Article

Light Shelves Optimization for Daylight Improvement in Typical Public Classrooms in Saudi Arabia

Mostafa Sabbagh 1,*, Siraj Mandourah 1 and Raghda Hareri 2

1 Department of Architecture, Faculty of Architecture and Planning, King Abdulaziz University, Jeddah 22254, Saudi Arabia
2 Department of Interior Design and Furniture, King Abdulaziz University, Jeddah 22254, Saudi Arabia
* Correspondence: mjsabbagh@kau.edu.sa

Abstract: Daylight is an essential component of the classroom environment, and its role in improving the education and productivity of students has been widely studied. This research focuses on daylight and studies the quality of lighting in a typical classroom in Saudi Arabia, where the classroom chosen as the research sample was identical to the standard model for designing schools in Saudi Arabia, to investigate the quality of natural lighting in this space. The amount and quality of the daylight in the sample classroom was studied by simulating the response of the classroom design to the daylight entering it, using the environmental variables of time, date, and direction. After reviewing the simulation results, the darkest cases were chosen to try to improve them by using light shelves. Two cases were chosen for this research: one with a western orientation and the other with a northern orientation. Four design alternatives were designed for the light shelves, and then their effects on the selected cases were simulated to determine the extent of their impact on the amount and quality of daylight in the classroom. After examining and studying the simulation results, the experiment demonstrated that the use of light shelves in this case was not very effective, but they can help in a simple way to reduce the effect of the difference in lighting levels between areas near the windows and areas deeper in the classroom, and to reduce the contrast in general.

Keywords: daylighting assessment; classroom; light shelves; visual comfort; natural illumination; lighting distribution

1. Introduction

Previous studies have demonstrated the importance of natural lighting and its impact on the quality of interior spaces in general, as well as its many other benefits for occupants’ performance, health, and mental wellbeing. Many researchers have focused on the topic of daylight and its importance in educational buildings in particular. Classrooms are typically used during the day, where early-morning activities aid students’ attention and learning. This is also true for students’ mental and physical health [1], improving visual clarity and comfort [2,3], and relieving symptoms of depression, sleep disorders, and mental health disorders [4–6]. Daylight affects human psychology and physiological features, as it can influence mood, awareness, and vision. In the learning environment, daylight plays a significant role in creating a better environment for teaching and learning, as poorly lit classrooms negatively affect students’ health and learning ability [7]. Moreover, lack of natural daylight may cause seasonal affective disorder, with symptoms such as depression, insomnia, and irritability [5]. One cause of this condition is spending most of our time in viewless spaces. Such spaces can consist of windowless spaces, or they can be spaces with windows but with poor daylight access design, prompting curtains to be mostly closed and obstructing open views. Many studies confirm that dealing with daylight appropriately may reduce these problems. Some studies have also observed a strong link with eye-damaging diseases caused by uncontrolled glare [8]. Usually, visual comfort data are based
on user surveys, as they relate to the physical discomfort experienced by individuals in their reaction to excessive light [9]. The amount of natural daylight and its balance are also primary drivers of good environmental quality in classrooms. Typical effective solutions in improving the quality of the space and its visual comfort include the use of shading and sunbreakers [10,11]. Thus, classrooms need to be appropriately designed to maximize lighting and ventilation [12].

The importance of studying daylight in classrooms and school contexts has received much attention in the last few decades [1,13–15]. Moreover, daylight has played a significant role in the design of educational spaces [16,17]. Studies have shown that good daylight in schools enhances academic performance [18], where high-quality daylight was found to improve students’ learning performance [19]. Classrooms with good natural views can positively increase students’ levels of perception and their academic performance. According to Benfield et al. [20], daylight is believed to decrease stress levels and enhance productivity. Several studies have found that appropriate amounts of daylight in classrooms help improve learning and raise the levels of student engagement. In a study conducted on students’ performance, it was found that the students’ results were improved by a large margin in classrooms that had natural lighting most of the time, as the results of students’ mathematics tests improved by 20%, reading tests improved by 25%, and there was a general improvement of 15–23% in results throughout the academic year [5].

This study aimed to investigate the potential of the adoption of light shelves as a retrofit solution for improving existing typical public-school classrooms in Saudi Arabia at minimal cost and with minimal impact on the design. The quality of natural lighting in typical classrooms was studied and evaluated by simulating the final light received under specific conditions, and we investigated one of the most widely used techniques to improve natural lighting in interior environments, i.e., the use of light shelves in architectural design. It is recognized that light shelves are used to redistribute natural lighting in empty spaces, so that the light is distributed to deliver it to dark spaces in the rooms. Hence, we tested their effect on the spaces chosen in this paper.

2. Literature Review

2.1. Classroom Design

Daylight is an essential part of architectural design. This can be particularly important in the case of schools, to accommodate the type and needs of activities carried out within them, creating an optimal environment for students, and improving their ability to concentrate and perform visual tasks such as reading and writing. The process of successful daylighting in classrooms requires early consideration of many aspects of design and architecture, including studying the building’s location, climate, functional requirements, and orientation. In addition, decisions need to be made related to the arrangement of the building’s openings (e.g., doors and windows), shading systems, glazing materials, and artificial lighting systems [21]. The provision of an appropriate amount of uniformly distributed light with glare protection is a significant factor in classroom design [22]. Moreover, daylight has also become an important design issue with respect to the growing interest in green architecture [4]. The evaluation of daylight in real environments is necessary to design sustainable buildings [23]. Thus, integrating smart, innovative daylighting strategies in buildings’ architectural design could significantly reduce electricity consumption while enhancing the light quality of the interior environment [24].

2.2. Daylight and Windows

Windows provide a view, connecting the interior with the outdoor environment. Window openings’ proportions may influence how the room appear (i.e., smaller or larger) as well as its visual comfort. Increased daylight exposure through windows leads to improved student testing results. Conversely, poor window control and shading negatively affect students’ educational performance [25]. In another study conducted on 3000 students—some in classrooms with windows and others in windowless classrooms—it was found that 94%
of the participants preferred the classrooms with windows, and only 4% preferred the other classrooms. Teachers participating in this study described how students in the classroom without windows appeared to be shyer and more likely to complain [16]. Daylight design without proper considerations of shading and protection can cause high luminance and uncomfortable glare. Advanced daylighting strategies pay attention to this issue, assigning different functions to the suitable areas of the facades to maintain views from windows without compromising other functions [24]. Daylighting systems can range from simple static features (such as louvers, light shelves, fixed overhangs, laser-cut panels, prismatic elements, and anidolic systems) to adaptable dynamic elements (e.g., blinds, movable lamellae, advanced glazing, holographic optical elements) and/or a combination of these elements [26]. In another study, simulation results of five out of six classrooms detected glare problems. The usage of external and internal shading devices and the positioning and dimensions of openings reduced the glare from 64.1% to 6.7% and showed a positive effect [27]. Based on these outcomes, retrofit solutions that are aimed at reducing or redirecting direct sunlight—such as external overhangs, light shelves, louvers, and reflective ceilings—have been designed and their efficacy tested by recalculating all of the static and dynamic metrics [28].

2.3. Light Shelves

Light shelves are horizontal elements that reflect the daylight into an internal space. According to studies conducted in Greek schools, external shading elements on selected facade orientations can enhance the indoor visual comfort and decrease glare and heating issues [5]. Read examined six different conditions of light shelves under different inclinations: three were fully attached externally but with different widths, and the other three were partially used inside the study room. It was found that light shelves are one of the most suitable types of daylighting elements for classrooms and are also highly suitable for activity rooms and offices [5]. According to Meresi [29], combining light shelves and semitransparent movable external blinds increases daylight in classrooms, providing both shade and uniform distribution of daylight throughout the room. Similarly, after studying some common types of shading and reflection systems and their effects on different educational spaces, according to a previous study, energy savings may reach 40–50% when natural lighting is integrated into the design of schools [30]. In another study, Lee [31] investigated the use of light shelves to reduce energy consumption, where the focus was on changing the angles of the light shelves and their impact on the quality of natural lighting. The study stressed the importance of changing the angle according to the direction of the facade and the angle of the Sun in different seasons. Thus, it is necessary to know the angle of the Sun in the summer and winter and adjust the angle of the light shelves to suit the season, as shown in Figure 1.

![Figure 1. Light shelves with different angles and their effects on daylight.](image)

According to this study, the main elements and variables that affect the performance of light shelves are the height, width, the material used, the angle of the shelves, and whether the shelves are internal or external [31], as shown in Figure 2.
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Hobday [8] also notes that light shelves are not always in the form of a simple horizontal slab, but can be designed with different shapes, sizes, and materials, and that the interior and architectural design variables directly affect the performance of the light shelves and the extent of their effectiveness in improving natural lighting, as shown in Figure 4.

Light shelves can be positioned inside or outside the envelope (Figure 5). External shelves effectively prevent direct sunlight from hitting the window opening and can help in reducing glare; however, they can be limited in terms of how deeply the daylight is reflected inwards. Internal shelves can be more effective in reflecting light inwards toward the ceiling. For some positions, combining internal and external shelves together can be more effective [27,28].
Light shelves also need to be positioned relatively high compared to the window cell, taking into account users’ line of sight to avoid the risk of reflective glare and avoiding obstruction of view. Preferably, the level of light shelves should be approximately 2.4 m above floor level (Figure 6), since low light shelves can cause glare when sunlight reflects on them [32].

In another classification, Sabry [33] divided the components of light shelves into three main configurations: the first is their position—either external, internal, or a combination of the two; the second is the shelves’ angle, i.e., whether it is horizontal or at a certain angle; and the third is the shape of the light shelves, as shown in Figure 7, i.e., whether they are straight, curved, or irregular. Any change in these components changes the efficiency of the shelves, either positively or negatively [33]. Kontadakis et al. [34] introduced a calculation method for the optimal dimensions of light shelves (Figure 8).

![Figure 5. Effects of light shelves’ position: external, internal, and both.](image)

![Figure 6. The effect of light shelves’ height.](image)

![Figure 7. Various shapes for the design of light shelves.](image)
2.4. Time Factor

Daylight differs throughout the day. The amount of glare and adequate daylight in the room changes according to the building’s orientation, the Sun’s solstice, and the time of day. The subjects of this study were the east and west orientations, as these two sides receive the most glare during the morning and evening periods, respectively. Building orientation has an impact on the energy needs within the building. Lowering the western exposure of a building will reduce the energy costs in warm climates and seasons, as the building will require less annual cooling [5]. In addition, being aware of the Sun’s path over a particular building helps designers to provide the most efficient solution for the window openings and proposed shading systems.

Both the summer and winter solstice periods are studied within this field, as the angle of sunlight in the summer is at its highest, while in winter it is at its lowest levels. As Read [5] states, schools mostly use the peak of the winter and summer solstices from August to May. The study of the Sun’s position helps to anticipate the best options for shading devices at specific angles and times in order to minimize morning glare but obtain adequate daylight within the room [29].

The level of daylighting was studied during the day at three different times, according to the working hours of the students: the morning period (08:00), the middle of the working period (12:00), and the end of the working period (15:00). In another study [5], the amount of daylight entering the classroom was examined on 21 December at 09:00 and 12:00 and on 21 March at 12:00. The results showed the differences in daylight throughout the study room at the highest and lowest peaks of the Sun, which affect the type and the angle of the proposed shading devices [29].

2.5. Preliminary Studies through Simulation Programs

The use of simulation programs plays an essential part in analyzing the different daylight conditions under various circumstances. With the right input, these applications can provide results that are close to reality. The model used in quantitative research to study daylight in schools shows how well the building functions in its current location. For example, Read [5] found that Revit software proved to be most useful in analysis and comparison, as it simulates the effects of various shading and reflection systems on internal spaces. In another study, it was found that the daylight factors obtained from different types of software—such as Radiance and Autodesk Ecotect—matched the daylight factor (DF) values measured within a real study room, establishing the quality of input provided by such software [29]. Thus, simulation software can provide insights into real daylight conditions and help to examine the effects of various conditions.
3. Methodology

This study investigated the potential of the adoption of light shelves to help improve daylight quality in typical public classrooms. The evaluation was based on field measurement data taken from four different public classrooms representing northern, western, eastern, and southern orientation [35], and then averaged for each orientation. The study also identified the geometry and properties of the typical public classroom. A standard classroom was modeled using Revit and simulated for daylight analyses for all four orientations, considering the schoolday timeframe (09:00 and 13:00) and accounting for the summer/winter solstice, as shown in Figure 9. Field measurements were used to calibrate the simulation results. The results of the calibrated simulation cases were used to identify cases that had the lowest distribution quality of daylight, i.e.,. Those cases (Figure 10) were then chosen for testing the light shelves scenarios. Four alternative light shelf designs were then tested on the calibrated model for the subject cases, identifying which scenario would present the highest potential. The design with the best potential was then tested against all other scenarios to reaffirm the general improvement in all facade orientations during the schoolday.

![Environmental variables](image)

**Figure 9.** Environmental variables.

This study took the following lux level for daylight standards of illumination according to the space function:
- 300 lux: Classrooms, tutorial rooms; music practice rooms; computer practice rooms; language laboratories;
- 500 lux: Lecture halls; art rooms; practical rooms and laboratories; handicraft rooms; libraries and reading areas;
- 750–1000 lux: Technical drawing room; —Art rooms in art schools.

Field measurements were taken using a handheld light meter and simulated using Autodesk Insight: Building Performance Analysis.
3. Methodology

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Figure 9. Environmental variables.

Figure 10. Study framework—research sequence steps.

4. Selected Classroom/Research Sample

The chosen research sample was a standard classroom in a public school in Saudi Arabia that adheres to the usual local design standards and requirements. To assess the effectiveness of these standard classrooms. The classroom in question was also considered in terms of natural lighting, and matched the specifications appropriate for this research, so the same study approach was adopted as at the locations of the experiments in the research. The classroom is shown in Figure 11 [35]. The attributes of the selected classrooms are shown in Table 1. The classroom elements, surface finishing, and materials at the school are listed in Table 2.

Figure 11. Selected classroom [35].
Table 1. Attributes of selected classrooms.

<table>
<thead>
<tr>
<th>Classroom Dimension (m)</th>
<th>Area (m²)</th>
<th>Window Size (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 L × 7 W × 3.3 H</td>
<td>63</td>
<td>5 W × 1.6 H</td>
</tr>
</tbody>
</table>

Table 2. Classroom elements, surface finishing, and materials at the school.

<table>
<thead>
<tr>
<th>Category</th>
<th>Element</th>
<th>Classroom—School A</th>
<th>Classroom—School B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furniture layout</td>
<td>Desk and chair</td>
<td>Communal tables in groups of five students each</td>
<td>Desks and chairs facing the whiteboard</td>
</tr>
<tr>
<td>Teaching equipment</td>
<td>Type</td>
<td>Projector, whiteboard, interactive smart board</td>
<td>Projector, whiteboard</td>
</tr>
<tr>
<td>Surface material and finish</td>
<td>Walls</td>
<td>Painted</td>
<td>Painted</td>
</tr>
<tr>
<td>Flooring</td>
<td>60 × 60 cm ceramic tiles</td>
<td>60 × 60 cm ceramic tiles</td>
<td></td>
</tr>
<tr>
<td>Ceiling</td>
<td>False ceiling, painted</td>
<td>False ceiling, painted, with a drop bulkhead for AC ducting</td>
<td></td>
</tr>
</tbody>
</table>

5. Simulation of Existing Designs

5.1. Calibration with Simulation Model

After specifying the study rooms and noting their specifications, we can move to the next stage, which is the simulation of the effect of natural lighting on the selected study case. Before starting the simulation process, it must be ensured that the results of the simulation program are close to what is present in reality, so a comparison must be made between field measurements and the simulation program for a particular case under the same experimental conditions of time, date, and specification to the model, where field studies are taken from the previous research [35] and compared to the simulation results later, as shown in Figure 12. A review of the finishing materials for the classroom was taken from site and used to reflect in the model, as shown in Table 3. On-site readings showed the highest classroom daylight intensity in the southern orientation, as the results were between 470 and 4900 lux during the morning period, as shown in Table 4. The results of the afternoon readings were similar. The opposite was in the eastern orientation, where the lowest results were recorded. As for the western orientation, there was a big contrast in the results during the afternoon period, as the daylight intensity ranged between 150 and 2800 lux, as shown in Table 5.

![Figure 12. Comparison of the field measurements with the simulation.](image-url)
Table 3. Classroom space specifications.

<table>
<thead>
<tr>
<th>Component</th>
<th>Reflectance</th>
<th>Transmittance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal walls</td>
<td>0.70</td>
<td>White</td>
</tr>
<tr>
<td>Floor</td>
<td>0.40</td>
<td>Polished granite</td>
</tr>
<tr>
<td>Ceiling</td>
<td>0.80</td>
<td>Flat</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Windows</th>
<th>Transmittance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glazing</td>
<td>0.55</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Others Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surroundings</td>
</tr>
<tr>
<td>No obstruction from adjacent buildings 0.75m</td>
</tr>
<tr>
<td>Simulation plane height</td>
</tr>
</tbody>
</table>

Table 4. Classroom daylight intensity, morning period.

<table>
<thead>
<tr>
<th>During Morning</th>
<th>North Orientation</th>
<th>East Orientation</th>
<th>West Orientation</th>
<th>South Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min.</td>
<td>116 Lux</td>
<td>300 Lux</td>
<td>200 Lux</td>
<td>470 Lux</td>
</tr>
<tr>
<td>Avg.</td>
<td>390 Lux</td>
<td>470 Lux</td>
<td>390 Lux</td>
<td>980 Lux</td>
</tr>
<tr>
<td>Max.</td>
<td>550 Lux</td>
<td>1025 Lux</td>
<td>2800 Lux</td>
<td>4900 Lux</td>
</tr>
</tbody>
</table>

Table 5. Classroom daylight intensity, afternoon period.

<table>
<thead>
<tr>
<th>During Afternoon</th>
<th>North Orientation</th>
<th>East Orientation</th>
<th>West Orientation</th>
<th>South Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min.</td>
<td>233 Lux</td>
<td>150 Lux</td>
<td>150 Lux</td>
<td>430 Lux</td>
</tr>
<tr>
<td>Avg.</td>
<td>360 Lux</td>
<td>290 Lux</td>
<td>360 Lux</td>
<td>830 Lux</td>
</tr>
<tr>
<td>Max.</td>
<td>668 Lux</td>
<td>602 Lux</td>
<td>2800 Lux</td>
<td>3700 Lux</td>
</tr>
</tbody>
</table>

5.2. Daylight Simulation for the Models of the Selected Classrooms

The simulated results were calibrated to closely match the field measurements. This was done to account for the variables of date, time, and orientation. Based on the results of simulating the natural lighting in the classroom model shown in Figure 13, we found that for most cases the simulations were generally the same, except for four different cases: two of them with very low natural lighting (winter solstice, north 09:00 and west 09:00), while the other two were the opposite, with high levels of lighting in most of the space (summer solstice east, 09:00 and winter solstice south, 13:00).

5.3. Cases Selected to Study the Effects of Light Shelves

After looking at the results of the previous simulations in Figure 13, specific cases were specified for a specific time, date, and orientation, so as to study the effects of light shelves on the rooms’ levels of lighting. Since the main function of light shelves is to redistribute the light into the space and project it into the depths of the classroom, the darker cases were chosen to see if there was an improvement in the lighting with light shelves. Two cases were chosen: the first in the western orientation at 09:00 in the morning on the day of the winter solstice, and the second case at the same time and date but in the northern orientation (Figure 14). The graphical display scale was changed to increase the brightness of the light (Figure 15).
Table 4. Classroom daylight intensity, morning period.

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Min.</th>
<th>Avg.</th>
<th>Max.</th>
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</thead>
<tbody>
<tr>
<td>North</td>
<td>200 Lux</td>
<td>980 Lux</td>
<td>4900 Lux</td>
</tr>
<tr>
<td>East</td>
<td>300 Lux</td>
<td>470 Lux</td>
<td>1025 Lux</td>
</tr>
<tr>
<td>West</td>
<td>2800 Lux</td>
<td>390 Lux</td>
<td>2800 Lux</td>
</tr>
<tr>
<td>South</td>
<td>470 Lux</td>
<td>980 Lux</td>
<td>4900 Lux</td>
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Table 5. Classroom daylight intensity, afternoon period.

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<th>Orientation</th>
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<td>150 Lux</td>
<td>290 Lux</td>
<td>602 Lux</td>
</tr>
<tr>
<td>West</td>
<td>150 Lux</td>
<td>360 Lux</td>
<td>2800 Lux</td>
</tr>
<tr>
<td>South</td>
<td>430 Lux</td>
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6. Simulating the Different Types of Light Shelves

Following the literature review, four light shelf design types were incorporated. Figure 16 shows the four light shelf retrofit proposals that were used for the comparison. Type A followed the standard equation included Figure 8, while types B, C, and D...
were further derivatives of the same design used in the first type. The light shelves were modeled as Lambertian reflecting surfaces.

Figure 16. Design proposals for types of light shelves.

The four types of light shelves were modeled and simulated. The effects of these light shelves types on natural lighting in the space are simulated for both, west and north cases. The first case simulation is shown in Figure 17 and graphed for Illuminance values at different distances from windows in Figure 18.

- First case (western orientation, 09:00, 21 Dec.)

Figure 17. Daylight simulation for models of the selected classrooms with light shelves—9 a.m., western orientation.
The four types of light shelves were modeled and simulated. The effects of these light shelves on natural lighting in the space are simulated for both, west and north cases.

- First case (western orientation, 09:00, 21 Dec.)
- Second case (northern orientation, 09:00, 21 Dec.)

Based on the results of the analyses of the simulated natural lighting values in the classroom for the first case (Figure 18), we can see that the lighting response to the light shelves is not particularly significant, but the light shelves generally helped in reducing the contrast in the light intensity between the areas near the windows and the interior areas away from the light source. In terms of the different types of light shelves, we can see that the results for types A and B are very similar in values. These were the best types for reducing the contrast of natural lighting, as they increased the level of lighting in the interior of the classroom and reduced it near the windows. In Figure 19, the effects of light shelves on natural lighting in the space are shown for the second case, with a northern orientation.

**Figure 18.** Illuminance values at different distances from windows—9 a.m., western orientation.

<table>
<thead>
<tr>
<th>Illumination Level (Lux)</th>
<th>1m</th>
<th>2m</th>
<th>3m</th>
<th>4m</th>
<th>5m</th>
<th>6m</th>
<th>7m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>390</td>
<td>300</td>
<td>220</td>
<td>155</td>
<td>129</td>
<td>116</td>
<td>148</td>
</tr>
<tr>
<td>Type A</td>
<td>350</td>
<td>295</td>
<td>249</td>
<td>208</td>
<td>194</td>
<td>194</td>
<td>235</td>
</tr>
<tr>
<td>Type B</td>
<td>341</td>
<td>287</td>
<td>240</td>
<td>204</td>
<td>187</td>
<td>182</td>
<td>224</td>
</tr>
<tr>
<td>Type C</td>
<td>314</td>
<td>271</td>
<td>211</td>
<td>163</td>
<td>139</td>
<td>135</td>
<td>164</td>
</tr>
<tr>
<td>Type D</td>
<td>346</td>
<td>280</td>
<td>225</td>
<td>182</td>
<td>159</td>
<td>157</td>
<td>192</td>
</tr>
</tbody>
</table>

**Figure 19.** Daylight simulation for models of the selected classrooms with light shelves—9 a.m., northern orientation.

Based on the results of the analyses of simulated natural lighting values in the classroom for the second case (Figure 20), we can see that the lighting response to the light shelves was also similar, but the light shelves in general helped to reduce the contrast of illumination between the areas near windows and the interior areas far from the light sources—especially in the first case (A) and in case D, where type A was the best, followed by type D.
7. Conclusions

This research investigated the potential of the adoption of light shelves as a retrofit solution for improving existing typical public school classrooms in Saudi Arabia, as a minimum-cost and minimum-impact solution for improving daylight. The cases with the most severe daylight conditions—winter solstice on 21 December 9 a.m. for the western and northern orientations—were selected to be tested against several types of light shelves. Although the improvements were not large, it was found that the light shelves did provide some effect on the quality and distribution of daylight within the classrooms. This improvement is reflected in the reduced contrast between the area close to the window and the interior of the classroom. For both tested cases, we compared the original lux values to the type A light shelves—very close to 200 lux, generally findings 15% and 17% improvements for the western and northern orientations, respectively, and greater improvements for the other orientations. Thus, in conclusion, light shelves can be a reliable option for quick and cheap daylight improvements for standard classrooms in Saudi school buildings. This solution can be discriminately applied as a retrofit design to all facades, orientations, and locations in Saudi Arabia. Additional improvements to achieve optimal daylight levels in classrooms could be implemented through other approaches, such as solar tubes and the Fiber Optic Daylighting System, which can be further improved, along with other technologies that help increase lighting and improve the quality of the interior environment.

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References

28. Costanzo, V.; Evola, G.; Marletta, L.; Pistone Nascone, F. Application of Climate Based Daylight Modelling to the Refurbishment of a School Building in Sicily. *Sustainability* 2018, 10, 2653. [CrossRef]
