BIOMIMETIC FACADES FOR OPTIMIZING DAYLIGHTING PERFORMANCE IN OFFICE BUILDINGS

DOAA AHMED[1], MORAD ABDELKADER[2] and ASHRAF NESSIM[3]

[1]Ph.D. researcher from the Department of Architecture, Faculty of Engineering, Ain shams University, Egypt.
[1]Teaching Assistant of Architecture, October High Institute for Engineering and Technology-Giza, Egypt.
[2]Professor of Architecture, Faculty of Engineering, Ain shams University, Egypt.
[3]Asst. Professor of Architecture, Faculty of Engineering, Ain shams University, Egypt.

Abstract:

Architecture is considered one of the biomimetic fields demanding to learn from nature. Biomimetic helped the designer's on discovering new techniques that could enrich the building performance. This paper explored the relative relationships between Useful Daylight Illuminance (UDI), and daylight glare probability (DGP) with modifications on Voronoi screen variables. It aimed to evaluate the effect of biomimetic sunscreen configuration on achieving a balance between illuminance level and glare inside a selected space. Generic office model had been chosen as a base model-oriented south in Cairo, Egypt. The daylighting and glare simulations were combined by using Grasshopper, Diva, and opossum to the office facade. Finally, the results demonstrated that the proposed biomimetic screen technique provided satisfactory daylighting levels within the office space. The optimization with the genetic algorithm system had proved to be successful and the best four solutions for the Voronoi screens were chosen regarding UDI, with a percentage of 88.7%, 88.6%, 84.78%, 77.72%, respectively. Then the DGP percentage tested for the best four cases regarding the worst five camera positions from 8, and the results showed that case 1 and case 3 tend to represent acceptable performance; where the intolerable glare prevented and decreased values of the Daylight glare probability sensation level to perceptible and imperceptible glare.

Keywords: Biomimicry; Daylighting; Glare; Voronoi; Rhino software; Grasshopper; Diva.

1. Introduction

Daylighting in the work environment is important for improving visual comfort and occupants' health and performance (Chen and Wei, 2013). One of the daylighting problems in working environments is glare. Discomfort glare, the type of glare that caused an irritating impact, is accrued when a high luminance can be seen in the visual field (Boyce and Wilkins, 2018). Glare from daylighting causes variation in luminance and, the luminance is often not uniform and quite high, especially if direct radiation occurs, and frequently covers a large part of the visual field.

Façades are the direct link between the external and the internal environments, its key role is to protect the indoor space from the external aspects and provide indoor comfort. Therefore, most efforts are focused on optimizing facade components through several methods. Many methods need to be developed to meet these challenging requirements. Many studies had shown that the biomimetic facade system can overcome the limitations of existing facades (Radwan and Osama, 2016).

Nature remains the first teacher and main source of inspiration in Architecture. Over the years, human has been on a quest to discover solutions to challenges facing the world. Biomimicry

is among the emerging discoveries which offer a lot of potential for solutions to world environmental requirements (Lodson and Jahromi 2018). Biomimetics as a design process divided into two approaches as shown in figure 1: from design to biology by defining proposal issues and finding a biological or ecological system that solves this problem for identifying a particular behavior (Guild, B., 2007), or from biology toward design by identity a specific behavior, function in an organism Ecosystem and transform it into the design (Mardaljevic, Andersen, Roy, & Christoffersen, 2012).
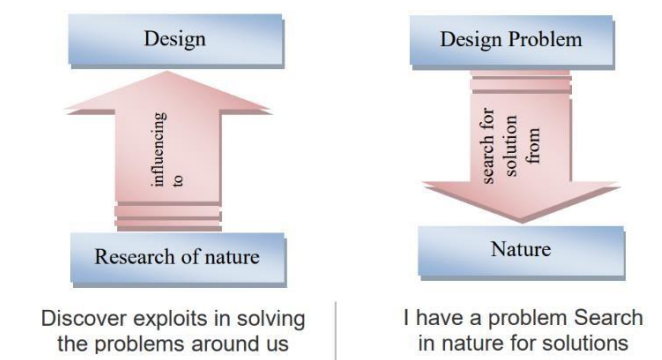
Figure 1: Biomimicry approaches (Shahda et al., 2014)

Many related research papers have investigated façade's parameters for achieving efficient daylighting performance. The following academic research papers concentrated on daylighting and louvers design-based studies in office buildings, optimization studies, and biomimetic screens. These studies had generally centered on getting optimum solutions.

Ahmad and Reffat (2018) conducted a comparative study of various daylighting shadingsfor an office building. This paper focused on increasing louver design alternatives by including different orientations, for selecting the best alternatives. The study found that the utilization of the same daylighting system of the base case in North-East and south-west orientations achieved savings in the energy of 16–24%. González and Fiorito(2015). Designed a daylight louver for office buildings in Australia. The method was done by using simulation and combined tools such as Grasshopper and DIVA plug-in which are used as the main tool. Gutiérrez et al (2019) investigated the design and daylight performance of an adaptive louver screen for office buildings in Madrid. The screen was evaluated in the south, southeast, and southwest. For three different material finishes: specular aluminum and two types of ceramic finishes, the method in this paper was done by using Daylight Factor and Daylight Autonomy and Useful Daylight Illuminance. The study found that the dark silver ceramic louvers performed equal to or better than its aluminum version. The results for the white ceramic louvers reached to 80%in the term of UDI average.

Wortmann (2017) benchmarked several optimization tools in Grasshopper on daylightingand glare in Singapore, such as Opossum which the author is the lead developer. The case study was a room that had a South-facing, proposes a screen with a triangular grid. By generating the parametric geometry and performing the daylighting and glare simulations. Tabadkani et

al (2019) examined the advancement procedure of adaptation solar facade based on tools with a daylight optimization. The aim was to design a hexagonal façade. Then, the parametric approach established in Grasshopper was introduced as tool. Theresult reached a maximum UDI of 90%. Jahanara et al (2017) explored the possibilities pattern inspired by the biomimetic approach as a hexagonal pattern for enhancing daylighting performance. Finally; the biomimetic façade achieved better daylighting performance. Angelucci et al (2018) investigated the applications of Voronoi for highrise buildings with high wind load conditions and areas of high seismicity. This paper proved that the irregular patterns represented a valid alternative to the classical grid. Fantini and Curto (2017) created manufacturability of biomimetic structure and Voronoi forms by generated design. Results demonstrated that this methodology is possible for a plan and assembling nature-based complex structures and could be appropriate to other mechanical items. Limitations of this methodology can be expected to the solid connection between the size of the complex 3D cross-section model and computational weight. Lee and Han (2016) concluded that Computer-aided simulation could deal with data and non-linear algorithms like Delaunay, and Voronoi pattern. Consequently, this research revealed how shading design methods are evaluated by computer- aided simulations. This paper provided a sample conceptual Voronoi façade.

Finally, from the literature review, most previous research had focused on different facade solutions to enhance daylighting performance in office buildings and reduce glare; using optimization tools. By comparing the previous researches results, the biomimetic skins were more effective in the term of daylighting performance.

Most of the researchers that evaluated the Voronoi, they concentrated on its impact on the ventilation, the structure, and earthquake loads, and other space types. But this research concentrated on its effect on daylighting performance in an office space. Thus, this paper studied the uniform daylighting distribution and preventing glare during the working hours, by using the biomimetic facades technique through abstracting the behavior of an organism or ecosystem. Therefore, this research paper aimed to link the Voronoi façade and genetic optimization system for achieving visual comfort.

2.   Methodology

2.1   Base Case

The case study was selected to be a generic model for office space in Cairo, Egypt at (30°6′N, 31°24′E, alt. 75m) as categorized with a clear sky (Hegazy & Shehata, 2017). The model is a side-lit space with natural light located on the third floor-oriented south, thus it hasdirect solar radiation. The parameters are as follows: 5m *6m *3.45m (Width *Length * Height) it is a simple model representing an office cell. The internal surfaces materials and theirreflectance are in table 1. It has 8 fixed desks referred to as workplaces) as shown in figure 2.
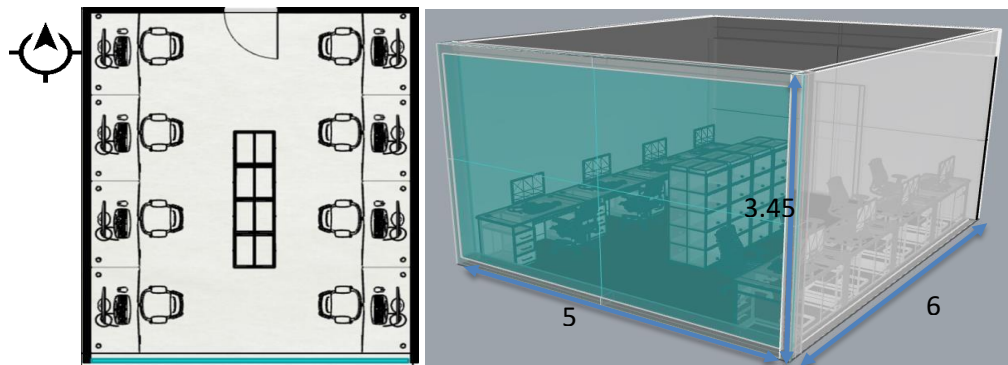
Figure 2: A generic office Space Parameters by the researcher

Table 1: Internal reflectance of materials

Internal Surfaces Materials		
Walls	Reflectance= 50%	White Paint
Ceiling	Reflectance= 80%	Medium Off- White Paint
Floor	Reflectance= 28%	Rubber
Glazing	Reflectance= 88%	Single Pane
Glazing Type	Visible Transmittance VT =89%	
Glazing Thickness	6mm	
Window-to-wall ratio	(WWR)=100%	

For the simulation properties, the height of the workplace grid is 0.75 m with grid spacing of 0.45m as shown in figure 3 and employed scheduled from eight am to five pm. The height of the camera is 1.2m, which is used to simulate the average eye level of the occupants while the sitting posture at the desk (Konstantzos and Tzempelikos, 2015) as shown in figure 4

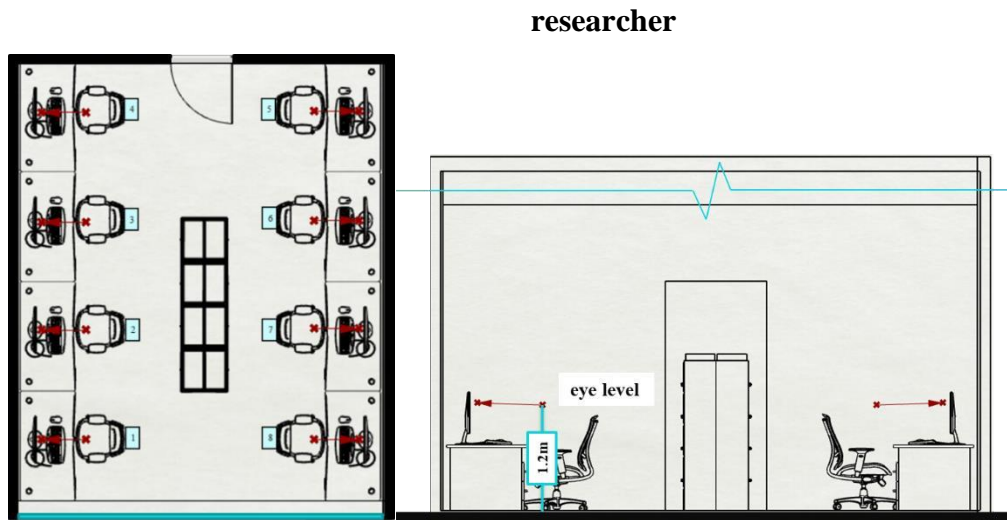**Figure 3: The height of the workplace grid is 0.75 m with grid spacing by the**

researcher

Figure 4: A Generic model shows 8 cameras positions and its height by the researcher

2.2Biomimetic Screen Design

The technique used in this research paper is the second biomimetic approach from biology to design by finding the behavior of an organism or ecosystem and abstracting it in building design. From the literature review, a Voronoi approach was selected to develop facade solutions for a generic office space. Voronoi is defined by mathematical patterns that are predominantly in animal skins and natural phenomena as shown in figure 5. It is known as Voronoi tessellation as shown in figure 6. (Ali,Wang& Alvarado, 2019).

Figure 5: Inspiring Voronoi patterns found in nature.

Figure 6: Schematic drawings of a Voronoi facade design unit. (Ali,Wang& Alvarado, 2019).

The main Voronoi screen that selected was a static module with dimensions of 5m *3.45m (Width * Height) as shown in Figure 7, generated by a series of variables; open percentage (20-30-40-50-60-70-80%) as shown in figure 8, depth (5:15 cm) as shown in Figure 9, the random number of seeds for insertion (20-25-30-35-40), and the number of cells (count) (100-120-140-160) as shown in Figure 10. the screen panels material is made of glass fiber reinforced cement(GRC) with a reflectance of 70%.

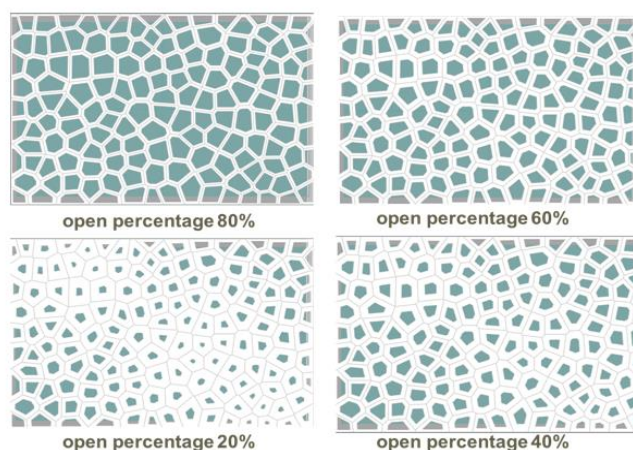**Figure 7: Voronoi pattern screen parameters by the researcher**

Figure 8: Voronoi pattern open percentage from 80% to 20% by the researcher
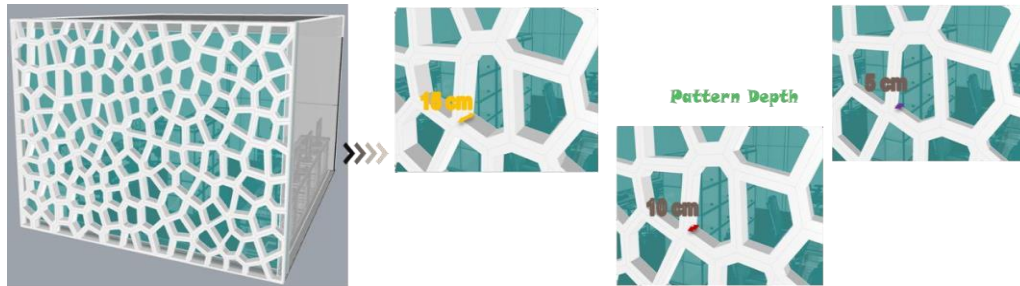
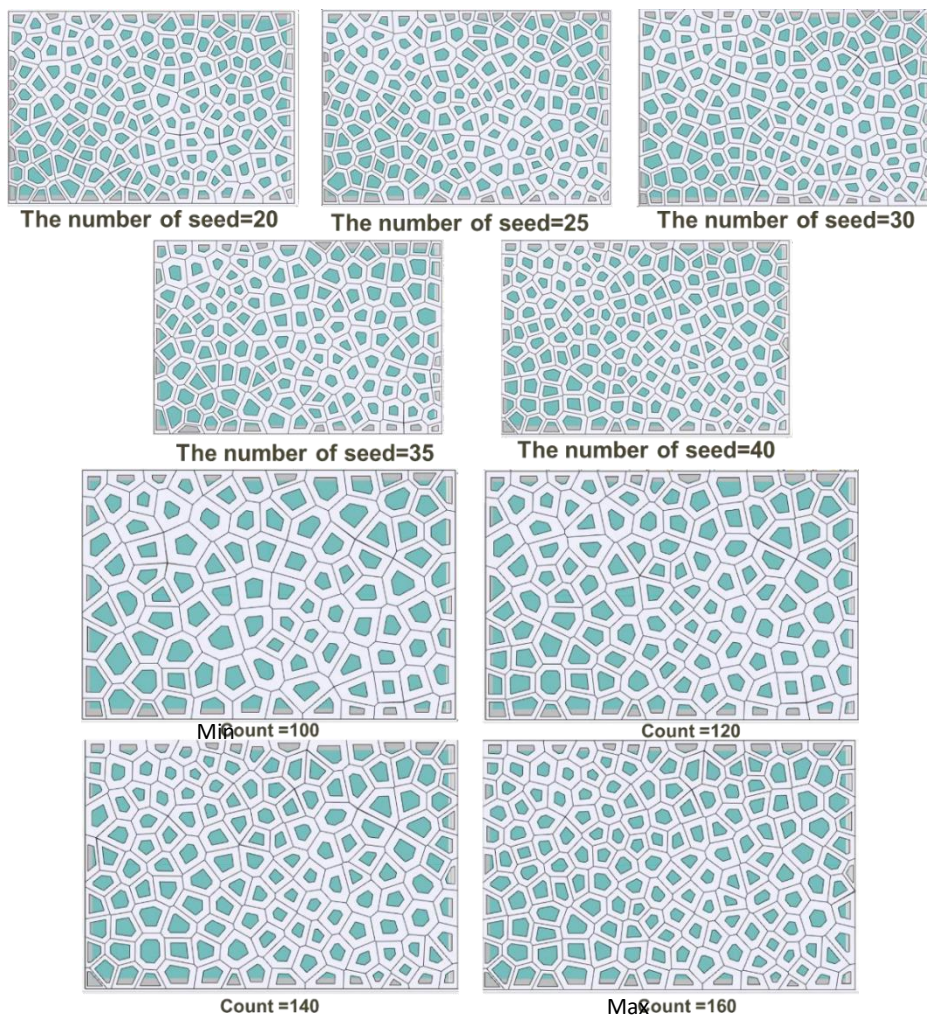**Figure 9: Voronoi pattern depth from 5cm to 15 cm by the researcher**

Figure 10: The random number of seeds for insertion, and the number of Voronoi cells (count) by the researcher

2.3 Simulation Tools

In this paper, the selected tools were "Rhinoceros 7" software, "Grasshopper" and "Diva 4", which are plugins for Rhinoceros software. Then the optimization phase to get the optimum façade solution by "Opossum", developed by "Thomas Wortmann", which is a genetic algorithm tool and TT toolbox plugin which connected the opossum with Excel for ranking the results, as shown in figure11.
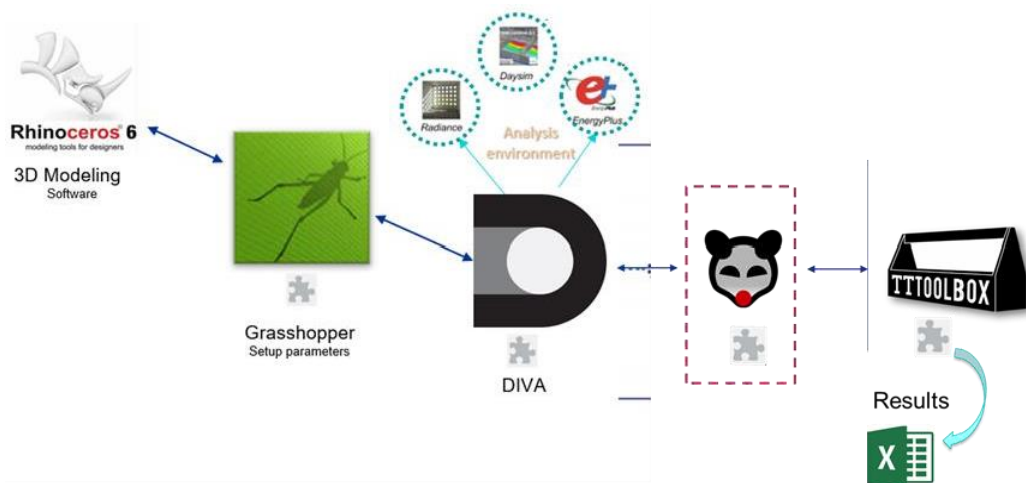

Figure 11: Methodology for the simulation tools by the researcher

2.4   Simulation Process: -

In this paper, the simulation process is divided into two Phases.

The first phase (base case): by finding the simulations for the base case, it was also divided into 2 stages.

Stage one; by finding the value of annual simulations for average Useful Daylight Illuminance (UDI), which is defined as an annual Illumination in the working plane ranging between 100 and 3,000 lux (Mardaljevic et al., 2012).

Stage two; by finding the monthly simulations for DGP in eight camera positions at three hours a day, 11 am, 1 pm, 3 pm, and two different seasons on 21 June, 21 Dec. Then identify which desk had a worse DGP value.

The second phase (Optimization): by applying the Voronoi solar screen patternby using the optimization tool "Opossum".

Stage one; by finding the best value of annual simulations for average UDI for the Voronoi screens, then ranking the best four Voronoi cases for UDI.

Stage two; by testing the best four solutions with DGP simulations in the worse camera positions from phase 1, then selected the best screens from four cases on the UDI, DGP ratio.

2.5   Criteria

This section aimed to identify the daylighting and glare criteria. Thus, from related research's DGP stands for the daylight glare probability as shown in figure 12, the criteria were that if the results less than 40% (perceptible glare) it could be acceptable. The criteria for UDI were that if the results of more than 75% the result could be acceptable.
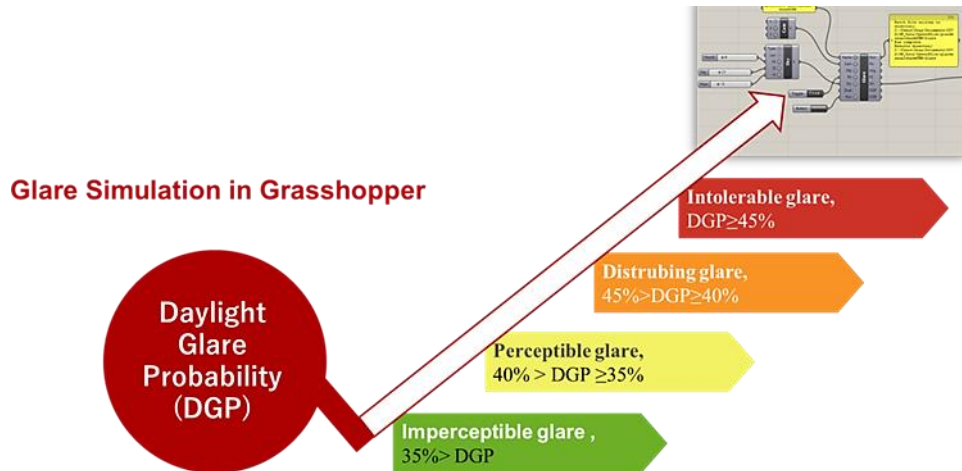

Figure 12: Daylight Glare probability levels

3.   Results and Discussion

3.1   Results of the First Phase

3.1.1 Stage one

This stage showed the results of the annual simulation in different metrics (UDI- Overlit UDI - UnderLit UDI) by using plugin Diva.
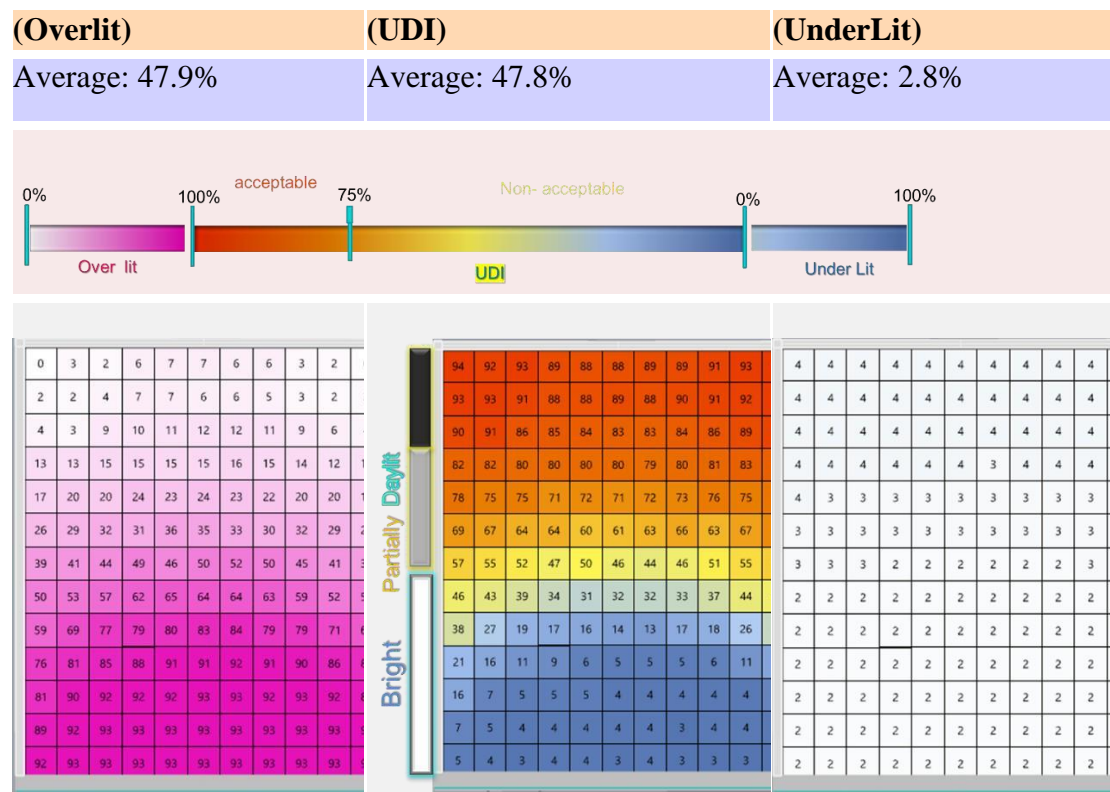
Figure 13: Floor plan showed the average annual UDI distribution for the base case by the researcher

As shown in figure 13 the result for the average UDI of the base case without any façade solutions, was 47.8% which less than the percentage of the Criteria 75%, thus it needed for optimizing. It was achieved an over-lit average: 47.9%, and an underlit of 2.8% in the deepest space. The next stage has shown the results of the monthly DGP simulations in June & December.

3.1.2 Stage two

This stage has shown the results of the monthly DGP simulations for the base case in eight camera positions at three hours a day, 11 am, 1 pm, 3 pm, and two different seasons on 21 June, 21 Dec. The simulations are done by using plugin Diva.
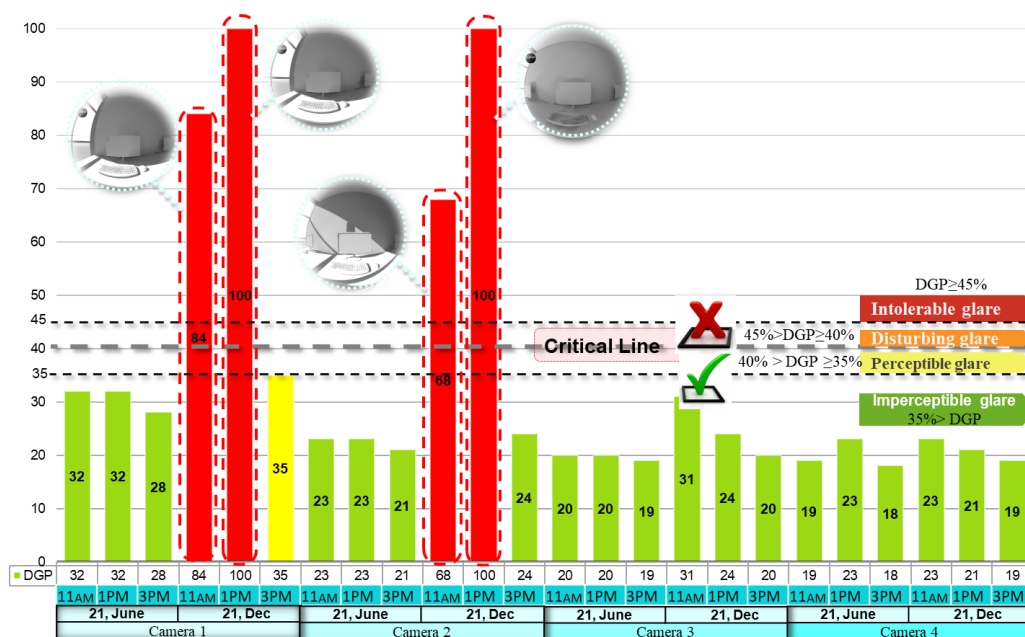
Figure 14: The average of monthly DGP simulations in camera 1, 2, 3 and 4 on June and Dec. by the researcher

The results of DGP in camera 1 on 21 June were demonstrated according to the glare studies, it was imperceptible glare which reached to the acceptable DGP percentage with 32%, 32%and 28% at 11 AM, 1 PM, and 3 PM respectively. On 21 Dec. it demonstrated with an intolerable glare which reached to the non-acceptable DGP percentage with 84%, 100% at 11 AM, 1 PM respectively but it achieved acceptable DGP percentage with 35% at 3 PM.

In camera 2 on 21 June, the glare was imperceptible which reached the acceptable DGP percentage with 23%, 23% and 21% at 11 AM, 1 PM, and 3 PM respectively. On 21 Dec. it demonstrated with an intolerable glare which reached the non-acceptable DGP percentage with 68%, 100% at 11 AM, 1 PM respectively but it achieved acceptable DGP percentage with 24% at 3 PM.

In camera 3 on 21 June, the glare was imperceptible which reached the acceptable DGP percentage with 20%, 20% and 19% at 11 AM, 1 PM, and 3 PM respectively. On 21 Dec. it was imperceptible glare which reached the acceptable DGP percentage with 31%, 24%and 20% at 11 AM, 1 PM, and 3 PM respectively.

In camera 4 on 21 June, the glare was imperceptible which reached the acceptable DGP percentage with 19%, 23% and 18% at 11 AM, 1 PM, and 3 PM respectively. On 21 Dec. it was imperceptible glare which reached the acceptable DGP percentage with 23%, 21% and 19% at 11 AM, 1 PM, and 3 PM respectively. As shown in figure 14. So, it was a glaring problem in camera 1, 2.
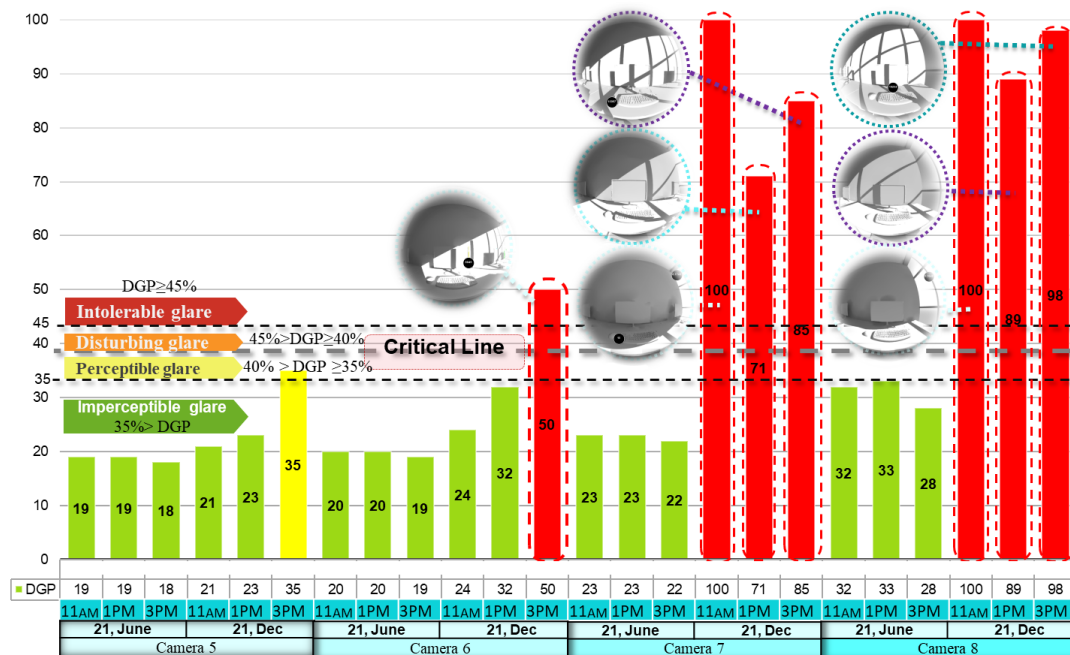
Figure 15: The average of monthly DGP simulations in camera 1, 2, 3 and 4 on June and Dec by the researcher

The results of DGP in camera 5 on 21 June. Demonstrated according to the glare studies, it was imperceptible glare which reached the acceptable DGP percentage with 19%, 19% and 18% at 11 AM, 1 PM, and 3 PM respectively. On 21 Dec. it demonstrated an imperceptible glare which reached the acceptable DGP percentage with 21%, 23% at 11 AM, 1 PM respectively butit achieved a perceptible glare percentage with 35% at 3 PM.

In camera 6 on 21 June, the glare was imperceptible which reached the acceptable DGP percentage with 20%, 20% and 19% at 11 AM, 1 PM, and 3 PM respectively. On 21 Dec. it demonstrated with an imperceptible glare which reached the acceptable DGP percentage with 24%, 32% at 11 AM, 1 PM respectively but it achieved non-acceptable DGP intolerable with 50% at 3 PM.

In camera 7 on 21 June, the glare was imperceptible which reached the acceptable DGP percentage with 23%, 23% and 22% at 11 AM, 1 PM, and 3 PM respectively. On 21 Dec. it demonstrated with an intolerable glare which reached the non-acceptable DGP percentage with 100%, 71% and 85% at 11 AM, 1 PM, and 3 PM respectively.

In camera 8 on 21 June, the glare was imperceptible which reached the acceptable DGP percentage with 32%, 33% and 28% at 11 AM, 1 PM, and 3 PM respectively. On 21 Dec. it demonstrated with an intolerable glare which reached the non-acceptable DGP percentage with 100%, 89% and 98% at 11 AM, 1 PM, and 3 PM respectively, so it appeared a glaring problem in camera 6,7, and 8 as shown in figure 15.

Stage two concluded that the worst results of the DGP from all 8 positions were in five camera

positions (1, 2, 6, 7, and 8) which were located near the window and had a glaring problem only in December. Also, they were exceeding the percentage of the Criteria 40%. The next phase has shown the results of the optimization process.
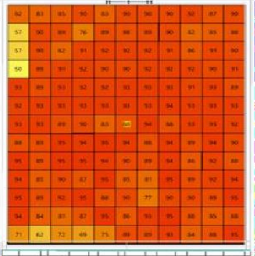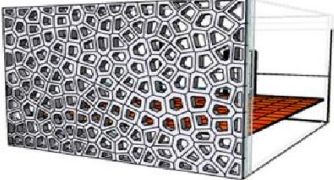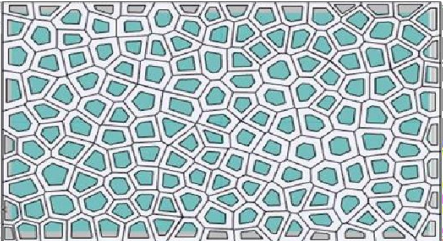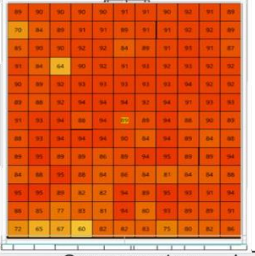
3.2 Results of the Second Phase

3.2.1 Stage one

This stage has shown the results of the annual UDI simulation for the four optimal Voronoi screens cases.

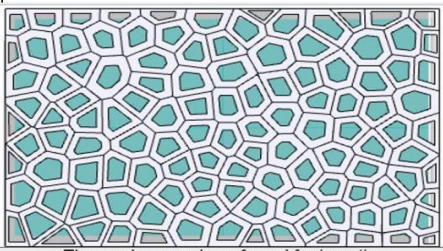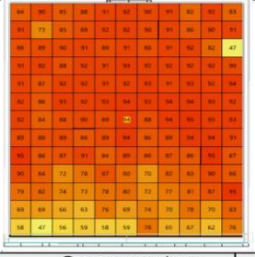**Optimization simulation:-**The results maximized the fitness value of annual UDI by using plugin Opossum. From the simulation, the results of the optimization had proved to be successful compared with the criteria in case 1,2,3, and 4, with a percentage of 88.7%, 88.6%, 84.78%, 77.72%, respectively as shown in table 2.

Table 2: A comparison between the best four Voronoi screen results for annual UDI simulations by the researcher

Open percentage	Depth	Patterns count	The random number of seed for insertion
40%	11cm	160	40

In case one the variables were; opening percentage 50%, depth 15cm, a random number of seeds 30, and a number of cells (count)160. In case two the variables were; opening percentage 50%, depth 15cm, a random number of seeds 35, and a number of cells (count) 120. In case three the variables were; opening percentage 50%, depth 10cm, a random number of seeds 30, and a number of cells (count) 120. In case four the variables were; opening percentage40%, depth 11cm, a random number of seeds 40, and a number of cells (count) 160.

It is noticeable that the results achieved a high percentage of UDI compared to the base case, and in the best 4 cases, the opening percentage was approximately 50%, which resulted in a good view and link between the indoor and the outdoor.

3.2.2 Stage two

The results were tested the best four Voronoi cases with DGP simulations in the worse five camera positions. The results of DGP in camera 1 on 21 Dec. demonstrated according to the glare studies, it was imperceptible glare which reached the acceptable DGP at 11 AM,1 PMfor case 1,2, and 4, but in case 3 at 11 AM was perceptible glare which reached the acceptable DGP too. The results of DGP in camera 2 on 21 Dec. demonstrated an imperceptible glare which reached the acceptable DGP at 11 AM, 1 PM. as shown in figure 16.

Figure 16: Compared the average of monthly DGP simulations in camera 1, 2 on Dec for the best 4 cases and the base case by the researcher

The results of DGP in camera 6 on 21 Dec. demonstrated an imperceptible glare which reached the acceptable DGP at 3 PM. as shown in figure 17.

Figure 17: Compared the average of monthly DGP simulations in camera 6 on Dec for the best 4 cases and the base case by the researcher

The results of DGP in camera 7 on 21 Dec. demonstrated according to the glare studies, incase one it was perceptible glare DGP at 11 AM, it was imperceptible glare 1 PM and 3 PM which reached the acceptable.

In case two it was imperceptible glare 1 PM and 3 PM, but at 11 AM, it was disturbing which reached the non – acceptable percentage.

In case three it was perceptible glare DGP at 11 AM, it was imperceptible glare 1 PM and3 PM which reached the acceptable.

In case four it was imperceptible glare 1 PM and 3 PM, but at 11 AM, it was intolerable which reached the non – acceptable percentage as shown in figure 18.

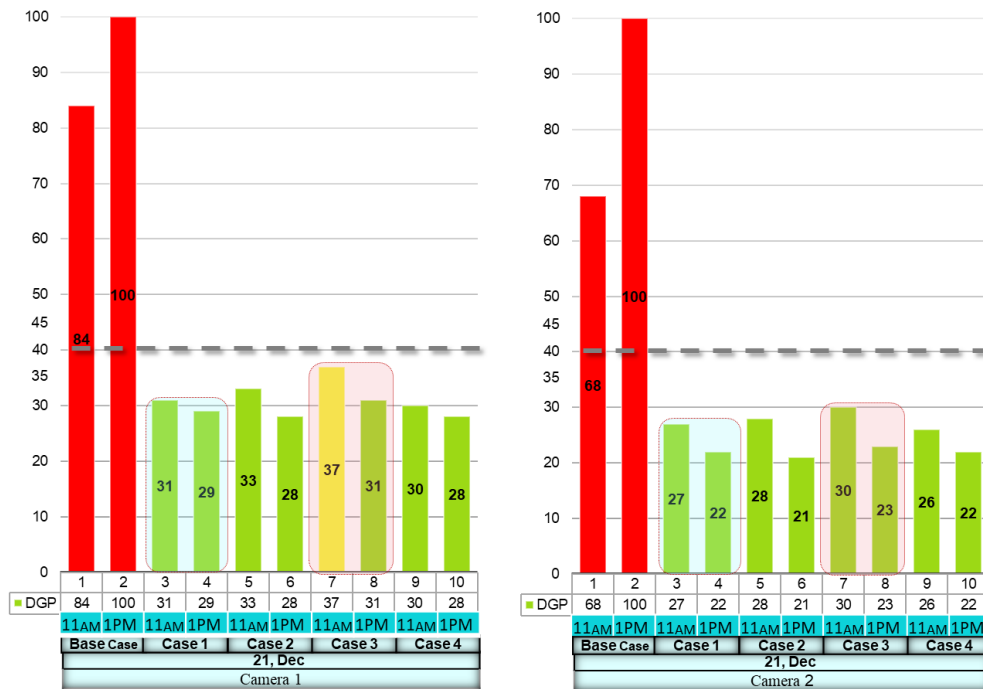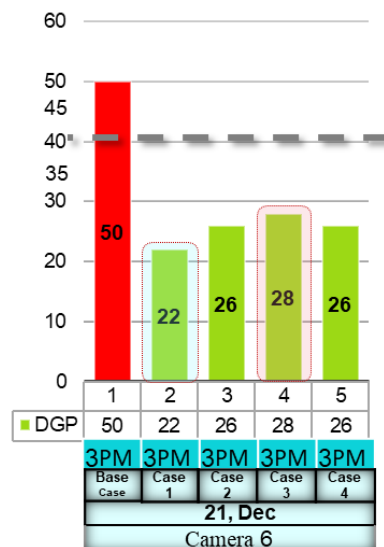|	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
DGP	100	71	85	37	29	27	43	31	28	39	33	31	47	28	26
	11AM	1PM	3PM	11AM	1PM	3PM	11AM	1PM	3PM	11AM	1PM	3PM	11AM	1PM	3PM
	Base Case			Case 1			Case 2			Case 3			Case 4		
	21, Dec														
	Camera 7														

Figure 18: Compared the average of monthly DGP simulations in camera 6 on Dec for the best 4 cases and the base case by the researcher

The results of DGP in camera 8 on 21 Dec. demonstrated according to the glare studies, incase one it was imperceptible glare DGP at 11 AM, 1 PM, and 3 PM which reached the acceptable.

In case two it was imperceptible glare 1 PM and 3 PM, but at 11 AM, it was intolerable which reached the non – acceptable percentage.

In case three it was imperceptible glare DGP at 11 AM, it was perceptible glare 1 PM and3 PM which reached the acceptable.

In case four it was imperceptible glare 1 PM and 3 PM, but at 11 AM, it was intolerable which

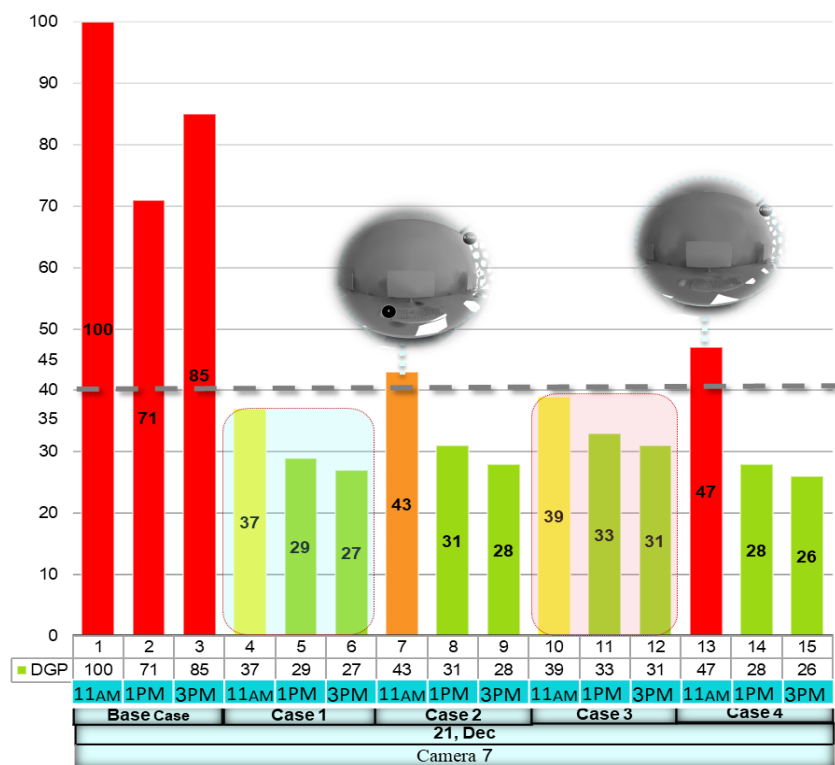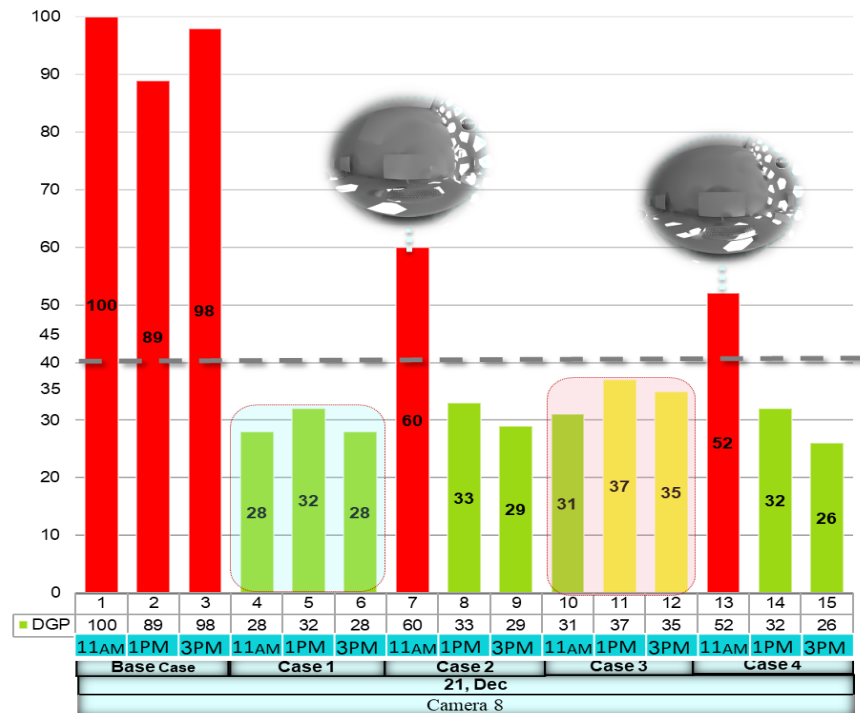reached the non – acceptable percentage, as shown in figure 19.

Figure 19: Compared the average of monthly DGP simulations in camera 6 on Dec for the best 4 cases and the base case by the researcher

From the results of phase two; case 1 and case 3 achieved the most efficient configurationsand represented acceptable performance, where the values of the Daylight glare probability for these 2 cases were decreased sensation level to perceptible and imperceptible glare. It is noticeable that by comparing the results for the four cases, the percentage of average UDI was convergent and increased daylighting performance, however, the results of average DGP were an uneven percentage.

4. Conclusion

This paper studied the daylighting and glare performance for the Voronoi screen created by the genetic optimization system. It was based on the integration of the performance simulation tool with the genetic optimization design approach and the biomimetic method using DIVA, Grasshopper respectively. The Voronoi main screen is controlled by a series of variables, these variables are opening percentage, depth, a random number of seeds, and a number of cells (count). These variables form various configurations through the optimizationprocess to enhance occupants' comfort.

In this paper, the simulation process is divided into two phases, the first phase concerned with the base case to evaluate daylighting performance, it divided into 2 stages. Stage one for founding the value of annual simulations for average Useful Daylight Illuminance (UDI 100

/ 3,000 lux), the result of the Percentage of the UDI without any solutions was 47.8% which was less than the percentage of the Criteria 75%, thus needed optimizing. Stage two for founding the monthly simulations for DGP in eight camera positions at three hours a day, and two different seasons on 21 June, 21 Dec., the worst result of the DGP without any solutions was five camera positions. Which is more than the percentage of the Criteria 40%.

The second phase concerned the optimization by applied the Voronoi solar screen pattern by using the optimization tool "Opossum". Stage one; by finding the best value of annual simulations for average UDI for the Voronoi screens, then ranking the optimal cases for four Voronoi cases for UDI. The results of the optimization had proved to be successful with a percentage of 88.7%, 88.6%, 84.78%, 77.72%, respectively. Stage two; by testing the best four solutions with DGP simulations in the worse five camera positions. The results found that case 1 and case 3 achieved the most efficient configurations and tend to represent acceptable performance, with variables were opening percentage 50%, 50, depth 15,10cm, a random number of seeds30, 30, and a number of cells (count) 160,120, respectively. Where the values of the Daylight glare probability for these 2 cases were decreased sensation level to perceptible and imperceptible glare.

Overall, the use of a biomimetic approach to creating solar screens is very effective for generating different patterns that conform to daylighting performance thereby providing a wide range of parameters that vary with climate change.

This paper had Limitations; this work concentrated on daylighting conditions. Other variables could be incorporated, for example, thermal comfort, natural ventilation, and building energy use. Different orientations and sky conditions had an important role in daylight utilization within an indoor environment. But, the methodology in this study was only focusing on south orientation to achieve occupant's visual comfort.

Further study is required to follow other options for the dynamic and kinetic systems to create more adapted facades with the external factors and give a better guide for designing high-performance facades. We should consider the different building types, open-plan offices, investigating various novel screen patterns and configurations following the methodology of this research, in further study.

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