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Bio-inspired interactive kinetic façade: Using dynamic transitory-sensitive area to improve multiple occupants’ visual comfort

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Abstract The architectural form of the façade determines its identity as well as interactions with micro-climate forces of the ambient environment, such as solar radiation. The dynamic nature of daylight and occupants’ positions can cause some issues such as heat gains and visual discomfort, which need to be controlled in real-time operation. Improving daylight performance and preventing visual discomfort for multiple occupants simultaneously is challenging. However, integrating the biomimicry principles of morphological adaptation with dynamic, complex fenestration, and human-in-loop systems can lead us to find an optimal solution. This research builds on relevant literature study, biomimicry morphological approaches, and parametric simulations, to develop a bio-inspired interactive kinetic façade for improving multiple occupants’ visual comfort simultaneously, inspired by plant’s stomata movement and behavior principles. Learning from the transitory stage and hunting new position of stomata’s patchy patterns, leads us to identify the dynamic transitory-sensitive area of attraction point on the façade that is triggered by the dynamic sun-timing position and multiple occupants. The annual climate-based metrics and luminance-based metric simulation results of 810 bio-inspired interactive kinetic façade alternatives prove that the elastic-deformable-complex-kinetic form triggered by the dynamic transitory-sensitive area can improve the visual comfort of multiple occupants simultaneously. In particular, the bio-inspired interactive kinetic façade with grid division 8x1 displays extraordinary daylight performance for south direction that prevents visual discomfort by keeping cases in the imperceptible range while providing an
1. Introduction

Since natural light, as a renewable and permanent source, has positive physical, psychological, and mental effects on occupants’ health (ASHRAE Press, 2006; Konis and Selkowitz, 2017b; Tzempelikos, 2017), supplying sufficient useful daylight at interior space is one of the influential subjects for designing facades. Interactive kinetic facades, whether adaptive (Loonen, 2015; López et al., 2015) or responsive (Shahin, 2019), change their configurations in response to building’s ambient climate and occupants’ activity in real-time operation for improving the well-being and productivity of residents. “Adaptive building skin refers to a morphogenetic evolution and real-time physical adaptation of a design in relation to its surrounding environment” (Al-Obaidi et al., 2017). Biomimicry and biological strategies, such as plant adaptations, provide underlying principles for proposing climate-adaptive and interactive kinetic façade designs’ concepts (Han et al., 2016; Houda and Mohamed, 2018; Mazzoleni, 2013).

Biomimicry as “the study of overlapping fields of biology and architecture that show innovative potential for architectural problems” (Radwan and Osama, 2016) has been applied pervasively to explore nature for finding an appropriate logic to develop the unique façade idea. Also, biomimicry is defined by Janine (Benyus, 2002) as “the new science that studies nature’s models and imitating these designs to solve human problems”. Numerous movable components in nature, including that of plants, animals, and humans, provide adaptability by several motions and transformations. Lacking movements and dependency on a specific location are similar attributes of buildings and plants. However, plants benefit from flexible and curved bodies as well as kinetic components such as leaves and petals (Hosseini, Mohammadi, Rosemann, et al., 2019; López et al., 2015). Hence, the architecture of plants, especially their morphological approach, is a source of inspiration to extract unique adaptive strategies to light (Badarnah, 2017; Houda and Mohamed, 2018). In particular, motion principles detected in plant movement (whether micro or macro scale) can be transferred to a larger scale as technical solutions for the kinetic shading façade that change from static to dynamic (Hosseini et al., 2021; Schleicher et al., 2015a). Design rules derived from biological systems provide an opportunity to achieve adaptive morphological change in different ways (Vincent, 2007). “The movement of plants or plant parts occurs over a wide range of sizes and time scales (Forterre, 2013).” For example, the leaves of the Venus Fly Trap have High-speed shutting in 1/25 s (Forterre, 2013; Körner et al., 2018). Similarly, an adaptive shading façade is inspired by the hinge-less motion of the underwater snap trap of Aldrovand Vesiculosa (Körner et al., 2018). Due to existing buildings, Council House 2 in Melbourne is inspired by tree organisms and their behavior. This biomimicry approach results on energy savings of 82% and reduces energy use for artificial light and mechanical ventilation by 65% (Radwan and Osama, 2016).

Investigation of daylighting guide systems inspired by biomimicry provides an extensive range of information about building scale, system and movement types, influential elements, geometric form, functions, ways of admitting daylight, and climate. Generally, daylighting guide systems inspired by biomimicry have been used in different climates especially temperate and warm-desert based on Koppen climate classification (Chen and Chen, 2013). The systems are used for making adaptive and responsive envelope, and kinetic shading facades (López et al., 2015; Shahin, 2019). They frequently applied complex, flexible, foldable, and hierarchical self-shading forms using smart and semi-transparent materials (Badarnah et al., 2010; Körner et al., 2018). The geometric forms can be divided into three groups: a) complex form, b) convertible structure, and c) hierarchical structure. Complex forms are used pervasively, while hierarchical self-changed structures demonstrate a growing trend. The main functions are real-time daylight control, sufficient supply of daylight, daylight performance, glare protection, and thermal regulation (Schieber et al., 2017; Schleicher et al., 2015a; Xing et al., 2018). However, aesthetics, privacy protection, and visual contact to the exterior are also topics under development. The influential elements benefit from morphology, responsiveness, and smart materials. The responsive systems use programmable actuation for sensing and self-transformation. The façade morphology (which triggered by the responsive system) is transformed based on elastic deformation (Pohl and Nachtigall, 2015a; Schieber et al., 2017; Schleicher et al., 2015b), moveable components (Badarnah et al., 2010), shape-changing panels (Xing et al., 2018), and self-shading geometries (Hertzschs, 2010; Pohl and Nachtigall, 2015c). In summary, an efficient daylighting system can be extracted from the façade’s components in grid forms. The façade needs to be kinetic under the navigation of a responsive decentralized system to provide a hierarchically self-shading form resulting in a bio-inspired interactive façade with respect to users (occupants).

Due to the high-potential of the biomimicry approach for extracting technical solutions and the “lacking quantitative performance analysis of bio-adaptive building skins” (Kuru et al., 2019), there is an opportunity for developing an interactive logic to provide a communication between multiple occupants positions and dynamic sun-timing
positions. Moreover, the logic can be applied into kinetic-responsive decentralized and human-in-loop systems for improving multiple occupants’ visual comfort simultaneously (Fig. 1). This research aims to develop an interactive kinetic shading façade to improve multiple occupants’ visual comfort simultaneously inspired by plant’s kinetic movements and behavior. Therefore, the current research will be conducted through the following questions: What are the characteristics of kinetic shading facades inspired by biomimicry? How can the biomimicry principles from the plant inspire façade form’s configuration to improve occupants’ visual comfort simultaneously for multiple occupants’ positions?

2. Method

This research builds on a relevant literature study, a biomimicry morphological approach, and parametric simulation to develop a bio-inspired interactive kinetic façade for improving multiple occupants’ visual comfort simultaneously. The first part of the research (Section 3) uses Google scholar and Scopus to represent the main theory of the kinetic movement and behavior through biomimicry. Furthermore, in Sections 3.2 and 3.3, the study applies the biomimicry morphological approach (Badarnah, 2017) to design the interaction of the kinetic façade inspired by stomata distribution and movement. The third part (Section 4) of the study performs comprehensive Daylight performance simulations of parametric bio-inspired interactive kinetic façade alternatives (810 different cases) to investigate the improvement on visual comfort of multiple occupants simultaneously. Moreover, their daylight performance and visual comfort are studied through climate-luminance based daylight metrics using daylight performance prediction guidelines from Reinhart (Reinhart, 2011, 2019). The metrics applied in the study consist of spatial Daylight autonomy (sDA), Useful Daylight Illuminance (UDI), Exceed Useful Daylight Illuminance (EUDI), and Daylight Glare Probability (DGP). This research aims to propose an approach for integrating biomimicry principles of morphological adaptation with dynamic and human-in-loop systems for improving occupants’ visual comfort. The well-known software and plugins Rhino 6, Grasshopper and Diva 4 are used to evaluate daylight performance.

3. Kinetic façade development

3.1. Developing a bioinspired interactive kinetic façade through biomimicry morphological approach

Biomimicry levels are categorized as physiology, morphology and behavior (Badarnah, 2017), thus, detecting suitable analogies significantly depends on exploring the appropriate level. Many researches applied biomimicry morphological level to design facades that adapt to the ambient environment using complex and flexible forms (Al-Obaidi et al., 2017; Badarnah, 2016a, 2017; Brodofeanu et al., 2016; Charpentier et al., 2017; Eldin et al., 2016; Knippers and Speck, 2012; Körner et al., 2018; Li and Wang, 2016; López et al., 2017; Pohl and Nachtigall, 2015b; Rivière et al., 2017; Schieber et al., 2017; Speck et al., 2017), convertible elements (Charpentier et al., 2017; Knippers and Speck, 2012; Pohl and Nachtigall, 2015b), and hierarchical structures (Knippers and Speck, 2012; Schieber et al., 2017). A variety of well-designed self-shading forms in nature can be found in plants. For example, the vertical fleshy ribs of cactus provide a self-shading form that adapts to harsh climate by reducing incident solar radiation (Hertzsch, 2010). Combination of bio-inspired forms and their transformability characteristics provide an opportunity to create new façade systems that are intelligent (Li and Wang, 2016; Speck et al., 2017), responsive (Körner et al., 2018), and adaptive (Al-Obaidi et al., 2017; Badarnah, 2016b, 2017; Eldin et al., 2016; López et al., 2015; Schieber et al., 2017) to environmental conditions. To illustrate, based on Badarnah (Badarnah, 2017) conclusion that “form follow environment”, the mimicking extensibility of plant cells’ walls in the shape of Voronoi patterns results in a Bio-interactive façade’s complex form. This façade can hierarchically change scale and extrude modular elements for real-time daylight control (Fig. 2). Since responsive façades have to interact with external and internal stimuli, plant adaptation principles can be recognized as an influential source for generating interactive kinetic façade forms to improve occupants’ visual comfort (Houda and Mohamed, 2018).

3.2. Stomata

Many plants possess unique adaptions for sensing and reaching adequate sunlight as well as coordinating whole-plant growth by enabling greater photosynthesis efficiency (Aanouluwapo and Ohis, 2017; Burris et al., 2018). The elastic and dynamic movements of plants can inspire kinetic shading façade systems that interact to internal and external stimuli through morphological adaptation (Prabhakaran et al., 2019). Although plants benefit from their flowers and leaves in the macro-scale to adjust angle and orientation with respect to sunlight, exploring plants in the micro-scale provides an opportunity to detect optimal principles for future resilient building design. “Plant cell walls are highly dynamic structures offering dynamic and multiple functionality (Xing et al., 2018).” In particular, stomata of plant’s leaves open and close to facilitate photosynthesis by controlling gas exchange, air humidity and light between plant and environment (Hörak et al., 2017; López et al., 2017; Prabhakaran et al., 2019). Stomata are pores in the surface of aerial parts of higher plants that are made by a pair of the guard cells and neighboring subsidiary cells. Their influential functions allow an adequate amount of CO2 to enter the leaf while conserving as much water as possible (Willmer and Fricker, 1996a). Stomata locate in equidistant and regular rows and their pores are considerably symmetrical. “Stomata frequency, according to cell size and smaller guard cells can be modified by environmental factors and leaf morphology” (Willmer and Fricker, 1996b) (Fig. 3a). Intrinsic and extrinsic factors cause a general variability in stomatal aperture and size resulting in heterogeneity in biological systems for achieving adaptability. Sudden environmental conditions’ changes give rise to patchy behaviors of
stomata. The patchy pattern has a transitory stage that hunts for new conditions and positions in response to immediate environmental changes. The stomata within the area react in harmony and independency from neighboring areas (Fig. 3b). Hence, optimized apertures in size and shape maintain the stable internal conditions while tolerating external changes (Willmer and Fricker, 1996b).

3.3. Designing interaction of the kinetic façade inspired by stomata distribution and movement

The interactive kinetic façade inspired by stomata distribution and movement can meet the daylight performance and visual comfort requirement. The kinetic façade configuration is interactive due to the use of dynamic

Fig. 1 Improvement the performance of the interactive kinetic façade for meeting visual comfort requirement from a single occupant to multiple occupants by employing biomimicry morphological approach.

Fig. 2 Mimicking extensibility of plant cell walls in Voronoi patterns resulting bio-interactive facade complex form.
daylight and multiple occupants’ positions. The façade design follows three phases to change from static into the interactive-kinetic:

Phase 1) Regular and equidistance rows of stomata allow applying the grid form and positioning of kinetic elements in the façade surface (Fig. 5).

Phase 2) Defining the logic of multiple dynamic attraction points in the façade by following two steps (Fig. 6): a) Making a user field of the vision (UFV) line between the sun (timing) position and occupants’ positions in the office; and b) Identifying the intersection points between the UFV lines and the façade surface as the attraction points.

Phase 3) Generating complex form triggered by a dynamic transitory-sensitive area (TSA) of attraction point (Fig. 7) (inspired by Stomata patchy pattern transitory stage (Fig. 4)): a) Transitory-sensitive area is defined as a region of the façade in which the kinetic elements within the area react in harmony and entirely independent from neighboring areas; b) The center of the TSA is determined by the attraction point’s position; c) The shape of the TSA is

Fig. 3 Identification of appropriate biomimicry principles from Stomata of plant’s leaf: a) Stomata general characteristics, b) Stomata patchy pattern transitory stage.

Fig. 4 Abstracting biomimicry principles of stomata and translating to design solutions, adapted from (Badarnah, 2017).

Fig. 5 Regular and equidistance rows of stomata give rise to apply grid form and positioning of kinetic elements in the façade surface.
Fig. 6  a) Defining the logic of multiple dynamic attraction points and dynamic transitory sensitive area in façade, b) Interactive kinetic facade 4 GD Divisions by hierarchy rotational and sliding movements of kinetic elements, c) Kinetic elements on the façade frame with details, material, and mechanism.
assumed as a circle; d) The radius range of the TSA can be
changed from 0.1R to R with an interval of 0.1; e) The
amount of R is defined as a maximum distance between the
attraction point and the farthest kinetic element on the
façade; f) Depth and rotation of the kinetic elements within
the TSA are hierarchically changed based on their distance
from the attraction point; g) The number of TSA in the
façade is equal to the number of the occupants; h) The
dynamic characteristic of the TSA generates an interactive-
kinetic-complex-hierarchy- self-shading form.

Figure 6b presented the kinetic concept of the system
through several views consist of top, front, and perspective.
The kinetic elements are positioned in grid forms with
equal distances that take hierarchy movements in depth
and angle based on their distances from the attraction
point within the TSA area (Table 1). Elements which that
were placed out of the TAS, remained without any move-
ments. According to Fig. 6c, structure of the biomimetic
façade has been constructed by a single span frame which
has some rail profiles made from stainless steel in between.
Moving mechanisms on the side rail provide two functions
including a connection between the kinetic elements and
rail profile, and their horizontal movements on the rail. The
kinetic elements have different movement options and
supplying connection tools for holding the tensile material.
First, an aluminum telescopic bar controls the depth of the
element. Second, a rotational joint changes an angle be-
tween two telescopic bars. Third, the two aluminum tele-
scopic bars, as the angle sides, can be contracted and
extracted based on their distances from the attraction
point position. Finally, the tensile material can be
expanded and stabled by the connection tools on the
telescopic bars to cover the whole of the façade surface.
The combination of the telescopic bars and the rotational
joint movements provides an exceptional opportunity to
change the façade configuration through several kinetic
options. Therefore, the biomimetic kinetic façade can
regulate occupants’ visual comfort based on dynamic sun
positions and occupant positions.

Table 1  Rotation and sliding movements of kinetic ele-
ments in 4 grid divisions based on the given points on
Fig. 6b.

<table>
<thead>
<tr>
<th>Points</th>
<th>Depth Movement (cm)</th>
<th>Angle (Deg)</th>
<th>Points</th>
<th>Depth Movement (cm)</th>
<th>Angle (Deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>0</td>
<td>0</td>
<td>P17</td>
<td>23.87</td>
<td>9.92</td>
</tr>
<tr>
<td>P2</td>
<td>13.37</td>
<td>5.56</td>
<td>P18</td>
<td>7.55</td>
<td>3.14</td>
</tr>
<tr>
<td>P3</td>
<td>30.43</td>
<td>12.65</td>
<td>P19</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>P4</td>
<td>48</td>
<td>19.96</td>
<td>P20</td>
<td>9.17</td>
<td>3.81</td>
</tr>
<tr>
<td>P5</td>
<td>65.38</td>
<td>27.19</td>
<td>P21</td>
<td>13.74</td>
<td>5.71</td>
</tr>
<tr>
<td>P6</td>
<td>81.15</td>
<td>33.75</td>
<td>P22</td>
<td>15.57</td>
<td>6.47</td>
</tr>
<tr>
<td>P7</td>
<td>88.3</td>
<td>36.73</td>
<td>P23</td>
<td>12.97</td>
<td>5.39</td>
</tr>
<tr>
<td>P8</td>
<td>77.69</td>
<td>32.31</td>
<td>P24</td>
<td>10.89</td>
<td>4.53</td>
</tr>
<tr>
<td>P9</td>
<td>61.42</td>
<td>25.55</td>
<td>P25</td>
<td>23.87</td>
<td>9.92</td>
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<tr>
<td>P10</td>
<td>43.82</td>
<td>18.22</td>
<td>P26</td>
<td>35.31</td>
<td>14.68</td>
</tr>
<tr>
<td>P11</td>
<td>58.66</td>
<td>24.40</td>
<td>P27</td>
<td>42.6</td>
<td>17.72</td>
</tr>
<tr>
<td>P12</td>
<td>71.65</td>
<td>29.80</td>
<td>P28</td>
<td>45.07</td>
<td>18.74</td>
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<tr>
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<td>32.31</td>
<td>P29</td>
<td>41.89</td>
<td>17.42</td>
</tr>
<tr>
<td>P14</td>
<td>70.38</td>
<td>29.27</td>
<td>P30</td>
<td>34.25</td>
<td>14.24</td>
</tr>
<tr>
<td>P15</td>
<td>57.1</td>
<td>23.75</td>
<td>P31</td>
<td>22.81</td>
<td>9.48</td>
</tr>
<tr>
<td>P16</td>
<td>41.17</td>
<td>17.12</td>
<td>P32</td>
<td>9.43</td>
<td>3.92</td>
</tr>
</tbody>
</table>

Fig. 7  Generating complex form triggered by a dynamic transitory-sensitive area (TSA) of attraction point (inspired by Stomata patchy pattern transitory stage).
4. Daylight performance simulation of parametric bio-inspired interactive kinetic facade alternatives

Visual comfort and daylight performance of the interactive kinetic facade has been investigated through 540 different configurations due to following influential parameters (Fig. 8): 1) Grid divisions, 2) Radius of Transitory-sensitive area, 3) Hierarchically deformable louvers (Integration of depth change and rotation change), 4) Sun-timing positions, 5) Position of occupants (multiple occupants simultaneously), 6) Orientations (East, South, West). We set the parametric simulation results in the 6 sections based on the grid divisions of the facade consist of 4, 8, and 12 divisions. The 90 interactive kinetic facade’s configurations for every grid are simulated. We assumed 4 divisions of the Kiefer Technic Showroom’s facade, designed by Ernst Giselbrecht + Partner (Kiefer Technic Showroom/Ernst Giselbrecht + Partner, 2010), as a departure point for the facade’s grid divisions. The daylight performance results of different alternatives are compared together as well as with the base case (simple plain window).

4.1. Daylight performance evaluation criteria through climate-based metrics and luminance-based metric

Daylight performance of the complex kinetic facade has been studied through climate-based metrics comprising spatial Daylight Autonomy (sDA), Useful Daylight Illuminance (UDI), Exceeded Useful Daylight Illuminance (EUDI) and luminance-based metric including Daylight Glare Probability (DGP) (Reinhart, 2019). sDA is identified as “the percentage of the occupied hours of the year when a minimum illuminance threshold is met by daylight alone” and for a point to be considered ‘daylit,’ the sDA at the point has to be 50%, in short sDA ≥ 300 lux [50%] (Reinhart, 2019). UDI is defined when “there is useful daylight in the back two-thirds of the space (UDI 100-300 Lux), while EUDI (UDI > 3000 Lux) flags on over-supply of daylight near the facade” (Reinhart, 2011, 2019). 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” (Reinhart, 2011). The increasingly popular discomfort glare metric suggested by Wienold and Christoffersen (Reinhart, 2019; Wienold and Christoffersen, 2006) 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) (Reinhart, 2011). In particular, DGP has been measured at points assigned to occupants’ positions in the room.

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. Yazd has been classified as a hot desert climate (BWh), which has clear sky based on Koppen climate classification (Chen and Chen, 2013). 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 (National Renewable Energy Laboratory, 2019). The width and depth of the floor plan are respectively 4.4 m and 4.1 m based on the standard office layout (Neufert and Neufert, 2000). Building elements are modeled with a thickness of 0.2 m for walls, 0.3 m for ceiling and floor (Fig. 9). 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 facade with a ratio of 0.85 for the window to wall. Climate based metrics including spatial Daylight Autonomy (sDA), Useful Daylight Illuminance (UDI), and Exceeded Useful Daylight Illuminance (EUDI) are calculated annually for every individual facade configuration. The luminance metric to evaluate visual discomfort is
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 (Reinhart, 2011, 2019). 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 300 Lux on the work plane in height of 0.85 m from the floor, occupancy schedule (8–16), a grid of sensors will be 0.5 m wide in Y and X directions, no shading and artificial light (Reinhart, 2011).

4.2. Base case (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 sDA 93.8% of the time), the UDI amount (16.6%) indicates that most of the admitted light is higher than 3000 Lux, resulting in visual & thermal discomfort. A value of EUDI (76.75%) proves the results. For the prediction of risk of glare, most of the cases are in the intolerable range (Table 3). Table 3 indicates the complete visual discomfort for the occupants who suffer from daylight glare throughout the year.

4.3. Bio-inspired interactive kinetic facades’ results

The simulation results of 810 bio-inspired interactive kinetic facades (BIKF), with the several grid divisions of 4x1, 8x1, 12x1, confirm the significant improvement in visual comfort and daylight performance, due to different size of the TAS, compared to the base case. Since the TSA influenced by dynamic sun timing and occupants’ positions, the BIKF changes its configurations in the timing individual scenario which equal 9 different façade’s forms. As we have 10 distinctive radiuses of the TSA, thus all the possible configurations for every grid division are 90 cases. The simulation results have been filtered based on the minimum sDA of 50% with 1% safety and maximum EUDI of 10% to identify the optimal BIKF with specific transitory sensitive area’s radius for different directions consisting of west, east and south.

Tables 4–6 represent the percentage of climatic-luminance based daylight metrics (sDA, UDI, EUDI) on the solstice and equinox days (at 9, 12, 15) for the best options of BIKF with 4GD, 8GD, and 12GD of every direction.

4.3.1. Bio-inspired interactive kinetic façade’s result for the west direction

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 rotating movements of modular elements to control daylight regarding sun and occupant positions based on different daytime

---

**Table 2** Optical Properties of common material surfaces (Reinhart, 2011).

<table>
<thead>
<tr>
<th>Material Surface</th>
<th>Reflectance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interior Floor</td>
<td>20%</td>
</tr>
<tr>
<td>Interior wall</td>
<td>50%</td>
</tr>
<tr>
<td>Interior ceiling</td>
<td>80%</td>
</tr>
<tr>
<td>Single glazing</td>
<td>90% direct visual transmittance</td>
</tr>
<tr>
<td>Exterior building surfaces</td>
<td>35%</td>
</tr>
<tr>
<td>Exterior ground</td>
<td>20%</td>
</tr>
</tbody>
</table>

**Table 3** Plain window room daylight performance Glare probability evaluation for different scenarios based on sun-timing position and occupant position.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>9:00</th>
<th>12:00</th>
<th>15:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Person 1/Jan 21st</td>
<td>59</td>
<td>77</td>
<td>58</td>
</tr>
<tr>
<td>Person 1/Mar 21st</td>
<td>45</td>
<td>55</td>
<td>42</td>
</tr>
<tr>
<td>Person 1/Dec 21st</td>
<td>62</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Person 2/Jan 21st</td>
<td>53</td>
<td>54</td>
<td>41</td>
</tr>
<tr>
<td>Person 2/Mar 21st</td>
<td>39</td>
<td>45</td>
<td>35</td>
</tr>
<tr>
<td>Person 2/Dec 21st</td>
<td>100</td>
<td>100</td>
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scenarios. Table 4 demonstrates the bioinspired interactive kinetic facades (BIKF) performances by employing 4, 8, and 12 grid divisions (GD) for the west direction. The only facade configuration that can meet the minimum sDA of 50% is 4GD with the TSA's radiuses of 0.3R. Moreover, this alternative provides the acceptable ranges of Useful Daylight Illuminance (UDI), and Exceed Useful Daylight Illuminance (EUDI) between (75–96), (1.7–23) respectively. The 4GD improves UDI up to 4 times regarding the base case as well as reduction of EUDI more than 86%. Although 8GD with TSA's radiuses of 0.1R represents a satisfied average of UDI and EUDI by 94.73 and 0.47 respectively, the amount of sDA with the number of 28.33 cannot meet adequate requirements of daylight performance. The BIKF 12GD with TSA's radiuses of 0.1R has an unacceptable daylight performance by the average sDA of 2.17% (Fig. 10).

4.3.2. Bio-inspired interactive kinetic facade's result for the east direction

Table 5 shows the positive impact of the transitory sensitive area (TSA) to achieve a compromised configuration in the BIKF with the grid division of 4. The alternative has the potential to provide adequate daylight in the interior space while preventing visual discomfort. Due to climate-based daylight metrics evaluation, the BIKF 4GD with TSA's 0.3R shows the high capability to meet annual daylight metrics' requirements including sDA, UDI, and EUDI with an average percentage of 49.55, 82.28, and 13.09 respectively. The BIKF 4GD improves UDI up to 4 times regarding the base case as well as reduction of EUDI more than 83%. Although, the BIKF 8GD with TSA's 0.1R increases the amount of UDI by 10.23% regarding the 4GD, the amount of sDA (28.26) indicates that the BIKF 8GD hasn’t a capability to enter adequate daylight into interior space. The climate-based daylight metrics evaluation of the BIKF 12GD with TSA’s 0.1R clearly shows that the facade cannot provide satisfied amount of useful daylight in the room by average sDA, UDI, and EUDI of 1.72, 59.95, and 2.03 respectively (Fig. 11).

4.3.3. Bio-inspired interactive kinetic facade’s result for the south directions

Analyzing the daylight performance numbers in Table 6 reveals the significant effects of dynamic transitory-sensitive area (TSA) with radiuses of 0.3R and 0.5R of 8, and 4 grid divisions respectively to improve multiple occupants’ visual comfort (Fig. 12). The BIKF 4GD with TSA’s 0.5R shows the high capability to meet annual daylight metrics’ requirements including sDA, UDI, and EUDI with an average percentage of 54.8, 82.05, and 13.16 respectively. In contrast, the BIKF 8GD with TSA’s 0.3R improves the amount of sDA, UDI, and EUDI with the average number of 60.55 and 90.46, and 2.94 respectively. It refers to the high-performance of the BIKF for meeting occupants’ daylight performance by an improvement of 4.43 times in increasing UDI and decreasing the EUDI up to 96.15% compared to the base case while keeping sDA in the satisfactory range. Moreover, the BIKF 8GD with TSA’s 0.3R improves the amount of sDA and UDI by the percentage of 10.49% and 10.25% respectively while decreases the amount of EUDI up to 3.47 times respecting the 4GD with TSA’s 0.5R (Fig. 12).
### Table 5  
**Daylight performance investigation of bioinspired interactive kinetic façade (BIKF) 4GD, 8GD, 12GD with the TSA’s radii of 0.3R, 0.1R, 0.1R respectively for the East direction through climate-based daylight metrics.**

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### Table 6  
**Daylight performance investigation of bioinspired interactive kinetic façade (BIKF) 4GD, 8GD, 12GD with the TSA’s radii of 0.5R, 0.3R, 0.1R respectively for the South direction through climate-based daylight metrics.**

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4.3.4. Luminance based metric evaluation of the best bioinspired interactive kinetic facades of South, East, and West directions

Figure 13 displays the DGP value of the best bioinspired interactive kinetic facades of South, East, and West directions based on occupants sitting position at the room on the solstice and equinox days. The BIKF forms show significant performance for preventing visual discomfort by decreasing Daylight Glare Probability (DGP) compared to the base case on different days and hours. The BIKF 8 GD with TSA's 0.3R indicates the substantial improvement of DGP values while keeping the sDA in the acceptable ranges. In particular, the kinetic facade has 7 cases in the imperceptible, and 2 cases in the perceptible ranges (Fig. 13a). To sum up, the BIKF with 8 grid division provides maximum useful daylight in the interior space while preventing visual discomfort as well as overheating nearby the facade for the south direction.

Figure 13b displays a remarkable effect of the TSA with a radius of 0.3R to achieve an optimal configuration due to the improvement of visual comfort in the BIKF with 4 grid divisions for the east direction. Analyzing the luminance-based metrics diagram mentions the high capability of BIKF to keep daylight glare probability in the acceptable ranges. The BIKF has 7 cases in the imperceptible, and 2 cases in the perceptible ranges for occupant’s number two while 5 cases in the imperceptible, 2 cases in the perceptible, and only 1 case in the disturbing ranges for occupants’ number one and three.

Considering Fig. 13c indicates the high capability of BIKF 4 grid divisions with TSA radius of 0.3R to meet visual comfort requirements respecting daylight glare probability evaluation for west directions. The BIKF has 6 cases in the imperceptible, 2 cases in the perceptible, and 1 case in the intolerable ranges for occupant’s number two while 5 cases in the imperceptible, 2 cases in the perceptible, and only 1
case in the intolerable ranges for occupants’ number one and three. The results point out the flexibility of the BIKF for achieving a compromised solution regarding the visual comfort and daylight performance of multiple occupants simultaneously.

5. Discussion

Since an optimal facade form significantly affects the amount of useful daylight, it presents an opportunity to investigate and develop real-time form findings logics. In particular, buildings, which have high daylight performance apply dynamic, complex fenestration, and human-in-loop systems (Hosseini, Mohammadi and Guerra-Santin, 2019; Hosseini, Mohammadi, Rosemann, et al., 2019; Konis and Selkowitz, 2017). The façade needs to be kinetic and interactive under the navigation of a responsive decentralized system to provide a hierarchically self-shading form resulting in an interactive façade due to user engagement (occupants). Since the interactive kinetic façade function (improving visual comfort) has been proved through annual climate based metrics and luminance-based metric (Reinhart, 2011) simulation only for a single occupant in different positions of a test room. Façades need to be kinetic under the navigation of a responsive decentralized system to provide a hierarchically self-shading form resulting in a bio-inspired interactive façade with respect to occupants. Due to the high-potential of biomimicry approach for extracting technical solutions and lacking quantitative performance analysis of bio-adaptive building skins, this research aims to develop an interactive kinetic shading façade, for the first time, to improve multiple occupants’ visual comfort simultaneously inspired by plant movements.

The interactive kinetic façade, inspired by stomata distribution and movement, has the capability to meet the daylight performance and visual comfort requirement for multiple occupants. Indeed, the abstraction of biomimicry principles from stomata’s general characteristics, and stomata patchy pattern transitory stage can propel the development of the real-time morphological logic for the interactive kinetic façade design. Regular and equidistance rows of stomata give rise to apply grid form and positioning of kinetic elements in the façade surface. Also, the transitory stage and hunting new position of stomata’s patchy pattern, leads to identify the dynamic transitory-sensitive area (TSA) which is triggered by the dynamic sun-timing position and multiple occupants. Accordingly, the elastic-deformable-complex-kinetic form triggered by the dynamic TSA of attraction point (Figs. 5–7) can improve the visual comfort of multiple occupants simultaneously.

The parametric simulation results of 810 bio-inspired interactive kinetic facade (BIKF) alternatives, with the several grid divisions of 4x1, 8x1, 12x1 in three different directions (south, east, and west), prove the significant improvement in visual comfort and daylight performance of multiple occupants, due to different size of the TAS, compared to the base case. Due to annual climate-based daylight metrics evaluation specifically Spatial Daylight Autonomy (Minimum 50%), we can categorize the BIKFs alternatives into two groups: 1) Grid divisions 4x1, 8x1, 2) Grid divisions 12x1. The first group can provide adequate daylight and prevent visual discomfort while the second group cannot supply enough daylight. Indeed, this fact emphasizes that having more kinetic components can’t guarantee the daylight performance of the façade.

The first group that has the BIKFs with the grid divisions 4x1, 8x1 demonstrates high performance for supplying adequate daylight in the interior space while preventing visual discomfort specifically through using the TSA’s radius in different ranges. Annual climate-based metrics and luminance based metric evaluations infer the significant impact of the transitory-sensitive area with different radiuses to achieve a compromised configuration in the BIKF alternatives. Due to the grid divisions, the acceptable
Fig. 13  Daylight glare probability evaluation of three occupants through bio-inspired interactive kinetic façade (BIKF): a) 8GD with the TSA’s radius of 0.3R for the south direction, b) 4GD with the TSA’s radius of 0.3R for the east direction, c) 4GD with the TSA’s radius of 0.3R for the west direction.
ranges of TSA's radiuses for improving multiple occupants’ visual comfort are recognized consist of 0.3-0.6R for grid division 4x1, 0.1-0.3R for grid division 8x1. In particular, the BIKF with grid division 8x1 and TSA's 0.3R displays extraordinary daylight performance which is recognized as the best case between the first group for the south direction. This alternative prevents visual discomfort with having 7 cases in the imperceptible, and 2 cases in the perceptible ranges while providing adequate average sDA of 60.5%, UDI of 90.47%, and EUDI of 2.94% indeed, it mentions to the high potential of this BIKF to admit adequate useful daylight and preventing thermal discomfort while keeping the DGP values of all occupants in the acceptable ranges. Regarding the east and west directions, BIKFs with the grid divisions 4x1 shows the remarkable daylight performance. Especially, the BIKF with TSA's radius of 0.3R has 7 cases in the perceptible, and 2 cases in the perceptible ranges while providing adequate average sDA of 60.5%, UDI of 83.28%, and EUDI of 13.1% for the east orientation. In addition, the BIKF has 6 cases in the imperceptible, 2 cases in the perceptible, and 1 case in the intolerable ranges for the west direction. The facade can supply average sDA of 50.29%, UDI of 87.26%, and EUDI of 10.10% as well.

The second group includes the BIKFs with the grid divisions 12x1(TSA's 0.1R) can't meet the minimum sDA with the percentage of 2.16, 1.72, 26.81 for the west, east, and south directions respectively. However, the facade show the high capability for preventing visual discomfort that have 8 cases in imperceptible and 1 case in the perceptible ranges. Since admitting adequate daylight is the priority for choosing the best options for improving visual comfort, thus the BIKFs with the grid divisions 12x1 is not a proper choice for the bio-inspired interactive kinetic façade.

6. Conclusion

Reviewing the literature reveals a Lack of the interactive logics of kinetic facades for improving multiple occupants’ visual comfort simultaneously. Due to the dynamic characteristics of influential parameters, such as sun-timing positions, local climate variation, and multiple occupants’ positions, it is imperative to increase the flexibility and performance of the automated process in the façade design. Applying an interactive logic is a way to facilitate communication between the dynamic parameters. The design concept of kinetic shading façade can benefit from the biomimicry morphological approach for developing an interactive logic to change from static to dynamic. Hence, the architecture of the plant, especially motion principles of stomata in micro-scale, is a source of exploring and extracting unique adaptive strategies to light. This research aims to develop an interactive kinetic shading façade, for the first time, to improve multiple occupants’ visual comfort simultaneously inspired by the plant’s kinetic movements and behavior. Integrating biomimicry morphological principles with kinetic-responsive decentralized, and human-in-loop systems provide an opportunity to develop an interactive kinetic façade with complex geometry.

Considering the functional convergence between buildings and plants regarding daylighting and visual comfort reveals that the plant’s stomata filter and harness daylight through different ways consist of interception, redirection, scattering, and transmission. Due to stomata kinetic movements and behavior, there are many options to control daylight comprising symmetrical pores, regular and equidistant rows, transitory sensitive area, reacting in harmony within the area and independent from neighboring areas, hunting new position and shape due to immediate changes in the environment. The extracted movements and kinetic behaviors are translated into the design solutions consist of grid form, symmetrical elements, identification of a dynamic transitory-sensitive area (TSA), dynamic sizes and positions of TSA, defining the logic of dynamic multiple TSA, locally decentralized façades' shape change.

Learning from the plant’s stomata movements and behavior directs us to identify the transitory-sensitive area of attraction point on the façade. The TSA is triggered by sun timing and multiple occupants’ positions that has the capability for controlling the interactive façade as well as a real-time generating complex form. The proposed interactive logics improves the performance of the interactive kinetic façade for meeting visual comfort requirement from a single occupant to multiple occupants by employing biomimicry morphological approach. The parametric daylight simulation of 810 bio-inspired interactive kinetic façade (BIKF) alternatives proves the high-performance of the elastic-deformable-complex-kinetic form triggered by the dynamic transitory-sensitive area. In particular, the bio-inspired interactive kinetic façade with grid division 8x1 displays extraordinary daylight performance for south direction that prevents visual discomfort by keeping cases in the imperceptible range while providing an adequate average Spatial Daylight Autonomy of 60.5%, Useful...
Daylight illuminance of 90.47%, and Exceed Useful Daylight illuminance of 2.94%. Regarding the east and west directions, BIKFs with the grid divisions 4x1 shows the remarkable daylight performance. Especially, the BIKF with TSA’s radius of 0.3R provides adequate average sDA of 49.56%, UDI of 83.28%, and EUDI of 13.1% for the east orientation while supplying average sDA of 50.29%, UDI of 87.26%, and EUDI of 10.10% for the west side.

Since the shapes and areas (circle) of both TSA on the individual façade case are the same, we propose investigating about different sizes and shapes of the TSA for every attraction point at the same time as future research. Regarding the architectural design viewpoint, there is an opportunity to develop the BIKF with TSA through various subjects including proportion, scale, relation to the human body, usability, materiality, haptics, feel the atmosphere, etc. Learning from biological analogies is a precious resource for architects and engineers to develop innovative solutions for architectural design problems. Hence, a close collaboration of biologists, engineers, and designers can support interdisciplinary topics resulting in constructing multi-functional buildings' components. Due to the optimization, the interactive behavior of the kinetic façades has the potential to be improved using a reinforcement learning method. Machine learning methods can be applied to predict the optimal functions of the kinetic façade based on the dynamic characteristics consist of occupants’ behavior, positions, sun-timing positions and dynamic orientations, space functions, and layout design… etc.

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.

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Badarnah, L., 2016b. Water management lessons from nature for ASHRAE Press, 2006. 4


