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# Shaping light to influence occupants' experience of space: a kinetic shading system with composite materials

Joëlle Baehr-Bruyère<sup>1,2</sup>, Kynthia Chamilothoni<sup>1</sup>, Anastasios P. Vassilopoulos<sup>2</sup>, Jan Wienold<sup>1</sup>, Marilyne Andersen<sup>1</sup>

<sup>1</sup> Laboratory of Integrated Performance in Design (LIPID), École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

<sup>2</sup> Composite Construction Laboratory (CCLAB), École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

joelle.baehrbruyere@gmail.com

**Abstract** Adaptive kinetic façades are systems capable of modifying their shape to optimize their behavior regarding real time outdoor and indoor conditions. They are typically evaluated based on quantifiable physical parameters such as illuminance levels, with little attention – for lack of evaluation criteria – given to subjective appreciation of the façade and the resulting daylight patterns. The present study investigates the daylighting performance of a kinetic shading system based on simulations combined with physical mock-up testing, to assess its viability as an alternative shading solution that complements conventional functions by enhancing the occupants' experience of the space. Based on performance assessment and perceptual studies, the shortcomings of traditional blinds are identified and a promising prototype design, controlling the blinds' opening by means of torsional deformations, is proposed.

## 1 Introduction

Given the critical role of the building envelope for building energy consumption and occupant comfort [1], [2], daylighting control systems are of particular importance. Over the last decades, energy efficiency issues fostered the development of adaptive facades. Among them, adaptive shading systems perform motions to benefit from potential natural daylighting provided by sunlight while offering solar control: such systems change states in response to exterior conditions and interior requirements, aiming to achieve a balance between solar gains, view access, daylight and discomfort glare [3], thus aiming to improve buildings' energy efficiency together with users' comfort [4].

While dynamic façades represent a novel direction in architecture, the explicit motivation in the application of such systems remains widely the same as for static configurations, revolving around building energy consumption and user comfort [5]. However, experimental studies in real and virtual environments have demonstrated that conventional shading systems such as horizontal and vertical blinds are often perceived as unappealing and visually uninteresting [6], [7]. In contrast, less linear openings have been shown to lead to a 10% increase in evaluations of interest and excitement compared to vertical blinds [8], indicating important potential in this research direction.

This paper aims to address the shortcomings of existing shading systems through the development of a new type of adaptive shading system which increases the potential of conventional vertical blinds. By associating potential occupant activities of working and socializing to specific changes on daylight metrics, this paper aims to demonstrate that the proposed system provides adequate visual comfort for multiple scenarios of space use, while exhibiting new potential for increasing the pleasantness and visual interest of a space in social conditions.



## 2 Design concept and methodology

The proposed design fulfills the base function of a shading system (i.e. protecting against glare and allowing daylight penetration when glare is not problematic) and goes further by introducing torsion as a new degree of freedom in vertical blinds, generating slightly curved openings expected to improve perceptual impressions [8]. Elements are designed to shift from a fully open state maximizing the view out to a fully closed state minimizing the incident solar radiation, with intermediate twisted states that allow partial view access while creating visual interest in the scene.

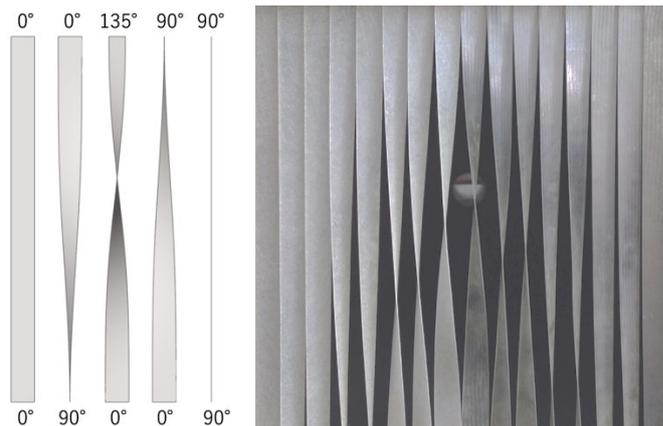


Figure 1a illustrates the design concept, depicting a single element that changes shape through individual rotations of the top and bottom edges. Figure 1b shows the design concept with variations in the rotation of the elements in a mockup model. In order to realize this design concept, the authors employed glass fiber reinforced polymers (GFRP), since they can assume significant elastic deformations before failure and offer a high degree of customizability of the material structural and optical properties.

**Figure 1.** (a) Studied system states. (b) Illustration of design concept in a mockup model (1:5 scale)

This work investigates the performance of the different slat states, focusing first on the optimization of the base performance of the shading system (fully open and fully closed state). It then combines these states by proposing actual application scenarios through a control algorithm so as to assess the daylight performance of the kinetic shading system's behavior as a whole. The evaluation of the daylight and glare protection performance is based on the standards "Daylight in Buildings" EN17037:2019 [9] and "Blinds and Shutters" prEN14501:2019 [10].

The paper describes the different phases of work. First, the material properties are optimized to ensure glare protection in the closed state and good daylight provision in the open state. Afterwards, the behavior of different intermediate twisted states is investigated by evaluating their annual performance. Then the positive aspects of the façade patterns resulting from the blinds' control algorithm are analysed by taking into account the influence of the context (working or social). A discussion about technical implementation in terms of structural design, and further investigations needed for a full quantification of energy savings is provided.

### 2.1. Modelling, daylight simulations

To investigate the daylighting performance of the proposed system, we selected an existing space as a case study, to which two scenarios of use (working and socializing) were applied, each translated into different requirements on glare protection. The chosen space was a large multi-use room located on the EPFL campus in Lausanne (SG building), where light-demanding activities like group work or exhibitions are often hosted. The space is located on the first floor and is oriented to the East with dimensions of 43.5x11 m. It has a large glazed facade of 2.36 meters height, as shown in figure 2. For this study, we assumed a usage area of max 5.5m depth and 21.5m width to remain consistent with a "reference office" size [11]. The modeling software Rhinoceros was used to create the 3D model of the space, while the variations of the shading system elements were parametrically defined in Grasshopper and imported to Rhinoceros. The surfaces' optical properties were defined using photometric and spectrophotometer measurements and are reported in Table 1. The blinds were modelled as purely translucent material without forward peak.

The Rhinoceros plug-in DIVA was used for daylighting simulations [12]. Average local weather data corresponds to IWEC weather data for Geneva [13]. All grid-based metrics were evaluated on a grid of sensor nodes set at a distance of 0.85m from the ground. Each node is representative for a section of floor area (43cm\*38 cm in our model), for 611 nodes in total. Typical Radiance simulation parameters were used (cf. Table 2). Glare simulations were performed at the mean eye-level of a standing person (1.56m) with a viewing direction towards South-East (30° towards South from East direction). This is a worst-case scenario given the building's East orientation, where highest glare levels are due to S-E morning direct sunlight (cf. Figure 2).



**Figure 2.** Example space simulated at 9:00 on March 15<sup>th</sup> in sunny conditions with all slats tilted at 135°.

**Table 1.** Radiance material properties

Surface	Type	Reflectance	Specularity
Ceiling	plastic	94.5%	0
Floor	plastic	31.0%	0
Walls	plastic	93.5%	0
Glazing	glass	<b>Visual Transmittance 80%</b>	

**Table 2.** Radiance calculation parameters

-ab	-ad	-as	-ar	-aa
3	1000	20	300	0.1

## 2.2 Applied metrics

The daylight factor, DF, gives an indication of the daylight performance of the space under overcast conditions. This simple metric was thus used for an initial assessment of the performance of the shading system with fully open blinds and to evaluate the influence of the composite material reflectance on this performance. To evaluate efficiency of the shading system regarding adequate annual illumination and glare protection we used the definitions of the annual daylight provision (DP) and the annual daylight glare probability ( $DGP_{e<5\%}$ ) described in EN17037:2019 [9]. While the DP takes into account local weather data during daylight hours (i.e. irradiance  $> 20 \text{ W/m}^2$ ) and blind states to describe the performance of the space regarding daylight provision, the  $DGP_{e<5\%}$  value allows to determine the DGP value that is not exceeded more than 5% of the total occupied hours. For the evaluation of the control algorithm, we defined an annual spatial illuminance  $ASI_{50,50}$  concept, defined as the illuminance level reached over 50% of the floor area for 50% of the relevant time steps (here: occupancy during daylight hours).

## 3 Results & discussion

### 3.1 Base performance

The authors first investigated appropriate optical material properties to take advantage of GFRP translucency while ensuring an adequate performance of the open and closed blinds' states, based on the medium recommendation level from standard EN17037:2019 [9] regarding daylight provision (DP) and achieving a "good effect" regarding glare protection according to prEN14501:2019 [10] (glare control class 3). Achieving class 3 requires to limit the visual transmittance to 15% and to avoid any direct transmittance. The different states of the shading system are referred to as 'degree of rotation at the top – degree of rotation at the bottom', following Figure 1a.

Results using a material with 15% transmittance showed that the closed state (0-0) sufficiently prevents from discomfort glare ( $DGP_{e<5\%}=0.35$ , i.e. below the medium recommendation level of 0.4), while GFRP remains luminous compared to classical opaque elements. For the daylight provision in the open state (90-90) we tested the effect of a change in reflectance value from 35% to 65%: it resulted in

a change of the DF from 4.08% to 4.48%. Given this low sensitivity we selected a reflectance value of 50%. Following these findings, a material with 15% transmittance and 50% reflectance was applied to the shading system elements for the calculation of the annual daylight performance of each state in an annual basis, shown in Table 3. Note that the case without blinds is a reference case for the maximum daylight provision in this room.

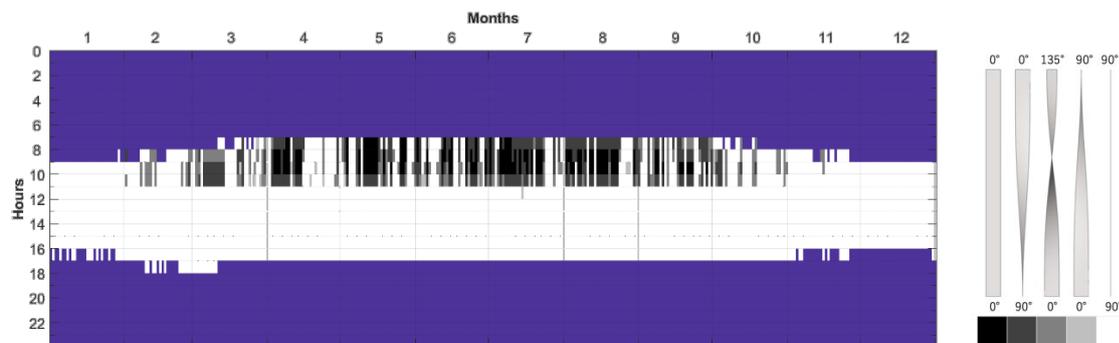
**Table 3.** Annual daylight provision DP and glare probability for studied states, noted ‘top rotation - bottom rotation’ and sorted in increasing protection i.e. decreasing DGP.

Blinds position	No blinds (ref.)	90-90	90-0	135-0	0-90	0-0
DP[300lux]50%	100 %	78 %	64%	62 %	35 %	7 %
DP[500lux]50%	82%	48%	39%	39%	21%	0%
DGP <sub>e&lt;5%</sub>	0.89	0.59	0.53	0.46	0.37	0.35

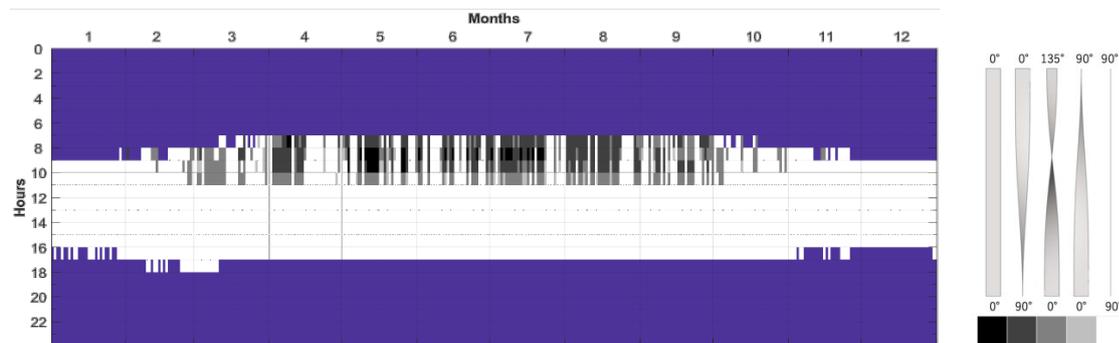
### 3.2 State choice and annual schedule

A custom function was developed to optimize the choice of the façade state for every hourly time step. Hourly data were simulated in advance for all states and stored in a database. The function included three simultaneous conditions to satisfy at each step: (1) maximizing the work plane illuminance reached by at least 50% of the floor area (= median illuminance), while (2) avoiding direct sun penetration, and (3) limiting the point-in time DGP to a maximum ("cut-off") value chosen according to the studied scenario. The point-in-time cut-off DGP is selected according to the targeted annual DGP performance  $DGP_{e<5\%,annual}$ .

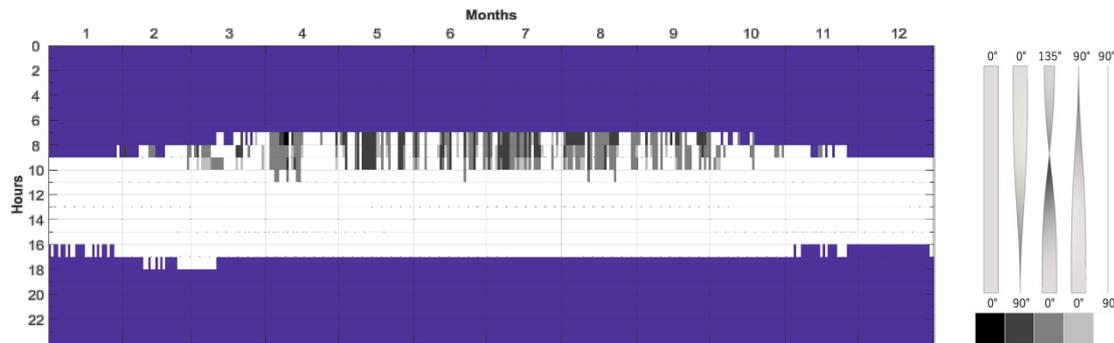
Both working and social usages could be addressed by changing this threshold, as the discomfort glare perception is highly influenced by the difficulty of the task performed [14]. Figure 3 shows the control of the shading system and the corresponding choice of states across a year, using a low cut-off threshold, representative of workspaces (Figure 3a), as well as higher cut-off thresholds (Figures 3b and 3c) which are suitable for social functions of the space. Time steps coloured in violet are not relevant for the evaluation, please refer to subsection 2.2.



**3a.** DGP cutoff set to 0.40 → DP<sub>e<5%,annual</sub> = 0.388 ; ASI<sub>50,50,morning</sub> = 879 lux



**3b.** DGP cutoff set to 0.45 → DP<sub>e<5%,annual</sub> = 0.428 ; ASI<sub>50,50,morning</sub> = 953 lux



3c. DGP cutoff set to 0.50  $\rightarrow$   $DP_{e<5\%,annual} = 0.481$  ;  $ASI_{50,50,morning} = 953 \text{ lux}$

**Figure 3.** Variations in the annual blinds' state-change controls observed for different cut-off conditions on the admissible point-in-time DGP. Note that due to the East orientation, the blinds can stay open all afternoon without the occurrence of glare (using the 90°-90° state). The indicator  $ASI_{50,50}$  is stable to 521 lux but mainly reflects the illuminance level reached during this period. To better interpret the schedule's influence, the same indicator is calculated in Figure 3 taking only into account time steps before 12:00.

Control 3a satisfies the requirements for workspace usage of the space ( $DGP_{e<5\%,annual} < 0.40$ ). The fully closed state is needed only during few hours of the year, the 0°-90° mostly provide enough glare protection in the morning. For the controls 3b and 3c, when occupants can be more tolerant of glare as they do not perform complex visual tasks, only few cases require a complete closure of the blinds. In control 3b, the 135°-0° state provides a very good protection between 10:00 and 11:00 A.M, even higher than the 90°-0° state that would be sufficient for the control 3c. In this latter schedule only twisted states are used. However, the annual DGP increases without improving the daylight provision, compared to situation 3b. This result highlights that if constraints on visual comfort are too loose then the need for a kinetic shading system becomes questionable. Figure 3 also shows that twisted states are very often sufficient in providing adequate glare protection, so that an automatic closing of the blinds could be avoided and a higher acceptance can be achieved.

### 3.3 Technical implementation & limitations

Glass fiber reinforced polymers (GFRP) are made of layers of fiberglass fabric casted into resin. They were selected for their resistance to environmental attacks, e.g. rain and UV-radiation, along with the customization of their structural performance through the choice of fibers' types and orientations. Besides the simulation study on the daylight performance, the optimization of the dimensions of the external shading system were investigated. The elements must resist against, mainly, wind loads, having a certain degree of flexibility to be able to twist. Unidirectional glass fibers and epoxy resin were selected. Following full structural calculations described in [15], the thickness of 2.5 m high elements was minimized to 12 mm. A mock-up has been built (see Figure 1b), with laminates fabricated by a vacuum assisted resin infusion technique to produce the prototype façade elements. Following previous work on the transmittance of GFRP [16], the theoretical expected transmittance of 12mm thick full-scale elements reaches 25%. Further investigations will consider using additives in the epoxy resin to reach the maximum 15% allowed (cf. subsection 3.1.).

The reduction of solar heat gains (expressed e.g. by the shading coefficient  $F_c$ ) might not be sufficient with 15% transmittance for thermal reasons. Typical  $F_c$  values for closed aluminium venetian blinds are in the range of 0.12 (perpendicular incidence) [17] while the system of this study is slightly higher ( $F_c=0.15$ ) under the same conditions. In a lesser extent, the façade actuators also consume electricity. The torque force required to twist one element up to 135° is about 540 N.m which is also a challenging mechanical engineering topic.

Lastly, the support system must offer the option to slide and store the blinds away when solar protection is not required. Table 3 indeed shows that a non-retractable system cuts half of the light for an East oriented building (annual Daylight Provision[500lux]<sub>50%</sub> of the open state is 48%).

#### 4 Conclusion and discussions

This work showed that with this new kinetic façade a balance between glare protection and daylight provision could be achieved. Using GFRP materials leads to more (diffuse) light penetration even in the closed or partially closed states, intrinsically reducing the overall electrical lighting. However, energy savings for the lighting have to be seen in relation to the thermal effects of the façade, i.e. solar heat gains in summer and, to a lesser extent, in relation to the electrical consumption of the façade's actuators.

The range of states of the shading allows to adjust to users' needs without systematically closing the blinds, where automatic closing was shown to be poorly accepted by the occupants [18]. The kinetic system also adapts to different usage types, showing its potential for social functions of the space, which can allow less severe quantitative requirements regarding glare prevention. Following the findings in [8], the twisted states were considered to generally increase the pleasantness and visual interest of the space. Further studies should address occupants' responses to variations in these twisted blinds.

The coupling of perceptual impressions of occupants (such as visual interest) with current daylight metrics is a first step towards the integration of the human performance in smart façade controllers. Regarding this perceptual component, the prediction of the desired state is a complex and highly user-dependent issue. As highlighted in [4] concerning the future of adaptive facades (AF), "AF must go through a soft-landing process [...] to customize and adapt the AF technology to users' needs and expectations". Given all the possible intermediate twisted states and the variability of user-specific data, it becomes difficult to design optimal control algorithms. Further implementation of self-learning multi-objective algorithms as decision functions is promising to achieve automatic customization [19], [20].

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