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# Parametric Optimization of a Responsive Façade System for Daylight Performance

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## Abstract

*The effective use of daylight is a critical design input that increases spatial qualities, sustainability, and energy efficiency targets in buildings. The emerging kinetic architecture concept supports these goals. It also recommends the use of building elements that are suitable for the design of dynamically environment-responsive façades. This study aims to explore the potential of kinetic envelopes for the design of optimal daylight efficient façades. The methodology is based on computational models of kinetic façade patterns applied to a generic building, which are further optimized to reveal the most efficient design. The façade features a modular pattern based on triangles, which, by simple rotation around the vertical axis, provides both daylight control and visual comfort. The results of a parametric analysis of the panel configurations based on daylight metrics, show that the proposed design helped achieving the most effective configuration for daylight savings.*

***Keywords:*** *Sustainability, responsive façade system, parametric design, daylight performance*

# Gün Işığı Performansı için Tepkisel Bir Cephe Sisteminin Parametrik Optimizasyonu

## Öz

*Gün ışığının etkin kullanımı, binalarda mekânsal nitelikleri, sürdürülebilirliği ve enerji verimliliği hedeflerini artıran kritik bir tasarım girdisidir. Ortaya çıkan kinetik mimari konsepti bu hedefleri desteklemektedir. Ayrıca dinamik olarak çevreye duyarlı cephelerin tasarımına uygun yapı elemanlarının kullanılmasını önerir. Bu çalışma, optimum gün ışığı verimli cephelerin tasarımı için kinetik cephe sistemlerinin potansiyelini araştırmayı amaçlamaktadır. Metodoloji, en verimli tasarımı ortaya çıkarmak için optimize edilmiş, çalışma kapsamında oluşturulmuş bir binaya uygulanan kinetik cephe modellerinin hesaplamalı modellerine dayanmaktadır. Cephe, dikey eksen etrafında basit bir dönüşle hem gün ışığı kontrolü hem de görsel konfor sağlayan üçgenlere dayalı modüler bir desene sahiptir. Gün ışığı ölçümlerine dayalı panel konfigürasyonlarının parametrik analizinin sonuçları, önerilen tasarımın gün ışığından yararlanma için en etkili konfigürasyonun elde edilmesine yardımcı olduğunu göstermektedir.*

***Anahtar Kelimeler:*** *Sürdürülebilirlik, tepkisel cephe sistemi, parametrik tasarım, gün ışığı performansı*

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## 1. Introduction

Ever-changing environmental conditions and limited energy resources are among the most influential factors that affect building design decisions and approaches. Consequently, the idea of integrating the concept of sustainability into designs has become highly important. Sustainable architecture supports building design that respects the environment by minimizing the use of natural resources while creating comfortable spaces (Ragheb et al., 2016). The effective use of daylight is needed to increase both sustainability of the design and the efficient use of energy in buildings (Fontoynont, 2014). Thus, a systematic evaluation is required for this effective use, starting from the early design stages.

The most important elements that regulate energy efficiency and daylight control in buildings are the façade and its components (Çıldır et al., 2020). Because the static elements in traditional façade systems are insufficient to respond to the changing environmental conditions and the daily needs of the building occupants, many responsive façade systems have been developed (Hosseini et al., 2020). These façade systems can be used effectively by maximizing the use of daylight to reduce cooling load, solar heat gain, and lighting energy. It is essential to develop a practical methodology for the correct evaluation of daylight, which has a powerful effect on energy efficiency due to its benefits such as artificial lighting, reduction of heating load.

Computational modelling, simulation, and optimization are powerful tools for evaluating daylight solutions in architecture. There are many studies on daylight simulation techniques and different types of responsive façade systems (Ahmed et al., 2015; Manzan & Clarich, 2017; Tabadkani et al., 2018; Hosseini et al., 2019; Prieto et al., 2018). Current studies address systems that, based on simple geometries, can evolve from two to three dimensions, and systems combining parametric design and complex geometries to provide daylight and visual comfort. However, responsive façade design alternatives feature unlimited potentials, which can help to solve the problems and deficiencies derived from applications to different façades and in varied locations. Therefore, in-depth research on daylight, parametric façade systems, and visual comfort metrics through computational simulations is still needed.

This study aims to design a simple responsive façade system that allows daylight to enter the building to achieve a sustainable architectural solution, while controlling daylight without creating glare and visual discomfort. The focus of the study is the design of a west façade with rotational triangular elements. The proposed elements move at different angles to balance and control the daylight coming from the west. For this purpose, the performance of the facade at the end of the movements of the panels was evaluated based on dynamic daylight metrics. These metrics were chosen as spatial daylight autonomy (sDA), which measures whether the selected and analyzed space reaches a sufficient amount of daylight according to the determined standards throughout the year, and annual sunlight exposure (ASE), which measures glare to ensure the comfort of the user while this sufficient daylight is taken into the space.

## 2. Background

The façade and its elements compose a building layer that separates interior and exterior spaces. Since architecture changes according to the users' living conditions and needs, there are always questions about existing structures and architectural solutions and how these solutions can be developed, along with the inadequacy of the existing ones. In this scenario, façades play a critical role in the consumption of energy resources, which are being exhausted by the increasing demand of responsive façades. Responsive facade systems can continuously change their functions, features, or behaviors over time to provide comfort according to the demands of users, with the help of advanced control systems and mechanisms (Matin et al., 2017). These façades use energy for maintaining the thermal and visual comfort according to the needs of the building occupants, while subjected to significant regulations in building energy use and $CO_2$ emissions (Aeleneia et al., 2016). These systems can change their geometric configurations by performing various motion types such as rotation, translation, folding and adapt to environmental conditions. Responsive systems on the façade adapt to environmental conditions by changing their geometric configurations, and thus regulate the amount of sunlight entering the building, reduce energy consumption by optimizing its use, and provide optimal indoor comfort to users (Moloney 2011; Selkowitz et al., 2003). Additionally, recent studies have highlighted the significant impact of facade design on indoor daylight quality to increase occupant comfort (Shen and Tzempelikos, 2012; Freewan, 2014). However, daylight can cause visual disturbances such as glare and unwanted reflections (Pauley, 2004). Therefore, in an effective daylight design, designers try to strike a balance between maximizing daylight utilization and controlling the potential risk of disturbance (Banihashemi et al. 2012).

In this context, responsive façades are used to control daylight, while utilizing analysis made in the early design stages. Building performance simulations are used continuously to improve energy consumption and building comfort conditions in buildings. The use of computational simulations to evaluate “architectural sustainability” has shown significant improvement in recent years (Orhon and Altın, 2017). In terms of sustainability, simulation software can help determine the thermal performance of the building and evaluate the thermal comfort of the building, active/passive solar design, and daylight use of the building.

Assessment of daylight is based on dynamic daylight performance metrics such as daylight autonomy, continuous daylight autonomy, maximum daylight autonomy, useful daylight illuminance, spatial daylight autonomy (sDA), and annual sunlight exposure (ASE) (Mardaljevic et al., 2009). They define daylight performance in monthly, seasonal, or annual time intervals by including daylight variation based on annual climate data (Mardaljevic et al., 2009). Among these metrics, sDA and ASE can be seen as complementary to each other. Recent studies show that as the sDA value increases, the amount of useful daylight entering the interior also increases, and the ASE value, which measures user comfort, keeps this sDA value in balance.

The sDA metric is applied to evaluate daylight in different places such as classrooms and offices (IES, 2013). sDA is an annual daylight measurement used to describe the percentage of floor area that receives adequate daylight during working hours. Instead of physically collecting data or making measurements in the space to be analyzed, the sDA value is obtained virtually through simulations. During the analysis, the floor of the space is determined as the study area and grids are assigned. The obtained data can vary between 0% and 100%. If at least 50% of the floor area receives at least 300 lux of light during the daily working hours of this work area, the threshold value is considered to be met. When sDA is between 55% and 74%, it is considered 'nominal' by the user, while these values are classified as 'preferred' if sDA is over 75% (Lee et al., 2019).

The ASE metric balances the sDA value to control exposure to sunlight and is mainly concerned with reducing visual disturbance. Higher levels of daylight can also bring glare and unwanted heating problem. For this reason, it is aimed to limit daylight by examining the ASE value. Like sDA measurements, ASE measurements are made using horizontal grids through simulations and the obtained value varies between 0% and 100%. Specifically, ASE measures the percentage of floor area that receives at least 1000 lux for at least 250 occupied hours per year. This rate should not be more than 10% for user comfort (USGBC, 2017).

## 3. Methodology

The methodological approach of this study incorporates modelling, simulation, and optimization. The paper consists of three stages. First is the literature review to compile information about sustainability, responsive façades, and daylight metrics. The second stage proposes a façade system design by creating a triangular geometry that works efficiently for daylight control. The modules form the façade of an overall mass with a footprint of 8 m x 6 m and a height of 4 m to approximately represent the dimensions of a space in a real building. This building is located in the province of Izmir, where the number of sunny days is quite high throughout the year. Finally, various plugins of the Rhinoceros 3D simulation software package, including Grasshopper, Climate Studio, and Octopus are used to model and optimize this system to find the most effective configuration.

The configurations consider an independent rotation of two-module groups between $0^o$ to $90^o$ by $10^o$ increments. The parameters to optimize are optimized dynamic daylight metrics of sDA and ASE.

According to the following steps, the design phase progressed from geometric design to mobility. The first step is defining the pattern that will cover the façade. In the façade system, basic geometries are used to support simplicity in terms of geometry and ease of movement. During this conceptual design phase, the choice is for a façade with triangular modules. These modules would respond to the sun path and perform a rotational movement. The dimensions of the modules are designed in such a way that each module can rotate freely without the need for additional supports, and in addition, it is aimed to create a minimum number of profiles while rotating in these dimensions. For this reason, each triangular module is designed from floor to ceiling and with a floor length of 40 cm. After studying the module size, the parametric model is generated.

The first stage of the modelling creates the outlines of the triangular modules on the façade by using Grasshopper (Figure 1). The procedure begins with the placement of points, then the edges are formed by joining these points, and later these edges are grouped with other related edges. The distance between the points is 80 cm horizontally and 400 cm vertically to create a vertically extended along the façade. The triangle formed by the grouped sides is divided vertically into two triangles. Thus, a new vertical edge appears. Then the edges are transformed into surfaces. After this stage, the first completed triangular module was rotated 180 degrees and placed adjacent to the edge of the first module. Finally, horizontally copying these two modules reveals the façade composition (Figure 2).

The vertical axis formed by dividing the basic triangle in two is the axis of rotation. This rotational motion is separate for group 1 and group 2, and these two groups can move individually. The created elements complete the rotational movement in the vertical axis from $0^o$ to $90^o$ (Figure 3).

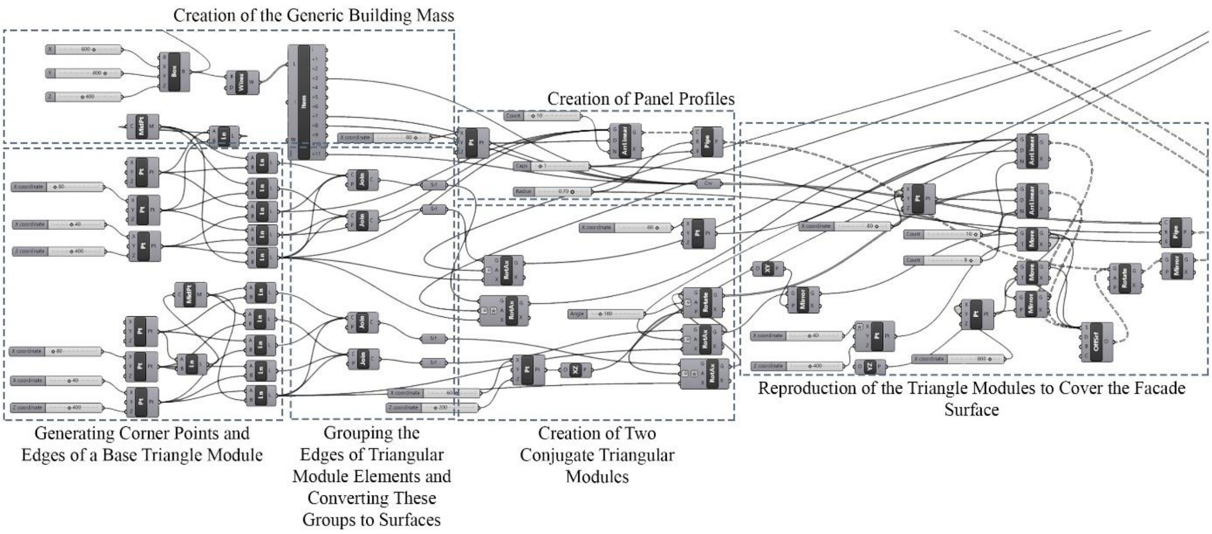


**Figure 1.** Grasshopper definition and design steps of the proposed façade system

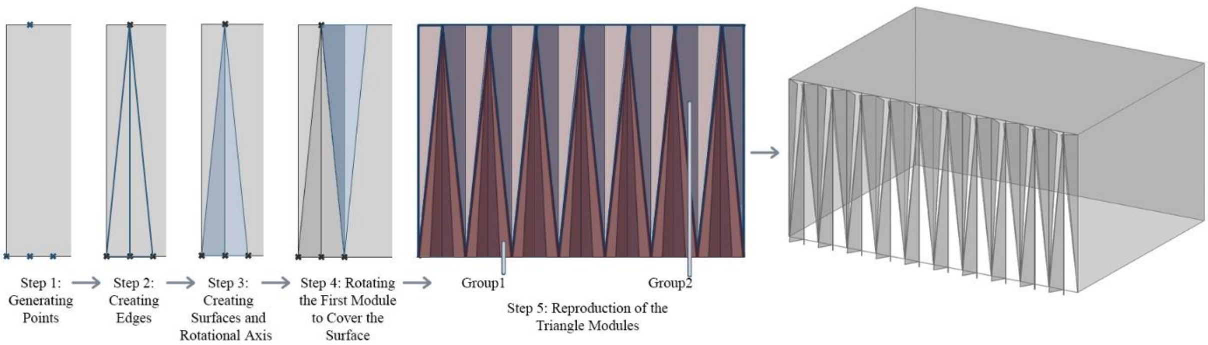


**Figure 2.** Creation and placement of elements and modules

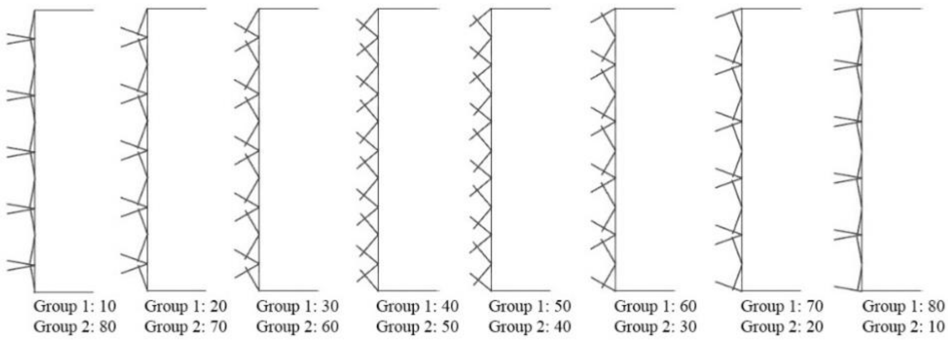


**Figure 3**. Top view of angular states of panels

## 4. Computational Performance Analysis and Research Findings

After modelling the façade system with Grasshopper, the proposed façade is placed vertically on the building's 8-meter-long and 4-meter-high façade. In order to protect the space from sun radiation that will disturb the user, the west direction was chosen as the facade where the system will be placed, and the study was limited by not including other facades in the scope of the study. The Climate Studio plugin assigned different building materials to the elements of the building and the façade elements, so that transparent surfaces and other surfaces differ in the simulation (Figure 4). The type of glass is not differentiated in the base model and the model in which the façade system is applied. Double glazing with the same transmittance was used in both models and other glass types were excluded within the scope of the study. The annual daylight performance evaluation uses 0.5m on grid size on the ground (Figure 5), which should not exceed 0.6m as specified in the LEED v4 (USGBC, 2021). The location information is related to İzmir, Turkey, to provide whole year average weather data.

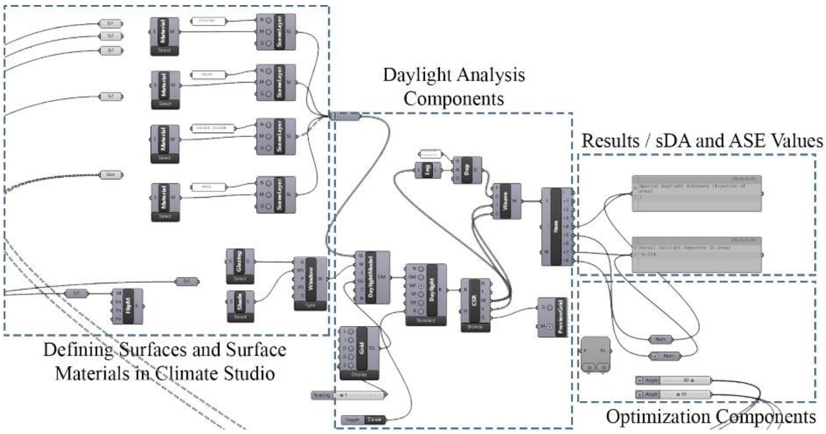


**Figure 4.** Daylight analysis definition and model

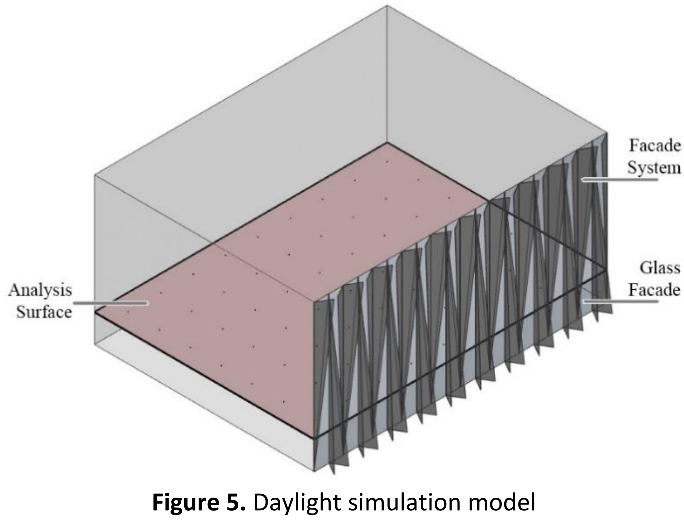


**Figure 5.** Daylight simulation model

The comparison with the base model shows the efficiency of the proposed design. The west façade of the base model is entirely glass. This analysis results show sDA and ASE values of 100% and 88.54%, respectively (Figure 6). As Lee and other researchers (2019) stated in their study and in LEED v4, the sDA value falls into acceptable or even preferable levels, while the ASE value is much higher than the expected 10%. However, the ASE value should be below 10% without lowering the sDA value below 75%.

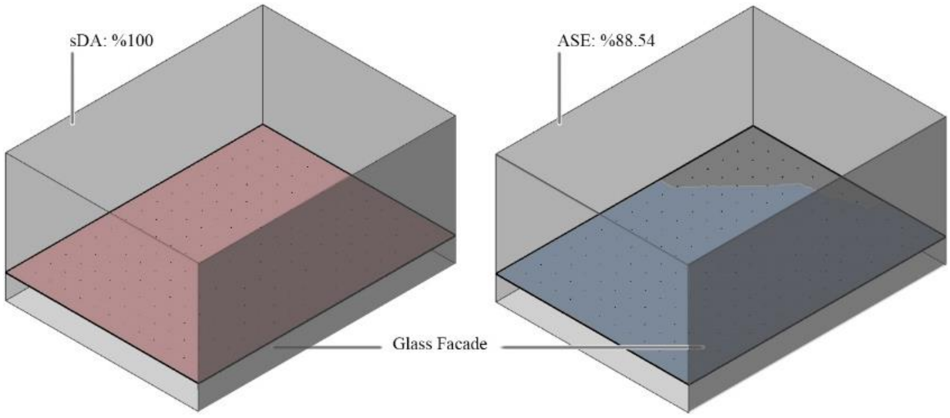


**Figure 6.** Daylight simulation visuals and results of the base model

Accordingly, both the movement of the façade elements at different angles and the effects of multiple configurations are investigated. As mentioned earlier, the Octopus optimization plugin helps reaching the sDA and ASE targets. The optimization process compares different configurations and yields several potential suitable solutions (Figure 7). This method has also been used in studies aimed at similar daylight performance analysis and optimization (Ziaee & Vakilinezha 2022; Lakhdari et al., 2021; Shahbazi et al., 2019).

To start the process, the rotation angles of the panels, grouped into two, are input parameters. The sDA and ASE values are objective functions. The objectives are maximization of sDA and minimization of ASE. The value was multiplied by "–" to minimize the ASE. The optimization reaches an effective result with conflicting objectives.

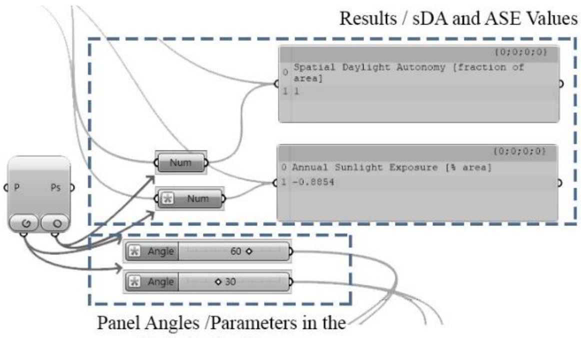


**Figure 7.** Parameters of optimization process

The optimization was completed through the Octopus plugin to find the most appropriate and efficient result by systematically simulating the selected parameters in different configurations. In order to reduce computational time, the population size is 50, and the maximum generation number is 2. Each configuration was generated in approximately 41.28 s (Figure 8).

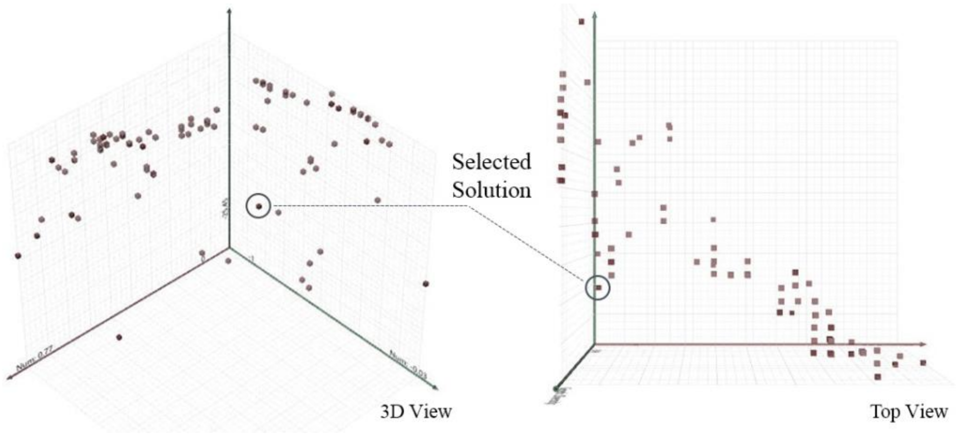


**Figure 8.** Optimization results

The graphics were analyzed to find the highest sDA value and lowest ASE value among various configurations. A wide variety of sDA and ASE values were obtained in the options tried among these configurations. High ASE values and low sDA values were also obtained in many tested configurations. However, there are also configurations with the highest possible sDA value and the low ASE value. Among these configurations, there is also an option with group 1 at 20 degrees and group 2 at 70 degrees.

The analysis value obtained with this configuration was observed as the closest value to the target among the results produced. In this configuration, the sDA value was 77.41% and the ASE value was 9.89% (Figures 9 and Figure 10). This configuration provides the minimum and maximum values that should have been specified in previous studies, while getting sufficient daylight while keeping sunlight exposure as low as possible for user's comfort.

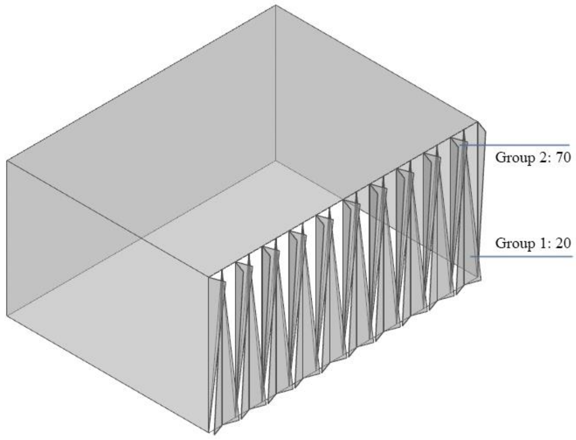


**Figure 9.** States of the panels in the selected configuration

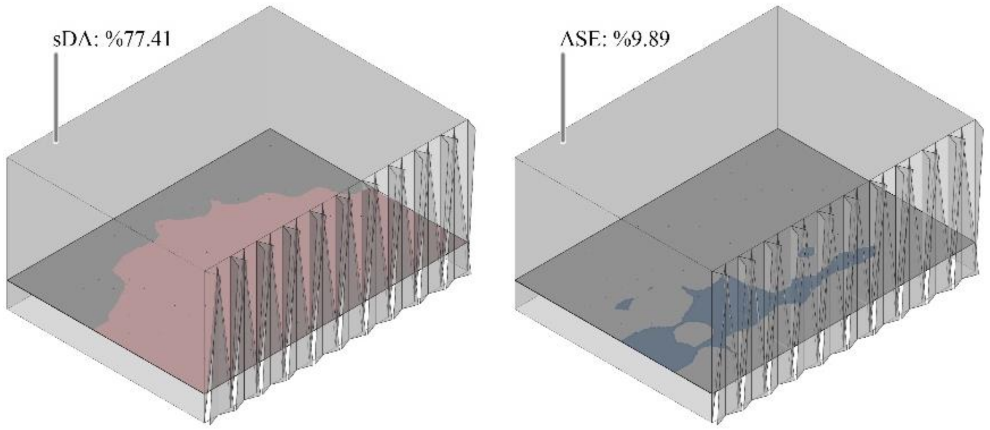


**Figure 10.** Simulation visuals and results of the selected configuration

## 5. Discussion and Conclusion

A proposed responsive façade system analysis was conducted to evaluate daylight control on the west façade and create a suitable environment for the users. The parametrically modelled façade system aims to keep the sDA as high as possible while reducing the ASE value to below 10% for visual disturbance. Thus, it was analyzed that a more efficient responsive system was designed than a static one, and the most efficient configuration for use throughout the year investigation took place through simulations.

To improve the daylight data obtained from the initial model, the simulation and optimization process were carried out using Rhinoceros 3D, Grasshopper, Climate Studio and Octopus software and plugins, and targeted maximum efficiency. The 100% sDA and 88.54% ASE values obtained at the beginning, which do not support user comfort, show that although the annual daylight taken into the space is sufficient, the sunlight exposure values are well above what they should be. Nevertheless, their performance shows a range of changes and finds a solution cloud, which is open to interpretation for performance and architectural reasons. At the end of the optimization, it was seen that the targeted solution was achieved among the different configurations tried. The two groups of elements are positioned at different angles from each other, both letting in sufficient amount of daylight and limiting the sunlight exposure at a level that will not disturb the user. Moreover, the designed facade system can be used to create and provide completely dark spaces according to the user's request, while it can be used in a completely open configuration after sunset. As a result, the proposed system and method were effective in daylight control and resulted in much better results than the initial model.

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### Author Contribution and Conflict of Interest Declaration Information

All authors contributed equally to the article. There is no conflict of interest.

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