Interactive kinetic façade

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Interactive kinetic façade: Improving visual comfort based on dynamic daylight and occupant's positions by 2D and 3D shape changes

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A R T I C L E   I N F O

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A B S T R A C T

Applying active occupant engagement into a responsive façade concept leads us to a transition from the façade regulatory function to the interactive phase. The Interactive façade has the capacity for hierarchically filtering daylight and real-time control, and preventing daylight discomfort. This research applied the combination of qualitative and quantitative methods for studying innovative daylight guide systems functions, relation with building forms and development of kinetic façade forms as advanced real-time daylight control. Literature referred to the responsive modular elements which can be adapted to dynamic daylight by continuously changing façade configurations. In particular, parametric decentralized façade's apertures interact with sun radiation based on relationship between external environment, interior space and occupant position as well. In this study, we develop a kinetic interactive façade with the capability to be transformed based on dynamic daylight and occupant position (functional scenario based) in order to meet visual comfort. Also, daylight parametric simulation investigates visual comfort performance provided by the kinetic façade forms through climate based daylight metrics. The simulation results prove high performance of the kinetic interactive façades for improving visual comfort regarding the base case. In particular, the three dimensional shape changes façade provides more visual comfort improvement than the two dimensional shape changes one regarding UDI, Exceed UDI and DGP metrics. Also, the results refer to multifunctional aspects of the three dimensional shape changes façade, as an advanced interactive daylighting system, which has a capability to control solar radiation in the façade ambient environment for preventing thermal discomfort.

1. Introduction

Natural light provides positive psychological, mental and physiological effects on building occupants [1–4]. The available daylight as a renewable source can reduce artificial lighting using direct sunlight and diffusing light from the sky and ambient environment [5]. "Buildings designed to host and move in concert with passing streams of sun are able to keep us connected with a flowing natural world" [6]. However there are some issues such as heat gains and visual discomfort (daylight glare) that should be considered to obtain visual comfort. Enhancing the useful daylight of interior spaces, as much as possible, has been considered an important goal for architects, building engineers and designers. Since "nature is always in motion, never at a standstill" [6], Balancing visual comfort and taking advantage of daylight is always challenging [2,4,7]; because of the need to study the relationship between human needs and natural lighting based on specific factors such as: amount of light, uniformity of light, quality of light in rendering color, and the risk of glare for occupants" [3,8–10].

Architectural form is an important factor when defining the identity of buildings and determining their interaction with the surrounding environment [1,11]. An optimal building form significantly affects the amount of useful daylight that is admitted in the interior space [1]. For example, the building form in Ludwig museum at Koln in Germany with specific openings provides a daylight control that is appropriate for the illumination of art objects [5] (Fig. 1). In addition, the application of internal and external lightwells, atriums, courtyards and galleries in the building form, is the alternative formal solutions for admitting daylight into interior spaces [5]. Reaching optimum natural lighting with building form characteristics, is a frequent research subject based on several factors and components. Among the factors, we can find orientation, geometry, shape and layout, compactness, opening characteristics, proportions and material, while the components include shading devices, vegetation, water pools and verandas [12–22]. In particular, courtyard building, as a traditional form of dwelling, has been pervasively applied in old times, climates and locations such as Iran, China and Middle East. Despite the socio-cultural aspects,
courtyard buildings have demonstrated extraordinary response to climate, specifically in harsh conditions [23,24]. In addition, its hierarchical procedure for controlling sun radiation affects air movement, daylight, ventilation and living style, resulting in improving visual and thermal comfort in enclosed public areas and surrounding spaces [25] (Fig. 2). In this procedure, hierarchical steps are applied to filter the intense sun irradiation by means of following steps: 1) use of geometry and building orientation as light storage, 2) use of greenery and water pools for light scattering and diffusing, 3) use of galleries and verandas as shading elements, 4) use of glazing type, color and frame patterns to provide adequate useful daylight in interior space by filtering and diffusing intense sunlight, and 5) use of interior height, depth and width to control the amount of interested daylight in different parts of a room. Moreover, the building form and its relation with occupant activities provides an opportunity for daily migration (use of different spaces according to the activity and time of the day) between interior spaces due to dynamic nature of daylight. This fact gives rise to apply kinetic interactive concept for the building façade in order to meet occupants’ comfort requirements.

Finding an optimal form in early decision-making stages of the design process will improve energy consumption, visual and thermal comfort. For example, Yi & Malkawi [26], used performance-based form-making by using a genetic algorithm for controlling hierarchically relationships between points in order to discover a new and optimal building form better suited to the environment. Similarly, Caruso and Kämpf [27] applied parametric simulation, using orientation, compactness factor and following a self-shading concept, to achieve an optimal form after 10000 up to 20000 simulations with a number of variables between 18 and 26. However, balancing visual comfort and daylight is challenging due to dynamic nature of daylight and occupants positions (Fig. 3). With respect to real time operation and dynamic characteristics of sun light, buildings need to be protected from the solar irradiation, while letting an adequate amount of daylight entering the interior space. Therefore, self-shading building forms, hierarchical steps for regulating daylight and changing configurations [2] have significant potential to be integrated in the shape of kinetic façades to improve visual comfort in response to dynamic daylight.

The demand for thermal and visual comfort from occupants has been increased considerably. Since comfort concept has been evolved in the course of time, notion of changing façade configuration over time is an approach to improve thermal & visual comfort [2]. Three dimensional shape changes in façade elements, have a potential to control the microclimate forces (solar and wind). For instance Al Bahar Towers [28] and Helio Trace Centre of Architecture [29] are responsive façades which provide daylight performance, thermal and visual comfort by controlling solar heat gain and reducing glare. The responsive kinetic façade, using sensors and actuators to interact morphologically with the ambient environment for enhancing occupant comfort [30]. Most of them are the second façade layers which interact with environmental stimuli by means of several kind of movements including folding, rotating, translating, extracting and contracting [2]. Therefore, kinetic façade has a potential to be more investigated for providing occupant visual and thermal comfort respecting dynamic stimuli comprising sun timing positions and occupant positions.

This research aims to understand hierarchical filtering steps of transferring daylight between sun and occupants, which identify three different façade functions: conservative, regulator and interactive (Fig. 4). Firstly, a façade is recognized as a “conservative element for conveying a sense of stability and permanence” [30], while, on a second level, the regulatory functions of façades provide interaction between dynamic daylight and the interior space. Finally, the advanced interactive characteristic of façades can adapt according to dynamic daylight (time of the day, day of the year) and occupants’ positions. In this study, we develop a kinetic interactive façade with the capability to be transformed based on dynamic daylight and occupant position (functional scenario based) in order to meet visual comfort. The research
procedure will be navigated through following questions: 1) what are the possible solutions to occupants’ visual comfort currently offered by different building facade configurations? How can interactive kinetic façades, improve natural lighting control to meet visual comfort criteria based on dynamic daylight and occupant’s position? What is the improvement on visual comfort from simple glazing facade to 2D shape-change façade to 3D shape-change facade?

2. Methods

The research questions need to be investigated through qualitative and quantitative approaches. The first part of the research (Section 3) was based on literature review. Google scholar and Scopus were used to find relevant articles. These articles were analyzed based on innovative daylighting guide systems elements, functions, and relation with the building form and kinetic façade forms as a real-time daylight controls. The second part of the study (Section 4) consisted on daylight parametric simulation to investigate visual comfort provided by kinetic façade forms triggered by sun timing position and occupant position (Fig. 5). Climate-based daylight metrics (CBDM) were used in the simulations in three different scenarios: plain window frame, two-dimensional-shape-change façade (2D-SCF) and three-dimensional-shape-change façade (3D-SCF) (Fig. 7). The aim of the simulations is to meet Daylight Autonomy (DA) criteria, which refers to “the percentage of the occupied hours of the year when a minimum illuminance threshold is met by daylight alone”, while keeping Useful Daylight Illuminance (UDI100-2000 Lux) within an appropriate range in order to reach the back two thirds of the space. Exceed Useful Daylight Illuminance is defined as higher than 2000Lux, which indicates an oversupply of daylight near the façade [10]. Furthermore, Daylight Glare Probability (DGP) is used to predict the risk of glare for occupants. Glare is identified as “a human sensation that describes light within the field of vision that is brighter than the brightness to which the eyes are adapted” [31]. Daylight glare probability has been classified in the four groups containing imperceptible, perceptible, disturbing and intolerable that are ranged from 30 to 35, 35–40, 40–45 and 45–100% respectively [10]. In this research, daylight glare probability is calculated at different points, which are specified as occupants’ positions in the floor plan of the simulation model (Fig. 8a and b).

3. State of the art

3.1. Innovative daylighting guide system using building form

Nowadays, daylighting is taken into account as a primary consideration in early design stages of buildings, because of its significant impact on physical, psychological and mental health of occupants. Admitting as much useful daylight as possible, from both, vertical
façades and roofs has turned to be one of the most important subject for architects and engineers. Depending on the time of day, size, depth, direction, geometry of openings and daylighting guide systems, different amount of natural light is directed into interior spaces contributing to the richness of the spatial composition, improving daylight performance and visual comfort as well [24,25]. Hence, to investigate

Fig. 5. Sun timing position and occupant position as triggers for façade shape changes.

Fig. 6. a) Module transformation process, b) Kinetic façade by means of hierarchical transformable modules in rectangular grids.
innovative daylighting guide systems, we collect information about different ways for admitting daylight, their functions and influential elements through literature study. The results can be found in Table 1.

Based on building element types allowing natural light entrance, innovative daylighting guide systems are usually categorized into side and roof lighting systems. However, the static or dynamic (kinetic) status of the main façade components is a new approach for classifying these systems.

The static status of the systems benefits from specific forms, geometries of elements, and from following hierarchical steps to receive useful daylight in the interior space. With respect to geometry, Anidolic elements [34], geometrically optimized mirror [35], diamond dome [36], perforated metal screen in macro and micro scale [38,41], lens walled compound parabolic concentrator [44], transparent prismatic geometry [48], geometry of screen’s pattern [51] and linear glass type of Fresnel lenses [54] provide several functions comprising daylight performance, reducing glare, external view satisfaction, daylight transfer path, daylight diffusing, generating electricity and reduction of artificial lighting consumption. Moreover, aforementioned geometrical approaches have an opportunity to be hierarchically coordinated together for achieving higher daylight performance functions such as integrating an intelligent glazing and shading devices [38] and Anidolic ceiling system [34].

Kinetic (dynamic) phase of innovative light guide systems can be classified into active sun tracking systems [45,46], dynamic phase change materials [50,52] and dynamic configurations [37,42,53,55]. Dynamic sun tracking systems apply active PV shading elements and their optimal shapes, adaptive reflective panels in the façade for generating electricity [45], daylight performance and reducing glare [47,55] and real-time daylight control [46,53]. Phase change materials provide the capability to have different levels of transparency. The transparency of the dynamic phase change material, based on solar shading [50] and high-tech windows with trapped gas and a thin layer of colored liquid [52] as sun shades, is changed between transparent and translucent phases to make a real-time control for daylighting. However, for reaching higher daylighting performance without glare, a dynamic configuration (specifically kinetic façades) [2,55] offers a broad range of functions, including real-time sun tracking, higher performance for generating electricity, adjusting to dynamic daylight, daylight performance without glare, external view satisfaction and reducing artificial light consumption. In particular, a movable device uses real-time kinetic movements, in order to detect an optimal orientation and configuration for adapting to dynamic daylight. For example, in Ref. [51] a kinetic façade with hexagonal patterns was allowed to change through modular elements movements, using individual rotations and translations to improve daylight performance with real-time control [55]. A closer look at Table 1 shows that most of the research has focused on daylight performance and reducing artificial light consumption. However, there are no adequate investigations for external view satisfaction. Reducing glare and real-time daylight control are the two fields under developing, which offer possibilities to influence visual comfort, external view satisfaction, energy consumption and daylight performance at the same time. In particular, based on the dynamic nature of daylight and occupants’ position, the innovative daylighting systems need to have real-time control with kinetic configuration for meeting all of the requirements.

3.2. Kinetic façade configurations as a real-time daylight controller

Kinetic systems can be classified in automatic and responsive (adaptive) façades, which change the configuration of their kinetic elements with different types of movements including flapping, folding, translating, rotating, sliding, scaling, expanding and extracting. Since responsive systems have capabilities to be adjusted to the dynamic daylight using real-time shape changes, these systems are more extensively suggested than automatic cases.

Table 2 shows several kinetic façades that are investigated regarding climate, characteristic elements, movement types, kinetic elements scale and functions to control dynamic daylight. Although these studies covered a broad range of the climates, the systems are more often applied in mild temperate regions (Csa) and warm deserts (Bwh). With respect to their characteristics elements, the kinetic systems are categorized into two main groups including louvers and modular patterns. The louvers kinetic systems are distinguished based on using automatic or responsive façade. For example, automated Venetian blinds [56], perforated vertical fins [57], dynamic external louvers [58], as parts of the façade provide several functions comprising daylight performance, reducing glare, controlling solar heating and reducing energy consumption. On the other hand, the climate adaptive horizontal louvers [59], as a large element in façade, use a responsive system for real-time controlling of solar heat, daylight and glare.

Modular elements have been applied extensively in kinetic façades’ automatic and responsive systems. Automatic modular elements, such as kinetic cladding components [60] and 3D parametric screens [62], as large elements in façade, show high performance for improving daylight performance and visual comfort. However, the responsive (adaptive) modular elements can be adapted to dynamic daylight by continuously changing façade configurations [2,28,29,68,69,72-74]. For example, a self-response Auxetic structure in Ref. [63], by means of pivot-rotating, expanding and extracting, provides real-time daylight performance and reduces glare in three different climates. Similarly, a flexible biomimetic shading device in Ref. [65], as a whole façade, uses several movements types to adapt to dynamic daylight. However, new trends for the responsive kinetic modular elements have emerged, such as parametric decentralized façades apertures [64], which interact with sun irradiation based on the relationship between external environment, interior space and occupants. In addition, recent research in Ref. [65] studied an oriental sun-responsive shading system with Rosette modules and louvers that rotate modular patterns between 0 and 90° in a two-dimensional surface. This resulted in improved daylight performance and reduced glare in different scenarios by real-time shape changes and form adaptations. Therefore, applying active occupant engagement into a responsive façade concept leads to a transition from the façade regulatory function to the interactive phase, which provides an opportunity for real-time controlling of façade regarding dynamic characteristics of daylight and occupants position simultaneously (Figs. 4 and 5).

The literature review revealed the necessity of moving toward real-time daylight control by kinetic façade and a hierarchically daylight filtering procedure resulting in preventing direct light which is “between 5 and 10 times stronger than diffuse light” [9]. Kinetic façade
configurations have a significant effect on real-time daylight control, providing visual comfort for occupants. In particular, transition from two to three-dimensional shape changes in façades is a challenging decision which considerably impacts the façade’s aesthetics and performance [75]. With respect to the field of incident solar radiation and energy consumption [76], prismatic forms apply to inclined walls, and self-shading characteristics [27,77] to redirect daylight for enhancing indoor natural light and reducing risk of glare [48] should be considered. Consequently, the kinetic prismatic modular elements diffuse daylight with hierarchical and self-shading façade configurations for decreasing the intensity of the direct sun radiation and letting adequate useful daylight entering to the interior space. In particular, this façade morphologically performs the focused tasks in two scales consisting of an individual module (Fig. 6a) and whole façade form (Fig. 6b).

4. Simulation of daylight performance

4.1. Simulation criteria

The simulation is performed, using Rhinoceros®, Grasshopper, and Diva for analyzing daylighting and energy modeling. The simulation is made assuming that the office building is located in Yazd, Iran, which
Table 1
Innovative daylighting guide systems elements, functions and relation with the building form.

| Innovative daylighting guide system | Year | Way of admitting daylight | Function | Influential element | Building elements for light entrance |
|------------------------------------|------|---------------------------|----------|---------------------|-------------------------------------|
| Sun pipe with dome [33]            | 1974 | C, R, Red, D              | DTP, RALC, DD, EUFS | Diamond dome, pipe tube and diffuser | Roof |
| Anidolic ceiling system [34]       | 1990 | C, Con, R, Red, D         | DTP, RALC, DD, EUFS, TDD, DP, RG | Anidolic Zenithal Collector and Anidolic element as a diffuser | Facade |
| Heliostat and Light Pipes systems [35] | 1995 | C, ST, Red, R, D          | DTP, RALC, DD, EUFS, RALC | Geometrically optimized mirror | Facade, Roof |
| Heliosalt Light Shaft [35]         | 1995 | C, R, Red                 | DTP, DTP, EVS | Geometrically optimized mirror | Roof |
| Sun pipe, sun catcher [36]         | 1995 | C, R, Red, D              | DTP, EUFS, RALC, DD | Diamond Dome, SUPER-SILVER mirror-finished aluminum tube, ceiling diffuser | Roof |
| Dynamic PV blinds [37]             | 2017 | C, ST, R, Red, D, B       | GE, RDC | Double skin façade using photovoltaic (PV) blinds as a shading device by changing angle and space between blind panels | Facade |
| Integrating intelligent glazing and shading devices [38] | 2018 | B, Red, F                 | VC, DP, EVS | ATG intelligent window, vertical & horizontal shading, perforated metal screen | Facade |
| Smart switchable glazing [39]      | 2018 | F, D                      | DP, RDC | Electrically actuated electrochromic, liquid crystal and suspended particle device glazing systems | Facade |
| Fabric membranes as daylight controller [40] | 2015 | B, F, D                   | DP, R | Form, range of colours and translucencies | Facade |
| Micro-perforated screen [41]       | 2015 | B, Red, D                 | DP, EVS, R | The angular selective micro-perforated screen | Facade |
| external and movable complex fenestration systems [42] | 2017 | B, R, Red, D              | RDC, VC, DP, RALC | movable venetian blinds and perforated curved louvers, smart light control with dimmer, actuator and sensor | Facade |
| Movable solar shading [43]         | 2015 | C, B, Red                 | VC, DP, RALC, RDC | Movable device | Facade |
| lens-walled compound parabolic concentrator [44] | 2018 | C, Con, R, H, Red         | GE, DP, VC | Transparent PV material, lens-walled CPC with geometric concentration ratio | Roof |
| A photovoltaic window with sun-tracking shading elements [45] | 2018 | ST, C, H, D, B            | GE, DP, RG | Active PV shading elements and their shape, View point of 3-DOF sun tracking, Window | Facade |
| A reflective adaptive façade [46]  | 2018 | ST, R, Red, D             | DP, VC, RDC | adaptive reflective solar panels and sun tracking system | Facade |
| Intelligent glazed façade [47]     | 2015 | R, Red, D, B              | DP, R, EVS | Controlling shutters, blinds and openings | Facade |
| Dynamic liquid filled prismatic louver (rotatable) [48] | 2017 | R, Red, R, D              | DP, R | Transparent daylight redirecting prismatic geometry | Facade |
| An integrated daylighting system for deep-plan spaces [49] | 2017 | C, R, Red, D, B           | DP, R, DTP, RALC, DD, EUFS, TDD | Roof light, Dynamic shading and Fiber optic daylighting system | façade and roof |
| Dynamic Phase Change Materials based solar shading [50] | 2017 | B, Red, D                 | DP, R, RDC | Phase change materials (different levels of transparency) | Facade |
| External perforated window Solar Screens [51] | 2012 | B, Red, D                 | VC, RG, RALC | Geometry of screen pattern, changing the perforation percentage and depth of the screens | Facade |
| High-tech smart windows [52]       | 2016 | F, Red, D                 | RDC, DP, RALC | A trapped gas with a thin layer of a colored liquid as a sunshade, A transparent-translucent fluid | Facade |
| Dynamic BIPV shading [53]          | 2017 | ST, C, H, D               | GE, DP, RALC, RDC | Dynamic configurations, determining the optimal orientation of the photovoltaic panels | Facade |

Ways of admitting daylight: Collecting: C, Concentrating: Con, Reflection: R, Diffusing: D, Redirecting: Red, Solar Tracking: ST, Blocking: B, Filtering: F; Functions: Daylight Transfer Path: DTP, Reducing Artificial lighting Consumption: RALC, Distributing Daylight: DD, Transmitting Daylight Deep: TDD, Reducing Glare: RG, Efficient Use of Floor Space: EUFS, Daylight Performance: DP, External View Satisfaction: EVS, Real-time daylight control: RDC, Visual Comfort: VC, Generating Electricity: GE.
Table 2
Analyzing kinetic façades systems regarding dynamic daylight through climate, functions, movement types and characteristic elements.

| Kinetic system                                                                 | Year | Climate | Characteristic element | Movement type | Kinetic element scale | Function                  |
|--------------------------------------------------------------------------------|------|---------|------------------------|---------------|----------------------|---------------------------|
| Automated solar shading Venetian blind [56]                                   | 2011 | Cfb     | P, Ret                 | PF            | DP, RG, IIC, REC, CSH |                           |
| Kinetic cladding component system based on a pantograph principle [60]         | 2013 |         | Fo, EC                 | LEF           | DP, RG, AMNV          |                           |
| Solar powered automatic perforated vertical fins [57]                         | 2015 | Aw      | R                      | PF            | DP, CSH, RG, GEF, REC |                           |
| An adaptive kinetic shading system [61]                                       | 2016 | Bwh     | S, R                   | PF            | DP, CSH, REC          |                           |
| Dynamic external louver [58]                                                   | 2017 | Csa     | P, R                   | PF            | DP                    |                           |
| 3D parametric screens [62]                                                     | 2017 | All     | Sc, R                  | LEF           | DP, CSH, RG, REC      |                           |
| Climate adaptive Horizontal louvers [59]                                      | 2018 | Cfa, Cfb| P, R                   | LEF           | DP, RG, CSH           |                           |
| Self-response Auxetic Structure as a daylight control system [63]              | 2018 | Am, Dfa, Dfc | P, R, EC           | LEF           | DP, RG                |                           |
| Elliptical parametric apertures façade [64]                                   | 2010 | Csa     | Sc, R, EC              | LEF           | DP, CSH, RG, AMNV     |                           |
| Flexible biomimetic shading devices for double curved facades [65]            | 2015 | All     | P, R, EC, F            | WF            | DP, CSH, RG           |                           |
| Adaptive curved line foldable configuration [66]                               | 2013 | All     | Fo, EC                 | LEF           | DP, CSH, RG, REC      |                           | (continued on next page)
| Kinetic system                                                                 | Year | Climate | Characteristic element | Movement type | Kinetic element scale | Function          |
|--------------------------------------------------------------------------------|------|---------|------------------------|---------------|----------------------|------------------|
| Shape Variable Mashrabiya as a Daylighting System [67]                         | 2014 | Bwh     | S                      | PF            | DP, RG, CSH, REC     |                  |
| Adaptive façade with Ron Resch Origami pattern [68]                            | 2015 |         | P, F, Fo, EC,          | LEF           | DP, RG, CSH, REC     |                  |
| The Barcelona Media-ICT building [69]                                          | 2011 | Csa     | EC, PH                 |               | DP                   |                  |
| Al Bahar Towers [28]                                                           | 2012 | Bwh     | Fo, EC                 | LEF           | DP, RG, CSH          |                  |
| Helio Trace Centre of Architecture [29]                                         | 2010 | Dfb     | P, R, F                | LEF           | DP, RG, CSH          |                  |
| Kinetic photovoltaic modular façade [70]                                        | 2018 | Dfb     | P, R                   | LEF           | GEF, REC             |                  |
| Kinetic facades with hexagonal modular patterns [55]                           | 2016 | Bwh     | R, P, S                | LEF           | DP, RG               |                  |
| Tensegrity solutions for the design of active façades with foldable and deployable elements [71] | 2017 | Cfb     | Fo, EC                 | LEF           | GEF                  |                  |
| an oriental sun responsive shading system with Rosette modules and louvers [72] | 2018 | Csa     | R, EC                  | LEF           | DP, RG               |                  |
| Adaptive kinetic façade with Hexagonal Kaleidocycle patterns [68]              | 2019 | Csa     | R, F, Fo, EC           | LEF           | DP, RG               |                  |

(continued on next page)
has hot and arid climatic condition. Yazd has been classified in the (BWh) hot desert climate, which has clear sky based on Koppen climate classification [78]. Furthermore, Yazd weather data used for the simulation process is available from EnergyPlus website and arranged by World Meteorological Organization region and Country [79]. The width and depth of the floor plan are respectively 4.2 m and 7 m. Building elements are modeled with 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 window to wall (Fig. 8a and b).

Table 2 (continued)

| Kinetic system | Year | Climate | Characteristic element | Movement type | Kinetic element scale | Function |
|----------------|------|---------|------------------------|---------------|----------------------|----------|
| Adaptive biomimetic facades with foldable modular element [73] | 2019 | BSh | Fo, S | LEF | REC | |

Climate: Am: Tropical Monsoon, Dfc: Continental Subarctic, Dfb: Humid continental, Dfa: Hot Summer Continental, Cfb: Temperate, Cfa: Humid Subtropical Climate, BWh: Warm desert, Cfb: Marine West Coast, Csa: mild, semi-humid, Aw: tropical, savanna, BSh: Semi-arid; Movement type: F: Flap, Fo: Fold, R: Rotate, Ret: Retractable, P: Pivot, S: Slide, Sc: Scale, EC: Expand & Contract, PH: Pneumatic or Hydraulic; Scale of kinetic element: WF: The whole facade as one piece, PF: Parts or volumes in the façade, LEF: Larger element in façade, SEF: Small elements in façade; Functions: GEF: Generating energy in façade, RG: Reducing Glare, DP: Daylight Performance, CSH: Control Solar Heating, AMNV: Air Movement & Natural Ventilation, REC: Reducing Energy Consumption.

Table 3

| Optical Properties of common material surfaces [10]. |
|---------------------------------------------|
|                | 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 |
| Single glazing | 90% direct visual transmittance |

Table 4

| Plain window room daylight performance through climate based daylight metrics investigation. |
|---------------------------------------------|
| Scenario | Office Hours |
|          | 9:00 | 12:00 | 15:00 |
| Person 1/Mar 21st | 53 | 69 | 57 |
| Person 1/Jul 21st | 46 | 58 | 100 |
| Person 1/Dec 21st | 57 | 100 | 100 |
| Person 2/Mar 21st | 35 | 43 | 100 |
| Person 2/Jul 21st | 49 | 59 | 40 |
| Person 2/Dec 21st | 100 | 40 | 40 |
| Person 3/Mar 21st | 38 | 48 | 38 |
| Person 3/Jul 21st | 35 | 42 | 34 |
| Person 3/Dec 21st | 46 | 66 | 55 |

Fig. 9. Climate based daylight metrics grid evaluation for the case study with plain window.
Climatic and luminance-based metrics are simulated regarding kinetic facade formal alternatives on solstice and equinox days, containing 21 Climatic and luminance-based metrics are simulated regarding kinetic facade formal alternatives on solstice and equinox days, containing 21 Climatic and luminance-based metrics are simulated regarding kinetic facade formal alternatives on solstice and equinox days, containing 21 Climatic and luminance-based metrics are simulated regarding kinetic facade formal alternatives on solstice and equinox days, containing 21 Climatic and luminance-based metrics are simulated regarding kinetic facade formal alternatives on solstice and equinox days, containing 21 Climatic and luminance-based metrics are simulated regarding kinetic facade formal alternatives on solstice and equinox days, containing 21 Climatic and luminance-based metrics are simulated regarding kinetic facade formal alternatives on solstice and equinox days, containing 21 Climatic and luminance-based metrics are simulated regarding kinetic facade formal alternatives on solstice and equinox days, containing 21 Climatic and luminance-based metrics are simulated regarding kinetic facade formal alternatives on solstice and equinox days, containing 21 Climatic and luminance-based metrics are simulated regarding kinetic facade formal alternatives on solstice and equinox days, containing 21 Climatic and luminance-based metrics are simulated regarding kinetic facade formal alternatives on solstice and equinox days, containing 21 Climatic and luminance-based metrics are simulated regarding kinetic facade formal alternatives on solstice and equinox days, containing 21

Table 5

| Scenario         | 9:00  | 12:00 | 15:00 |
|------------------|-------|-------|-------|
|                  | DA    | UDI   | EUDI  | DGP  | DA    | UDI   | EUDI  | DGP  | DA    | UDI   | EUDI  | DGP  |
| Person 1/Mar 21st| 88.35 | 53.1  | 40    | 30   | 77.65 | 69.85 | 23.5  | 35   | 82.25 | 62.65 | 30.6  | 41   |
| Person 1/Jul 21st| 89.3  | 53.05 | 40    | 28   | 70.1  | 74.15 | 18.95 | 41   | 85.8  | 54.35 | 38.95 | 35   |
| Person 1/Dec 21st| 90.5  | 49.7  | 43.7  | 30   | 85.2  | 62.1  | 31.2  | 32   | 89.3  | 45.95 | 47.4  | 36   |
| Person 2/Mar 21st| 82.3  | 67.1  | 26.05 | 44   | 75.4  | 68.45 | 24.35 | 35   | 86.05 | 53.3  | 39.9  | 28   |
| Person 2/Jul 21st| 88    | 53.3  | 39.7  | 39   | 75.45 | 69.85 | 23   | 38   | 86.05 | 53.25 | 40    | 27   |
| Person 2/Dec 21st| 89.85 | 42.95 | 50.4  | 100  | 81.15 | 63.2  | 29.9  | 31   | 87.25 | 50    | 43.15 | 25   |
| Person 3/Mar 21st| 87.85 | 56    | 37.2  | 28   | 77.05 | 70.4  | 22.75 | 32   | 85.7  | 55.8  | 37.4  | 33   |
| Person 3/Jul 21st| 88.05 | 53.35 | 40.05 | 26   | 68.15 | 75.35 | 17.5  | 33   | 85.45 | 55.05 | 38.2  | 30   |
| Person 3/Dec 21st| 89.9  | 51.45 | 41.85 | 29   | 81.45 | 69.15 | 24.15 | 32   | 85.8  | 54.85 | 38.5  | 35   |
| Person 4/Mar 21st| 87.95 | 55.5  | 37.85 | 36   | 72.8  | 71.2  | 21.5  | 31   | 86    | 55.4  | 37.8  | 26   |
| Person 4/Jul 21st| 87.65 | 53.8  | 39.55 | 31   | 68.15 | 73.6  | 19.05 | 31   | 86.7  | 53.65 | 39.65 | 26   |
| Person 4/Dec 21st| 84.6  | 62.7  | 30.55 | 42   | 78.4  | 68.75 | 24.4  | 31   | 87.05 | 51.7  | 41.6  | 26   |

4.2. The kinetic façade interaction - results

The simulation evaluates the daylight performance of the kinetic model, which is interactive due to use of dynamic daylight and occupant's position. The kinetic façade follows an interactive logic in four steps for improving visual comfort and daylight performance (Fig. 8):

I. Making a user field of vision (UFV) line between sun (timing) position and occupant position in the office.

II. Identifying an intersection point between UFV line and the façade surface as an attraction point.

III. Applying the attraction point as a trigger of a parametric decentralized façade apertures logic in order to reconfigure the façade modular elements.

IV. Improving occupant visual comfort using the real-time shape-change, hierarchy and self-shading façade form.

The simulation procedure investigates daylight performance according to climate based daylight metrics, based on several occupant's and sun's positions scenarios for three façade cases consist of plain window (static), two dimensional shape changes (kinetic) and three dimensional shape changes (kinetic).

4.2.2. Two dimensional shape changes façade

The simulation results confirm the high performance of the kinetic interactive façade for improving visual comfort regarding the base-case. In this case, the kinetic façade changes its configuration using hierarchical scaling movements of modular elements to control daylight regarding sun and occupant positions based on different daytime scenarios. Table 5 reveals that two-dimensional-shape-changes in the façade brings an average DA and UDI of 87% and 54% respectively for scenarios at 9:00 and 15:00, while scenarios at 12:00 show an average of 76% for DA and 70% for UDI. Although, the DA remains in satisfactory level for all of the scenarios, the results point to a significant improvement of UDI by means of 2D-SCF in comparison to the base-case. In addition, comparing Exceed UDI value for plain window and the 2D-SCF, shows dramatic decrease in the amount of Exceed UDI from 37% to 78% in relation to the base-case. The average Exceed UDI for scenarios at 9:00 and 15:00 is 39%, while the scenarios at 12:00 demonstrate better conditions with the average of 23%. Risk of glare prediction, as one of the important metrics for evaluating visual comfort, depends considerably on the direction between occupants’ vision and dynamic daylight. Therefore, scenario-based façade-changes provides average DGP of 38%, 33.5% and 31% for the entire scenarios at 9:00, 12:00, and 15:00 respectively. In particular, among the 36 scenarios analysis, in contrast to the base-case, most of them stand in imperceptible and perceptible range with percentages of 63.9% and 22.2% respectively. Only, 11.1% of them is found in the disturbing range, and 2.8% in intolerable. For example, the 2D-SCF cannot meet DGP requirements for some of scenarios including Person 2/Mar & Dec at 9:00 and Person 1/Jan at 12:00 (Table 6).

4.2.3. Three dimensional shape changes façade

The integration of scaling and translating movements, in the shape of kinetic prismatic modular elements, provides hierarchical configurations and self-shading geometry for the façade, resulting in improved visual comfort. Table 7 proves the possibilities of the three-dimensional-shape-changes to satisfy occupant visual comfort criteria. The average DA and UDI are 79% and 67% for scenarios at 9:00 and 15:00, while for the scenarios at 12:00 they resulted in 48% and 82% (Table 7). The kinetic façade facilitates a great increase in the UDI from 4 to 6 times more than the base-case model. Furthermore, the average Exceed UDI for the scenarios at 9:00 and 15:00 is 26%, while for the scenarios at 12:00 is 8.6%. Therefore, the 3D-SCF provides a significant decrease of about 56%–98.5% for Exceed UDI amount regarding the base-case model. Furthermore, the kinetic façade yields an average DGP value of 31%, 30% and 28% for all of the scenarios at 9:00, 12:00 and 15:00 respectively. Moreover, the DGP simulation confirms that 86.1% of the scenarios are found in imperceptible and 13.9% in perceptible ranges. There is no scenario in the disturbing and intolerable ranges.
Table 6
2Dimensional shape change DGP and Façade renders based on the dynamic occupant and sun positions scenarios.

| Scenario       | 9:00 | 12:00 | 15:00 |
|----------------|------|-------|-------|
| Person 1/Mar 21th | DGP Render | Kinetic facade | DGP Render | Kinetic facade | DGP Render | Kinetic facade |
| Person 1/ Jun 21th | DGP Render | Kinetic facade | DGP Render | Kinetic facade | DGP Render | Kinetic facade |
| Person 1/ Dec 21th | DGP Render | Kinetic facade | DGP Render | Kinetic facade | DGP Render | Kinetic facade |
| Person 2/Mar 21th | DGP Render | Kinetic facade | DGP Render | Kinetic facade | DGP Render | Kinetic facade |
| Person 2/ Jun 21th | DGP Render | Kinetic facade | DGP Render | Kinetic facade | DGP Render | Kinetic facade |
| Person 2/ Dec 21th | DGP Render | Kinetic facade | DGP Render | Kinetic facade | DGP Render | Kinetic facade |
| Person 3/Mar 21th | DGP Render | Kinetic facade | DGP Render | Kinetic facade | DGP Render | Kinetic facade |
| Person 3/ Jun 21th | DGP Render | Kinetic facade | DGP Render | Kinetic facade | DGP Render | Kinetic facade |
| Person 3/ Dec 21th | DGP Render | Kinetic facade | DGP Render | Kinetic facade | DGP Render | Kinetic facade |
| Person 4/Mar 21th | DGP Render | Kinetic facade | DGP Render | Kinetic facade | DGP Render | Kinetic facade |
| Person 4/ Jun 21th | DGP Render | Kinetic facade | DGP Render | Kinetic facade | DGP Render | Kinetic facade |
| Person 4/ Dec 21th | DGP Render | Kinetic facade | DGP Render | Kinetic facade | DGP Render | Kinetic facade |
resulting in complete visual comfort through climate based daylight metrics analysis (Table 8).

### 4.3. Difference between three dimensional and two dimensional shape changes façade

Although both kinetic façades offer a significant potential for meeting visual comfort requirements, the simulation results reveal a considerable difference between the 2D-SCF and 3D-SCF (Fig. 10). Both façades keep DA amount within satisfactory ranges for occupants, while the 2D-SCF lets more daylight entering, specifically in the scenarios at 12:00 with the average difference of 28% to the 3D-SCF. However, the 3D-SCF provides more useful daylight than the two dimensional one on horizontal work plane, which ranges between 17.8% and 24%. In addition, the 3D-SCF shows high efficiency for decreasing Exceed UDI from about 26.88% up to 93.4% in relation to the two dimensional one; resulting in avoiding thermal discomfort while meeting visual comfort criteria. Therefore, controlling UDI and Exceed UDI by means of a 3D-SCF, indicates its multifunctional aspect to regulate microclimate forces in the façade ambient environment. Also, the 3D-SCF meets daylight glare probability criteria, which is found in the imperceptible and perceptible ranges, while the 2D-SCF does not meet DGP requirements for 13.9% of the simulated scenarios, which are found in the disturbing and intolerable zones.

### 5. Discussion and conclusion

The architectural form of a building defines the façade’s interaction with the ambient environment, which has a fundamental effect on admitted useful daylight into interior spaces. Performance-based-form-making in an early design stage leads us to reach optimum natural light in terms of quality and quantity. In particular, due to dynamic nature of daylight and occupant’s positions, the innovative daylighting guide systems needs to have real-time control with kinetic configuration for influencing visual comfort, daylight performance and reducing glare. Kinetic façades use real-time movements to detect an optimal orientation and configuration for meeting visual comfort requirements. Although kinetic façades are classified in responsive and automatic cases, the responsive ones have capabilities to be adapted to the dynamic daylight using real-time shape changes mostly in the mild temperate regions (Csa) and warm deserts (Bwh).

The responsive modular elements can be adapted to dynamic daylight by continuously changing façade configurations. Specifically, parametric decentralized façade’s apertures that interact with sun radiation based on the relationship between external environment, interior space and occupants’ position (Fig. 8). Therefore, applying active occupant engagement into a responsive façade concept leads us to a transition from the façade regulatory function to the interactive phase, which provides an interactive kinetic façade, which has the capacity for hierarchically filtering daylight and real-time control, preventing daylight discomfort (Figs. 4 and 5).

Prismatic forms have been applied as kinetic modular elements because of their self-shading characteristics and inclined walls for diffusing and redirecting daylight. These elements allow to decrease the intensity of the direct sun radiation and to let adequate useful daylight entering the interior space (Fig. 6). In addition, transition from two to three-dimensional-shape-changes in the kinetic façade is an influential decision, which considerably impacts daylight performance and visual comfort requirements. Parametric simulation through climate based daylight metrics, based on several occupant and sun positions scenarios were performed for three case studies consisting of: plain window (static), 2D-SCF (kinetic) and 3D-SCF (kinetic). The simulation results show the fully visual discomfort for the plain window with a value of 93.45%, 13.85% and 79.8% for DA, UDI and Exceed UDI respectively. Also, the analysis of daylight glare probability metrics for the 36 scenarios, based on the occupant and dynamic daylight positions, showed that most of the scenarios are found in intolerable (66.7%) and disturbing (13.9%) ranges.

The simulation results prove high performance of the both kinetic interactive façades for improving visual comfort regarding the base case. Both kinetic façades keep the DA in a satisfactory level for all of the scenarios, while the results point out to a significant improvement of daylight metrics with an average UDI in the ranges of 54%–70% and 67%–82% for two and three-dimensional-shape-changes respectively. Similarly, due to Exceed UDI, the parametric simulation shows dramatic decreases from 37% to 78% and 56%–98.5% for the both kinetic façades comprising two and three-dimensional-shape-changes. With respect to the prediction risk of glare, in contrast to the base model, the most of the scenarios stand in imperceptible and perceptible range with percentage of 63.9% and 22.2% respectively for the 2D-SCF. However, the 3D-SCF demonstrates an extraordinary performance for meeting DGP requirements. Precisely, 86.1% of the scenarios locate in imperceptible and 13.9% in perceptible range without any scenarios in the disturbing and intolerable area.

The 3D-SCF provides more useful daylight than the 2D-SCF (17.8%–24%). Furthermore, 3D-SCF represents high efficiency for decreasing Exceed UDI from 26.88% up to 93.4% respect to the 2D-SCF; resulting in avoiding thermal discomfort besides meeting visual comfort criteria. The results refer to multifunctional aspects of the three dimensional shape changes façade, as an advanced interactive daylighting system, which has a capability to control microclimate notable force (solar) in the façade ambient environment.

Looking at existing responsive kinetic façades comprising of the Al Bahr Towers, Helio Trace Centre of Architecture, Barcelona Media-ICT

### Table 7

| Scenario | 9:00 | 12:00 | 15:00 |
|----------|------|-------|-------|
|          | DA | UDI | EUDI | DGP | DA | UDI | EUDI | DGP | DA | UDI | EUDI | DGP |
| Person 1/Jan 21st | 83.55 | 66.75 | 26.5 | 28 | 51.9 | 81.95 | 11 | 30 | 66.1 | 73.5 | 18.45 | 32 |
| Person 1/Mar 21st | 82.6 | 66.35 | 27 | 27 | 33.9 | 88 | 1.45 | 38 | 79.8 | 65.95 | 26.95 | 33 |
| Person 2/Jan 21st | 83.25 | 64.6 | 28.8 | 28 | 68.6 | 74.9 | 18.55 | 29 | 82.9 | 64.45 | 28.6 | 29 |
| Person 2/Mar 21st | 65.05 | 76.7 | 16.5 | 36 | 49.85 | 79.2 | 11.2 | 30 | 78.4 | 66.55 | 26.3 | 26 |
| Person 3/Jan 21st | 81.35 | 67.55 | 25.7 | 36 | 40 | 85.9 | 4.4 | 35 | 78.15 | 65.8 | 26.8 | 26 |
| Person 3/Mar 21st | 87.6 | 56.6 | 36.85 | 38 | 66.4 | 73 | 18.9 | 29 | 81.4 | 64.45 | 28.5 | 25 |
| Person 4/Jan 21st | 80.55 | 68.15 | 25 | 27 | 39.95 | 86.75 | 3.6 | 30 | 76.65 | 69.5 | 23.15 | 30 |
| Person 4/Mar 21st | 82.95 | 66.3 | 26.85 | 26 | 31.1 | 85.9 | 1.15 | 31 | 79.05 | 66.05 | 26.6 | 29 |
| Person 5/Mar 21st | 84.75 | 64.7 | 28.45 | 28 | 55.05 | 80.35 | 12.45 | 30 | 77.45 | 68.2 | 24.6 | 31 |
| Person 6/Mar 21st | 79.4 | 70.1 | 23.2 | 33 | 42.7 | 86.2 | 4 | 29 | 76.8 | 68.45 | 24.15 | 25 |
| Person 7/Mar 21st | 81.8 | 67.2 | 26 | 30 | 38.15 | 87.2 | 3 | 30 | 79.25 | 66.35 | 26.65 | 25 |
| Person 8/Mar 21st | 65.85 | 74.55 | 18.65 | 36 | 54.15 | 77.1 | 13.7 | 28 | 80.65 | 64.55 | 28.4 | 25 |
Table 8
3Dimensional shape change DGP and Façade renders based on the dynamic occupant and sun positions scenarios.

| Person 1/ | Mar 21th | Person 1/ | Jun 21th | Person 1/ | Dec 21th | Person 2/ | Mar 21th | Person 2/ | Jun 21th | Person 2/ | Dec 21th | Person 3/ | Mar 21th | Person 3/ | Jun 21th | Person 3/ | Dec 21th | Person 4/ | Mar 21th | Person 4/ | Jun 21th | Person 4/ | Dec 21th |
|-----------|----------|-----------|----------|-----------|----------|-----------|----------|-----------|----------|-----------|----------|-----------|----------|-----------|----------|-----------|----------|-----------|----------|-----------|----------|-----------|
| DGP Render|          | Kinetic facade | DGP Render |          | Kinetic facade | DGP Render |          | Kinetic facade | DGP Render |          | Kinetic facade | DGP Render |          | Kinetic facade | DGP Render |          | Kinetic facade | DGP Render |          | Kinetic facade | DGP Render |          | Kinetic facade |
building shows their high daylight efficiency. In general, it can be concluded that the daylight performance of the whole facades is equivalent with the kinetic 3D-SCF. However, based on the detailed results comparison, the 3D-SCF has the capability to decrease solar heat gain more than 98% respecting the base case, while Al Bahar Towers, Helio Trace Centre of Architecture and Media-ICT can only decrease solar heat gains by only 50%, 81% and 85% respectively [2,29,80].

Since all of the facades use three dimensional shape changes, this

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**Fig. 10.** Climate based daylight metrics grid evaluation for the scenario Person 3/Jun 21st at 12:00; a) 2Dimensional shape changes façade, b) 3Dimensional shape changes façade.
amount of improvement in decreasing solar heat gain in 3D-SF Could be achieved through the parametric decentralized façade apertures logic triggered by the occupant position and dynamic sun position. The kinetic façade as a new trend for improving comfort condition still is under development. Therefore the next step would be applying this logic to a real kinetic façade and study its feasibility and daylight performance in an experimental research.

Since many parameters have been applied in the simulation, both 2D & 3D SFs provide visual comfort based on interacting with an occupant in different positions, individually. Therefore, future research needs to focus on the performance of interactive façades for meeting all occupants comfort condition simultaneously. Also, based on the multifunctional aspects of the kinetic façades, a broad range of the functions have potential to be integrated in the kinetic façade including thermal and visual comfort, reducing artificial light, sun tracking and producing electricity. Regarding the high performance of the 3D-SF to meet comfort criteria, applying biomimicry approach might lead us to detect high performance, adjustable and unique alternatives for the interactive façade geometry. Also, the kinetic façade, as an interactive component, could learn and adapt to occupant activities and behavior, resulting in the need for a machine learning approach for developing interactive designs.

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