

# Auxetic Structures and Advanced Daylight Control Systems

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## Abstract

*Building envelopes in general and, in particular, fenestrations are the places in which most interactions between indoor and outdoor environment take place. As a result, an effective shading structure for windows, which can provide sufficient illuminance levels and at the same time ensure acceptable visual comfort by controlling the glare is highly desirable.*

*Static daylight control systems are mostly designed to either completely shade the façade from sunlight or admit and re-direct it to the indoor spaces. Dynamic control systems adjust the amount of intake sunlight with assistance from users or mechanical devices. Studies to date have not thoroughly and comprehensively developed an alternative system in which a self-morphing structure that is responsive to outdoor environmental conditions can function as an "adaptive daylight control system".*

*This paper has investigated the effects of the adaptable auxetic shading structure with varying geometries to optimise illuminance levels and reduce probability of glare. The paper developed a model to be tested in various locations in the U.S., to evaluate the illuminance and glare performance. The results suggest that the auxetic shading structure can effectively block sunlight from entering the space by adjusting its geometry in response to varying outdoor and sky conditions. In addition, a strong correlation can be concluded among daylight availability, sun exposure, and glare probability. Additionally, the optimisation of daylighting parameters such as illuminance and glare show a clear correlation between the location of the case study and its corresponding sun angles, and the performance of the shading structure. Future studies may explore the effect of auxetic shading structures on energy consumption and thermal comfort parameters. In addition, the relation between auxetic shading devices and the health and well-being of building occupants may be another factor to be considered in the evaluation of effectiveness of this new generation of shading devices.*

## Keywords

*adaptable shading system, auxetic structures, optimisation, illuminance, glare*

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## 1 INTRODUCTION

The impact of building envelopes on indoor environmental quality (IEQ) and energy consumption in built environments is well documented. The building industry in the United States accounts for nearly 40% of total U.S. energy consumption (Ge et al., 2015). The concept of net-zero energy buildings, where the building makes no energy demands on the grid and is 'energy self-sufficient' has recently been gaining significant attention.

The interactions between built and natural environments mostly occur at the building envelope, which makes any improvements in its performance critical in terms of achieving energy self-sufficiency. The design and use of new energy efficient materials and technologies is also crucial to meeting net-zero energy goals. Due to their significant interactions with the ambient conditions, there has been tremendous interest in harnessing roofs, skylights, and fenestrations such as windows (Debije, 2010; Gutierrez & Lee, 2013; Gutierrez & Zohdi, 2014) in the push for energy self-sufficiency.

In addition to impacting energy use, building fenestrations also have undeniable impacts on daylight admission and consequently indoor environmental conditions. Among all contributions that building envelopes can have on IEQ, the control of incoming daylight is particularly important given the extensive effects that daylighting can have on occupants' health and well-being. To capitalise on these effects, designers and engineers have developed 'intelligent' building envelope systems in which the building envelope components, such as shading systems, are responsive to changing outdoor environmental conditions.

This research addresses the subject of adaptable daylight control systems and their contributions to illuminance levels and glare in indoor spaces. Through the use of an auxetic shading structure, this study explores the effects of varying geometries of shading structure on illuminance availability, as well as glare probability, in multiple locations representing different latitudes. The main research question is - for each location - what are the specifications of auxetic structure, particularly in terms of geometry and pattern, that produce maximum acceptable illuminance while reducing lighting energy requirements?

## 2 GEOMETRY OF AUXETIC STRUCTURES

Fig. 1 shows a process in which an auxetic structure can be formed. The definition of auxetic structure in this paper is a structure that can be expanded and contracted with a simple force, which can provide a great opportunity for daylight control. It is worth noting that the geometric patterns of auxetic structures can be seen around the world, e.g. in decorations and finishing in ancient Islamic architecture, which has intriguing patterns that interest many audiences (Fig. 2). For these reasons, this paper aims to develop a shading structure in which the geometric patterns and symbols are based on Islamic architecture.

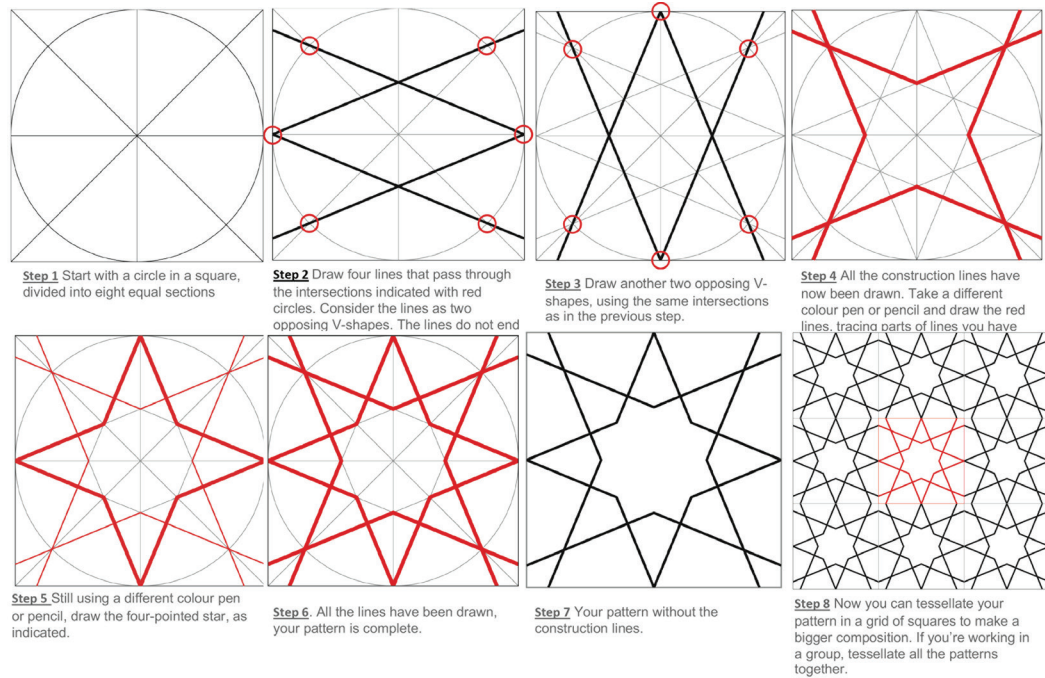


FIG. 1 Process of forming an auxetic structure (School of Islamic Geometric Design, 2018)

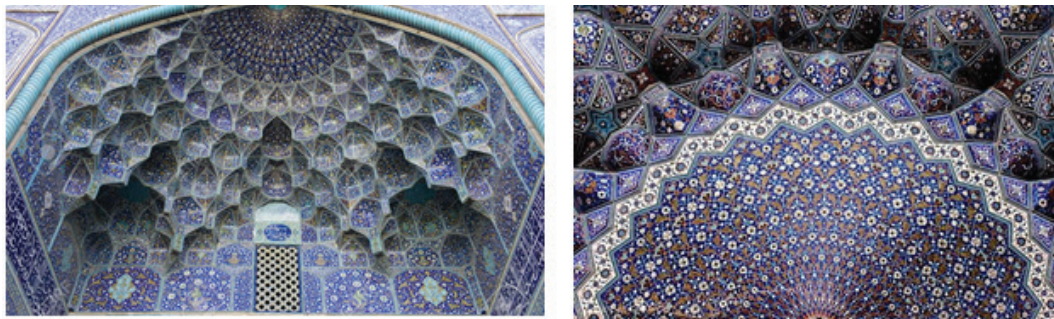


FIG. 2 Imam Mosque, Isfahan, Iran (Shah Mosque, 2018)

Fig. 3 (top) shows one of the typical auxetic patterns, which can be relatively easily drafted by following the steps described. As shown, the basic element of 'Step A' is hinged at the midpoint, and then when connected to another hinged element, creates the 'Step B' geometry, which in turn creates the 'Step C' geometry. 'Step C' connects two other basic elements to the geometry created in 'Step B'. At the end of 'Step D', two more basis elements are added to the geometry leading to the first semi-complete auxetic 'cell'. 'Step E' is a demonstration of how this newly-built geometry responds to the tensile forces to which it has been subjected. By continuing to add more elements to the geometry, one can create a complete set of elements as shown in the figure. As previously indicated, this 'system' can now expand and contract in response to applied tensile or compressive forces, which can be used as a 'shading device' for the purposes of daylight control. However, this pattern covers a relatively small area, which can reduce its effectiveness in terms of providing adequate shading. To address this problem, the geometry was advanced through changing the shape of basic element to a triangle and thereby increasing the coverage area provided by the element (Fig.3 (bottom)). Although the initial geometries of each have a similar construction process, with additional surface areas the new geometry can provide greater shading and, subsequently, greater daylight control.

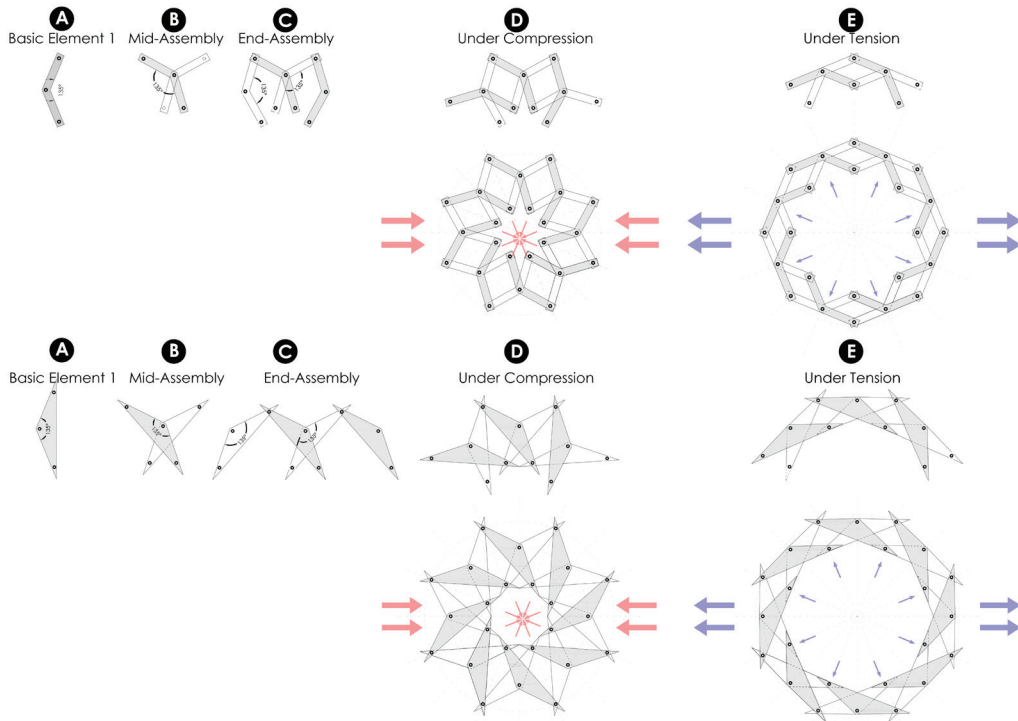


FIG. 3 Process of developing auxetic geometry

Additionally, the pattern can be created by using following equation to find the number of angles. The number of vertices is determined by the following equation:

$$\text{No. of vertices} = 360^\circ / (180^\circ - \text{Angle}) \quad (1)$$

$$= 360^\circ / (180^\circ - 135^\circ) = 8^\circ$$

Table 1 shows the efficiency comparison between both patterns. 'Area closed' represents the area of fenestration that has been covered by the shading structure. 'Area open' indicates what amount of window area is admitting daylight and not shaded. 'Window length' and 'Area % Decrease' demonstrate the overall dimension of the fenestration and the percentage of fenestration coverage, respectively. As shown, Pattern II (2<sup>nd</sup> geometry) provides 3% more efficiency than Pattern I (1<sup>st</sup> geometry), however, the second pattern leads to an even higher efficiency as four modules of it cover a large fenestration area and create a greater degree of shading. Therefore, Pattern II was selected as the final shading geometry.

	ANGLE (°)	NUMBER OF VERTICES	AREA CLOSED(M2)	AREA OPEN(M2)	WINDOW LENGTH (M)	AREA % DECREASED
Patten I	135	8	0.032	0.044	1.62	23.03
Patten II	135	8	0.045	0.065	2.05	30.00

TABLE 1 Efficiency comparison between auxetic geometry patterns

### 3 OPTIMISATION

The proposed auxetic structure in this paper is sufficiently flexible that it can deform when subjected to even small forces. This characteristic makes this geometry a suitable candidate as a shading system that can be either adjusted manually or integrated with a mechanical system that would change the geometry through motors. However, both methods have significant limitations, which can hinder their capability to improve daylight control. The manual control system can remain irresponsive to changing outdoor conditions as it would require constant attention by building users to adjust the shading blinds. The mechanically controlled system can also underperform as easily, due to potential malfunctioning of light sensors. Another option would be to utilise 'smart materials' that automatically respond to varying outdoor conditions. Yi (2018) showed a promising outcome for this method. However, these new materials are still in development stage and further research is needed before they can be implemented in building applications.

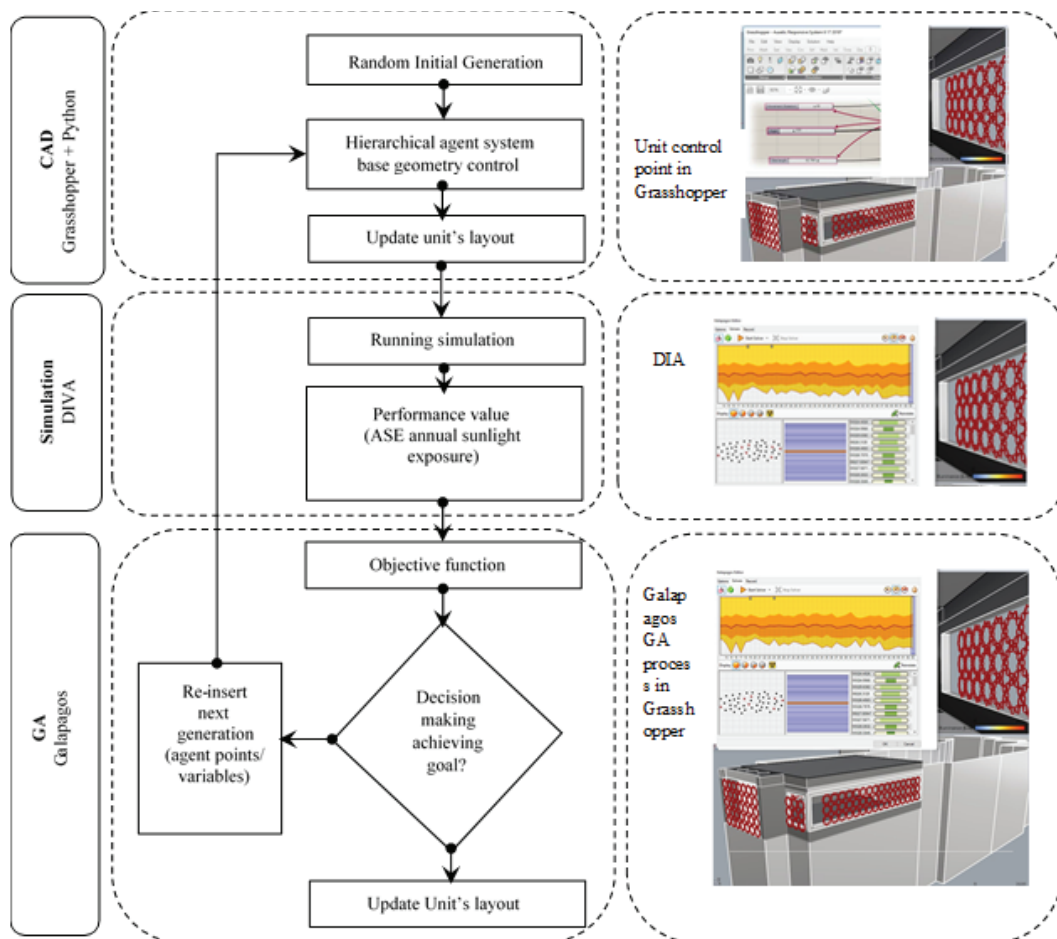


FIG. 4 Summary of research methodology

In this paper, authors chose a different approach to introduce a greater and more efficient responsiveness into the shading system. The chosen method is to find an optimum configuration of shading geometry for a given location, which has been customised for that location and is able to

reduce manual and/or mechanical interferences. To find optimal configuration, the paper follows a process to find optimal shapes for different locations as shown in Fig. 4.

Initially, random agent point values are generated and passed to a hierarchical agent point system in a CAD model, which updates the auxetic system configuration. Once the shape is changed by the agent point's values, a simulation tool calculates the annual daylight accessibility received by each measuring node. Next, these performance values (sDA, ASE, DGP) are passed to the evaluation process to check where the objective values satisfy the goal. If the performance value is not satisfied, the reproduction process starts. The reproduced 'offspring', containing new agent point values, are passed to a CAD model that updates the auxetic system and simulation program to generate the next generation's (iteration) performance values. These values are then used in the evaluation process and will continue until either the objective function value is satisfied, or the maximum generation has been reached.

For implementation, this paper uses Grasshopper, a plugin for a CAD tool called Rhinoceros (Robert McNeel & Associates, 2017) as CAD tool to control geometry. It should be noted that Grasshopper contains several plugins that allow users to utilise various functions without leaving the tool itself. This feature allows users to easily and seamlessly integrate different functions by eliminating the need to share information between different software tools, specifically, geometric information.

The performance measure for daylight is Spatial Daylight Autonomy (sDA). sDA measures how much of a space receives sufficient daylight. Specifically, it describes the percentage of floor area that receives at least 300 lux for at least 50% of the annual occupied hours, which indicates how much daylight an indoor space can receive overall, annually. To calculate the sDA of each measuring point, this paper uses a tool called DIVA (Solemma, 2017) which utilises a Radiance tool to predict several measures of daylight based on sky conditions acquired from location-specific meteorological data. In addition to sDA, this study also uses Annual Sun Exposure (ASE) and Daylight Glare Probability (DGP). The ASE represents a percentage of area which has had an illuminance level higher than 1000 lux for more than 250 hours a year, and the DGP indicates the percentage probability of glare occurrence. Wienold (2009) defines  $DGP \leq 35\%$  as the 'class A', meaning that it is the best class and one in which 95% of office-time glare is weaker than 'imperceptible'. Therefore, in this study, a DGP value of 35% was chosen as the criterion for glare. For optimisation purposes, the paper uses another grasshopper tool called Galapagos. Galapagos is the built-in optimisation application for Grasshopper and is used widely by designers.

## 4 METHODOLOGY / SIMULATION SET-UP

The test case study was an office space on the 3<sup>rd</sup> floor of Temple Buell Hall (TBH) located on the campus of University of Illinois at Urbana-Champaign (UIUC). The room, which currently serves as an architectural design studio, is 12m x 10m with a height of 5m, and has openings towards the south, west, and east orientations. Fig. 5 shows the location of TBH on the UIUC campus, and the exterior and interior of the test study room.



FIG. 5 Site map and test case exterior and interior view

The auxetic shading structure was added to south, east, and west oriented façades using the Grasshopper plug-in. This model was controlled to expand or contract to find the appropriate form of the auxetic shading structure, based on annual sun exposure, daylight autonomy (DA300 lux), and glare probability given specific locations and times of the year. Three U.S. cities including Miami, Florida (latitude: 25.7617° N), Champaign, Illinois (latitude: 40.1164° N), and Sitka, Alaska (latitude: 57.0531° N) were chosen as the locations based on their various climate zones, which, in turn, have effects on sun altitude, and consequently illuminance levels and glare conditions. For glare analysis, three times of the day were selected: 8 a.m., 12 p.m., and 4 p.m. on December 21<sup>st</sup>. The reason to choose this particular date was due to the sun altitude being expectedly low at this time, and therefore the chance of glare occurrence (to be overcome by the shading structure) would be high. 8 a.m. and 4 p.m. were the times at which the sunrise and sunset would occur for the studied locations, except for Sitka, AK, where these times had to be adjusted for this location to 9 a.m. and 3 p.m., respectively, to accommodate low sun altitude.

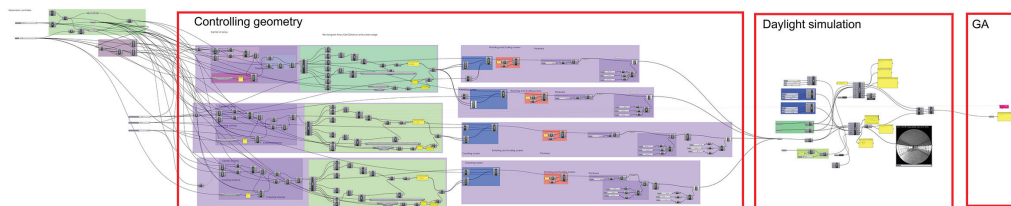


FIG. 6 Screenshot of Grasshopper file

Fig. 6 shows a screenshot of the Grasshopper file that conducted simulation. The optimisation process was carried out by Galapagos, which is one of the Grasshopper's commands, providing 'evolutionary computing' for the geometric variables of the shading structure. Galapagos is GA optimisation that is used for single objective optimisation. However, in order to optimise the shape and geometry of the auxetic shading structure, the following three performance standards were focused on to evaluate the extent to which, simultaneously: 1) annual sun exposure (ASE) would be minimised; 2) spatial daylight autonomy (sDA) would be maximised, and; 3) daylight glare probability (DGP) would be minimised. In order to test a case that contains three objectives to optimise, it requires that three objectives be combined into a single objective in order to utilise Galapagos.

The governing equation for the objective function can be written as:

$$\min_{x \in X} f(x) = \sum_{i=1}^n (r_{ASE})_n + (r_{sDA})_n + (r_{DGP})_n = -1 \quad (2)$$

where:

$$r_{ASE} = \frac{(r_{ASE})_n - 10}{100} = 0 \quad (3)$$

$$r_{sDA} = -\left(\frac{(r_{sDA})_n}{100}\right) = -1 \quad (4)$$

$$r_{DGP} = \frac{(r_{DGP})_n - 0.35}{0.35} = 0 \quad (5)$$

The objective is to maintain an ASE less than 10%, therefore, given equation 3, the minimum ASE must be 0. As for sDA, the greater the area percentage, the greater the sDA. Therefore, according to equation 4, the minimum sDA must be -1. As mentioned before, 'class A' DGP requires a value less than or equal to 35%. By using equation 5, the minimum DGP is determined to be 0.

Therefore, the overall minimum value to be assigned to Galapagos, as indicated in equation 2, is

$$(\text{minimum ASE} + \text{minimum sDA} + \text{minimum DGP}) = -1 \quad (6)$$



## 5 RESULTS

Fig. 7 shows the best-case scenario for each location with respect to optimised solution. In other words, the geometry of the auxetic shading structure shown in the images has produced the closest objective goal.

As shown in Fig. 7, the auxetic shading structures demonstrate different geometry patterns in response to different sky conditions in various locations. While in Champaign the shading structure opens up to the sunlight, in Miami, and particularly in Sitka, the degree of 'openness' is considerably lower. In fact, in Sitka, the shading structure almost completely blocks the sunlight from entering the space. This variety can be attributed to the simulation requirement to limit the sun exposure in Miami, where the sun altitude is high ( $40.6^\circ$  at noon on 12/21/2018), and glare probability in Sitka, where the sun altitude is low ( $9^\circ$  at a similar time). Table 2 shows the best-case scenario for optimised variables at each location.

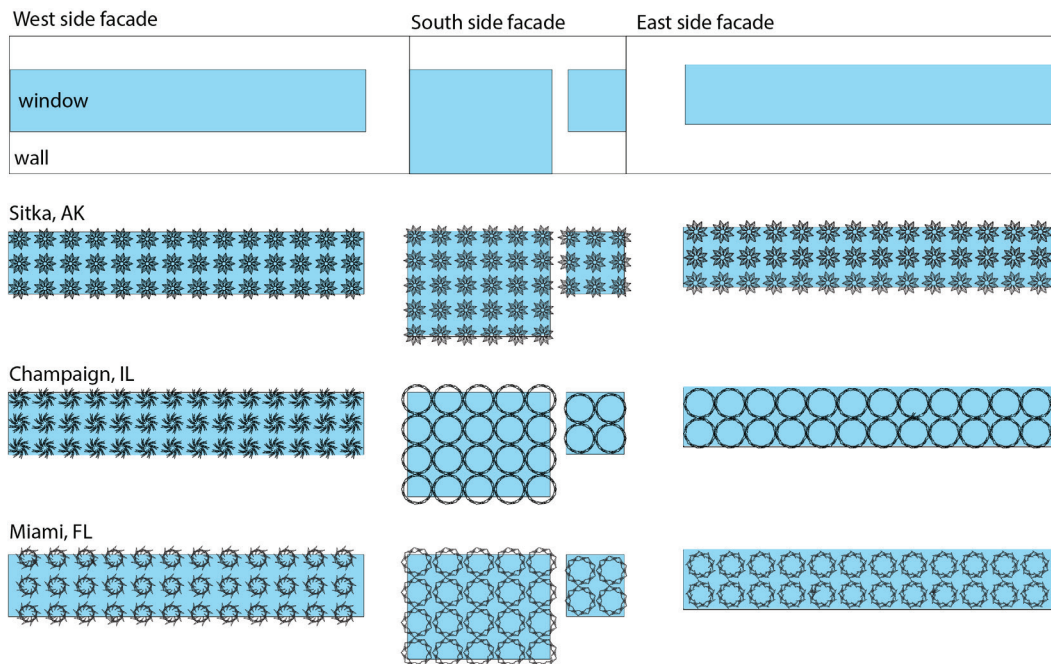


FIG. 7 Optimised shading structure in three different locations

As shown in Table 2, Sitka has the closest Galapagos value to the target value of -1, followed by Champaign, and then Miami. This phenomenon can be correlated with the lowest and highest sun altitudes in this study represented by Sitka and Miami, respectively. In Champaign, the shading structure in the south and east façades have a greater degree of 'openness', while the west façade is significantly more shaded. Higher temperature and lower sun angle in the afternoon are primary reasons for this outcome. In Miami, south and east façades call for greater shading, which is expected given Miami's considerably higher sun altitude ( $40.6^\circ$  compared to  $26.5^\circ$  in Champaign). However, similar to Champaign, the west façade requires more shading in the afternoon. Sitka shows the greatest degree of shading in all three façades, compared to the other two locations. The main reason is the significantly lower sun altitudes that create glare. Therefore, the shading structure

ought to be further congested to provide adequate visual comfort for occupants. The next section will discuss the effects of auxetic shading structures on DGP in more detail.

LOCATION	MOVEMENT (VARIABLES VALUE)			OBJECTIVE VALUE
	South facade	East facade	West facade	
Miami, FL	60	78	110	-0.715
Champaign, IL	24	17	128	-0.825
Sitka, AK	128	123	128	-0.982

TABLE 2 Optimised Galapagos values in various locations

## 5.1 GLARE

Figs. 8-10 demonstrate the level of glare in each location for December 21<sup>st</sup>, 2018, at 8 a.m., 12 p.m. and 4 p.m. These are the approximate times for sunrise, noon, and sunset, respectively. However, due to the high latitude in Sitka, sunrise and sunset do not take place around 8 a.m. and 4 p.m. so, for the sake of consistency, the times were adjusted to 9 a.m. and 3 p.m., respectively. The images below are the outcome of DIVA/Radiance simulations in which the inside camera is facing the south façade.

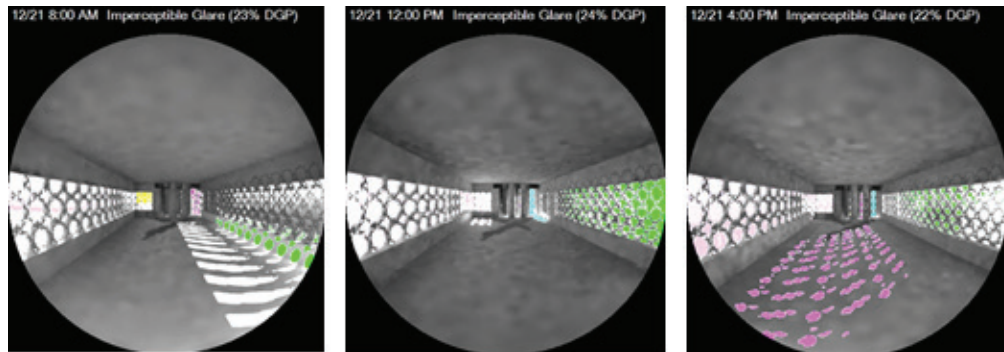


FIG. 8 Glare occurrence and DGP results in Miami at 8 a.m. (left), 12 p.m. (middle), and 4 p.m. (right)

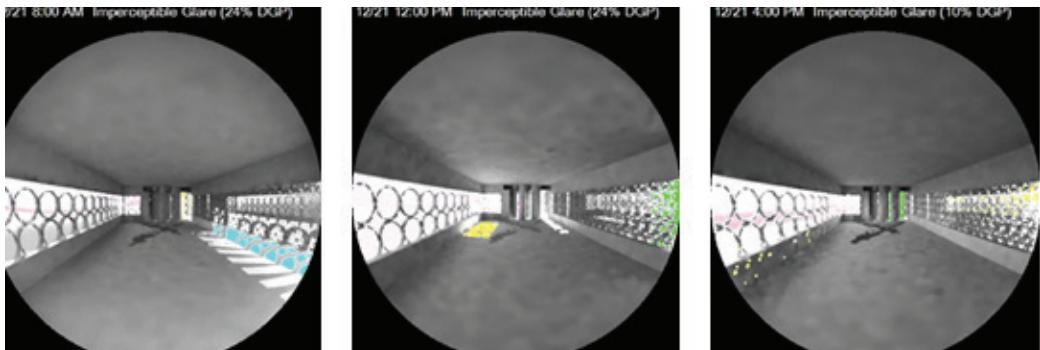


FIG. 9 Glare occurrence and DGP results in Champaign at 8 a.m. (left), 12 p.m. (middle), and 4 p.m. (right)

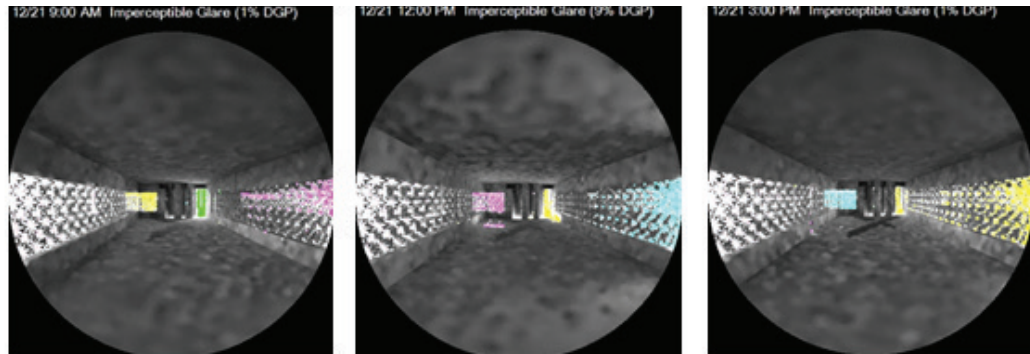


FIG. 10 Glare occurrence and DGP results in Sitka at 9 a.m. (left), 12 p.m. (middle), and 3 p.m (right)

In Miami, for all three times of day, the DGP is less than 35%. It is also interesting to observe that all three DGPs are fairly close, which suggests that the high sun altitude, and likely a more uniform sun exposure compared to other the two locations, can reduce the presence of glare in indoor environments.

In Champaign, the DGP values resulting from east and south sun exposures are similar, while it is much lower in the west façade suggesting that the lower sun altitude in the month of December causes significantly less glare in the afternoon in comparison with other times in the same location, and comparable times in locations with lower latitudes such as Miami.

Although one would expect to observe the largest degree of glare in Sitka due to its higher latitude, glare results show the lowest degree of probability among all case studies. It appears that in response to the simulation requirements, the auxetic shading structure has blocked the sunlight so effectively that a location with a comparatively high latitude demonstrates the lowest DGP. In addition, the minimal sun exposure in Sitka as shown in Table 3 can also be a major contributor to this phenomenon. Table 2 summarises the results for sDA, ASE, and DGP for each location.

As shown in this table, Miami and Champaign have fairly similar sDAs, ASEs, and DGPs, however, the value of these parameters are significantly lower in Sitka. It can be concluded that there is a strong correlation between daylight availability, sun exposure, and glare occurrence.

LOCATION	SDA (%)	ASE (%)	DGP (%)		
			8:00 am	12:00 pm	4:00 pm
Miami, FL	73.3	46.5	23	24	22
Champaign, IL	79.4	51.4	24	24	10
Sitka, AK	0.2	1.4	1 (9 am)	9	1 (3 pm)

TABLE 3 sDA, ASE, and DGP values in various locations

## CONCLUSIONS

This study has investigated the effects of an auxetic shading structure with varying geometries on illuminance levels and glare probability. The simulation research methodology using Grasshopper, DIVA, and Rhino (interface) carried out the assessment for three U.S. cities including Miami,

Champaign, and Sitka. The case study office space was an architectural design studio located on the third floor of TBH on the UIUC campus. The optimisation of the following parameters was conducted to evaluate the performance of the shading structure: sDA, ASE, and DGP, where the optimisation objective for the Galapagos parameter was to simultaneously maximise sDA and minimise ASE and DGP.

The results suggest that the auxetic shading structure can effectively block the sunlight from entering the room by adjusting its geometry in response to varying outdoor and sky conditions. Furthermore, a strong correlation can also be drawn between sDA, ASE, and DGP in each location. In other words, the greater the illuminance level and sun exposure, the higher the probability of glare occurrence. In addition, the optimised Galapagos value shows a clear correlation between the location of case study and the optimisation performance of auxetic structures meaning the higher the latitude, the better the optimisation.

The main purpose of this paper is utilising an auxetic structure to easily customise shading for a specific location. To maximise the daylight control system, each location requires a specific configuration to design such a daylight control system. However, the proposed system can change its shape to satisfy the performance goal without specifically configuring its daylight control system.

This paper is the initial investigation of utilising an auxetic structure at building scale. The auxetic structure proposed in this paper can be operated with a simple force to expand and contract. It can be further coupled with Shape-Memory Alloys (SMA) to develop an alternative system whereby a system responds to constantly changing outdoor environmental conditions. It is a self-morphing structure that can function as a 'Self-response daylight control system'

In addition, one may want to investigate the effect of varying auxetic shading structures on energy use (lighting, heating, and cooling), and thermal comfort performance of the case studies. In addition, the relationship between adaptable shading structures, of which the auxetic structure is one, and the health and well-being of building occupants is another opportunity to thoroughly evaluate the effects of this new generation of shading devices.

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