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Integrating interactive kinetic façade design with colored glass to improve daylight performance based on occupants' position

Seyed Morteza Hosseini [a,*], Masi Mohammadi [a], Torsten Schröder [b], Olivia Guerra-Santin [a]

[a] Smart Architectural Technologies, Department of the Built Environment, Eindhoven University of Technology, Netherlands

[b] Architectural Design and Engineering, Department of the Built Environment, Eindhoven University of Technology, Netherlands

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ABSTRACT

The dynamic nature of daylight and occupant's position can cause some issues such as heat gains and visual discomfort, which need to be controlled in real-time operation. Responsive facades have been pervasively used for preventing daylight glare and meeting daylight performance requirements. However, some passive strategies such as the colored glass of the Orosi typical architectural elements used in Iranian central courtyard buildings have the potential to filter excess daylight, as well as providing other functions such as aesthetics and privacy. This paper explores, for the first time, the possibility of coupling a kinetic façade with colored glasses to improve the daylight performance. This research builds on a combination of relevant literature and parametric simulation to investigate the development of integration of colored glass from Orosi with interactive kinetic façades, triggered by sun timing and occupants' positions. In total, 72 interactive kinetic façade cases are parametrically simulated, and their daylight performance is evaluated through climate-luminance based metrics. The simulation results confirm the high performance of the interactive kinetic facades for improving daylight performance regarding a base case. The integrated interactive kinetic façade with colored glass provides a real-time adaptation of the multifunctional passive strategy to sun timing and occupants' position. The integrated interactive kinetic façade with colored glass which uses parametric decentralized and hierarchical rotating (0–45°) movements, shows more improvement in daylight performance compared to other cases based on climate-luminance based metrics evaluation.

1. Introduction

The operation of buildings contributes to approximately one-third of the global energy use and a similar share to the greenhouse gas emission [1]. Several building façade designs have been developed to provide comfortable conditions for occupants. These facades interact with their ambient environment using renewable energy sources on or near the buildings [2,3]. Applying passive strategies in the early stage of design, using smart functions, leads to improve occupants' comfort and decrease energy consumption by controlling the intensity of solar radiation [4]. Efficient solar design as a main passive strategy can decrease heat gains and visual glare improving visual and thermal comfort [5–7]. The passive design of buildings, employs orientation, geometry, shape, layout compactness, opening characteristics and material as factors, influencing occupants' comfort conditions [8–15]. However, active technology has potential to improve the control of buildings employing multifunctional systems, and automatic, responsive and reconfigurable components to meet users' comfort [16–19]. For example, the kinetic interactive façades of al-Bahr towers [20] and Helio Trace Centre of Architecture [21], by using responsive and smart components, reduce solar heat gains by 50% and 81% respectively, when compared with fixed façades. Therefore, integrating passive strategies with active technology in the shape of kinetic façades has the potential to improve occupants' comfort in real-time, responding to environmental parameters.

Natural light, as a renewable and permanent source, has positive effects on building occupants, including psychological, mental and physiological [15,22–24]. Nonetheless, the dynamic nature of daylight causes some issues such as heat gains and visual discomfort, which need to be controlled in real-time operation. Although responsive components have been pervasively used for regulating daylight glare and daylight performance, some passive strategies have not been investigated such as colored glass in Iranian central courtyard building which provides an opportunity to be integrated with kinetic façade to improve

* Corresponding author.
E-mail address: s.m.hosseini@tue.nl (S.M. Hosseini).

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visual comfort. This application offers two important reactions response to daylight: real-time responding and simultaneous filtering. A closer look at the Iranian latticed window with colorful pieces of glass called Orosi (Fig. 1) reveals their high daylight performance as well as other functions such as aesthetic, privacy and psychological effects [25–31]. It appears that applying colored glass in the window and estimating the appropriate percentage of each colored glass, depend considerably on space function, material, user preferences, local climate and design purpose [28,32]. Therefore, this paper explores, for the first time, the possibility of coupling a kinetic façade with colored glasses to improve the daylight performance. This research aims to investigate the integration of colored glass from Orosi with an interactive kinetic façade triggered by sun timing and occupant positions. The research is framed by the following questions: 1) what is the function of Orosi in traditional buildings and what are the most applied colored glass in Orosi windows of Iranian traditional courtyard buildings? What is their daylight performance regarding climate-based daylight metrics? What is the improvement in daylight performance of integrated interactive kinetic façades with colored glass in comparison with interactive kinetic façades with opaque panels?

2. Method

This research builds on a relevant literature study and parametric simulation to investigate the integration between colored glass Orosi elements and interactive kinetic façade triggered by sun timing and occupant positions. The first part (sections 3.1, 3.2) of the research investigates the function of Orosi elements in traditional Iranian buildings and discerns the most applied colored glasses in the central courtyard building of Iran using relevant literature. Moreover, their daylight performance and visual comfort are studied through climate-luminance based daylight metrics using daylight performance prediction guidelines from Reinhart (2011) [34]. The second part (sections 3.3, 3.4) of the study focuses on research and case studies related to the kinetic interactive shading façade to develop an innovative kinetic façade using colored glass. This research leads to a proposal for an innovative combination of kinetic façade and colored glass triggered by sun timing and occupant's position which activates a passive strategy in a real-time operation (Fig. 2). In a final step (section 3.5), daylight performance of the interactive kinetic façade is evaluated in two steps: a) interactive kinetic façade (IKF) and b) integrated interactive kinetic façade with colored glass (IIKFCG). Well-known software and plugins are used to evaluate daylight performance, including Rhino 6, Grasshopper and Diva 4.

3. Colored glass and orosi

Designing of religious and remarkable buildings in the medieval period depends considerably on correlation of lighting, architecture and climate to demonstrate the aesthetics of the interior spaces [36,37]. Glass as an influential material in the façade allows an adequate amount of daylight to enter interior spaces. Consequently, glass production for architectural buildings in central Europe increased significantly between 1250 and 1500 [38]. In particular, stained glass as a multifunctional element was used in both religious and civil architecture for ornamental and iconographic functions, and for filtering light [36,37,39]. Emerging Gothic style in the thirteenth century caused to use of colored glass and large windows in church façades, which encouraged decreasing in glazing transmission. Moreover, "Gothic apertures were often filled with richly colored glass that restricted interior lighting" [37]. Exporting colored glass to the Middle East, specifically to Iran provided an exceptional opportunity for integration of colored glass with rich Iranian traditional architecture. This combination led to invent a multifunctional architectural element called Orosi.

3.1. Orosi in Iranian architecture

Iranian traditional architecture demonstrates a regulatory function of buildings to modify notable microclimate forces specifically sunlight. "Traditional Persian house can be considered to be a world that is organized to suit the spirits and bodies of its residents using water, earth, wind and sun" [40]. Gharavi Alkhansari [40] emphasizes the responsive characteristics of the traditional Persian house that responds to several issues "such as human scale, climatic situation, light, view, and lifestyle through general solutions." In particular, the central courtyard building, as an old form of dwelling, benefits from unique and varied ways of responding to harsh climatic conditions [15,41–43]. This type of building uses several components to provide daylight, air movement and natural ventilation, energy efficiency, thermal comfort, and visual comfort. Multifunctional components in the traditional Persian house such as Orosi windows provide comfortable conditions and energy efficiency as well as beauty and decoration tasks [28,32,44]. Furthermore, Orosi as one of the main architectural elements in the traditional Persian house is a window with a latticed wooden structural frame filled with colorful pieces of glass. This operable full-wall window, facing the south, has fixed or vertical sliding apertures mediating between the interior space and the garden or courtyard [33,44–46]. Several signs denote Tabriz in Iran (the capital of Safavid dynasty 1501–1555) as the birthplace of Orosi. The Orosi, as a luxurious and precious building component, has been pervasively used in the floors of royal palaces, lobbies and residential buildings with different geometries and patterns [44,45]. However, the moveable Orosi, as a seasonal window provides several

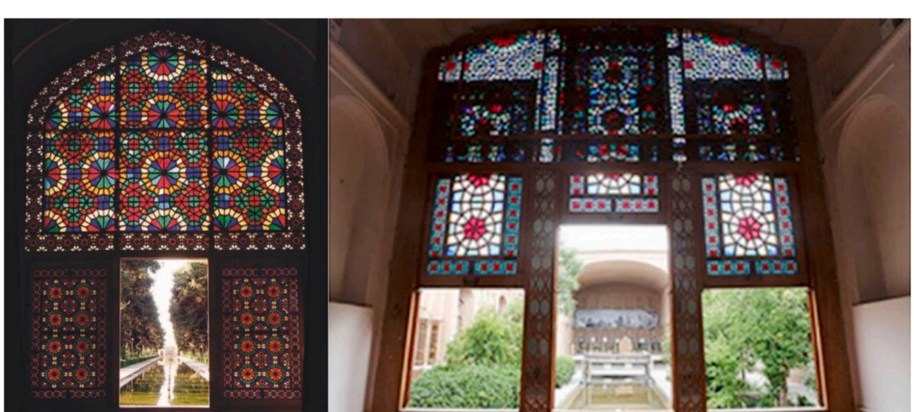

a b

Fig. 1. a) Orosi window in Dowlat Abad Garden Iran, b) Vertical movement of Orosi window for controlling daylight and providing airflow [33].

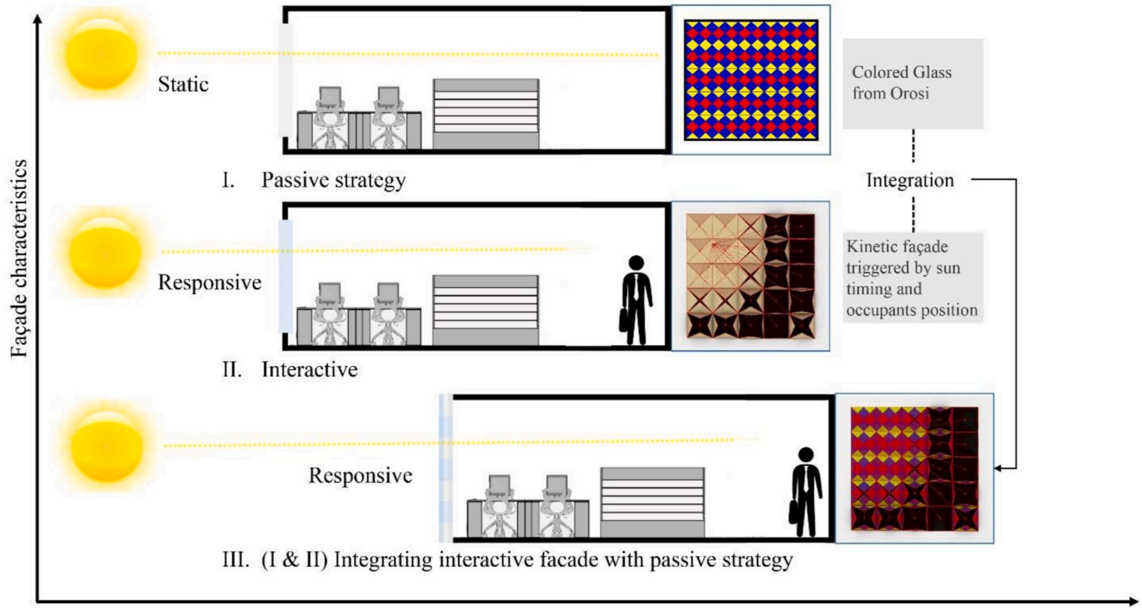


Fig. 2. Innovative integration between colored glass from Orosi and interactive kinetic façade triggered by sun timing and occupant position.

functions comprising daylight controller, facilitating airflow and natural ventilation, view of courtyard and privacy [27,28,32,33,47,48]. Table 1 briefly demonstrates the variety of Orosi windows which have been studied based on climate, function, window pattern and geometry, and colors of glass..

- Although, Orosi windows were used in different climatic conditions in Iran, the climatic functions comprising daylight control, natural ventilation, and airflow have been applied extensively in hot and desert climate (Fig. 3).
- The Orosi window, either fixed or moveable provides several functions consisting of aesthetic, privacy, positive psychological effects, daylight controller, view to the outside, providing airflow, religious belief, and repelling insects.
- The Orosi window shows a variety of patterns and geometries, which have applied in the window's frame. However, most of them use general principles and patterns, including grid form, grid centralized curved pattern, centralized curved pattern, and curved pattern.
- Based on the literature, the most applied colors are red, blue, green and yellow.

The Orosi window as an influential component of the building envelope controls the amount and intensity of admitted daylight into an interior space to provide visual comfort and sufficient daylight for occupants. Orosi window with colored glass creates a sufficient balance between the penetration of daylight and users' visual comfort based on climate-luminance daylight metrics. Although several researchers have studied the positive mental and psychological effects of Orosi on occupant comfort, investigating Orosi windows as a passive strategy for controlling intense daylight is rare. Over recent years, the Orosi windows and colored glass have been studied from daylight performance point of view through quantitative, experimental and simulation methods [27,28,32]. Results from previous research show a considerable potential of the Orosi window and colored glass for improving occupant visual comfort and daylight performance. Using the appropriate color for glass depends significantly on space function, local climate, sun timing position and occupant position. Therefore, integrating colored glass and geometrical patterns with a kinetic facade has huge potential to achieve real-time daylight adaptation due to occupant position and dynamic daylight position (see Table 1).

3.2. Daylight performance simulation of colored glass

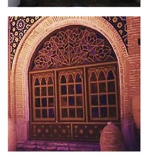
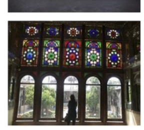
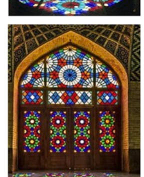
The simulation is performed using Rhinoceros®, Grasshopper, and Diva [35] for analyzing daylighting and energy modeling. The simulation is made assuming that the office building is located in Yazd, Iran. Yazd has been classified in a hot desert climate (*BWh*), which has clear sky based on Koppen climate classification [56]. Furthermore, Yazd weather data used for the simulation process are available from the EnergyPlus website and arranged by the World Meteorological Organization region and Country [57]. Due to the privacy and lighting aspect, Iranian traditional buildings follow a hierarchy arrangement, resulting in the division of interior space into three layers: vicinity of façade (bright layer), intermediate space (semi-dark layer) and private space (dark layer) [29,30]. Therefore, simulation is performed based on these layers (Fig. 4). The width and depth of the floor plan are respectively 4.2 m and 7 m. Building elements are modeled with a thickness of 0.2 m for walls, 0.3 m for ceiling and floor. The height of the room from the top of the floor to the bottom of the ceiling is 2.8 m. Moreover, the window is located on the south façade with a ratio of 0.85 for the window to wall (Fig. 4). Climate based metrics including Daylight Autonomy (DA), Useful Daylight Illuminance (UDI), Exceeded Useful Daylight Illuminance (EUDI) are calculated annually for each façade configuration. The metric to evaluate luminance is the Daylight Glare Probability (DGP) which is evaluated regarding the kinetic façade alternatives on the solstice and equinox days, containing December 21st, March 21st and June 21st [34]. Also, basic elements for studying daylight performance simulation defined in Table 2. The following assumptions are applied to the daylight performance simulation: clear sky with sun, minimum of 500 Lux on the work plane in height of 0.85 m from the floor, occupancy schedule (8–16), a grid of sensors in a scale of 0.5*0.5 m^2, no shading and artificial light.

3.2.1. Optical properties of different colored glass

The Radiance engine is used to perform the daylight simulation in the simulating process. Based on The RADIANCE 5.1 Synthetic Imaging System [58], transmittance "is the total light transmitted through the pane including multiple reflections". Transmissivity (tn) is calculated from transmittance (Tn) using this formula:

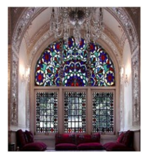
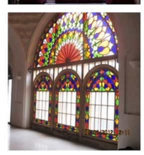
tn = (sqrt(.8402528435+.0072522239*Tn*Tn)-.9166530661)/.0036261119/Tn"

Table 1
Orosi windows analysis based on climate, function, window pattern and geometry, and colors of glass.

Author	Year	Climate	Pattern/Geometry of Window	Function	Window Pattern	Color
Koliji [45]	2016	BWh		A, PE	GF, GCCP	R, G, Y, B
Haghshenas et al [28]	2016	BWh		DC, P, A	CCP, CP	R, G, Y, B
Babaei et al [44]	2013	BWh		DC, VO, A, PAF	GF, GCCP	R, G, Y, B
Wahdattalan and Nikmaram [49]	2017	BSk		A	GF, CCP	R, G, Y, B, O
Valibeig & Ranjbar [47]	2017	BSk		A, DC	GF, CP	R, G, Y, B, O, P
Shahamat [48]	2014	BWh		A, DC	GF, CCP, CP	R, G, Y, B
Zarghami [33]	2017	BWh, BSk		DC, VO, A, PAF, P	GF, GCCP	R, G, Y, B
Habib et al [50]	2013	BWh		P, A, PE, RB,RI	GF, CCP	R, G, Y, B
Tokhmechian & Gharehbaglou [51]	2018	BWh		A, PE	CP, CCP	R, G, O, B
Ahani [52]	2011	BWh		A, PE	GF, CCP	R, G, Y, B
Mehrizi & Marasy [53]	2017	BWh		A, PE, RI	GF, GCCP	R, G, Y, B
Armaghan et al [54]	2014	BWh		A, P, VO	GF, CCP	R, G, Y, B

(continued on next page)

Table 1 (*continued*)

Author	Year	Climate	Pattern/Geometry of Window	Function	Window Pattern	Color
Shirazi [55]	2011	BWh	 	A, P, and VO	GF, CP	R, G, Y, B
Pirnia [31]	2011	BWh		P, DC, A, PE, RB, RI	GF, CCP	R, G, Y, B
Feridonzadeh & Cyrus Sabri [27]	2014	BSk		P, DC, A, PE	GF, CCP	R, G, Y, B

Climate_ BWh: Warm desert, BSk: Tropical and Subtropical Steppe; Functions_ A: Aesthetic, P: Privacy, PE: Psychological Effect, DC: Daylight Controller, VO: View to the Outside, PAF: Providing Air Flow, RB: Religious Belief, RI: Repelling Insect; Color_ R: Red, G: Green, B: Blue, Y: Yellow, P: Purple, O: Orange; Window Pattern_ GF: Grid Form, GCCP: Grid Centralized Curved Pattern, CCP: Centralized Curved Pattern, CP: Curved Pattern.

An RGP transmissivity of *pattern modifying glass* will affect the transmissivity [58]. This pattern includes three parameters consisting of *rtn*, *gtn*, and *btn*. We use this pattern with different proportions of the aforementioned parameters to simulate the transmissivity of the colored glass (Table 3).

3.2.2. *Daylight performance evaluation through climatic-luminance based metrics of colored glass*

Daylight performance of colored glass has been studied through climatic-luminance based metrics comprising Daylight Autonomy (DA), Useful Daylight Illuminance (UDI), Exceeded Useful Daylight Illuminance (EUDI) and Daylight Glare Probability (DGP). DA is identified as “the percentage of the occupied hours of the year when a minimum illuminance threshold is met by daylight alone” [1]. UDI is defined when “there is useful daylight in the back two-thirds of the space (UDI 100–2000 Lux), while EUDI (UDI > 2000 Lux) flags on over-supply of daylight near the façade” [34]. Glare is a human sensation, defined by Harper Collins, “describes light within the field of vision that is brighter than brightness which the eyes are adapted [34]”. The well-known metric suggested by Wienold and Christofersen [59] is Daylight Glare Probability, which uses “CCD Camera based luminance mapping technology.” Furthermore, DGP has been categorized into four groups comprising imperceptible (30–35), perceptible (35–40), disturbing (40–45) and intolerable (45–100) [34]. In particular, DGP has been measured at points assigned to occupants’ positions in the room. Also, Climatic-based daylight metrics have been calculated for test room floors, which have been divided into three sections containing *Bright*, *Semi-dark* and *Dark* parts (Fig. 4).

Results from climate-based daylight metrics (Table 4) clearly distinguish colored glass in two groups. The first group has red, blue and Orosi, while the second includes green, yellow and colorless. At *Bright section*, although the two groups meet the minimum amount of DA appropriate for an office function, red, blue and Orosi provide sufficient and optimal UDI as well. Even though the second group has a higher value of DA compare to the first one, it provides more EUDI resulting in overloading daylight irradiation, and visual & thermal discomfort. Red, blue and Orosi are, in that order, the best options for the *Bright section* for improving daylight performance in the room. Although avoiding excess daylight is a priority for the *Bright section*, choosing appropriate colors for the *Semi-dark section* depends significantly on the space function. In particular, the second group (green, yellow and colorless) is the optimal choice if more daylight is required, while more UDI and the least EUDI achieved by the first group (red, blue and Orosi). It appears that red glass is the best choice for the *Semi-dark section*, having enough potential to meet most of the requirements.

Daylight performance simulation for the *Dark section* differentiates the same two groups. The second group, containing yellow, green and colorless has more DA and UDI value in comparison with the first group. Therefore, yellow and colorless are the best cases for the *Dark section*.

Table 5 displays the DGP value of different colors at a point in the middle of the room, 1 m away from the window on the solstice and equinox days. Simulation results have been carried out in three specific times, including (9:00, 12:00, 15:00) for these days. Based on the DGP value in Table 4, colors are distinguished in two groups comprising the first group (blue, Orosi and red) and the second group (yellow, green and colorless). Daylight Glare Probability is significantly affected by the first group. In particular, red, blue and Orosi decrease considerably the DGP percentage during office time. A closer look reveals that blue reduces DGP more than red and Orosi in all of the options. Furthermore, Orosi decreases DGP value more than red on the 21st of December, while red has better performance than Orosi on the 21st of March and June. Even though, all of the colors are placed in the intolerable range for the 21st December, blue and Orosi display their capabilities for decreasing DGP percentage, as much as possible, comparing with the other colors. In contrast to the first group, the second one has not met DGP visual requirements most of the time. Specifically, without color and yellow glasses are almost in the intolerable range with DGP above 45%.

Overall, applying colored glasses in the south window improves daylight performance. The simulation study emphasizes the light controlling application of colored glass. In particular, blue, Orosi and red improve daylight performance by preventing glare and overloading light (illuminance > 2000 Lux), while yellow, green and without color admit

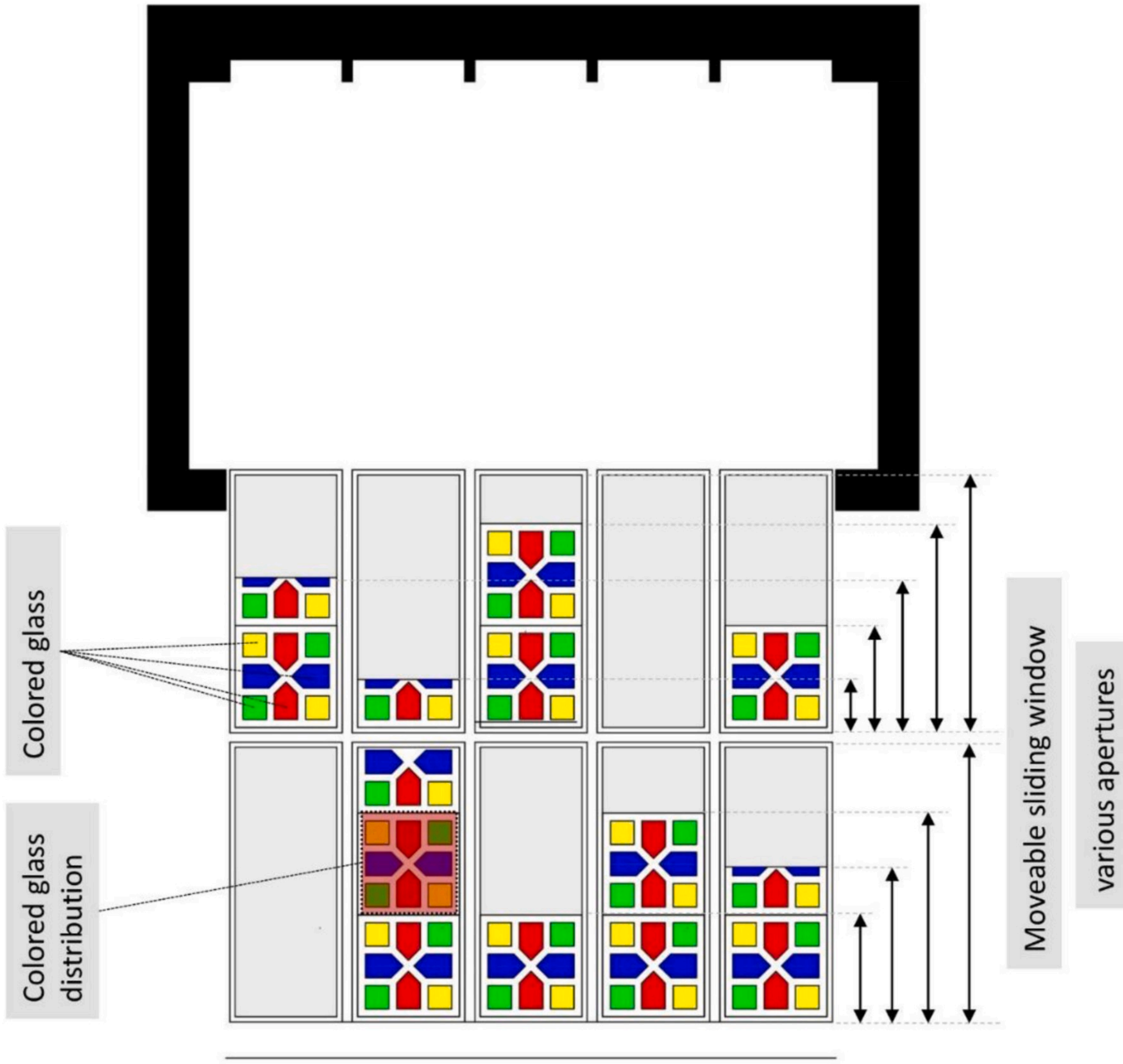


Fig. 3. Combination of elevation (bottom) and plan (top) illustration of movable colored glass apertures concept which control daylight with kinetic movement. Adapted from [45].

daylight to interior space as much as possible. Controlling how deep daylight penetrates space is an important option for designers that can be achieved by colored glass combination in windows. Also, they have an opportunity to consider supplementary artificial light for the individual floor sections. Calculating the ideal percentage of every single colored glass for the Orosi window is challenging work, which considerably depends on space function, interior material and occupants' behavior.

3.3. Integration of interactive kinetic façade with colored glass

Kinetic façades, whether automatic or responsive, benefit from different kinds of movements including translating, rotating, sliding, scaling, expanding and extracting to respond to ambient environmental parameters [15]. Kinetic (dynamic) phase of innovative light guide systems can be classified into the: 1) active sun tracking systems [60,61], 2) dynamic phase change materials [62] and dynamic configurations [63,64]. Dynamic sun-tracking systems apply active PV shading elements and their optimal shapes, adaptive reflective panels in the façade for generating electricity [60], daylight performance and reducing glare [64] and real-time daylight control [61]. The integration of dynamic sun-tracking systems and dynamic configuration has the potential to be applied as an interactive kinetic façade.

The responsive modular components in façades are increasingly used to improve their adaptability to continuous environmental changes. For example, kinetic cladding components [65] and 3D parametric screens [66] demonstrate high performance in meeting daylight performance and visual comfort requirements. The responsive (adaptive) modular elements can be adapted to dynamic daylight by continuously changing façade configurations [15,18,20,21,67,68]. Moreover, parametric decentralized façade configuration can interact with exterior and interior stimuli simultaneously. Applying active occupant engagement into a responsive façade concept facilitates the transition from the façade regulatory function to the interactive phase [69]. Consequently, the interactive kinetic façade, as a multifunctional component, adjusts with different situations and has an opportunity for real-time control regarding sun timing and occupant's positions [69].

Responding to unexpected environmental and interior changes, specifically, sun timing position and dynamic occupants' positions, requires complex interactive behavior in the façade forms that can be achieved by simple relationships between its morphological aspects [15,69,70]. For example, Thyssen Krupp cube building located in Essen in Germany and campus building of the Southern University of Denmark applied flapping and pivot movements with triangular elements for providing interactivity to dynamic daylight resulting in daylight performance and reducing glare [71]. However, Al Bahr towers [20,21]

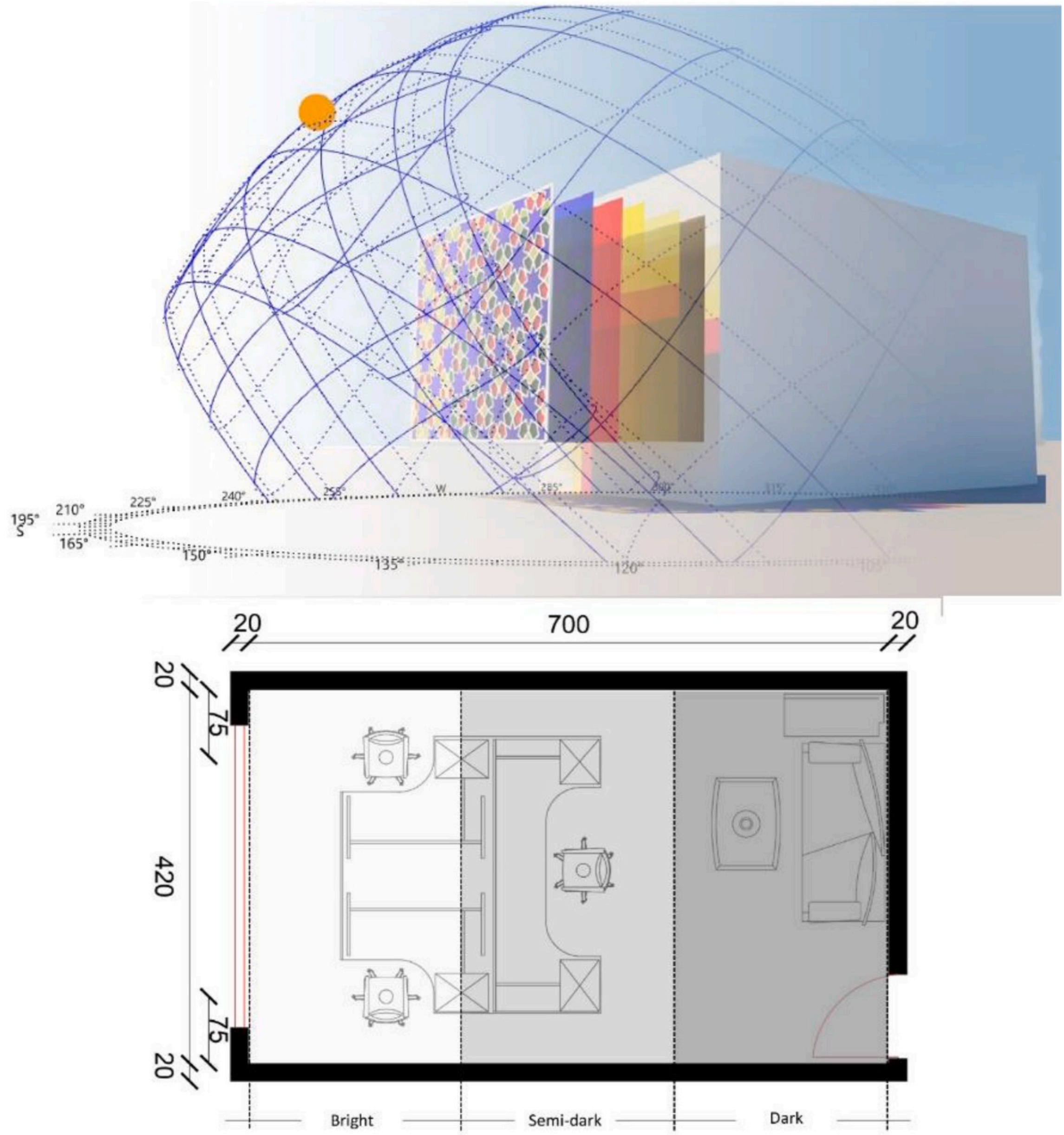


Fig. 4. Test room model for daylight performance simulation with colorful glasses and Orosi. Adapted from [32].

Table 2
Optical Properties of common material surfaces [34].

Interior Floor	20% Diffuse Reflectance
Interior wall	50% Diffuse Reflectance
Interior ceiling	80% Diffuse Reflectance
Single glazing	90% direct visual transmittance
Exterior building surfaces	35% Diffuse Reflectance
Exterior ground	20% Diffuse Reflectance

Table 3
Optical Properties of colored glass.

Glass type (colors)	RGP Transmissivity Parameters		
	Rtn	gtn	btn
Red	0.96	0	0
Green	0	0.96	0
Blue	0	0	0.96
Yellow	0.96	0.96	0
Single Glazing (without color)	0.96	0.96	0.96

used folding, expanding and contracting movements with a parametric decentralized system to deliver daylight interactivity in real-time operation respect to interior space (Fig. 5). This responsive façade, besides the aesthetic function, decreases solar heat gains by more than 50%.

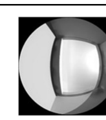
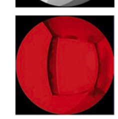
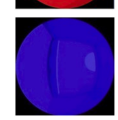
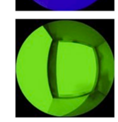
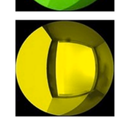
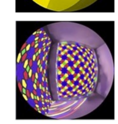
The recent researches by Hosseini et al. (2019) [69] and Tabadkani et al. (2019) [68] indicate the high performance of interactive three-dimensional shape changes in façades for improving visual comfort regarding the sun-timing position and dynamic occupants' positions. Literature briefly displays daylight performance of interactive kinetic façades or colored glass as individual aspects in several functions and scenarios. However, there is a lack of research about the integration of these two design strategies together. Indeed, the interactive kinetic façade, as an active and novel strategy, can be integrated with colored glass, as a passive and traditional strategy, to improve daylight performance and visual comfort. This innovative combination uses passive

Table 4
Daylight Climatic-based metrics evaluation.

Glass color	Daylight Autonomy			Useful Daylight illuminance			Useful Daylight illuminance (Exceeded)			Picture
	Bright	Semi-dark	Dark	Bright	Semi-dark	Dark	Bright	Semi-dark	Dark	
Colorless	94	88	63	8	65	93	85	28	0	
Red	87	36	1.5	50	87	82	43	4	0	
Blue	52	5	0	75	66	19	16	0.22	0	
Green	93	75	25	24	84	92	70	9	0	
Yellow	94	87	57	10	70	93	83	24	0	
Orosi[a]	45	3	0	78	42	8	11	0.83	0	

[a] Percentage of each color participation in the Orosi sample for simulation: Islamic star pattern: 37.95%, Blue: 27%, Red: 15.05%. Yellow: 15.05%, Green: 4.95%.

Table 5
Daylight Luminance-based metric evaluation.

Glass color	Luminance-based metrics Daylight Glare Probability									Picture
	21st March			21st June			21st December			
	9:00	12:00	15:00	9:00	12:00	15:00	9:00	12:00	15:00	
Without color	62	71	50	40	50	37	100	100	49	
Red	29	31	25	23	26	22	100	100	27	
Blue	19	20	18	17	18	15	68	75	20	
Green	48	55	40	33	40	30	100	100	40	
Yellow	61	70	50	40	50	36	100	100	49	
Orosi*	30	32	28	27	29	26	73	77	29	

functions of colored glass (controlling daylight) in an interactive way resulting in developing new complex strategies. Consequently, the new integrated approach revives the useful passive strategy of colored glass and facilitates its multi-functionality in the building (Fig. 6).

3.4. The kinetic façades interaction - results

The simulation evaluates the daylight performance of the kinetic models, which is interactive due to the use of dynamic daylight and occupant's position. The final goal of the simulation is improving visual comfort (specifically preventing glare) and daylight performance. Consequently, the colored glass distribution in the façade (Fig. 7b) has different portions as following: Blue (50%), Red (25%) and Yellow (25%). The kinetic façades follow an interactive logic in four steps for improving visual comfort and daylight performance (Fig. 7c) [69]:

I. Making a user field of vision (UFV) line between the sun (timing) position and occupant position in the office.
II. Identifying an intersection point between the UFV line and the façade surface as an attraction point.

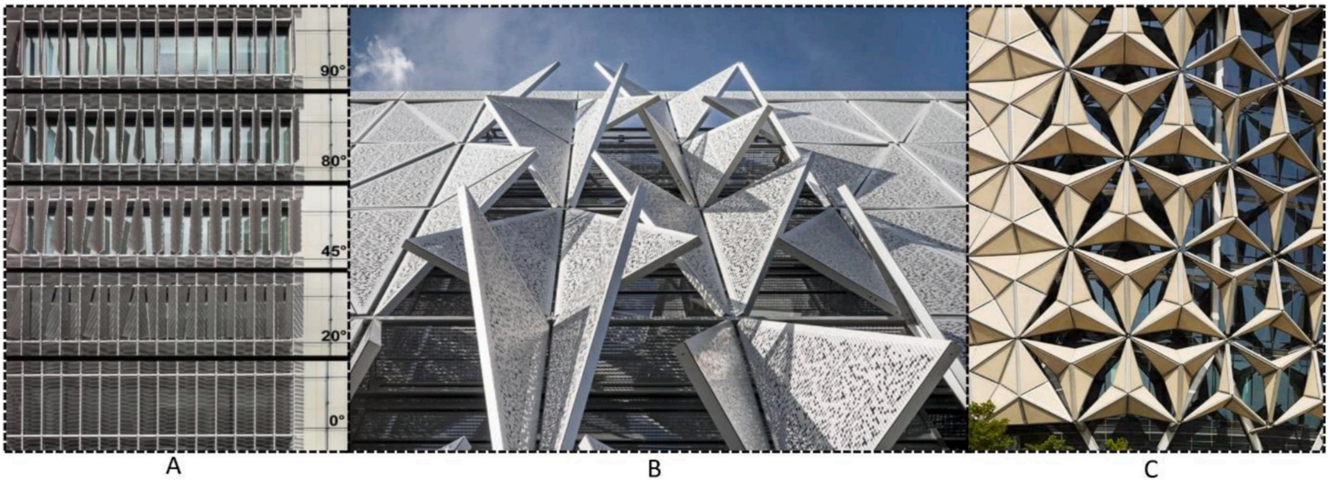


Fig. 5. A) Thysse Krupp cube [71], SDU Campus [71], Al Bahr Tower [20].

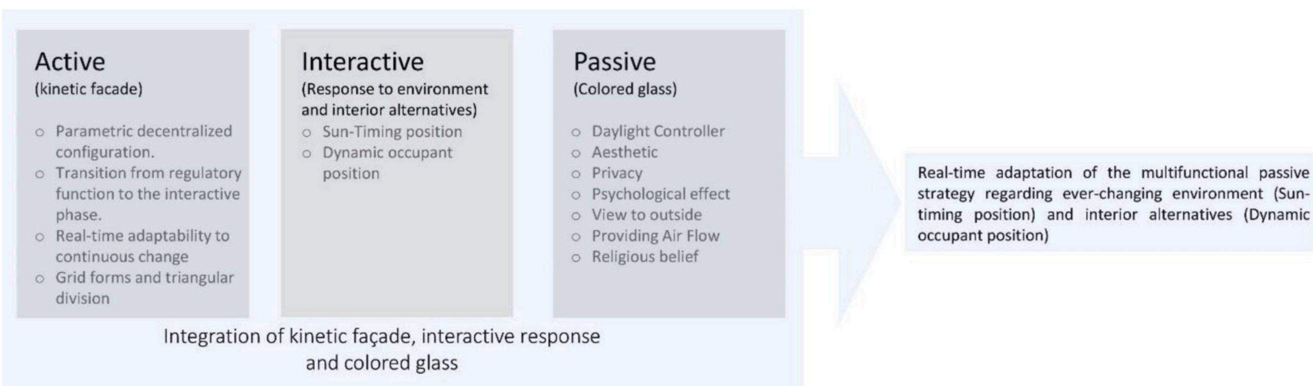


Fig. 6. Integrated approach for interactive kinetic façade and colored glass application.

III. Applying the attraction point as a trigger of a parametric decentralized façade apertures logic to reconfigure the façade modular elements.
IV. Improving daylight performance using the real-time three-dimensional-shape-change, hierarchy and self-shading façade form and colored glass distribution based on the intended function

Visual comfort and daylight performance of interactive kinetic façade have been investigated with three distinct models comprising plain window room, interactive kinetic façade (IKF) and integrated interactive kinetic façade with colored glass (IIKFCG) (Fig. 8).

3.5. Daylight performance simulation results for the three cases

Since the interactive kinetic façade is triggered by occupant position and sun-timing position, for each façade we parametrically simulate 18 different configurations that totally are 72 cases regarding various scenarios (Tables 7–10). These tables represent daylight performance of the facades through climate-based metrics (annual simulation) as well as luminance base.

3.5.1. Plain window room

The evaluation of daylight performance of plain window (base case) through climate-based daylight metrics show that not enough useful daylight is provided to satisfy occupants' requirements. Although enough daylight is admitted into the room (satisfactory DA 90% of the time), the UDI amount (21%) indicates that most of the admitted light is higher than 2000 Lux, resulting in visual & thermal discomfort (Fig. 9). A value of Exceed UDI (72%) proves the aforementioned results. For the prediction of risk of glare, we define three groups based on the occupants' positions and their directions towards the sun. The simulation results locate the room performance in imperceptible (10 cases), perceptible (3 cases) and intolerable (5 cases) ranges. Therefore, approximately in half of the cases, the occupant would suffer from daylight glare and visual discomfort specifically on 21st of December with DGP between 46 and 100% (Table 6).

3.5.2. Integrated interactive kinetic façade with colored glass (IIKFCG)

The simulation results prove the high performance of the integrated interactive kinetic façade with colored glass (IIKFCG) for improving daylight performance in comparison to the base-case. The IIKFCG changes its configuration using colored glass panels integrated with parametric decentralized and hierarchical rotating movements of modular elements to control and filter daylight regarding sun's and occupants' positions based on different daytime scenarios. The Kinetic modular elements rotate parametrically, in two domains, comprising 0–45 and 0–90° (Fig. 10a and b).

Table 7 displays the simulation results for the IIKFCG $_{(0\text{-}45)}$. The results show an average DA, UDI, and EUDI of 54.60%, 72.05%, and 14.05% respectively in all scenarios. The average value of DA indicates sufficient daylight amount in the room and UDI of 72.05% indicates a considerable improvement of useful daylight (100–2000 Lux), in the order of 3.4 times more than the base case. Similarly, the EUDI value achieved by IIKFCG $_{(0\text{-}45)}$ decreases 5 times in comparison with the base case resulting in preventing visual & thermal discomfort. Glare

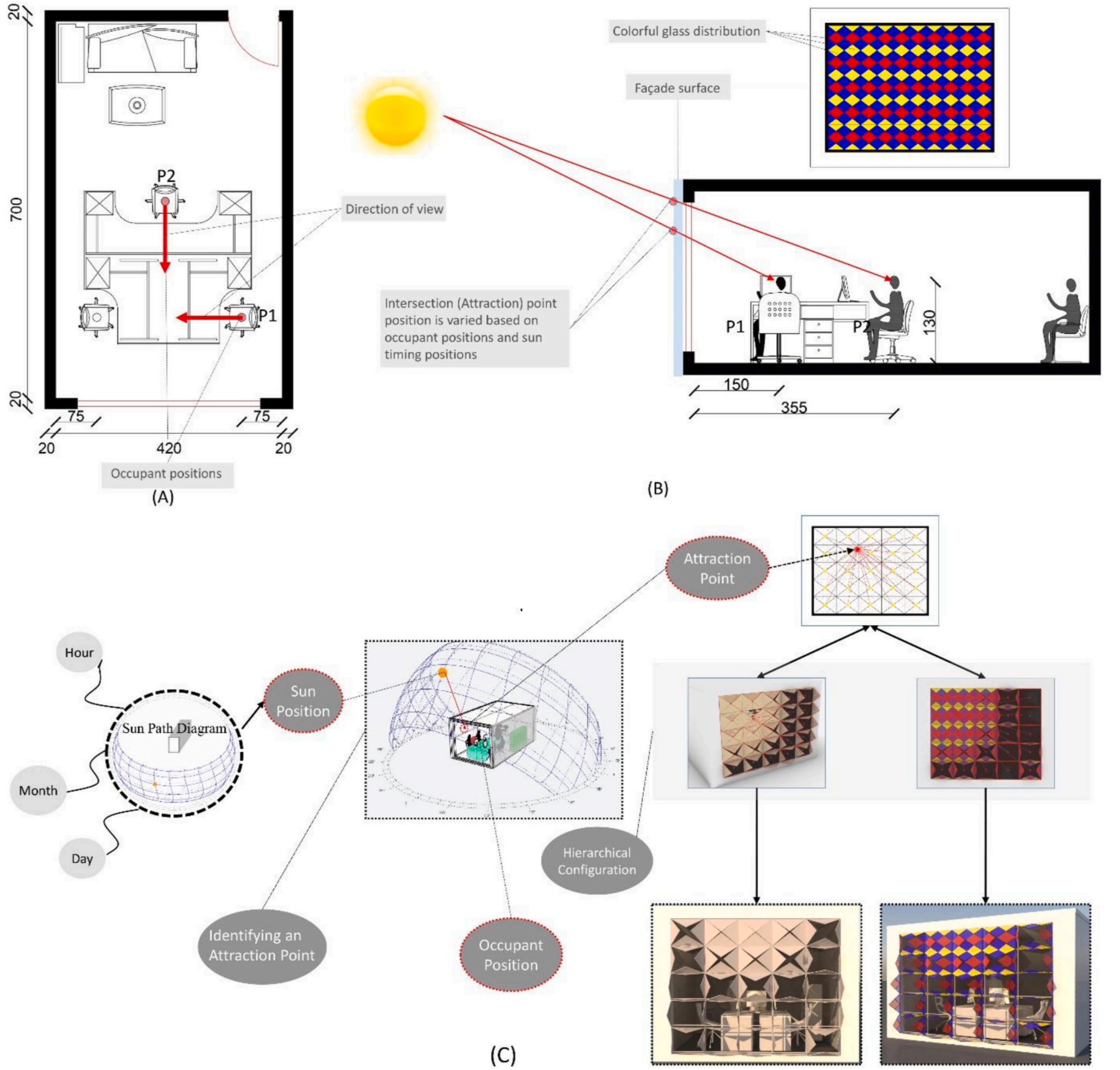


Fig. 7. Interaction of the kinetic façades with sun timing position and occupant position based on the attraction point location and parametric decentralized façade apertures logic resulting in hierarchical modular elements configuration.

evaluation shows that all scenarios are located in the imperceptible zone, except two cases including P1/Dec 21st at 12:00 and 15:00 with DGP of 51 and 59 respectively. The luminance-based metric results indicate that IIKFCG (0–45) improves daylight performance by more than 80% regarding the based case.

Table 8 shows that IIKFCG $_{(0\text{-}90)}$ provides an average DA, UDI and EUDI of 77%, 57.60%, and 34.55% respectively for the whole of the scenarios. With the distribution of colored glass kinetic-panels with pivot-rotation between 0 and 90°, the DA and UDI values remain within the satisfactory range, providing adequate useful daylight in the office room. The DA amount is decreased by more than 40% regarding the base case, however, the UDI amount is increased more than 2.7 times, preventing solar heat gain. Same as IIKFCG $_{(0\text{-}45)}$, DGP is improved in relation to the based case. Only two cases are found in the intolerable zone comprising P1/Dec 21st at 12:00 and 15:00, with DGP of 54 and 62 respectively.

Even though both IIKFCGs improve significantly visual comfort and daylight performance, there is some difference between them. IIKFCG $_{(0\text{-}90)}$ provides an average DA 17.44% higher than IIKFCG $_{(0\text{-}45)}$, while IIKFCG $_{(0\text{-}45)}$ decreases average EUDI 2.4 times less than IIKFCG $_{(0\text{-}90)}$. This means, that IIKFCG $_{(0\text{-}45)}$ brings sufficient daylight to the room, and prevents considerably exceed daylight and solar heat gain resulting in more useful daylight (Fig. 11).

3.5.3. *Interactive kinetic façade (IKF)*

The interactive kinetic façade (IKF) demonstrates a considerable improved daylight performance and visual comfort regarding the base-case. Pivot-rotational movements of modular elements use parametric-decentralized configuration, which provides hierarchical configurations and self-shading geometry for the façade, resulting in improved

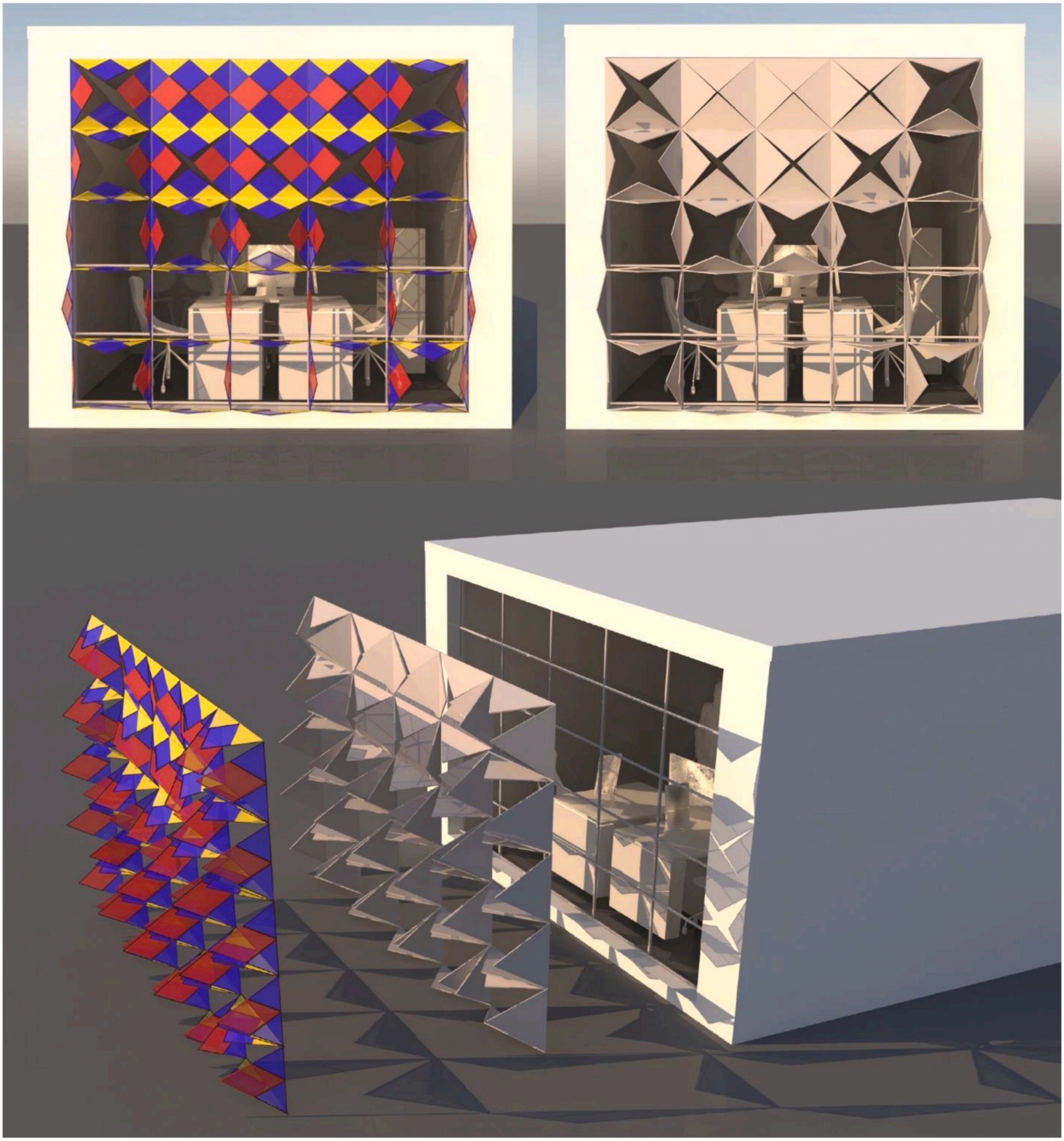


Fig. 8. Test room model for three cases comprising window frame, interactive kinetic façade (IKF) and integrated interactive kinetic façade with colored glass (IIKFCG).

daylight performance (Fig. 12a and b).

Table 9 shows that IKF $_{(0\text{-}45)}$ provides an average DA, UDI and EUDI of 19.72%, 64.94% and 4% respectively in all scenarios. Although the DA value indicates an insufficient amount of daylight in the room, UDI of 64.94% indicates a considerable improvement of useful daylight (100–2000 Lux), in the order of 3.09 times more than the base case. Moreover, IKF $_{(0\text{-}45)}$ decrease the EUDI to 94.44% regarding the base case resulting in completely preventing solar heat gains, visual and thermal discomfort. The evaluation of Daylight glare probability shows that all scenarios are in the imperceptible zone. Even though the façade cannot provide adequate daylight in the space, the luminance-based metric results emphasize the IKF $_{(0\text{-}45)}$ performance for improving daylight performance regarding the based case in all scenarios.

Table 10 shows that IKF $_{(0\text{-}90)}$ provides an average DA, UDI and EUDI of 70.66%, 65.61% and 25.94% respectively for all scenarios. With the distribution of modular kinetic-panels with pivot-rotation between 0 and 90°, the DA and UDI values remain within the satisfied range, which provide adequate useful daylight in the office room (Fig. 13). The DA amount decreases more than 41.61% regarding the base case, however the UDI amount increases more than 3.12 times. Moreover, the IKF $_{(0\text{-}90)}$ reduces EUDI by 63.97% regarding the base-case. Same as with IKF $_{(0\text{-}45)}$, DGP shows a considerable improvement in relation to the

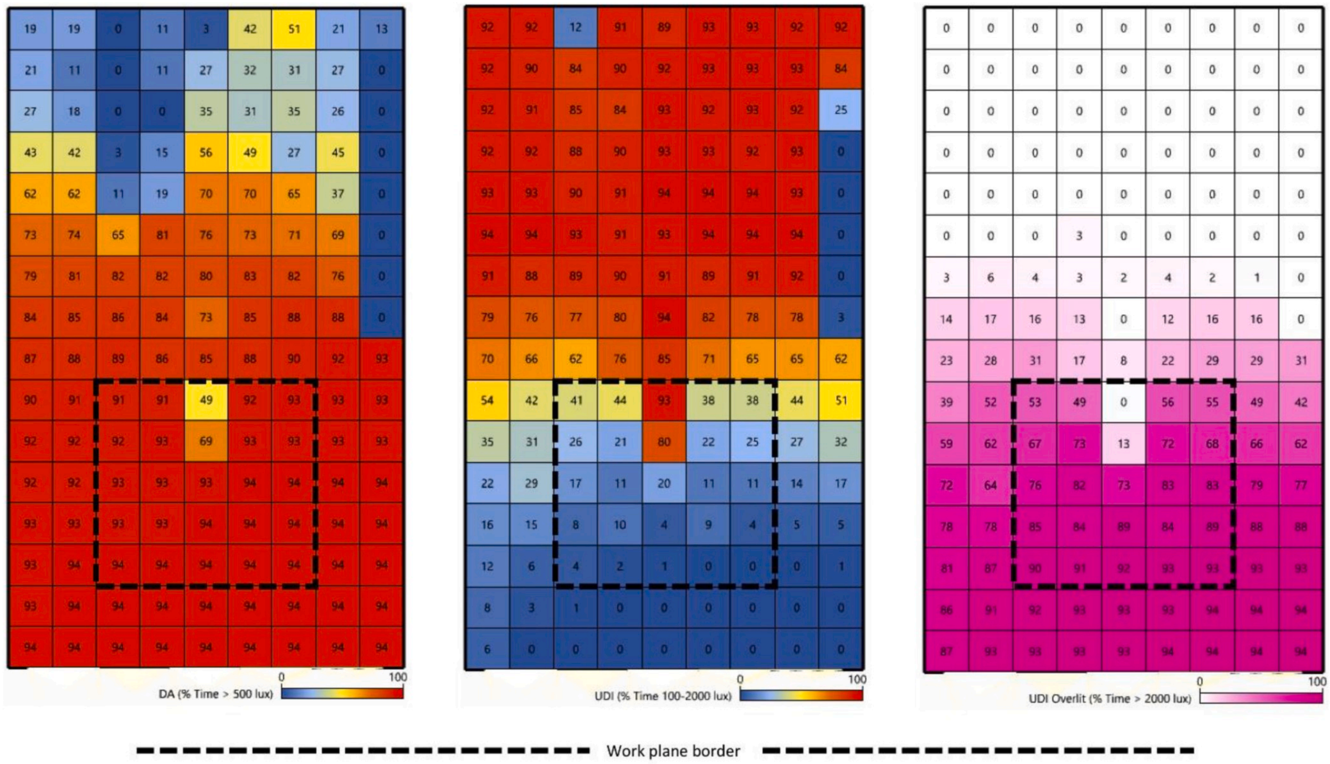


Fig. 9. Climate based daylight metrics grid evaluation (annual simulation) for the case study with plain window. From left to right DA, UDI, EUDI respectively.

Table 6
Plain window room daylight performance Glare probability evaluation for different scenarios based on sun-timing position and occupant position.

Scenario	Office Hours		
	9:00	12:00	15:00
	DGP	DGP	DGP
Person 1/Mar 21st	31	38	33
Person 1/Jun 21st	27	31	28
Person 1/Dec 21st	53	100	100
Person 2/Mar 21st	34	36	31
Person 2/Jun 21st	29	33	29
Person 2/Dec 21st	46	53	36

based case, and IKF $_{(0\text{-}90)}$ fully meets daylight performance requirements.

3.5.4. Difference between IIKFCG and IKF

Although both of the interactive kinetic façades offer a noteworthy potential for improving daylight performance requirements, the simulation results reveal some differences between them specifically through the pivot-rotation changes from 0 to 45 to 0–90°. Both facades $_{(0\text{-}45)}$ keep UDI and EUDI amount within satisfactory ranges for occupants, while the DA amount of IKF $_{(0\text{-}45)}$ could not meet the minimum requirements. In particular, IIKFCG $_{(0\text{-}45)}$ shows high efficiency for keeping DA metric in a sufficient amount, 34.89% more than IKF $_{(0\text{-}45)}$. Both cases are equally efficient to avoid thermal discomfort while meeting daylight performance criteria. However, IKF $_{(0\text{-}45)}$ is more effective than IIKFCG

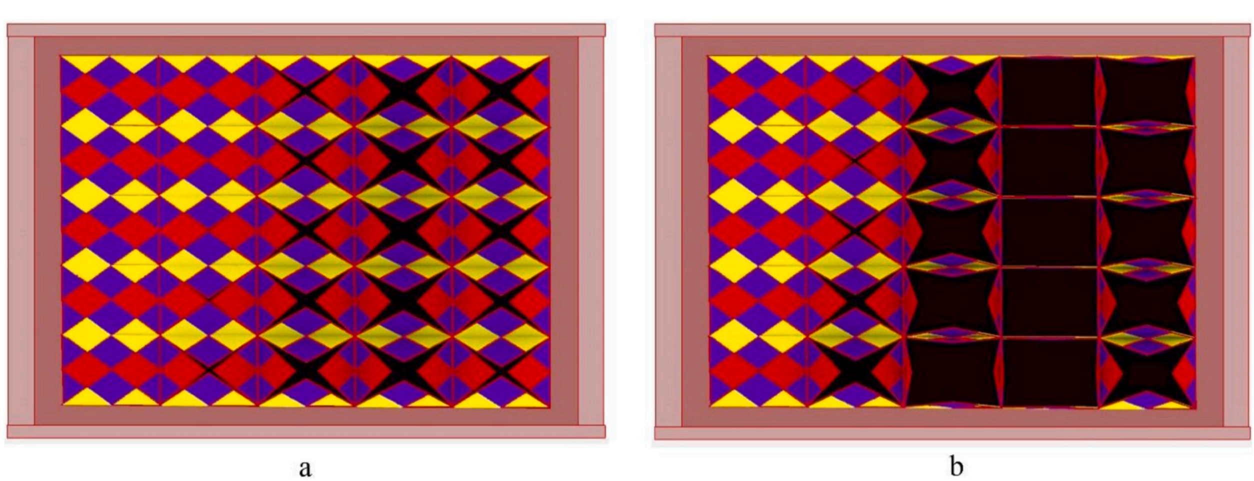


Fig. 10. Integrated interactive kinetic façade with colored glass (IIKFCG) using parametric decentralized façade configuration: a) Pivot-rotation 0–45° and b) Pivot-rotation 0–90°..

Table 7
Daylight performance of integrated interactive kinetic façade with colored glass through climate-luminance based daylight metrics investigation. (Rotation between 0 and 45 Degrees).

Scenario	Office Hours											
	9:00				12:00				15:00			
	DA	UDI	EUDI	DGP	DA	UDI	EUDI	DGP	DA	UDI	EUDI	DGP
Person 1/Mar 21st	59	73	15	22	55	72	12	24	55	71	15	22
Person 1/Jun 21st	61	72	15	21	45	74	10	22	57	70	15	21
Person 1/Dec 21st	56	73	14	29	50	72	13	51	57	73	14	59
Person 2/Mar 21st	58	71	16	26	48	73	11	26	59	72	15	25
Person 2/Jun 21st	58	71	17	25	48	73	12	26	56	71	15	24
Person 2/Dec 21st	58	72	15	28	48	72	13	31	55	72	16	25

Table 8
Daylight performance of integrated interactive kinetic façade with colored glass through climate-luminance based daylight metrics investigation. (Rotation between 0 and 90 Degrees).

Scenario	Office Hours											
	9:00				12:00				15:00			
	DA	UDI	EUDI	DGP	DA	UDI	EUDI	DGP	DA	UDI	EUDI	DGP
Person 1/Mar 21st	79	55	38	24	76	63	29	27	78	55	37	24
Person 1/Jun 21st	80	54	38	23	73	65	26	25	79	54	38	22
Person 1/Dec 21st	80	54	39	32	73	65	27	54	78	55	37	62
Person 2/Mar 21st	79	55	38	27	73	65	27	28	78	53	40	26
Person 2/Jun 21st	80	54	38	25	72	63	29	28	79	53	38	25
Person 2/Dec 21st	79	55	38	31	72	64	28	34	78	55	37	26

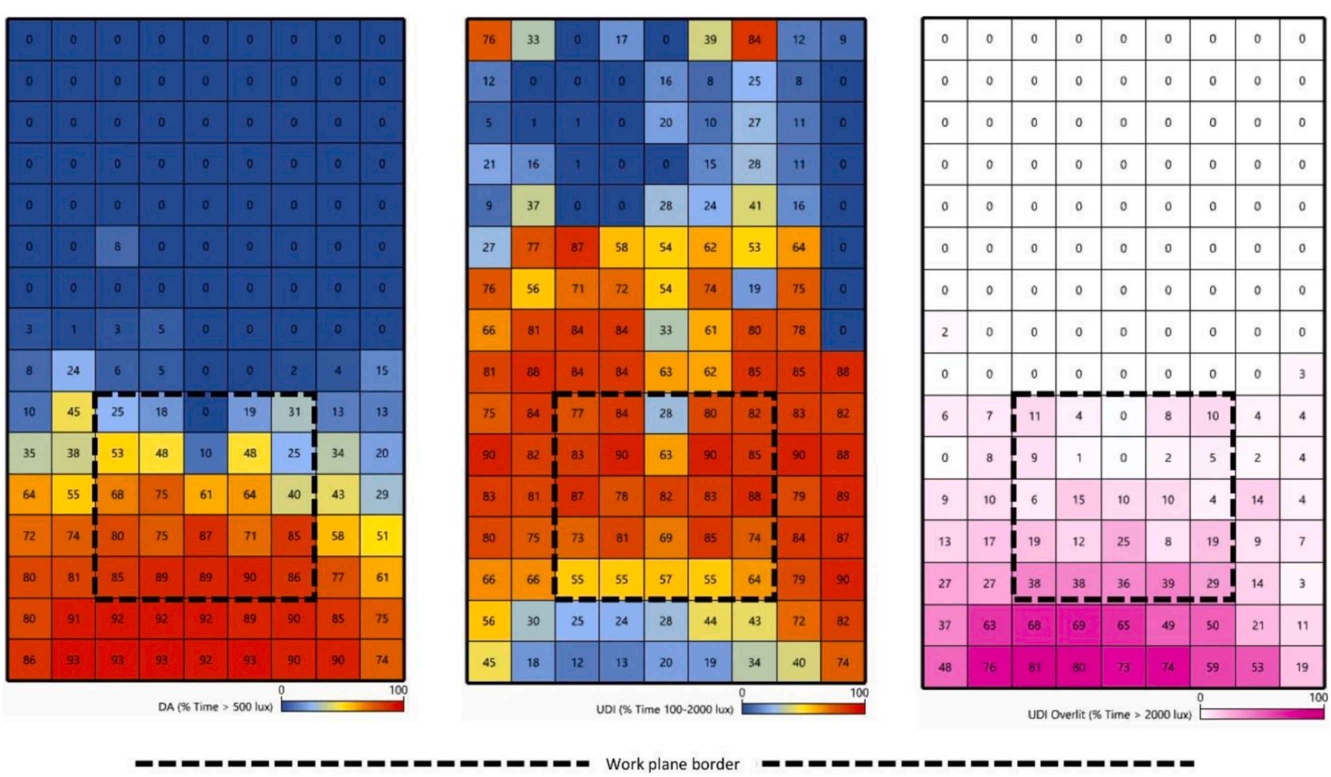


Fig. 11. Climate based daylight metrics grid evaluation (annual simulation) for the IIKFCG $_{(0\text{-}45)}$ configuration triggered by the scenario of Person 1/Dec 21st at 15:00.

$_{(0\text{-}45)}$ regarding meeting daylight glare probability criteria. Façades $_{(0\text{-}90)}$, are in the same situation for UDI and EUDI providing adequate useful daylight in the office room while keeping DA amount in the acceptable value. The simulation for Risk of glare prediction demonstrates that all scenarios locate in the imperceptible zone for IKF $_{(0\text{-}90)}$ while IIKFCG $_{(0\text{-}90)}$ has two scenarios in the intolerable area (Table 11).

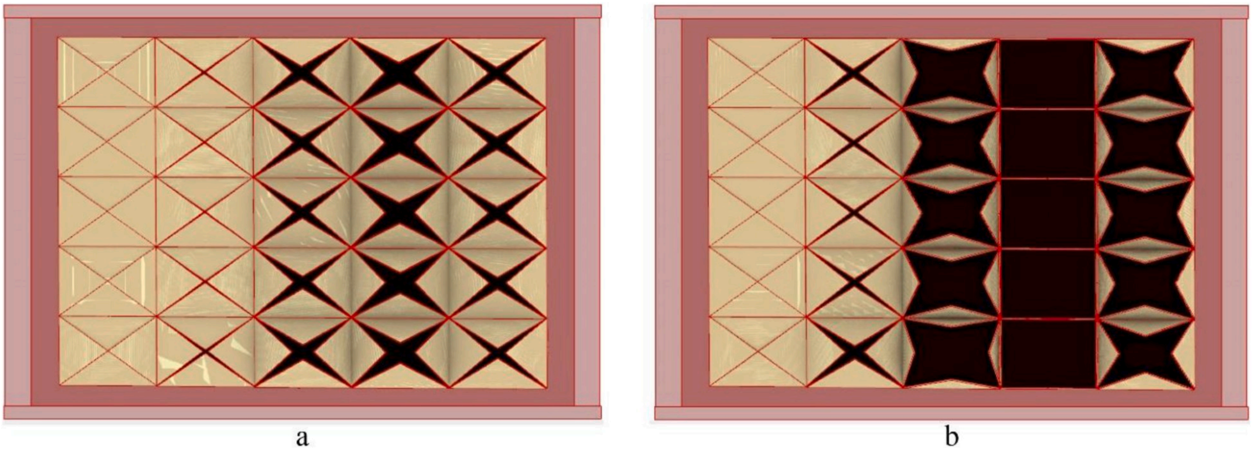


Fig. 12. Interactive kinetic façade (IKF) with Parametric decentralized façade configuration: a) Pivot-rotation 0–45° and b) Pivot-rotation 0–90°..

Table 9
Daylight performance of interactive kinetic façade through climate-luminance based daylight metrics investigation. (Rotation between 0 and 45 Degrees).

Scenario	Office Hours											
	9:00				12:00				15:00			
	DA	UDI	EUDI	DGP	DA	UDI	EUDI	DGP	DA	UDI	EUDI	DGP
Person 1/Mar 21st	25	69	5	22	15	59	4	23	22	69	5	20
Person 1/Jun 21st	22	71	5	21	8	52	2	23	24	67	5	15
Person 1/Dec 21st	28	71	5	26	15	58	4	24	22	65	4	18
Person 2/Mar 21st	25	73	4	24	2	52	2	23	26	71	4	23
Person 2/Jun 21st	26	72	4	20	10	57	2	24	24	67	5	11
Person 2/Dec 21st	23	70	4	25	11	59	3	26	27	67	5	24

Table 10
Daylight performance of interactive kinetic façade through climate-luminance based daylight metrics investigation. (Rotation between 0 and 90 Degrees).

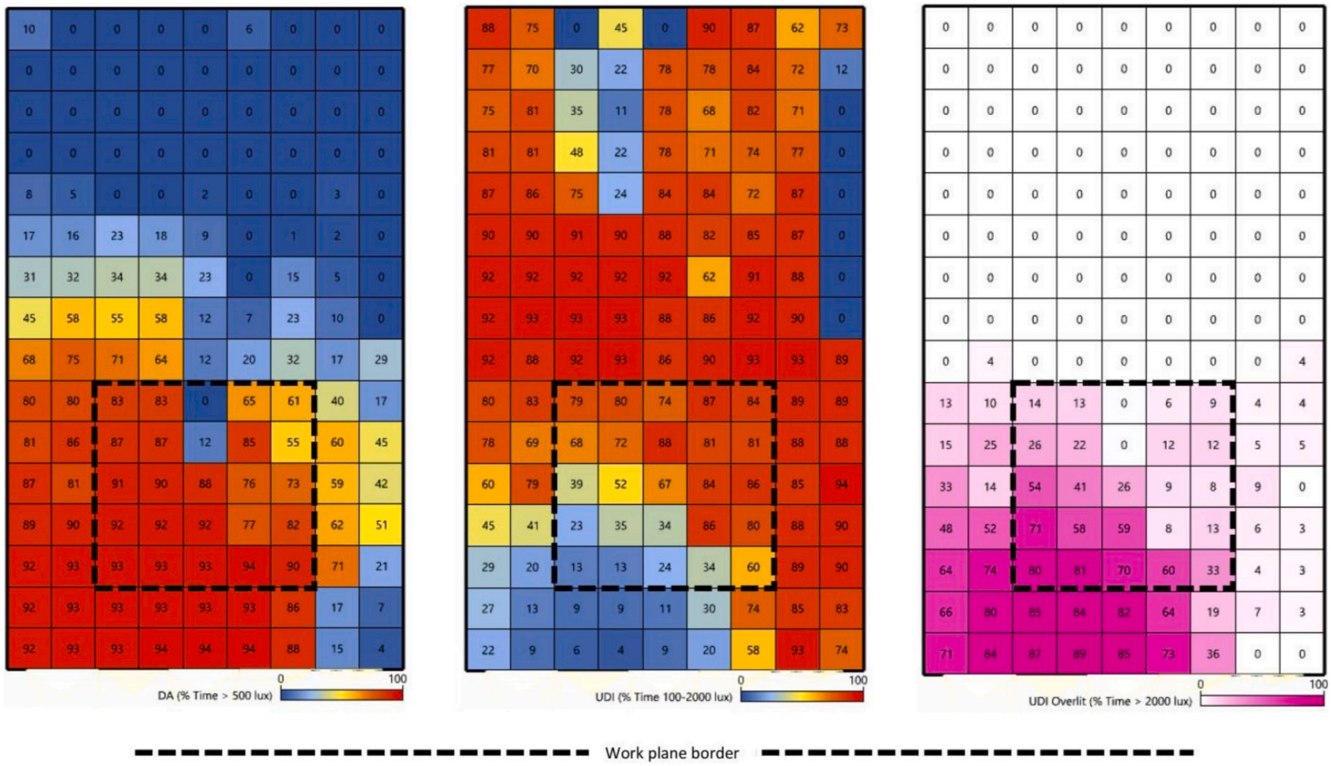
Scenario	Office Hours											
	9:00				12:00				15:00			
	DA	UDI	EUDI	DGP	DA	UDI	EUDI	DGP	DA	UDI	EUDI	DGP
Person 1/Mar 21st	76	61	31	25	66	70	20	26	72	64	29	23
Person 1/Jun 21st	76	61	32	24	60	77	14	25	74	61	30	22
Person 1/Dec 21st	76	62	30	28	57	72	18	28	73	64	27	22
Person 2/Mar 21st	77	61	31	26	62	76	15	26	75	60	32	26
Person 2/Jun 21st	76	62	31	24	65	72	18	26	74	61	30	24
Person 2/Dec 21st	76	62	31	29	63	74	17	29	74	61	31	26

Overall, bringing adequate DA amount, controlling UDI and Exceed UDI by means of IKF $_{(0\text{-}45)}$, IKF $_{(0\text{-}90)}$, IIKFCG $_{(0\text{-}45)}$ and IIKFCG $_{(0\text{-}90)}$ indicate that the facades' multifunctional aspect to regulate dynamic daylight in the ambient environment result in the improvement of daylight performance and the potential to prevent thermal discomfort. Fig. 14 represents the average of annual simulation of climate-based daylight metrics for all the scenarios of the kinetic facade cases individually. It clearly shows the potential of IIKFCG $_{(0\text{-}45)}$ for admitting adequate daylight to the room while providing the maximum useful daylight compared to the other cases resulting in keeping Exceed UDI under 15%.

4. Discussion & conclusion

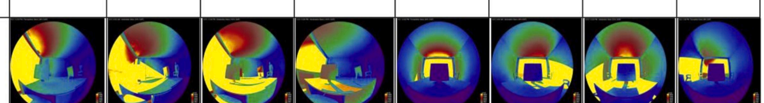
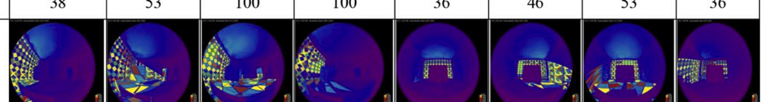
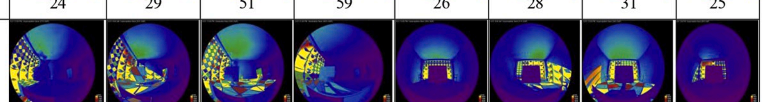
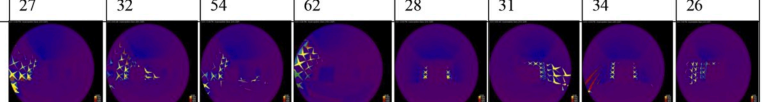
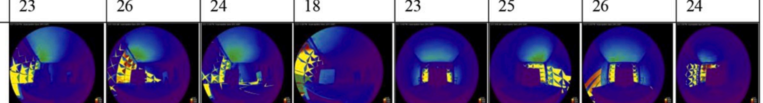
In this study, we have explored the function of Orosi elements in Iranian traditional buildings and distinguished the most applied colored glasses. In the next phase, we developed, for the first time, the possibility of coupling a kinetic façade with colored glasses to improve the daylight performance. This research aims to investigate the integration of colored glass from Orosi with interactive kinetic façade triggered by sun timing and occupant's positions. Since the dynamic nature of daylight causes some issues such as heat gain and visual discomfort, real-time responding and simultaneous filtering are useful to avoid these issues. Therefore, integrating passive strategy with active technology in the shape of kinetic façade has the potential to improve daylight performance with real-time responding to environmental parameters.

On one hand, Orosi windows (as a passive strategy) from Iranian traditional architecture, either fixed or moveable provides several functions consisting of aesthetic, privacy, psychological effects, daylight controller, view to the outside, providing air flow, religious belief, and repelling insect. The simulation study emphasizes the light controlling application of the colored glass. In particular, blue, Orosi and red improve daylight performance by preventing glare and overloading light (illuminance > 2000 Lux), while yellow, green and without color admit daylight to interior space as much as possible. Calculating the ideal percentage of every single colored glass for Orosi window is challenging



ig. 13. Climate based daylight metrics grid evaluation (annual simulation) for IKF $_{(0\text{-}90)}$ configuration triggered by the scenario of Person 2/Mar 21st at 15:00.

Table 11
Daylight Glare Probability (DGP) comparison of the interactive kinetic façades comprising IKF $_{(0\text{-}45)}$, IKF $_{(0\text{-}90)}$, IIKFCG $_{(0\text{-}45)}$ and IIKFCG $_{(0\text{-}90)}$ respect to the base case in the critical scenarios. DGP categorized in four groups comprising imperceptible (30–35), perceptible (35–40), disturbing (40–45) and intolerable (45–100).

Scenarios	P1/Mar/12:00	P1/Dec/9:00	P1/Dec/12:00	P1/Dec/15:00	P2/Mar/12:00	P2/Dec/9:00	P2/Dec/12:00	P2/Dec/15:00
Base-Case								
	38	53	100	100	36	46	53	36
IIKFCG $_{(0\text{-}45)}$								
	24	29	51	59	26	28	31	25
IIKFCG $_{(0\text{-}90)}$								
	27	32	54	62	28	31	34	26
IKF $_{(0\text{-}45)}$								
	23	26	24	18	23	25	26	24
IKF $_{(0\text{-}90)}$								
	26	28	28	22	26	29	29	26

work which depends considerably on space function, interior material and occupants' behavior.

On the other hand, the kinetic façade as an active technology benefits from interactivity to sunlight and occupant's positions. Hosseini et al. (2019) [69] mentions the high performance of interactive three-dimensional shape changes in façade for improving daylight

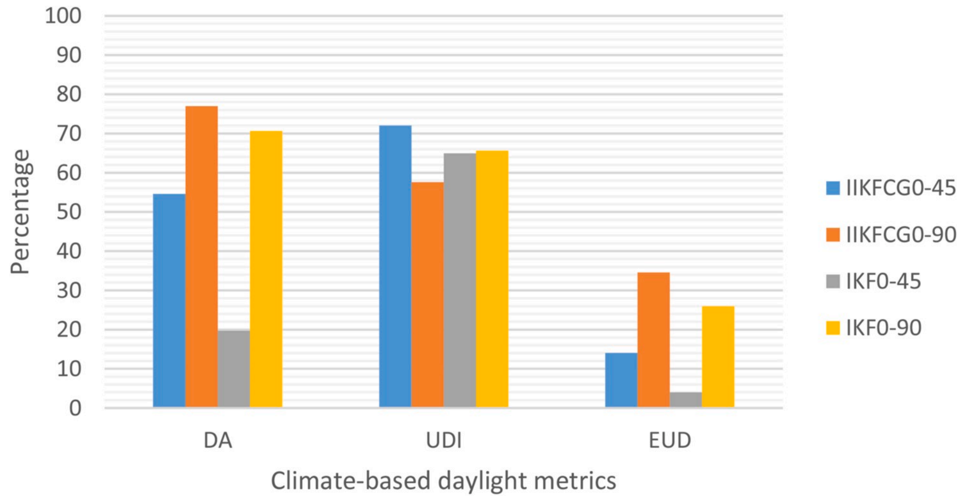


Fig. 14. Average of annual simulation of Climate-based daylight metrics for all the scenarios of the kinetic facade cases comprising interactive kinetic façade (IKF $_{(0-45),\ (0-90)}$) and integrated interactive kinetic façade with colored glass (IIKFCG $_{(0-45),\ (0-90)}$).

performance regarding the sun-timing position and dynamic occupant positions.

The existing literature mentions the daylight performance of the interactive kinetic façade and colored glass individually in several functions and scenarios. However, there is a lack of research on the integration of these two design strategies. Indeed, integrating interactive kinetic façade with colored glass improves the Orosi applications (especially controlling daylight) in real-time operation.

The simulation results of this study confirm the high performance of the interactive kinetic facades comprising IKF $_{(0-45)}$, IKF $_{(0-90)}$, IIKFCG $_{(0-45)}$ and IIKFCG $_{(0-90)}$ for improving daylight performance regarding the base case. However, the simulation results reveal some differences between them specifically through the pivot-rotation changes from 0 to 45 to 0–90°. Both facades $_{(0-45)}$ keep UDI and EUDI amount within satisfactory ranges for occupants, while DA amount of IKF $_{(0-45)}$ could not meet the minimum requirements. In particular, IIKFCG $_{(0-45)}$ shows high efficiency for keeping DA metric in a sufficient amount, 34.89% more than IKF $_{(0-45)}$. Both cases are efficient in avoiding thermal discomfort while meeting daylight performance criteria. In terms of façades $_{(0-90)}$, they bring adequate useful daylight to the office room and avoid thermal discomfort as well, while keeping DA amount within an acceptable range. Regarding DGP evaluation, all of the scenarios locate in the imperceptible zone for IKF $_{(0-90)\ \&\ (0-45)}$ while IIKFCG $_{(0-90)\ \&\ (0-45)}$ have two scenarios in the intolerable area. Overall, the integrated interactive kinetic façade with colored glass shows satisfying feedback for improving daylight performance that is so close to daylight performance of the interactive kinetic façade with the opaque panel. Especially, IIKFCG $_{(0-45)}$ shows a great opportunity for improving occupants' daylight performance compared to other cases based on climate-luminance based metrics evaluation.

To conclude, the interactive kinetic façade, as an active and novel strategy, has a great potential to be integrated with colored glass, as a passive and traditional strategy, for improving daylight performance and visual comfort. Furthermore, this innovative combination enables the façade to benefit from the multi-functionality of colored glass including aesthetic, privacy, psychological in the real-time operation. This new integrated approach revives the useful passive strategy of colored glass in the building application through the interactive way. For future research, the percentage of each colored glass will be customized based on space function, local climate, occupant behavior and interior material. The types of geometries which are used in the Orosi window and their daylight performance need to be investigated. Also, there are opportunities for future investigation in the domain of aesthetic, psychological and privacy effects of the interactive facades with colored glass. Lastly, the interactive behavior of the kinetic façades has the potential to be improved using a reinforcement learning method [72] based on intended aims.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Seyed Morteza Hosseini: Conceptualization, Methodology, Software, Data curation, Writing - original draft, Visualization, Investigation, Validation, Writing - review & editing. **Masi Mohammadi:** Supervision. **Torsten Schröder:** Supervision. **Olivia Guerra-Santin:** Supervision, Writing - review & editing.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2020.101404.

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