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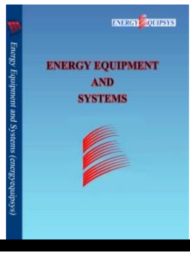

Parametric study of skylight design parameters to improve the indoor visual quality in exhibition areas

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ABSTRACT

Daylight is one of the most influential parameters of visual quality, especially in spaces like art exhibitions. Skylights are proper choices to provide daylight, improve visual comfort, and reduce artificial lighting energy consumption. In this paper, the effect of the main design parameters of skylights on the visual quality is studied using DesignBuilder software. An 81 m² exhibition area is assessed as a test case. The design variables are the skylight form, orientation, location, glazing type, and splay angle. Also, luminance uniformity, spatial daylight autonomy (sDA), and useful daylight illuminance (UDI) are used as evaluation metrics. The north-oriented curved skylight leads to the best visual quality among the studied cases based on the results. Installing the skylight on the north side of the exhibition roof is better to provide the best luminance uniformity. Besides, the results showed that triple Low-E glazing provides the most uniform and the least maximum luminance. However, it may slightly reduce sDA. Finally, although the effect of splay angle on the visual comfort indexes depends on the intended time, 45° to 60° angles work satisfactorily.

Keywords: Daylighting, Skylight, Visual Comfort, Spatial Daylight Autonomy (sDA), Useful Daylight Illuminance (UDI).

1. Introduction

Daylighting has a vital role in the occupants' visual comfort due to providing a complete color spectrum without any blinking, besides its benefits in saving energy consumption. The daylight depends on the geographical location, climate, season, and building specifications, including its form and direction. Many studies regarding the effect of the indoor environment on occupants showed that daylighting considerably improves lighting quality and resultant visual satisfaction [1]. However, without a proper design of windows and skylights, the daylight may lead to difficulties such as excessive heat gain [2] and glare due to high brightness or considerable variation in visual field illuminance [3]. During recent decades, some methods have been proposed to evaluate glare, e.g., Discomfort Glare Index (DGI), Unified Glare Rating (UGR), and Visual Comfort Probability (VCP).

In 2020, Marzouk et al. [4] optimized the skylights of an Egyptian heritage building to maximize indoor thermal and visual comfort and minimize annual energy consumption. They used Grasshopper and Diva software for energy and daylighting modeling, respectively. Besides, the multi-objective genetic algorithm was implemented using the Rhino Octopus plugin. They reported that the optimized strategy could intelligently reduce energy consumption using daylight. In relevant

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research, Huang et el. [5] studied the visual metrics including Daylight Factor (DF), Uniformity Daylight Factor (UDF), and DGI in a museum exhibition space. They concluded that visitors' visual comfort could be enhanced by choosing the proper daylighting strategy. Fazlee and Fadzil [6] investigated the performance of typical top-lit and side-lit skylights in the tropical climate of Malaysia using VELUX software. Based on the results, the side-lit skylight with four-sided glazing without an overhang leads to the most uniform daylight among the studied models. However, it cannot provide enough DF. In 2021, Eiz et al. [7] compared the operation of different skylight designs in terms of DF, DGI, and cooling load by modeling 12 various cases. In recent work, Badawy Ahmed [8] assessed the daylighting potential of dynamic shadings in a university classroom. They tried to find the optimum hourly shading angle using Spatial Daylight Autonomy (sDA), Annual Sun Exposure (ASE), and Useful Daylight Illuminance (UDI) indexes. She combined DesignBuilder, RADIANCE, and DAYSIM software and experimentally evaluated the results. The results validated the effectiveness of the proposed dynamic shading program in enhancing indoor visual quality by 58% and 45% increment of UDI and ASE metrics, respectively.

Previous research works showed that skylights are valuable architectural forms for daylighting in exhibition areas [9]. In this study, the design parameters of skylights in a typical art exhibition space in Iran are numerically assessed in terms of visual quality indexes. The results may be helpful for energy analysts and architects to choose effective forms in the early stages of building design.

2. Material and Methods

In this research, a typical art exhibition area in Tehran is studied using DesignBuilder 6.1 [10], in which EnergyPlus and DAYSIM have been implemented as the energy and lighting modeling engines, respectively. The space's length, width, and height are 9, 9, and 4.5 meters, respectively. The base model is equipped with a north-oriented skylight with 3/3/3 mm triple-layer Low-E glazing with 13 mm air gap, as shown in Fig. 1. Other model specifications are similar to Acosta et al. [11]. A preliminary study showed that DesginBuilder could successfully predict the simulation results of Acosta et al. [11].

Figure 2 shows the general flowchart of the investigation procedure. For the parametric study, the design variables are the skylight form, direction, location, glazing type, and splay angles. Three visual metrics, including Uniformity Ratio (UR), Useful Daylight Illuminance (UDI), and Spatial Daylight

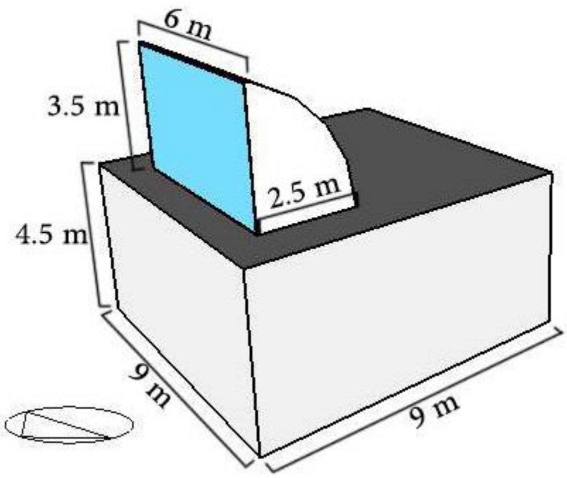


Fig. 1. The schematic of the studied art exhibition

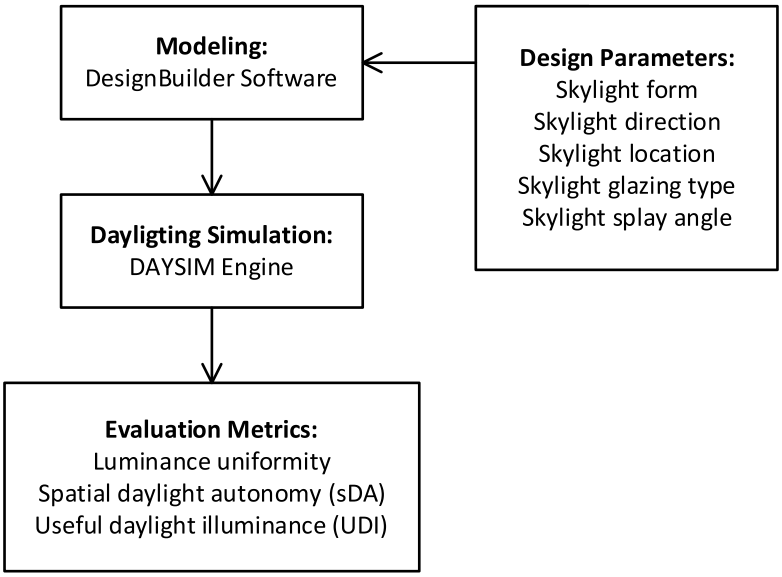


Fig. 2. General flowchart of the investigation procedure

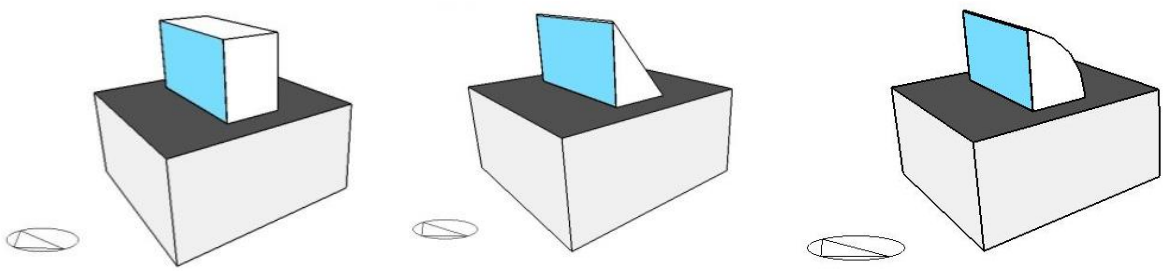
Autonomy (sDA), are used to assess the performance of the skylight. The uniformity ratio is defined as the maximum to minimum luminance ratio in an area at a specific time. Useful daylight illuminance is the annual experience of daylight illuminance distribution within the useful range [10]. Finally, sDA, which is recommended by Illuminating Engineering Society of North America (IESNA), is the percentage of the area that receives a minimum of 300 lux daylight illuminance at more than 50% of the occupied times [12]. Based on these explanations, it is obvious that UR is an instantaneous parameter while UDI and sDA are annual ones. In this study, the uniformity ratio is evaluated in January, March, and June at 8 a.m., noon, and 6 p.m.

3. Results and Discussion

3.1. Skylight Form

As presented in Fig. 3, three types of skylight forms, including rectangular, triangular, and curved ones, are studied to evaluate their effect on visual quality.

Table 1 shows the minimum and maximum illuminance and the uniformity ratio in January, March, and June at 8 a.m., noon, and 6 p.m. for different skylight forms. Based on the results, in most cases, the curved form leads to higher minimum luminance than the others, mainly due to its lower refraction of the sunlight. However, as shown in the table, the rectangular form provides the maximum luminance level.



(a) rectangular **(b)** triangular **(c)** curved

Fig. 3. Three forms of skylight assessed in this study

It should be noted that these parameters are not directly related to the indoor visual quality as their values are not compared with the comfort level. As a result, only the daylight uniformity can be judged based on these data, which shows that the curved form has the most uniformity ratio in all cases.

As discussed previously, sDA and UDI are metrics that take the luminance comfort level into account. The results showed that the skylight form has no considerable impact on UDI. However, as shown in Fig. 4, the curved skylight leads to the best sDA, although its performance is only slightly better than the triangular one. The curved skylight can be suggested among the investigated models based on the abovementioned discussions.

Table 1. The effect of the skylight forms on the daylight luminance

Form	Month	Time	Max. Luminance (lux)	Min. Luminance (lux)	Uniformity Ratio (-)
Rectangular	January	8 a.m.	111	24	0.21
		Noon	174	36	0.20
		4 p.m.	112	22	0.19
	March	8 a.m.	194	36	0.18
		Noon	211	35	0.16
		4 p.m.	193	38	0.19
	June	8 a.m.	56	332	0.17
		Noon	53	392	0.13
		4 p.m.	50	342	0.14
Triangular	January	8 a.m.	135	28	0.20
		Noon	205	44	0.21
		4 p.m.	135	28	0.20
	March	8 a.m.	222	43	0.19
		Noon	251	49	0.19
		4 p.m.	232	44	0.18
	June	8 a.m.	388	63	0.16
		Noon	466	62	0.13
		4 p.m.	385	63	0.16
Curved	January	8 a.m.	129	29	0.22
		Noon	205	44	0.21
		4 p.m.	128	28	0.22
	March	8 a.m.	214	44	0.20
		Noon	245	45	0.18
		4 p.m.	214	46	0.21
	June	8 a.m.	381	67	0.17
		Noon	442	64	0.14
		4 p.m.	381	67	0.17

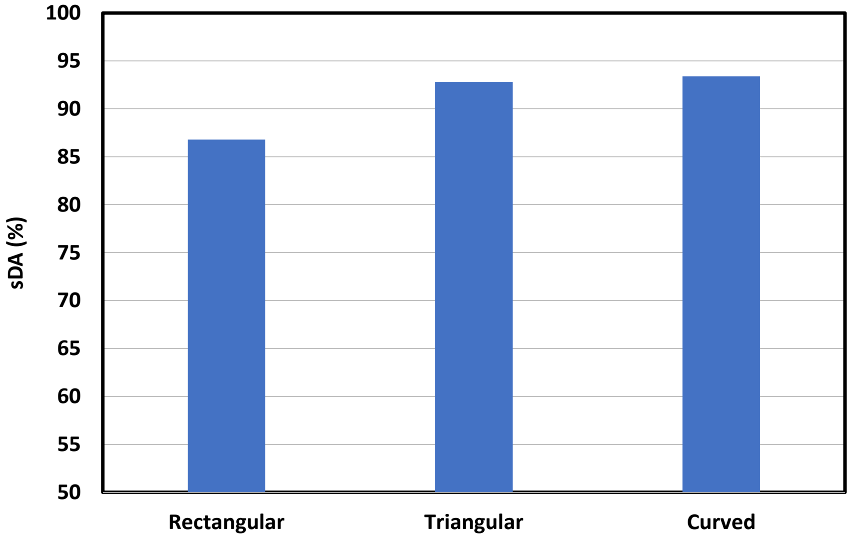


Fig. 4. The effect of the skylight form on sDA

3.2. Skylight Direction

The direction of the skylight is a critical factor in protecting the exhibition area from direct sunlight. Based on the results summarized in Table 2, the east-oriented skylight provides the most uniform daylight illuminance in the cold season morning and the hot season evening. On the contrary, the west-oriented skylight leads to the most uniformity in the hot season morning and the cold season evening. In all cases, the north-oriented skylight has the highest UR in the middle seasons or near noon. As an overall conclusion, it seems that the north-oriented skylight can annually provide the most uniform daylight.

The skylight direction has no significant impact on UDI based on the results. Besides, as depicted in Fig. 5, the south- and north-oriented skylights have the most and the least sDA, respectively, which is predictable due to their potential in providing sunlight. As a result, the selection of the skylight orientation depends on the final objective. If daylight uniformity is essential, usually applied to art exhibitions, the north works better than the other directions. However, directing skylights to the south is the best design to increase the useful annual daylight.

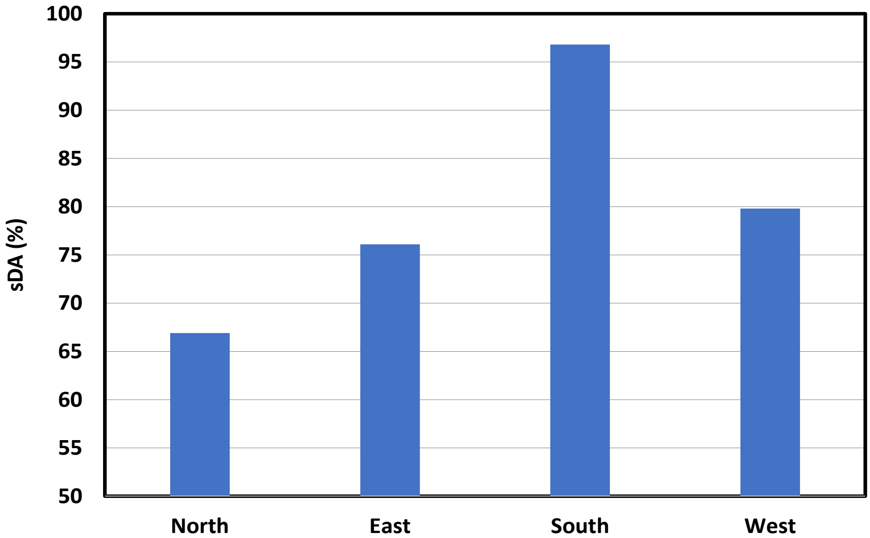


Fig. 5. The effect of the skylight direction on sDA.

Table 2. The effect of the skylight direction on the daylight luminance.

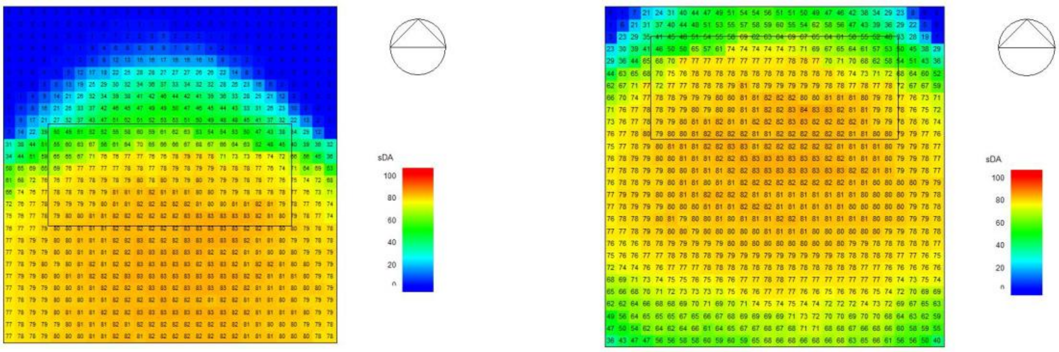
Direction	Month	Time	Max. Luminance (lux)	Min. Luminance (lux)	Uniformity Ratio (-)
North	January	8 a.m.	131	19	0.14
		Noon	196	31	0.16
		4 p.m.	131	18	0.13
	March	8 a.m.	222	28	0.12
		Noon	254	31	0.12
		4 p.m.	222	30	0.13
	June	8 a.m.	405	37	0.09
		Noon	450	40	0.08
		4 p.m.	384	38	0.09
East	January	8 a.m.	291	48	0.16
		Noon	311	34	0.10
		4 p.m.	136	19	0.13
	March	8 a.m.	770	88	0.11
		Noon	434	36	0.08
		4 p.m.	186	26	0.13
	June	8 a.m.	1117	94	0.08
		Noon	598	45	0.07
		4 p.m.	224	28	0.12
South	January	8 a.m.	246	36	0.14
		Noon	896	93	0.10
		4 p.m.	252	36	0.14
	March	8 a.m.	375	39	0.10
		Noon	1120	64	0.05
		4 p.m.	375	41	0.10
	June	8 a.m.	325	33	0.10
		Noon	861	50	0.05
		4 p.m.	336	34	0.10
West	January	8 a.m.	129	17	0.13
		Noon	326	33	0.10
		4 p.m.	284	46	0.16
	March	8 a.m.	184	25	0.13
		Noon	436	35	0.08
		4 p.m.	703	83	0.11
	June	8 a.m.	220	28	0.12
		Noon	620	42	0.06
		4 p.m.	1036	88	0.08

3.3. Skylight Location

Two north-oriented curved skylights are evaluated to study the effect of skylight location on its visual performance. One of the skylights is on the center of the exhibition roof, and the other one locates on its north side. As shown in Table 3, installing the skylight at the north side of the exhibition roof results in better performance at all times due to providing a higher uniformity ratio. Besides, although UDI is similar in both cases, sDA are 61.7 and 90.3 for the central and north-side installation, which agrees with the previous conclusion. The sDA index is shown in Fig. 6 for two skylight locations to clarify this issue, which clearly shows that its location can highly influence the resulting visual quality.

Table 3. The effect of the skylight location on the daylight luminance.

Location	Month	Time	Max. Luminance (lux)	Min. Luminance (lux)	Uniformity Ratio
		8 a.m.	125	18	0.14
	January	Noon	192	28	0.14
		4 p.m.	132	18	0.13
		8 a.m.	212	29	0.13
Center	March	Noon	229	29	0.12
		4 p.m.	208	28	0.13
		8 a.m.	379	38	0.09
	June	Noon	429	40	0.09
		4 p.m.	380	38	0.10
		8 a.m.	125	24	0.19
	January	Noon	187	38	0.20
		4 p.m.	126	24	0.19
		8 a.m.	218	37	0.16
North	March	Noon	242	43	0.17
		4 p.m.	208	38	0.18
		8 a.m.	372	56	0.15
	June	Noon	423	53	0.12
		4 p.m.	356	55	0.15



(a) Central Installation

(b) North-side Installation

Fig. 6. The effect of the skylight location on sDA.

3.4. Skylight Glazing Type

The potential of the exhibition area to use daylight is affected by the material of the skylight glazing. To evaluate the sensitivity of the results, five types of glazing are investigated in a model with north-side north-oriented curved skylight as follows:

- Type 1: 3 mm single-layer clear glazing
- Type 2: 6/6 mm double-layer clear glazing with 6 mm air gap
- Type 3: 3/3 mm double-layer clear glazing with 13 mm air gap
- Type 4: 3/3 mm double-layer Low-E glazing with 13 mm air gap
- Type 5: 3/3/3 mm triple-layer Low-E glazing with 13 mm air gap

To summarize the results, only the daylight luminance at noon of July is presented in Table 4. Also, the resultant sDA is shown in Fig. 7. According to Table 4, the least luminance and the most uniformity ratio is related to type 5 (triple-layer Low-E glazing), providing the best visual quality among the models. On the contrary, type 1 (single layer clear glazing) is the worst case, leading to the most luminance and the least uniformity. However, as illustrated in Fig. 7, triple-layer Low-E glazing may somehow decrease sDA index to prevent the sunlight from entering the occupied space. However, this reduction is only about 5% which is not considerable. It is worthy of mentioning that the glazing type has no significant impact on UDI metric.

Table 4. The effect of glazing type on the daylight luminance at noon in July.

Glazing Type	Max. Luminance (lux)	Min. Luminance (lux)	Uniformity Ratio
Type 1	638	83	0.13
Type 2	514	72	0.14
Type 3	537	75	0.14
Type 4	526	71	0.13
Type 5	442	64	0.14

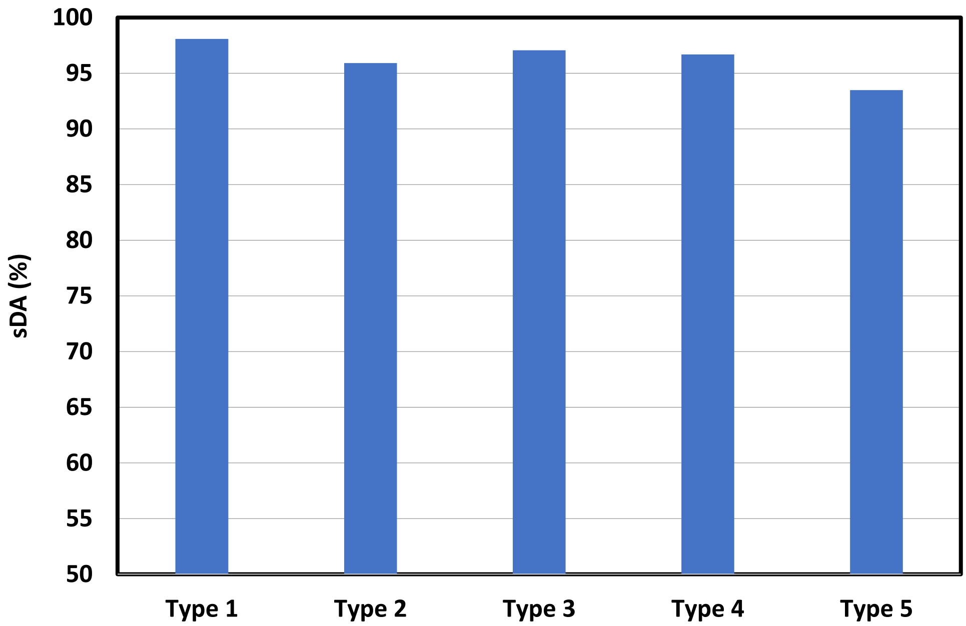
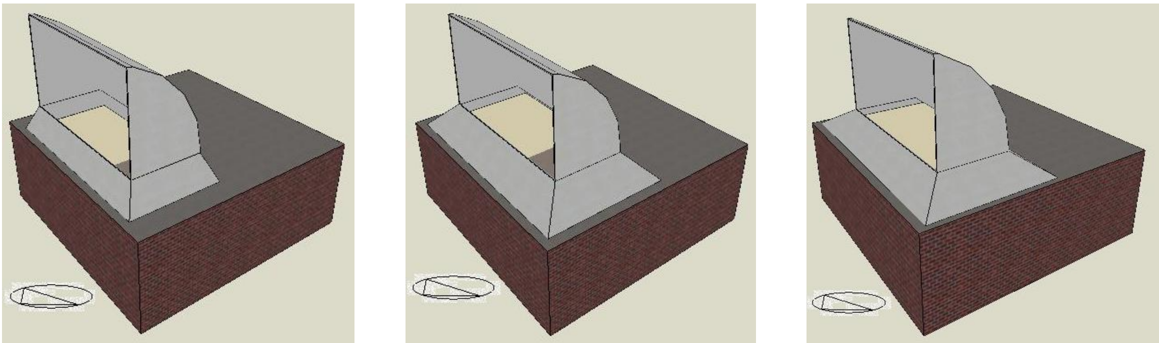


Fig. 7. The effect of glazing type on sDA.

3.5. Skylight Splay Angle

The splay is a part that may be attached to the skylight to increase the light scattering and enhance the resultant visual comfort. In the design of splays, the splay angle is a crucial parameter. As shown in Fig. 8, in this research work, three angles of 30°, 45°, and 60° are investigated. The splay height is 1 m in all cases. As shown in Table 5 and Fig. 9, the 30° splay cannot provide sufficient visual quality regarding the uniformity ratio and sDA. The performance of 45° and 60° splays depends on the season and time. In the cold season, the 60° splay leads to more luminance uniformity at noon, while the 45° splay works better at other times. On the other hand, in the hot season, the splay's behavior is reversed due to different elevations of the sun. As a result, the 45° splay provides better visual quality than 60° one at times other than noon. A general guideline can be concluded by referring to Fig. 9, which depicts sDA metric. So, the 30° splay is the worst case while the 60° one leads to the best visual comfort index among the studied models.



(a) 30° **(b)** 45° **(c)** 60°

Fig. 8. Three splay angles were evaluated in this research.

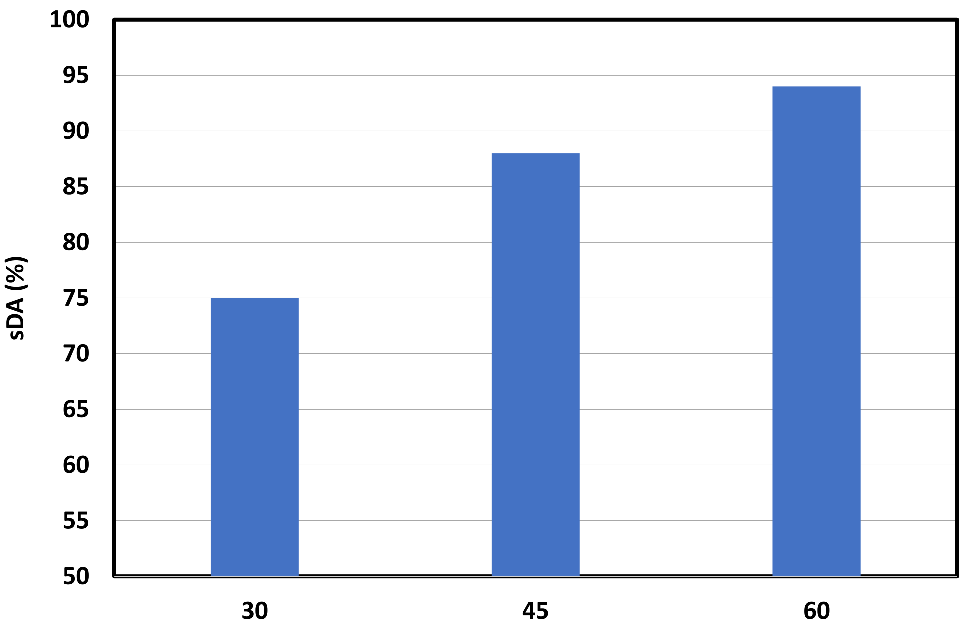


Fig. 9. The effect of the splay angle on sDA.

Table 5. The effect of the splay angle on the daylight luminance.

Splay Angle	Month	Time	Max. Luminance (lux)	Min. Luminance (lux)	Uniformity Ratio
30°	January	8 a.m.	141	5	0.03
		Noon	211	14	0.06
		4 p.m.	134	12	0.09
	March	8 a.m.	231	18	0.07
		Noon	272	11	0.04
		4 p.m.	228	7	0.03
	June	8 a.m.	395	20	0.05
		Noon	480	17	0.03
		4 p.m.	399	11	0.02
45°	January	8 a.m.	132	30	0.22
		Noon	223	49	0.21
		4 p.m.	139	32	0.22
	March	8 a.m.	230	50	0.21
		Noon	259	50	0.19
		4 p.m.	230	50	0.22
	June	8 a.m.	404	64	0.15
		Noon	463	67	0.14
		4 p.m.	382	60	0.15
60°	January	8 a.m.	137	30	0.22
		Noon	219	52	0.28
		4 p.m.	146	29	0.19
	March	8 a.m.	246	47	0.19
		Noon	282	54	0.19
		4 p.m.	241	48	0.19
	June	8 a.m.	425	74	0.17
		Noon	428	67	0.14
		4 p.m.	403	66	0.16

4. Conclusion

In this research work, the effect of the skylight's main design parameters, including its form, orientation, location, glazing type, and splay angle, on visual quality were numerically studied for a specific exhibition area. The visual metrics were the maximum and minimum luminance, the uniformity ratio at different times, sDA and UDI. The results can be summarized as follow:

- The curved skylight leads to the best luminance uniformity and sDA. This form has the lowest deflection of sunlight among investigated models.
- The north-oriented skylight is the best solution in providing luminance uniformity, although it may decrease sDA index.
- Installation of the skylight on the north side of the roof can improve the visual quality, both in the luminance uniformity and sDA points of view.
- The triple Low-E glazing can provide the most uniform and the least maximum luminance. However, using this type of glazing may slightly reduce sDA.
- The effect of the splay angle on the visual quality depends on the use time. Accordingly, 45° or 60° splays are proper choices, while 30° one never works satisfactorily.
- The evaluated parameters have no considerable effect on UDI metric.

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