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Multi-Objective Optimization of a Folding Kinetic Facade System Proposal for Thermal, Daylight, and Energy Performance

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Highlights

- The study proposes a folding façade system that adapts to changing environmental conditions.
- The aim of study is to reduce energy consumption and increase thermal and visual comfort of users.
- The results showed a 90% improvement in thermal comfort and a slight increase in energy consumption.
- Annual sunlight exposure falls below the target; spatial daylight autonomy increases significantly.

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Abstract

Efficient utilization of daylight and energy resources significantly influences the quality of indoor spaces, user comfort, and overall efficiency. This study presents a folding facade proposal through the design alternatives offered by kinetic architecture and parametric design to enhance efficiency. This alternative design method integrates and coordinates the design components simultaneously and makes any intervention easier when compared with traditional design methods. In this context, the method is based on computational models, aiming to find the most efficient design alternative by optimization. The proposed facade design specifically targets an indoor office space within a university. The modular system, integrated into existing windows, facilitates a folding movement. This dynamic feature aims to optimize illumination within the space, effectively controlling daylight without causing disruptions to users. Simultaneously, the design seeks to balance energy consumption and ensure thermal comfort. The results show that it provides a significant improvement over the base case. The proposed kinetic façade system improved indoor thermal comfort by 80.68-98.11% while slightly increasing energy use (4.72% at most). The average improvement in Spatial Daylight Autonomy (sDA) is 34.98%. Although the number of solutions meeting LEED in terms of Annual Solar Exposure (ASE) is small, there is an average improvement of up to 64% compared to the base case. In conclusion, the proposed kinetic facade system proves to be a valuable intervention for enhancing the indoor environment of an office space at Dokuz Eylül University.

1. INTRODUCTION

While depleting energy resources and changing climate conditions make efficiency targets more critical, this approach also affects building design decisions. In order to build structures that use environmental resources more efficiently, the decisions taken at the design stage become critical to improving building performance and supporting sustainability [1]. According to Çıldır et al. [2], the most significant components controlling the efficient use of energy in buildings are facade and facade components. Because of their static properties, traditional building facades cannot always provide the desired solutions to changing climatic conditions, which change daily and seasonally [3]. Due to their static properties, traditional building facades cannot always provide the desired solution to daily and seasonally changing climatic conditions. One of the strategies for building facades that ensure efficient use of energy and reduce heat losses and gains is the use of insulation materials with low U value. Çetintaş and Yılmaz [4] emphasized the importance of optimizing the insulation thickness in the Mediterranean climate and stated that increasing insulation material thickness in the Mediterranean climate prevents night cooling, thus, an increase in cooling energy demand. Hence, the use of external shading devices is one of the most effective strategies to reduce cooling demand, especially in hot climates, as it protects the building from solar

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radiation before it reaches the glazed area in summer conditions [5]. Other technologies include the active and selective management of the energy and mass transfer between the interior and the exterior environment of the building-on-building facades [6]. An example of these technologies is the design of facades that can respond to changes in outdoor conditions. While various terms such as dynamic, kinetic, responsive, active, smart, interactive, transforming, and flexible have been used in the existing literature to describe these facade systems [7-11], this study focuses on technological applications referred to as kinetic. Through these technological applications, optimizing daylight utilization and reducing energy consumption are achievable by maximizing thermal and visual comfort [12,13].

Computational design, modelling, and optimization software are potent tools for evaluating these solutions and designs [14]. These tools can provide various solutions to design problems, adjust the design parameters, and achieve goals such as optimizing thermal comfort and efficiently utilizing daylight [15-17]. Shafaghat and Keyvanfar [18] provide a systematic review of dynamic façades design including typologies, technologies, measurement techniques, and physical performances across thermal, optical, ventilation, and electricity generation. As the use of software increases, the development of kinetic facade systems draws attention in the literature [19]. For example, Moesas et al. [20] proposed a kinetic facade system to predict environmental changes and obtain more efficient results. They proposed a folding-based façade module and evaluated these modules with a two-stage parametric comparative daylight simulation. The results showed that the daylight performance of the proposed system was better than the static case. Le-Thanh et al. [21] proposed a folding shading element for an office facade in Vietnam with a tropical monsoon climate. They aimed to improve daylight performance and reduce energy consumption by folding motion in eight directions. For this purpose, they developed a simulation-based optimization procedure and investigated the effect of optimized solutions on energy consumption. Their results showed that the proposed design helped the building achieve targeted points in LEED v4 for four different directions while checking sDA (Spatial Daylight Autonomy) and ASE (Annual Sunlight Exposure), including North, North-East, South, and North-West, significantly reducing cooling loads. Tabadkani et al. [22] examined an office's daylight and visual performance in Iran through a movable shading system. They investigated the ASE and DGP (Daylight Glare Probability) index with the Galapagos optimization tool to minimize ASE and maximize sDA. The results showed an improvement in the performance of dynamic facades compared to static systems with an increase in sDA while minimizing 10% for ASE and providing a glare-free indoor environment for the occupants. Wadgy et al. [23] proposed a movable facade system based on a grid of hollow boxes as a facade-mounted dynamic shading system. This mechanism can change configurations with horizontal and vertical rotational movements. All modules move simultaneously at the same angle. The system aims to reduce sunlight exposure by maximizing the illumination.

Outdoor shading devices, especially movable ones can significantly improve thermal comfort in addition to lighting and visual comfort [24]. In thermal comfort studies, the thermal comfort of kinetic facades has generally been evaluated based on their potential to reduce solar heat gain. Elzeyadi [25] investigated building energy saving, daylight distribution, glare control and solar insulation management for different dynamic shading elements for eight different climate zones. The results showed that most dynamic systems positively reduced solar thermal loads on building facades. Another façade proposal by Rizi and Eltaweel [15] was to develop a method that considers the position of the user in order to improve both visual comfort by checking UDI (Useful Daylight Illuminance), DGP, illuminance levels and also heat gain. The study method was a parametric simulation and multi-objective optimization. According to the analyses made at times that require maximizing or minimizing heat gain, the proposed system has improved the advantages and shortcomings of the no-shading and traditional shading situations. Hosseini et al. [26] mentioned that using measurable metrics for comfort evaluation accelerates the renewal process of parametric facade configuration. Yao [27] proposed a movable solar shading on the south facade of a residential building in China. Determined indices are energy performance, room floor temperature, transmitted solar radiation, PMV-PPD distribution, and Discomfort Glare Index (DGI), and there were simulations for these performance analyses. The results show that the proposed system increases indoor thermal comfort in summer months, significantly reduces alarming risks and has a high energy-saving potential.

Research in the design of optimal shading elements and kinetic facades continues to increase in number. However, the researchers must thoroughly examine daylighting and energy consumption or thermal comfort. An examination of the literature shows that a limited number of studies examine daylight, energy and thermal comfort metrics simultaneously. Hence, this study will distinguish itself from other studies by proposing a folding kinetic façade system and evaluating its performance in Mediterranean climate conditions and using optimization to find the best configuration of the system movement. The windows in the studied office space can be opened, yet they are constantly closed because of thermal and lighting concerns. Near the window, there are glare and overheating problems while near the corridor does not have enough natural light. Therefore, the multi-purpose optimization in this study aims to enhance the users' thermal and visual comfort by minimizing EUI, TCV and ASE and maximizing SDA. Thus, it will reveal whether this system has the potential to improve daylight and energy performance without compromising indoor comfort conditions. The design draft was done using the 3D drawing software Rhinoceros, while the simulations and optimizations took place via several plugins integrated with the Grasshopper visual programming platform.

2. MATERIAL METHOD

The office considered in this study is in Dokuz Eylül University Tınaztepe Campus, Izmir, Türkiye. The optimization in the study was designed based on variables related to daylight, energy, and thermal comfort. Therefore, the flow chart depicted in Figure 1 was applied. Different tools are used holistically in the flow chart, which consists of 4 basic steps.

The first step is defining the building model with movable modules on the facade, where simulations and optimizations occur. Parametric design variables are determined. The parametric model is based on Rhinoceros/Grasshopper. The second step includes the model setup required for the energy and daylight simulation. On the one side of EnergyPlus, the Openstudio engine is for energy simulation; on the other side, the Radiance Daysim engine is used for daylight simulation. In the third step, multi-objective optimization is performed using embedded genetic algorithms via the Octopus plugin in Grasshopper. Optimization objectives are related to daylight, energy and thermal comfort and will enable the analysis of the relationship between building design variables and performance measures. In the last step, the data obtained from all the results were transferred to Excel via TT Toolbox and processed. A comparison was made between some promising Pareto-optimal solutions and the base case.

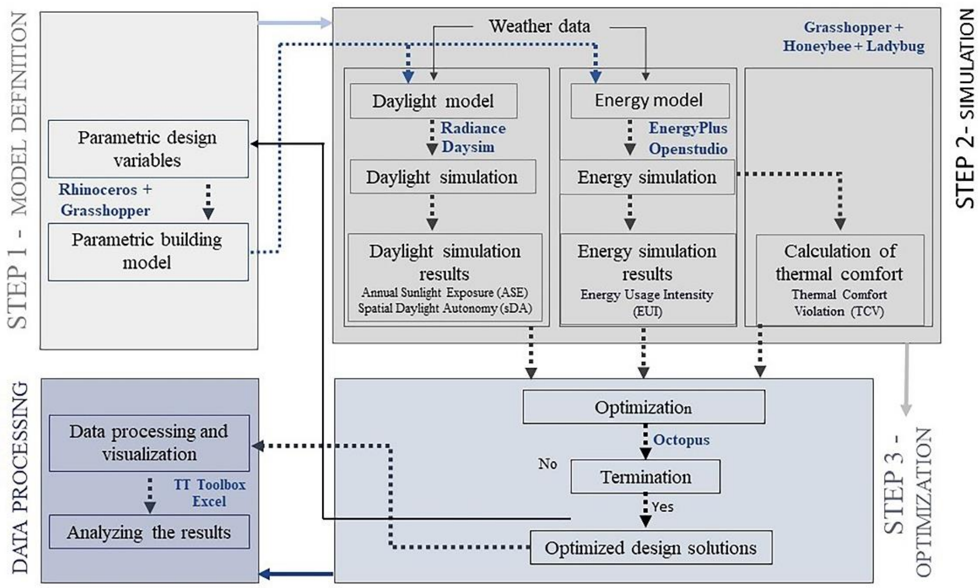

Figure 1. *Flow chart of the study*

2.1. Model Definition

Parametric design, frequently used in architecture recently, is a computer-based design approach that expresses the modelling process of creating geometry using parameters and functions. Compared to the traditional design method, it has significant advantages such as integrating and coordinating the design components simultaneously, changing and improving the design efficiently, and saving time for the designer. After establishing the relationships between geometry and parameters in a parametric design, all possible situations can be examined by changing any parameter, and it is possible to produce many alternatives.

In the modelling process, at first, the building geometry (Figure 2) was created in Rhinoceros. The modelled office building consists of a basement, ground floor and four floors, and the orientation of the proposed kinetic façade is 200° relative to the north. All the rooms within the building have been depicted as masses on the Rhinoceros screen. Then, the drawn masses were defined in the Grasshopper interface. When multi-zone energy simulations are performed in Grasshopper, adjacent surfaces must be matched, and heat flow between spaces must be ensured to perform energy simulations correctly. Therefore, the defined masses are linked to the intersecting mass component, thus establishing connections between the masses. Then, to define the masses as thermal zones, the program of each zone was determined by connecting to the Masses2Zones component.

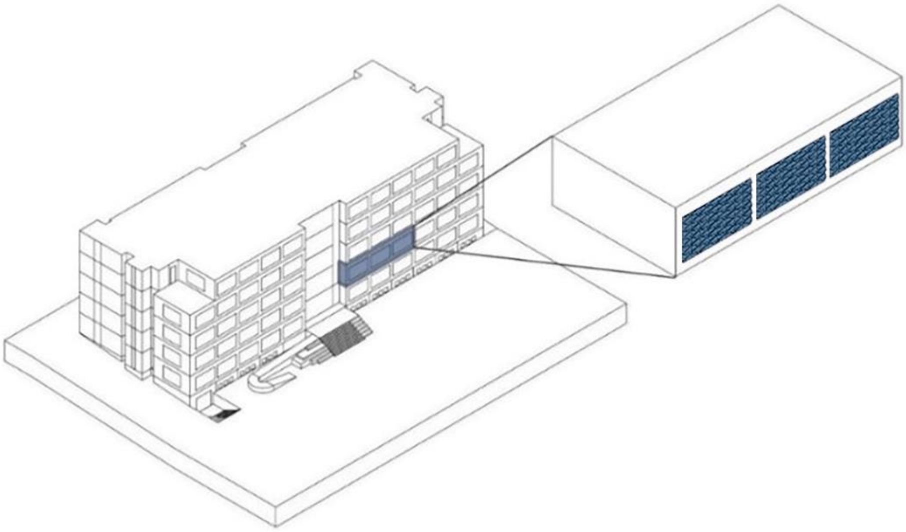

Figure 2. *Building model and office selected for façade design*

2.2. Creation of the Parametric Building Model and Facade System

The size of modules intended for use on the façade is to fit into the three windows on the façade of the selected building's specific office. The design phase covers all the steps, from the geometric design to the movement of the modules. Basic geometries form the system's foundation for ease of movement and design. The intention behind using triangular panels in the design is to make a folding movement. These triangular panels combine to obtain a module with the tasselation technique, which is common in architecture. For example, Swiss RE building's façade has a regular triangle pattern tessalation while Ravensbourne Collage's façade is inspired by flower patterns and consists of different geometries. Besides these two-dimensional tasselations, the façade of the Storey Hall is irregular and three dimensional, the rhombuses on the façade continues to interior walls and ceiling. Additionally, generating kinetic façades is possible with tessalation like the Dancing Pavillion in Brazil, which has mirrors that rotate horizontally according to data from sensors. A more comple example is the umbrella like shape of the Al-Bahr Towers controlled to regulate light and energy requirements. The generated façade system in this paper uses triangular elements because 1. They are easy to iterate and reproduce in modular systems, 2. They can avoid gaps and overlaps, 3. They can create different patterns and configurations according to user requirements, 4. They can operate wih a simple system [26].

The proposed façade system in this paper has twenty-four modules, in six rows and four columns, covering each window. In the first stage, points and lines are used to create folding movement (Figure 3 - Step 1). Since the dimensions of the windows are 420 x 240 cm and 24 modules are used in each window, the length of a module is 40 cm with a width of 105 cm. After creating points suitable for these dimensions on the three-dimensional axis, the points are combined, lines are created, and the rotation axis of these lines is determined (Figure 3 - Step 2). In the next step, lines are created by combining the copied points on the x-axis, and surfaces are created by combining these related lines (Figure 3 - Step 3). The module, which performs folding movement on the horizontal axis, is copied to the x-axis and its movement is provided with the help of a single slider (Figure 3 - Step 4). The two modules are copied horizontally three more times to cover the window (Figure 3 - Step 5). These six modules are copied horizontally to the other windows, creating the facade composition (Figure 3 - Step 6). In all three windows, six rows of facade elements from top to bottom are grouped for joint movement for ease of optimization—the created elements complete rotation in the vertical axis from 0º to 90º. Configurations consider the independent rotation of the six module groups from 0º to 90º in increments of 5º. The variables are the degrees of movement of the six groups separately. While some studies, including [28, 29] look at how the kinetic façade moves in real life or uses external drivers like sunlight to make the kinetic façade move [30, 31], the technical aspects of the movement is out of scope in this study; to highlight the practicality and flexibility of the design.

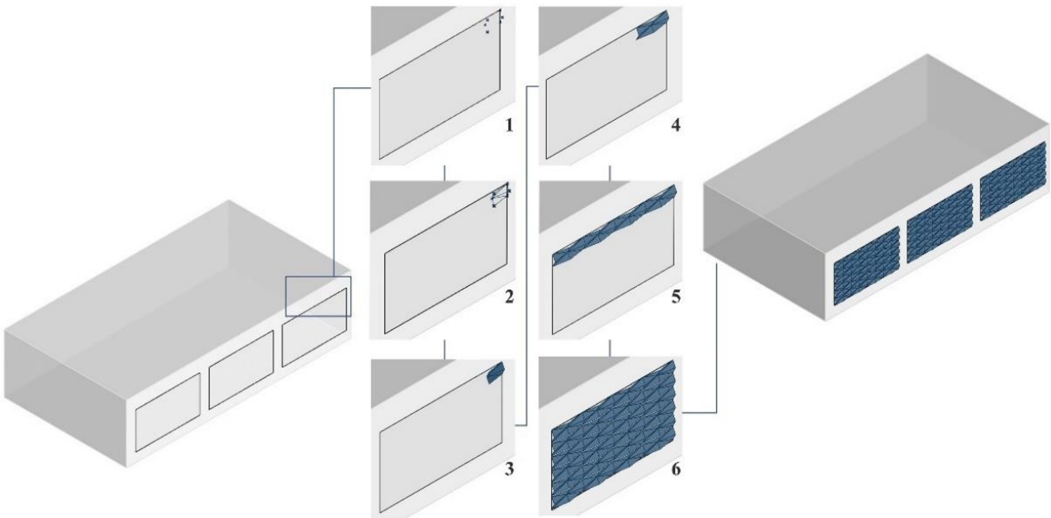

Figure 3. *Steps to create the façade system*

2.3. Materials of the Selected Building Components

Opaque and transparent materials were defined separately, and layers of each component were created and transferred to the EnergyPlus library. The material layers of the building components are in Table 1. It is seen that the U-values of the building components do not meet the recommended values according to the TS825 regulation in Turkey. For this climatic region, the thermal transmittance is higher for the walls and floor, while it is sufficient for the roof. The optical properties of the components were transferred to the Radiance library for daylight simulation. Reflection of the ceiling, floor, interior, exterior walls and shading are 0.8, 0.2, 0.5, 0.5 and 0.35, respectively. A pyranometer and a lux meter were used for calculating the visible transmittance of the existing window, and catalog values were used for the shading element design. The optical properties of the building components are in Table 2. The window has three windows, and the window-to-wall ratio is 80%. The light transmittance of the existing window of the building is 26%, the U value is 3.02 W/m^{2}K, and the SHGC is 0.30.

2.4. Simulation

In this section, the Grasshopper definitions required for the simulations necessary to measure the intended values for testing the facade have been completed. The steps required for each stage are shown in Figure 4. Settings that influence energy consumption, such as indoor temperature control, air conditioning systems, internal loads (including equipment and human density per square meter), and occupancy-dependent programs, are configured for energy simulations. The building is open between 07:00 and 19:00 on weekdays. The heating and cooling setpoint of the HVAC system were set at 22°C and 24°C, respectively.

The natural ventilation conditions were set as, no window opens if the outside temperature rises above 28°C in the cooling season and falls below 18°C in the heating season. The number of people per unit area is 0.11 ppl/m². The equipment load per area is 7.64 W/m² and lighting density per area is 11.84 W/m². The climate weather file for İzmir, which has a hot, humid climate, was taken from Ladybug. The output obtained and evaluated as a result of the energy simulation is the Energy Use Intensity (EUI). EUI is a unit of measure representing energy use in buildings, calculated by dividing the total energy consumed by the building in a year by the total gross floor area. The units of EUI are kBtu/ft²year or kWh/m^{2}year. EUI is an essential indicator for evaluating building energy performance and energy-saving potential. In general, a lower EUI indicates better energy performance [32].

Table 1. *Layers of building components*

Exterior wall	**U value**	**Interior floor**	**U value**
Aluminium panel (0.0005 m) Polyethylene (0.003 m) Aluminium panel (0.0005 m) Non-ventilated gap expanded polystyrene (EPS) foam (0.03 m) Cement-based exterior plaster (0.002 m) Brick Wall (0.2 m) Plaster (0.002 m)	0.75 W/m^{2}K	Wood flooring (0.03 m) Levelling screed (0.08 m) Reinforced concrete hollow block (0.40 m) Ceiling plaster (0.002 m) Non-ventilated gap Rockwool board suspended ceiling (0.02 m)	0.66 W/m^{2}K
Interior wall	**U value**	**Windows**	**U value:** 3.02 W/m²k **SHGC:** 0.302 **VT:** 0.236
Gypsum plaster (0.002 m) Plasterboard Panel x2 (0.015 m) Rockwool thermal insulation (0.06 m) Plasterboard Panel x2 (0.015 m) Gypsum plaster (0.002 m)	0.42 W/m^{2}K	Double glazing	
		Shading	
		Metal cladding	

Table 2. *Optical properties of building materials*

Construction	**Material Type**	**Values**
Interior wall	Radiance opaque material	Reflectance: 0.5
Interior ceiling	Radiance opaque material	Reflectance: 0.8
Interior floor	Radiance opaque material	Reflectance: 0.2
Window	Radiance glass material	Visible transmittance: 0.70
Shading	Radiance metal material	Reflectance: 1

A sequence of simulations was conducted to simulate daylight scenarios, with the creation of a test surface to augment these simulations. As stated in LEED v4, this surface was 76 cm above the ground and had a grid at 50 cm intervals. The radiance material properties required for daylight simulation are in Table 2. The metrics used to evaluate the daylight performance of the building are spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). The sDA metric proposed by the IES to measure and evaluate the amount of daylight in spaces is used to define the percentage of floor area that receives adequate daylight during the working hours of the day, on an annual basis, of the space intended to be evaluated [33]. In other words, it measures whether the analyzed area receives sufficient sunlight throughout the year [34]. In the latest version of the LEED green building evaluation system, information about this value is updated to state that this value should be at least 55%. In addition to the information about the sDA value in LEED v4, the ASE metric is also mentioned for daylight assessment. This value relates to the user's comfort and reduces the visual disturbance while maximizing the daylight taken into the space. To define it more precisely, ASE measures the percentage of floor area that receives at least 1000 lux for at least 250 occupied hours per year. This value varies between 0% and 100% and should not be more than 10% for user comfort [35]. The amount of daylight at the test points on the surface was averaged to obtain the percentage of sDA and ASE metrics. The energy simulation results allowed the calculation of thermal comfort violation (TCV). According to ASHRAE 55 [36] standards, the acceptable thermal environment for general comfort is a situation where the Predicted Mean Vote (PMV) range is between -0.5 and 0.5. TCV is defined as "the percentage of time during which the absolute value of the PMV index in all living areas is greater than 0.5 when the building is occupied" [37]. ASHRAE 55 [36] recommends less than 10% TCV.

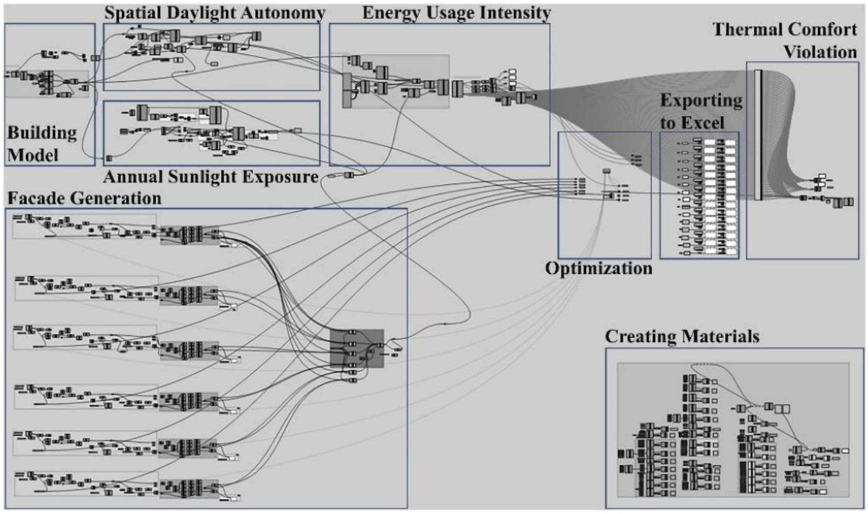

Figure 4. *Defining simulation and optimization models in grasshopper*

2.5. Optimization

This study uses a multi-objective optimization method. Octopus, a plugin in Grasshopper, was used as the optimization tool. The HypE algorithm was chosen in the optimization settings because it can optimize better than other evolutionary algorithms [38]. The design variables are connected to the Octopus input, and the simulation outputs with performance measures are connected to the Octopus objective input. With Octopus, a logical balance between parameters to improve performance measures has been tried to establish. Design variables and objectives for optimization are given in Figure 5. As shown in Figure 5, the moving panels, each of which can change its position after the folding movement, and are grouped in 6 rows. Each group is defined as a design variable. At this stage, solutions are obtained to 1) To reduce the energy use intensity (EUI) value, 2) To keep Thermal Comfort Violation (TCV) and Annual Daylight Exposure (ASE) values below 10% and 3) Spatial Daylight Autonomy Keeping the (sDA) value above 55%.

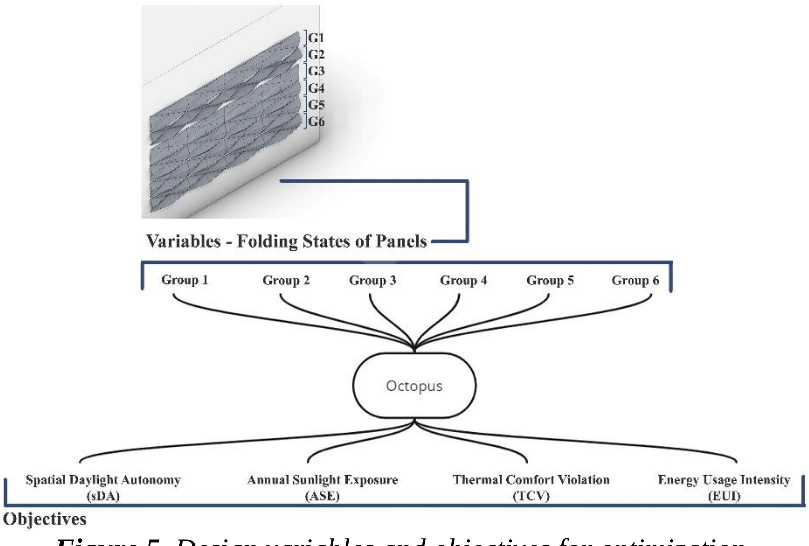

Figure 5. *Design variables and objectives for optimization*

2.6. Data Processing

The fitness function of individuals obtained at the end of the optimization shows balanced solutions between daylight, energy, and thermal comfort performance. The equations used for the fitness function are in 1 [39]

$$
\begin{aligned}
Fitness\ Function = {} & (sDA_i - sDA_{min}) \times \left(100 \times \left(\frac{1}{sDA_{max} - sDA_{min}}\right)\right) - \\
& (EUI_i - EUI_{min}) \times \left(100 \times \left(\frac{1}{EUI_{max} - EUI_{min}}\right)\right) - \\
& (TCV_i - TCV_{min}) \times \left(100 \times \left(\frac{1}{TCV_{max} - TCV_{min}}\right)\right) - \\
& (ASE_i - ASE_{min}) \times \left(100 \times \left(\frac{1}{ASE_{max} - ASE_{min}}\right)\right) \quad .
\end{aligned}
\tag{1}
$$

The data recorder component in Grasshopper recorded the data obtained due to the configurations. At the same time, a Microsoft Excel table was created by taking the optimized data from the Octopus plugin.

3. FINDINGS AND DISCUSSION

This section presents the results achieved through optimization. Initially, an analysis was conducted on the availability of daylight, glare conditions, the number and quality of uncomfortable hours during the year, and the distribution of energy consumption in the base case without the proposed system. Subsequently, optimal solutions aligned with the desired objectives were listed, followed by performance comparisons with the base case. A selection of these solutions was visualized and analyzed for further examination.

3.1. Performance Evaluation of the Base Case

The analysis results of the existing office in the building, which has three windows on the south façade have an sDA value of 43.53%, an ASE value of 48.16%, a total EUI value per m² of 131.88 kWh/m^2y, and finally, the TCV value is 8.46% (Figure 6). As illustrated in Figure 6, the aimed sDA value of at least 55% is currently 43.53%, indicating the need for improvement. However, the ASE, which should not exceed 10%, are well above the values and need lowering. In terms of energy consumption, most of the energy requirement is for heating. The maximum monthly energy spent on cooling is in August (4.93 kWh/m^2y), and the highest heating energy is in October, at 9.49 kWh/m^2y. The amount of electrical energy consumed for lighting is the least. According to the results of the thermal comfort analysis of the existing building, it was observed that the uncomfortable hours were due to heat, while there were no uncomfortable hours due to feeling cold. The number of uncomfortable hours with more than 0.5 (feeling hot) is 264. Hence, 8.46% of the total hours the office is used throughout the year corresponds to discomfort hours. The chart also reveals that certain weeks of the year are consistently uncomfortable. Like ASE, the TCV value should also be below 10%. Hence, design variations were tested in different configurations to approximate these metrics to the target values and the results are explained in detail.

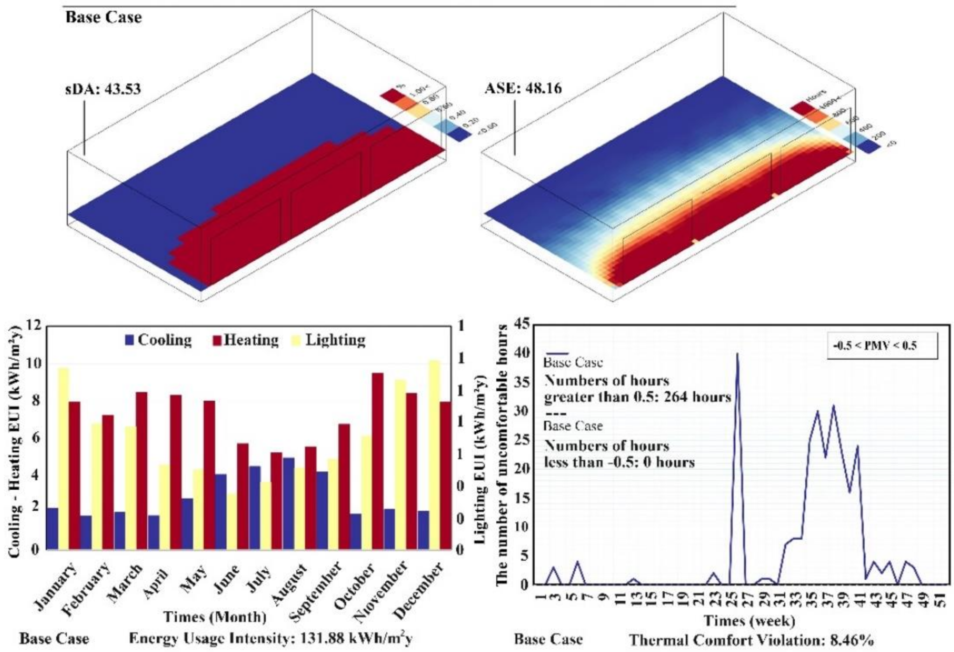

Figure 6. *Energy performance and thermal comfort evaluation of the base case model*

3.2. Performance Evaluation of Optimization Results

The performance analysis of the current office indicated that a window with higher light transmittance would be more advantageous. Consequently, such glass is used in the system simulation. The window properties of the replaced glass are 80% light transmittance, SHGC of 0.75 and U value of 2.9 W/m2K. The results obtained by performing the optimization made it possible to reach the desired objective function with different configurations, that is, with more than one alternative. The best fifteen configurations and values that give the most efficient values are in Table 3 by order of closeness to the target values. The distance of the data obtained from these selected configurations to the target data ranges from 21.02% to -15.59%. The fitness function is negative and far from the objective, probably because of the number of building performance metrics to minimize. Considering the values obtained in the configuration closest to the target, the TCV value is 0.35%, the sDA value is 55.39%, the ASE value is 5.3%, and the EUI value is 128.50 kWh/m2y, while the values obtained in the farthest configuration are 1.60% TCV, 62.93% sDA, 27% ASE and 125.65 kWh/m2y EUI.

Table 3. *Pareto optimal solutions*

1st row	*2nd row*	*3rd row*	*4th row*	*5th row*	*6th row*	*EUI* $(\frac{kWh}{m^2y})$	*TCV (%)*	*sDA (%)*	*ASE (%)*	*Cooling* $(\frac{kWh}{m^2y})$	*Heating* $(\frac{kWh}{m^2y})$	*Lighting* $(\frac{kWh}{m^2y})$	*Fitness Function*
85°	55°	25°	30°	15°	50°	128.50	0.35	55.39	5.3	31.01	90.61	6.88	21.02
85°	55°	30°	15°	15°	60°	128.78	0.16	55.82	6.5	30.85	90.97	6.92	19.16
70°	60°	40°	25°	10°	45°	128.50	0.17	55.00	9.4	30.42	91.17	6.92	13.51
85°	15°	75°	15°	10°	45°	128.40	0.12	55.17	11.9	30.15	91.49	6.76	9.34
90°	55°	25°	25°	25°	40°	12573	1.68	55.82	8.1	33.71	90.13	17.66	-0.72
70°	20°	65°	20°	25°	90°	127.82	0.16	56.03	18.9	27.91	92.67	7.24	-2.16
85°	20°	70°	35°	15°	20°	128.32	0.22	55.00	17.3	30.47	90.96	6.89	-3.55
90°	20°	70°	35°	10°	20°	128.29	0.28	56.47	19.2	30.39	91.06	6.84	-6.58
55°	55°	90°	15°	15°	15°	125.67	1.63	61.21	22.3	24.95	93.96	6.76	-7.48
5°	60°	90°	15°	10°	40°	126.03	1.63	57.11	19.6	25.04	93.94	7.05	-8.15

20°	60°	50°	15°	50°	90	126.64	1.63	55.17	18.3	25.24	93.78	7.62	-11.09
55°	55°	70°	25°	10°	50°	128.25	0.13	60.56	24.3	29.72	91.82	6.71	-11.68
50°	60°	50°	15°	45°	90°	125.74	1.63	64.66	25.7	25.07	93.88	6.78	-11.89
85°	35°	30°	70°	90°	45°	126.51	1.51	75	29.9	27.10	92.86	6.55	-13.45
90°	25°	90°	15°	10°	40°	125.65	1.60	62.93	27.0	25.06	93.91	6.68	-15.59

The results show that finding an optimal situation, in which all the metrics reach the target value simultaneously, is limited because of four conflicting objective functions. The number of discomfort hours decreased significantly in all solutions compared to the base case and was below the ASHRAE recommended value of 10%. Considering the daylight performance, many obtained values were above 55% regarding sDA, but values below 10% ASE were few. However, in all cases, the proposed kinetic shading device keeps the ASE value significantly below the threshold value compared to the base case, and much better visual comfort results were obtained. The existence of studies in the literature on reducing the ASE value of kinetic facades also supports this situation. Le-Thanh et al. [19] reported that with their proposed kinetic façade design, the ASE decreases compared to the base case, and there is a relationship with the energy required for cooling, and the cooling load decreases as the ASE decreases. Examining the amount of energy consumed demonstrates that the share of heating energy in the total consumption during the year is high. The kinetic façade's shading function improves cooling loads since it reduces unwanted heat gain in summer, yet there is an increase in heating loads as it simultaneously reduces heat gain in winter. For a more comprehensive examination of the results, the first three configurations (shown in Table 3) closest to the target are visualized and compared with the base case.

In the first Pareto optimal configuration, the panel angles are 85, 55, 25, 30, 15 and 50 from top to bottom, respectively. In the second configuration, these folding angles are 85, 55, 30, 15, 15 and 60. The angles in the third configuration are 70. 60, 40, 25, 10 and 45. Compared to the base case, the sDA value improved by 27.25%, 28.23% and 26.35%, respectively. The ASE value obtained in the three configurations compared with the base case shows an improvement of 89.08%, 86.50% and 80.50%, respectively in Figure 7. All three solutions met the criteria required by LEED. According to the base case, they significantly improved visual comfort by helping to reduce discomfort from direct sunlight in front of the window.

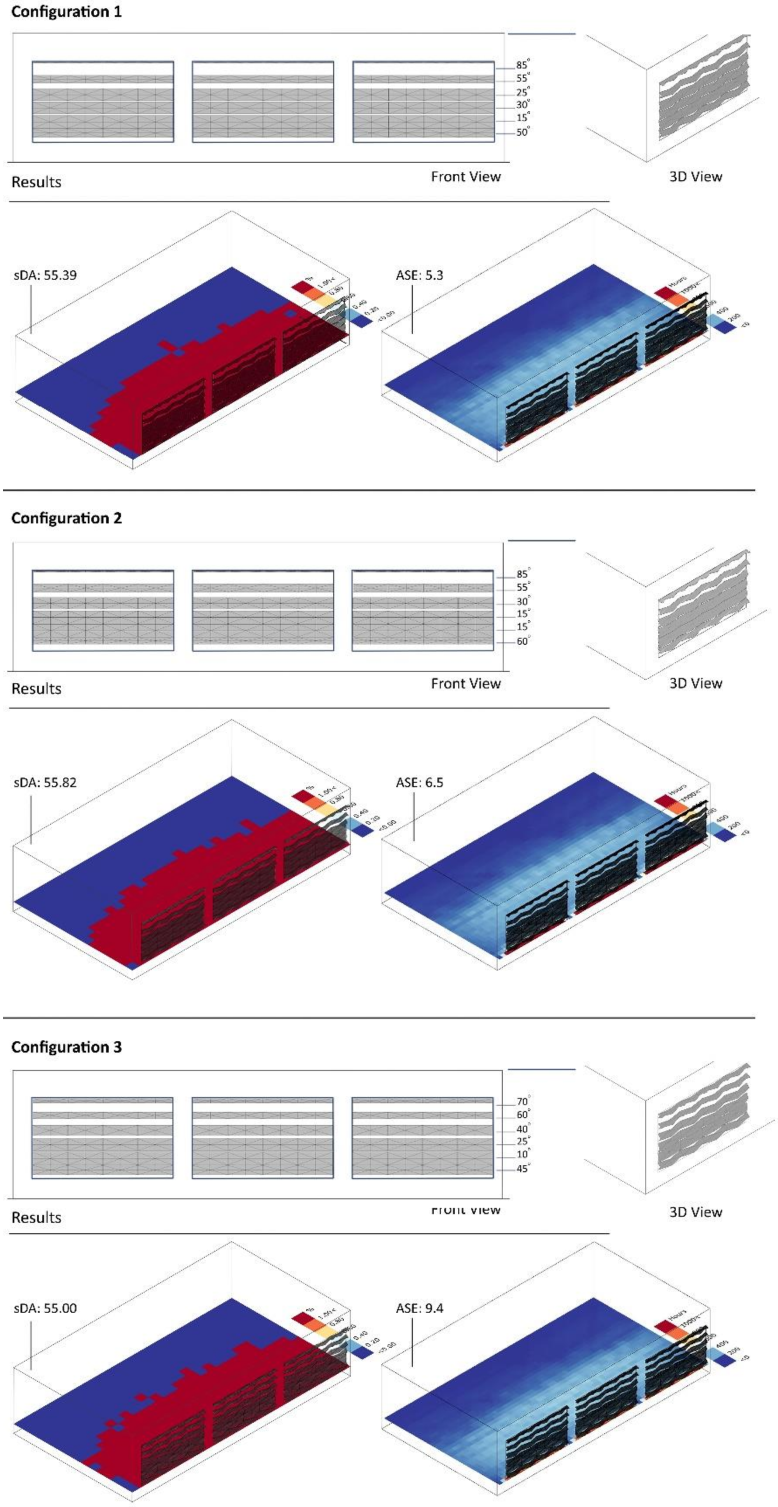

Figure 7. *Comparison of configurations with base case in terms of daylight performance*

An evaluation of the energy performance of the selected solutions showed that the total energy consumed decreased about 2.50% compared to the base level (Figure 8). While the energy consumed for cooling was 34.48 kWh/m^{2}y in the base case, almost 11% improvement was achieved with the proposed facade system. Regardless, the alternative facade configurations caused an increase in heating energy as a side effect. This study evaluated the alternative configurations annually. The energy spent on lighting decreased by 19.50%, 19.04%, and 19.06%, respectively. Including the daylight-dependent lighting schedule in the simulation contributed to this result. Examining the effect of panel movement on energy consumption reveals that it is necessary to have higher panel angles to obtain natural light and a higher sDA value, yet, in this case, the heating energy is negatively affected. In addition, ASE and TCV are adversely affected by this situation. As the panels close, the cooling and lighting energy increases. Therefore, movements of a kinetic facade are the crucial parameters to be considered in the early design phase to calculate solar heat gain [40, 41].

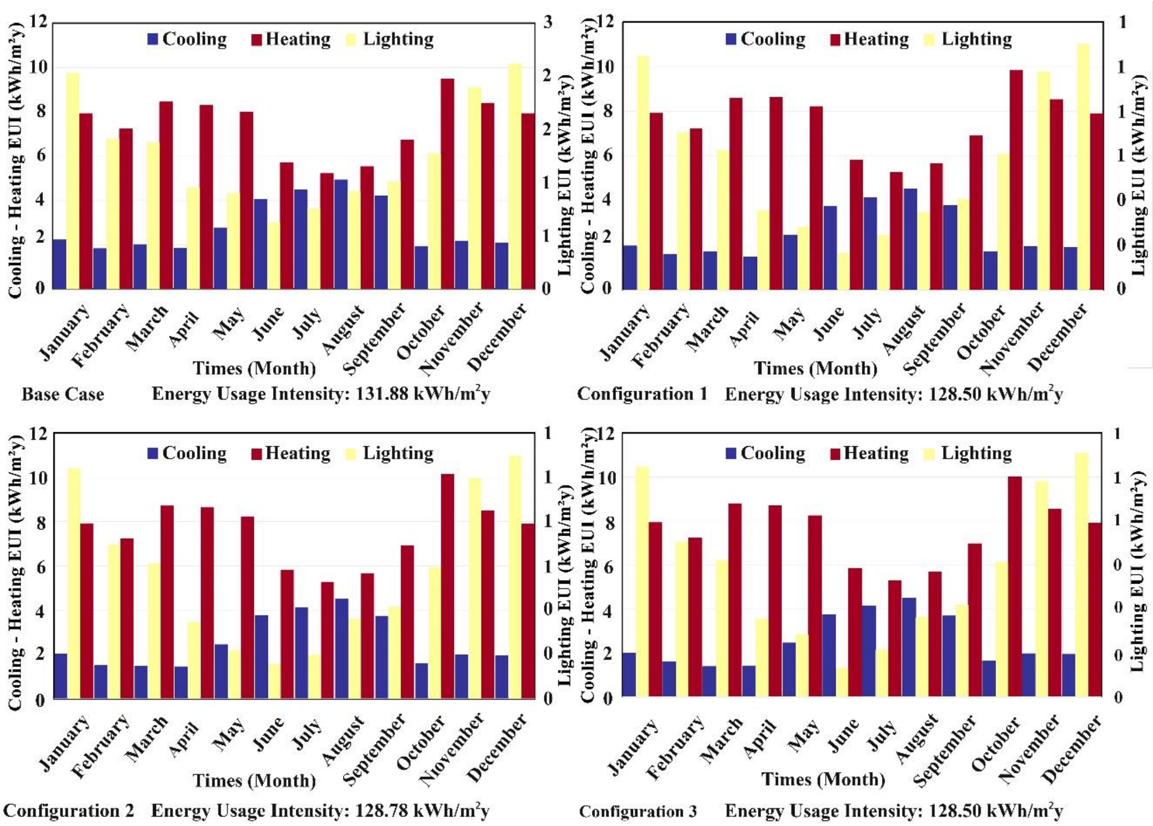

Figure 8. *Comparison of configurations with base case in terms of energy performance*

In the thermal comfort evaluation, the number of discomfort hours decreased considerably compared to the initial situation. 95.83%, 98.11% and 97.99% improvements were achieved, respectively. As detailed in Figure 9, the discomfort experienced by feeling hot decreased from 264 hours to 8, 5, and 6 hours, resulting in an improvement of 96.97%, 98.11% and 97.73%, respectively. On the other hand, no change was observed in the alternatives caused by the discomfort caused by the cold. The proposed facade system has helped to reduce the heat gains in the interior for the summer season. Yao [27], in his study with a movable external shading device, also confirmed that such a system reduces heat gains and improves indoor thermal comfort by 21% in summer. Rizi and Eltaweel [15] also achieved an average of 60% improvement in heat gain through the proposed kinetic façade compared to conventional shading. While more heat gain reduction is possible with different configurations, the Pareto optimal solution set also considered many criteria; therefore, the resulting reductions are less than the literature that only focus on heat gain reduction.

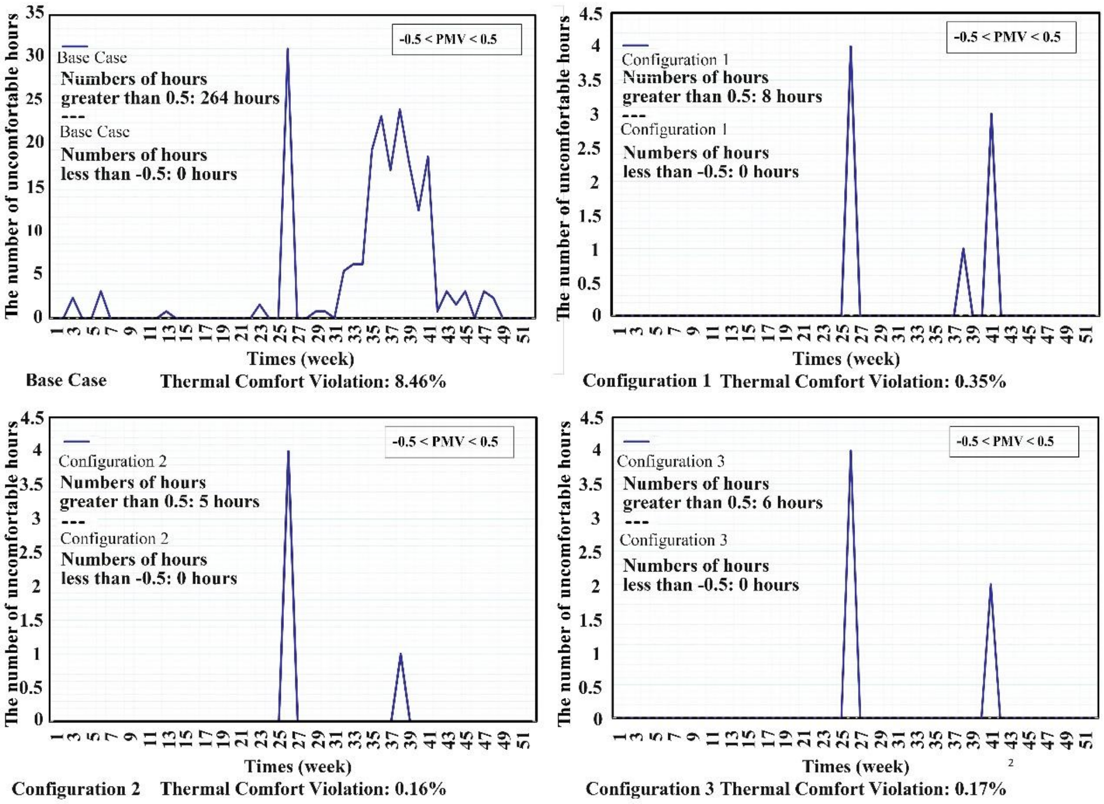

Figure 9. *Comparison of configurations with base case in terms of thermal comfort*

4. CONCLUSION

During the design process, necessary precautions should be taken to use daylight and energy effectively in buildings and provide user comfort as much as possible. One of the critical decisions and effective parameters in this process is related to the building envelope. Analyzing the performance of any change in the building envelope is crucial for making well-considered decisions. Multi-objective optimization significantly helps architectural projects as it can solve complex problems with various parameters and provide the best solutions to a defined problem. Accordingly, the folding kinetic facade system proposed in this study controls daylight, energy consumption and thermal comfort. A multi-objective optimization study was used to find the balance between these contradictory and highly complex building performances using TCV, EUI, sDA and ASE metrics.

The optimization results show that the proposed kinetic façade system improves indoor thermal comfort between 80.68-98.11%. Although sDA demonstrated an average daylight performance improvement of 34.98%, achieving the desired value by LEED in ASE was minimal. Nonetheless, there was an improvement ranging from 37.95% to 89.08% compared to the base case. A reduction in the total energy load was achieved between 2.39% and 4.72%. The proposed system reduced cooling loads by 17.42% on average and modestly increased heating loads. Lighting loads have improved significantly compared to the baseline condition. Despite this situation in energy performance, thermal and visual comfort improvements reveal that this system is effective. The recommended configurations in terms of thermal comfort ensured that the solar heat gain was kept at the desired level during the cooling and heating periods and reduced the risk of discomfort.

A designer can select between the Pareto-optimal solution set according to other architectural and implementation criteria such as aesthetics, building material and costs. The proposed façade is a modern and practical solution compared to traditional fixed facade systems; the simulation results clearly show that more than one configuration gives positive results when considered yearly. In addition, different configurations provide efficient results and flexibility to the user. Hence, one solution worth investigating in the future is arranging different façade configurations for summer and winter periods. Therefore, the results support the concept of a movable system. While more research is necessary to make this movable shading element usable in an actual building, this study showcases the advantages of using a kinetic façade element in the Mediterranean climate to improve visual comfort without increasing energy consumption or decreasing thermal comfort.

CONFLICTS OF INTEREST

There is no conflict of interest to declare by the authors.

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