

Article

# Daylighting Retrofit Methods as a Tool for Enhancing Daylight Provision in Existing Educational Spaces—A Case Study

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**Abstract:** Adequate illuminance has a great effect on the health, comfort, and performance of pupils. It can be achieved by either artificial lighting or daylighting. Daylighting is usually preferred due to psychological, physiological, and economic purposes. This study aims to improve the daylight provision in existing classrooms, by investigating various retrofit methods for passive daylighting techniques in northerly oriented classrooms at Jordan University of Science and Technology (JUST). Data for this research are obtained using computer simulation. The retrofit methods are evaluated in terms of illuminance levels on the desks plane and the chalkboard. The retrofit methods investigated in this study included improving the material reflectance, adding clerestory to the classroom, lightshelves, anidolic ducts, as well as various combinations between these cases. By comparing the results, and in light of the recommended lighting level by The Lighting Guide 5: Lighting for Education released by Chartered Institution of Building Services Engineers (CIBSE) in 2011, the combination of the clerestory window and the anidolic ducts result in the best results. While CIBSE recommended a target illuminance of 300 lx on desks plane and 500 lx on the board, the combination registers an average of 249 lx–300 lx on the desks plane in all sensors compared to 42 lx–105 lx in the base case, and an average of 275 lx–345 lx on the board for the tested dates compared to an average of 45 lx–115 lx in the base case.

**Keywords:** classrooms; retrofit; passive daylight techniques; daylight provision; simulation

## 1. Introduction

Educational facilities need to have the best indoor environmental quality, for the reason that teachers and pupils spend around 30% of their time in universities and schools [1]. The indoor environmental quality of classrooms has a great effect on the quality of teaching [2]. The most notable similarities between most of the existing educational facilities are high-energy consumption, and the need for retrofitting in order to enhance the comfort level [3,4].

Visual comfort has a major contribution to the creation of adequate educational environments [5]. Studies proved that lighting is important for pupils' learning. It was found that pupils and teachers have different tendencies toward the preferred type and level of lighting. For example, a study found that teachers prefer daylight to artificial light [6]. Another study indicated the preference of teachers to have control over the lighting levels in the classroom [7]. While some researchers indicated that daylight helps students to focus and learn better [8], other researchers addressed the need for the integration of daylighting and artificial lighting [9]. However, most researchers emphasized the importance of daylighting for both visual comfort and energy efficiency [10].

Visual comfort depends on the physical quantities describing the amount of light and its distribution in space, the physiology of the human eye, and the spectral emission of the light source [11].

The assessment of visual comfort in accordance to human needs includes many parameters, such as the amount of light and its uniformity, the risk of glare for occupants, the luminance distribution, and the quality of light in rendering colors [12].

Visual comfort can be achieved either by artificial lighting or by daylighting. Daylighting is usually preferred due to psychological, physiological, and economic aspects [13–16]. It is an important strategy to achieve visual comfort and energy efficiency [17]. Besides, the up-to-date artificial light does not produce the same spectrum or instantaneous variability of daylight [17–19].

In classrooms, providing a comfortable indoor environment is as important as adequate energy use [20]. The high occupancy of classrooms calls for high standards of ventilation, lighting and thermal conditions [21]. To contribute in achieving the visual comfort requirements, researchers evaluated many daylighting techniques that can be applied to classrooms. Most of the daylighting techniques used in the classrooms are applied to the fenestration system, for the reason that the classrooms are usually side-lit, arranged in the form of corridor–classrooms or classrooms–corridor–classrooms [22].

This research investigates various retrofit methods to enhance daylight provision in selected educational spaces. It assesses the performance of various daylighting retrofit techniques on the northern and/or southern elevations of a typical classroom at Jordan University of Science and Technology (JUST), Jordan. Due to the special construction system used in JUST of having precast concrete walls with bearing loads, the investigated techniques are selected to have minimal modifications to the building envelope.

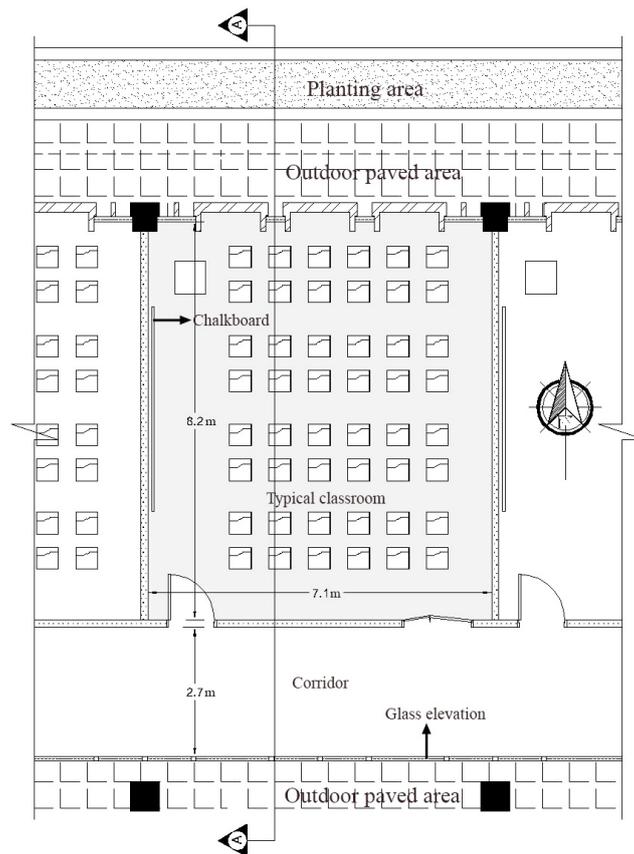
### *1.1. Lighting Codes for Classrooms*

Activities taking place in classrooms, such as writing and reading from the chalkboard and desks, require suitable and specific illuminance levels [23]. Every country has its own codes of lighting in classrooms, but it all ranges from 300–500 lx [24]. Lighting codes mostly originate from the ones released by the European Committee for Standardization (CEN) and the Illuminating Engineering Society of North America (IESNA). Both committees recommend a target illuminance of 300 lx for classrooms [25]. The Lighting Guide 5: Lighting for Education (LG5), released by Chartered Institution of Building Services Engineers (CIBSE) in 2011, recommended a target illuminance of 300 lx on the desks plane and 500 lx on the chalkboard [26], while the EN 17037 standard, released by CEN, recommended that the high target illuminance on vertical and inclined daylight openings should not exceed 750 lx [27].

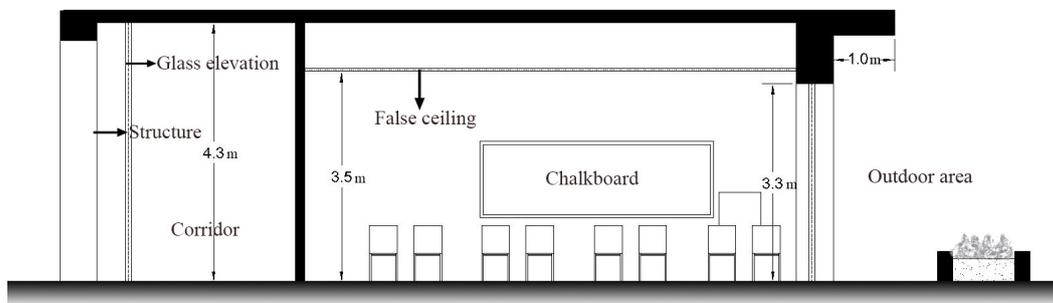
### *1.2. Sample of the Space under Investigation*

A sample classroom, located on the ground floor, representing about 60% of typical classrooms of JUST, is chosen. The dimensions of the classroom are 7.1 m long and 8.2 m wide. All the classrooms at JUST are accessed through single loaded corridors of 2.7 m width, as seen in Figure 1. The classroom is 3.5 m high, ending with a 0.8 m false ceiling, as illustrated in Figure 2. The classroom is side-lit by vertical and narrow openings directed toward the north. The windows are 0.3 m in width and 3.3 m in height. The glazing of the windows is 6 mm clear single-pane glass. The window-to-wall ratio (WWR) is 19%. The floors above the classroom create a projection of 1 m over the windows. The typical capacity of each classroom at JUST is 48 pupils.

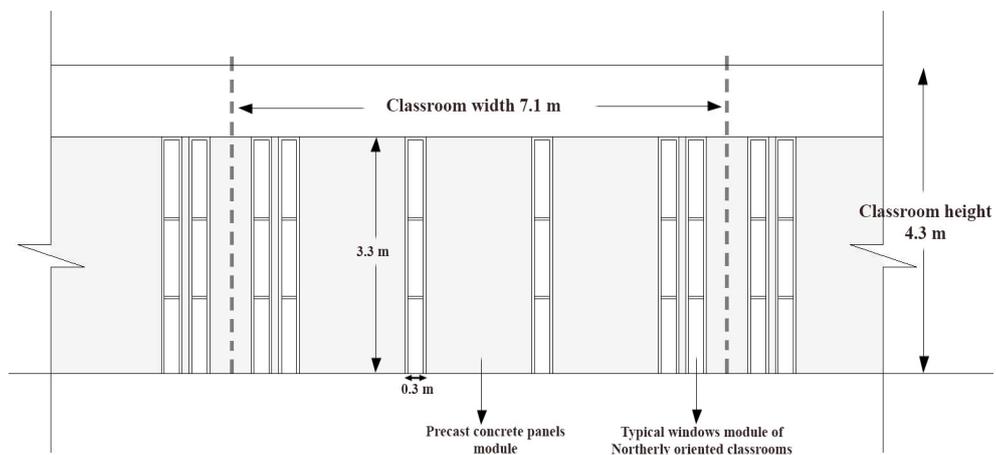
Figure 3 shows a typical elevation of a classroom at JUST. The fenestration system was designed as narrow openings in a response to the hot climate of the area. Because most of the classrooms are northerly oriented, there was no need for shading devices. Various shading devices were used on the other elevations.



**Figure 1.** Plan of a typical classroom at Jordan University of Science and Technology (JUST) showing seating layout, and windows' and chalkboard locations.



**Figure 2.** Section at a typical classroom at JUST showing the class geometry and desks plane level.



**Figure 3.** Northern elevation of a typical classroom at JUST showing the windows' shape and location.

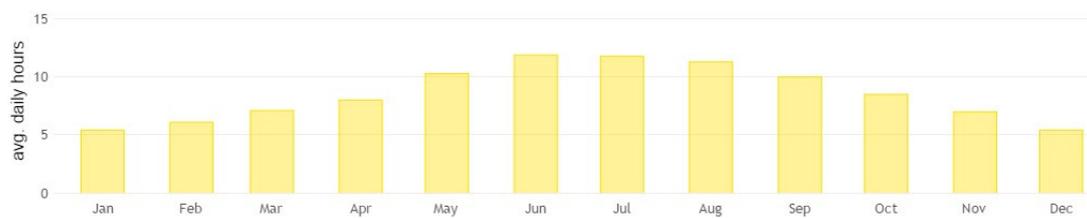
The most important attribute of the material for lighting design is the material reflectance. The reflectance values used in the simulation are obtained from the real buildings of JUST. The Visible Light Transmittance (VLT) of the windows' glass is 0.9. The simulated models include a ground plane with a reflectance value of 0.2 to account for the external reflectance and the shadows under the overhangs. The reflectance of the materials used to build up the simulation model of the classroom is shown in Table 1.

**Table 1.** Materials' reflectance of a typical classroom at JUST.

Member	Material Reflectance
Ceiling	0.70
Floor	0.44
Walls	0.56
Desks plane	0.21
The chalkboard	0.10
External ground	0.20

### 1.3. Daily Sunshine at the Area of Study

The study is conducted at JUST, Irbid/Jordan. JUST's geographical coordinates are 32.5 North and 36 East. Figure 4 shows the average daily sunshine of Irbid. The minimum hours of sunshine occur from December to January with 5.4 hours, and the maximum in June with 11.9 hours. The average annual sunshine in Irbid is 8 hours.



**Figure 4.** Average daily sunshine in Irbid (<http://weather-averages.com>).

## 2. Materials and Methods

### 2.1. Simulation Software

In classrooms, tasks are performed on both horizontal and vertical planes, the desks plane and the chalkboard, respectively. Computer simulation was used to simulate the illuminance levels on both planes. Daylighting simulation software are categorized based on their approaches into three different types: BRE split flux which was developed at the British Building Research Establishment (BRE), radiosity, and raytracing [28]. BRE split flux simulate models only under diffuse sky conditions, where radiosity and raytracing are the two common approaches used under other different sky conditions.

Raytracing cannot predict the performance of complex shapes sufficiently [29]. Backward raytracing software such as Radiance can adequately simulate anidolic systems only under diffuse skies [30,31]. Standard CIE (The International Commission on Illuminance) overcast sky is usually used for daylight factor calculations. Forward raytracing software can be used to simulate anidolic systems with reliable results [32].

Radiosity-based software were used by many researches to study light redirecting systems, and their results were validated by real measurements [33–35]. Hence, FlucsDL, a radiosity-based engine, was used in this resaerch to simulate the cases that include anidolic ducts. Radiance, which is a backward raytracing software was also used to simulate the base case and the remaining cases. The results of both simulation software were presented as grids that show the daylighting readings with contour lines.

### 2.1.1. Simulation Time

Single point-by-point simulations were performed with clear sky condition three times a day: 9 am, 12 pm, and 3 pm, on 21<sup>st</sup> of March, June, September, and December. Clear sky condition was selected to depict the daylight variations within the space. The selected times of simulations were chosen to depict the daylighting conditions with the uttermost solar angles [36].

### 2.1.2. Radiance Parameters

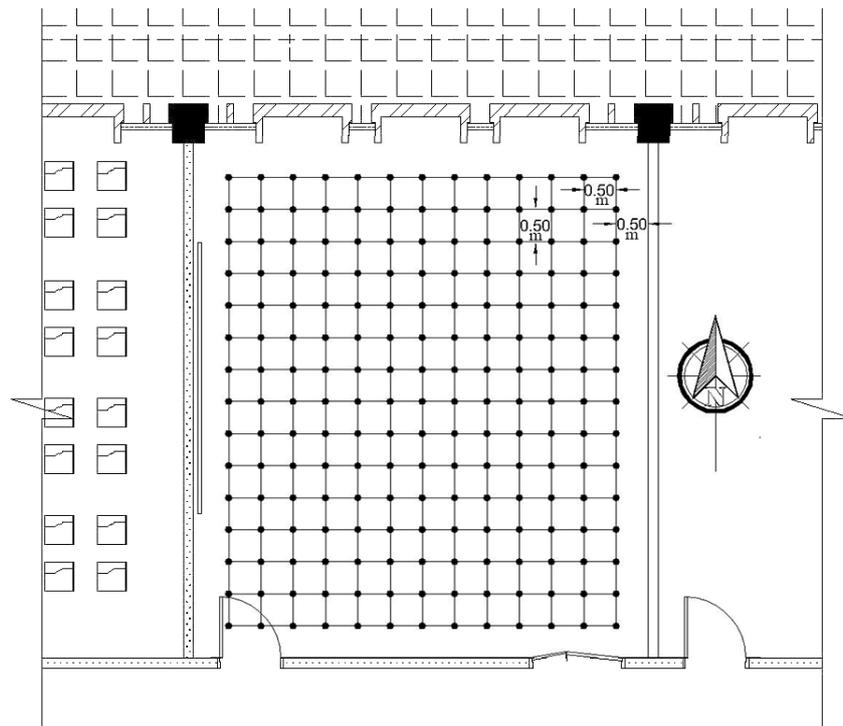
Accurate results of the Radiance simulation were an outcome of the proper choice of software parameters' values. Radiance parameters were chosen to achieve accurate results with the minimum simulation time. The values of Radiance parameters were chosen by trial. In this research, several values were tested, and it was found that the higher value of each parameter gives the best results within a reasonable time. Thus, the maximum value of each parameter was chosen. Tests also showed that a higher value of ambient accuracy (aa) doubles the simulation time with almost the same accuracy [37]. Hence, the value chosen for aa was 0.1, as recommended by the Radiance website. Table 2 shows the parameters' descriptions and values used in this research.

**Table 2.** Radiance parameters' values used in the research.

Parameter	Description	Value
-aa	Ambient accuracy	0.1
-ab	Ambient bounces	8
-ad	Ambient divisions	4096
-ar	Ambient resolution	2048
-as	Ambient super-samples	1024
-dc	Direct certainty	1
-dp	Direct-pretest density	2048
-dr	Direct relays	6
-ds	Source substructuring	1
-dt	Direct thresholding	0
-lr	Limit reflection	16
-lw	Limit weight	0
-ps	Pixel sampling rate	1
-pt	Sampling threshold	0
-sj	Specular jitter	0
-st	Specular threshold	0

### 2.1.3. Horizontal Sensors Grid

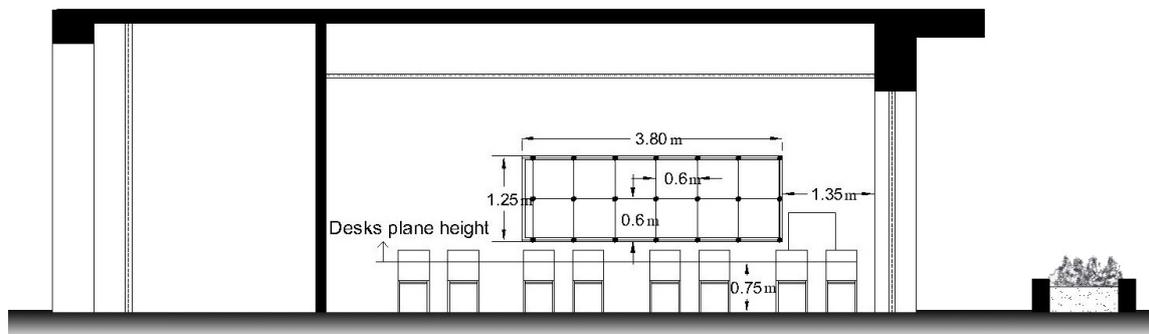
Sensors were used to measure the daylighting level in a software developed by the Integrated Environmental Solutions Ltd using a Virtual Environment (IES VE) and Radiance software. They were distributed symmetrically over the classroom plan, as shown in Figure 5. The sensors were placed at the desks plane, at a height of 0.75 m. The sensors grid, made of 195 sensors, was 0.5 m distant from the classroom perimeter and 0.5 m apart from each other.



**Figure 5.** Plan of a typical classroom showing the distribution of the horizontal sensors grid.

#### 2.1.4. Vertical Sensors Grid

The sensors used in the IES VE (FlucsDL) and Radiance simulations, to measure the daylighting level vertically, were distributed over the chalkboard, as shown in Figure 6. The vertical sensors grid was made of 24 sensors.



**Figure 6.** Elevation of the board wall showing vertical sensors grid.

#### 2.2. Suggested Retrofit Daylighting Techniques

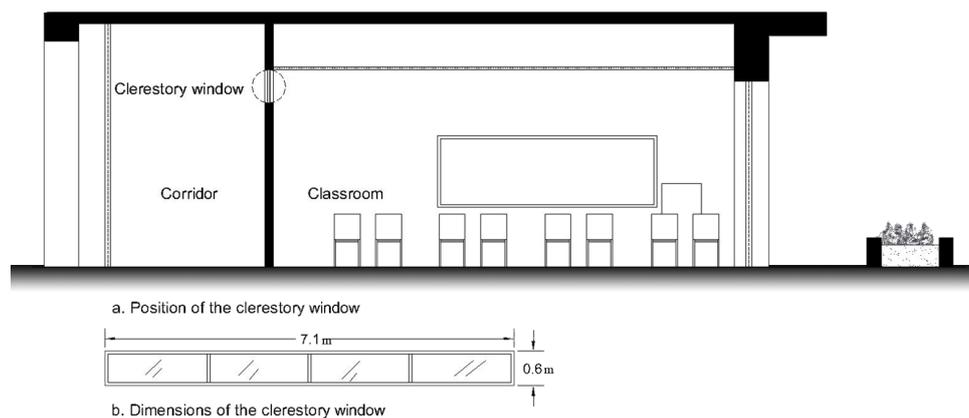
The following cases of passive daylight retrofit techniques were suggested as a tool for enhancing daylight provision in JUST classrooms. The use of precast concrete in the building envelope affected the current windows' shape and size, as well as the decision of choosing suitable retrofitting techniques.

- Case No.1: In this case, the changes applied to the classroom were limited to the reflectance of the ceiling and the wall facing the windows (back wall). The reflectance of these elements was modified as shown in Table 3.
- Case No.2: In this case, a clerestory window was constructed at the common wall between the classroom and the corridor, as illustrated in Figure 7. The window was double-glazed for acoustic purposes and had a transmittance value of 0.65.

- Case No.3: In this case, six lightshelves were installed within the frame of the northern windows, at a distance of  $\frac{2}{3}$  of the windows' height. The upper surface had a reflectance factor of 0.95, while the lower surface was matte. Every lightshelf was 0.3 m wide and extended 0.3 m to the outside and 0.3 m into the classroom, as illustrated in Figure 8.
- Case No.4: In this case, three anidolic ducts were installed between the false ceiling and the concrete slab, as shown in Figure 9. The anidolic duct was made of stainless steel, with an internal reflectance value is 0.95. The duct extended 1.6 m outside the windows to the north, and it ended at the deeper side of the classroom, as shown in Figure 10. The entry aperture of the anidolic duct was  $0.63 \text{ m} \times 0.7 \text{ m}$ , while the exit aperture was  $1.0 \text{ m} \times 0.7 \text{ m}$ . The duct was sealed with a single-pane glass of 0.9 VLT on both entry and exit apertures. The height of the duct was 0.5 m.
- Case No.5: In this case, three anidolic ducts were installed between the false ceiling and the concrete slab. The anidolic ducts were made of stainless steel and had an internal reflectance value of 0.95. The ducts in this case, shown in Figures 11 and 12, differed from the ducts in Case No.4 only by direction (to south). The exit apertures were the same for Case No.4 and Case No.5. As in Case No.4, the entry and exit apertures were sealed with a single-pane glass of 0.9 VLT.
- Case No.6: In this case, the settings of Case No.2 and Case No.5 were combined together, clerestory window and the anidolic ducts directed toward north. The characteristics of the two settings were the same as described previously.
- Case No.7: In this case, the settings of Case No.2 and Case No.6 were combined together, clerestory window and the anidolic ducts directed toward south. The characteristics of the two settings were the same as described previously.

**Table 3.** Measured and suggested values of materials' reflectance.

Element	Measured Reflectance in the Classroom	Simulated Reflectance in Case No.1
Ceiling	0.70	0.85
Back wall	0.56	0.70



**Figure 7.** Section of a typical classroom showing the added clerestory window dimensions and position.

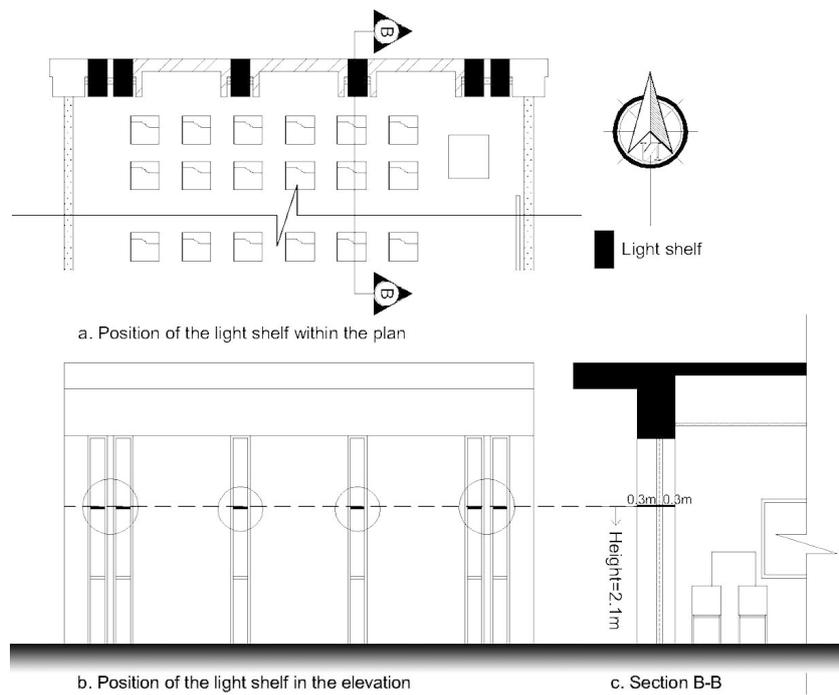


Figure 8. Lightshelves' location within the plan, elevation, and section of the classroom.

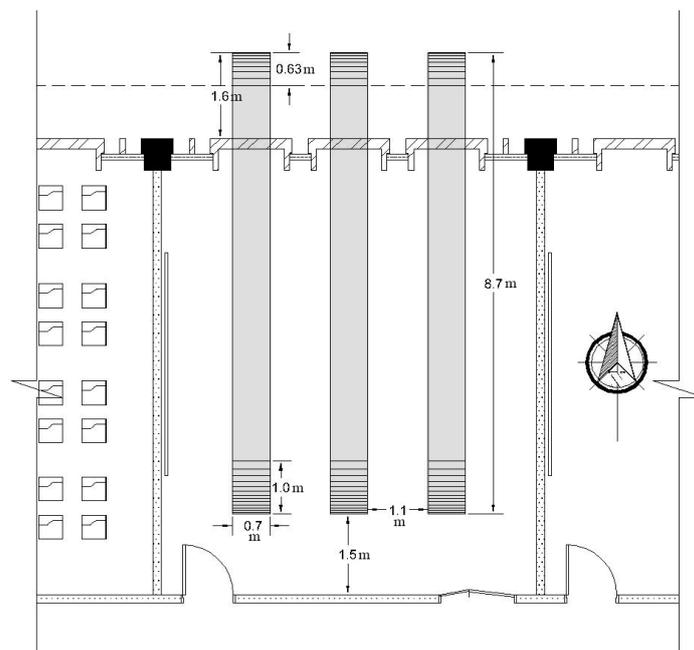
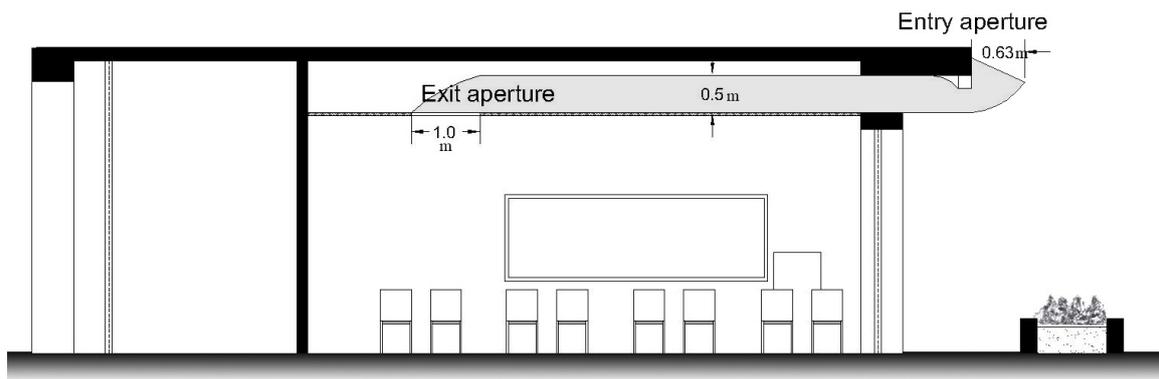
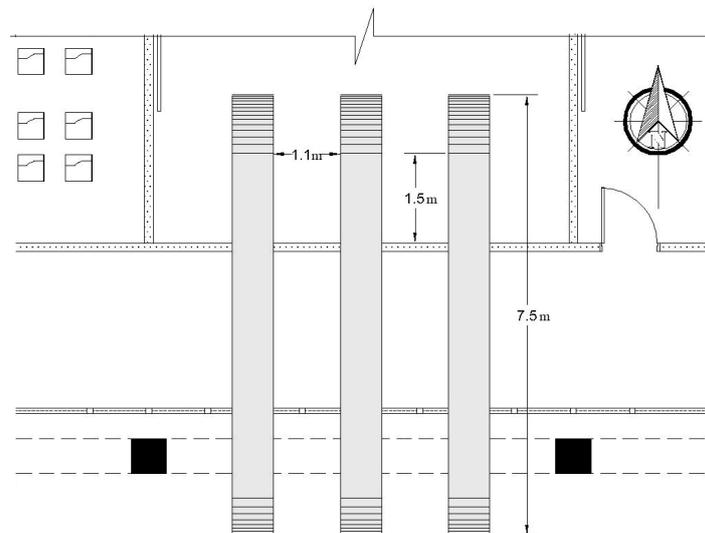


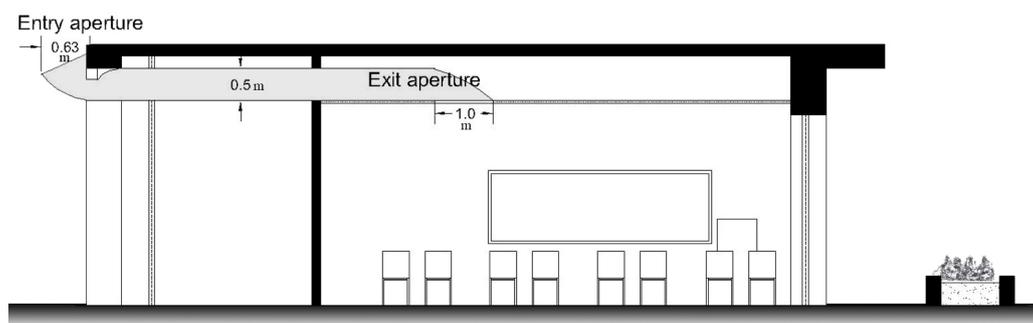
Figure 9. Ceiling plan of a typical classroom showing the suggested northern anidolic ducts.



**Figure 10.** Section in a typical classroom showing the suggested northern anidolic ducts.



**Figure 11.** Ceiling plan of a typical classroom showing the suggested southern anidolic duct.



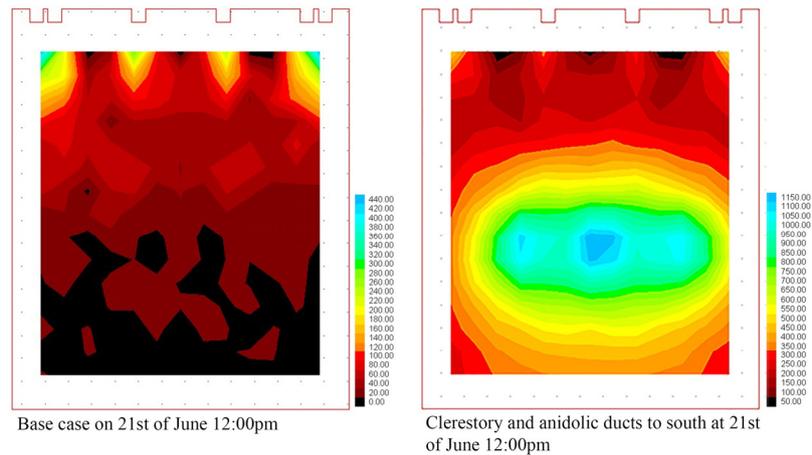
**Figure 12.** Section in a typical classroom showing the suggested southern anidolic duct.

### 3. Results and Discussion

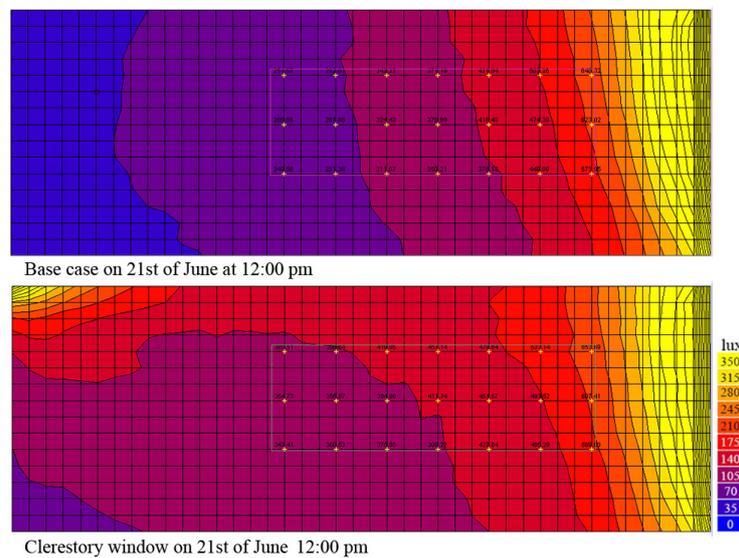
Computer simulation results included the illuminance level and distribution of the suggested cases on the horizontal plane (desks plane) and the vertical plane (the board).

#### 3.1. Illuminance Level and Distribution on Horizontal Plane

The results of the IES VE (FlucsDL) and Radiance simulations were shown as illuminance readings accompanied with contour lines. The simulation results of the suggested cases, conducted at selected times, were compared to the base case on the horizontal and vertical planes, as the examples shown in Figures 13 and 14.



**Figure 13.** Illuminance level and distribution on the horizontal plane (by IES VE—FlucsDL).



**Figure 14.** Illuminance levels and distribution on the vertical plane (by Radiance).

The sun path was the same for March and September, hence, the illuminance levels in these months were nearly the same. The illuminance of the suggested cases in March were set in comparison with the base case. Figures 15–23 compare the calculated average illuminance values of the suggested cases with the base case on the horizontal plane on 21<sup>st</sup> of March, June, and December, at 9:00 am, 12:00 pm, and 3:00 pm, respectively. According to the figures, the illuminance level of the base case, Case No.1, and Case No.3 followed a descending trend when moving from the window to the back wall all around the year. Case No.2: clerestory window showed a different trend. It started with high illuminance levels near the windows, it then decreased at the middle of the classroom, and it finally ascended towards the back wall and the clerestory window.

The figures show that Case No.1 impact was barely noticed. This was due to the absence of direct sunlight and the direction of windows toward the north. This agrees with what was found by a study on the influence of the reflectance values of materials when windows are northerly oriented [38]. The absence of direct sunlight led also to a reduction of the illuminance levels inside the classroom in Case No.3. The lightshelves worked as shading devices and prevented indirect sunlight entry instead of reflecting more daylight into the classroom [39]. The base case, Case No.1, Case No.2, and Case No.3 did not meet the target illuminance required in the classroom at any simulation time.

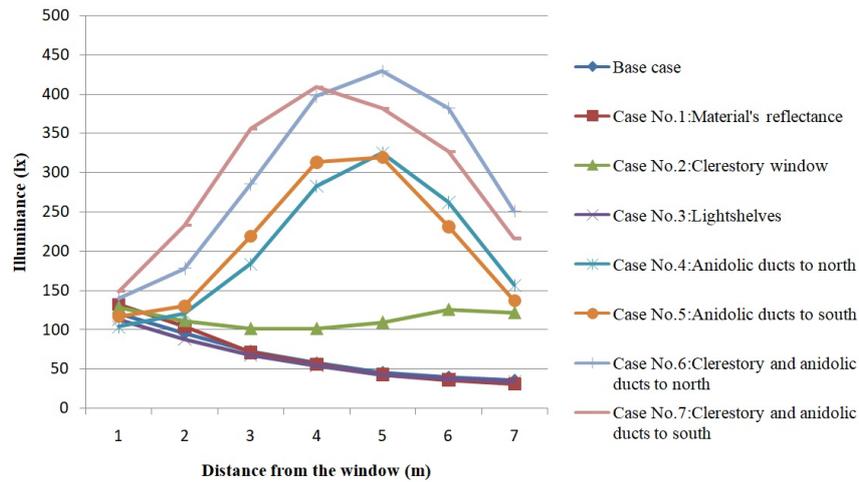


Figure 15. Comparison of average illuminance levels on the desks plane on 21<sup>st</sup> of March at 9:00 am.

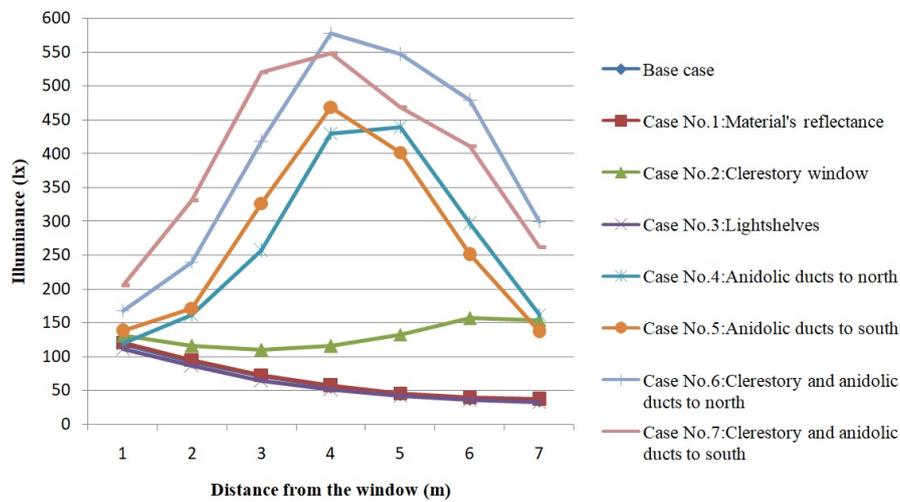


Figure 16. Comparison of average illuminance levels on the desks plane on 21<sup>st</sup> of March at 12:00 pm.

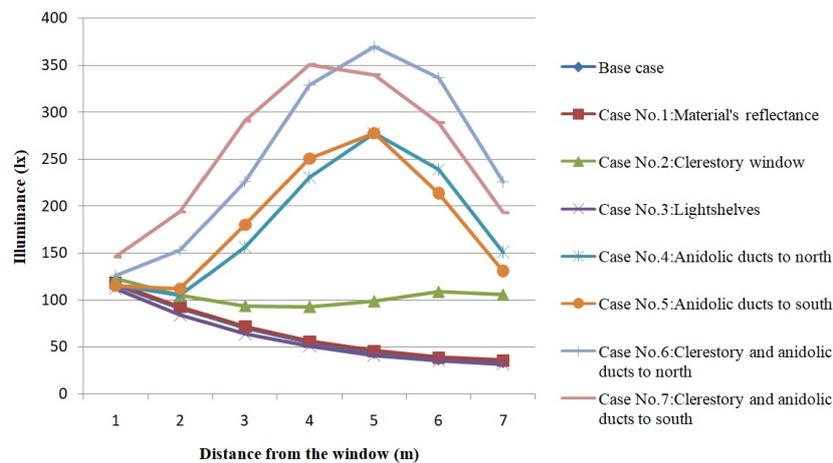


Figure 17. Comparison of average illuminance levels on the desks plane on 21<sup>st</sup> of March at 3:00 pm.

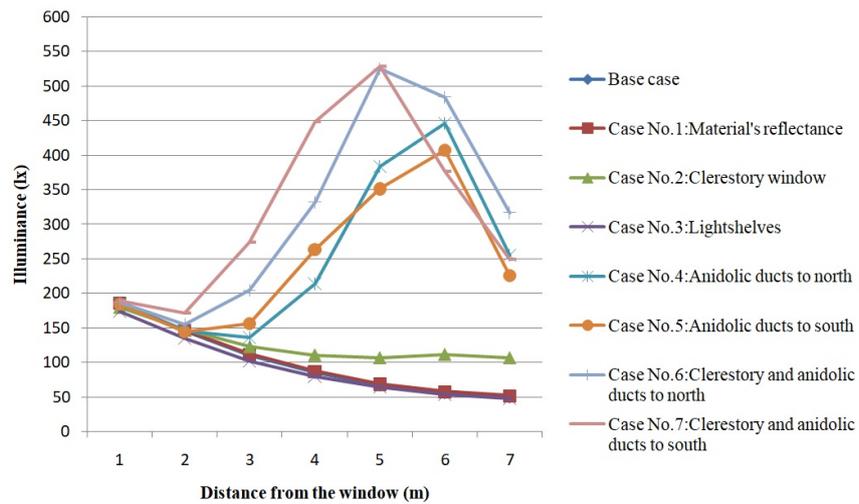


Figure 18. Comparison of average illuminance levels on the desks plane on 21<sup>st</sup> of June at 9:00 am.

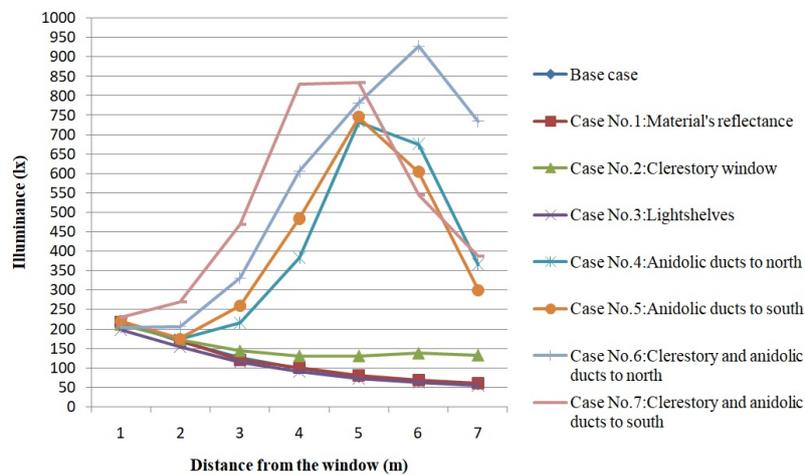


Figure 19. Comparison of average illuminance levels on the desks plane on 21<sup>st</sup> of June at 12:00 pm.

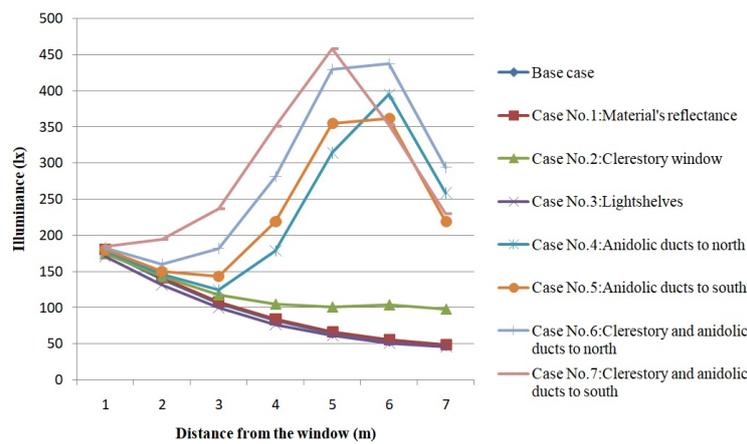


Figure 20. Comparison of average illuminance levels on the desks plane on 21<sup>st</sup> of June at 3:00 pm.

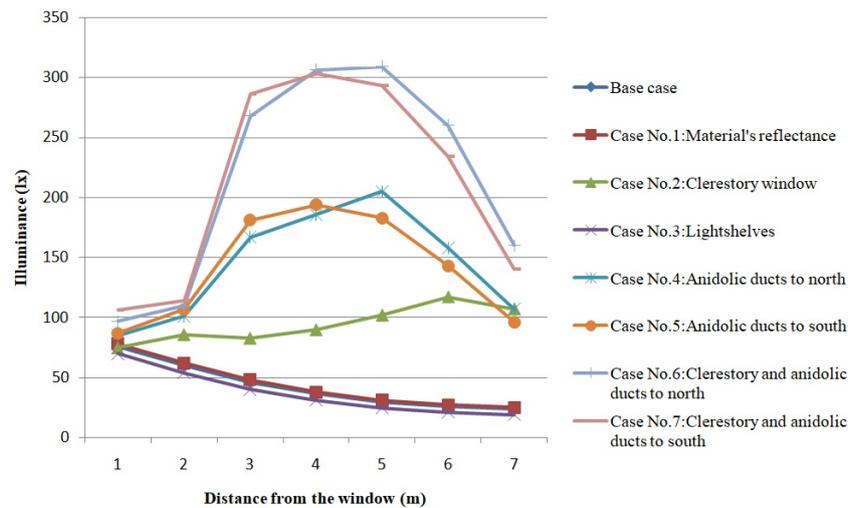


Figure 21. Comparison of average illuminance levels on the desks plane on 21<sup>st</sup> of December at 9:00 am.

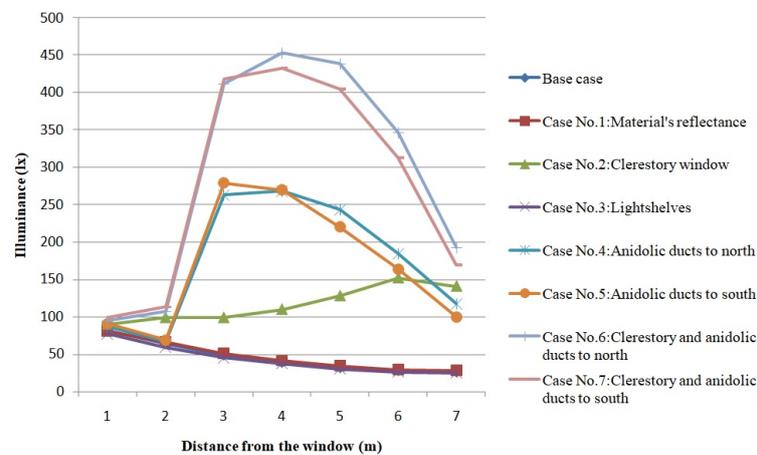


Figure 22. Comparison of average illuminance levels on the desks plane on 21<sup>st</sup> of December at 12:00 pm.

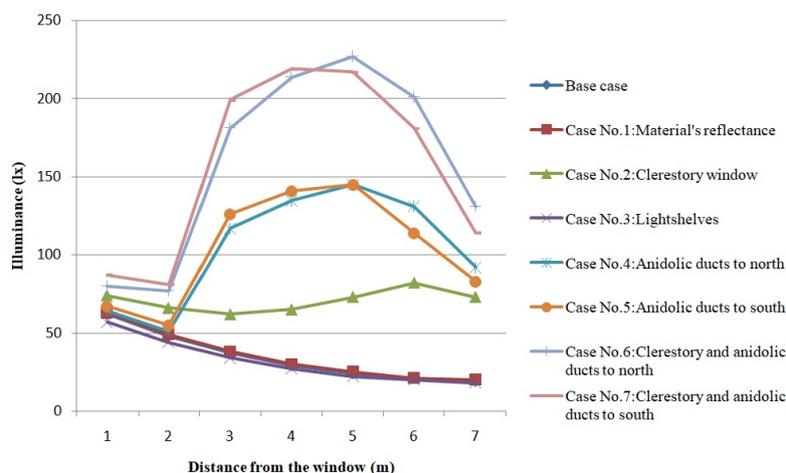


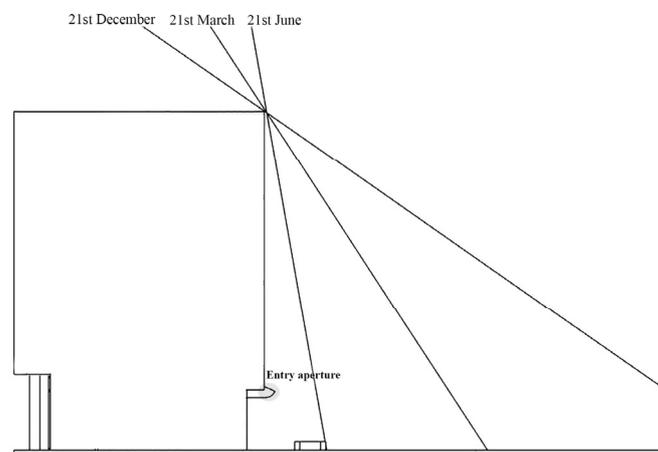
Figure 23. Comparison of average illuminance levels on the desks plane on 21<sup>st</sup> of December at 3:00 pm.

Case No.4, Case No.5, Case No.6, and Case No.7 introduced higher illuminance values and different contour lines to the space. The area under the exit apertures formed the origin of the contour lines with the highest illuminance levels. In all months, this area had double the illuminance than that at the perimeter area of the classroom. This is consistent with what was found with a study conducted

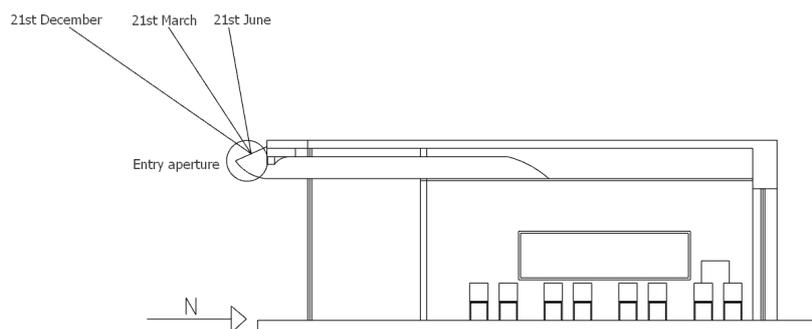
at the same climatic conditions. The study found that anidolic ducts can provide about four times the illuminance to the area under the ducts, and about one and a half times the illuminance to the surrounding areas [40].

The cases that included anidolic ducts directed toward south showed better results than those having anidolic ducts directed toward north. A study that aimed to improve the lighting conditions by using anidolic ducts in side-lit classrooms found that south-directed anidolic ducts give their best performance in summer and equinox times due to high sun elevation angles, while they fail to introduce a great improvement on illuminance in winter because of lower sun angles. It also found that only the small area under the exit apertures witnessed a great improvement [41].

In this study, the best results of Case No.4 and Case No.5 were seen on 21<sup>st</sup> of June at noon. This was due to the solar altitude in relation to the entry apertures of the anidolic ducts, as illustrated in Figures 24 and 25. In June, more sunrays can go through the anidolic ducts. At noon, the sun is nearly perpendicular to the entry aperture. Case No.6 and Case No.7 also give their best results on 21<sup>st</sup> of June at noon.



**Figure 24.** Solar altitudes of 21<sup>st</sup> of March, June, and December in relation to the entry aperture of the northern anidolic ducts.



**Figure 25.** Solar altitudes of 21<sup>st</sup> of March, June, and December in relation to the entry aperture of the southern anidolic ducts.

In general, the cases that have anidolic ducts exceeded the targeted illuminance value of 300 lx at the area under the exit apertures in March, June, and September, while they did not meet the targeted illuminance at the peripheral areas of the classroom. In December, the area under the exit apertures reached the targeted illuminance just at noon. Generally, none of the suggested cases nor the base case introduced the target illuminance required in the classroom in December, but applying Case No.7: clerestory and anidolic ducts to south, seems a promising solution, especially if a diffuser is used to provide more uniform and well-distributed illuminance.

In retrofitting situations, where modifications to the building envelope are very limited, the daylighting systems that improve the illuminance levels in the northerly oriented classrooms are the systems that depend on redirecting the sunlight to the deep spaces, such as anidolic ducts. Results of the anidolic ducts oriented toward south did not differ dramatically from those where anidolic ducts oriented toward north. It is all about redirecting the sunrays deeper in the classrooms. Cases including anidolic ducts work efficiently regardless of the performance of the windows or fenestration system. In similar retrofit cases, designers can determine the ducts' number and orientation based on functional, aesthetical, economical, and site limitations related to each case.

### 3.2. Illuminance Level and Distribution on the Vertical Plane

Figure 26 shows the comparison of illuminance levels of the suggested cases and the base case on the vertical plane in all simulated times. According to the figure, the cases that showed better illuminance levels than the base case were the clerestory window (Case No.2), anidolic ducts to north (Case No.4), anidolic ducts to south (Case No.5), the combination of clerestory and anidolic ducts to the north (Case No.7), and the combination of clerestory and anidolic ducts to the south (Case No.6), respectively. Case No.1 did not introduce any improvement, while Case No.3 reduced the illuminance on the vertical plane.

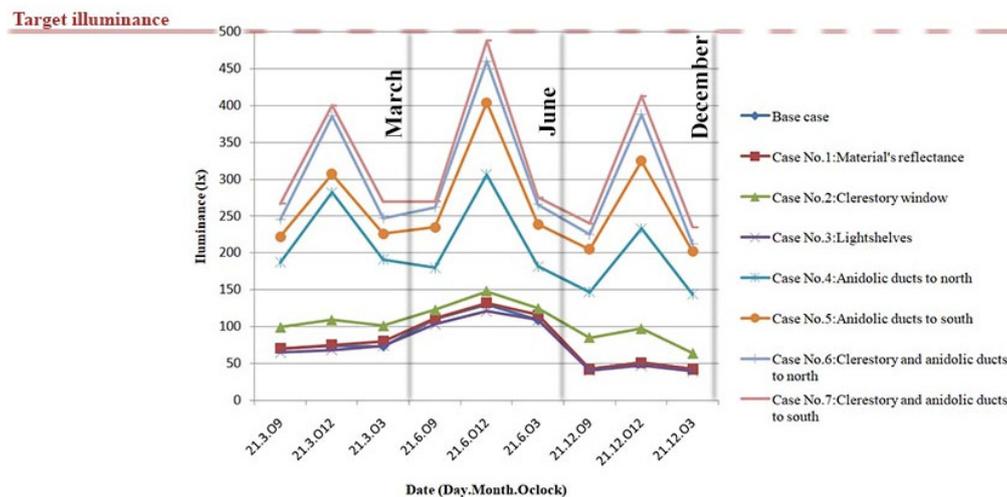


Figure 26. Comparison of illuminance levels of the suggested cases on the board.

In Case No.2, the improvement of illuminance values on the vertical plane was less than on the horizontal plane. The board is hung near the north wall, hence, it was less affected by the daylight coming from the clerestory on the south wall.

The best performance of Case No.4, Case No.5, Case No.6, and Case No.7 on the vertical plane was seen on 21<sup>st</sup> of June at noon. At this time, the solar altitude was nearly perpendicular to the entry apertures of the anidolic ducts (Figures 24 and 25). In Case No.4 and Case No.5, the direct sunlight was transported through the ducts, while in Case No.6 and Case No.7 the clerestory window allowed the passage of the diffuse skylight through the corridor, resulting in higher illuminance values than any other case.

All in all, Case No.2, Case No.4, Case No.5, Case No.6, and Case No.7 introduced better illuminance on the horizontal plane of the classroom, even though they did not achieve uniform illumination all over it. On the vertical plane, although none of the suggested cases introduced the targeted illuminance level, Case No.4, Case No.5, Case No.6, and Case No.7 achieved magnificent improvement. Case No.6 and Case No.7 achieved the best illuminance results on both planes, respectively.

#### 4. Conclusions

This research investigated various retrofit passive daylighting techniques to improve the daylight provision in classrooms. Taking place at JUST/Jordan, the objective of this research was to maximize the amount of daylight entering existing classrooms. Based on the spatial and architectural design of JUST, seven cases were suggested to be evaluated. The techniques were selected to have a minimal modification to the building envelope due to the special construction system used in the building—precast concrete with bearing loads. Computer simulation was the method used to assess the performance of each suggested case.

The suggested daylighting systems and cases were evaluated under clear sky condition, on 21<sup>st</sup> of March, June, September, and December, three times a day: 9:00 am, 12:00 pm, and 3:00 pm. Selecting these times was a way of depicting daylighting conditions with the uttermost sun angles.

Among the suggested cases, the combination of clerestory and anidolic ducts to the north (Case No.6) and the combination of clerestory and anidolic ducts to the south (Case No.7) achieved the best results of illuminance levels on horizontal and vertical planes, respectively. For the tested dates, the base case provided an average illuminance level of 42 lx–105 lx on the desks plane, while LG5 recommended a target of 300 lx. It also recommended a target illuminance of 500 lx on the vertical plane, but the base case provided an average of 45 lx–115 lx. For the same dates, Case No.6 and Case No.7 introduced an average of 300 lx of the targeted illuminance level on the horizontal plane except for 21<sup>st</sup> of December, where it provided an average of 249 lx. Case No.6 provided an average of about 275 lx–330 lx of the targeted illuminance level required on the vertical plane, while Case No.7 provided 295 lx–345 lx.

The daylighting systems that benefit most in retrofitting existing classrooms, especially northerly oriented, and improving illuminance levels are those systems that depend on redirecting the sunlight to the deep spaces such as anidolic ducts. These systems work efficiently regardless of the performance of the windows or fenestration system.

Besides their contribution in enhancing the illuminance levels, if these suggested cases were adopted, the energy consumption needed for reaching the required lighting levels would be reduced, as well as the cooling loads. Moreover, introducing more daylight into the classroom would enhance the pupils' performance as indicated by the previous studies.

Future work should include cost analysis and life cycle assessment (LCA) of the suggested techniques. Also, thermal analysis and energy consumption would give a full picture of the implementation of the systems. Moreover, different cases with different WWR should be compared to examine the effectiveness of each suggested system in the retrofitting procedure.

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