# Performative Periodic Tessellations: A Study of Parametric, Light-Responsive Façade Systems in the Museum Setting

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ABSTRACT: *This paper reports on the design and development of responsive façade systems as exemplar case studies for museum applications. Real-time visual outputs generated by physical models and computational simulation engines inform the design and analysis of performative periodic tessellations (PPT) leading to enhanced building–environment interactions. In this paper, different skin tessellation approaches are investigated to regulate solar gain, improve visual experience, and optimize view within the context of museums which can also be applied to other settings. Systematic generation and simulation of responsive façade systems are developed along with a parametric analysis of various tessellation techniques. The final results demonstrate a comparative study between two design iterations through a mixed methodology using physical and digital models where both qualitative and quantitative approaches inform the design, selection, and optimization of shading devices.*

KEYWORDS: Parametric, Tessellation, Computational Design, Façade, Museum

## 1. INTRODUCTION

Museum architecture has always been a significant source of attention aiming at improving museums' public role, educational impacts, and their interaction with the urban context. The controlled use of daylight in museums, along with its therapeutic and energy-saving qualities, can enhance the user experience and foster the link between the outdoor environment and the artwork and its surrounding atmosphere (Hudson 2008 and Soleimani 2013). Furthermore, the experience of an artwork is inseparable from the spatial dimension of the museum setting. In particular, the design of daylight openings in the museum is an integral part of the museum experience. As Louis Kahn noted, "no space is really an architectural space unless it has natural light" (Loud 1989). Nonetheless, allowing daylight in museums has always been a challenge for architects since excessive natural light can damage the artworks and cause a visual disturbance in museums. However, by regulating and filtering natural light in museums, the viewing of artworks and the museum experience of visitors can be enhanced significantly.

### 1.1 Background

The concept of 'light informing museum spaces' has been well-explored in different architects' work overtime. For one, Renzo Piano has his way of designing art spaces with light. "Every time you take a new job, the one thing that's constant is the magic of light," Piano says. "But everything else is different—the direction of the sun, the energy consumed, the people you are working with" (Keegan 2008). In general, there are two main approaches to enlighten museum spaces and the artwork inside: a poetic approach that uses diffused daylight to paint the space and artwork, and an artificial approach that uses electric lighting to create a high contrast between the artwork and its immediate surrounding. Renzo Piano's museums in Atlanta, Dallas, New York, Los Angles, and Chicago built upon the first approach using diffused natural light to fill the space. For example, the High Museum's roof in Atlanta is composed of 1,000 egg-crate-like skylights resembling a field of sunflowers where the flowers gain light from the north in contrary to a real sunflower, which looks for light from the south (Fig. 1).

In another example, the Broad Museum in Los Angeles was designed by Diller Scofidio + Renfro in a way to minimize the use of electric lighting during the year (Heyler 2015). The building benefits from a parametric 'veil' as a light filtration device allowing diffused natural light into the galleries in a controlled manner (Fig. 2).

Figure 1: The High Museum of Art Expansion, Atlanta, Architect: Renzo Piano.[1]

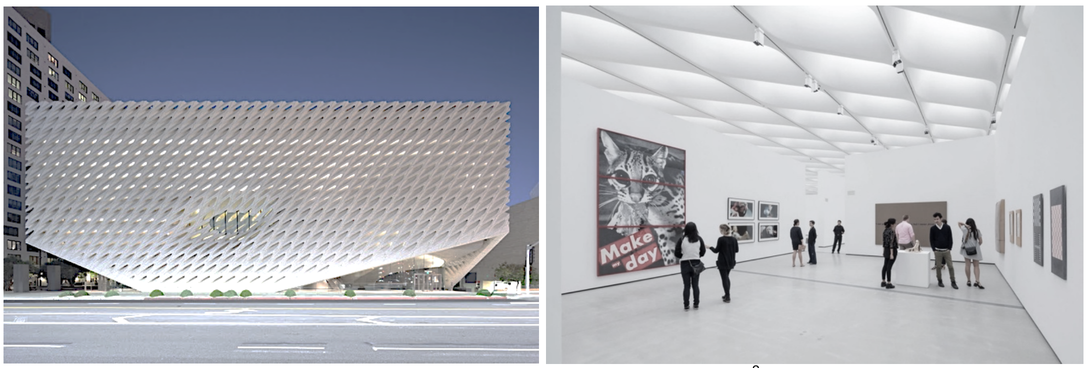


Figure 2: The Broad Museum, Los Angeles, Architects: Diller Scofidio + Renfro.[2]

## 1.2 Tessellations

One of the efficient strategies recently being used to enhance the daylight experience in museums is through the use of tessellation techniques. Tessellations are generated by several polygons stacked together to infinitely fill a surface area while leaving no gaps in-between the shapes (Pearce 1990). In general, tessellation techniques can be put into two main categories including periodic and quasi-periodic tessellations. Periodic tessellations are comprised of a “repeating unit” and a “repetitive structure.” Figure 3 illustrates different shapes of repeating units depending on the net type of the repetitive structure e.g., parallelogram, rectangle, square, and hexagonal (Abas and Salman 1994). Quasi-periodic tessellations, on the other hand, are comprised of a limited number of shapes that stack together to fill the surface area in a non-periodic way. This paper focuses on periodic tessellations informed by parametric, solar analyses. The proposed PPTs are tested based on the level of responsiveness to daylight variations and the level of exposure to sunlight in the museum setting (Pottmann et al. 2007 and Woodbury 2010).

## 1.3 Research Question

Building upon the concept of daylight integration in the museum setting, we argue that museums can further benefit from introducing parametric logics in the design of their building envelopes. Through design-based explorations, this paper investigates the application of two PPTs’ various configurations in the museum setting while answering the question of “How can Performative Periodic Tessellations (PPT) enhance the museum experience through the use of diffused daylight in a controlled way?”

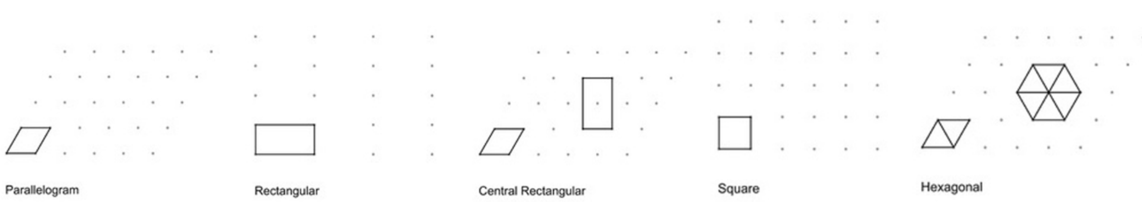



Figure 3: Five Net Types. Source: (Authors 2022)

## 1.4 Research Methodology

The research utilizes a sequential mixed-method approach to first develop performative periodic tessellations, and then conduct analysis to assess the performance of the proposed tessellations.

In the first phase of this research, various configurations of the two PPTs were designed and developed through extensive mathematical and geometric explorations. The parallelogram net type inspired both tessellation processes (Soleimani 2019).

In phase two, a mixed methodology guided the analysis and assessment of the two PPTs' configurations in the museum setting. First, we studied how a repetitive integration of various configurations of each PPT may regulate solar gain and museum experience. This part was conducted through digital modeling techniques and computational simulation—the assessment involved rating of various parameters through a Likert scale (Table 1 & 2). Afterward, we studied how a parametric logic—through curve attractors—can parametrically inform the design of one PPT including various configurations of each module in one design. This part was assessed through the making of physical models to further understand how a parametric logic can regulate shadow patterns and solar gain inside the museum setting.

## 2 DESIGN PROCESS

This section discusses the design process of two types of performative periodic tessellations: the diamond- and conifer-shaped iterations.

### 2.1 Performative Periotic Tessellation #1

An extended diamond-shaped module was designed to offer multiple configurations for different orientations; the embedded flaps within the module allow for more control over the amount of solar gain/exposure as desired inside the building. Figure 4 shows the tessellation process of PPT #1 as well as various configurations of the façade system in response to sunlight.

Since the proposed façade is facing the south, the horizontal configuration was selected over the vertical module. The geometric development and the analytical evaluation of the façade system suggest a sophisticated set of performance-driven skin configurations as a result of a computational dialogue between parametric modeling and daylight optimization. Based on the radiation maps, generated by Rhino's DIVA in Grasshopper (Fig. 4: TOP-RIGHT), four configurations were generated to allow various amounts of natural light inside the building (Fig. 4: BOTTOM-RIGHT). Configuration #1, with fully closed flaps, allows for no light to travel through the surface; Configuration #2 uses flaps at a 30-degree angle with minimal light transmission; Configuration #3 uses 60-degree flaps to allow moderate light transmission; and Configuration #4, with fully open flaps, allows for maximum solar gain. These four configurations can be further optimized by defining a parametric logic such as lines or points attractors in response to the radiation maps (Fig. 4: MIDDLE-RIGHT).

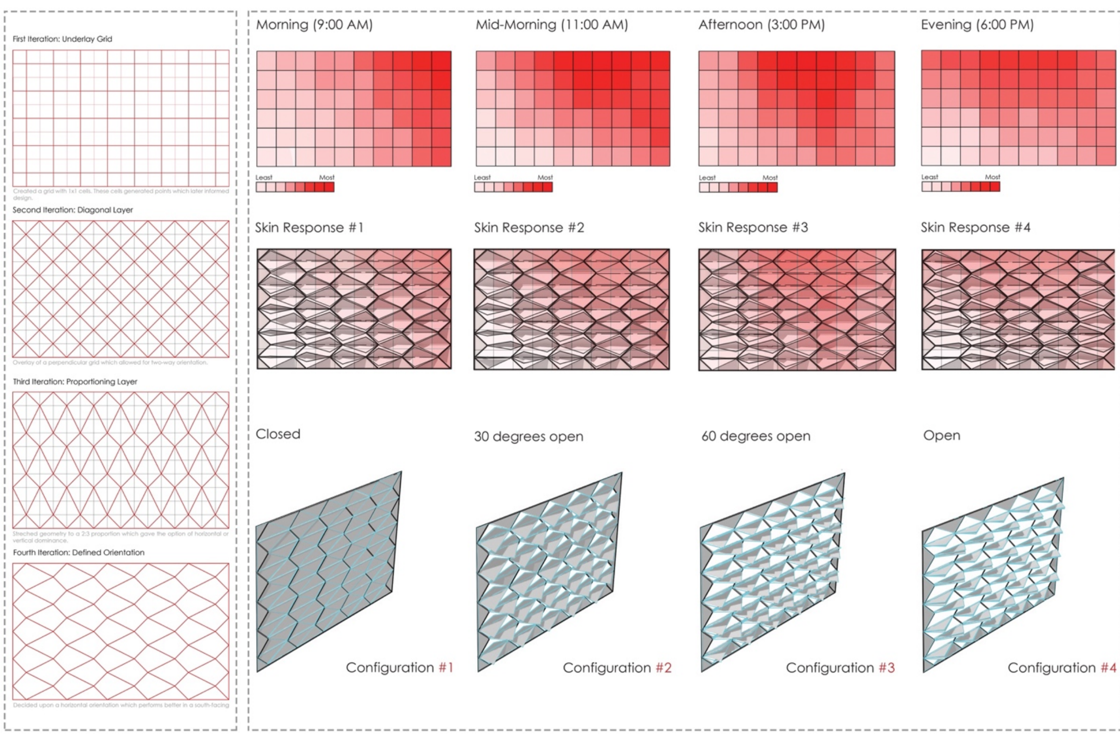



Figure 4: Tessellation process of PPT #1 (LEFT) and different configurations of PPT #1 in response to sunlight variations (RIGHT). Source: (Authors 2022)

## 2.2 Performative Periotic Tessellation #2

PPT #2 was inspired by the conifer cone shape. A square module was designed with two flaps, which resemble cone scales. The flaps offer various configurations for different orientations. Figure 5 shows four different configurations of the module as well as the tessellation patterns ranging from a fully closed to an open iteration.

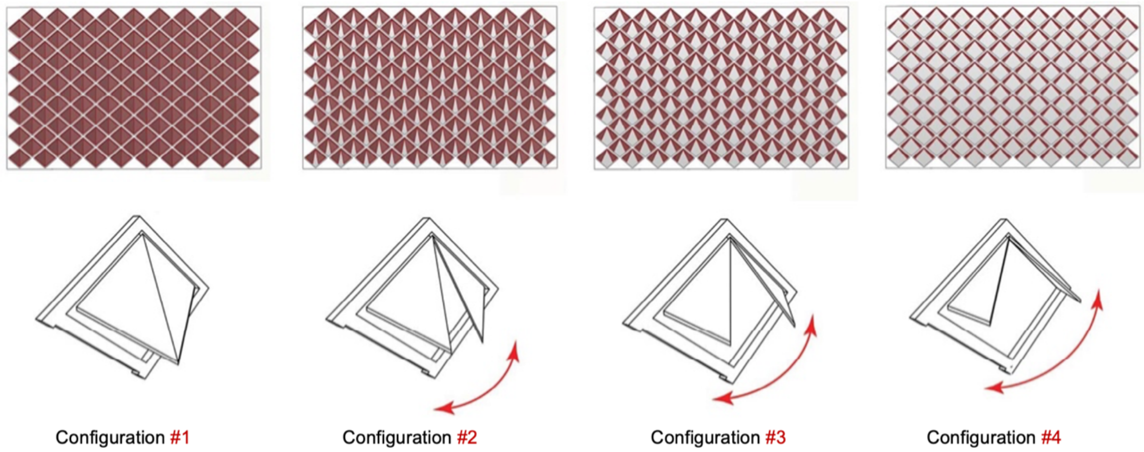



Figure 5: Different configurations of PPT #2 in response to sunlight variations. Source: (Authors 2022)

## 3 PPT ASSESSMENT

The proposed analytical approach can be applied to the design and assessment of various tessellations in order to measure different PPTs' performance levels qualitatively and quantitatively.

## 3.1 Qualitative Approach

Each PPT's configuration was evaluated based on Liljefors' "seven visual and perceptual factors" (Liljefors 2005) employing a five-point Likert scale for a qualitative assessment of the following factors (Iordanidou 2017) in a 25'wx10'dx15'h darkroom utilized with a south-oriented PPT at a time. The authors were the primary participants to study each iteration based on Liljefors' factors.

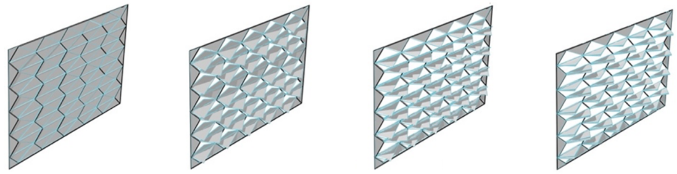
• Light Level: the level of brightness in the room
• Light Distribution: the level of light uniformity throughout the space
• Glare: the level of glare if it occurs inside the room
• Shadows: the level of disturbance if shadows appear inside the room
• Reflections: the level of disturbance if reflections occur inside the room
• Transparency: the amount of transparency connecting inside to outside
• Exterior View: the existence of outdoor view

Additionally, the qualitative approach benefited from the making of both physical and digital models of the PPTs. Digital models were built in Rhinoceros (Rhino). Grasshopper's DIVA plugin was used as the simulation engine for conducting radiation, reflection, and shadow analyses (Fig. 4: TOP)—aluminum with medium reflectivity was selected as the primary material. Two matrices of the findings were developed to assess repetitive PPTs' various configurations based on the seven factors suggesting the strengths and weaknesses of each configuration (Table 1 and 2).

The comparative study of the two PPTs suggests that symmetrical daylight modules, i.e., PPT #2's configurations, allow for better control of natural light transmission as well as offering more uniform light distribution inside the museum. Additionally, the orientation of the aperture flaps can play a key role in the amount of reflection inside the museum. The PPT #1 configurations 2, 3, and 4 allow for light penetration from the top of the modules which can result in undesired reflections/glare inside the space; however, the PPT #2 configurations have a better performance due to the way they block the south light coming from the top of each module.

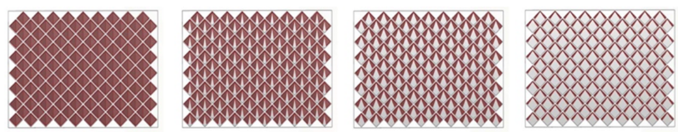
Based on what we learned about the weaknesses and strengths of different modules, two designs were developed for each PPT, where various configurations of one PPT informed one parametric design (Fig. 6 and 7). For both iterations, the daylight modules gradually open from one side to the other. Physical models were built and placed on a heliodon for daylight analysis.

Table 1: Assessment matrix evaluating PPT #1's four configurations' performance level based on Liljefors' seven visual and perceptual factors using a 5-point Likert scale.



| | CONFIGURATION #1 | CONFIGURATION #2 | CONFIGURATION #3 | CONFIGURATION #4 |
|---|---|---|---|---|
| **Light Level** (Dark–Bright) | 0 out of 5 | 1 out of 5 | 2 out of 5 | 3 out of 5 |
| **Light Distribution** (Uniform–Varied) | 0 out of 5 | 0.5 out of 5 | 1 out of 5 | 2 out of 5 |
| **Glare** (Invisible–Disturbing) | 0 out of 5 | 0 out of 5 | 0.5 out of 5 | 0.5 out of 5 |
| **Shadows** (Soft–Hard) | 0 out of 5 | 3 out of 5 | 4 out of 5 | 4 out of 5 |
| **Reflections** (Diffuse–Strong) | 0 out of 5 | 2 out of 5 | 3 out of 5 | 3 out of 5 |
| **Transparency** (Invisible–Visible) | 0 out of 5 | 1 out of 5 | 2 out of 5 | 3 out of 5 |
| **Exterior View** (Isolated–Open) | 0 out of 5 | 0.5 out of 5 | 1 out of 5 | 2 out of 5 |

Table 2: Assessment matrix evaluating PPT #2's four configurations' performance level based on Liljefors' seven visual and perceptual factors using a 5-point Likert scale.



| | CONFIGURATION #1 | CONFIGURATION #2 | CONFIGURATION #3 | CONFIGURATION #4 |
|---|---|---|---|---|
| **Light Level** (Dark–Bright) | 0 out of 5 | 1 out of 5 | 2 out of 5 | 3 out of 5 |
| **Light Distribution** (Uniform–Varied) | 0 out of 5 | 0.5 out of 5 | 1 out of 5 | 2 out of 5 |
| **Glare** (Invisible–Disturbing) | 0 out of 5 | 0 out of 5 | 0.5 out of 5 | 0.5 out of 5 |
| **Shadows** (Soft–Hard) | 0 out of 5 | 2 out of 5 | 3 out of 5 | 4 out of 5 |
| **Reflections** (Diffuse–Strong) | 0 out of 5 | 0 out of 5 | 0.5 out of 5 | 1 out of 5 |
| **Transparency** (Invisible–Visible) | 0 out of 5 | 1 out of 5 | 2 out of 5 | 3 out of 5 |
| **Exterior View** (Isolated–Open) | 0 out of 5 | 0.5 out of 5 | 1 out of 5 | 2 out of 5 |

Figure 6: PPT #1: Qualitative assessment of Liljefors' Visual and Perceptual Factors through physical model making. Source: (Authors 2022)

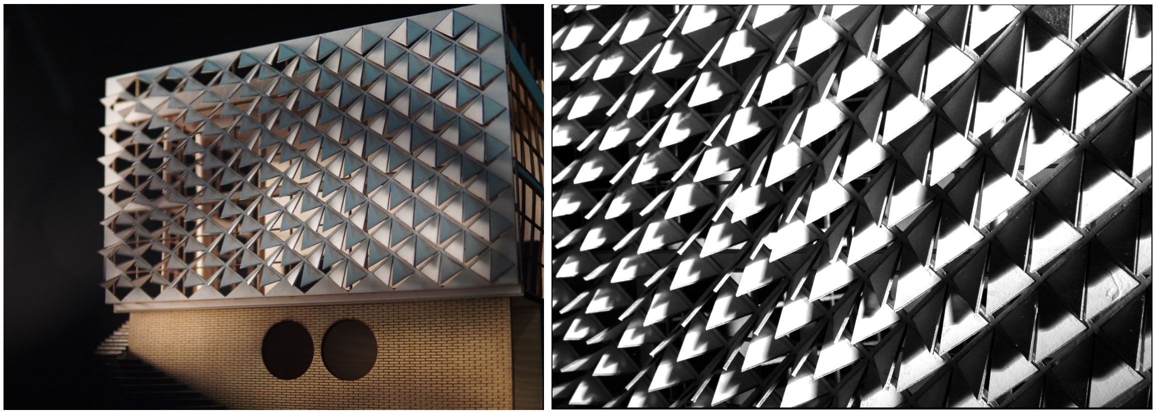


Figure 7: PPT #2: Qualitative assessment of Liljefors' Visual and Perceptual Factors through physical model making. Source: (Authors 2022)

The results suggest that although parametric models offer less uniform light distribution throughout the space, they offer varied lighting qualities in museum/gallery spaces which have a direct correlation with visitors' level of engagement as they explore different parts of the museum.

### 3.2 Quantitative Approach

A comparative study of the two PPTs was conducted to assess the efficiency of the daylight modules with regard to natural light transmission through each PPT. In each configuration, the Projection Factor (PF) was computed through the ratio of the horizontal depth of the repeating unit divided by the height of the vertical fenestration (Fig. 8 and 9).

PF = A / B PF: projection factor
A: horizontal depth of shading device
B: height of vertical fenestration

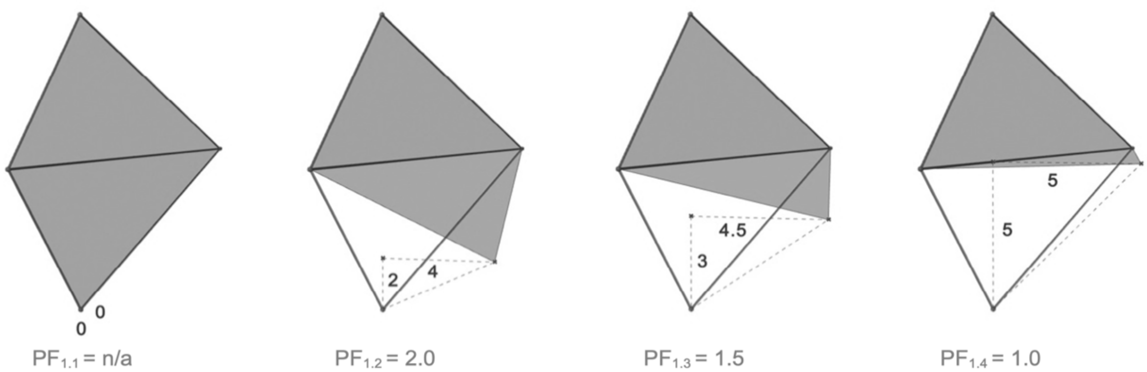



Figure 8: Computed projection factors for PPT #1's module configurations assuming the top flap at the fully closed condition. Source: (Authors 2022)

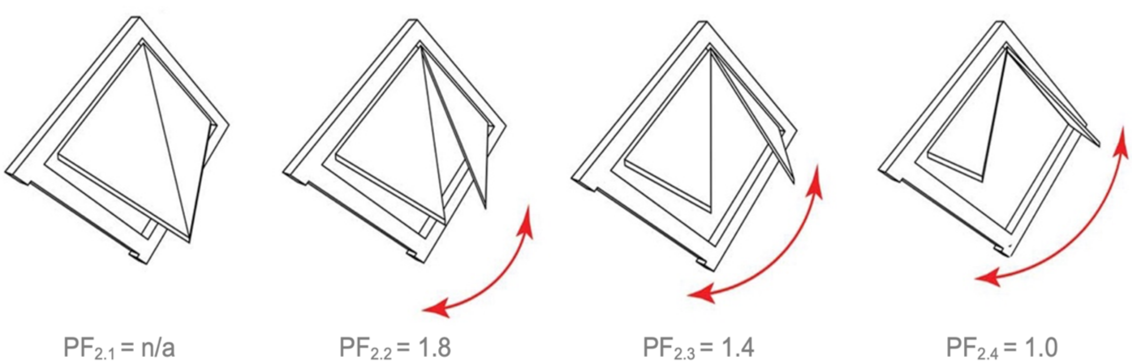



Figure 9: Computed projection factors for PPT #2's module configurations. Source: (Authors 2022)

## CONCLUSION

"I think we're all realizing that the idea of a museum as a place of galleries with storage in the basement is outmoded. Museums are about bringing art and people together. The means by which you can do that are anchored in the exposition and exhibition of a work of art but go far beyond that. You have to engage them in any way possible," says Aaron Betsky, the director of the Netherlands Architecture Institute (Betsky 2011).

The concept of daylighting in architecture has been well-explored since early constructions in history. The most important aspect of daylighting is its uniqueness where it changes every second in intensity, temperature, color rendering index, and the direction of radiance. This characteristic of daylight makes it an ever-changing phenomenon inside the building, which complicates the design of daylight apertures and shading devices. At the same time, it opens an opportunity for an investigation of geometries that respond to such dynamic physical conditions.

Nature utilizes tessellated structures as an efficient strategy to optimize performance at various scales. These structures are flexible enough to morph their physicogeometric characteristics (Pearce 1990) to offer a wide range of solutions that better suit the surrounding physical conditions. The parametrization of such structures thus provides the ability to investigate the whole spectrum of possible solutions in a performatively informed way, and on a single repetitive unit level. Inspired by that, in the museum setting where controlled daylight is desired, performative periodic tessellations can inform the design of shading devices for better control light transmission.

In this paper, we introduced how daylight can be integrated into museum settings where the interplay of controlled natural light in the museum space can foster the visitors' experience. This study, in particular, targeted museum settings; however, this research-based design approach can be applied to various building typologies with different desired daylight qualities that better suit the functionality of each building. For the larger Computer Aided Architectural Design (CAAD) community, the parametric approach that was introduced in the paper can showcase a forward-thinking process where the qualitative and quantitative investigations are enhanced through the power of computation.

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## END NOTE

[1.] https://www.pinterest.co.uk/pin/555772410242401051
[2.] https://dsrny.com/project/the-broad