buildings

Review

A Review of Factors Affecting the Lighting Performance of Light Shelves and Controlling Solar Heat Gain

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Abstract: In areas with a deep floor plan, the distribution of natural light is not uniform. Consequently, relying solely on daylight may not suffice to meet the space's lighting requirements, necessitating the use of artificial lighting in darker areas. Therefore, a lighting system is needed that not only controls the glare near the windows but also increases the light at the end of the room and provides uniform daylight. One of the widely used systems is the "light shelf", which has three main functions: shading, increasing the depth of light penetration, and reducing glare. Review articles about light shelves were published in 2015 and 2017, while more than 80% of the studies have been carried out since 2016, and light shelves with more diverse forms and dynamic elements and many consolidations have been proposed. Therefore, there is a need for a more comprehensive review. The main question of this research is how different parameters (including climate, material, ceiling, and integrated systems) can help to increase the efficiency of light shelves. By using a systematic review, studies in the past three decades were classified in order to determine the effect of these parameters on improving lighting performance and controlling solar heat gain.

Keywords: light shelf; daylighting; energy use; solar heat gain; buildings

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1. Introduction

Climate changes caused by the excessive consumption of fossil fuels in recent years make clear the necessity of replacing non-renewable energies with renewable energies, including energy from the sun. One of the basic steps in this regard is the optimal use of daylight, which, while reducing energy consumption, improves the quality of space and also has significant effects on human mental and physical health. Research conducted by the National Renewable Energy Laboratory (NREL) investigated the impact of daylight exposure on individuals. They found that occupants working in full-spectrum office buildings reported an increase in general well-being. These specific office environments were associated with numerous advantages, such as improved health outcomes, decreased absenteeism rates, heightened productivity levels, cost savings, and a preference among employees for this type of workspace [1]. The distribution of daylight in spaces with a deep plan is not uniform; the part of the room that is near the window receives additional light, and there is not enough light in the other part, so daylight alone cannot provide the required light for the space. Both traditional and modern architectural designs frequently use external overhangs and fins for several reasons: Firstly, they can effectively control solar heat gain by blocking the solar radiation before it reaches the window. Secondly, they maintain a visual connection with the outdoor environment, and lastly, they enhance daylighting performance by maximizing daylight admission while minimizing visual discomfort [2]. Although the extra light near the window will disappear by using these shades, there will be very little light at the end of the room, and if the depth of the space is large, this issue will be more important. So, there is a need for artificial lighting to create enough light in the dark parts of the room. To solve this problem, we need a light system that, while shading near the window, increases the light at the end of the room. A "light shelf" is a passive light transmission system in the form of a horizontal shade, the upper surface of which is made of reflective materials, and while shading, increases the depth of light penetration and reduces electricity consumption.

1.1. A Brief Review of Light Shelves

Light shelves redirect a significant part of the light towards the ceiling and then reflect it into the room. In this way, glare near the window is minimized, and the light at the end of the room increases. This system divides the window into upper and lower parts. The main use of the lower part is to see outside and ventilate (view), and the upper part (clerestory) is for bringing light into the space [3]. Light shelves (in terms of placement) are divided into three general categories: internal, external, and a combination of both. The external part brings the function of shading and reducing the cooling load of the building in the summer, and the internal part provides more visual comfort against glare and directs the light deep into the room. The design of external light shelves should deal with rain runoff, dust, and debris accumulation, which reduce the light shelf's reflectivity [4]. In sunny weather, the internal shelf provides the highest average amount of illumination compared to external shelves. In contrast, the uniformity and distribution of illumination in the depth of the room is greater for external shelves [5]. In summer, when the sun is higher in the sky, light shelves primarily act as shading, and light penetration into the depth of space is limited. However, in winter, when the sun is lower in the sky, light is transmitted to a greater depth of space (Figure 1).

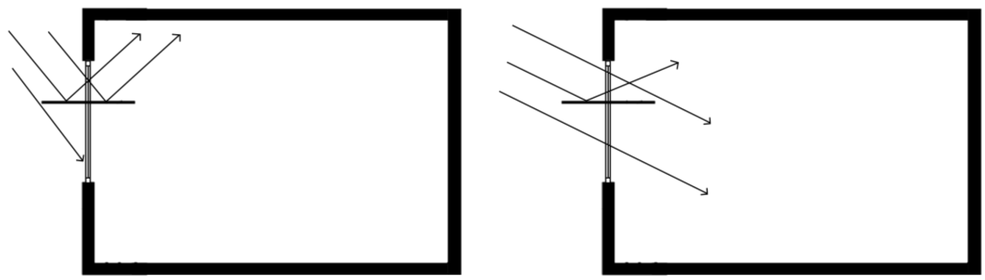

Figure 1. Light shelf performance in summer (**Left**) and winter (**Right**).

1.2. Light Shelf Development through History

Mirrors have been used as a way to redirect sunlight since ancient times. The first model of the light shelf was used in the Hagia Sophia Mosque in Turkey [6]. In the sixth century AD, reflective shelves were used to reflect sunlight to the inner surface of the dome. Forty windows all around the dome gave a mystical quality to the dome and increased its brightness (Figure 2). In the late 19th century, reflectors were developed to increase indoor lighting, which was presented at the Berlin Trade Fair in 1889 [6]. It is not yet known when the term "light shelf" was used, but the first research in this field was in the early 1950s at the Building Research Center to illuminate several deep-plan hospitals. The first one was Larkfield in Scotland, which was carried out with the aim of increasing the quality of daylight and creating visual comfort for patients [3].

A lot of research has been carried out in the field of light shelves, several methods have been proposed to increase their efficiency, and many light shelf designs have been suggested. Review articles about light shelves were published in 2015 and 2017 [3,6], while more than 80% of the studies have been carried out since 2016, and light shelves with more diverse forms and dynamic elements and many consolidations have been proposed. Therefore, there is a need for a more comprehensive review article in this field. In this research, using a systematic review, studies from the last three decades were classified in order to obtain solutions to improve the lighting and thermal performance of light shelves. The research path is shown in Figure 3.

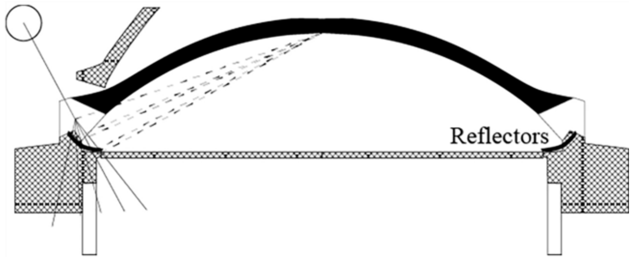

Figure 2. Schematic representation of the parapet of Hagia Sophia based on Anthemius's reflector superimposed over the cross-section of the original dome [6].

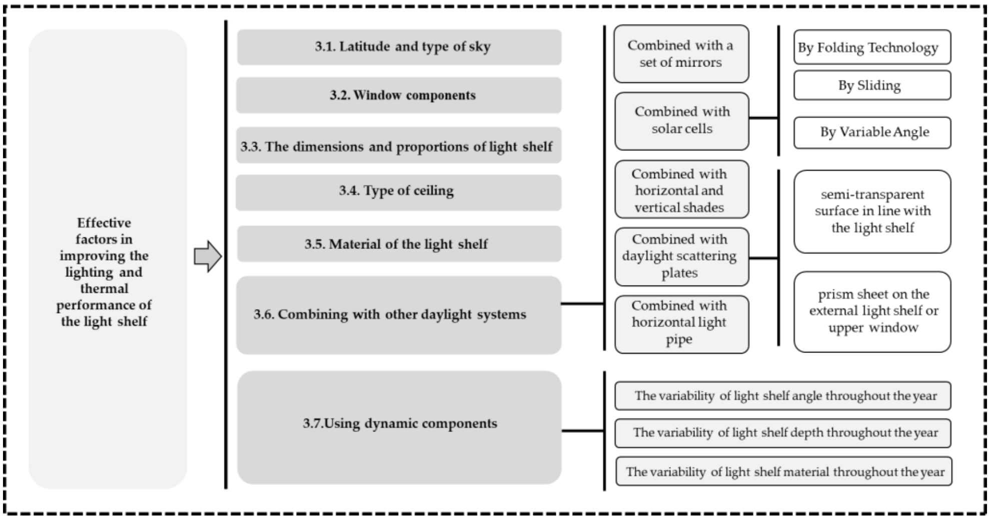

Figure 3. This research study's methodological framework.

2. Materials and Methods

According to previous studies [7–10], light shelves can affect the quality of daylight and the amount of energy consumption. Some research studies only evaluated the quality of light. In contrast, in order to achieve an optimal light shelf, it is necessary to pay attention to the light, solar heat gain, and energy simultaneously. The variety of methods to increase the efficiency of light shelves, as well as the evaluated factors in studies, have made it difficult to choose the best option for light shelves, so this study systematically reviews the literature on the aspects of light shelves. The authors of this paper searched through three main databases: Science Direct, Taylor & Francis, and ProQuest. The search terms related to light shelves, daylight, energy consumption, and solar heat gain in articles, titles, abstracts, and keywords. The studies carried out in this field have two general research methods: software simulation and field measurement. So, studies were categorized in two tables based on their research method. Table 1 classifies the studies using simulation methods, and Table 2 classifies the studies with only field measurement research methods employed. Also, the following items were identified in each of the studies: space utilization, type of light shelf (static/dynamic), orientation, field of investigation (daylight function of light shelf, thermal function of light shelf, or an integrative approach), room dimensions, and approaches. In cases where the light shelf is integrated with other systems, the type of integrated system is mentioned.

Table 1. Classification of studies with software simulation research methods.

Ref. Number	Publication Year	Testing Method	Space Utilization	Type of Light Shelf (Static/Dynamic)	Orientation	Field of Investigation (Daylight Quality–Energy Consumption–Thermal Comfort)	Room Dimensions	Approaches
[7]	2023	IESVE	Official	Static	South–west–east–north	Daylight quality	12 × 6 × 2.7	Combined with horizontal light pipe
[11]	2020	DIVA	Official	Static	South	Daylight quality Energy consumption	8 × 4.6 × 3	Combined with PV cells
[12]	2015	DIVA	-	Static	South	Daylight quality	10 × 6 × 2.5	Application of complex ceiling forms
[13]	2016	DIVA	Educational	Static	South–west–east–north	Daylight quality	8 × 7 × 3.5	Investigating the influence of light shelf geometry parameters on daylight performance and visual comfort
[14]	2018	DIVA	Dental Hospital	Static	East–west	Daylight quality	19 × 14.2 × 2.7	Optimization of daylight admission based on modifications of light shelf design parameters
[15]	2020	DIVA	Educational	Static	South	Daylight quality	8 × 7 × 3.2	Investigating the effect of the light shelf on the quality of the interior light
[16]	2021	Honeybee and Ladybug	Official	Static	South	Daylight quality Energy consumption	8 × 5 × 2.8	Sensitivity analysis linked to multi-objective optimization for adjustments of light shelves design parameters
[17]	2022	Honeybee and Ladybug	Educational	Static	South	Daylight quality Energy consumption Thermal comfort	10 × 9 × 3.5	Combined with PV cells
[18]	2022	Honeybee and Ladybug/Open studio	Educational	Static	South–north	Daylight quality Thermal comfort	8 × 5.8 × 2.9	Multi-objective optimization of daylight performance and thermal comfort

Table 1. *Cont.*

Ref. Number	Publication Year	Testing Method	Space Utilization	Type of Light Shelf (Static/Dynamic)	Orientation	Field of Investigation (Daylight Quality–Energy Consumption–Thermal Comfort)	Room Dimensions	Approaches
[19]	2020	Honeybee	Residential	Static	Northwest–northeast–southeast–southwest	Daylight quality Thermal comfort	6 × 5 × 3.5	Combination of multiple light shelves
[20]	2020	Honeybee and Ladybug–field measurement	Official	Static	South	Daylight quality	8 × 5 × 2.8	Optimization of daylight performance based on controllable light shelf parameters
[21]	2016	Ecotect	Educational	Dynamic	South	Daylight quality	8.1 × 6 × 3.3	Combined with louvers
[22]	2016	Ecotect–field measurement	Educational	Static	South	Daylight quality	7 × 7 × 3.2	Combined with louvers
[23]	2017	Radiance/Ecotect	Official	Static	South	Daylight quality	14 × 8 × 2.8	A new method for light shelf design according to latitudes: CUN-OKAY, light shelf curves
[24]	2010	Radiance	-	Static	South	Daylight quality	8 × 6 × 3.25	Application of curved ceiling
[25]	2016	Radiance–field measurement	Official	Dynamic	South–west–east–north	Daylight quality	8.4 × 8.4 × 2.7	Dynamic internal light shelf for tropical climate
[26]	2008	Radiance–field measurement	-	Static	South	Daylight quality	8 × 6 × 3.25	Modifying ceiling geometry in highly luminous climates
[8]	2018	Radiance–field measurement	Official	Dynamic	South–west–east	Daylight quality Energy consumption	12 × 9 × 3	Combined with a set of mirrors
[27]	2019	Relux	Educational	Static	Northeast–southwest–northwest	Daylight quality	29.7 × 19 × 4.3	Performance testing of a light shelf-reflective louver system
[28]	2014	TracePro7.0	Residential	Static	South	Daylight quality	8 × 6 × 3.25	New design of clerestory windows

Table 1. *Cont.*

Ref. Number	Publication Year	Testing Method	Space Utilization	Type of Light Shelf (Static/Dynamic)	Orientation	Field of Investigation (Daylight Quality–Energy Consumption–Thermal Comfort)	Room Dimensions	Approaches
[29]	2021	Design Builder	Educational	Static	West–east	Daylight quality Energy consumption Thermal comfort	7.9 × 3.2 × 2.8	Performance evaluation of a light shelf
[30]	2019	DIALux 4.13 program	Educational	Static	South–west–east–north	Daylight quality	8 × 5 × 3.5	Combination of multiple light shelves with composition
[2]	2013	Energy Plus/Comfen	Official	Dynamic	South	Daylight quality	7.62 × 6.1 × 3.6	Combined with horizontal and vertical shades
[31]	2021	DeLuminae	Official	Static	South–west–east–north	Daylight quality	12 × 6 × 4	Combined with translucent ceiling
[32]	2020	Lightscape	Official	Static	South	Daylight quality Energy consumption	10 × 5 × 3	Combined with louvers

Table 2. Classification of research with only field measurement research methods.

Ref. Number	Publication Year	Testing Method	Space Utilization	Type of Light Shelf (Static/Dynamic)	Orientation	Field of Investigation (Daylight Quality–Energy Consumption–Thermal Comfort)	Room Dimensions	Approaches
[9]	2019	Field measurement	-	Static	South	Daylight quality Energy consumption	6.6 × 4.9 × 2.5	Combined with PV cells
[10]	2022	Field measurement	-	Dynamic	South	Daylight quality Energy consumption	6.6 × 4.9 × 2.5	Combined with PV cells
[33]	2021	Field measurement	-	Dynamic	South	Daylight quality Energy consumption Thermal comfort	6.6 × 4.9 × 2.5	Combined with PV cells
[34]	2022	Field measurement	-	Dynamic	South	Daylight quality Energy consumption	6.6 × 4.9 × 2.5	Combined with PV cells

Table 2. *Cont.*

Ref. Number	Publication Year	Testing Method	Space Utilization	Type of Light Shelf (Static/Dynamic)	Orientation	Field of Investigation (Daylight Quality–Energy Consumption–Thermal Comfort)	Room Dimensions	Approaches
[35]	2018	Field measurement	-	Static	South	Daylight quality Energy consumption	6.6 × 4.9 × 2.5	Combined with diffusion sheet
[36]	2020	Field measurement	-	Dynamic	South	Daylight quality Energy consumption	6.6 × 4.9 × 2.5	Combined with a prism sheet
[37]	2018	Field measurement	-	Dynamic	South	Daylight quality	6.6 × 4.9 × 2.5	combined with an awning system
[38]	2020	Field measurement	-	Dynamic	South	Daylight quality Energy consumption	6.6 × 4.9 × 2.5	Movable light shelf with a rolling reflector that can change reflectivity
[39]	2019	Field measurement	-	Dynamic	South	Daylight quality Energy consumption	6.6 × 4.9 × 2.5	Performance evaluation of a light shelf based on reflector curvature
[40]	2017	Field measurement	-	Dynamic	South	Daylight quality Energy consumption	6.6 × 4.9 × 2.5	Development and performance evaluation of light shelves using width-adjustable reflectors

3. Effective Factors in Light Shelf Performance

3.1. Latitude and Type of Sky

Latitude and sky conditions are important factors in the efficiency of light shelves. The performance of light shelves in cloudy skies is not as good as in sunny skies (Figure 4). In climates with fully cloudy skies, such as England, they do not have good efficiency, although their shading performance in summer and light penetration in winter can be useful [41]. In one of the research studies, the efficiency of light shelves at different latitudes was investigated. The greatest increase in daylight occurs in tropical climates that have more sunny hours per year [42] and do not penetrate deep into space, so the maximum depth of the room in these countries should not be considered more than 10 m [42]. In cold climates, reflectors with a higher reflection coefficient can be used, while in hot climates, in order to prevent excess heat, combining the light shelf with other daylight systems such as shade louvers or using a low-emissivity coating on the light shelf is common. Interior light shelves are not suitable for hot climates because they allow for the sun's rays to enter [43].

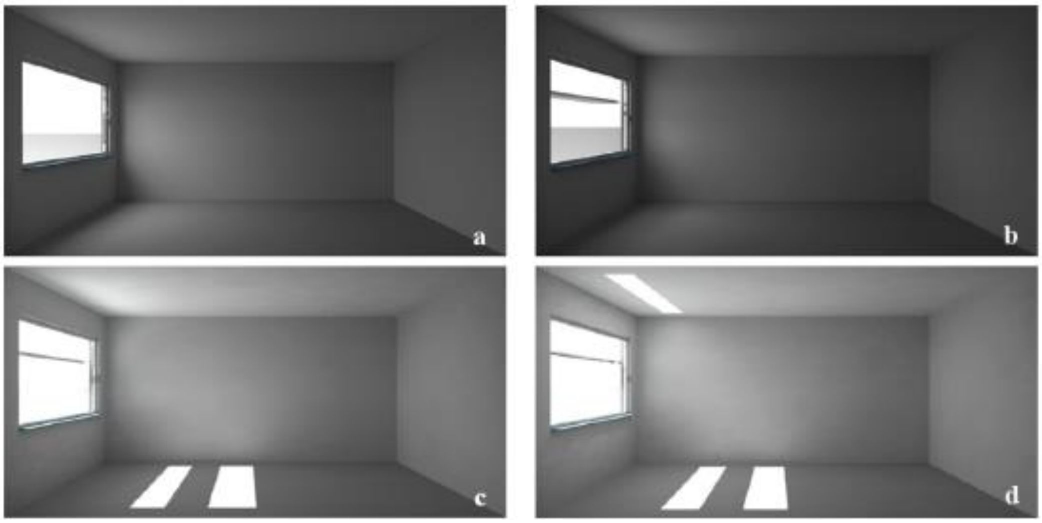

Figure 4. Various interior radiance renderings of a south-oriented room with dimensions 4 × 6 × 3 m and a window-to-floor ratio equal to 20% equipped with (**a**) no light shelf under overcast sky; (**b**) a perfectly diffuse external horizontal light shelf with 0.5 m depth (reflectance 0.8), under overcast sky; (**c**) a perfectly diffuse external horizontal light shelf with 0.5 m depth, under clear sky conditions, sun's elevation 37.8°; (**d**) like (**c**) but with a mirror external horizontal light shelf [6].

3.2. Window Components

Since the light shelf is installed on the window, the optimal dimensions of the window must be obtained in the design. In a study conducted in China, the role of the form and deviation of the glass above the light shelf was discussed, and the wide glass at the top and narrow at the bottom with a deviation of 44.3 to 90 degrees was the best option to provide more brightness along uniformity [28] (Figure 5).

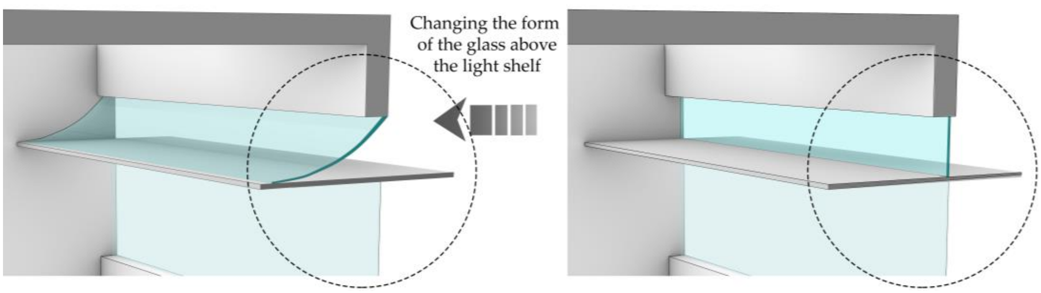

Figure 5. Changing the form of the glass above the light shelf.

By using smart windows, the amount of light, visibility, heating, and cooling can be controlled, and glare can be prevented. The combination of these windows with light shelves is very useful. So, window components also play an important role in ensuring the efficiency of the light shelf.

3.3. Dimensions, Types, and Proportions of Light Shelves

The optimal dimensions and proportions of light shelves are determined according to building features, climatic conditions, and users. Usually, the length of the shelves is the same as that of the windows, but when the sun is entering from the sides, direct radiation should be avoided. So, the light shelf can be considered longer than the width of the window, or a piece can be added vertically from the sides [44]. For south-facing rooms, the depth of the internal shelf is approximately equal to the height of the window above the light shelf, and for rooms with a 20-degree deviation to the south, 1.5 to 2 times the height of the upper window is recommended [45]. The greater the depth of the light shelf, the less glare that occurs, but the entry of light also decreases. If the height of the sun is low in the sky, a deeper shelf is needed to reflect more light onto the ceiling. Light shelves may block the area covered by fire sprinklers, so either their maximum depth should not be more than 120 cm or sprinklers on the light shelf itself should be used [43].

Regarding the installation height, the light shelf should be above eye height (about 2 m from the ground) to prevent glare. Light shelves are classified into four categories in terms of the shape of reflectors: flat, angled, curved, and wavy (Figure 6). The wavy mode has better performance due to the depth of light penetration and the quality of light distribution; it reflects more uniform light in the space.

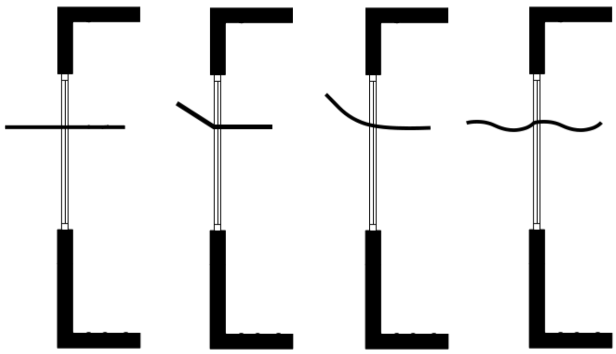

Figure 6. Types of light shelves (flat, angled, curved, and wavy).

In angled light shelves, if the slope is outward, the shading on the lower window is increased but prevents the penetration of light, while if its slope is inward, the depth of light penetration is increased, and the shading is reduced (Figure 7). A horizontal light shelf usually provides an optimal condition for the required shading and daylight distribution [43].

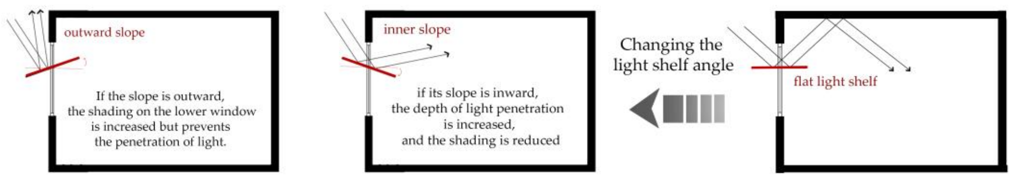

Figure 7. The role of light shelf slope in light penetration.

3.4. Type of Ceiling

The ceiling is an important part of the system because light shelves redirect the light towards the ceiling and then reflect it into the room [5] (Figure 8). In research, Freewan found that the curvature in the ceiling has a significant effect (10%) on the uniformity of the light [24]. In another study, considering three—sloping, pitched, and curved—ceilings, it was concluded that a curved ceiling followed by pitched ceiling increase the amount of light in the depth of the room, and that these two are better than a flat or sloping ceiling [26]. Gabled and curved ceilings that have upward slopes through the window towards the center of the space increase the penetration of light inside. Although a ceiling with a glossy surface reflects more light into the space, it is necessary to avoid the reflection of the ceiling's radiation. Therefore, it is better to have a matte white color on the ceiling [5].

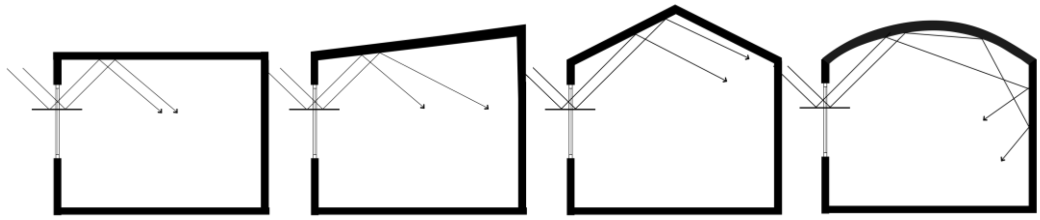

Figure 8. The penetration depth of light by different ceilings.

3.5. Material of the Light Shelf

The performance modes of reflectors can be classified into mirror, semi-mirror, and matte surfaces. Semi-mirror (foil) surfaces on the light shelf perform best. Although the mirror surface provides more light, it has a negative effect on the attractiveness and quality of the space, especially because of reflections on computer monitors. At the same time, it is heavy, expensive, and difficult to install [42]. Soler and Claros investigated the use of methacrylate and mirror materials on the surfaces of light shelves and concluded that in the middle months of the year, the shelf with methacrylate material, and in the early months of the year, the mirror shelf perform better. The average changes made by methacrylate material are less than those of mirror material [46].

3.6. Other Lighting Systems Combined with Light Shelves

Based on the type of climate and location, to prevent glare and solar heat gain, it may not be enough to use only a light shelf. It is suggested to use a combination of other daylight systems with a light shelf. These systems can be horizontal and vertical shades, a set of mirrors, solar cells, light scattering plates, louvres, or light pipes and can be fixed or dynamically combined with light shelves. The systems' functions and their efficiencies are explained below.

3.6.1. Combination of Light Shelves with Vertical and Horizontal Shades

In Abboushi's master's thesis, an optimal combination of horizontal and vertical dynamic shades with a light shelf was presented. In his model, the use of horizontal and vertical shades that change throughout the year while adding a low-e coating on light shelves in hot and dry weather can prevent the increase in the cooling load and improve the increase in useful light [2] (Figure 9).

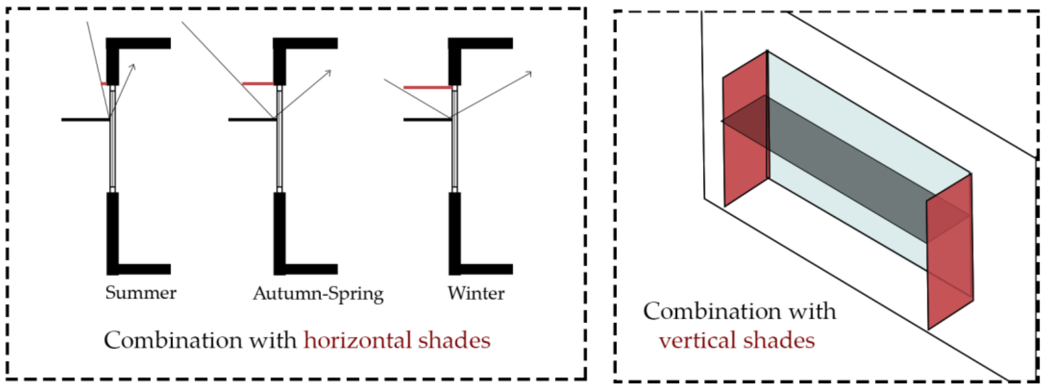

Figure 9. Combination of light shelves with vertical and horizontal shades.

3.6.2. Creating a Light Shelf by Combining a Set of Mirrors

In another type of combined light shelf, in order to change the direction of sunlight, the light shelf is combined with a set of mirrors that can move in two axes based on the direction of sunlight using a solar tracker [47]. Research results show that the reduction in room energy consumption when using movable mirrors is 17–35% more than when using fixed mirrors [47] (Figure 10).

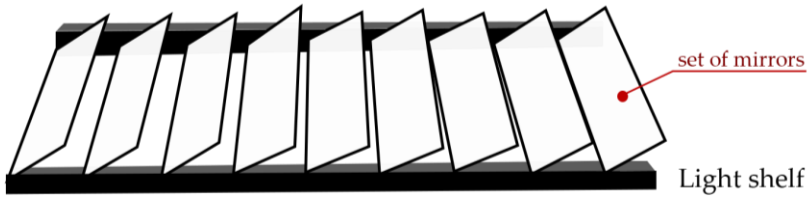

Figure 10. The combination of a light shelf with a set of mirrors.

3.6.3. Combining a Light Shelf with Louvers

In another study, with the introduction of the FLS (fragmented light shelf), the combination of a light shelf and louvers was found to be effective in reducing glare and creating uniform light in the space [47]. Research in Athens suggested a combination of angled light shelves (with an angle of 10 to 20 degrees) and louvers instead of the usual school curtains to improve the quality of light in classrooms. In this design, a light shelf is placed with louvers with a light transmission factor of 30%. Its advantages over common curtains in schools are in increasing visibility to the outside, not causing glare, and the uniformity of light [22] (Figure 11).

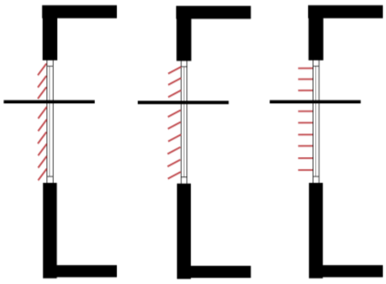

Figure 11. Combination of light shelves with louvers.

3.6.4. Combination of a Light Shelf with Prism Sheets (Diffusion Sheet)

In another type of integrated light shelf combination, diffusion sheets are used to reduce glare (especially in curved and sloping light shelves). This screen can be placed on the external light shelf or the upper window. The results show that the use of a prism sheet on the window above the light shelf with an angle of 30 degrees in autumn and spring and 20 degrees in winter increases the uniformity of light and eliminates glare [36]. By adding a diffusion sheet to the upper window, the light uniformity increased by 4.6% and energy consumption was saved by 2.9% [35]. In addition to combining the light shelf and horizontal louvers, a semi-transparent surface can be used in line with the light shelf so that the light penetrates deeper into the space, uniformity increases, and glare reduces [31] (Figure 12).

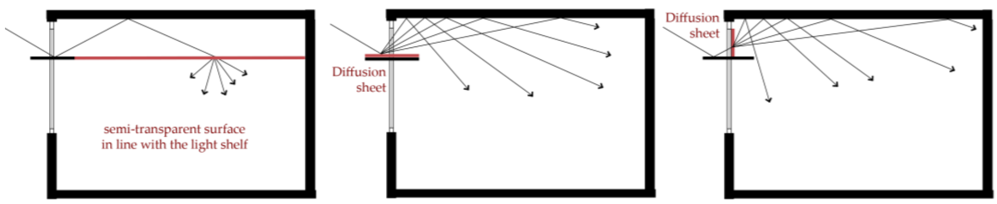

Figure 12. Combination of light shelf with diffusion sheet.

3.6.5. Combination of a Light Shelf with Solar Cells

Another category of combined light shelves is a combination with photovoltaic cells. The combination of a light shelf with solar cells is classified into three categories: 1. using folding technology to add solar cells; 2. adding sliding solar cells; 3. using variable-angle solar cells (Figure 13). Since it is not possible to increase the efficiency of the lighting system and electricity generation simultaneously, in one of the examples, folding technology was used to combine them. In this way, half of the diagonal plates are responsible for light transmission and the other half for energy production [34]. It should be noted that the photovoltaic panels themselves produce a significant amount of heat that can affect the energy consumption of the room. The results of the research show that the combination of solar cells with a light shelf in summer is not effective due to the high air temperature. In winter, due to the angle of the sun's rays, the level of light uniformity is reduced, and energy consumption is increased. Therefore, in one of the studies, solar cells are placed in sliding form and are only added to the light shelf in autumn and spring [33]. In another example, to increase the efficiency of the solar cells, photovoltaic panels with a variable angle are used. The solar panel has a smaller width than the light shelf and does not block direct sunlight. This example of integrating a light shelf with solar cells brings more uniform light into the space and produces more energy than the previous integrated examples [10].

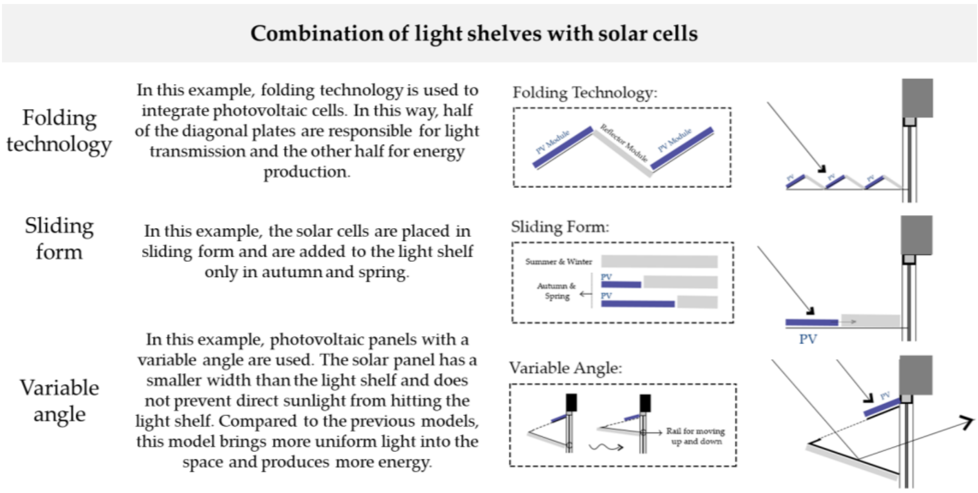

Figure 13. Classification of light shelves integrated with solar cells.

3.6.6. Combination of a Light Shelf with a Horizontal Light Pipe

In one of the studies, in order to increase the depth of light penetration in a high-rise office building with a deep plan in Malaysia, a light shelf (with an angle of −15 degrees) was combined with a horizontal semi-cylindrical light pipe. Two valves with an area of 2 square meters were installed on it (Figure 14). This combination reduces the intense glare near the window and also transmits the light to the depth of the space [7].

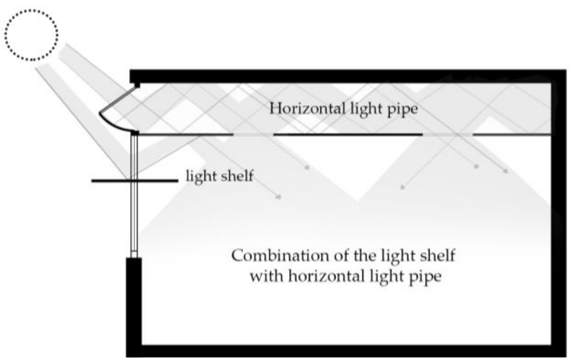

Figure 14. Combination of the light shelf with horizontal light pipe.

3.7. Using Dynamic Components

Light shelves can be static and dynamic. Considering that the daylighting condition of the environment around the building changes in the short term (day length) and long term (seasons), the dynamic light shelves correspond to the changes in the movement of the sun. At different hours of the day, they adjust their movements to meet the needs of users and create optimal conditions inside the space. These systems can be operated automatically or by the user. Static light shelves are cheaper than dynamic light shelves and require less maintenance. At the same time, dynamic systems are accessible for cleaning and dust removal with their height changes or the ability to be installed and dismantled. Cleaning the dust on the surface of the light shelf helps to increase its efficiency. Dynamic light shelves can be of different types with variable angles, inner and outer shelf depths, or reflector materials. The efficiency and performance of each are explained below:

3.7.1. Changing the Angle of the Light Shelf in Different Seasons

In one type of dynamic light shelf, while combining the light shelf with a horizontal shade, the angle of the external light shelf is changed throughout the year. The depth of the horizontal shade is also variable, and considering a rectangular hole in it, the light shines directly on the light shelf. By using this system, while preventing the increase in indoor air temperature by blocking direct sunlight, more uniform light enters the space and energy consumption is reduced [26] (Figure 15).

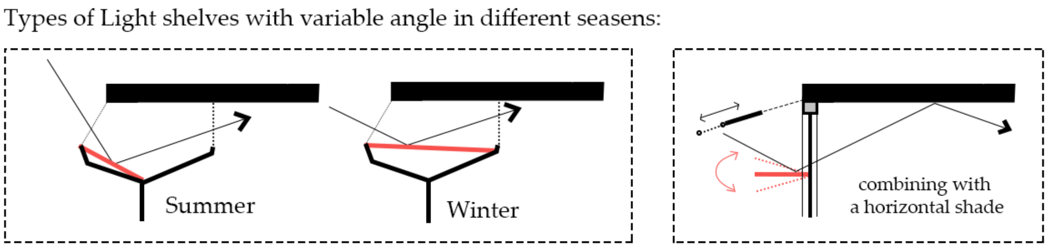

Figure 15. Changing the angle of the light shelf in different seasons.

3.7.2. Changing the Depth of the Inner and Outer Shelves

In research by Bani Rafael, three modes of light shelves—1. fixed shelf; 2. fixed internal and movable external shelves; 3. internal and external movable shelves—are considered. He showed that the third mode saves 12% more energy than the first mode [48]. In another research article, the inner shelf is movable and is separated in the summer season to provide the required light. In one of the examples, in addition to the variable depth of the light shelf in different seasons, the number of light shelves also varies [25] (Figure 16).

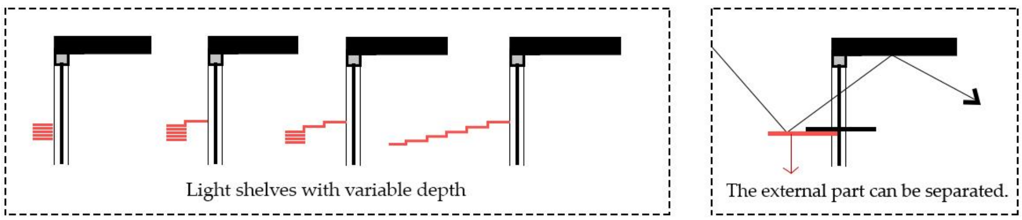

Figure 16. Changing the depth of the inner and outer shelves in different seasons.

3.7.3. Changing the Reflectivity of the Light Shelf

In one of the studies, in addition to the different angles of the reflective surface, the amount of reflection is also considered to be changed in different seasons. In this way, the reflection rate of the reflector is considered to be 97% in summer, spring, and autumn, and 85% in winter. The results show that changing the type of reflector throughout the year has a significant effect on reducing energy consumption [38].

4. Results

4.1. Space Utilization

Figure 17 shows the space utilization in the studies. The use of spaces was classified into commercial, educational, residential, official, and health categories. Since the occupied time of offices and educational spaces is during daylight hours, most of the studies investigated official spaces (24%) and then educational spaces (21%). In many studies, the utilization was unknown (43%), which can be considered as one of the gaps because different utilization requires different lighting characteristics, and ignoring these factors means omitting important variables. Many studies carried out in educational spaces have often ignored the effect of the height of the work plane on light shelf proportions and have considered a work plane with a fixed height for different educational levels.

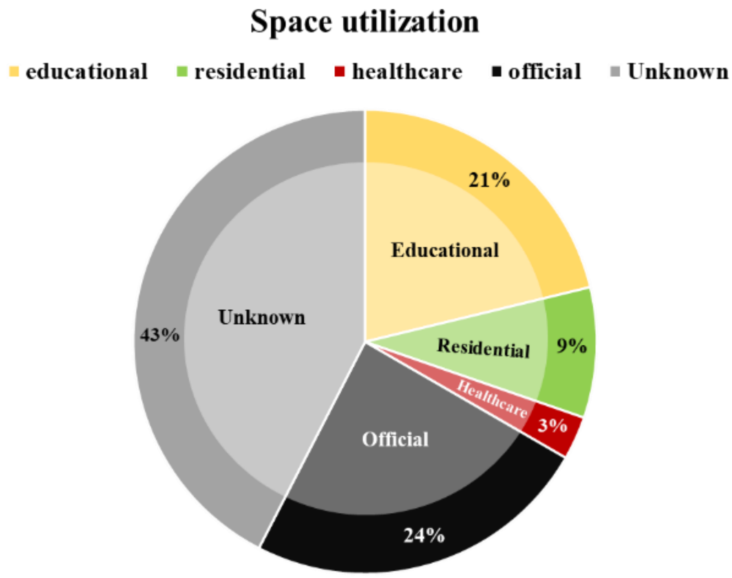

Figure 17. Space utilization chart.

4.2. Dispersion of Research Methods

The diagram below shows the distribution of methods used in the studies. The methods to evaluate the performance of light shelves can be divided into two categories: experimental, and simulation with software. Experimental studies can be performed under real or artificial skies, making a model at a smaller scale or a real scale. Among the methods, computer simulation is in first place (around 49%) due to the difficulty of predicting daylighting and the progress of various software programs in recent years. Of the total, 33% of studies used an experimental method, and 18% used both methods simultaneously. Using experimental methods along with simulation and comparing their results can help in evaluating the correctness of results (Figure 18).

The abundance of software and plugins used to simulate daylight are categorized in Figure 19. Among the simulation tools, the Radiance Engine and Honey Bee–Ladybug plugin are used more, and after them, Ecotect and Diva were most popular. Other tools such as Climate Studio, IES, Comfen, Lightscape, Deluminae, and Teacepro7 have also been used for simulation. Dialux software can also be used to combine the light shelf with artificial lighting systems.

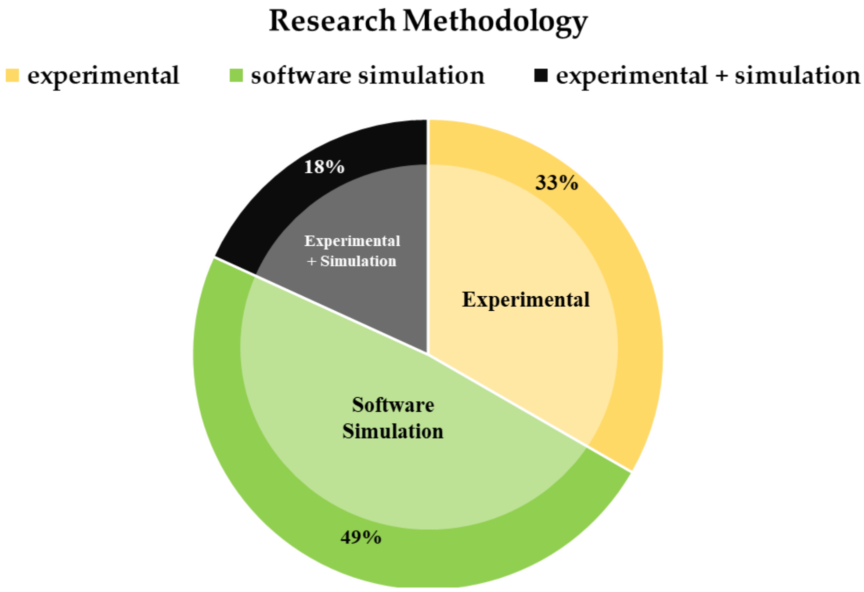

Figure 18. The research methods employed in the studies.

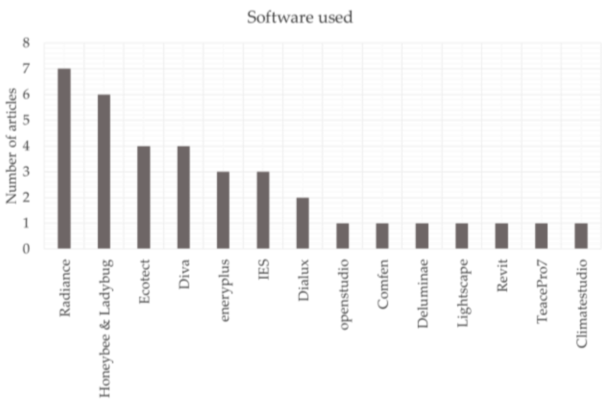

Figure 19. Software used for simulation.

4.3. The Parameters Investigated in the Studies

In Figure 20, the distribution of the investigated parameters in the research can be examined. Most of the studies focused on optimization with the aim of improving lighting quality, while a large part of them were carried out on the combination of these systems with photovoltaic panels. In these studies, it is very important to pay attention to the heat produced by the panels. In addition to increasing the temperature in the room, these panels become less efficient and produce less energy. Therefore, it is essential to consider the thermal comfort in such studies. Among the studies, 49% only focused on improving the quality of daylight, 6% only examined energy consumption, 33% were concerned with lighting quality and energy consumption at the same time, and only 9% of studies investigated daylight quality, thermal comfort, and energy consumption simultaneously.

The daylight quality of the space can be checked from various aspects, such as daylight autonomy, lack of glare and uniformity. Some studies evaluated the quality of vision in addition to these items. A separate index is defined in the simulation to evaluate each of these items. The indicators examined in each field are categorized in Table 3.

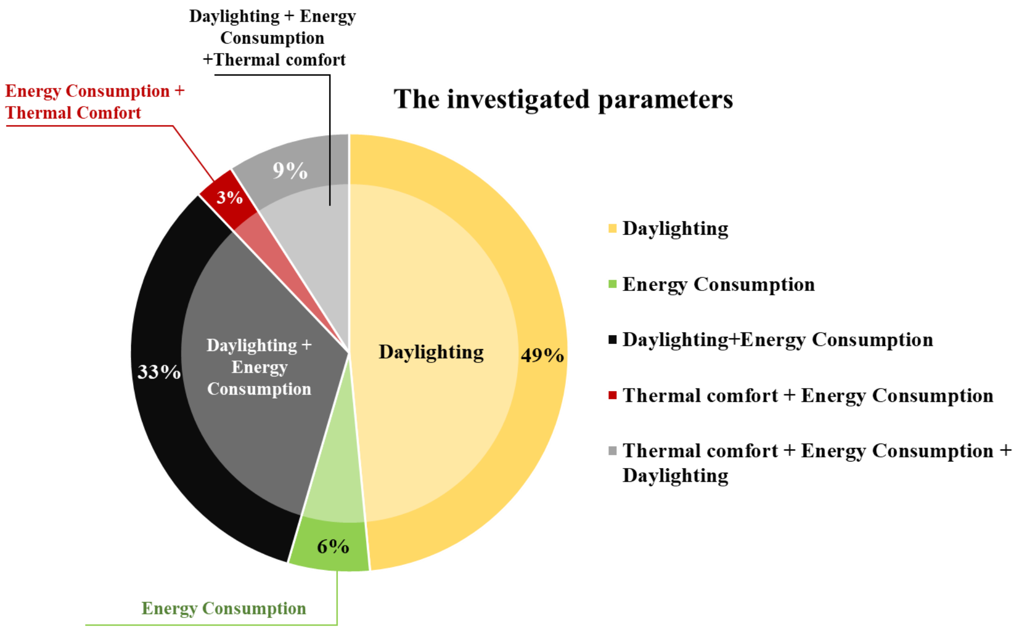

Figure 20. The investigated parameters.

Table 3. The indicators examined in the studies.

The Indicators Examined in the Studies	
Daylight	DF(Daylight Factor) – WPI – UI – UDI – Sda – DA – Cda – Illuminance -DR DGP – DGI – CGI – ASE – SGA - GVCP Uniformity Ratio View
Energy Consumption	EUI - Power Generation - Cooling Capacity - Electric Lighting
Thermal Comfort	PPD – PMV – IndoorTemperature - Operative Temperature

4.4. Orientation Considered in the Studies

Most of the research conducted in the northern hemisphere investigated the effect of the light shelf in the south windows, which receives direct sunlight (Figure 21). Various studies have shown that the use of a light shelf on the southern front is the most effective and has no advantage on other fronts. Vertical light shelves have been proposed for the east and west orientations in some studies.

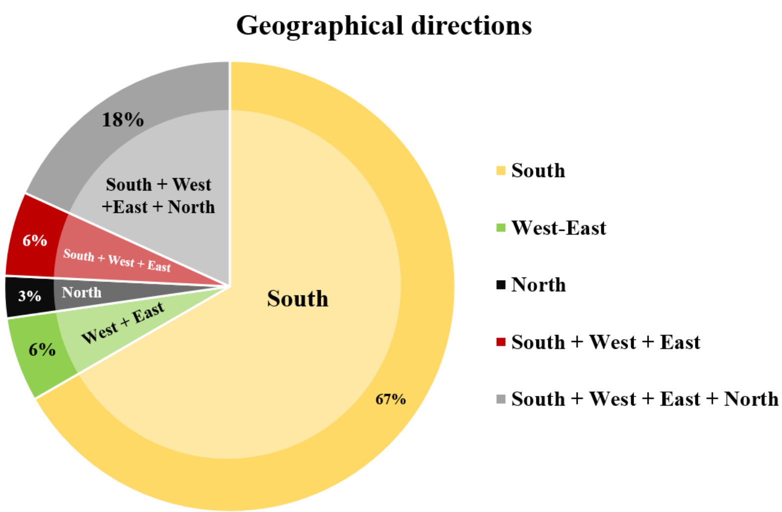

Figure 21. Orientations in the studies.

5. Conclusions

According to the examined samples, we reached important conclusions about light shelves:

- Based on the type of climate and location, it may not be enough to use only a light shelf, and a combination of daylight systems is suggested. Integrated systems can be horizontal and vertical shades, a set of mirrors, solar cells, scattering plates, louvers, or light pipes. Since each of these systems can bring more or less light into space or even produce heat like solar cells, considering thermal comfort is essential.
- Curved or angled light shelves perform better than flat ones, but the probability of glare is higher in such shelves. So, one of the solutions can be combining the light shelf with a daylight diffusion sheet. These surfaces can be installed on the external shelf or the window above it. Also, it can be used as a horizontal semi-transparent screen along the light shelf. Installing this screen on the window above the light shelf can improve the distribution of light and has higher efficiency than when placing it on the shelf. In winter, the use of these panels may reduce the entry of natural light and increase the building's heating load, so it is better to separate this panel from the light shelf in winter.
- In hot climates, it is more suitable to use louvers, horizontal and vertical shades, and daylight scattering screens, which, while preventing glare, introduce less heat into the environment. In order to avoid increasing the cooling load, it is suggested to use light shelves in combination with low-emissivity coating, PCM materials, or materials with high thermal delay. Also, it is better to use shades with variable depth that, while providing shade in the summer, do not prevent the sunlight from entering during cold seasons. For colder climates, it is more appropriate to use a daylight-diffusing surface in line with the light shelf inside the room.
- Sometimes, to change the direction of the sun's rays, light shelves can be combined with a set of mirrors. In this case, if these mirrors have a solar tracking system and change the angle based on the direction of the sun, they have higher efficiency.
- Light shelves can be integrated with solar cells. Solar cells produce a significant amount of heat and may affect the cooling load of the building. As the temperature rises, the efficiency of the solar cells decreases, so it is not recommended to use them in summer. In winter, due to the oblique radiation of the sun, these systems are practically ineffective, so it is better to use dynamic systems. In summer and winter, the solar cells are separated from the light shelf and combined only in spring and autumn. The angle of the sun's radiation to solar cells is very important to their efficiency, so using a system that can adjust the angle of the solar panels according to the angle of the sun's radiation is very effective. Another consideration worth mentioning in the integration of solar cells is that with the passage of time and dust sitting on the solar cells, their efficiency decreases. Therefore, economic analysis regarding the efficiency of the cells should be taken into consideration.

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