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Article

The Visual and Thermal Impact of Skylight Design on the Interior Space of an Educational Building in a Hot Climate

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Abstract. Skylights have been among the important devices in architecture for providing sufficient daylight in an interior space. The design of a skylight, in terms of shape, orientation, and glazing specification, has a great visual and thermal impact on any internal space, and thus on the choice for its optimum design. This study evaluates the daylight factor, glare, and cooling loads for different skylight designs and compares them with one another to select the best design among them. In addition to the base skylight-free case, twelve cases, categorized into three groups, were analyzed and compared. The groups, named A, B, and C, have sets of fixed parameters that differ from one group to another. The cases in Group A showed a sharp increment in cooling loads, which became significantly higher than the other two groups had, although the lighting levels were not necessarily so. Groups B and C showed varying increments in lighting levels, while the cooling loads were relatively close. Case B-4 was considered the best among the twelve studied cases.

Keywords: Daylight, skylight, Ecotect, Radiance, Evalglare.

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1. Introduction

1.1. Research Background

Throughout architectural history, introducing natural daylight for indoor spaces has been a crucial and essential aspect of buildings, especially when new techniques were developed that enabled architects to insert large, wide-spanning windows. These can be seen in buildings of the Modernist era in the work of Le Corbusier, Richard Neutra, Frank Lloyd Wright, and Mies van der Rohe. Natural light, throughout history, has always been the primary source of light, whereas artificial sources were only supplementary. However, in the late nineteenth century, the economics of structure encouraged the lowering of ceilings that reduced the overall volume of the building to be heated or cooled but also reduced the penetration of daylight. Many building professionals became more dependent on artificial lighting, and most of them tended to overlook the importance of natural light altogether, arguing that daylight was a luxury that could be disregarded since ample light could be supplied economically by fluorescent lighting. However, since then, natural lighting has regained public attention due to the recent movements that encourage green building and passive design [1].

Nowadays, heating, cooling, and lighting are the three main uses of energy in buildings. Fossil fuels are used for generating 84% of the heating and cooling loads, and most of the electricity is used for artificial lighting [2]. 1 kW of power in a site uses approximately 3-4 kW of primary energy in the power plant, while the rest is lost as heat energy during the conversion process [3]. Preliminary studies, however, show that 20-77% of electrical lighting loads can be reduced with the implementation of good daylighting practices [4]. Thus, the importance of introducing daylight indoors, while its impact on heating and cooling loads needs careful consideration, can have a substantial effect on a building, not only in terms of environmental and economic factors but also in its contribution to the wellbeing of the occupants [2]. Natural light offers greater visual comfort than artificial light, as can be seen in a human visual function test [5]. All buildings, in general, need a source of daylight, but in educational buildings, it is highly important. It has been demonstrated that the presence of daylight has a direct link to the performance of the students since human health and mental function are influenced by the intensity and duration of exposure to light throughout the day [6]. The importance of proper lighting in schools is connected to the spectral content of the incident light, which relates to the comfort or stress of the eyes of students; poor spectral light can strain their eyes, impairing their ability to process information and learn and leading to higher stress levels [7]. According to a study conducted by the Heschong Mahone Group, professional consulting services in the field of building energy efficiency, which compares students' learning levels to the presence of daylighting in the classroom, "classrooms with the most amount of daylighting are seen to be associated with a 20% to 26% faster learning rate, as evidenced by increased student test scores over one school year, compared to classrooms with the least amount of daylighting" [8]. The difficulty is that adequate daylight for internal space differs in different climates. In desert climates, the challenge is to increase the daylight factor while minimizing the heat gain due to solar radiation [9]. Solar radiation is the total incident energy, both visible and invisible, from the sun, while daylight is the visible portion of this electromagnetic radiation as perceived by the occupants' eyes [10]. Natural light usually reaches internal spaces in three forms: direct sunlight, direct skylight (diffused light from the sky), and reflected light, either light directly from the sunlight or a skylight, from the ground and nearby surfaces. Controlling the way in which the light enters the space is important to ensure the quality of the light for e users of the building [9]. Many methods can be used to introduce natural light to interior space, but each has limitations. One of these methods is the use of skylights. This is a system that allows natural light to pass through the roof and reach internal spaces; it is used when sufficient daylight cannot be obtained by the use of windows alone because of their size, location, or the complete lack of them in some internal spaces. While skylights are a favorable solution in cold climates where solar radiations through skylights can help to reduce heating loads, cooling loads in hot climates can increase significantly due to solar radiation from the skylight [11]. Thus, the type of glass that is in a skylight can make a big difference when the cooling load is in question [12]. While the glass material plays an important role in the amount of heat gain and light level in the room, these factors also directly depend on the size and position of the daylighting source in the room, for example, the position and orientation of the skylight [13][14].

1.2. UAE and Sharjah Background and Climate Conditions

UAE was founded in 1971 and consists of 7 emirates. Sharjah has the third largest area of all the emirates in the UAE, after Abu Dhabi and Dubai [15]. Sharjah has a desert climate, with high temperatures [16]. In general, the climate in the UAE is considered one of the harshest in the world, with a temperature that can rise as high as approximately 50^{0}C in the summer [17]. In the UAE this lasts from May to October with temperatures ranging from 28^{0}C to 36^{0}C, reaching a maximum of 48^{0}C in July and August. November to April of the following year constitutes the winter season in the UAE with temperatures ranging from 17^{0}C to 27^{0}C [18].

1.3. Case Study Background

One school in Sharjah was taken as a case study for this paper. This is the Victoria International School in Sharjah (VISS). It is an Australian school designed by Taylor Oppenheim architects; a firm specialized in educational facilities. The architectural design of the school adopts sustainable practices and techniques to reduce power consumption and increase the quality of the space for the students. Skylights were used in the school mostly in corridors and internal spaces where no windows could be provided, but a few were also used in classrooms with exterior windows. Since this study aims to investigate the effect of a skylight on the luminous environment of internal classrooms as well as the extra cooling load caused by the presence of the skylight, one classroom located in the north-west of the building without a skylight is considered the Case-0 (Figs. 1 and 2). The field measurement of the illuminance of the class using a light-meter indicates a reading of an average of 150 lux, which is considerably lower than other classrooms, some of which registered up to 600 lux. The present study investigates some of the designs for skylights that could be used to provide sufficient light during the day with minimal need for artificial light while avoiding glare and minimizing the increment in cooling loads due to the introduction of a skylight.

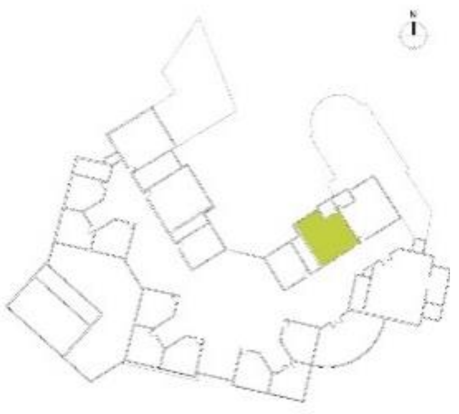


Fig. 1. Case study first floor plan.

Fig. 2. Case study Interior view of the class.

2. Objectives of The Study

The objectives of this study are as follows:

- Set a *base case* modelled on the existing classroom and analyze the natural daylight factor and the cooling loads.
- Add skylights to the investigated classroom and analyze the effects of different skylights with different parameters on the daylight factor, glare, and cooling loads of the space.
- Compare the results and choose the best case among those that were studied.

3. Research Methodology

This study used Ecotect for lighting and thermal analysis and Radiance and Evalglare for lighting render and glare study. Although the use of Ecotect for thermal loads and illuminance level simulations is not recommended, due to its limitations in terms of input setting, using it in the early stage of a design is acceptable when accurate results for the building industry is needed [19], since the basis of any comparative calculations is fixed and the relative accuracy is maintained throughout the study [20]. Thus, using Ecotect in this study is acceptable and serves the purpose of the present paper.

Thirteen cases were studied and analyzed using the above software. These cases were divided into three groups: A, B, and C. The members of each group had one or more common parameters. The groups differed from one another in terms of the shape of the skylight and/or the type of glass used. Group A cases had a 30^{o} skylight (Fig. 4). The shape of the skylights in Group A resembled the shape of the skylights in other spaces in the case study, but the size, orientation, and type of glazing were modified in this study. Group B cases had one or more 90^{o} skylights (Fig. 5) with clear glass, while Group C cases had one or more 90^{o} skylights with translucent glass. Cases within the same group differed from one another in terms of number of skylights, orientation of skylight(s) (Fig. 6), and how many faces of the skylight were glazed. Table 1 indicates the simulation parameters of the 13 cases.

All the simulated cases used the following fixed data:

- Weather data file: Abu Dhabi, UAE
- Design sky illuminance: 11,000 lux
- Visible transmittance (0-1):
  - Clear glass: 0.611
  - Translucent glass: 0.658
- U-Value (W/m2k):
  - Walls: 1.72
  - Floor: 0.88
  - Clear glass: 2.41
  - Translucent glass: 1.40
- Room area: 93.6 m2

The following time setting was used for all of the Radiance and Evalglare simulations:

- Date: 21st – March
- Time: 13:00

Table 1. Parameters of the cases.

Case	Orientation of Skylight	Slope degree	Types of glass	Glazing sides	No. of skylights
Base Case	No skylight	-	-	-	-
Case A-1	North-South	30º	Clear	All sides	1
Case A-2	East-West	30º	Clear	All sides	1
Case A-3	East-West	30º	Translucent	All sides	1
Case A-4	East-West	30º	Clear	Only north-facing side	1
Case B-1	East-West	90º	Clear	All sides	1
Case B-2	East-West	90º	Clear	Only north-facing side	1
Case B-3	East-West	90º	Clear	All sides	2
Case B-4	East-West	90º	Clear	All sides [a]	2
Case B-5	North-South	90º	Clear	All sides	3
Case C-1	East-West	90º	Translucent	All sides	1
Case C-2	East-West	90º	Translucent	All sides	2
Case C-3	North-South	90º	Translucent	All sides	3

[a] South side with horizontal shading

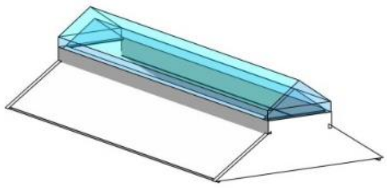


Fig. 3. 30º skylight (used in Cases A-1, A-2, A-3, and A-4).

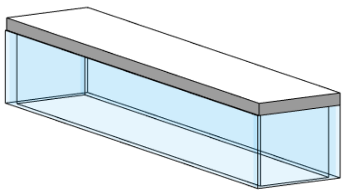


Fig. 4. 90º skylight (used in Cases B-1, B-2, B-3, B-4, B-5, C-1, C-2, and C-3).

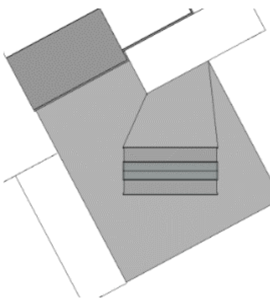


Fig. 5. East-West oriented skylight (used in Cases A-1, B-5, and C-3).

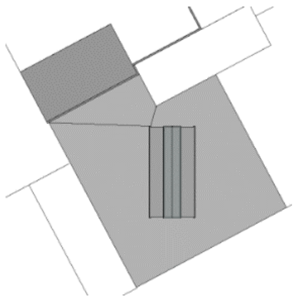


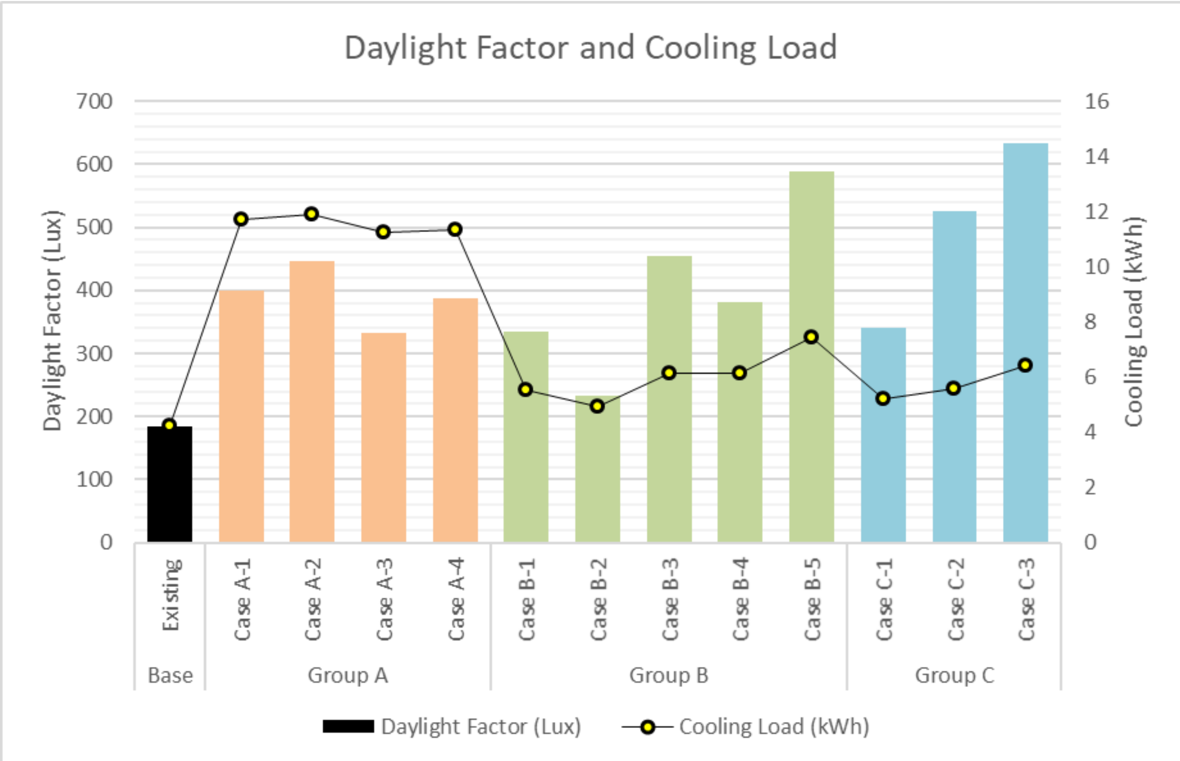
Fig. 6. North-South oriented skylight (used in all cases except, Cases A-1, B-5, and C-3).

4. Simulation Results

Table 2 shows the results of each of the simulated cases in terms of daylight factor and cooling loads. These results are shown in graphic form in Graph 1 where it clarifies the relationship between the cooling loads and the daylight factors. The higher the daylight factor and the lower the cooling load, the better the case is. However, this graph does not show the glare levels in the space and hence cannot yield a sufficiently good result on its own.

Table 2. Cases' results.

		Daylight Factor (Lux)	% of increment compared to Existing	Cooling Load (kWh)	% of increment compared to Existing
Base	Existing	184.0		4.2	
Group A	Case A-1	400.6	117.7 %	11.7	178.0 %
	Case A-2	446.0	142.3 %	11.9	182.1 %
	Case A-3	332.9	80.9 %	11.3	166.9 %
	Case A-4	386.9	110.2 %	11.3	168.6 %
Group B	Case B-1	334.9	82.0 %	5.5	31.2 %
	Case B-2	232.4	26.3 %	4.9	17.1 %
	Case B-3	454.8	147.2 %	6.1	45.7 %
	Case B-4	380.3	106.7 %	6.2	45.9 %
	Case B-5	589.5	220.3 %	7.4	75.8 %
Group C	Case C-1	339.7	84.6 %	5.2	23.8 %
	Case C-2	525.2	185.4 %	5.6	32.7 %
	Case C-3	634.5	244.8 %	6.4	52.0 %



Graph 1. Comparisons between all the studied cases in terms of daylight levels vs. the cooling load.

4.1. Base Case – Existing

It can be observed, by both field measurement and a virtual analytical model, that the natural daylight in the existing case is not satisfactory. The average daylight factor is 1.67%, which is perceptibly low. Illuminance in the center is around 120 lux. The field measurement showed an average of 150 lux at the center, which is quite similar to the calculated value and can be accepted for the purpose of this paper. The cooling load was also simulated using Ecotect for comparison with the modified cases. See Fig. 8.

4.2. Group A - Skylights with 300 Angle

With regard to the daylight factor, all cases in Group-A have a significant increment compared with the base case, which is expected. However, the cooling loads increased steeply reaching almost triple the value of the base case (Graph 1).

Changing the orientation of the skylights from North-East, case A-1 (Fig. 9), to East-West, case A-2 (Fig. 10) had a minimal effect on the cooling load but showed better results in terms of the daylight factor. Replacing the clear glass in case A-2 by translucent glass in A-3 (Fig. 11) reduced the cooling loads by 5%, but it also reduced the lighting level by 25% while retaining a similar glare in the

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space. Compared to case A-2, allowing the light to come through the north side of the skylight only in case A-4 also reduced the cooling load by around 5%, but the reduction in lighting levels was around 13%, compared to 25% in case A-3, and glare in the space was reduced as well (Fig. 12).

Overall, Case A-4 was the best case in terms of creating a balance between cooling load, lighting levels, and glare reduction. However, the large increment in cooling loads made it impossible for the design parameters in Group-A to achieve the intended purpose of this paper, and thus all cases in Group A were rejected.

4.3. Case B - Skylights with 900 Angle with Clear Glass

Changing the degree of skylight glazing inclination from 30^{o} used in Group A to 90^{o} decreased the cooling loads significantly. Case B-1 showed a 31% increment in the cooling load and an 82% increment in the daylight factor beyond the existing case. However, the glare was relieved by only a small amount in this case (Fig. 13). Blocking the south side in Case B-2 reduced glare and slightly reduced the cooling loads but also reduced the daylight factor, making it the lowest in all cases in terms of daylight (Fig. 14). Compared to Case B-1, adding another skylight in Case B-3 increased the daylight factor but also increased the cooling loads and caused significant glare (Fig. 15). Adding horizontal shading on the south side of the skylight in Case B-4 reduced the daylight factor by 16% and maintained the same cooling loads as in case B-3, but it improved the light distribution in the space by avoiding the glare Fig. 16). Changing the orientation of case B-3 to North-South in case B-5 increases the lighting levels considerably, up to 29.6%, making it the case with the highest level of daylight factor while the cooling load increased 20.6%. However, the glare in the space significantly increased (Fig. 17).

4.4. Case C - Skylights with 900 Angle with Translucent Glass

Clear glass was replaced by a translucent panel in Group C in an attempt to protect students from glare. In case C-1, lighting levels increased by 85% compared to the base case, and the cooling load increased by 24 %, but the glare was not avoided (Fig. 18). Adding one more skylight in case C-2 increased the lighting levels, cooling loads, and glare in the space (Fig, 19). In case C-3, the orientation of the skylight was changed, and one more skylight was added, to give a total of three skylights. This change caused a sharp increase in daylight, making it the case with the highest daylight level. However, it let in a great amount of glare (Fig. 20).

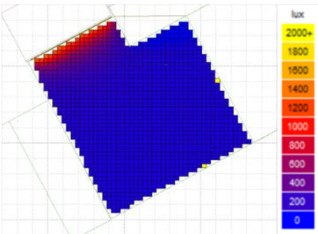

Fig. 8.a. Base Case – plan

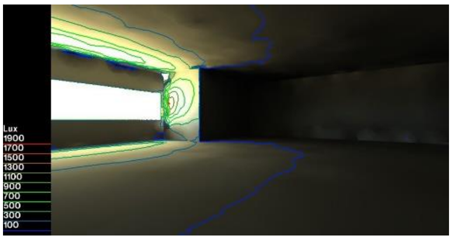

Fig. 8.b. Base case – illuminance

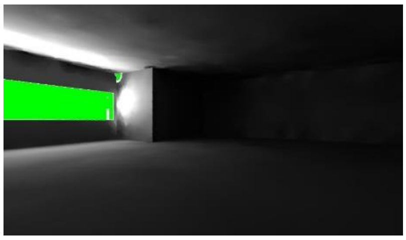
Fig. 8.c. Base case – glare source

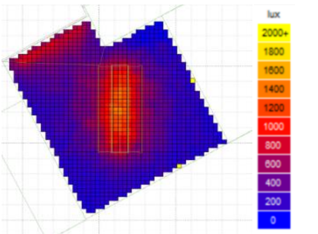

Fig. 9.a. Case A-1 – plan

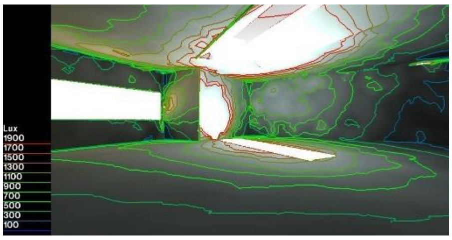

Fig. 9.b. Case A-1 – illuminance

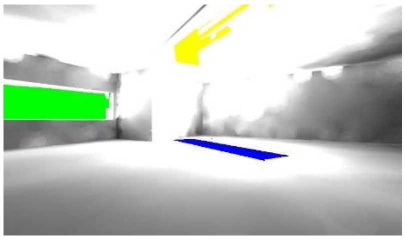
Fig. 9.c. Case A-1 – glare source

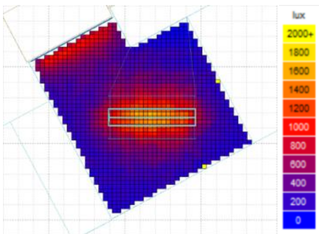

Fig. 10.a. Case A-2 – plan

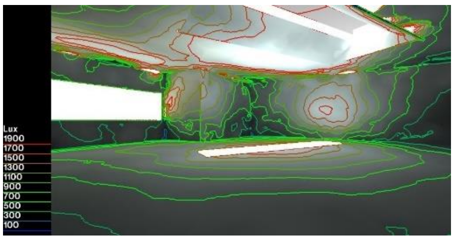

Fig. 10.b. Case A-2 – illuminance


Fig. 10.c. Case A-2 – glare source

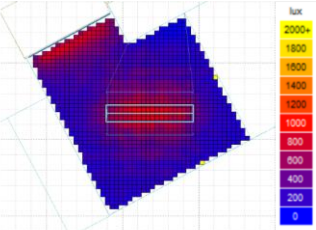

Fig. 11.a. Case A-3 – plan

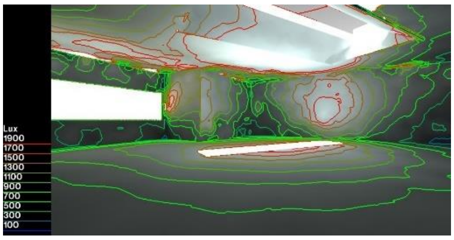

Fig. 11.b. Case A-3 – illuminance

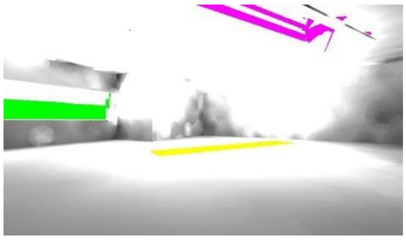
Fig. 11.c. Case A-3 – glare source

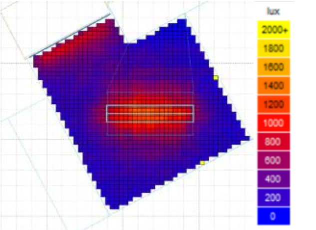

Fig. 12.a. Case A-4 – plan

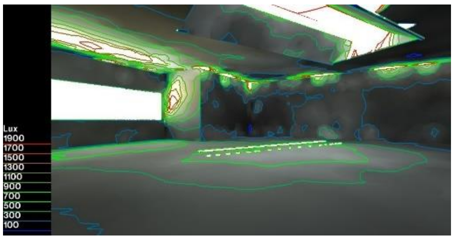

Fig. 12.b. Case A-4 – illuminance

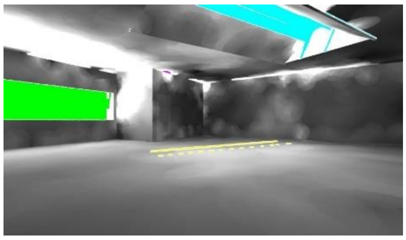
Fig. 12.c. Case A-4 – glare source

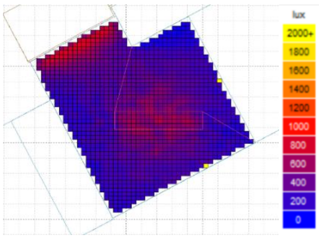

Fig. 13.a. Case B-1 – plan

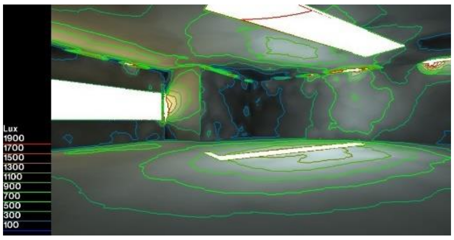

Fig. 13.b. Case B-1 – illuminance

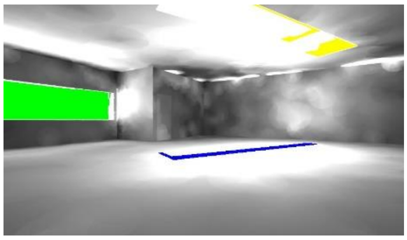
Fig. 13.c. Case B-1 – glare source

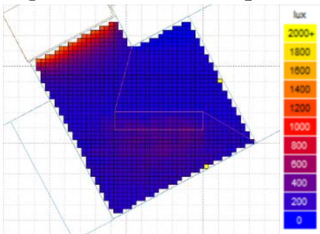

Fig. 14.a. Case B-2 – plan

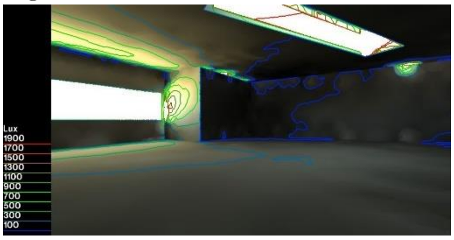

Fig. 14.b. Case B-2 – illuminance

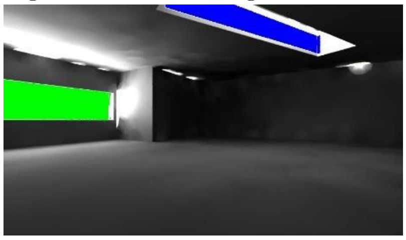
Fig. 14.c. Case B-2 – glare source

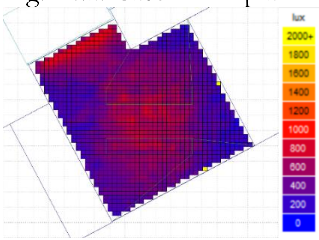

Fig. 15.a. Case B-3 – plan

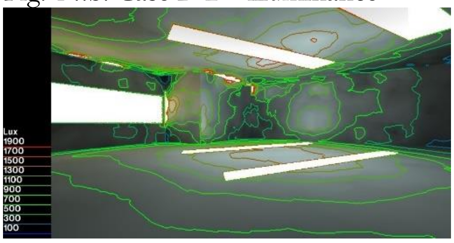

Fig. 15.b. Case B-3 – illuminance

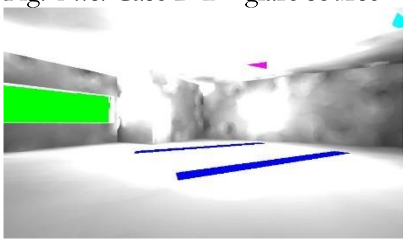
Fig. 15.c. Case B-3 – glare source

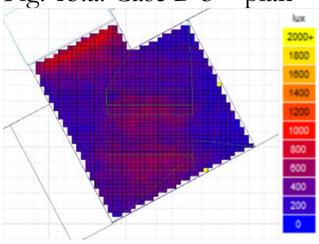

Fig. 16.a. Case B-4 – plan

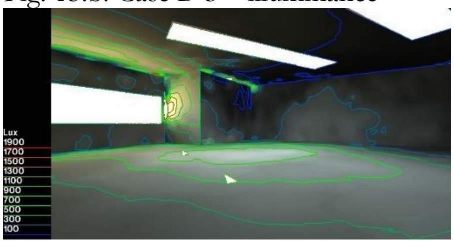

Fig. 16.b. Case B-4 – illuminance


Fig. 16.c. Case B-4 – glare source

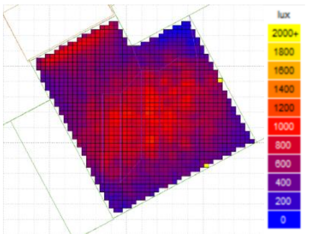

Fig. 17.a. Case B-5 – plan

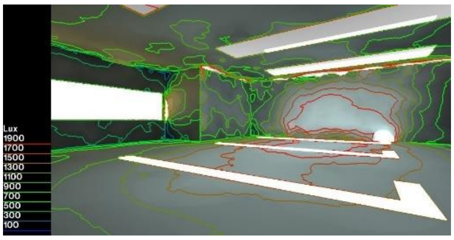

Fig. 17.b. Case B-5 – illuminance

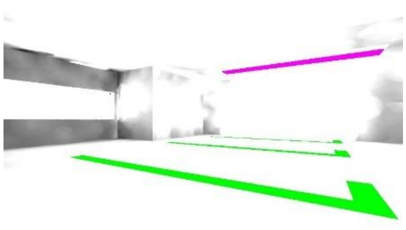
Fig. 17.c. Case B-5 – glare source

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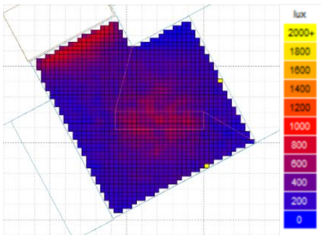


Fig. 18.a. Case C-1 – plan

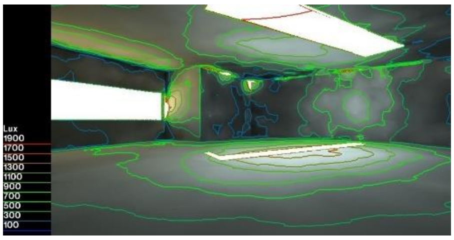


Fig. 18.b. Case C-1 – illuminance

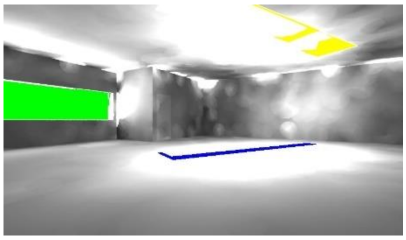


Fig. 18.c. Case C-1 – glare source

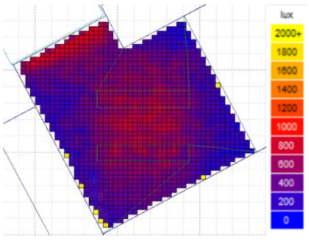


Fig. 19.a. Case C-2 – plan

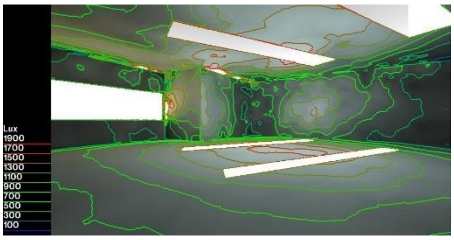


Fig. 19.b. Case C-2 – illuminance

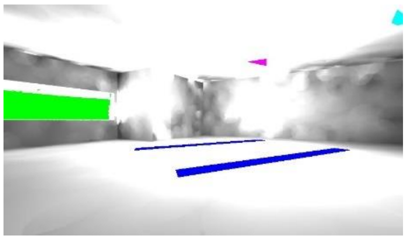


Fig. 19.c. Case C-2 – glare source

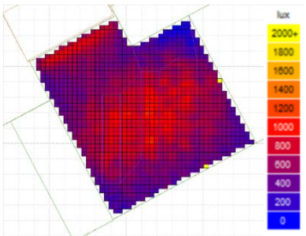


Fig. 20.a. Case C-3 – plan

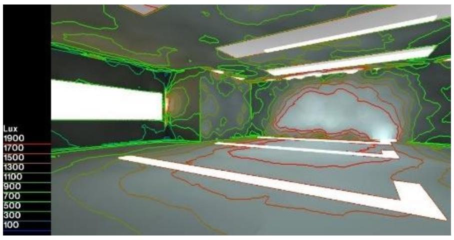


Fig. 20.b. Case C-3 – illuminance

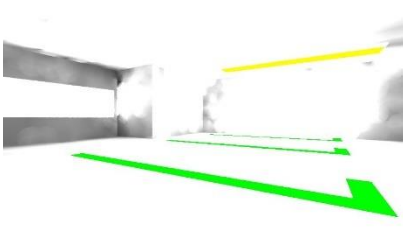


Fig. 20.c. Case C-3 – glare source

5. Analysis and Discussion

To better understand the results, the effect of each parameter should be studied individually to track its effects on lighting levels, cooling loads, and glare.

5.1. Shape of Skylight

Overall, the two shapes of skylight used produced a wide difference in the cooling load. The 90º sloped skylights reduced the cooling load dramatically in comparison to the 30º sloped skylights. This comparison can be seen in Table 3.

5.2. Orientation of Skylight

Changing the orientation of the skylight, as in case A-1 compared with case A-2, showed that an East-West orientation results in better lighting levels while slightly increasing the cooling load. This comparison can be seen in Table 4.

5.3. Glazed Sides of the Skylight

In the case of East-West orientation, allowing the light to pass only through the north side of the skylight decreased the daylighting levels as well as decreasing the cooling loads and the glare. However, the decrease in daylighting levels was more than double the decrease in the cooling load. This comparison can be seen in Table 5.

5.4. Adding Shading

In the case of East-West orientation, adding shading to the south side reduced the lighting levels by 16.4% and also significantly reduced the glare, while the cooling load was improved only by 8.3%. This comparison can be seen in Table 6.

5.5. Type of Glass

Changing the type of glass, as in case B-1 compared with case C-1 and case B-5 compared with case C-3, showed similar daylighting levels. Using translucent material reduced the cooling load but failed to reduce glare in the space. This comparison can be seen in Table 7.

Table 3. Effect of skylight shape.

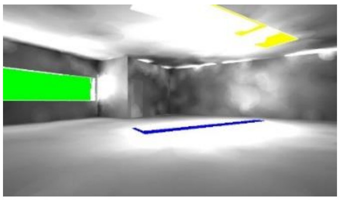
	30° (Case A-2)	**90° (Case B-1)**	**Better case and % difference**
Lighting levels (lux)	446.0	334.9	30° skylight 33.2 %
Cooling load (kWh)	11.9	5.5	90° skylight 53.8%
Glare analysis			90° skylight

Table 4. Effects of changing glass' material.

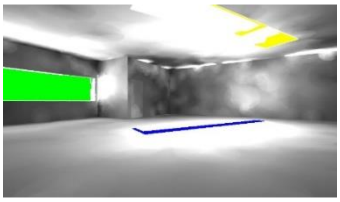
	North-South (Case A-1)	**East-West (Case A-2)**	**Better case % difference**
Lighting levels (lux)	400.6	446.0	East-West 10.2%
Cooling load (kWh)	11.7	11.9	North-South 1.7%
Glare analysis			North-South

Table 5. Effects of reducing the number of glazed sides.

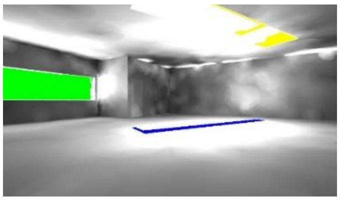
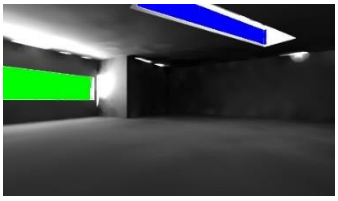
	All sides glazed (Case B-1)	**Northside only (Case B-2)**	**Better case % difference**
Lighting levels (lux)	334.9	232.4	All sides 30.6%
Cooling load (kWh)	5.5	4.9	North side 12.2%
Glare analysis			North-Side

Table 6. Effects of adding horizontal shading for the south side.

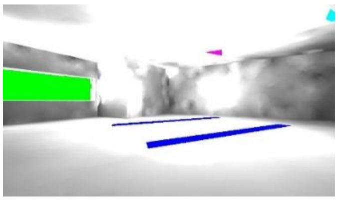
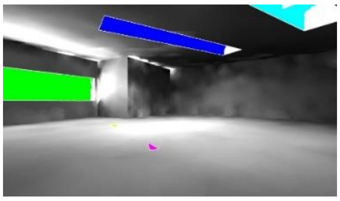
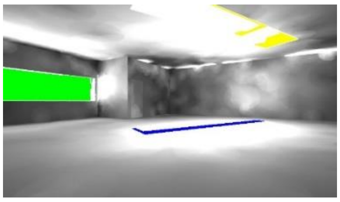
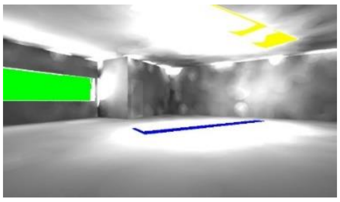
	Without shading (Case B-3)	**Southside shaded (Case B-4)**	**Better case % difference**
Lighting levels (lux)	454.8	380.3	Without 16.4%
Cooling load (kWh)	22.1	20.4	With 8.3%
Glare analysis			With

Table 7. Effects of changing glass' material.

	Clear (Case B-1)	**Translucent (Case C-1)**	**Better case % difference**
Lighting levels (lux)	334.9	339.7	Translucent 1.4%
Cooling load (kWh)	5.5	5.2	Translucent 5.5%
Glare analysis			Similar

6. Conclusions

The following conclusions can be drawn:

- Modifying the geometry of the skylight from a 30^{o} slope to a 90^{o} slope had a dramatic impact on cooling loads without compromising the amount of daylight entering the space. Thus, an optimum case would have a 90^{o} slope.
- The East-West orientation showed much better results than a North-South orientation in terms of daylighting levels, while the effect on the cooling load was negligible. However, it introduced glare. The East-West orientation might be more favorable if other techniques could be used to mitigate the glare.
- Allowing the light to go through the north side only is not favorable because it reduces the daylighting levels much more than it reduces the cooling load.
- Adding horizontal shading for the south side can be used to reduce glare. It yields better results than closing the south side completely.
- Replacing clear glass with translucent panels improved the daylighting factor and the cooling load but still admitted almost similar glare. While these results can be considered a positive effect, the change was almost negligible. Further study would have to be used to achieve better results.
- Among all the examined cases, Case B-4 was found to be the optimum case where all the results were within the accepted range. However, better results should be pursued in the future.

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