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The impacts of dynamic façade shading typologies on building energy performance and occupant's multi-comfort

Ihab Elzeyadi

High Performance Environments Lab (HiPE), School of Architecture & Environment, University of Oregon, Eugene, OR, USA

ABSTRACT

Despite a growing interest in dynamic facades shading systems, few studies have measured their actual performance in the field using full-scale prototypes or evaluated their performance in a comparative way. This paper reports on an important yet understudied topic related to comparing the performance of different dynamic shading typologies and assessing their impacts on building energy savings, daylighting distribution, glare control, and solar insolation management for a typical office space in ASHRAE Climate Zone 4C. Results show variations in performance across the dynamic shading typologies studied. While some systems show superior performance in reducing solar loads and building energy consumption, other typologies studied performed better in managing glare and providing better spatial daylight autonomy. The paper concludes with a framework for the parametric design and assessment of dynamic shade systems based on their performance and climatic suitability for the main eight ASHRAE's climate zones.

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Dynamic shades; high-performance envelopes; commercial buildings; indoor comfort; energy performance; simulations; field testing

Introduction

There is an urgent need to develop the science and engineering knowledge that will enable designers, architects, and developers to accurately predict energy performance and emissions reductions for installed high-performance dynamic façades and shade technologies (Lutzkendorf and Lorenz 2005; Malmqvist 2008). Dynamic façades and shade technologies are the components of advanced exterior fenestration systems that allow light, air, and solar energy to be managed by allowing the façade system to react and change its geometry in relation to the outdoor climate, daylighting demands, and solar altitude angles, while maximizing occupant's comfort and energy savings. They include systems that can allow solar and light energies to be captured and transmitted into the interior of a building; this energy can be collected and transmitted for other uses in the building, in a controlled system (Bahaj, James, and Jentch 2008; Elzeyadi 2009). With adequate research and development, dynamic shading systems can be proposed, but no matter how advanced the designs of the dynamic shade systems are, if architects and engineers do not evaluate their performance by comparing modelling and simulations to field testing of prototypes, we will continue to face actual energy performance that falls short of design predictions (Brown and Cole 2009; Elzeyadi 2012; Leeman and Bordass 2007).

Despite a growing interest in dynamic shades, few studies have documented their actual performance in the field in full-scale applications (Lee, DiBartolomeo, and Selkowitz 1998). In comparison to fixed and optimized shades, dynamic/movable shades have not attracted the same attention in field analysis and studies (Batool and Elzeyadi 2014; Vignola et al. 2010). In the US, 41% of primary energy is consumed by buildings and 5% is attributed to heat gains and losses of the building envelope (DOE 2015). This will increase the demand on building professionals to provide dynamic shading systems that have been field-tested and verified (Eichholtz, Kok, and Quigley 2009).

This study targets this problem by investigating the performance of six dynamic shading typologies and assessing their impact on daylighting distribution, glare control, and solar insolation management for ASHRAE Climate Zone 4C. The results will be synthesized and interpolated based on a conceptual framework for classifying and assessing the performance of dynamic shade systems based on their performance and climatic suitability for the main eight ASHRAE's climate zones of the US.

Dynamic shading framework

A systemic framework for active dynamic shading systems squarely categorizes their performance based on their ability to accommodate change in their geometry and properties with respect to sun angles, solar insolation, daylight levels, and intensity (Figure 1) (Elzeyadi et al. 2016). A high-performance system will adjust to these conditions on an hourly, daily, and seasonal basis to accommodate climate variations and capitalize on available opportunities contributing positively to building energy performance, indoor environmental quality (IEQ), and occupant's multi-comfort.

The main difference between dynamic shades and fixed ones is the ability of the former to change according to internal needs by the occupants to maintain indoor comfort and the external loads placed on the building façade (Figure 1).

CONTACT Ihab Elzeyadi ihab@uoregon.edu High Performance Environments Lab (HiPE), School of Architecture & Allied Arts, University of Oregon, Eugene, 97403-1206 OR, USA

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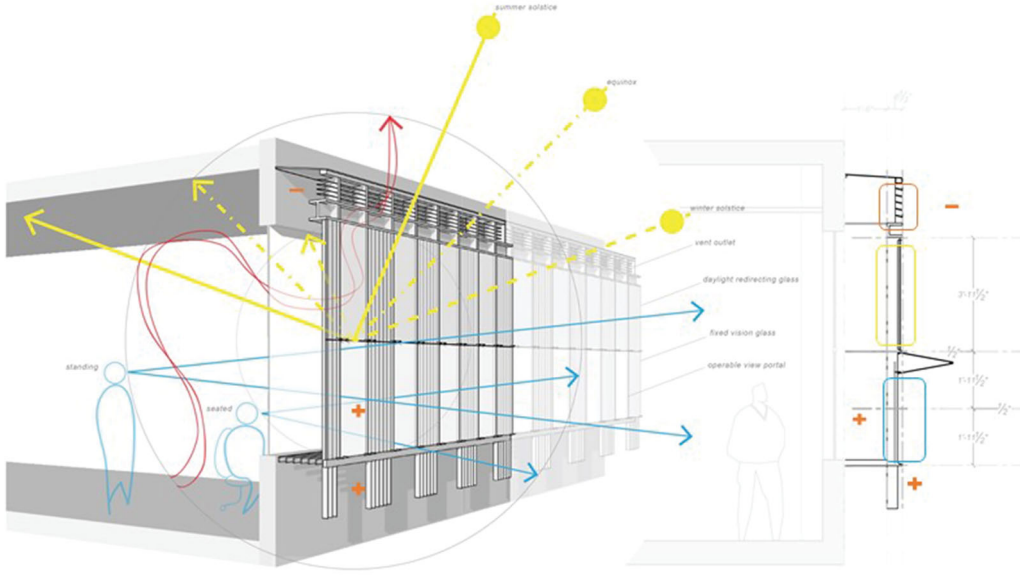


Figure 1. Dynamic shades ability to accommodate change through movement, optical, or thermal processes (after Elzeyadi et al. 2016).

Fixed shades, on the other hand are typically optimized based on proposed reduction for the building thermal loads during the cooling season. Dynamic shades can be categorized based on six processes/typologies by which they can adjust to control and manage lighting, solar insolation, and thermal radiation on a building façade. These dynamic processes are: Automated Exterior Blinds, Dynamic Egg-Crates, Optical Elements Panels, Thermal Change Planes, Stretched Fabrics/Weaved Panels, and Automated Movable Screens (deep planar screens, 3-D paramedic screens, and 3-D geometric screens).

The characteristics of each typology are illustrated in Figure 2 and a review of previous studies for each typology is discussed in the following sections. This review was used to develop the meta-analysis of energy performance for each typology.

Automated Exterior Blinds: Compared to static and manually controlled blinds systems, automated blinds systems can provide additional dynamic control that improves visual and thermal comfort, and reduces energy consumption.

Egg-Crate/Fins: These fins combine movable vertical and horizontal shades (egg-crates) and are typically in grid formation as well as other geometric configurations. The egg-crate typology combines both protection from high vertical sun angles as well as lower horizontal early morning and late afternoon sun angles typical of east and west orientations. Previous studies have shown that these types of shades could save 20–38.5% in energy use for commercial buildings especially in hot and dry climates (Batool and Elzeyadi 2014).

Optical/Thermal Elements: Optical and thermal driven dynamic shades employ a variety of films, coatings, light and heat refraction and reflection mechanisms, and material changes to control direct solar radiation and manage glare while increasing daylight penetration deeper into space.

Solar Screens: Solar screens have been commonly related to the architecture of North Africa and the Middle East in hot and dry climates, such as Morocco and Egypt. The implementation of these screen solutions was to mitigate overheating and reduce cooling loads by employing screened devices such



Figure 2. Dynamic shade typologies.

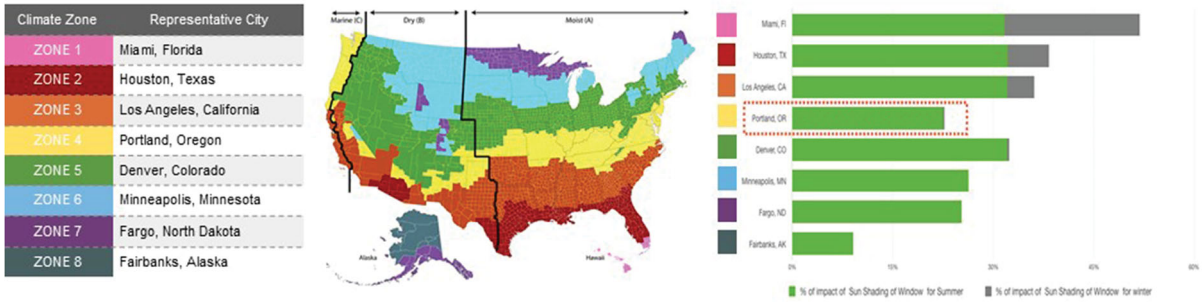


Figure 3. Shading impacts for eight main climate zones in the US.

as Mashrabeyas, Jali screens, and Gus walls (Sherif, Sabry, and Rakha 2012).

Screens can also be classified according to their operability as: (1) fixed optimized screens, such as (1.1) deep perforated panels, (1.2) plant vines, and (1.3) lattice interwoven elements; or (2) dynamic screens, such as (2.1) deep planar with operable shutters, (2.2) geometrical with movable projections, and (2.3) parametric screens with multi-planar movement.

Climate zones and dynamic shading

A climatic analysis for impacts of shading on the eight main ASHRAE climate zones (CZ 1–8) was carried out using Climate Consultant 6.0 software (Figure 3) (http://www.energy-design-tools.aud.ucla.edu). The comparison focused on the impacts of shading strategies on indoor comfort probability based on the psychrometric chart plot for ASHRAE-55 comfort metrics. For CZ 1, 2, 3, and 5, shading strategies provided substantial increase in indoor comfort for both cooling and heating seasons ranging from 13.3% to 26.9% increase in the amount of time spent within the comfort range for building envelopes with appropriate shading systems (Figure 3).

It can be concluded that successful implementation of shading strategies can have a bigger impact during the summer months for climate zones in hot dry and hot humid regions as well as colder mid-western regions with substantial cooling summer loads. A small saving through solar shading in a zone with high solar impact may be more important than a larger saving in a zone with low solar impact. The total average impact of solar shading on providing thermal comfort for all climate zones is 13.75% (Figure 4).

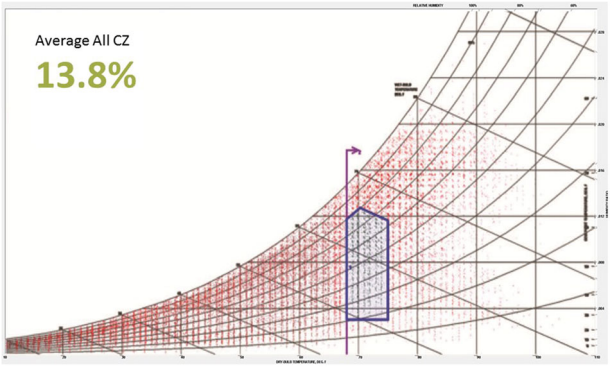


Figure 4. Shading strategies and indoor comfort (all climate zones).

Multiple effects of dynamic shading on energy consumption

When properly designed and controlled, shading systems not only can improve visual and thermal comfort, but also can greatly reduce electric lighting, cooling, and heating energy consumption (Lee, DiBartolomeo, and Selkowitz 1998). Previous studies (Atzeri, Cappelletti, and Gasparella 2014; Correia, Leal, and Andersen 2012; De Carli and De Giuli 2009) showed that the amount of energy reductions attained varies depending on shading type, envelope systems, behavioural control patterns, and climatic variations. Therefore, an integrative dynamic approach to the design of shadings systems is essential to maximize energy savings.

Meek and Breshears (2010) assessed energy performance of dynamic venetian blind systems in California, based on their envelope position. Findings from their study concluded that dynamic exterior shading provides the highest daylight and view quality with lowest possible energy consumption. These findings are in line with results of another study (Atzeri, Cappelletti, and Gasparella 2014) which concluded that, by using external shading, cooling loads are reduced and heating loads are slightly increased. However, by adjusting the solar transmittance, reflectivity, and distance between the shading device and the window, energy performance of internal shading can be greatly improved (Ye et al. 2016). Lee et al. (2009) compared lighting energy use between conventional and innovative venetian blind systems and found that the difference is small −11% to 5%. Another study (Hammad and Abu-hijleh 2010) concluded that dynamic louvers achieved additional 5–14% energy savings compared to static louvers, with both using light dimming strategy.

To balance daylighting and thermal performance, dynamic venetian blinds were found to offer 12% more of annual electric lighting savings over conventional dynamic venetian blinds (Olbina and Hu 2012). Split electrochromic glazing systems reduce the need to operate the blinds (Fernandes, Lee, and Ward 2013) and achieve 48% and 37% energy savings, respectively, with and without overhang.

Previous studies of movable fins and egg-crate shading systems reported 8.9–20% reduction in energy use especially during cooling seasons (Palmero-Marrero and Oliveira 2010). Further studies have shown that additional savings in hot dry climates could reach 20–38.5% in energy savings (Batool and Elzeyadi 2014). This additional energy savings was higher by employing dynamic external louvers in combination with vertical fins.

Recent studies have shown that solar screens improve indoor comfort and when adopted to contemporary buildings can result in substantial energy savings between 2% and 38% depending on the screen geometry, patterns, depth, perforation, solid/void ratio, materiality, and operability/ability to change (Batool and Elzeyadi 2014; Sherif, Sabry, and Rakha 2012). An optimum range of perforation of 80% for west and south and depth/opening width ratio of 1:1, respectively, was associated with 30% annual energy use reduction (Sherif et al. 2011). With shallower depth and more perforation, screens have shown modest to low impact on reducing solar heat gains during cooling seasons and a reduction in energy use (Batool and Elzeyadi 2014).

Effects of dynamic shading on IEQ

Automated louvers can increase areas with daylight factor of 2% or more by 70–150% compared to static louvers (Nielsen, Vraa, and Bjerregaard 2011). Daylight glare index (DGI) values were reduced from 'just uncomfortable' to 'just acceptable' levels by using an automated split venetian blind compared to manually adjusted split venetian blinds (Konis, Lee, and Clear 2011). Meek and Brennan (2014) simulated manual and automated blinds and found that automated blinds can increase the percentage of area with spatial daylight autonomy (sDA 300) from 36% (with manually operated blinds) to 52%. Although effects of solar radiation on thermal comfort have been established (Hodder and Parsons 2006; Hoffmann, Jedek, and Arens 2012; Tzempelikos et al. 2010), there is a lack of studies that investigate and compare thermal comfort with different types of automated blinds.

In climates with lower solar radiation and diverse seasonal changes, egg crate shading with various degrees of opening proportions enabled solar insolation during heating seasons as a passive strategy (Palmero-Marrero and Oliveira 2010). In addition, adjustments for dynamic louvers address various diurnal and seasonal sun angles and result in minimizing glare and solar heat gains during the summer months while maximizing outdoor views and daylighting distribution leading to occupant's higher indoor multi-comfort and satisfaction (Hammad and Abu-hijleh 2010).

Glass X study (2013) showed that light guiding and dispersion films can improve daylighting distribution in workspaces by redirecting light into the ceiling avoiding direct glare and decreeing electric lighting use by 40%. Similarly, Bahaj, James, and Jentch (2008) studied the performance of holographic optical elements (HOE) on the performance of a high rise building in a hot arid climate. Their study showed that HOE are predicted to reduce air conditioning loads by approximately 30% over conventional windows using radiation blocking fixed external blinds. This is accomplished by reflecting the incident beam radiation away from the window while allowing diffuse light to pass through. The view from the window remains relatively unobstructed and the HOE glazing acts as another movable layer in-between a double glazed construction.

Daylighting penetration of solar screens was found to be lower in rounded screens having larger cell diameters (Sherif, El-Zafrany, and Arafa 2012). This is attributed to the ratio of openings to solid parts of the screen panel and thus a dynamic aperture screen with a 1:1 ratio of width:depth would provide a more optimized solution to balance energy savings and daylighting penetration (Batool and Elzeyadi 2014).

The national focus on net zero energy and carbon-neutral buildings, clearly part of the public policy framework, will increase the demand on building professionals to provide an array of transformational technologies for building shading systems (Eichholtz, Kok, and Quigley 2009). It also increases the drive to understand technological performance as well as occupants' behaviour and their capacity to adapt their behaviour (Humphreys 2005). The human factor is perceived by architects, engineers, developers, and investors to pose risks to tenant satisfaction, organizational productivity and building energy performance (Brown and Cole 2009; Miller et al. 2009). Based on previous studies, dynamic shades have shown a positive impact on energy reductions in commercial buildings (Bahaj, James, and Jentch 2008; Batool and Elzeyadi 2014; Tzempelikos et al. 2010).

In addition, dynamic exterior shading impacts on improving IEQ in buildings is multifaceted. From a daylighting perspective, previous studies have shown the impacts of dynamic shades at managing daylighting autonomy (Reinhart and Walkenhorst 2001), limiting glare problems (Chan and Tzempelikos 2013), and electric lighting management with advanced daylighting controls (Reinhart 2004). The impacts of dynamic shades on controlling solar gains and cooling demands in buildings have been examined using experimental test cells and simulators (Konstantzos, Tzempelikos, and Chan 2015). Studies have shown that their ability to impact cooling loads in buildings are more detrimental on the control and automation schedules (Chan and Tzempelikos 2013).

Measure twice – cut once

This paper conceptualizes dynamic shades as a spatial element of the building envelope (Figure 2). This conceptualization relies on the general assumption that building shades act as a 'switch' between occupants and the exterior environment and are both impacted by the surrounding context on one side and by the building's systems on the other. Thus the shading system is explored as a 'perimeter zone' that stretches five feet outside and inside the building façade in both directions. This perimeter zone plays a double role in impacting the building systems and its energy performance and contributing to occupant's multi-comfort and well-being.

To compare the performance of the dynamic shading systems, experimental prototypes representing the six main shade typologies described earlier were constructed and tested (Figure 5). The prototypes were constructed by architecture senior and graduate students enrolled in an advanced building technology seminar at the department of architecture, University of Oregon during fall 2014 and 2015, respectively. To minimize any site obstructions or local shade impacts, each test cell was divided into two sections a control bay (highlighted in Figure 5) and an experimental bay immediately next to each other.

The analysis was conducted in two phases. First a digital model was constructed and analysed using a dynamic parametric simulation engine (IES VE^{TM}). The simulation focused on testing the performance of the shading systems on a

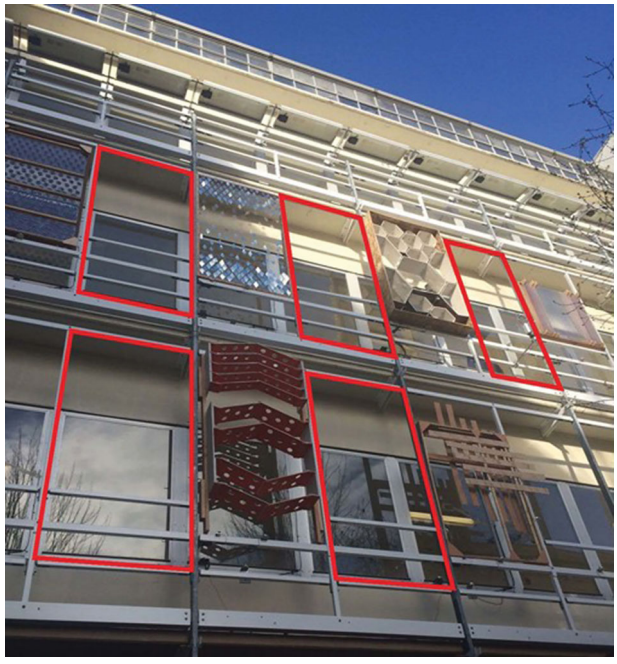


Figure 5. Various façade prototypes investigated on the FIT facility (http://facade.uoregon.edu/), with experimental and control test cells.

single-sided typical-floor bay, 20 ft. wide and 30 ft. deep of a south-facing commercial office building with 14′ floor to floor height. The analysis was limited to the south-facing orientation only to compare the performance of the shading prototypes from digital simulations and full-scale constructed prototypes mounted on the test facility with south-facing exoskeleton grid. The simulations were executed using Radiance™ ray tracing and Apache™ thermal loads engines, respectively, to test for dynamic daylighting metrics, glare indices, solar insolation, and solar heat gain coefficient (SHGC) reduction on the glazing. Energy impacts of the prototypes were interpolated using meta-analysis of previous published studies (see references).

Following the computational analysis, students were tasked with building a full-scale prototype of a portion of the dynamic shading or a scaled-down area to fit within a 53″ × 95″ experimental bay situated on the façade innovative technology (FIT) facility (Figure 5). These prototypes were constructed using simplified materials with similar optical and thermal properties to those of the actual shading designs. Data was collected from the FIT facility's on-line data logger portal in the form of light levels (lux), solar insolation (watts/m^2), irradiance (watts), surface temperature (°C), ambient temperature (°C), and relative humidity (%) for the entire calendar year. Data was recorded using a CR310 Campbell Scientific (http://www.campbellsci.com/cr310) data logger system with various multiplexers to record the data for every second and report the averaged data per minute increments. Data was recorded for the outside conditions outside every test cell, within the plane of the shading system, directly inside the envelope, and 5 ft. to the inside of the envelope. Comparative performance analyses were conducted and analysed for each prototype and in-between prototypes.

A dual comparison was conducted between the studied shading system, a control bay, and a typical optimized brise-soliel. Limitation in prototype construction did not allow for changes in the shading geometry and properties on a regular basis. Instead, yearly and daily climatic and solar geometry changes were analysed with response to the prototype performance in order to evaluate potential impacts of dynamic changes on the prototype functionality. Two-settings were interpolated based on the simulation and the full-scale prototype testing collected data. These were an 'open setting' which allowed the geometry of the prototype to achieve maximum aperture and exposure to exterior elements and 'closed setting' allowing minimum aperture and protection from the exterior elements. The shading systems were manually adjusted for both the open and closed position of the test cells by employing the service space directly behind the shading system for this adjustment. The shading control mechanism was not intended to allow the occupants to adjust the shading system from the interior space to limit the interference of the occupants with the experimental conditions. In real settings, the shading system is intended to be either automated or computerized based on pre-designed schedules for the open and closed settings.

Analysis

The six typologies are compared and analysed for visual comfort, spatial daylighting autonomy (sDA_{300lux}), SHGC, energy savings, and climate suitability for ASHRAE Climate Zone 4C. This represents a moderate climate zone in the middle of the range of values for shading impacts on energy and occupant's indoor comfort (Figure 3). Energy savings range was calculated based on a meta-analysis of previously published studies that documented energy consumption savings of a typology of the dynamic shading systems. Since previous studies combined both simulation and field test experiments in different climate locations, the meta-analysis was reported as a range of values and followed a normal distribution statistical pattern for each typology (Figure 6).

SHGC reduction was calculated from solar radiation energy (w/m^2) percentage decrease between the irradiance in the plane of the shade and the glazed plane behind the dynamic shade prototype. Each test cell was compared to the immediate control test cell next to it to minimize any site condition impacts on the FIT facility (Figure 7). Glare was analysed by ray-tracing images taken from the occupant's view-shed generated by computer simulations using radiance through IES VE™ interface. Visual comfort indices were operationalized by calculating the incidents above the brightness threshold of the scene within the field of vision. These incidents were identified through rendered circles in the images representing threshold for glare (1:7 luminance ratios). Glare thresholds within the direct view were weighed to those in the peripheral vision (Figure 8).

Glare threshold outside the field of view was neglected. Evaluation of visual comfort was achieved by using the glare threshold scale in Table 1. In addition, daylight glare probability (DGP) and DGI were calculated based on radiance simulations of the various shading systems studied from the view shed of a standing and seated occupant situated 15 and 7 ft away from the exterior envelope and looking directly towards the façade from inside the space (see Figure 1). As with previous studies, neither DGP nor DGI proved to be reliable metrics in spaces with low luminance ratios below 1000 cd/m^2 (Elzeyadi and Lockyear

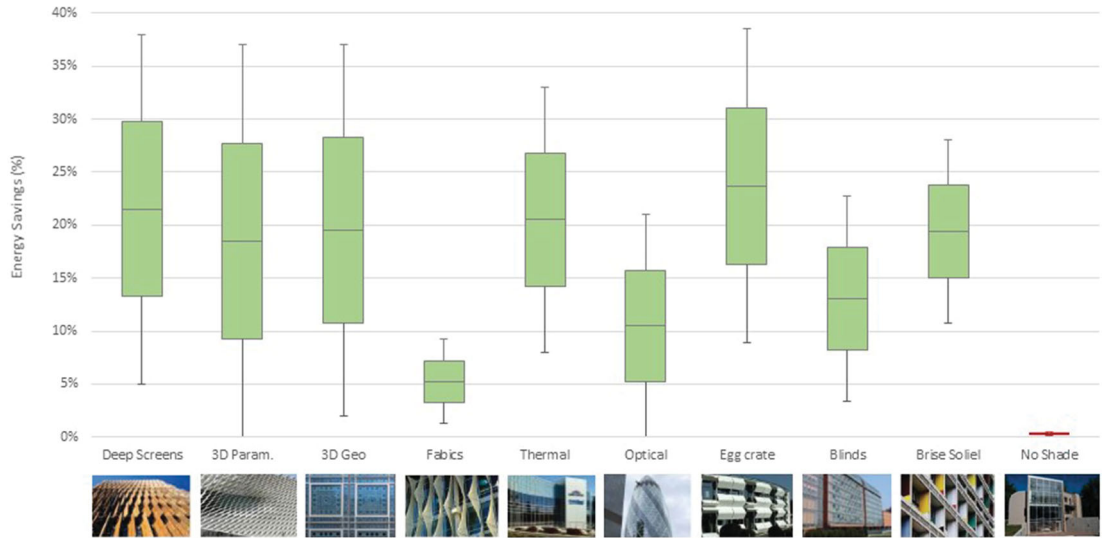


Figure 6. Comparative analysis of the energy savings %.

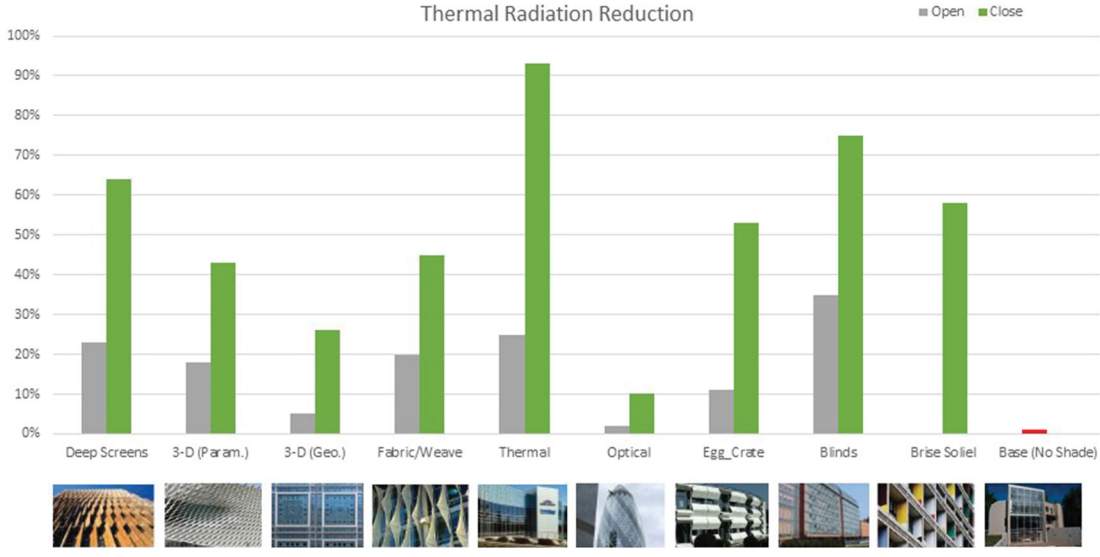


Figure 7. Comparative analysis of the reduction in thermal solar heat gains.

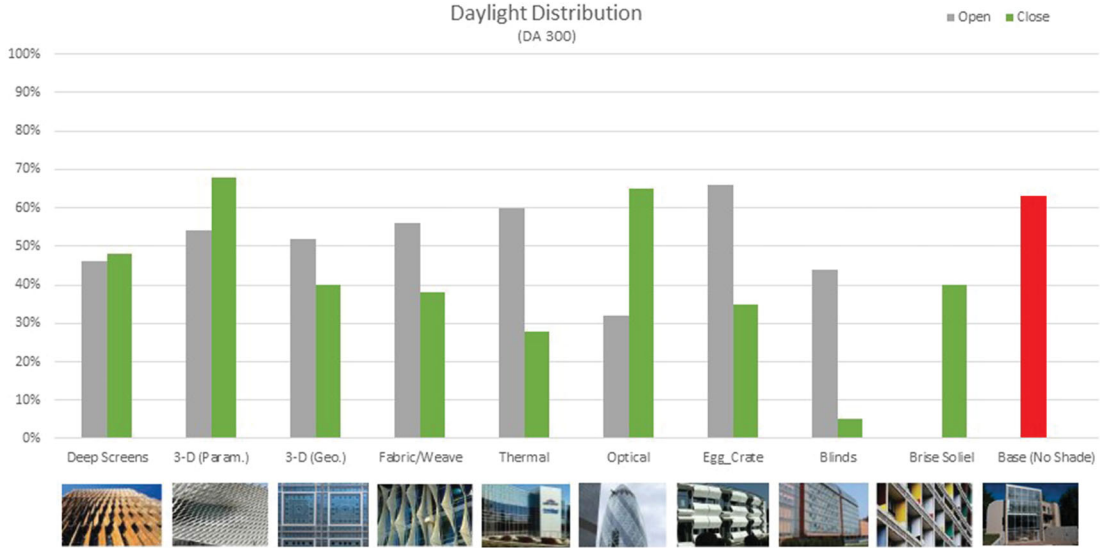


Figure 8. Comparative analysis of useful daylight autonomy (% of room area meeting design threshold).

Table 1. Glare threshold and visual comfort scale.

Unnoticeable	0–1
Tolerable	2–3
Uncomfortable	4–5
Intolerable	5+

2010; Jakubiec and Reinhart 2012). Since the shade systems evaluated were successful in eliminating and controlling for direct sunlight penetration in the scene – with the exception of the base case – DGP and DGI metrics were not sensitive to distinguish between the various shading systems as their values fell within the unnoticeable glare category (Reinhart and Wienold 2011). For this reason, a modified scale based on the glare threshold calculated in the scene was established. This scale (Table 1) compared different shading systems performance based on incidents of glare threshold within the scene with 0–1 incidents above the glare threshold rated as unnoticeable and more than five incidents rated as intolerable.

Daylighting distribution was calculated as the area of the test bay achieving spatial daylighting autonomy above 300 lux annually (Figure 9). Based on the comparative analysis, it is evident that there is higher chance of glare discomfort when the optical elements devices are open than closed. And it is more evident for automated blinds and movable fabrics typologies.

Findings

To compare the performance of the dynamic shading systems typologies, detailed analysis was conducted to evaluate their impact on building energy use, solar thermal load reduction, daylight distribution (sDA_{300}), and glare management.

Building energy savings

Reduction in energy utilization intensity (EUI) for a typical model building was compared across the multiple shading systems tested (Figure 6). Most dynamic screens systems typologies performed well with average EUI savings of 20–30%. Similarly, egg-crate shading systems came close in their performance with average savings of 25%. The least EUI savings were associated with dynamic fabric sails systems, optical systems, and external horizontal blinds (Figure 6).

Façade thermal load reduction (% reduction in solar heat gains between exterior and interior)

Dynamic shading systems provide reduction in solar thermal loads on the building facades. This in-turn can provide better occupant's thermal comfort as well as cooling energy demand savings. Most dynamic systems tested provide positive reductions of thermal loads on the building facades (Figure 7). Thermal and vertical blinds systems are the most successful in reducing solar thermal loads with 75–92% savings in the closed mode. Deep screens and egg-crates systems came second with solar thermal loads reductions between 50–64%. Optical and geometric screens were the lowest performers accounting for 10% savings in the activated (closed) phase and less than 2% savings in the non-activated (open) phase (Figure 7).

Daylighting and visual comfort

From a dynamic daylighting metrics (IES LM-83), all dynamic shading systems were compared and evaluated for the sDA300 metric for both open and closed shading phases (Figure 8). While many shading systems met the standard for the open phase – 55% of the floor area meeting or exceeding the 300 lux threshold for 50% of the year – few systems met these metrics in the closed phase. The only exception is the 3-D parametric system as it is designed to optimize daylighting autonomy with solar exposure control. The rest of the systems met the standards in either the open or the closed dynamic phase with the exception of the static optimized brise-soliel which did not meet the standards in its one and only static phase (Figure 8). On the contrary, the 3-D

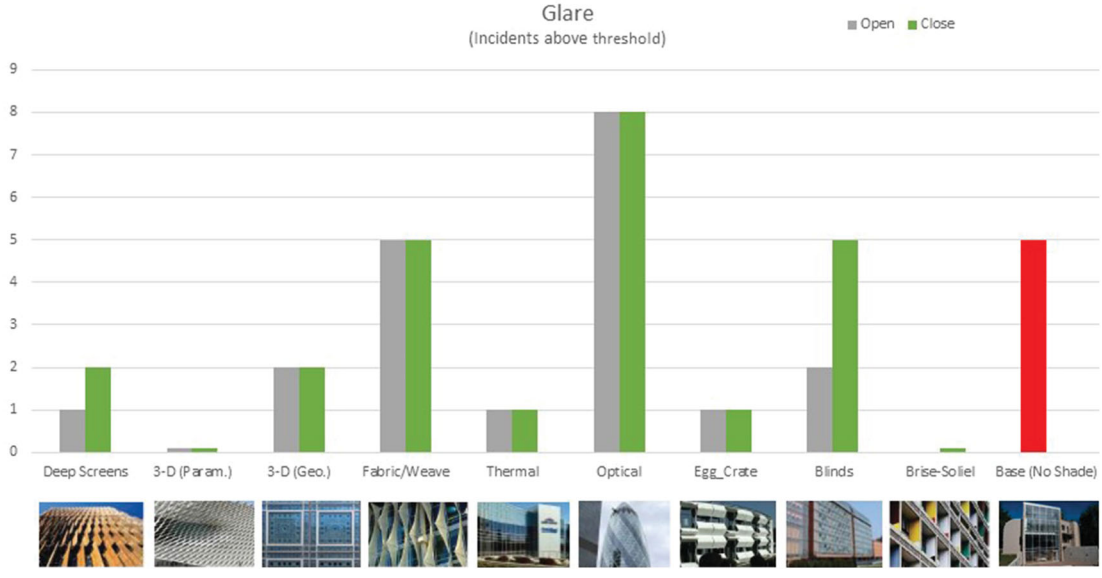


Figure 9. Comparative analysis of glare threshold incidence.

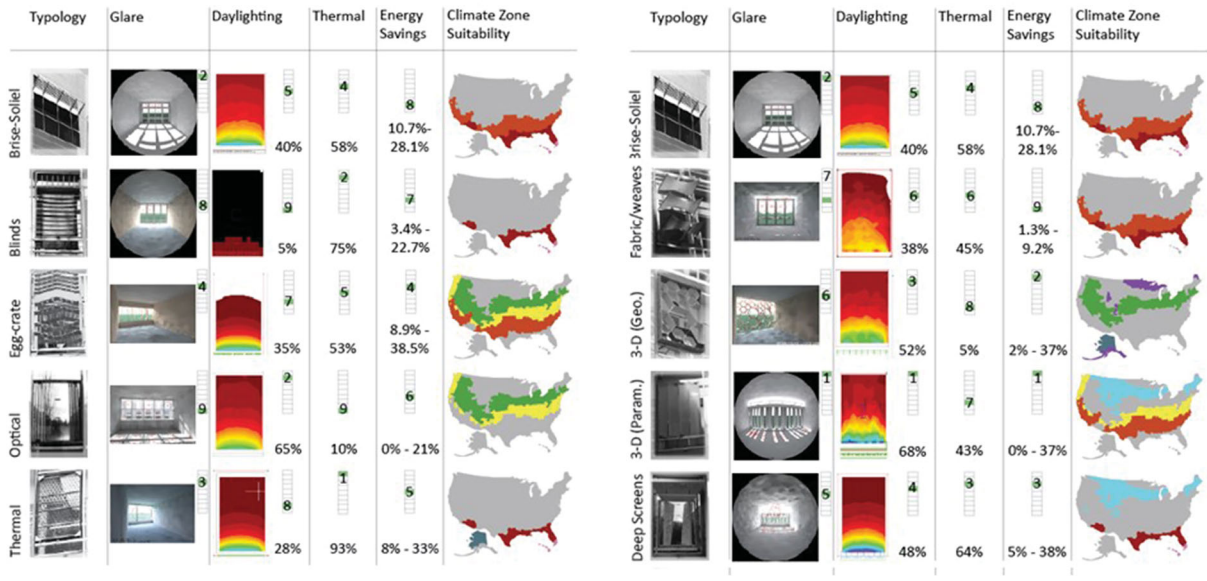


Figure 10. A comparative matrix for dynamic shade typologies performance ranking and climate suitability.

parametric system out-performed all other dynamic screen systems with respect to glare management (Figure 9). Other shading screens, egg-crate, and dynamic thermal (electrochromic glazing) typologies managed glare successfully resulting in few noticeable glare incidents above the discomfort threshold ratios. Optical and fabric systems were the least successful in managing glare which resulted in noticeable incidents above the glare threshold within the occupant's field of vision (Figure 9).

Conclusions

A framework for classifying dynamic shading systems typologies is presented (Figure 10). This framework can guide selection and design processes of high performance and indoor comfort-enhancing dynamic shading systems for high-performance facades. Out of the six systems compared, dynamic screens provide the most positive and consistent performance across most climates as well as automated egg-crates/blinds and thermal elements (e.g. electrochromic glazing). The best typology in terms of minimizing glare discomfort is 3D parametric screens followed by thermal systems such as electrochromic glazing and operable egg-crates. It can be concluded that screens or any design systems that can filter light can help reduce glare source within the field of view of the occupant, improve SHGC, and optimize daylighting distribution. On the contrary, movable fabric shades and optical elements tend to be the least performing.

The study is limited in testing the actual prototype performance of the dynamic shades in the open and closed conditions only. It is assumed that partially closed or partially open conditions might better perform during different seasonal and daily solar geometry variations. In addition, only south-facing façade prototypes of ASHRAE Climate Zone 4C were tested due to the limitation in the actual orientation of the test facility. Occupant's controls were eliminated from the study to limit the interference of the occupants with the testing conditions. These limitations are noted and proposed for future studies. It is the aim of this study to explore the feasibility of an evidence-based classification framework and performance taxonomy for dynamic shades. It is hoped that architectural design students and professionals can use this information and the metrics it raises in their early selection of dynamic shades for high-performance buildings.

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Disclosure statement

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