Electropolymeric Technology for Dynamic Building Envelopes

Elizabeth A. Krietemeyer[1], Anna H. Dyson[1]

[1]Rensselaer Polytechnic Institute Center for Architecture Science and Ecology (CASE)

Human health and energy problems associated with the lack of control of natural light in contemporary buildings have necessitated research into dynamic windows for energy efficient buildings. Existing dynamic glazing technologies have made limited progress towards greater energy performance for curtain wall systems because they are still unable to respond to dynamic solar conditions, fluctuating building demands, and a range of user preferences for visual comfort and individual control. Recent breakthroughs in the field of information display provide opportunities to transfer electropolymeric technology to building envelopes that can achieve geometric and spectral selectivity in concert with pattern variation within the façade. Integrating electroactive polymers within the surfaces of an insulated glazing unit (IGU) could dramatically improve the energy performance of windows while enabling user empowerment through the control of the visual quality of this micro-material assembly, in addition to allowing for the switchable patterning of information display. Using parametric modeling as a generative design and analysis tool, this

paper examines the technical intricacies linking system variables with visual comfort, daylight quality, and

Introduction

In the last several decades, there has been increasing interest in improving the energy and daylighting performance of windows for building facades. This is due to two main concerns: human health and energy conservation. Standardized mechanical and artificial lighting systems have created homogeneous indoor environments, shifting the dependence on natural daylight and fresh air to that of mechanical means. While the thermal and visual homogeneity of these indoor environments was initially considered to constitute ideal working conditions, instead it created severe energy concerns and problems for human health. The energy crisis during the 1970s was evidence that artificial means of heating, cooling, and lighting indoor environments had to be reconsidered (Carmody et al., 2004). The persistent desire for transparency in modern buildings warranted a thrust in research towards windows that could mitigate solar heat gains (Lee et al., 2006). Studies revealing the vital relationship of daylight to human circadian systems (Figueiro et al., 2002) suggested the need for windows that provided views and access to modulated daylight. Concurrently, extensive research has been undertaken into glazing technologies that can modulate energy flows while addressing needs for human comfort.

Comparable technologies

Numerous glazing technologies have been developed to address these demands, including glass coatings and tints, spectrally selective glazing, low-emittance (low-E) glass, and most recently, electrochromic glazing (Carmody et al., 2004). Electrochromic glazing is a switchable chromogenic film device that can provide seasonal and diurnal control over solar gains by switching on and off the number two surface of an IGU in order to

pattern design of the proposed electropolymeric dynamic facade technology.

mitigate solar gains. While electrochromic windows may be capable of providing significant savings on energy bills (DOE, 2006), the technology does not perform well in terms of visual comfort. Electrochromic windows have difficulty mitigating discomfort glare, providing usable daylight, and permitting clear views to the exterior. Because the ‘on’ position constitutes a flat blue tinted coating, it cannot selectively intercept direct solar rays. Often having to face away from the window during periods of low solar angles in order to avoid glare, people are typically dissatisfied with the ‘unnatural’ color of daylight and the inability to control the system to a greater variable range (Clear et al., 2006). This variability is essential for both visual comfort and for diurnal and seasonal modulation of solar energy. Although comparative daylighting systems are making moderate progress towards greater energy performance for buildings (DOE, 2006, Lee et al, 2006), they remain limited in their response to bioclimatic conditions, programmatic requirements, and individual preferences. These technologies do not critically examine the integration of human desires for visual comfort and individual choice for control. Furthermore, with their limited material conditions, existing technologies offer few opportunities for design variation in the architecture. These aesthetic, technical and methodological drawbacks prevent the successful implementation of existing dynamic technologies into building systems.

Display technology for dynamic windows

Recent breakthroughs in the field of information display technology have provided opportunities to transfer emerging materials to glazing systems that can offer increased variability, solar modulation, and user control over visual effects. Electroactive polymers (EAPs) are one such technology for façades that could productively link environmental performance with improved visual comfort and design variability (Figure 1). Integrating pixilized electropolymeric films within the surfaces of an IGU produces a dynamic glazing technology that could respond to variations of sunlight while allowing for view and varying degrees of user control. The proposed concept for the EAP system is anticipated to outperform comparable technologies due to its effectiveness in modulating solar energy while addressing human desires for daylight, visual comfort and variable optical effects.

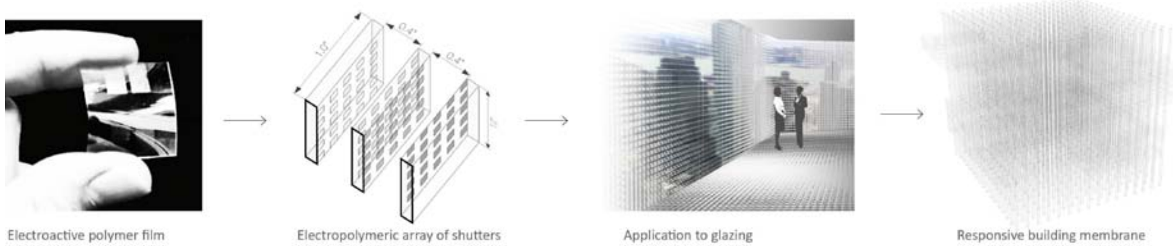

Figure 1. Integrating display technology within windows creates environmental modulation and visual diversity along the façade.

Applications potential for building envelopes

Electropolymeric window technology is a proprietary technology with many innovative properties. One of its main advantages is the ability to electrically control the physical position of very thin metalized polymers (Schlam et al., 2010). In transferring this technology to building applications, a gridded array of electropolymeric metalized films is adhered to the interior surfaces of an IGU (Figures 1 and 3). These films can be rolled up into miniature 'window shutters' with diameters small enough to fit within the air space of an IGU (Figures 2 and 3). Upon receipt of a small voltage along a transparent conductive coating (ITO), individual shutters can rapidly roll up or down for the passage of light and views.

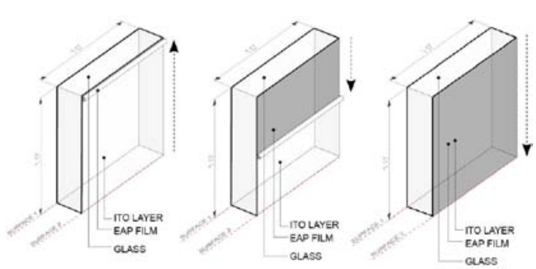

Figure 2. Single shutter movement of electropolymeric technology.

The electropolymeric shutters tackle an elemental problem for existing shading systems such as vertical or horizontal interior blinds that typically move in one axis only. This restricted physical movement results in a tracking system with more shading material than is required for blocking solar rays, thus blocking potential views and diffuse daylight. If electropolymeric shutters are applied as two layers of a pixilized array within an IGU, then selective solar tracking throughout the day and year is possible. This double layered pixilation creates a geometric and spectrally selective two-axis tracking system (Figure 3). When programmed to intercept all incident solar rays, the mechanical polymeric shutters can immediately roll up or down to potentially block glare while permitting view and ambient daylight to pass through the 'open' shutters.

Another significant benefit that electropolymeric glazing could provide is the modulation of heat gain through the building envelope in order to mitigate heating, cooling, and lighting loads. In a double-paned system, EAP glazing could eliminate unwanted heat gain during cooling degree days by rolling its shutters down on the number two surface of an IGU in order to block infrared rays before entering the window cavity. During heating degree days, the shutters could roll down on the number three surface to allow the infrared rays to enter the window cavity and re-radiate into the interior, blocking the low direct solar rays to decrease unwanted glare.[i] Through the switching of these surfaces and interception of direct solar rays, EAP glazing is anticipated to have substantial energy savings over the course of the year in comparison to existing fixed layer systems.

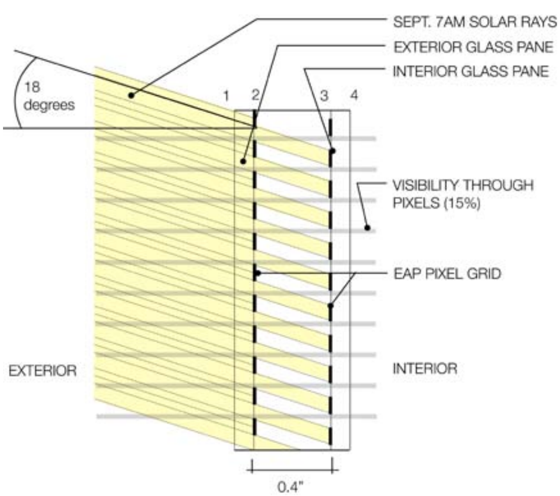

Figure 3. An IGU containing two layers of EAP shutters could continuously intercept direct solar rays while permitting the passage of usable daylight and views.

If the pixels are distributed over two or three panes of glass within the IGU, the shutter densities will be dispersed depending on the solar angles. This distribution of shading material would provide significantly increased ambient daylighting and views at certain times of the day and year (Figure 1).

In addition to its advantages in modulating environmental flows both seasonally and diurnally (Figure 4), the EAP system offers the benefits of individual control to its building occupants for the manipulation of visual effects along the IGU surface. The flexibility, immediate responsiveness, and remote switchability of the EAP system make individual choice over one's shading density, privacy, views, and dynamic visual effects entirely achievable (Figure 4).

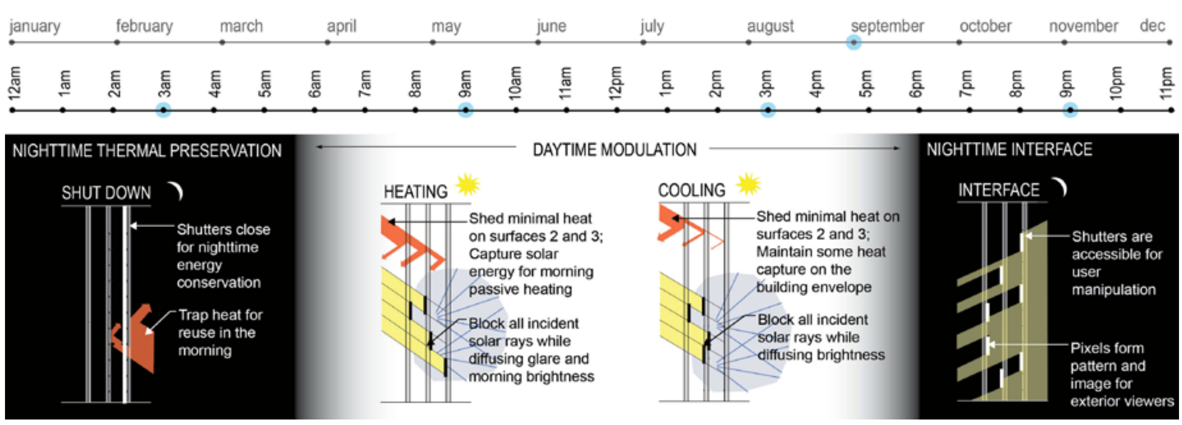

Figure 4. Section details of a triple pane electropolymeric glazing design over the course of a September day. Electropolymeric shutters modulate light for diurnal and seasonal variation; at night the façade system can preserve heat, or become an active interface for views

outward, privacy, or visual effects.

Modeling dynamic system variables

Because of the flexibility in the fabrication method of the electropolymeric shutters (Schlam et al., 2010), there are several technical variables to consider that could dramatically affect the visual quality and energy performance of the EAP system. For example, electropolymeric rollouts may have a transmittance from 6% to 94% based on the thickness of metallization and by a thin layer of printed ink. They can also range in scale, from 1/10” squares to a 5’ x 10’ single shade (Schlam et al., 2010). Rollouts can be printed with color, maintain a reflective outer coating, or be fabricated to a desired translucency or transparency (6-94%), depending on the architectural and energy requirements.

Scale, opacity and color of the polymeric shutters will create different visual effects in relationship to interior illuminance levels, glare, brightness and clarity of view. These variables are fixed conditions of the polymeric layer and thus must be designed specifically according to site, climate, solar, energy-use and programmatic conditions prior to fabrication. With such a range in possibilities between shutter scale, opacity and color, establishing a parametric relationship between variables will facilitate the appropriate design solutions for this dynamic multi-variate system according to specific design criteria.

In order to test the possible variations of the EAP glazing for visual quality, a parametric model was constructed for quick and varied explorations. Using the three-dimensional CAD modeler Rhinoceros in accordance with the Grasshopper plug-in, a 3’ x 4’ model of an IGU with EAP shutters applied to the number two surface was used to study various shutter sizes (Figure 5). These configurations were examined for shading capabilities and clarity of view to the exterior for three times of day and year for a south-facing window in New York City. The scalar studies used the Grasshopper slider tool to populate the glazing surface with a gridded array of electropolymeric shutters ranging in scale from 1” – 8” squares in a checkerboard formation. Selected scalar configurations were then analyzed as single-variant conditions using the Rhinoceros V-Ray plug-in to generate schematic interior renderings (Figure 6).

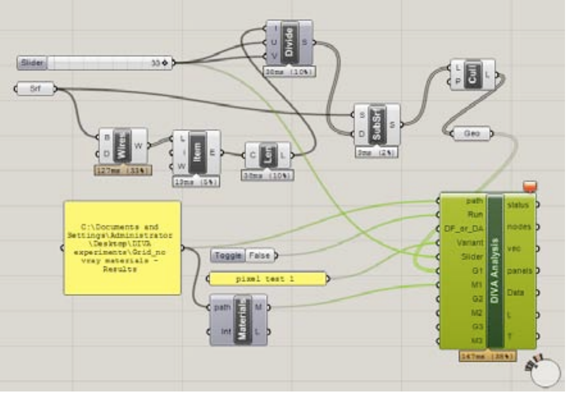

Figure 5. Parametric model for designs in shutter scale.

These initial visualizations indicate that an increase in shutter scale could potentially provide more clarity in views outward. However, a decrease in shutter scale could provide more effective shading as well as usable light (diffusion of brightness and glare), but less clarity in views outward. Further daylighting analysis that incorporates precise material properties is necessary for measuring fluctuating daylight quality and potential for glare. However, for interception of all direct solar rays, an increase in shutter size has to correspond with an increase in the spacing between the two panes of glass, thereby necessitating a ‘box-window’ type or non-standard deep mullion curtain wall unit for the larger pixels that would add considerably to the cost of the system, as compared with a standard IGU.

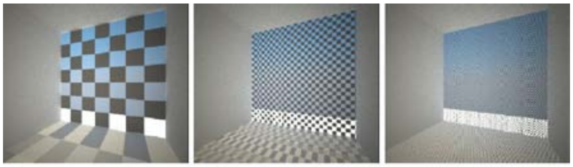

Figure 6. Iterative parametric visualizations of EAP shutter scale for a south-facing New York City façade at 12pm in September.

Because of the EAP system's dynamic characteristics, a principle challenge with simulating its performance relative to daylight is modeling its dynamic states against varying environmental boundary conditions. Prior to dynamic glazing, fixed glazing systems such as low-E glass could be modeled as a static condition. Its geometry could be imported into a daylighting simulation tool, such as Radiance, for performance analysis throughout the course of a day and year. However, the EAP glazing presents a moveable system being modeled against a dynamic boundary condition: rolling shutters and fluctuating sunlight. Simulating the movement of the EAP system with visualizations that illustrate the consequent changing light quality requires a large number of design iterations for comparison. Collapsing data and visualizations into an animated simulation is essential for the design workflow.

Parametric daylighting simulations

Until recently, many daylighting design analysis workflows involved several manual steps for obtaining simulation data, much like what was used to generate the visualizations in Figure 6. These steps included exporting and importing a geometry file to a daylighting analysis program, setting and running simulation parameters, and importing results back into a CAD program for visualizations (Lagios et al., 2010). This series of manual steps is time-consuming for testing a large number of design variants for environmental conditions over the course of a day and year. This is especially challenging for validating the possible multi-variate conditions for dynamic glazing such as the EAP system, which could be capable of continuously changing its thermal and optical properties in response to solar fluctuations.

A new tool linking Rhinoceros to daylight simulation software Daysim and Radiance is capable of merging this workflow, accelerating a previously laborious design process required for validating the EAP system variables. DIVA-for-Rhino is a design tool within Rhinoceros that directly exports geometries, material properties, and sensor grids into the Radiance/Daysim format. This format is capable of calculating a series of performance indicators including monthly or seasonal solar radiation (Lagios et al., 2010). Using Grasshopper to model the EAP system, the design parameters of shutter scale, opacity, and color can be changed incrementally and simulated using the DIVA plug-in. The simulation results are then combined into an animated building performance simulation. This simulation provides a dynamic visualization of the effect of these design variables on the daylight availability within the scene.

Simulation parameters

Preliminary experiments used DIVA to evaluate Daylight Glare Probability (DGP)[ii] for a large range of shutter scales. The previous model of a south-facing 3'x4' IGU in New York City with a single checkerboard surface of EAP shutters at 100% opacity was used for the simulations. Shutter scale was linked to the Grasshopper slider tool, and the simulations were run for three times of day (9am, 12pm, 3pm) for three times of year (June 21st, September 21st, and December 21st). Since discomfort glare from low sun angles is most prevalent during winter months in New York City, a range of shutter sizes for December 21st were selected for evaluation for differences in glare. The DIVA 'Image' tool produced an animated series of Radiance high dynamic range (HDR) images for varying shutter sizes, which identified glare sources with color as well as luminance (cd/m^2) with selected points. HDR images of large-scale (6.5") and small-scale (2") shutters were used for direct comparison to evaluate the DGP for December 21st, 12pm (Figure 7).

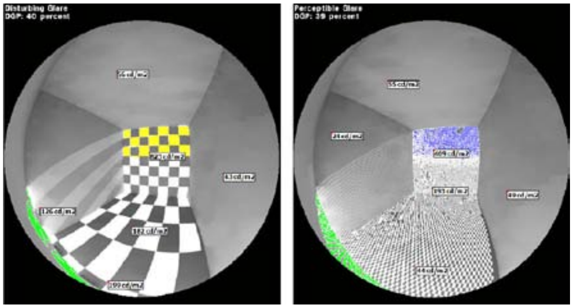

Figure 7. Radiance image viewer using the Evalglare tool to identify DGP for large- and small-scale shutter sizes on December 21st, 12pm.

The areas of yellow, green, and blue denote locations of high glare probability, indicating where shutters are 'open' and where the direct sunlight reaches the back wall. The DGP difference between the HDR images for the large- and small-scale shutters is relatively minimal (40% vs. 39%). However, when calculated and compared for three times of day over the course of the year, the large-scale shutters produce an overall greater DGP than the small-scale shutters (Figure 8).

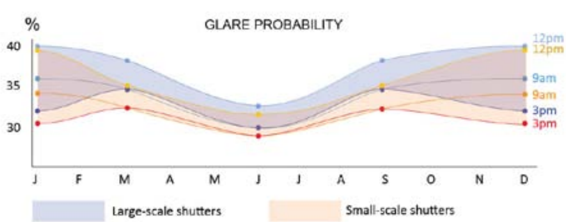

Figure 8. Glare probability for large- and small-scale shutter sizes on a south-facing New York City façade indicate that larger shutter sizes could cause more glare over the course of a year.

The DGP was also calculated for two layers of large- and small-scale EAP shutters within an IGU (surfaces two and three) using the same environmental parameters from the prior simulation. Between the two layers of the IGU, two checkerboards of shutters are positioned to block direct solar rays, as seen in Figure 3. Initial results of this simulation series suggest that with two layers of EAP shutters within the IGU, the larger-scaled shutters would be more effective in reducing glare for low winter sun angles (Figure 9).

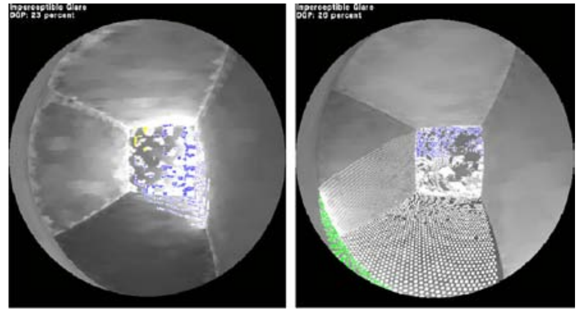

Figure 9. Glare probability for a double-layered IGU of both large- and small-scale shutter sizes on a south-facing New York City façade.

The simulation results imply that for a single-layered system, a smaller shutter scale decreases discomfort glare at this particular site and orientation. However, when double-layered EAP shutters are positioned to intercept solar rays, effectively modulating solar gain, larger-scaled shutters could potentially lower discomfort glare. One of the trade-off design decisions to be made in this case is the negotiation between the mitigation of glare and the privileging of views, since smaller shutters permit greater visible transmittance through the EAP system, and therefore greater ambient daylight. Another design parameter to consider in this scenario is decreased shutter opacity, which could significantly improve the ambient daylight quality while still blocking unwanted glare. However, the DIVA workflow does not yet consider material opacity and color in its current version, although methods to incorporate these modification tools are in progress (Lagios, et al., 2010). While shutter scale and number of polymeric layers are just two of several variables to consider in the design of the EAP system, the DIVA workflow provided a quick and extensive analysis for comparison of a large number of design possibilities.

Trajectory and speculations

In addition to designing and analyzing combinations of EAP system component variables, parametric modeling was used for explorations in surface patterning. Studies in Grasshopper uncovered methods for achieving certain visual effects in addition to the baseline EAP 'checkerboard.' Through strategic EAP shutter placement within multiple surfaces of an IGU, visual effects of texture, depth, and graphics could emerge while simultaneously mitigating glare and provide diffused daylight with views.

Additional studies were generated in Grasshopper to design the movement of the EAP shutters from morning to night, shifting shutter density for desired effects (Figure 10). These designs are currently being analyzed for visual comfort using the DIVA analysis tool (i.e. visible transmittance, glare probability, and interior illuminance levels) to determine appropriate pattern selections for certain times of day and year.

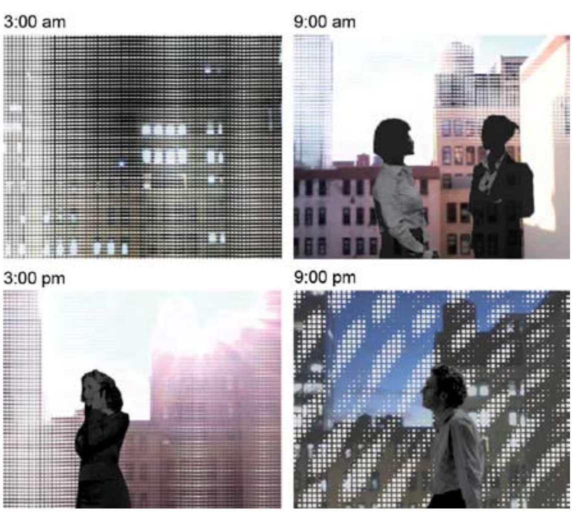

Figure 10. Animation stills from designed shifting EAP patterns for a south-facing New York City façade throughout the course of a September day.

Methods that examine the relationship between surface patterning and optical and thermal performance of the EAP system reveal ways in which parametric modeling can provide an evolutionary tool for linking visual effects to energy performance. This initial parametric framework for the EAP system provided real-time visualizations for the relationship of system variables to daylighting and visual comfort. The parametric framework also has the potential to operate at the micro-scale, linking pattern configurations to the thermal performance of the EAP system. Parametric models that control shutter placement within an IGU for shedding or capturing infrared heat could be directly linked to simulations for calculating solar heat gain coefficient (SHGC), U-value, and visible transmittance (Tvis). Pattern configurations could take on an entirely different visual meaning when their movement is in accordance with the modulation of light, heat, and human desires for visual effect. Developing a high-performance façade system and design tools informed by these architectural, social, and environmental issues is critical for the implementation of next-generation technologies to buildings.

Introducing design variability and individual choice over the visual quality of architectural envelopes and interior surfaces has the potential to satisfy the diverse needs of building occupants while reducing the energy consumption in buildings. The promotion of individual participation in the production of variety in the visual effects of the EAP system allows for occupants to partake in the modulation of natural light and information display through surface patterning. The glazing system's flexibility in response to bioclimatic, biological, psychological, and socio-economic demands and desires could create a visibly dynamic socio-cultural identity within the façade. These architectural possibilities raise questions with reference to the socio-cultural implications of dynamic building envelopes that merge energy performance with the opportunity for information exchange at the building scale.

Presently, modern facades lack a visual registration of the bioclimatic energy flows that are being circulated in and around buildings. Consequently, our existing building envelopes have become monotonous barriers against the infiltration of the solar resource, often impermeable to meaningful socio-cultural exchange, while missing the opportunity to benefit from the valuable visible spectrum of daylight. Visual variation through daylight and surface patterning can provide an atmospheric experience that collapses notions of energy, identity, and cultural expression within the façade. Through the potential for switchable patterning and information display, the dynamic façade may introduce opportunities for the existing modern curtain wall to visibly channel symbolic significance through user participation in the control of dynamic windows and interior surfaces, thus breaking out of the legacy of increasingly homogeneous modern architecture into a more culturally rich and expressive form of building.

References

Carmody, J., Selkowitz, S., Lee, E., Dariush, A., Willmert, T. Window Systems for High-Performance Buildings. New York: W.W. Norton & Company, Inc., 2004.

Clear, RD, V. Inkarojrit, Lee, E. “Subject responses to electrochromic windows.” Energy and Buildings 38 (2006): 758-779.

Figueiro, M., Rea, M., Stevens, R., Rea, A. “Daylighting and productivity: A possible link to circadian regulation.” Proc. LRO Lighting Research Symposium (2002).

Galasiu, A., Veitch, J. “Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review.” Energy and Buildings 38 (2006): 728-742.

Lagios, K., Niemasz, J., Reinhart, C. “Animated building performance simulation (ABPS) – Linking Rhinoceros/Grasshopper with Radiance/Daysim.” Proc. IBPSA-USA SimBuild (2010).

Lee, E., Yazdanaian, M., DiBartolomeo, D., Selkowitz, S., Klems. “Monitoring energy performance of electrochromic windows controlled for daylight and visual comfort.” ASHRAE Transactions 112 (2006).

Schlam, E. et al. “Low cost dynamic insulated glazing unit.” U.S. Patent #0170623 A1, 2010.

United States Department of Energy. “Zero energy window prototype: high performance window of the future.” Energy Efficienty and Renewable Energy, 2006.

Wienhold, J. “Daylight Glare in Offices.” PhD Thesis, University Karlsruhe (2010).

[i] In order for the EAP system to perform most effectively for shedding or retaining heat, a triple-pane IGU with multiple pixilated layers is preferred.

[ii] The daylight glare probability (DGP) illustrates the probability that a person is disturbed by daylight glare and is described by an empirical equation, based on the vertical illuminance at eye level and a term considering the glare sources (Wienhold, 2010).