designs by evaluating light shelf performance based on the ceiling type present using a light environment simulation method. This study analyzed the indoor illuminance distribution with Radiance to evaluate the performance according to light shelves and indoor space types. The results derived from this study are as follows: (1) In the case of a flat ceiling, the performance of an external light shelf can be improved by increasing its angle and width. However, adjusting the external light shelf angle to 30° during the middle of the season and 20° in winter is ineffective because natural light is not reflected by the ceiling surface. (2) The performance of a light shelf can be improved by increasing the slope and curvature of the ceiling types specified in this study. However, setting the light shelf angle to 30° during the middle season and to 30° and 20° in winter, when external natural light entering the indoor space is not reflected by the ceiling surface, is ineffective due to the low levels of daylight performance, regardless of the type of space. (3) To increase uniformity levels in gable ceilings and curved ceilings, it is advantageous to increase the number of reflections and diffusion areas on the ceiling's surface due to the uniqueness of these ceiling shapes. Furthermore, the optimal external light shelf angle for these ceiling types differs from that of other types. (4) Regarding the appropriate external light shelf size according to a particular ceiling type, installing an angle-controllable external light shelf with a width of 1.2 m can improve daylight performance.

Keywords: light shelf; ceiling types; performance evaluation; proper specification

check for updates

Citation: Jung, S.-y.; Lee, M.-G.; Lee, H. Evaluation of External Light Shelf Performance in Relation to the Ceiling Types Used in Indoor Spaces. *Energies* **2023**, *16*, 8107. https://doi.org/10.3390/en16248107

Academic Editor: Rajendra Singh Adhikari

Received: 27 November 2023
Revised: 12 December 2023
Accepted: 15 December 2023
Published: 17 December 2023

1. Introduction

An increase in energy use and CO_2 emissions in the building, transportation, and industrial sectors yearly significantly leads to negative environmental effects. Energy use and CO_2 emissions in the building sector are higher than in the transportation and industrial sectors, with energy use in the building sector increasing annually [1–3]. In fact, according to the 2020 report of the Global Alliance for Buildings and Construction, the overall energy consumption in 2019 was unchanged from the previous year. However, CO_2 emissions resulting from energy use in the building sector increased by 28%, which is the highest rate on record [4]. Heating, cooling, water heating, and lighting dominate the use of energy within the building sector, with lighting in energy use accounting for 10% of the total energy use in this sector, according to the U.S. Energy Information Administration's 2018 report "Commercial Buildings Energy Consumption Survey". As a result, the demand for research and the development of technology for reducing lighting energy use in the building sector is continuously growing. A light shelf is a type of natural lighting system that can help reduce the use of light energy in the building sector, and various studies have assessed its efficacy [5,6]. Installing a light shelf on a daylighting window enables natural light to enter the room and reach more indoor spaces, with the light enhanced by reflections from the light shelf reflector and ceiling surface of the indoor space. The daylighting effect created by a light shelf can improve the lighting environment of an indoor space while reducing lighting energy use [7,8]. However, previous studies that evaluated light shelf performances [9–23] focused on the variables of the light shelf itself without considering the various types of ceiling surfaces in indoor spaces where it is installed. Although some studies [22,23] have examined various shapes of indoor space, they have evaluated light shelf performance while fixing the size and shape of the indoor space. Thus, such studies have limitations when deriving data for the design of light shelves for various types of indoor spaces in the future.

Therefore, this study aims to derive fundamental data for future light shelf designs by evaluating light shelf performance according to its variables and the shape of the ceiling surface of the indoor space in which it is installed.

1.1. Light Shelf Concept and Review of Previous Studies

A light shelf is a natural lighting system that takes natural light entering a room through a daylighting window and enhances it to reach more indoor spaces (Figure 1). It accomplishes this through reflection, using both its reflector and the ceiling surface of the indoor space [24,25]. The light shelf can also contribute to solving the problem of daylighting imbalance in an indoor space by blocking a part of the natural light entering through a daylighting window. The width, angle, height, and reflectance determine the performance of a light shelf; additionally, proper operations and the control of its angle can improve daylighting performance [16,19]. In addition, there are different types of light shelves, including external, internal, and mixed types, that are used depending on the location in which they are installed. The external type has excellent daylighting performance [17].

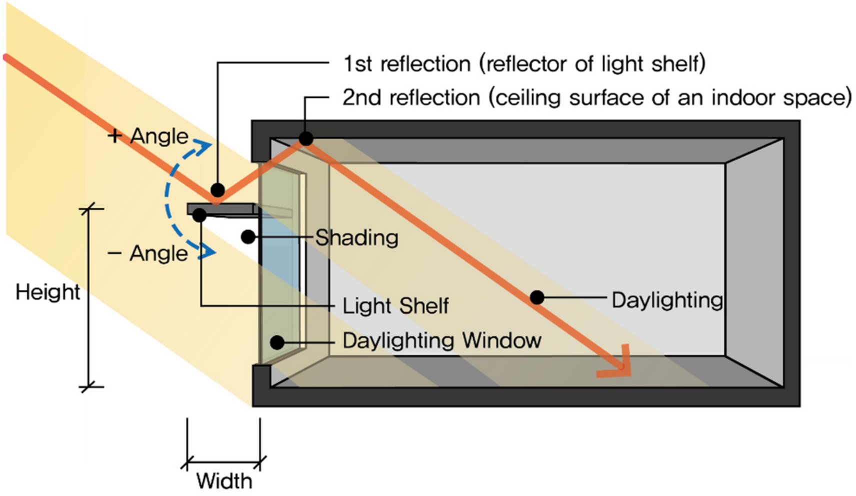


Figure 1. Concept and variables of a light shelf.

As shown in Table 1, this study reviewed previous research on light shelves [9–23], which is outlined here. Previous studies considered several variables of light shelves to evaluate their performance, such as their angle, width, and installation height. However, most studies limited the type of indoor space evaluated to rectangular-shaped rooms with flat ceilings. Some studies [22,23] have examined various ceiling surface shapes, such as sloped and curved ceilings. However, they have also evaluated the light shelf performance by adjusting the slope angle and curvature of the ceiling surface to specific values. In contrast, this study evaluates light shelf performance based on the shape of the ceiling in the space in which it is installed. This study also derives fundamental data that can be used to design light shelves for various types of spaces. Only the ceiling surface has been used as a space variable when evaluating light shelf performance because the reflection of a ceiling's surface can be a determining factor when assessing light shelf performance, as natural light is introduced into space through the light shelf and is reflected by the ceiling surface of an indoor space.

Table 1. Review of prior studies on light shelves.

Author (Year)	**Purpose**	**Indoor Space**		**Variables of Light Shelf**			
		Shape	**Size (m): Width × Depth × Height**	**Height (m)**	**Angle**	**Width (Type)**	**Reflectance (%)**
Umberto and Hamid (2015) [9]	Analyze illumination changes in an office building caused by the light shelf	Rectangle	15 × 10 × 3	2.25	0°	1.1 m (External), 0.5 m (Internal)	80
Aik (2016) [10]	Evaluate the performance of a blind-combined light shelf	Rectangle	7 × 7 × 3.2	2.0, 2.2	0°, 10°, 20°, 30°	1.0 m (External), 8.0 m (External), 6.0 m (External), 0.8 m (Mixed), 1.0 m (Mixed)	50
Lim and Heng (2016) [11]	Analyze the daylighting performance of a high-rise office building using light shelves	Rectangle	8.4 × 8.4 × 2.7	2.1, 1.8, 1.5	0°, 90°	0.6 m (Internal), 0.3 m (Internal)	51.29
Carrier and Benny (2017) [12]	Performance evaluation of daylighting and the visual comfort of light shelves	Rectangle	7 × 7 × 3.2	2.0	0°–90°	0.1 m–1.5 m (External), 1.5–2.5 (Mixed)	80
Navid and Roza (2022) [13]	Performance evaluation of daylighting and thermal comfort in classrooms with light shelves	Rectangle	8 × 5.8 × 2.9	2.0	−40°–50° (10° step)	0.3 m–1.0 m (External), 0.1 m –0.5 m (Internal)	80
Santiago and Alfonso (2002) [14]	Performance evaluation of a light shelf based on its reflectance	Rectangle	0.6 × 0.6 × 0.28	0.2	0°	0.1 m (External), 0.04 m (Internal)	89.4, 86.1, 84.0, 38.7
Lim et al. (2014) [15]	Performance evaluation of a light shelf under tropical sky conditions	Rectangle	0.42 × 0.42 × 0.135	0.105	0°	0.03 m (Internal)	51.29
Claros and Alfonso (2018) [16]	Performance evaluation of a light shelf and its overhangs	Rectangle	0.6 ×0.6 × 0.28	0.2	0°	Mixed 0.14	87.6

Table 1. *Cont.*

Author (Year)	**Purpose**	**Indoor Space**		**Variables of Light Shelf**			
		Shape	**Size (m): Width × Depth × Height**	**Height (m)**	**Angle**	**Width (Type)**	**Reflectance (%)**
Kim et al. (2019) [17]	Proposal and performance evaluation of light shelf technology with user recognition technology	Rectangle	4.9 × 6.6 × 2.5	1.8	−90°–90°	0.3 m (External), 0.6 m (Internal), 0.2 m (Internal)	85
Lee et al. (2022) [18]	Performance evaluation of a light shelf in Madrid, Spain	Rectangle	0.6 × 0.6 × 0.28	0.2	0°	0.14 m (Mixed)	91
Beltran et al. (1997) [19]	Development and performance evaluation of light shelves and light pipes	Rectangle	9.1 × 6.1 × 3.0	2.4	0°	0.4 m–1.1 m (Mixed)	-
Lee and Seo (2020) [20]	Performance evaluation of an external light shelf using a prism sheet	Rectangle	4.9 × 6.6 × 2.5	1.8	−10, 0, 10, 20, 30°	0.6 m	85
Lee et al. (2018) [21]	Development and performance evaluation of an awning system incorporating a light shelf	Rectangle	4.9 × 6.6 × 2.5	1.8	0°~30°	0.6 (External)	85
Freewan (2010) [22]	Analysis of the impact on the light shelf when installing various types of light shelves on a curved ceiling	Rectangle	8 × 6 × 3.25	2.0	Fixed angle type	1.65 (Mixed)	-
Freewan at al. (2008) [23]	Light shelf performance evaluation according to the geometric structure of indoor space	Rectangle	8 × 6 × 3.25	2.0	0°	1.65 (Mixed)	85

1.2. Indoor Illumination Standards

Maintaining proper illumination in an indoor space is important for ensuring the visual comfort of its occupants. The proper illumination of an indoor space is classified into different types according to the level of visual comfort required to conduct a certain type of work in that space. As shown in Table 2, this study examined the illuminance standards [26–31] proposed by the United States, Japan, Brazil, South Korea, Europe, and China, with standards differing across countries. The recommended illuminance standards in the US, Japan, Brazil, and Korea are based on general visual tasks, whereas in Europe and China, the standards are based on the spatial characteristics of offices and libraries. Therefore, this study set 500 lx as the illuminance standard for each country, which is also the standard used when evaluating light shelf performance according to the ceiling surface type. This standard was determined based on the indoor illuminance range common in each country.

Table 2. Indoor illumination standard by country.

Country/Illumination Standard	**Task Grade/Place**	**Illumination (lx)**		
		Minimum	**Standard**	**Maximum**
United States/IES [26]	General	500	750	1000
Japan/JIN Z 9110 [27]	General	300	500	600
Brazil/ABNT NBR 5413:1992 [28]	General	500	750	1000
South Korea/KS A 3011 [29]	General	300	400	600
Europe/EN 12464-1 [30]	Offices and libraries	-	500	-
China/GB 50034 [31]	Offices and libraries	-	500	-

2. Evaluation Methods

2.1. Performance Evaluation Methods

This study conducted a performance evaluation according to the shape of the ceiling surface of a given indoor space and the light shelf variables using the Radiance 2.0 simulation program as a tool for analysis. The details are as follows:

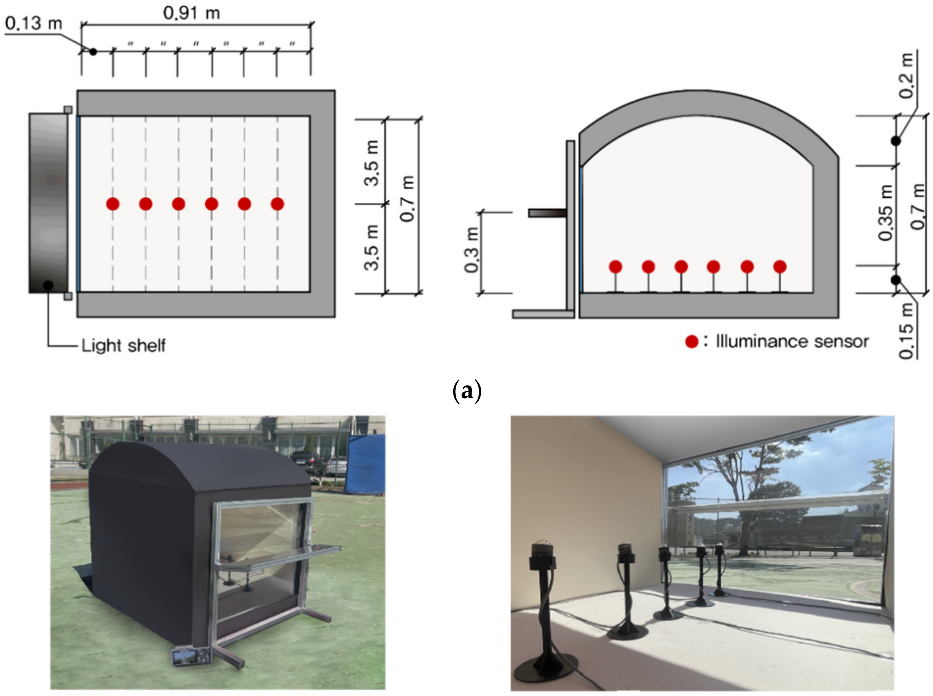
First, Radiance 2.0, which was used to evaluate performance in this study, is a popular ray-tracing software that can analyze the transmission, reflection, and diffusion of light. Radiance applies the Backwards Ray-Tracing Technique, which traces light backward from an observer to the light source and has been used to evaluate the performance of shading and lighting systems [32–35]. This study used version 2.0 of Radiance, which can be used with AutoCAD 2000 to analyze indoor illumination. This methodology is extensively used to analyze indoor illuminance in several studies [36–39] in conjunction with AutoCAD, validating its effectiveness. To assess the simulation capabilities of Radiance, which is used as part of this methodology for evaluating the light shelf based on the ceiling surface shape, this study compared and analyzed the performance evaluation results from both Radiance and the actual environment, as shown in Table 3. A scaled model was made for the curved ceiling surface, one of the ceiling surface shapes defined in this study, and its shape and size are shown in Figure 2. Due to the ceiling types set for a light shelf performance evaluation in this study, the curved ceiling shape was selected to evaluate the adequacy of the Radiance performance evaluation; it is the only one that reflects and diffuses daylight entering the room. As a result, the indoor illuminance measurements obtained via Radiance show an average difference of 6.6% from those collected in the actual environment (Figure 3). These results demonstrate the validity of the Radiance simulation analysis.

Second, this study derived the indoor space depth ratio satisfying 500 lx based on the indoor illuminance derived from the ceiling types and light shelf variables. The ratio of the indoor space depth that satisfies 500 lx is the distance value between the daylighting window that satisfies 500 lx for the indoor space depth and the x-axis column. A high value indicates that the natural light entering through the light shelf penetrates farther and effectively reduces the lighting energy use due to an improvement in daylighting performance. In addition, this study derived the uniformity of indoor illuminance, which is calculated as the ratio of the minimum illuminance to the average illuminance, to evaluate the light shelf performance.

Table 3. Scale model and Radiance-based indoor illumination analysis environments.

Metrics			Actual Environment and Scale Model-Based Performance Evaluation	Radiance-Based Performance Evaluation
Outdoor Environmental Conditions	Measurement Position		Cheonan, South Korea	Latitude: 36°30′0″ N, Longitude: 127°5′59″ E
	Summer	Time	3 June 2023, 12:32 p.m.	3 June 2023, 12:32 p.m.
		Sky and weather	* Cloud coverage 1.4%	CIE standard clear sky
	Winter	Time	11 December 2022, 12:32 p.m.	11 December 2022, 12:32 p.m.
		Sky and weather	* Cloud coverage 0.5%	CIE standard clear sky
	Middle Season	Time	10 March 2023, 12:32 p.m.	10 March 2023, 12:32 p.m.
		Sky and weather	* Cloud coverage 0.3%	CIE standard clear sky
	Solar altitude		76.7 (Summer), 29.7 (Winter), 53.2 (Middle Season)	Automated calculations based on location
Indoor Space	Ceiling type		Curved ceiling	Curved ceiling
	Floor Size (m): Width × Depth		0.91 × 0.7	0.91 × 0.7
	Ceiling height (m)		Min. 0.5 to Max. 0.7	Min. 0.5 to Max. 0.7
	Window size (m): Width × Height		0.7 × 0.5	0.7 × 0.5
	Window transmissivity (%)		80.0	80.8
	Reflectance (%) (floor, wall, ceiling)		25.0, 55.0, 75.0	25.1, 55.0, 75.9
Light Shelf	Reflector Size (m): Width × Depth × Height		0.7 × 0.15 × 0.025	0.7 × 0.15 × 0.025
	Height (m)		0.3	0.3
	Angle		0°	0°
	Reflectance (%)		85.0	85.8
Illumination Sensor			Product name: ML-020S-O, Detection range: 0–150,000 lx	-

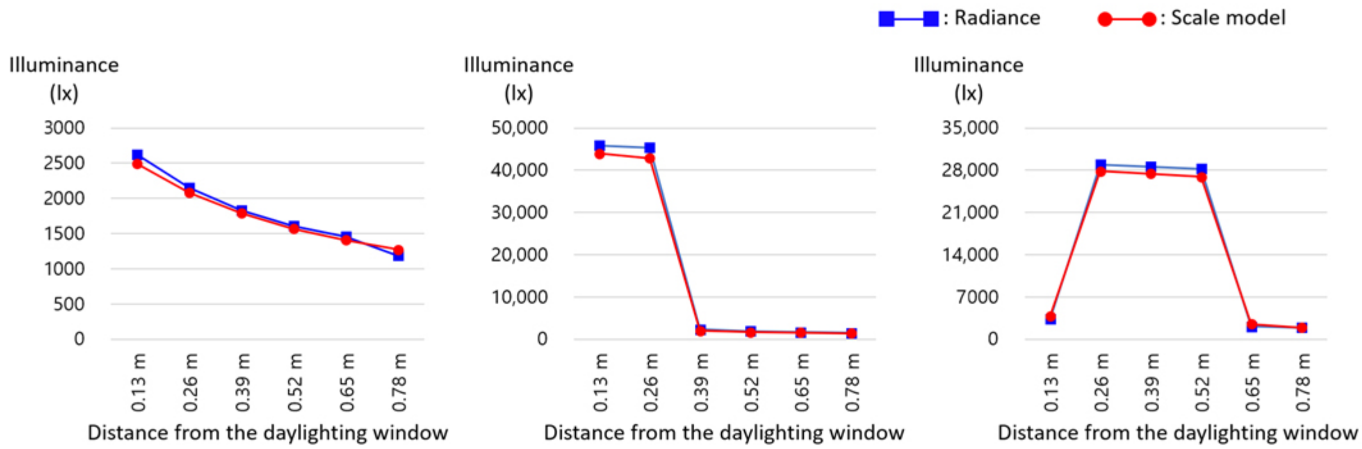
* Cloud coverage is based on the Korea Meteorological Administration's "Open MET Data".



(**a**)

(**b**)

Figure 2. Dimensions and fabrication of a scale model: (**a**) plane and cross-section of a scale model; (**b**) fabrication of a scale model.



(**a**) (**b**) (**c**)

Figure 3. Indoor illumination distribution by Radiance and scale model: (**a**) summer; (**b**) middle season; (**c**) winter.

Third, to analyze the performance evaluation results, this study derived the inflow process of natural light into an indoor space through its reflection from the light shelf and ceiling surface values. The altitude of the sun, incidence angle, and reflection angle were considered as parameters for the natural light inflow, and the data were visualized using AutoCAD.

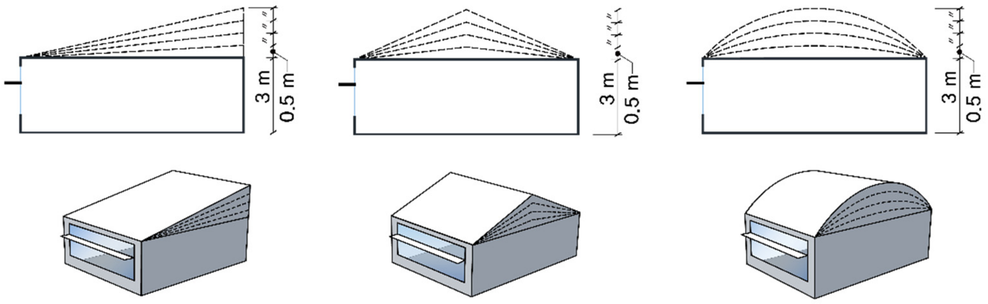
Fourth, this study derived the appropriate size of an external light shelf based on the ceiling type. The appropriate size of the external light shelf was deemed to be one with a high indoor space depth ratio that satisfied 500 lx. However, if many values satisfied 500 lx, the appropriate size of the light shelf was derived considering the uniformity of illumination.

2.2. Configuration of the Environment for Performance Evaluation

This study evaluated the external light shelf performance based on the ceiling type and the configuration of the evaluated environment.

First, the ceiling types of the indoor spaces considered in this study were set as sloped, gable, and curved (Figure 4). The size of the indoor space used for evaluating each ceiling type was 6 m wide × 9 m deep × 3 m high, and the maximum height of the ceiling increased by 3.5, 4.0, 4.5, and 5.0 m, depending on the ceiling type. The slope and curvature of the ceiling's surface according to its shape and height are shown in Table 4. The angles of the sloped ceilings were 3°, 6°, 9°, and 13°, depending on the height of the ceiling, and the gable ceiling had a higher slope than the sloped ceiling due to its shape. The ceiling's surface included a fixed daylighting window where the light shelf was installed. Under these conditions, increasing the slope and curvature of the surface of the ceiling increased the maximum height of the indoor space.

Second, the size of a daylighting window was set to 5 m × 2.2 m. The glass applied to the daylighting window had a transmittance of 80.8%. In addition, the daylighting window was positioned at the center of the indoor space, which was 0.7 m above the floor. The size and shape of the daylighting window were set to be the same regardless of the indoor space size and the shape of the ceiling's surface. This was performed so that the performance evaluation could be conducted based only on the variables of the light shelf and the shape of the ceiling surface, while the shape of the indoor space was kept as a controlled variable. The reflectance of the indoor space for the ceiling, wall, and floor was set to 75.9%, 55%, and 25.1%, respectively.



(**a**) (**b**) (**c**)

Figure 4. Configuration of ceiling types for light shelf performance evaluation: (**a**) sloped ceiling; (**b**) gable ceiling; (**c**) curved ceiling.

Table 4. Slope and curvature by ceiling type.

Ceiling Surface Type	Slope Angle	Curvature	Ceiling Height (m)	
			Lowest	Highest
Sloped	3°	-	3	3.5
	6°	-	3	4.0
	9°	-	3	4.5
	13°	-	3	5
Gable	6°	-	3	3.5
	13°	-	3	4.0
	18°	-	3	4.5
	24°	-	3	5
Curved	-	0.049	3	3.5
	-	0.094	3	4.0
	-	0.133	3	4.5
	-	0.165	3	5

Third, based on the relevant previous studies [9–23], the variables of the light shelf for performance evaluation were set as shown in Table 5. The type of light shelf selected for this study was limited to the external type, which is known for having excellent performance, as mentioned earlier, and the widths of the light shelf were set to 0.6, 0.9, and 1.2 m. The installation height of the light shelf was set to 2.0 m from the floor, considering the eye level of the occupants and the viewing range of the daylighting window.

Table 5. Light shelf variables for performance evaluation.

Variables	Specifications	Variables	Specifications
Width (Type)	0.6 m (External), 0.9 m (External), 1.2 m (External)	Height	2.0 m
Angle	10° increments from −30° to 30°	Reflectance	85.8%

Third, this study analyzed the indoor illumination distribution according to the ceiling types and light shelf variables. For this objective, the illumination measurement locations in the indoor space were set at 187 locations and 0.5 m intervals, as shown in Figure 5. In addition, the height for illuminance measurement was set to 0.85 m from the indoor floor space, considering the working surface size.

Fourth, the configuration of the outdoor environment for the performance evaluation was the same as validating Radiance in Table 4. However, as mentioned earlier, Radiance is used in conjunction with AutoCAD; therefore, the analysis is available only at a specific point in time due to version specifications, which is a limitation of this study.

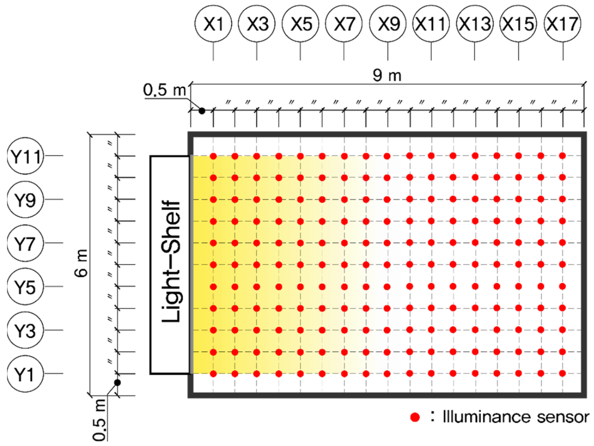


Figure 5. Indoor light measurement points for performance evaluation.

3. Results and Discussion

3.1. Performance Evaluation Results

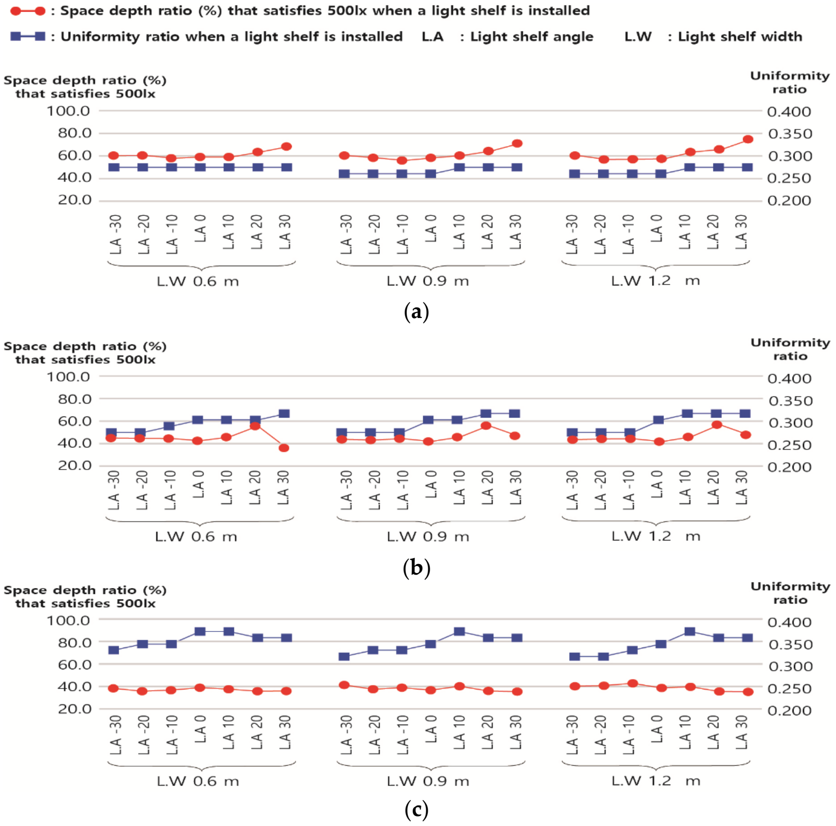
In this study, light shelf performance was evaluated according to the light shelf variables and the shape of the ceiling surface of a given indoor space. The results were as follows.

3.1.1. External Light Shelf Performance Evaluation Results for Flat Ceilings

The performance evaluation results of external light shelves for indoor spaces with a flat ceiling are shown in Figure 6. During summer, the daylighting performance of the light shelf is improved by increasing the amount of natural light entering the indoor space due to an increase in its width and angle, as shown in Figures 6a and 7a–c. Increasing the angle and width of an external light shelf in the middle season can increase the indoor space depth ratio that meets 500 lx, thus improving daylighting performance, as shown in Figure 7b. However, uniformity deteriorates when the external light shelf angle is set to 30° in the middle season and 20° in the winter. This is because the light shelf allows natural light from outside to enter the indoor space without a reflection from the ceiling's surface, as shown in Figure 7d,e. The external light shelf angles of 30° in the middle season and 20° in the winter were excluded when deriving an appropriate standard because they can cause glaring when the outside natural light penetrates the indoor space and deteriorates the uniformity of illumination. During winter, the external light shelf angle of 30° is unsuitable for light shelf daylighting performance because the space depth ratio satisfies 500 lx, and uniformity is reduced. This is likely due to the relatively low solar altitude in the winter compared to the summer and middle seasons, as shown in Figure 7f. In other words, the 30° angle set in winter is unsuitable for improving daylighting performance because natural light does not reach the upper reflector of the light shelf due to the winter solar altitude being 29.7° in this study. Furthermore, the external light shelf has a blocking effect. Therefore, it was excluded when deriving an appropriate standard for the external light shelf. The appropriate sizes of external light shelves for indoor spaces with a flat ceiling in this study were 1.2 m wide with a 30° angle, 1.2 m wide with a 20° angle, and 1.2 m wide with a 10° angle for the summer, middle, and winter seasons, respectively.

3.1.2. External Light Shelf Performance Evaluation Results for a Sloped Ceiling

The results of the external light shelf performance evaluation for a sloped ceiling are shown in Figure 8, and the light shelf illumination performance for the sloped ceiling showed a tendency to increase as the angle of a ceiling surface increased from 3° to 13°, which is the slope set used in this study. In addition, the results of the illumination performance for the sloped ceilings show a similar pattern because the entering process of natural light does not change significantly as it reaches the reflector and ceiling surface, as shown in Figure 9. In other words, a sloped ceiling defined in this study is considered suitable for improving the external light shelf performance. However, the external light shelf angle of 30° in the middle season and 20°/30° in winter are not affected by the ceiling surface when introducing natural light through an external light shelf; thus, they are inappropriate for improving daylighting performance, as is the case with the flat ceiling. Based on these findings, the appropriate specifications for a sloped ceiling were derived as 1.2 m wide with a 30° angle, 1.2 m wide with a 20° angle, and 1.2 m wide with a 10° angle for the summer, middle, and winter seasons, respectively.

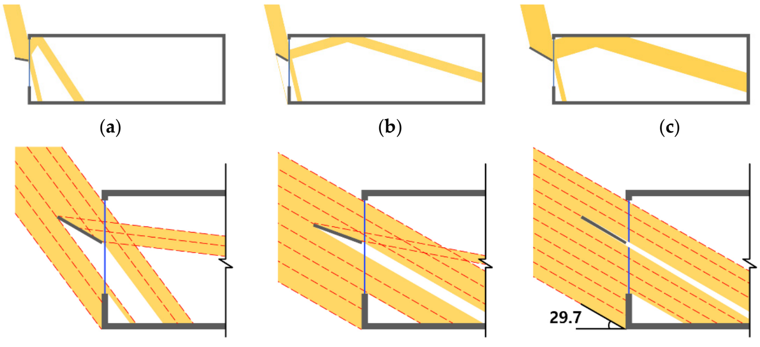


(**a**)

(**b**)

(**c**)

Figure 6. External light shelf performance evaluation results for flat ceilings: (**a**) summer, (**b**) middle season, and (**c**) winter.



(**a**) (**b**) (**c**)

(**d**) (**e**) (**f**)

Figure 7. Natural light inflow process according to external light shelf width and angle for flat ceilings: (**a**) light shelf with 0.6 m width and 10° angle in summer; (**b**) light shelf with 0.6 m width and 30° angle in summer; (**c**) light shelf with 1.2 m width and 30° angle in summer; (**d**) light shelf with 30° angle in middle season; (**e**) light shelf with 20° angle in winter; (**f**) light shelf with 30° angle in winter. These images show how light shelves reflect daylight into a room but do not consider the specular and diffuse reflection of light that occurs during the inflow and reflection process.

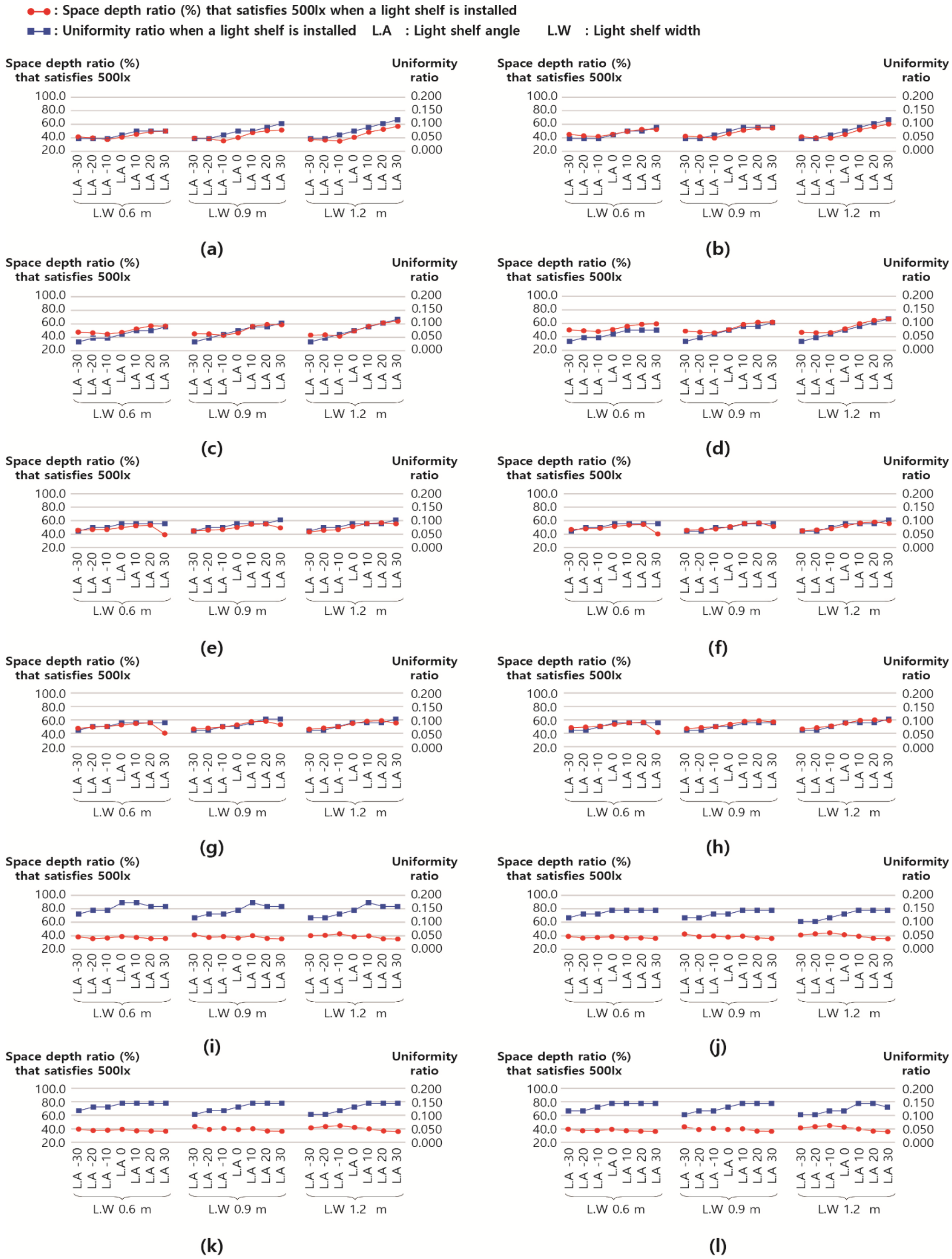


Figure 8. External light shelf performance evaluation results for a sloped ceiling: (**a**) sloped ceiling with an angle of 3° in summer; (**b**) sloped ceiling with an angle of 6° in summer; (**c**) sloped ceiling with an angle of 9° in summer; (**d**) sloped ceiling with an angle of 13° in summer; (**e**) sloped ceiling with an angle of 3° in middle season; (**f**) sloped ceiling with an angle of 6° in middle season; (**g**) sloped ceiling with an angle of 9° in middle season; (**h**) sloped ceiling with an angle of 13° in middle season (**i**) sloped ceiling with an angle of 3° in winter; (**j**) sloped ceiling with an angle of 6° in winter; (**k**) sloped ceiling with an angle of 9° in winter; (**l**) sloped ceiling with an angle of 13° in winter.

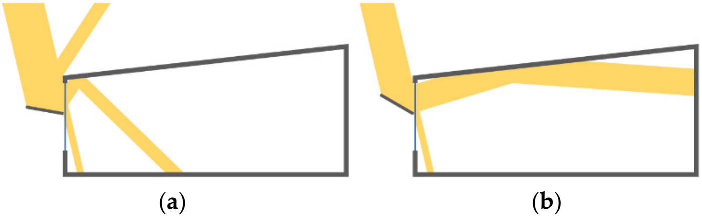


Figure 9. Natural light inflow depends on the shape of the sloped ceiling and the angle of the external light shelf: (**a**) a sloped ceiling in summer with an external light shelf at a 10° angle and width of 1.2 m; (**b**) a sloped ceiling in summer with an external light shelf of 30° angle and width of 1.2 m. These images show how light shelves reflect daylight into a room but do not consider the specular and diffuse reflection of light that occurs during the inflow and reflection process.

3.1.3. External Light Shelf Performance Evaluation Results for the Gable Ceiling

The performance evaluation results for a gable ceiling and the external light shelf variables are shown in Figure 10; the illumination performance tended to improve as the angle of a gable ceiling increased from 6° to 24°. In addition, the illumination performance of an external light shelf can be improved by increasing the angle and width of the external light shelf for a gable ceiling. This is similar to the results for the flat and sloped ceilings. However, an indoor space with a gable ceiling in the summer also shows a higher level of uniformity at a light shelf angle of 20° compared to an angle of 30°, as shown in Figure 10a–d. This is a unique characteristic of gable ceilings. As shown in Figure 11, the light shelf installed in an indoor space with a gable ceiling generates two reflections from the ceiling's surface when introducing natural light. The two reflections of natural light on the ceiling's surface, which has a high reflectance, can effectively improve the uniformity of illumination in the indoor space and introduce external natural light farther into the indoor space, as shown in Figure 10e–l. However, even for indoor spaces with gable ceilings, the external light shelf angles of 30° in the middle season and 20° and 30° in summer were determined to be ineffective for improving illumination uniformity because they are not affected by the shape of a ceiling when natural light enters an indoor space. The appropriate sizes of light shelves for gable ceilings are 1.2 m wide with an angle of 20°, 1.2 m wide with an angle of 20°, and 1.2 m wide with an angle of 10° for the summer, middle, and winter seasons, respectively.

3.1.4. Performance Evaluation Results of External Light Shelf for Curved Ceiling

The performance evaluation results of a curved ceiling and an external light shelf are shown in Figure 12; the daylighting performance of an external light shelf tends to improve as the curvature applied to the ceiling surface increases from 0.049 to 0.165. In particular, the curvature of the ceiling can diffuse natural light reflected from an external light shelf. This type of diffusion is suitable for improving the daylighting performance of an external light shelf. The curved ceiling specified in this study shows average improvement rates of 11.4% and 15.2% for an indoor space depth ratio that satisfies 500 lx and illumination uniformity, respectively, compared to a flat ceiling. However, the external light shelf angle of 30° in summer does not show diffusion compared to an angle of 20°, as shown in Figures 12a–d and 13, leading to low illumination uniformity. Light shelves must be controlled to ensure light diffusion in indoor spaces with curved ceilings to improve daylighting performance. For curved ceilings, the external light shelf angles of 30° in the middle season and 20° and 30° in summer are ineffective for improving daylighting performance, as shown in Figure 12e–l. The appropriate sizes of external light shelves for curved ceilings were determined as 1.2 m wide with an angle of 20°, 1.2 m wide with an angle of 20°, and 1.2 m wide with an angle of 10° for summer, middle, and winter seasons, respectively.

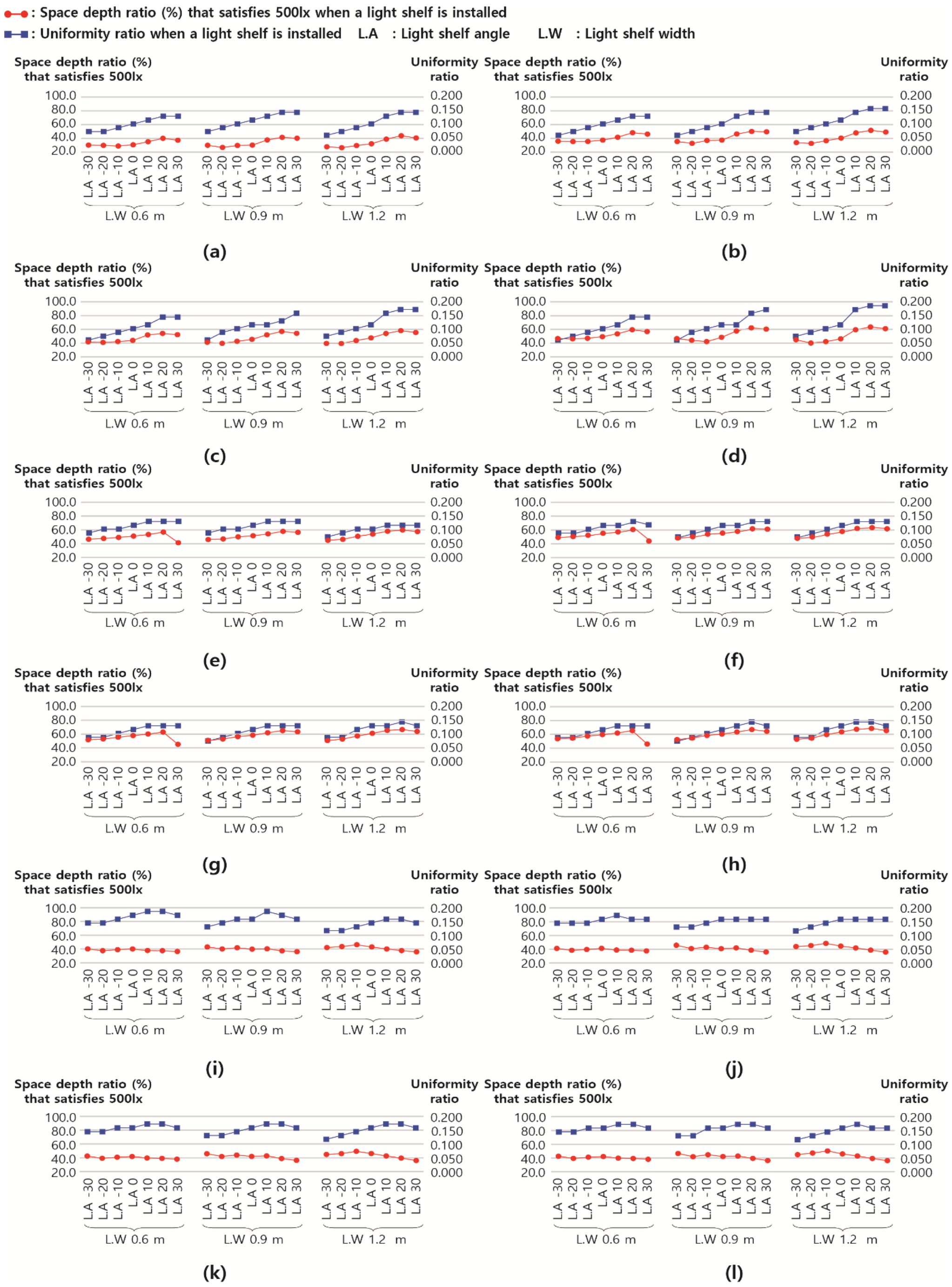


Figure 10. External light shelf performance evaluation results for gable ceiling: (**a**) gable ceiling with an angle of 6° in summer; (**b**) gable ceiling with an angle of 13° in summer; (**c**) gable ceiling with an angle of 18° in summer; (**d**) gable ceiling with an angle of 24° in summer; (**e**) gable ceiling with an angle of 6° in middle season; (**f**) gable ceiling with an angle of 13° in middle season; (**g**) gable ceiling with an angle of 18° in middle season; (**h**) gable ceiling with an angle of 24° in middle season; (**i**) gable ceiling with an angle of 6° in winter; (**j**) gable ceiling with an angle of 13° in winter; (**k**) gable ceiling with an angle of 18° in winter; (**l**) gable ceiling with an angle of 24° in winter.

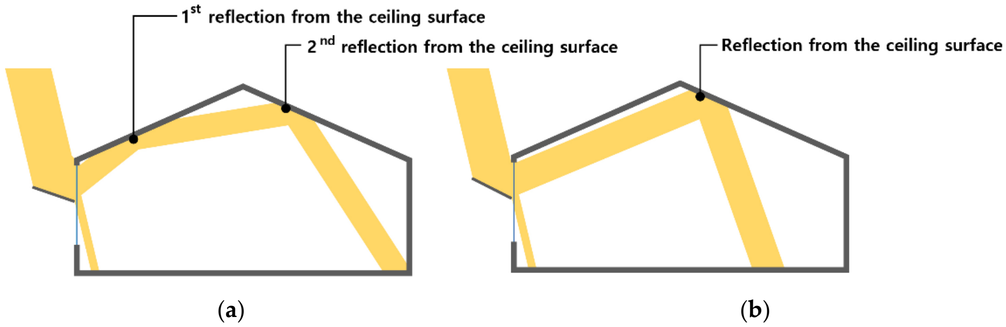


Figure 11. The natural light inflow process depending on the shape of a gable ceiling and the light shelf angle: (**a**) a gable ceiling with an angle of 24° in summer, an external light shelf with an angle of 20° and a width of 1.2 m; (**b**) a gable ceiling with an angle of 24° in summer, an external light shelf with an angle of 30°, and a width of 1.2 m. These images show how light shelves reflect daylight into a room but do not consider the specular and diffuse reflection of light that occurs during the inflow and reflection process.

3.2. Discussion

Herein, external light shelf performance was evaluated considering external light shelf variables and the shape of the ceiling surface of an indoor space. Based on the results, the appropriate size of external light shelves according to the ceiling type was derived. The optimal width of an external light shelf for flat ceilings, sloped ceilings, gable ceilings, and curved ceilings is 1.2 m, and the optimal angle of an external light shelf varies depending on the ceiling type and season. The angle of an external light shelf can be altered, so the optimal light shelf for the space type defined in this study is a movable light shelf with angle control and a width of 1.2 m. However, this study analyzed the performance of an external light shelf, and installing a 1.2 m wide light shelf in high-rise buildings has many limitations. In addition, during winter, securing sunlight from the outside is advantageous for reducing heating energy use, so an external light shelf with a suitable width should be used according to the situation rather than simply establishing a standard width of 1.2 m for use in all cases. The performance evaluation results of an external light shelf can vary depending on the type of space. This means that the shape of the ceiling's surface in an indoor space should be considered when designing future light shelves. In particular, gable and curved ceiling shapes can improve the illumination performance of an external light shelf by increasing the number of reflections from the ceiling surface or spreading the natural light entering the indoor space through the external light shelf.

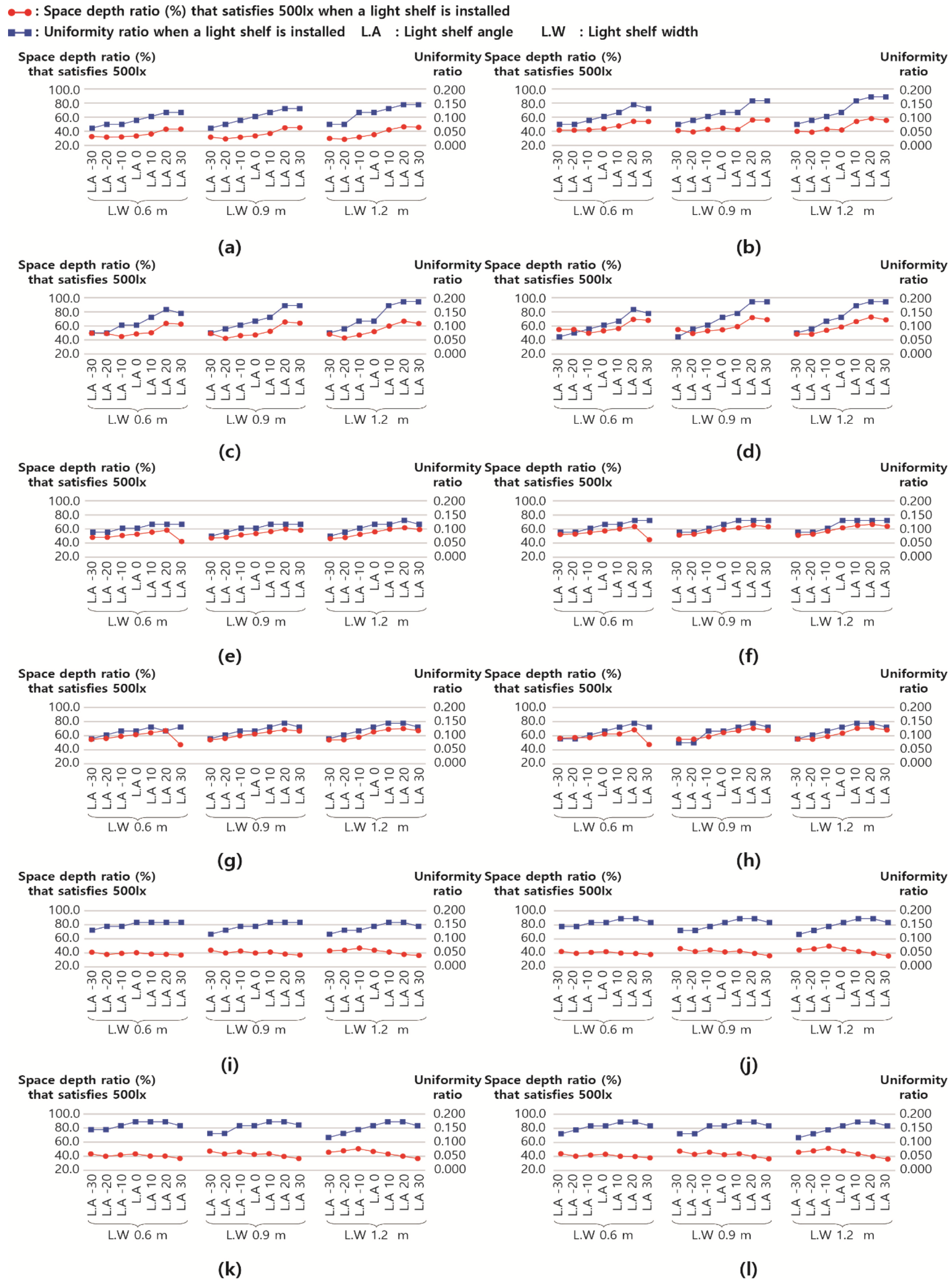


Figure 12. Results of performance evaluation of external light shelf for curved ceiling: (**a**) curved ceiling with curvature of 0.049 in summer; (**b**) curved ceiling with curvature of 0.094 in summer; (**c**) curved ceiling with curvature of 0.133 in summer; (**d**) curved ceiling with curvature of 0.165 in summer; (**e**) curved ceiling with curvature of 0.049 in middle season; (**f**) curved ceiling with curvature of 0.094 in middle season; (**g**) curved ceiling with curvature of 0.133 in middle season; (**h**) curved ceiling with curvature of 0.165 in middle season; (**i**) curved ceiling with curvature of 0.049 in winter; (**j**) curved ceiling with curvature of 0.094 in middle season; (**k**) curved ceiling with curvature of 0.133 in middle season; (**l**) curved ceiling with curvature of 0.165 in middle season.

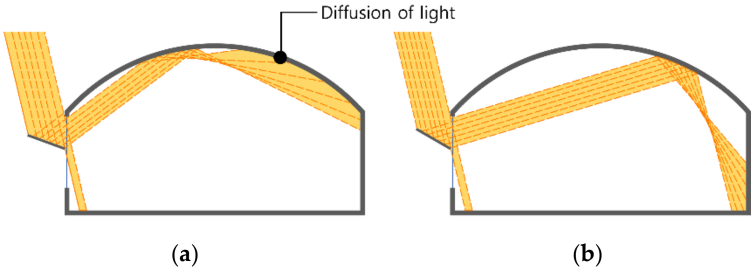


Figure 13. A natural light inflow process depending on the curved ceiling and external light shelf variables: (**a**) a curved ceiling with a curvature of 0.165 in summer, an external light shelf with an angle of 20°, and width of 1.2 m; (**b**) a curved ceiling with a curvature of 0.165 in summer, an external light shelf with an angle of 30°, and width of 1.2 m. These images show how light shelves reflect daylight into a room but do not consider the specular and diffuse reflection of light that occurs during the inflow and reflection process.

4. Conclusions

This study evaluated the performance of external light shelves considering the shape of ceiling surfaces and derived the validity and appropriate specifications for flat, sloped, gable, and curved ceilings. For this purpose, this study used Radiance, an external light environment analysis simulation program, and conducted a light shelf evaluation based on the indoor illumination value derived from Radiance by ascertaining the space depth that satisfies 500 lx, which is the proper indoor illumination level and illumination uniformity. The conclusions of this study are presented as follows.

First, increasing the angle and width of an external light shelf for a flat ceiling tends to improve its illumination performance. However, in the case of an external light shelf with an angle of 30° in the middle season and 20° in winter, the natural light from the outside entering the indoor space is reflected only by the external light shelf and not by the ceiling's surface, causing glare and a deterioration in uniformity. Furthermore, in the case of the angle of an external light shelf set to 30° during the winter, there is no inflow of natural light through the external light shelf, resulting in the deterioration of uniformity caused by shading due to the relatively low altitude of the sun.

Second, the illumination performance of an external light shelf can be improved by increasing the slope and curvature of sloped, gable, and curved ceilings, as specified in this study. This is because increasing the slope and curvature of sloped, gable, and curved ceilings increases the depth so that the daylight can flow into the room. Further, increasing the width and angle of an external light shelf tends to improve its illumination performance. However, external light shelf angles of 30° during the middle season and 30° and 20° in winter, which allow natural light to enter without reflection from the ceiling surface, are unsuitable because of their low daylighting performance regardless of the space type.

Third, due to the uniqueness of the gable and curved ceiling shapes, the natural light introduced into an indoor space by the light shelf can be more than doubled by reflecting it from the ceiling's surface, which is advantageous for daylighting performance. This is because the natural light from outside can be projected further by doubling its reflection from the ceiling.

Fourth, this study derived the appropriate size of an external light shelf according to the type of space defined in this study. The appropriate width of an external light shelf is generally 1.2 m, but the appropriate angle can vary. Thus, the optimal light shelf based on a given ceiling type of an indoor space can be a 1.2 m wide movable external light shelf with an adjustable angle.

This study is significant because it assesses the performance of an external light shelf based on the shape of a given ceiling surface, which determines the shape of indoor space. However, this study is limited in that it used only restricted periods of time to evaluate the performance of the light shelf and considered only the shape of the ceiling's surface rather than other characteristics of the indoor space. Further research should investigate the correlation between the ceiling surface shape and light shelves' performance.

Author Contributions: Conceptualization, S.-y.J. and H.L.; methodology, S.-y.J. and M.-G.L.; writing—original draft preparation, S.-y.J.; writing—review and editing, S.-y.J. and M.-G.L.; supervision, H.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research is funded by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (RS-2023-00208303) and the Energy Demand Management Core Technology Development of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea (no. 20212020900380).

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Nässén, J.; Holmberg, J.; Wadeskog, A.; Nyman, M. Direct and indirect energy use and carbon emissions in the production phase of buildings: An input–output analysis. *Energy* **2007**, *32*, 1593–1602. [CrossRef]
2. Huang, L.; Krigsvoll, G.; Johansen, F.; Liu, Y.; Zhang, X. Carbon emission of global construction sector. *Renew. Sustain. Energy Rev.* **2018**, *81*, 1906–1916. [CrossRef]
3. Wang, Y.; Guo, J.; Yue, Q.; Chen, W.Q.; Du, T.; Wang, H. Total CO_2 emissions associated with buildings in 266 Chinese cities: Characteristics and influencing factors. *Resour. Conserv. Recycl.* **2023**, *188*, 106692. [CrossRef]
4. United Nations Environment Programme. 2020 Global Status Report for Buildings and Construction. Available online: https://globalabc.org/news/globalabc-releases-2020-global-status-report-buildings-and-construction (accessed on 27 September 2023).
5. Mangkuto, R.A.; Feradi, F.; Putra, R.E.; Atmodipoero, R.T.; Favero, F. Optimisation of daylight admission based on modifications of light shelf design parameters. *J. Build Eng.* **2018**, *18*, 195–209. [CrossRef]
6. Kurtay, C.; Esen, O. A new method for light shelf design according to latitudes: CUN-OKAY light shelf curves. *J. Build Eng.* **2017**, *10*, 140–148. [CrossRef]
7. Ebrahimi-Moghadam, A.; Ildarabadi, P.; Aliakbari, K.; Fadaee, F. Sensitivity analysis and multi-objective optimization of energy consumption and thermal comfort by using interior light shelves in residential buildings. *Renew. Energ.* **2020**, *159*, 736–755. [CrossRef]
8. Jung, S.; Lee, H. Case study for deriving appropriate light shelf specifications based on indoor space depth. *Energy Build.* **2023**, *297*, 113450. [CrossRef]
9. Berardi, U.; Anaraki, H.K. Analysis of the impacts of light shelves on the useful daylight illuminance in office buildings in Toronto. *Energy Procedia* **2015**, *78*, 1793–1798. [CrossRef]
10. Meresi, A. Evaluating daylight performance of light shelves combined with external blinds in south-facing classrooms in Athens, Greece. *Energy Build.* **2016**, *116*, 190–205. [CrossRef]
11. Lim, Y.W.; Heng, C.Y.S. Dynamic internal light shelf for tropical daylighting in high-rise office buildings. *Build. Environ.* **2016**, *106*, 155–166. [CrossRef]
12. Warrier, G.A.; Raphael, B. Performance evaluation of light shelves. *Energy Build.* **2017**, *140*, 19–27. [CrossRef]
13. Ziaee, N.; Vakilinezhad, R. Multi-objective optimization of daylight performance and thermal comfort in classrooms with light-shelves: Case studies in Tehran and Sari, Iran. *Energy Build.* **2022**, *254*, 111590. [CrossRef]
14. Claros, S.T.; Soler, A. Indoor daylight climate–influence of light shelf and model reflectance on light shelf performance in Madrid for hours with unit sunshine fraction. *Build. Environ.* **2022**, *37*, 587–598. [CrossRef]
15. Lim, Y.W.; Ahmad, M.H. The effects of direct sunlight on light shelf performance under tropical sky. *Indoor Built Environ.* **2015**, *24*, 788–802. [CrossRef]
16. Claros, S.T.; Soler, A. Indoor daylight climate-comparison between light shelves and overhang performances in Madrid for hours with unit sunshine fraction and realistic values of model reflectance. *Sol. Energy* **2001**, *71*, 233–239. [CrossRef]
17. Kim, K.; Lee, H.; Jang, H.; Park, C.; Choi, C. Energy-saving performance of light shelves under the application of user-awareness technology and light-dimming control. *Sustain. Cities Soc.* **2019**, *44*, 582–596. [CrossRef]
18. Soler, A.; Oteiza, P. Light shelf performance in Madrid, Spain. *Build. Environ.* **1997**, *32*, 87–93. [CrossRef]
19. Beltran, L.O.; Lee, E.S.; Selkowitz, S.E. Advanced optical daylighting systems: Light shelves and light pipes. *J. Illum. Eng. Soc.* **1997**, *26*, 91–106. [CrossRef]
20. Lee, H.; Seo, J. Performance Evaluation of External Light Shelves by Applying a Prism Sheet. *Energies* **2020**, *13*, 4618. [CrossRef]
21. Lee, H.; Jang, H.I.; Seo, J. A preliminary study on the performance of an awning system with a built-in light shelf. *Build. Environ.* **2018**, *131*, 255–263. [CrossRef]
22. Freewan, A.A. Maximizing the lightshelf performance by interaction between lightshelf geometries and a curved ceiling. *Energy Convers. Manag.* **2010**, *51*, 1600–1604. [CrossRef]

23. Freewan, A.A.; Shao, L.; Riffat, S.J.S.E. Optimizing performance of the lightshelf by modifying ceiling geometry in highly luminous climates. *Sol. Energy* **2008**, *82*, 343–353. [CrossRef]
24. Ambadi, A.P.; Raphael, B. Experimental investigation on thermal performance of an actively cooled light shelf. *Sol. Energy* **2023**, *263*, 111932. [CrossRef]
25. Teo, Y.H.; Yap, J.H.; An, H.; Xie, N.; Chang, J.; Yu, S.C.M.; Cheong, K.H.A. Simulation-aided approach in examining the viability of passive daylighting techniques on inclined windows. *Energy Build.* **2023**, *282*, 112739. [CrossRef]
26. Illuminating Engineering Society. *The Lighting Handbook*, 10th ed.; Illuminating Engineering Society (IES): New York, NY, USA, 2011.
27. *JSA JIS Z 9110 AMD 1*; General Rules of Recommended Lighting Levels (Amendment 1). JSA-Japanese Standards Association: Tokyo, Japan, 2011.
28. *ABNT NBR 5413-1992*; Interior Lighting. Brazil Technical Standards. Brazilian National Standards Organization: Rio de Janeiro, Brazil, 2013.
29. *KSA 3011-2013*; Recommended Levels of Illumination. The Korean Standards. The Korean Standards Association: Seoul, Republic of Korea, 1998.
30. Bellia, L.; Spada, G.; Pedace, A.; Fragliasso, F. Methods to evaluate lighting quality in educational environments. *Energy Procedia* **2015**, *78*, 3138–3143. [CrossRef]
31. Hong, T. A close look at the China design standard for energy efficiency of public buildings. *Energy Build.* **2009**, *41*, 426–435. [CrossRef]
32. Acosta, I.; Navarro, J.; Sendra, J.J. Towards an analysis of daylighting simulation software. *Energies* **2011**, *4*, 1010–1024. [CrossRef]
33. Brzezicki, M. An evaluation of useful daylight illuminance in an office room with a light shelf and translucent ceiling at 51 N. *Buildings* **2021**, *11*, 494. [CrossRef]
34. Brzezicki, M. An evaluation of annual luminous exposure from daylight in a museum room with a translucent ceiling. *Buildings* **2021**, *11*, 193. [CrossRef]
35. Rabani, M.; Bayera Madessa, H.; Nord, N. Building retrofitting through coupling of building energy simulation-optimization tool with CFD and daylight programs. *Energies* **2021**, *14*, 2180. [CrossRef]
36. Santos, L.; Schleicher, S.; Caldas, L. Automation of CAD models to BEM models for performance based goal-oriented design methods. *Build. Environ.* **2017**, *112*, 144–158. [CrossRef]
37. Santos, L.; Leitão, A.; Caldas, L. A comparison of two light-redirecting fenestration systems using a modified modeling technique for Radiance 3-phase method simulations. *Sol. Energy* **2018**, *161*, 47–63. [CrossRef]
38. Kota, S.; Haberl, J.S.; Clayton, M.J.; Yan, W. Building Information Modeling (BIM)-based daylighting simulation and analysis. *Energy Build.* **2014**, *81*, 391–403. [CrossRef]
39. Reinhart, C.F.; Andersen, M. Development and validation of a Radiance model for a translucent panel. *Energy Build.* **2006**, *38*, 890–904. [CrossRef]