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Vertical Skylight Pattern Optimization for Public Spaces:

Daylighting and Visual Comfort Analysis for Changing the Shape of Sawtooth Opening in Airport's Holding Room in Cairo

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ABSTRACT

Well daylit public space, which ensures visual comfort, is one of the key design goals that architects and lighting designers seek. The public space such as airport's waiting hall is characterized by large dimensions which can get efficient daylighting levels from a skylight. In Cairo where the sunny and clear sky, improper skylight design can generate extensive heat gain and discomfort glare problems. This paper aims to study the effect of changing the vertical skylight pattern on the uniformity and availability of daylight in the public space of airport holding room. This investigation conducted through changing the shape of north oriented sawtooth opening from one rectangle opening shape to arched opening shape with multi-divisions. Generating the 3d models and analyzing the daylighting performance conducted through a parametric simulation approach. This approach included three software programs which are Grasshopper, Diva for Rhino and Evalglare. Simulations were conducted using the weather data file of Cairo, Egypt. The performance assessment was based on four metrics; IES approved method -Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) -, Daylight Availability (DA) and Daylight Glare Probability (DGP). Results show that the different patterns of sawtooth arched opening in Cairo reached the required daylighting performance and achieved the acceptance criteria of the assessment metrics according to the daylighting requirements of LEED V4.

KEYWORDS

Daylighting- Skylight- Sawtooth- Spatial Daylight Autonomy (sDA) - Annual Sunlight Exposure (ASE) - Daylight Availability (DA) - Daylight Glare Probability (DGP).

1. INTRODUCTION

Providing natural light in public spaces is a crucial design issue for creating a dynamic and pleasant environment while reducing the dependence on artificial light, hence, reducing the energy consumption. In Cairo where clear and sunny sky, uncontrolled daylighting could cause penetration of direct solar radiation and resulting in many problems such as uncomforting visual environment and overheating of spaces.

Vertical skylight such as sawtooth openings are typically used to control daylighting by allowing the penetration of indirect sun beam and redirect its rays and reflect them inside the space [1].

Orienting the sawtooth aperture away from sun direction provides the steadiest level of illumination with a minimum of glare and no solar heat gain [2]. However, many studies reported that using sawtooth systems often results in providing the required natural daylighting uniform levels. Sigrid A. et al. (2013) investigated and discussed the traditional north oriented light roof for several climatic zones by using framework of building energy simulation and optimization [3]. Soliman Y. (2015) studied the effect of sawtooth proportion on daylighting performance in multi-sport hall. The research resulted that the sawtooth height to spacing ratio (H: S) = 1: 5 is the best ratio to provide the even and uniform distributed daylighting levels under sunny clear sky of Cairo [4]. Nessim A. (2017) investigated enhancing daylighting performance in an existing toplit educational space which is a north-east oriented toplit drawing hall, located in the city of Cairo, Egypt [5].

Introducing daylighting through vertical skylight in public space of airport under sunny clear sky of Cairo wasn't given credit in many researches. This paper is a part of research aims at studying the effect of morphing

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skylight to optimize daylighting performance in public spaces under sunny clear sky and the effect of using different shading techniques on enhancing daylighting performance. In this paper sawtooth roof was chosen as a type of vertical skylight to investigate the effect of changing the shape and pattern of sawtooth aperture based on the proportion of sawtooth height to spacing ratio (H: S) = 1:5

2. CASE STUDY

The parameters of base case airport holding room [6] are as shown in (Table 1). The standard holding room should be comfortable, seating and free form aisle spaces include Seating, Gate podium and Emergency gates and wider. [7] (Figure 1). This base case with traditional sawtooth shape achieved the required daylighting levels.

Table 1: The parameters of airport holding room base case.

Space Dimension	
Floor level	Zero level
Over all Area Requirement	30 * 20 m
Clear Height	9 m
Internal surfaces Material	
Internal walls	Generic internal wall 50 %
Ceiling	High reflectance ceiling 90%
Floor	Generic floor 20%
Skylight Parameters for Base Case	
Frame / mullions	Metal diffuse
Glass	Glazing double pane clear 80

Source: The researcher

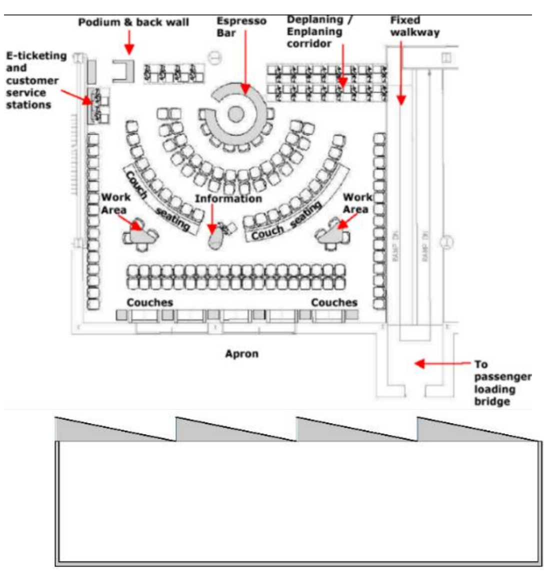


Figure 1: Holding Room plan and section
Source: The researcher

3. METHODOLOGY

3.1 Design Concept

This study will focus on morphing and changing the traditional open shape of sawtooth system to arched opening and changing the number of opening divisions in (x.y) Axis. This step conducted based on the rule of thumb of distributing and spacing sawtooth openings [8] which is the ratio for north oriented sawtooth is (H: S = 1:5) - where H is the sawtooth height and S is the sawtooth spacing- (Figure 2). The different design variables of 12 case studies are (Table 2):

- Number of division in U direction: 1, 2, 3, 4 (4 variables)
- Number of division in Y direction: 4, 6, 8 (3 variables)

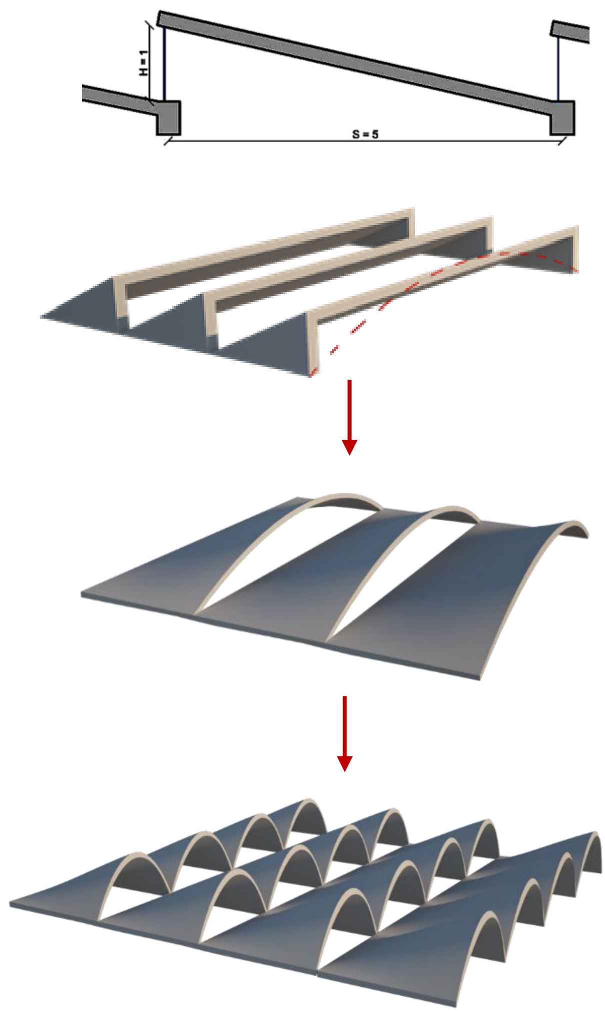
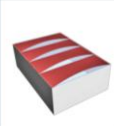
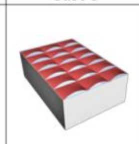
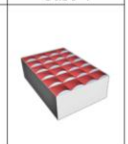
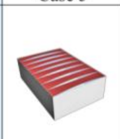
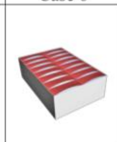
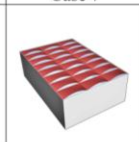
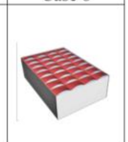


Figure 2: Design concept of converting rectangle-opening shape to arched shape and changing number of divisions
Source: The researcher

Table 2: Vertical skylight division variable case study models

Number of V division Units	Number of U Division Units			
	1	2	3	4
4	 Case 1	 Case 2	 Case 3	 Case 4
6	 Case 5	 Case 6	 Case 7	 Case 8
8	 Case 9	 Case10	 Case 11	 Case 12

Source: The researcher

3.2 Methodology of Results Assessments and Acceptance Criteria

Results assessment is conducted through a sequenced process (Figure 3). The first is to achieve the IES approved method of spatial daylight autonomy (sDA) and annual sunlight exposure (ASE). The second is to achieve the acceptance criteria of daylight availability. At last achieving the acceptance criteria of daylight glare probability (DGP).

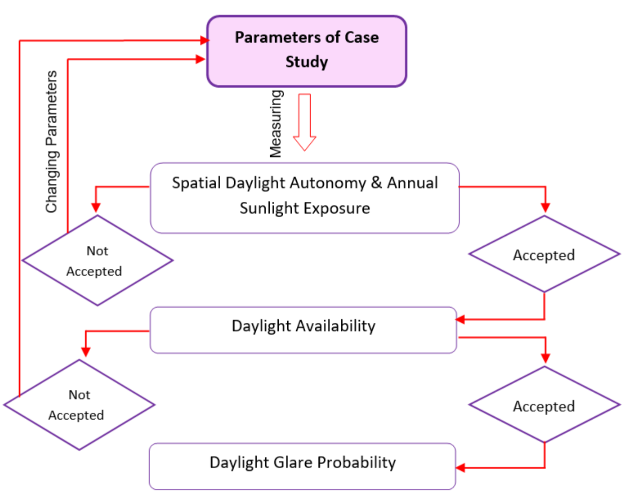


Figure 3: Results evaluation hierarchy
Source: The researcher

The indicator to accept simulation result of daylighting performance was determined according to the daylighting requirements of LEED V4. Which based on IES approved method for daylight metrics [9] and Daylight availability as highlighted in table 3 and 4. The highlighted parts were chosen as performance indicators in this research.

Table 3: : IES acceptance criteria for sDA and ASE

Spatial Daylight Autonomy ($sDA_{300, 50\%}$)	
$sDA_{300,50\%}$ =75%	Favorable
$sDA_{300,50\%}$ = 55%	Nominally
Annual Sunlight Exposure ($ASE_{1000,250h}$):	
$ASE_{1000,250h}$ >10%	Unsatisfactory visual comfort.
$ASE_{1000,250h}$ <7%	Neutral
$ASE_{1000,250h}$ <3%	Acceptable.

Source: The researcher, after The Daylight Metrics Committee, (2012): Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE).

Table 4: Daylight Availability acceptance criteria

Daylight Availability	
Day-lit areas ≥ 50	Accepted

Source: The researcher, after The Daylight Metrics Committee, (2012): Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE).

Also, Glare was evaluated by Evaglare and assisted by Daylight Glare Probability method [10] as represented in table 5.

Table 5: DGP acceptance criteria for sDA.

Daylight Glare Probability (DGP)	
DGP ≥ 45%	intolerable glare
45%> DGP ≥ 40%	disturbing glare
40%> DGP ≥ 35%	perceptible glare
DGP <35%	imperceptible glare

Source: The researcher, after The Daylight Metrics Committee, (2012): Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE).

3.3 Simulation Tools

The analysis was conducted by the following software: Rhinoceros v5.5, Diva-for-Rhino 2.2.0.0 plugin to interface Radiance and Daysim along with Grasshopper plugin for Rhinoceros. Evalglare was used for analyzing Radiance based fish-eye renderings of glare situations using the DGP (Daylight Glare Probability).

3.4 Software Simulation Setup

The process was divided into two main steps (figure 4). The first step is defining and gathering required information for simulation as inputs information. These Inputs are the Daylighting target, Weather data file, Design Variants / 3D models, Working plane and Metrics parameters. While the second step is collecting and analyzing results as outputs information. These out puts are the results of spatial daylight autonomy (sDA), Annual sunlight exposure (ASE), Daylight availability and daylight glare probability (DGP).

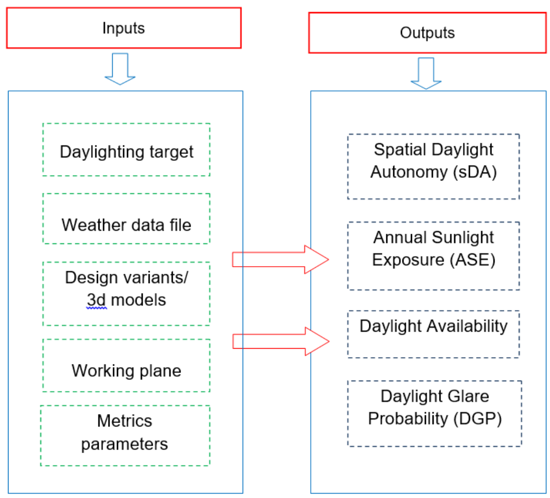


Figure 4: Methodology of Software Simulation Setup
Source: The researcher

3.4.1 Daylighting Target

The recommended minimum illuminance target for airport public spaces is as conditioned in IESNA lighting handbook. The target illuminance for ticket hall and waiting areas is 300 lux [11].

3.4.2 Weather Data File

The base case was chosen to be in the city of Cairo, Egypt (30° N- 31° E), which has a sunny clear-sky and hot arid zone. The used weather data file was chosen: Cairo IWEC weather file [12].

3.4.3 Working Plane

The working plane was chosen at 0.90 m height from the floor. The chosen analysis grid in this research is divided by 0.60 x 0.60 m and resulted in 1568 measuring points.

3.4.4Occupancy Schedule

The occupancy schedule was chosen to be from 8:00 AM till 6:00 PM (the period of occupancy in daylight).

4. ANALYSIS OF DAYLIGHTING PERFORMANCE RESULTS

4.1 Results of Spatial Daylight Autonomy (sDA), Annual Sunlight Exposure (ASE) and Daylight Availability

The twelve case studies achieved acceptance criteria in Cairo for IES approved method; and all the cases achieved the acceptance criteria for daylight availability as shown in table 6. The shaded results are the accepted results and the red highlighted results is the highest achieved results.

Table 6: Cairo Results of 12 cases of indirect skylight divisions

Case no.	U-Div.	V-Div.	GFR	DA	Partia-lly daylit	Overlit	sDA	ASE
1	1	4	13.89%	91.84	2.17	6.12	97.96	0
2	2	4	13.84%	98.34	1.53	0.13	98.47	0
3	3	4	13.79%	98.41	1.47	0.13	98.53	0
4	4	4	13.75%	98.53	1.28	0.19	98.72	0
5	1	6	13.90%	86.86	1.02	12.24	99.11	0
6	2	6	13.87%	98.98	0.83	0.19	99.17	0
7	3	6	13.84%	98.98	0.83	0.19	99.17	0
8	4	6	13.81%	99.11	0.77	0.13	99.23	0
9	1	8	13.90%	86.16	0.88	13.07	99.23	0
10	2	8	13.89%	98.92	0.77	0.32	99.23	0
11	3	8	13.86%	98.92	0.77	0.32	99.23	0
12	4	8	13.84%	99.04	0.77	0.19	99.23	0

Source: The researcher

The results of the 12 cases showed that, the spatial Daylight autonomy (sDA >97 %) and Annual sunlight exposure (ASE = 0 %), while daylit area > 85 % (Figure 5 and 6). The Case no.8 with (U: V Div. = 4:6) has achieved the highest results in sDA and DA (table 7). For that, this case was chosen to study glare phenomena

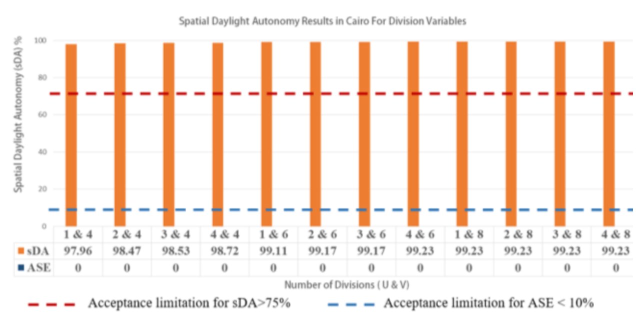


Figure 5: Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) for 12 cases of different division units in Cairo

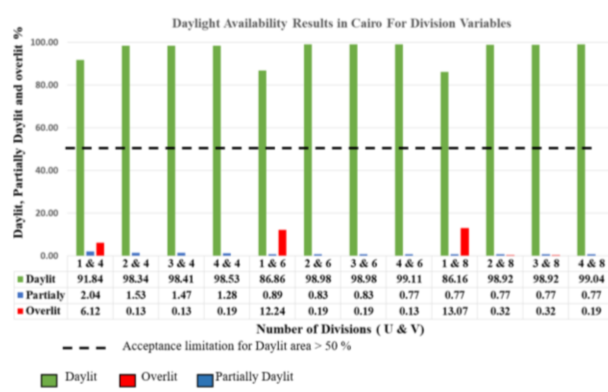
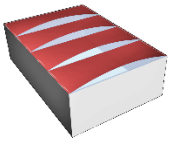
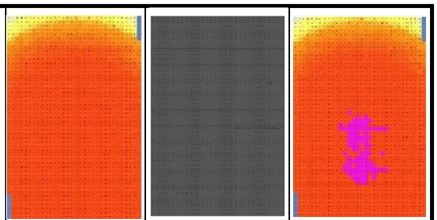
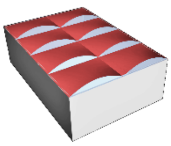
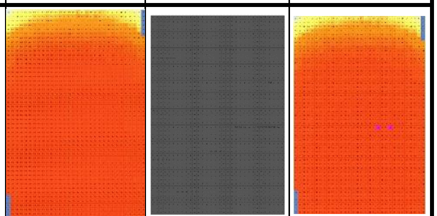
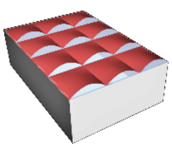
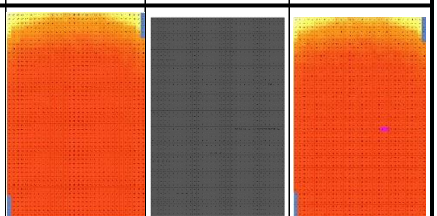
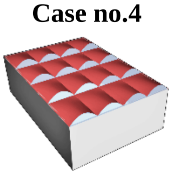
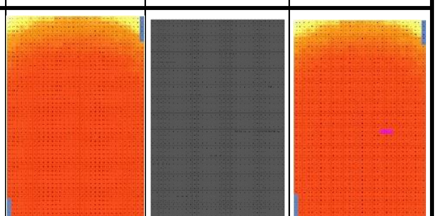
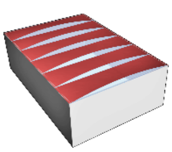
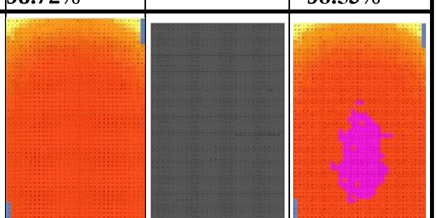
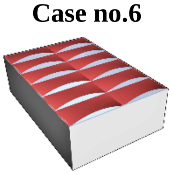
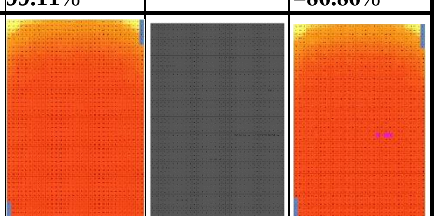
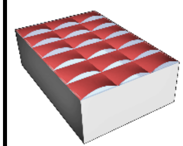
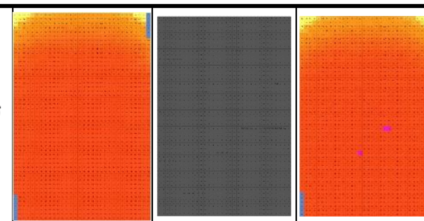
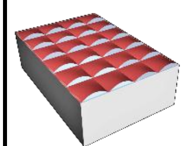
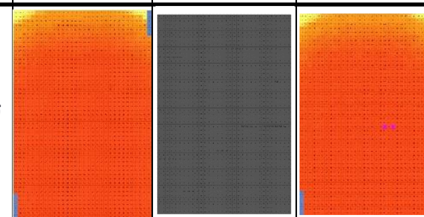
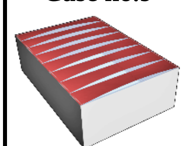
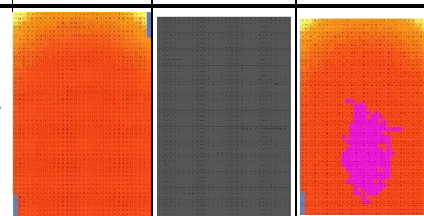
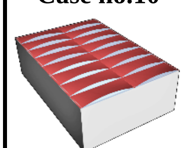
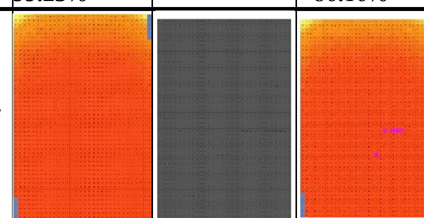
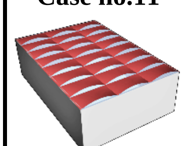
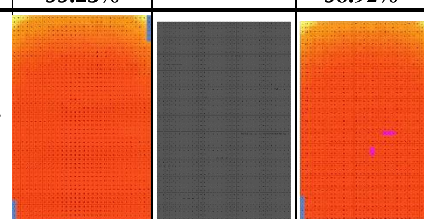
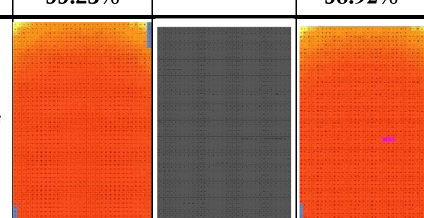


Figure 6: Daylight Availability for 12 cases of different division units in Cairo

Table 7: Daylighting Performance results and color maps for the 12 cases in north orientation in Cairo

Case	sDA	ASE	Day-lit
Case no.1  (U: V Div. = 1:4)	 sDA = **97.96%**	ASE = 0%	Day-lit =**91.84%**
Case no.2  (U: V Div. = 2:4)	 sDA = **98.47%**	ASE = 0%	Day-lit =**98.34%**
Case no.3  (U: V Div. = 3:4)	 sDA = **98.53%**	ASE = 0%	Day-lit =**98.41%**
Case no.4  (U: V Div. = 4:4)	 sDA = **98.72%**	ASE = 0%	Day-lit =**98.53%**
Case no.5  (U: V Div. = 1:6)	 sDA = **99.11%**	ASE = 0%	Day-lit =**86.86%**
Case no.6  (U: V Div. = 2:6)	 sDA = **99.17%**	ASE = 0%	Day-lit =**98.98%**
Case no.7  (U: V Div. = 3:6)	 sDA = **99.17%**	ASE = 0%	Day-lit =**98.98%**
Case no.8  (U: V Div. = 4:6)	 sDA = **99.23%**	ASE = 0%	Day-lit =**99.11%**
Case no.9  (U: V Div. = 1:8)	 sDA = **99.23%**	ASE = 0%	Day-lit =**86.16%**
Case no.10  (U: V Div. = 2:8)	 sDA = **99.23%**	ASE = 0%	Day-lit =**98.92%**
Case no.11  (U: V Div. = 3:8)	 sDA = **99.23%**	ASE = 0%	Day-lit =**98.92%**
Case no.12  (U: V Div. = 4:8)	 sDA = **99.23%**	ASE = 0%	Day-lit =**99.04%**

Source: The researcher

4.1 Results of Daylight Glare Probability (DGP)

The daylight glare probability (DGP) was measured for the highest performance case, which is case no. 8, on 21 December, September and June at 9.00 am, 12.00 pm and 15.00 pm (Table 8, 9 and 10). Results explained as follows:

- On December 21, at 9:00 am the simulation resulted in imperceptible glare DGP= 24%, while at 12:00 noon DGP= 22% and at 15:00 pm DGP=21%
- On September 21, at 9:00 am the simulation resulted in imperceptible glare DGP= 23%, while at 12:00 noon DGP= 24% and at 15:00 pm = 23%
- On June 21, at 9:00 am the simulation resulted in imperceptible glare DGP= 24%, while at 12:00 noon DGP= 30% and at 15:00 pm =26%

Glare was eliminated in this case in north orientation and it achieved DGP acceptance criteria.

Table 8: Daylight Glare Probability Results (DGP) of Case no. 8 with (U: V Div. = 4:6) at 9:00 am, 12:00 noon and 15:00 pm on December 21 in Cairo.

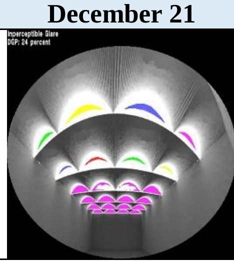
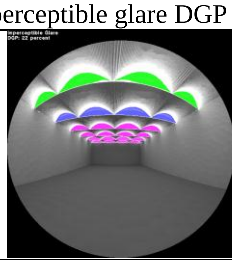
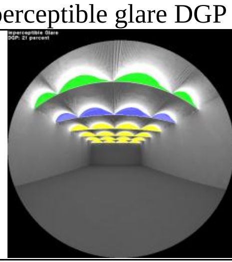
	December 21
9.00 am	 Imperceptible glare DGP 24%
12.00 pm	 Imperceptible glare DGP 22%
15.00 pm	 Imperceptible glare DGP 21%

Table 9: Daylight Glare Probability Results (DGP) of Case no. 8 with (U: V Div. = 4:6) at 9:00 am, 12:00 noon and 15:00 pm on September 21 in Cairo.

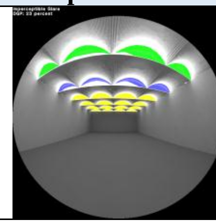
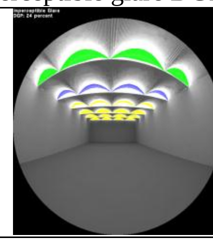
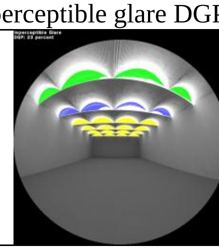
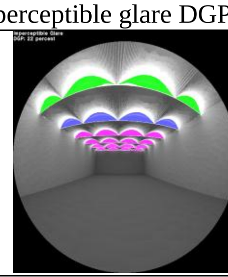
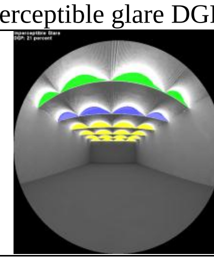
	September 21
9.00 am	 Imperceptible glare DGP 23%
12.00 pm	 Imperceptible glare DGP 24%
15.00 pm	 Imperceptible glare DGP 23%

Table 10: Daylight Glare Probability Results (DGP) of Case no. 8 with (U: V Div. = 4:6) at 9:00 am, 12:00 noon and 15:00 pm on June 21 in Cairo.

	June 21
9.00 am	 Imperceptible glare DGP 24%
12.00 pm	 Imperceptible glare DGP 30%
15.00 pm	 Imperceptible glare DGP 26%

5. CONCLUSION

The paper is a part of research that aims to study the effect of morphing skylight to optimize the daylighting performance in public space of airport holding room. This paper investigated the effect of changing the shape of sawtooth opening from traditional rectangle aperture to arched aperture with multi-units based on the ratio between the sawtooth height and its spacing (H: S) = 1:5 under the sunny clear sky of Cairo.

The analysis of Daylight Availability, Spatial Daylight Autonomy and Annual Sunlight Exposure for twelve cases study models showed that the arched aperture whether it was one single arched aperture or multi apertures in the two directions achieved the daylighting performance by achieving IES criteria and resulted the highest percentage of day-lit areas >86% to 99.11% and the lowest percentage of overlit areas<13% to 0.13% as long as these apertures oriented towards the north direction.

The Daylight Glare Probability (DGP) was investigated on 21 of December, September and June at 9:00 AM, 12:00 PM and 15:00 PM for the case with highest result. It had imperceptible glare in all analysis times and seasons by DGP <30%. The simulation results in north was optimum regardless the traditional or arched shape of sawtooth aperture.

The parametric and simulation approach in this study allows the architects to create different design variants with a well-studied daylighting design to create a delightful environment.

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"تحسين نمط الفتحات العلوية الرأسية في الفراغات العامة: تحليل الإضــاءة الطبيعية والراحة البصرية لتغيير شكـل فتحـات اسنـان المنشار في صالات الانتظـار بالمطارات في المنــاخ الحار لمدينة القاهرة"

الملخص

ان من الأهداف الرئيسية التي يهدف اليها المعماريين ومصممي الإضاءة هو توفير فراغات عامة مضاءة جيدا بالإضاءة الطبيعية. وتمتاز الفراغات العامة مثل قاعات الانتظار بالمطارات بأبعاد كبيرة والتي يمكن إضاءتها من خلال الفتحات العلوية بالأسقف. وقد يسبب تصميم الإضاءة الطبيعية الغير مناسب للفتحات العلوية لعدة مشاكل مثل توليد طاقة مكتسبة مهولة والابهار وعدم الراحة البصرية. تهدف هذه الدراسة الى الوصول لتأثير تغيير شكل الفتحات العلوية الرأسية على توحيد واتاحة الإضاءة الطبيعية في فراغ عام لصالة انتظار بالمطار. تمت هذه الدراسة من خلال تغيير الشكل التقليدي لفتحات علوية لسقف سن منشار موجه شمالا من فتحات مستطيلة الى فتحات مقوسة وبتقسيمات متعددة. تم استخدام منهج المحاكاة البارا مترية للتحكم في نمط الفتحات العلوية الراسية والابعاد المختلفة. واستخدم في نمذجة تلك البدائل برنامج تصميم ثلاثي الأبعاد Grasshopper for rhinoوبرنامج محاكاة وتحليل أداء الإضاءة الطبيعيةDiva for Rhino. and Evalglare وتم تقييم أداء الإضاءة الطبيعية بناءاً على أربعة مقاييس أداء وهي the IES approved : method of Annual sunlight Exposure (ASE) and Spatial Daylight Autonomy (sDA). The daylight availability and Daylight Glare Probability (DGP). وأوضحت النتائج ان تغيير شكل الفتحات لأسقف سن منشار من فتحات مستطيلة تقليدية الى فتحات مقوسة متعددة التقسيمات قد حقق الأداء المطلوب للإضاءة الطبيعية وحقق معايير تقييم الأداء لوحدات القياس الأربعة المستخدمة وفقا لمتطلبات LEED V4 .