Heliotropic shading: Daylighting a Rare Books Reading Room with Electrochromic Glass and Parametric Analysis

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This is an original manuscript of an article published by Taylor & Francis in LEUKOS vol19, Issue 4, on 12 July 2023, available at: https://doi.org/10.1080/15502724.2023.2219019.

Abstract

This paper introduces the design process and successful deployment of an electrically tintable glass, known as electrochromic glazing, for a fully daylit atrium sheltering a rare books reading room at a university library. The project demanded a novel design process where analysis and simulation data from a parametric model were directly used to program the final control system, merging quantitative and qualitative design workflows to develop a daylighting solution that could meet the client's visual and metric requirements. The final daylighting design employs a dynamic "heliotropic" shading control system that follows the sun path both geometrically, as well as photometrically, maintaining illuminance levels from daylight at the task plane below a specified threshold at all times throughout the year. This solution used an electrochromic glazing product that offered four transmission levels ranging from 60% VLT to 1% VLT, providing the shading required to support the archival needs for engaging with rare and light-sensitive artifacts while maintaining as much clear or minimally tinted glazing as possible to support the visual and experiential qualities of the space. The project was designed between 2015-2016 and installed 2017-2018.

Keywords

Daylighting design, electrochromic glazing, sustainability, high-performance buildings, visual comfort, lighting for sensitive works

1. Introduction

Historically, library reading rooms have relied heavily on daylight for illumination, often to the severe determent of the materials contained within. Since the advent of electric lighting, these spaces have tended to limit daylight access and the commensurate exposure of sensitive materials to solar radiation. Reading rooms for rare books and other sensitive materials tend to be located in rooms with a high degree of environmental control where lighting, temperature, and humidity may be tuned to the needs of the collection. Electric lighting can offer superior control at the expense of the lighting quality for occupants of the space.

The design of the Princeton Firestone Library Rare Books Reading Room upends the luminous environment typically found in contemporary rare books reading rooms. Situated in an existing daylit atrium, this renovated space employs a dynamic electrochromic shading system to continuously shield sensitive materials from excessive daylight at all times of the year, while also maximizing daylight availability for occupants.

This paper offers a novel design workflow and analysis method and demonstrates its application through a case study, where electrochromic (EC) glazing is deployed in a highly complex large daylit space. Through review of the project's design workflow, the author seeks to forward new methods for designing EC glazing controls that 'heliotrope' or follow the sun to deliver active daylighting design with benefits that include occupant visual comfort, protection of sensitive materials, and building energy performance. This design solution may be applied to similar spaces with large fully-glazed skylights in the future.

1.1 Heliotropism in Architecture

Heliotropism occurs in plants when a plant's leaves or flowers move in response to the direction of the sun throughout the day, caused by the chemical auxin (Vandenbrink et al., 2014). The concept is popular in biomimicry discourse, having previously been applied to solar energy collection, with a range of proposals for solar energy systems following the sun through a range of tracking devices (Desai & Natarajan, 2019; Li et al., 2012; Papageorgiou et al., 2014). The concept has also been applied more directly to architecture, such as the Revolving Houses by Francois Massau in mid-century Belgium or the Heliotrope House (1994) by German architect Rolf Disch ("Rolf Disch – The Heliotrope," 2017; Tagliabue, 2008). More recent projects such as the Arab World Institute by Atelier Jean Nouvel in Paris France (1987), Al Bahr Towers by AHR in Abu Dhabi, UAE (2013), and the Kiefer Technic Showroom by Ernst Giselbrecht + Partner in Steiermark Austria (2007) have shown the potential of expressive tectonic shading systems that dynamically follow the sun, often under the moniker "Adaptive Facades" (Attia, 2017; Naji, 2020). These structures employ architectural-scaled components with moving components to dynamically shade interiors during times of sun penetration, and redacting at other times.

Given the uptick in focus on climate-based architectural design, many researchers have studied methods of developing parametric models for allowing solar shading devices to track the sun and operate automatically as part of the architectural expression of the building (Mahmoud & Elghazi, 2016; Samadi et al., 2020). However, for various reasons including cost and maintenance, investing in movable, architectural-scaled components may not be an option for many projects.

1.2 Electrochromic Glazing Overview

Electrochromic glass typically consists of at least two glass panes with a thin layer of electrochromic material sandwiched between them, with an additional air gap in insulated glazing units. This material can be a variety of substances, including tungsten oxide, nickel oxide, or Prussian blue (Niklasson & Granqvist, 2007). When an electric current is applied to the electrochromic material, its optical properties change, causing the glass to darken or lighten. As such, the technology has emerged as an alternative to traditional methods of solar control in buildings such as louvers, brise soliels, or motorized shades, offering an integrated adaptive facade technology.

In the past decade, a mounting body of research has shown the potential benefits and limitations of the technology in architectural glazing. At the time of this manuscript's publication, a range of electrochromic technologies exist on the market, including those that tint to blue hues, as well as neutral density or grey hues. In the product used in this case study, "The peak in the spectral transmission curves gradually shifts from 565 nm in the clear state to 460 nm at full-tint. Thus the view through the glazing takes on a progressively deeper blue hue as it transitions from clear to full-tint" (Mardaljevic et al., 2016). Further details on the specific product used in this case study will be discussed in Section 3.2.

One of the key benefits of EC glazing is the minimal impact on views, which has been shown to be one of the key factors in occupant well-being within buildings (Heschong, 2021; Ko, Kent, et al., 2022; Ko, Schiavon, et al., 2022). Manufacturers of EC glazing products tout the ability to reduce visual light transmission without obscuring views to the exterior. Additionally, containing daylight control within the IGU reduces issues with maintenance, cleaning, and silent control with no noise from motors compared to roller shades. EC glass can also block ultraviolet (UV) light, which can be harmful to both people and materials, where prolonged exposure can cause skin damage, fade upholstery and carpets, and degrade materials like plastics, wood, or paper. Electrochromic glass can block a significant amount of UV radiation (T_{uv}) in the 300-380nm range, while still allowing visible light to pass through by adding UV-absorbing compounds to the electrochromic material or to one or both of the glass panes (Mortimer et al., 2015). An additional metric, 'Damage Weighted Transmittance' (T_{dw}) "assigns a specific damage weight factor to each wavelength of UV or visible light based on its contribution to fading," and that includes a larger swath of wavelengths from 300-600nm (Vitro Architectural Glass, n.d., p. 2). The application of electrochromic interlayers severely limits the T_{dw} percentage when the tint is applied.

However, EC glazing is not a one-size-fits-all solution for all architectural apertures. Unlike other architectural shading devices, EC glazing does not reduce views of the solar disk, it merely reduces light transmission. Jain, Karmann, and Wienhold found that tintable glazing's inability to reduce the size of the sun disk commensurately reduces EC glazing's ability to control glare (Jain et al., 2022). A follow-up study assessing user perceptions “found that participants experienced discomfort more often in blue-tinted glazing compared to color-neutral glazing, even though glare metrics would have predicted higher levels of discomfort in these latter cases”(Jain et al., 2023).

Moreover, Mehlika Inanici et al showed that EC glazing can have an adverse effect on circadian stimulus, noting “that shading devices which significantly alter the intensity and/or color of the daylight coming through the window have a very adverse effect on circadian potential."Altenberg Vaz & Inanici, 2021). This finding is likely due to the significant reduction in light levels entering the space, as the blue tint still maintains some of the peak wavelengths useful to circadian stimulus. While some manufacturers offer neutral density tinting, the technology must be cautiously approached in regularly occupied side-lit spaces. Further, recent research into the Myopia epidemic suggests that wavelength filtering by all architectural glazing, not just electrochromic, is having adverse effects on human eyeballs (Houser et al., 2023).

In spite of these limitations, EC glazing offers enormous potential for energy savings. Studies by DeForest et al have demonstrated that “dual-band EC glazings are capable of outperforming alternatives in a diverse set of locations and building types, including both heating and cooling-dominated regions” (DeForest et al., 2017). In light of this, in 2022, the United States passed the Inflation Reduction Act, which included a number of provisions for decarbonizing buildings. EC glazing was specifically included as a technology offering energy-saving potential and therefore available for tax credit (Markey, 2021). It’s clear that EC glazing has a strong future in controlling daylight and energy performance in buildings.

1.3 Daylighting for Sensitive Works

Daylight is considered a significant benefit in library spaces, offering psychological and physiological benefits for users (Heschong, 2021; Ward et al., 2019). However, rare books and other historical documentation on paper are highly susceptible to photodegradation due to ultraviolet light breaking down the chemical bonds of color molecules contained in the pigments of ink, as well as yellowing paper materials (Lindblom Patkus, 1999). Reading rooms for rare books tend to be situated in spaces with minimal daylight, or where it may be controlled to minimize detrimental effects on sensitive artifacts.

For general reading areas in libraries, the Illuminating Engineering Society (IES) recommends 500 lux (46fc) average at the task plane with a 2:1 average to minimum uniformity ratio; rare books reading areas should be limited to 300 lux (28fc) average at the task plane (*IES ANSI/IES RP-4-20 Recommended Practice: Lighting Library Spaces*, 2020). However, these criteria are generally concerned with electric lighting.

For artworks, a temporal value is a more valuable metric than instantaneous illuminance or irradiance, as continual exposure to 100 lux can potentially damage sensitive work more than short exposure to 10,000 lux. Museum curators often allot ‘light budgets’ that prescribe an acceptable amount of daylight exposure, measured in annual lux-hours, for illuminating sensitive works. Typical criteria include illuminance at the work in the range of 50-200lux and accumulated exposure during a year of anywhere from 15,000-150,000lux.h depending on materials (*Lights On...Cultural Heritage and Museums*, 2016, p. 7), where a dose of 150,000 lux hours is equivalent to an annual display in a museum at a level of 50 lux (Blades et al., 2020). The University of Michigan's (UM) Light-Exposure and Implementation Policy for Exhibitions, publically available on the Society of American Archivist's website, further expands these recommendations (Baker, 2014). UM categorizes materials into a range of sensitivity levels with acceptable annual illuminance exposure from 5,000lux.h-150,000lux.h. Many of the materials studied in a rare books reading room would be considered 'Sensitive' according to UM's criteria, assigned a 50,000 lux-hr/yr limit. This group includes paper containing lignin, dyed papers, pen inks (fountain pens, ball-point or felt-tip), most duplicating methods including photocopies, poor quality commercial offset printing inks, and a range of sensitive art materials.

2. Project Background & Base Conditions

Princeton University's Harvey S. Firestone Memorial Library maintains one of the world's premiere special collections of rare books, holding "approximately 350,000 rare and historically significant printed books in Western languages dating from the 15th century down to the present" (*Rare Book Division | Princeton University Library Special Collections*, n.d.). The facility is used by countless researchers, particularly during the summer. However, in the midst of renovating the building, the University and its cohort of architects and spatial planners determined to locate the rare books reading room within an existing, fully daylit atrium space. Understanding the complexity of this programming assignment, the Architect of Record hired the author's firm to develop an appropriate daylighting design. The primary objectives were to reduce illumination through the glazing while also maintaining the dynamic qualities of natural light.

Large chandelier pendants, outside the author's scope, were selected for the space by the project's Lighting Designer. Visually dominant in the space, the selected fixtures were estimated to provide approximately 100lux at the task plane and were excluded from the following design studies, as well as from the determined-daylighting limit, with the understanding the fixtures could be dimmed or turned off during daytime hours if required. Local task lights were also provided at each workstation for researchers' use, also not considered in this study.

As noted in the introduction, although a temporal metric has been widely used for limiting light damage on artworks, the Firestone Library's curatorial faculty imposed an instantaneous limit of 500 lux from daylight at the task plane at any given time, based on findings in the 2011 article 'Seeing Versus Saving" published in the American Library Association's Journal Library Resources & Technical Services (Horelick et al., 2011). Extrapolating this figure out based on the University of Michigan's aforementioned Policy limiting Sensitive materials to 50,000lux.h suggests that rare books could safely be open for approximately 100hrs per year if under 500lux of daylight. Since the reading room does not display any materials beyond the needs of research study, this limit was determined to be an appropriate threshold.

2.1 Baseline Solar Analysis

The Firestone Library, located in Princeton, New Jersey (40.35° N, 74.66° W), is rotated 18.95° to the west. The atrium space creates a nominal 6M wide by 43M long "airy buffer" between the original post-WW2 gothic revival library building and an understated 1980s-era addition housing library stacks, topped by a green roof. This space, designed as a general reading room, is sheltered by a sloped glass roof nominally 8-10m above the floor. The original skylight glazing was 14% visual light transmission (VLT), with a louvered screen mounted just below the glazing, providing an additional 50% openness for a total of 7% VLT. The skylight is comprised of 72x 60cm wide bands - in section, a 60cm tall clerestory window faces northwest, and 4 rows of 1.8m long panes comprise the slope. Cream-colored steel structure supports the skylight.

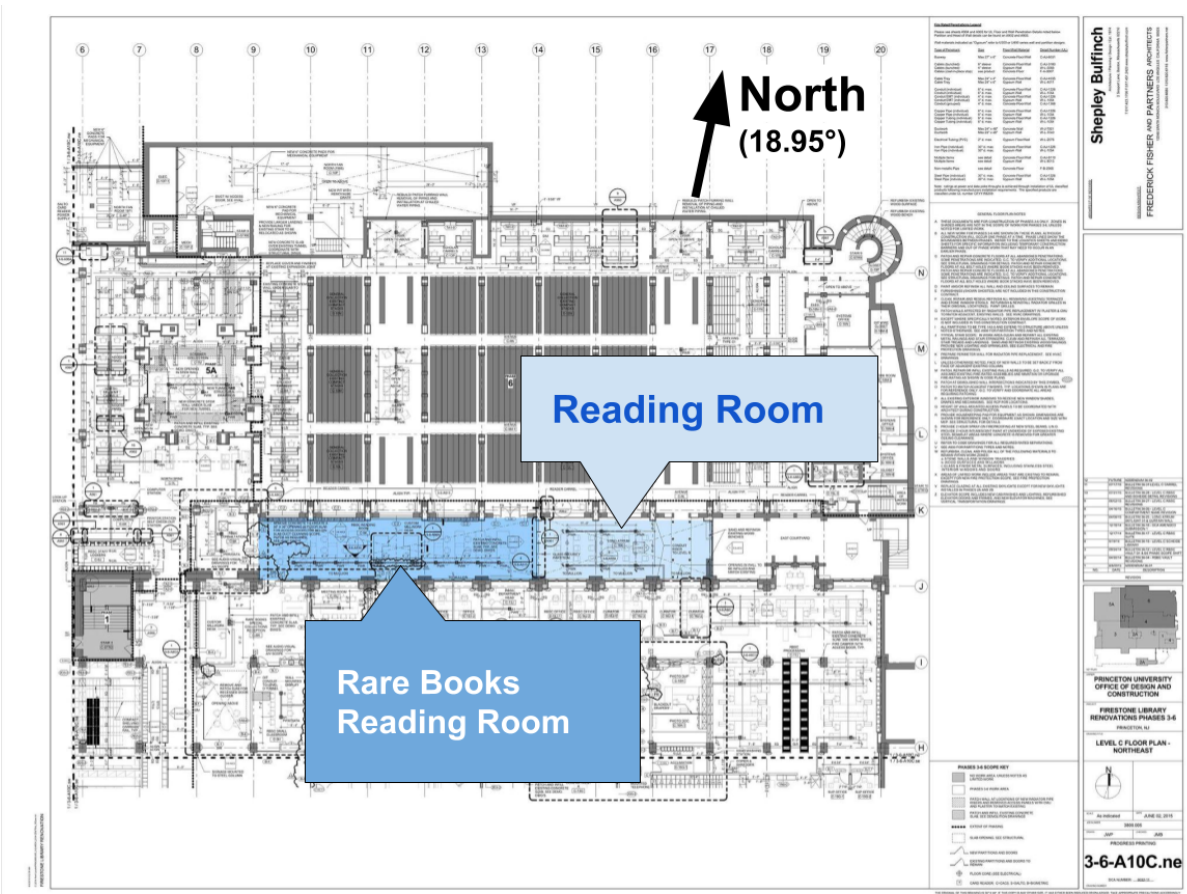

Figure 1: Architectural Plan of the northwest quadrant of the Firestone Library. The dark blue area represents the rare books reading room. The light blue area is a general reading room. Plans courtesy of Shepley Bulfinch, 2016.

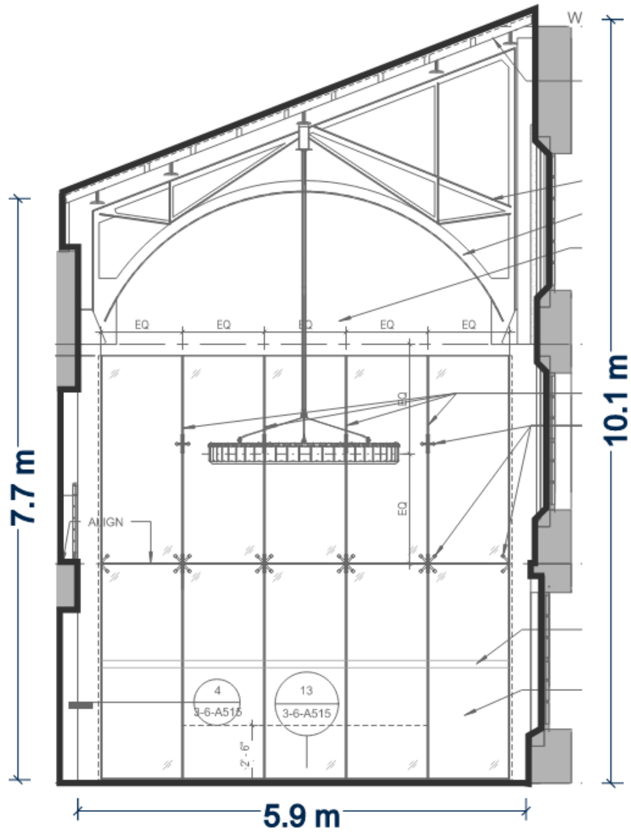

Figure 2: Section looking east. Background courtesy of Shepley Bulfinch, 2016.

Figure 3: Images of the reading room (looking west) before the renovation, showing the louvered sun shade. (credit for image on left unknown): Photo Credit: Antonio Barrera, Jan. 17,2007.

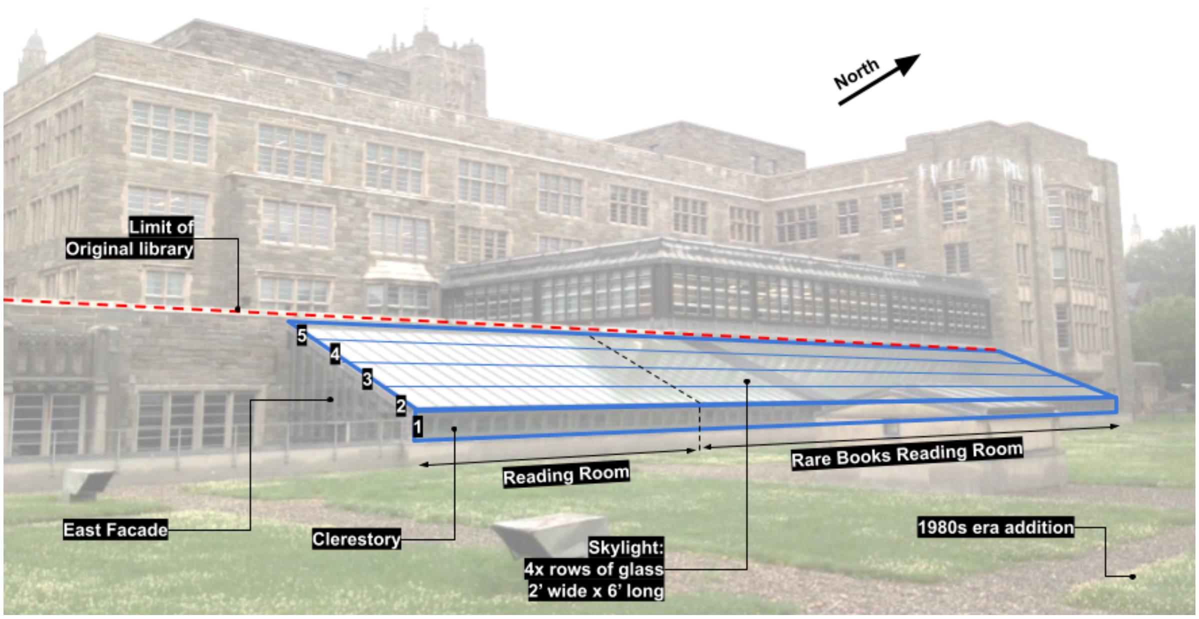

Figure 4. Diagram of the skylight exterior, taken from the roof of the addition before the renovation, showing glazing elements and orientation.

Table 1. Materials used in Simulations:

Floor, Context	20% R_{diff}

Historic Walls, Structure, Mullions	35% R_{diff}
Interior GWB walls	50% R_{diff}
East Facade Glazing	34% VLT
Interior Glazing	60% VLT
Skylight Glazing	7% VLT
Clerestory Glazing	14% VLT

Initial daylighting analysis of the existing skylight was performed using DIVA for Rhino in 2015, with a task plane located at 76cm, and grid points spaced 60cm x 60cm. The nearest weather file data available to the site was Trenton, NJ, (40.28° N, -74.82° W). During the preparation of this manuscript, the author re-ran the model using Solemma Climate Studio as shown in Figures 5A-5C. From the annual climate-based metric analysis, an average illuminance of approximately 300 lux at the task plane was measured throughout the year. However, an excess of 3000 lux was present during the summer months, (Figure 5). July 11, at 2 pm was selected as a representative time of extreme solar penetration due to the off-axis orientation of the space and spacing of the mullions. In the annual Useful Daylight Illuminance (UDI) simulation, with the maximum threshold set to 500lux, the space was found to be exceeding the threshold by at least 15% of the occupied hours in the areas furthest to the east.

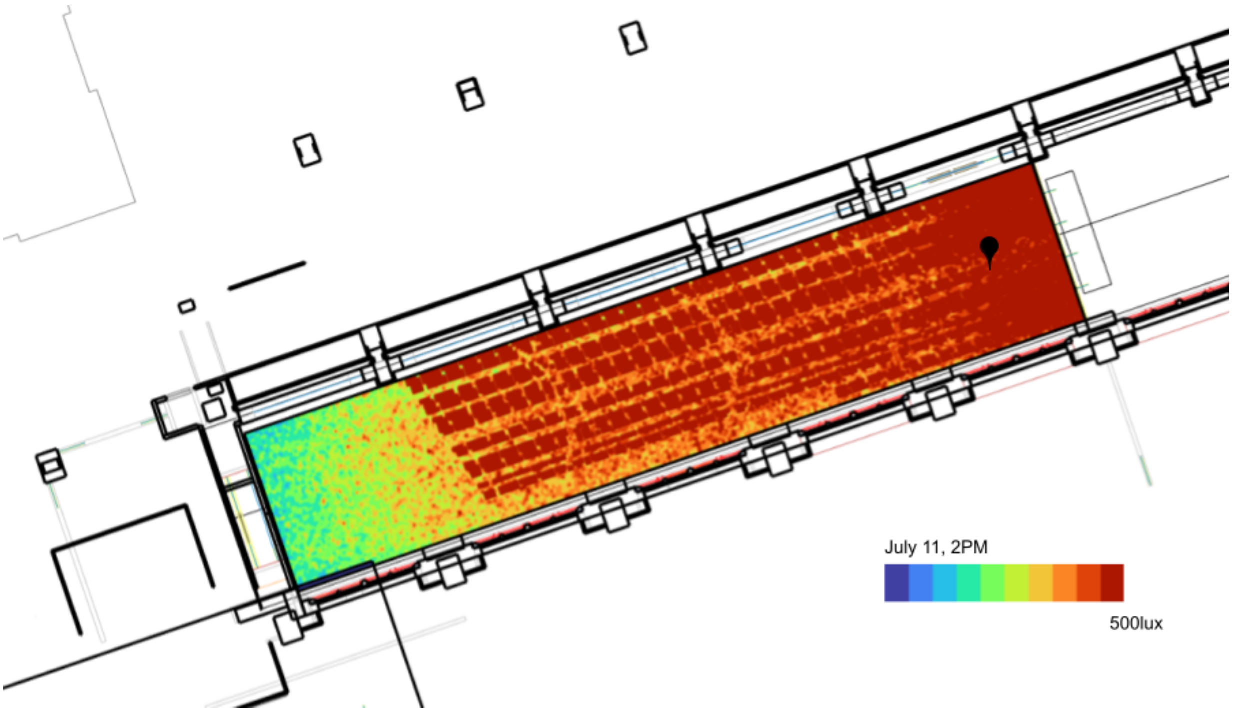

Figure 5A: Point-in-time illuminance at task plane of reading room on July 11, 2 pm (point of peak solar access due to building orientation). Black dot signifies annual sensor data shown in Figure 5B

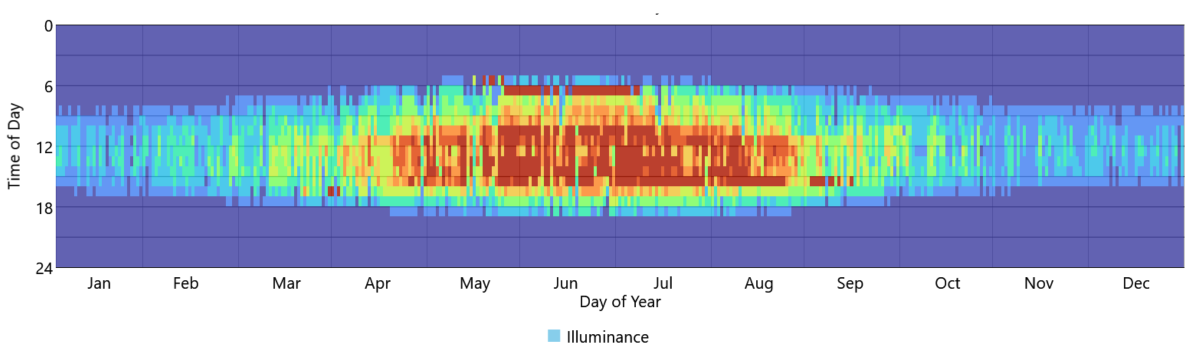

Figure 5B: Daily and Annual Useful Daylight Illuminance at the far-east bay, with the maximum threshold set to 500lux, showing extent of times between April and September when the threshold is exceeded.

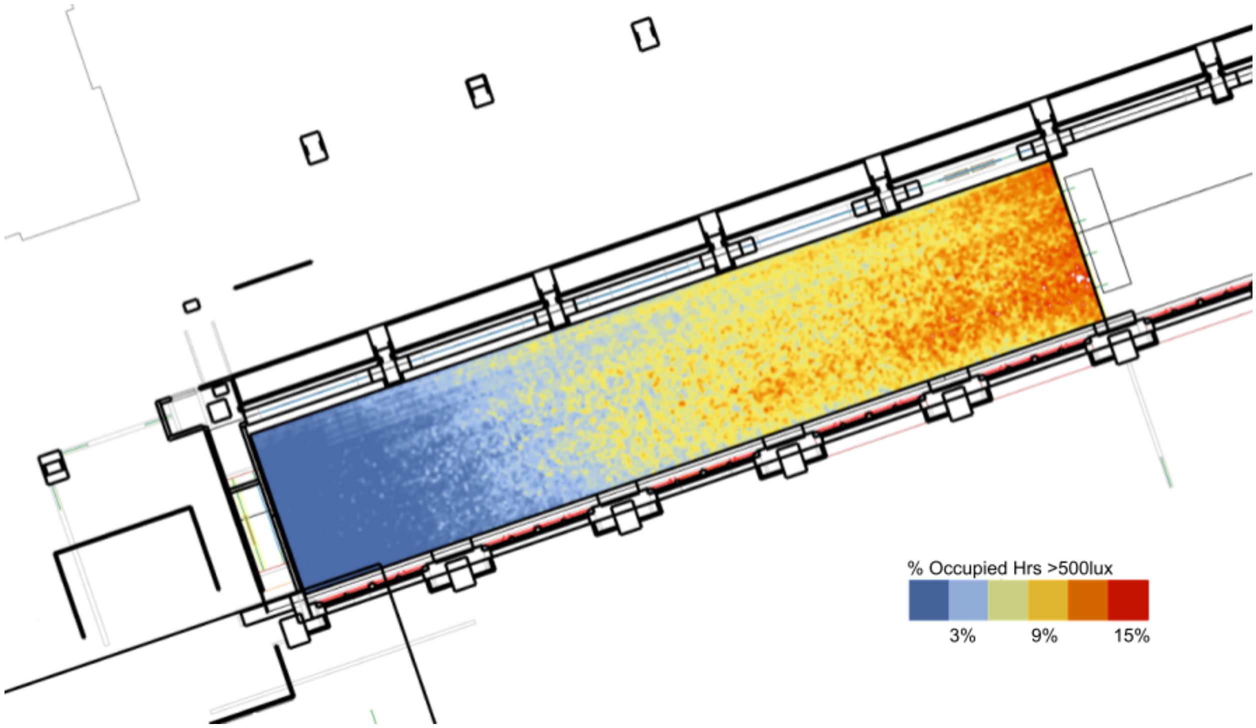

Figure 5C: Percentage of occupied hours above 500lux, calculated using Useful Daylight Illuminance with UDIe set to 500lux (Solemma Climate Studio).

3 Design Process Using Novel Workflow

Design iterations were as follows:

1. Iteration 1: Architectural interventions including baffles and solid panels
2. Iteration 2: Combinations of clear and translucent glazing
3. Iteration 3: EC glazing concept "Geometric Heliotropism"
4. Iteration 4: EC optimization and deployment "Photometric Heliotropism"

3.1 Iterations 1 & 2: Architectural Interventions

The first design proposal included three architectural interventions based on 'traditional' static daylighting design applications: 1) close off the middle two sloped glazing bays with solid panels 2) convert the top bay to translucent glazing to wash light down the facade wall while mitigating direct sun penetration 3) introduce vertical baffles at the bottom bay and north-facing clerestory to intersect low-angled late-day direct sun (Figure 6). This concept was rejected for both aesthetic and performance concerns. The architectural team did not want to introduce additional architectural surfaces into the space, nor close off the skylight if possible. Moreover, while the solution removed direct sun from the space, it would still require low VLT glazing in order to meet the illuminance performance requirements.

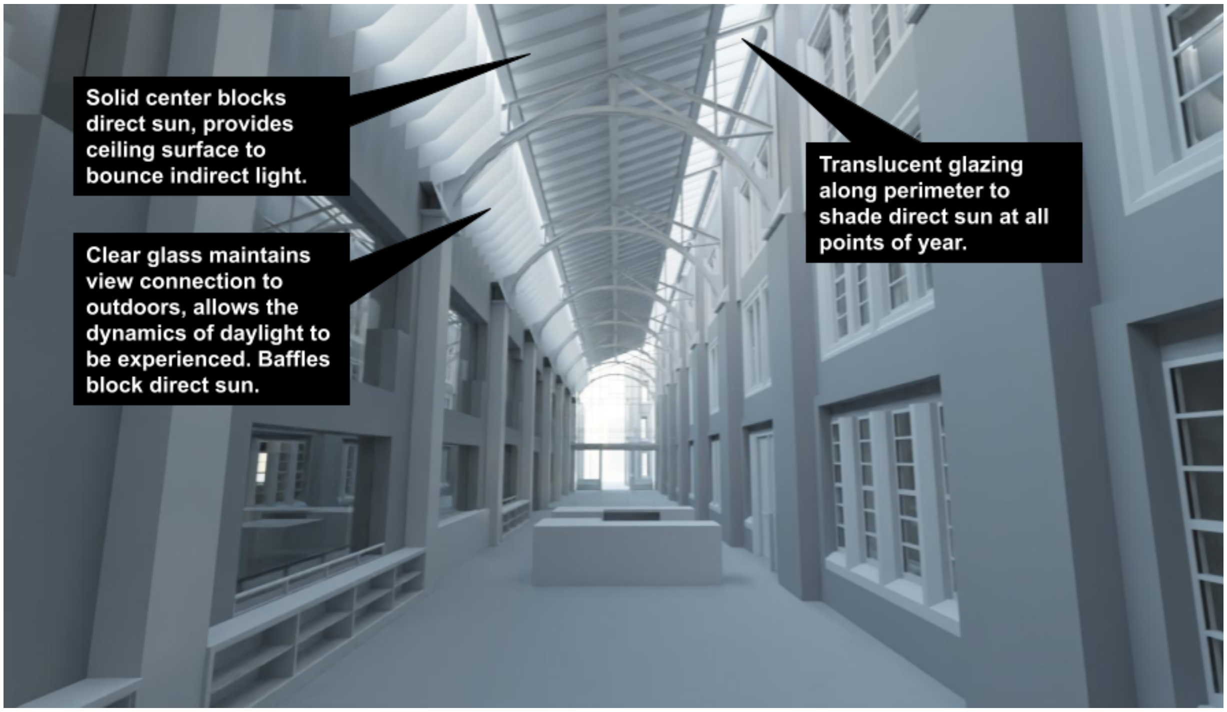

Figure 6: Iteration 1 Design proposal

Mindful of the aesthetic desires of the client, the second iteration included a series of trials combining clear, translucent, and opaque panels down the length of the skylight. These studies revealed that maintaining less than 500 lux at all times throughout the year would not be possible without also making the space feel gloomy and underlit during the winter months (Figure 7). With little confidence in these various combinatorial solutions' ability to produce an appropriate solution, it became clear that dynamic shading would be the only possible method to control daylight during the summer months while allowing sufficient daylight during the winter months. Motorized shades were quickly ruled out due to the number of individual motors, the potential noise, and maintenance concerns. The author proposed EC glazing, and after reviewing local installations, the client agreed to pursue the technology.

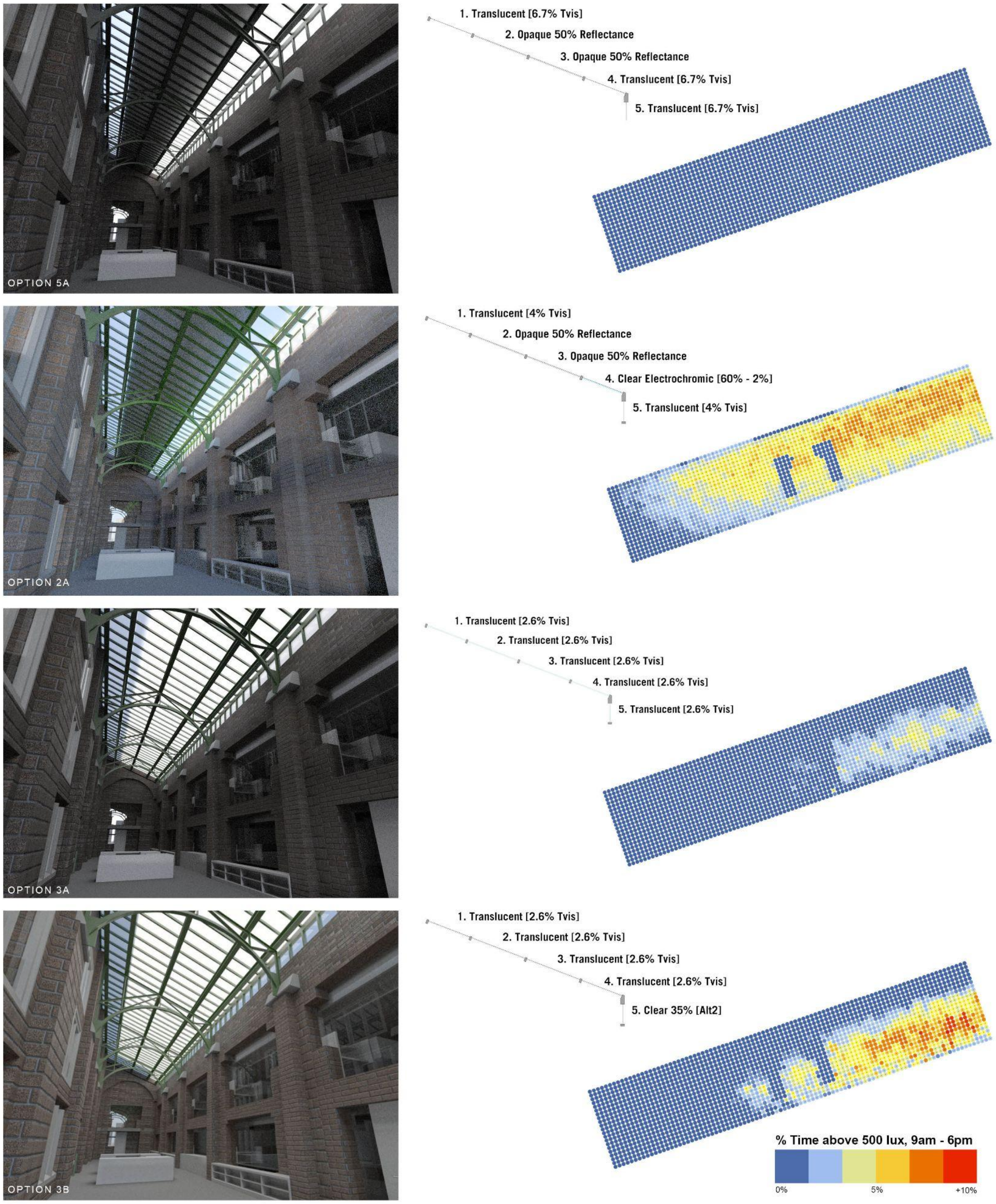

Figure 7: Iteration 2 - various combinations of clear, translucent, and opaque glazing. The annual analysis grid on right shows the percent of hours above 500lux, showing that only the first option would comply. However, the solution would create overly-gloomy visual conditions on the interior. The second option presented an early electrochromic solution for only a single band of glazing.

3.2 Iteration 3: Electrochromic Glazing

At the time of this project, the only available EC product on the market was "SAGEGLASS CLEAR" manufactured by Saint-Gobain, which provided three levels of blue-hued tinting within a clear 60% VLT IGU, reducing the VLT to 18%, 6%, and 1%. The transition between states is temperature dependent, as short as 2 minutes in warm weather up to 15-20 minutes in cold weather.

Table 2: Sageglass Clear Performance Data

	Tvis	Tsol	Tuv	Tdw-k
Clear State	60%	33%	0.40%	15%
Intermediate State 1	18%	7%	Not reported	5%
Intermediate State 2	6%	2%	Not reported	2%
Fully Tinted	1%	0.40%	0.00%	0.6%

Data provided by Sage Electronics, based on 4mm clear w/ SR2.0, 0.89mm SentryGlas, 2.2mm SageGlass, 12mm airspace w/90% Argon Fill, 6mm clear, calculated with WINDOW 6, SageGlass, 2016

As shown in Table 2, the EC interlayer cuts out ultraviolet wavelengths. The product further minimizes fading when the low tint levels are deployed as reported by $T_{dw\text{-}k}$. However commensurate with the increased tinting, color rendition is reduced. John Mardaljevic et al was contracted by Sage Glass to confirm the technology's viability as a suitable daylighting product, in particular reviewing concerns that tinting to saturated blue hues would overwhelm interior spaces with blue light. His findings showed that maintaining at least 10% of the glazing untinted in a given space would be sufficient to maintain appropriate color rendition (Mardaljevic et al., 2014). It is worth noting that an earlier version of Sage's product was used in Mardaljevic's studies, which tinted only to 2% VLT, but with similar chemical properties.

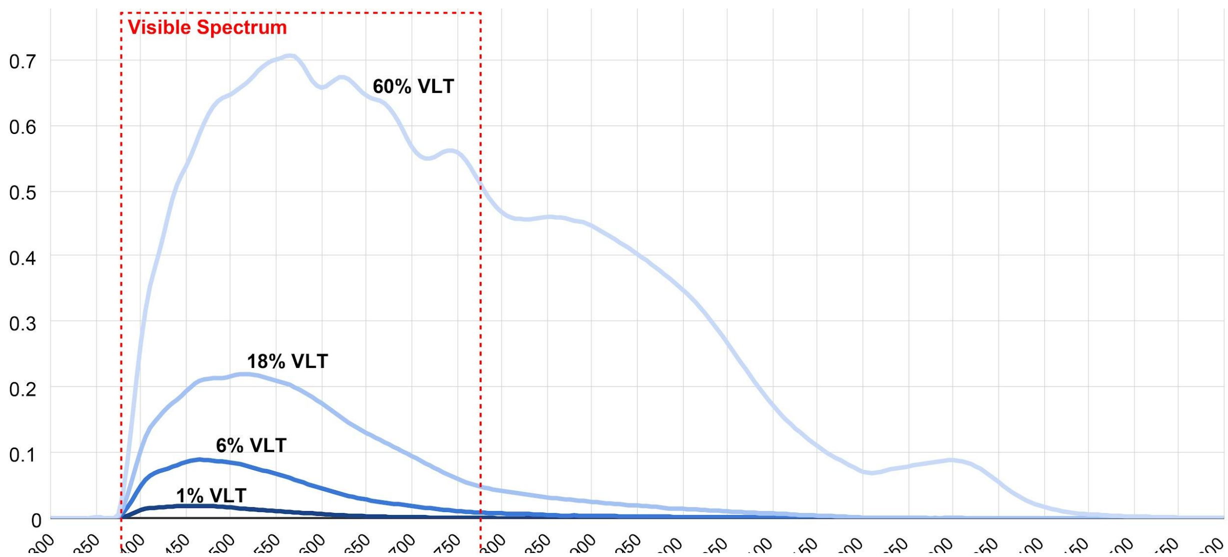

Figure 8: Spectral Power Distributions of the four tint states in Sage Glass. The red outline represents the visible spectrum from 380-780nm. Data sources: LBNL Optics6 including SageGlass_7_SR2_1dk.SAG, SageGlass_7_SR2_6int.SAG, SageGlass_7_SR2_18int.SAG, SageGlass_7_SR2_60clr.SAG

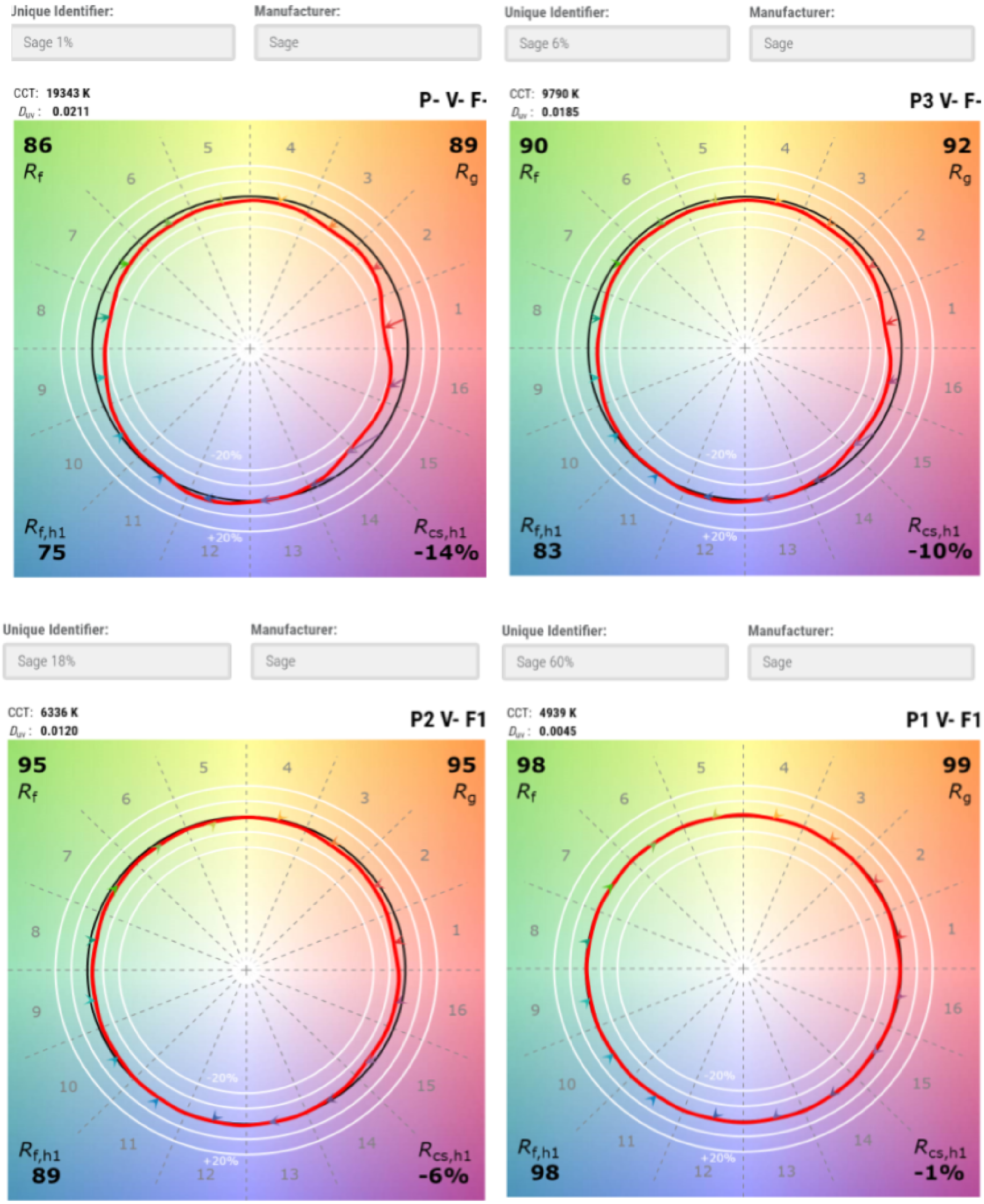

Figure 9: TM-30 color rendition calculations of Sage glazing tints from LBNL Optics6 and processed using IES TM-30 Calculator. This calculation assumes a D65 light source transmitted through the electrochromic material. Data sources include SageGlass_7_SR2_1dk.SAG, SageGlass_7_SR2_6int.SAG, SageGlass_7_SR2_18int.SAG, SageGlass_7_SR2_60clr.SAG

Given these criteria, the first step was to confirm that EC tinting would meet the 500 lux limit, while also maintaining at least 10% untinted glass. The east curtain wall, specified with a fixed 34% VLT glazing, totaled approximately 15% of the glazed area. Additionally, the clerestory glazing, at 7% of the skylight area, was left untinted for this study. The remaining skylight area was reduced to 1% VLT. This test used the same calculation criteria as previously noted, with the Trenton, NJ weather file. The results proved that the EC technology could limit peak illuminance levels to below 500lux at times of peak solar transmittance (Figure 10).

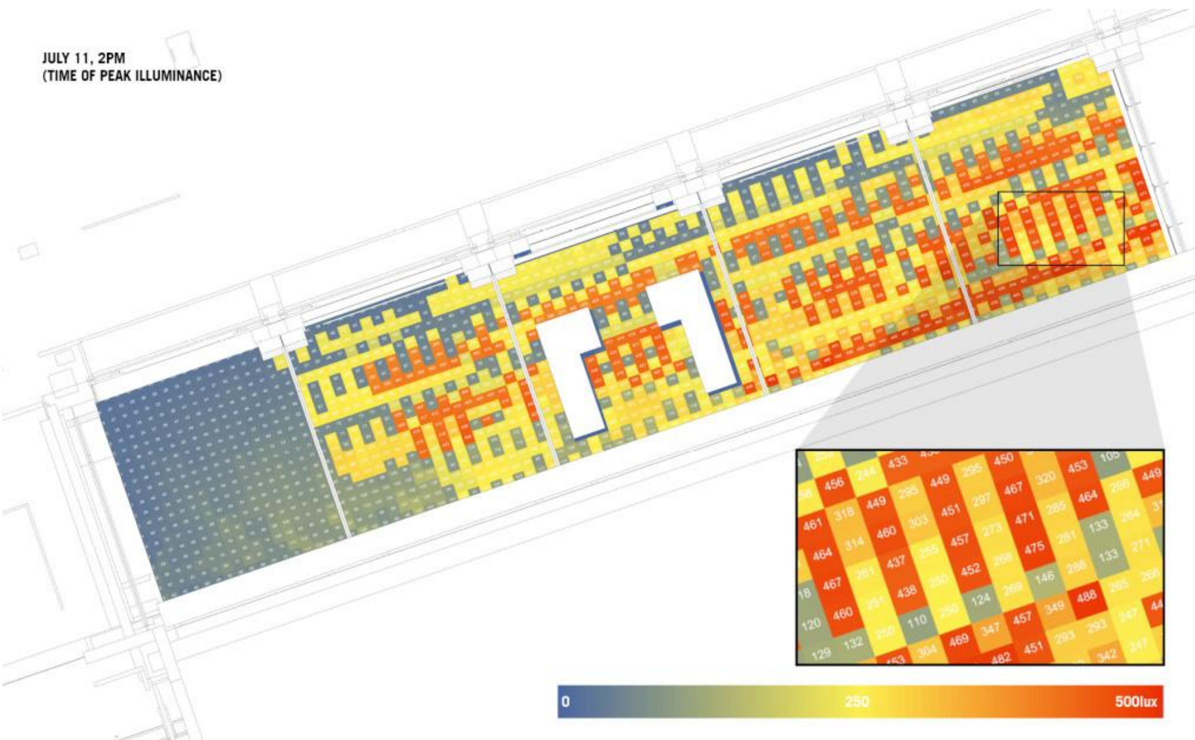

Figure 10: Test calculation with all skylight glazing tinted to 1%, clerestory untinted (60% VLT). Note that the checkerboarding is due to the close spacing of the mullions. Test calculation was performed in Diva4Rhino using materials noted in Table 1 and calculation parameters noted in Table 3 (high-resolution).

3.2.1 Design Proposal: Heliotropism

At the time of this case study's project design, most uses of EC glazing employed relatively simple control strategies. For example on vertical glazing, a typical control scenario would zone a series of horizontal bands, such that the upper zone could be darkened, leaving the vision glass clear. In skylights, the entirety of a unit skylight may be controlled as one zone or subdivided into a few zones depending on orientation (*Sage Glazing Products*, 2016).

However, in this reading room, grouping the glazing into large control zones would not be able to limit illuminance levels to the 500 lux threshold without severely over-tinting for longer than necessary. The EC manufacturer's technology allowed glass panes to be subdivided with hair-line breaks between zones to increase control resolution. By subdividing the 1.8M-long panes into 3x 60cm squares, the full skylight and clerestory resulted in a total of 923 individual cells. This provided enough resolution density to create a dynamic shading mask that could block direct sun from hitting desk surfaces throughout the day, following the sun as it moves across the sky, similar to a plant's tendency to move and follow the direction of the Sun. This dynamic shading mask made of EC glazing would shift across the skylight, transitioning each hour to maintain maximum shading of 1% VLT over the task plane, surrounded by bands of 6% and 18% tinted cells to reduce contrast. This scheme would therefore maximize the amount of clear or minimally tinted glass at all times.

To convince the clients of the concept, a simulation was created using Grasshopper for Rhinoceros3D. The algorithm employed a 'jig' (Figure 11) that directed the tinting of each glazing cell: any glazing cell that intercepted a ray en route to the task plane would tint darkest (dark blue in Figure 11); rays hitting the lower sections of walls would tint to 6% (Medium blue), then upper walls, 18% (Light blue), and any glass that didn't intercept any rays would remain clear (Grey-blue). This shading method is henceforth described as "Geometric Heliotropism," where the geometry of the tint pattern provides solar control, distinct from "Photometric Heliotropism" where photometric analysis confirmed illuminance levels - see section 3.3.

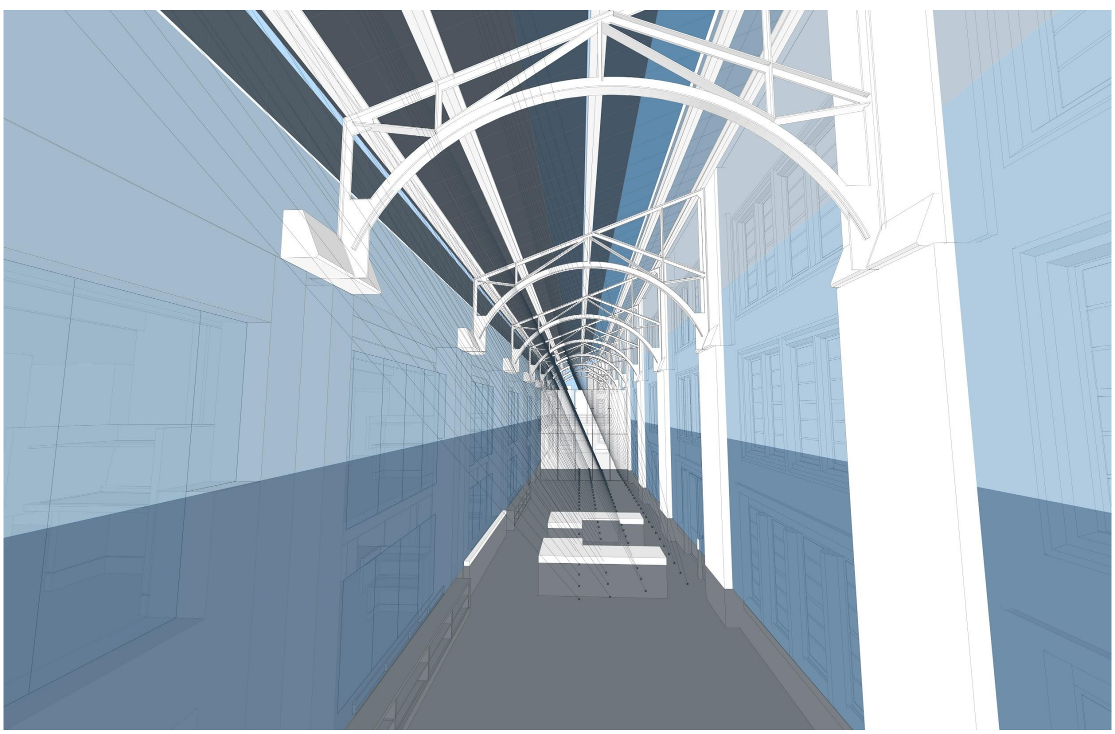

Fig 11: Geometric Jig. Task plane (dark blue) tints cells to 1% VLT; lower walls (Medium blue) tint glass to 6%, upper walls (Light blue) tint glass to 18%; top of the south wall (Grey-blue) any glass not intercepting rays remains clear.

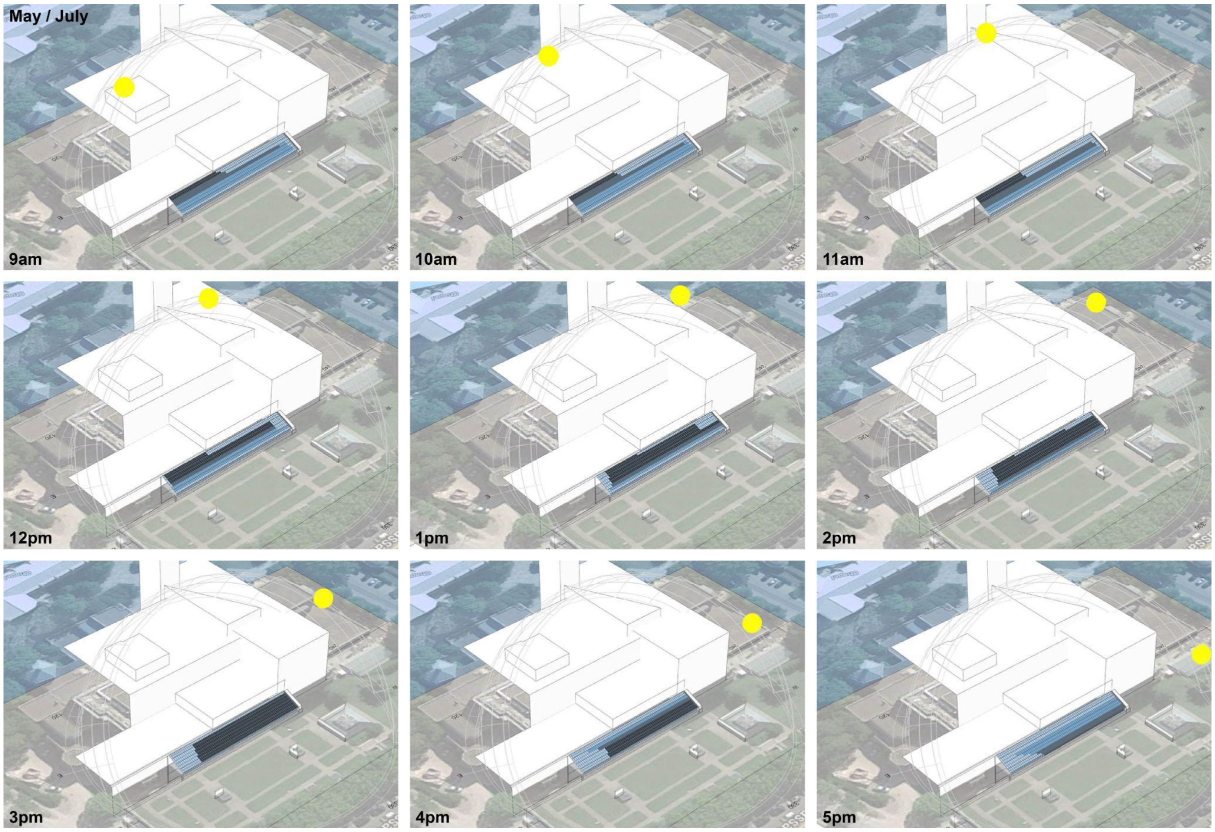

Fig 12: Geometric Heliotropism - Exterior view on May 21 /July 21 showing glazing tints based on intersections with building forms. Stills from an animation that diagrammed how the skylight would dynamically change over time (Fig 10). Surrounding building massing was included as part of the shading mask, allowing zones of glass occluded by building forms to be untinted.

This data was then imported into Autodesk 3ds Max, using the validated iRay rendering plugin to create photometrically accurate visualizations of a representative summer day (Figure 11). While these animations illustrated the concept, the transitions between frames were abrupt and not realistic of the 2-15 minute transition times actually found with EC technology. Secondly, the representations made clear that the shapes created at any given hour were not "pure geometries," as the structure is skewed off true north; and non-symmetrical building forms lead to "undesirable" patterns created in the tinting in the cells closest to the south (right) wall. The clients approved of the direction but requested simplifications.

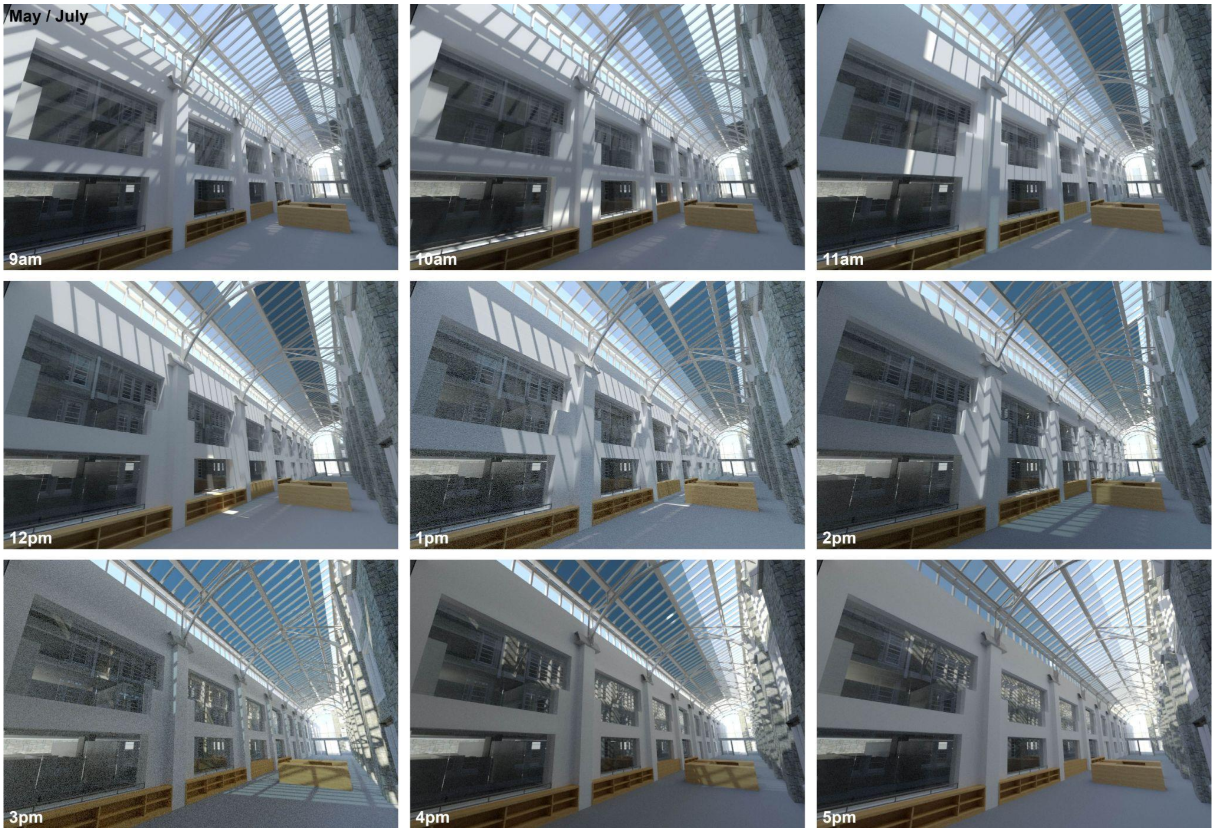

Fig 13. Geometric Heliotropism - interior view rendered in 3ds Max with iRay on July 11

3.3 Iteration 4: Calculation and Optimization

With hesitant approval from the design team and clients, the next task involved figuring out how to calculate each scene state throughout the year and assure the 500 lux limit would be maintained at all times. The Grasshopper definition, at this point, was only able to change tinting based on solar angle and obstructions. A nested looping algorithm (Figure 12) was developed using the Grasshopper plugins Anenome, Bumblebee, and Honeybee's Radiance calculation software (v0.59). The algorithm iteratively tested gradually darker tint patterns until a pattern emerged that would maintain illuminance levels below the 500lux threshold. The CIE Clear Sky with Sun was selected for use instead of TMY weather data since the goal was to design the maximum tint pattern required for every hour of the year; accounting for arbitrary 'typical' weather conditions would not be useful.

Before testing all hours of the year, it was necessary to find a method that could calculate illuminance levels at a reasonable pace given the project schedule. At the time of the project, a high-resolution calculation using 6 ambient bounces (ab) took multiple hours. Given that for each time step up to 45 calculations may be required to find an appropriate tint level, running each calculation at high precision was not viable. Therefore, logic was developed to allow for lower-resolution calculations:

At times when direct sun did not hit the task plane, more task plane illuminance would be provided from indirect bounces, and therefore depend more heavily on ab criteria. Sample test calculations with 6ab were compared to lower resolution calculations with 2ab, resulting in approximately a 10% decrease in light (Table 1). Therefore a more conservative 460 lux threshold was used at times when the direct sun did not hit the task plane. To confirm direct sun penetration of the results, the top six and bottom six values were then averaged respectively to reduce stochastic error, and max/min arithmetic performed. If the max/min was less than 3:1, that signified no direct sun on the task plane, directing the algorithm to employ the 460 lux threshold.

If the max/min ratio was greater than 3:1, this signified direct sun on some portion of the task plane. During these times it was deemed acceptable for the maximum illuminance to be slightly above 500lux, as the CIE Clear Sky with Sun resulted in slightly higher light levels than measured from the local weather file data. This meant that in mid-summer it was not possible to maintain 500 lux maximum through 1% tinting; the closest illuminance results were nominally 560 lux. In reality, these values would always be slightly lower due to haze, dirt on the glass, or other environmental factors.

Table 3: Simulation Parameters

Radiance parameters	High-Resolution Test Calculations	Low Resolution for Full Calculations
ab	6	2
aa	.15	0.25
ad	1024	512
ar	128	16
as	256	128

3.3.1 Algorithm Cadence

Upon initiation of the algorithm, date and time were selected, which in turn set the solar vector based on the project location (Figure 12). At iteration 0, cells that intersected a solar vector projected through the center of the cell and bisected the task plane tinted to 18% VLT. Then, a point-in-time illuminance calculation was run to determine illuminance across the task plane. If the resulting illuminance levels were above the aforementioned logic-based thresholds, the algorithm would nominally increase the tinting in the skylight and re-run the analysis. This was executed by slowly shifting the jig, first northwards, then up towards the skylight, effectively increasing the projected area of the task plane (Figure 13). This cycle repeated until the tint levels dropped illuminance levels below the threshold for that time step. The jig included 45 steps, and many times required as many as 40 iterations before landing on an appropriate tint pattern. Then the algorithm wrote the resulting tint-states of each cell to an external spreadsheet in Microsoft Excel and moved on to the next time.

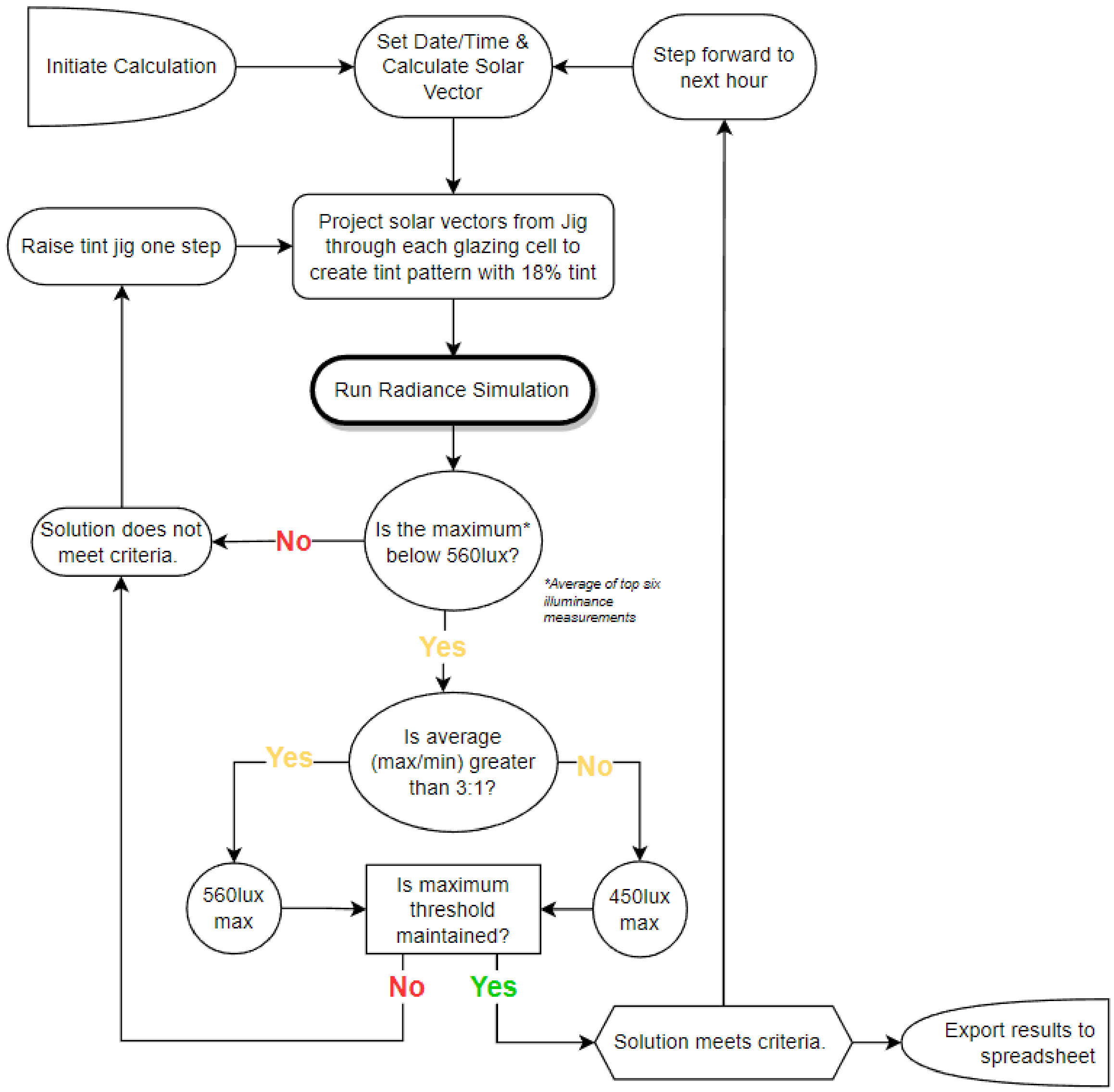

Figure 14: Flowchart explaining the Grasshopper-based looping algorithm for calculating all tint-states.

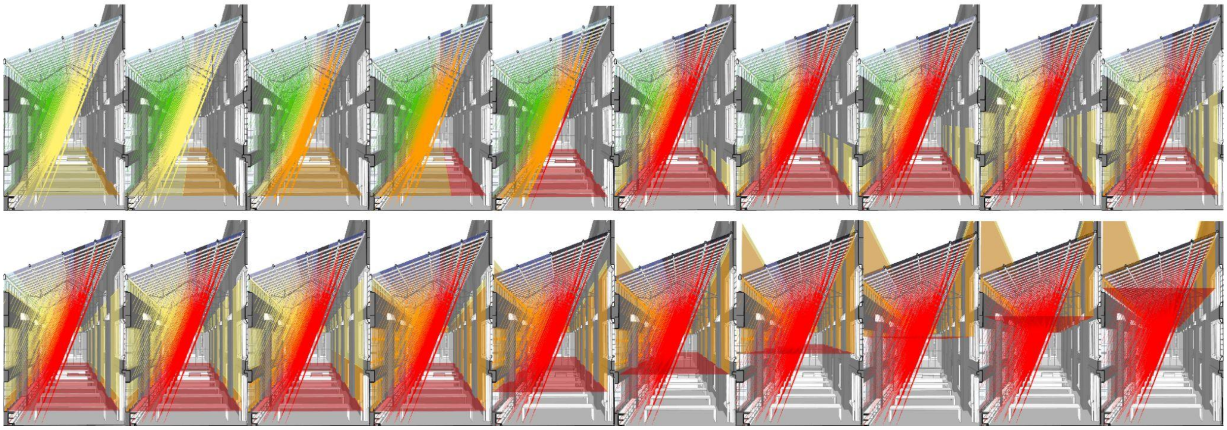

Figure 15: Movement of the jig showing solar vectors for July 11, 2pm. Jig included 45 total steps. Red = 1% tint, Orange = 5% tint, Yellow = 18% tint, Green = no tint (60% VLT).

3.3.2 Additional simulation parameters & weather

Not all hours required calculation to attain an annual program. First, solar geometry is symmetrical across the solstices, halving the calculable hours. In addition, the sun's movement in an hour equates to approximately two weeks of angular distance in altitude. This allows for one day's worth of tint states (7 am - 6 pm) to be reused for two weeks (Figure 14A-14B). 150 individual scene states were calculated for full sun weather conditions, significantly less than the +3500 daylight hours in Princeton, NJ within the occupancy schedule. Sub-hourly time steps were considered, but the transition time of EC glazing - upwards of 20min - meant that the skylight could be in motion more often than static if scheduled changes happened more often than hourly.

As previously noted, initial calculations used the CIE Clear Sky with Sun. However, Princeton experiences an average of 1650 sunny hours a year between 9 am-6 pm, accounting for only approximately 47% of the total hours in which the space may be occupied. The Manufacturer's standard programming was designed to account for local weather and provided logic for real-time weather monitoring via roof-mounted sensors, with the ability to switch between their four tint levels based on sensor input every 15min.

Extrapolating out to this skylight meant that the system could select between one of 4 tint *patterns* at any given time based on weather conditions. Therefore, three additional sky conditions were calculated using additional CIE skies: Intermediate With Sun, Intermediate Without Sun, and Cloudy Sky (Figure 14C). The Cloudy Sky scene, in which the solar disk was completely obscured, could likely have been accomplished without any apparent movement of tinting across the skylight. However, to maintain design intent it was decided to continue tinting as if the sun was visible, with minimal tinting as needed to maintain the illuminance thresholds.

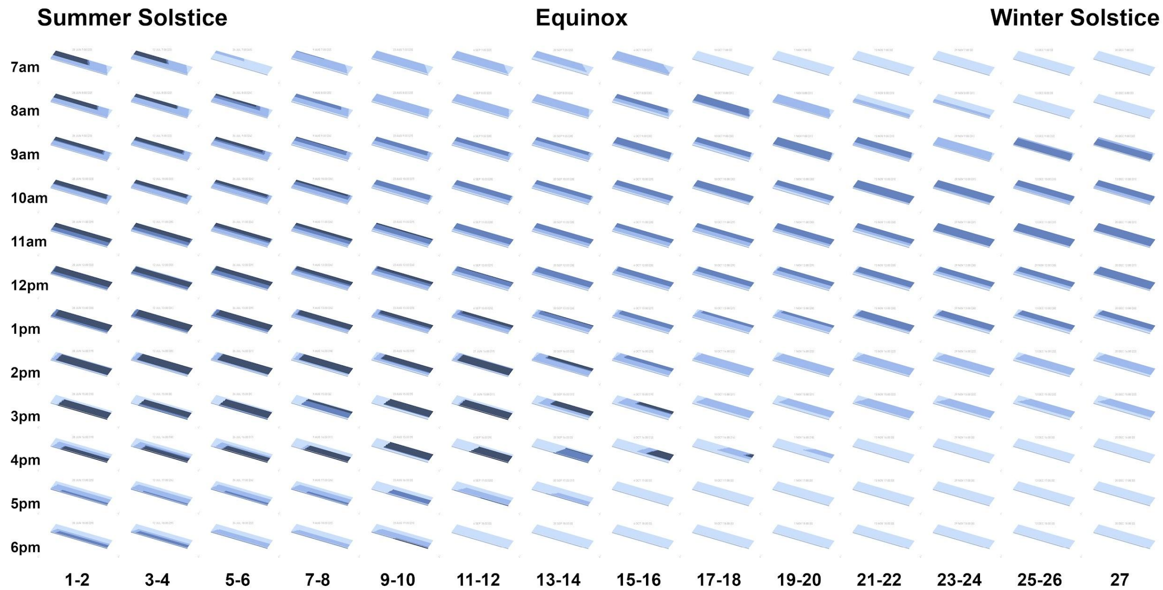

Figure 16A: Matrix of all unique scene states used throughout the year.
Note: scenes were calculated for 7 am, 8 am, and 6 pm, although the library is closed during those hours.

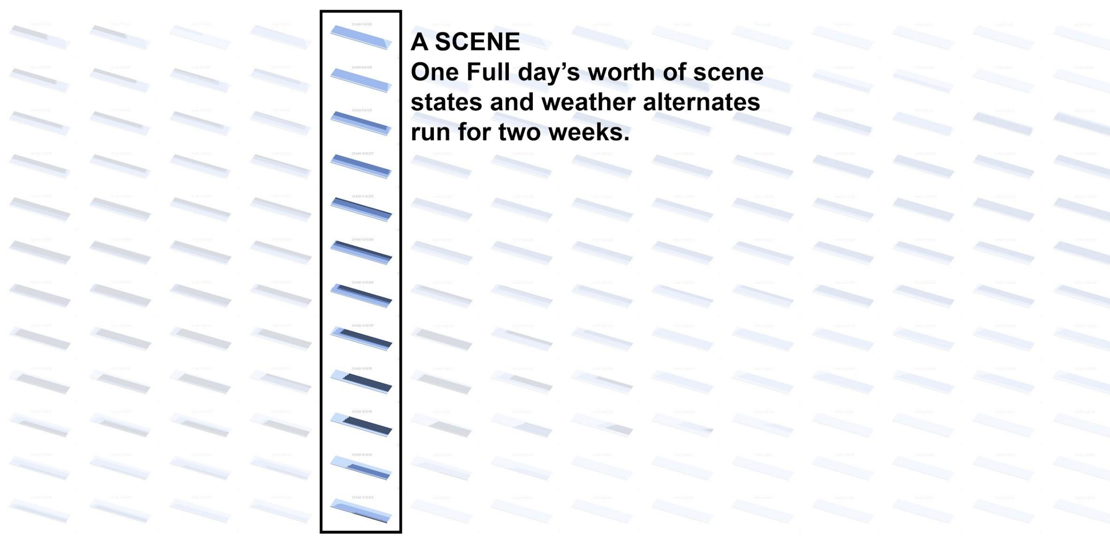

Figure 16B: One day's scene states are reused for two weeks

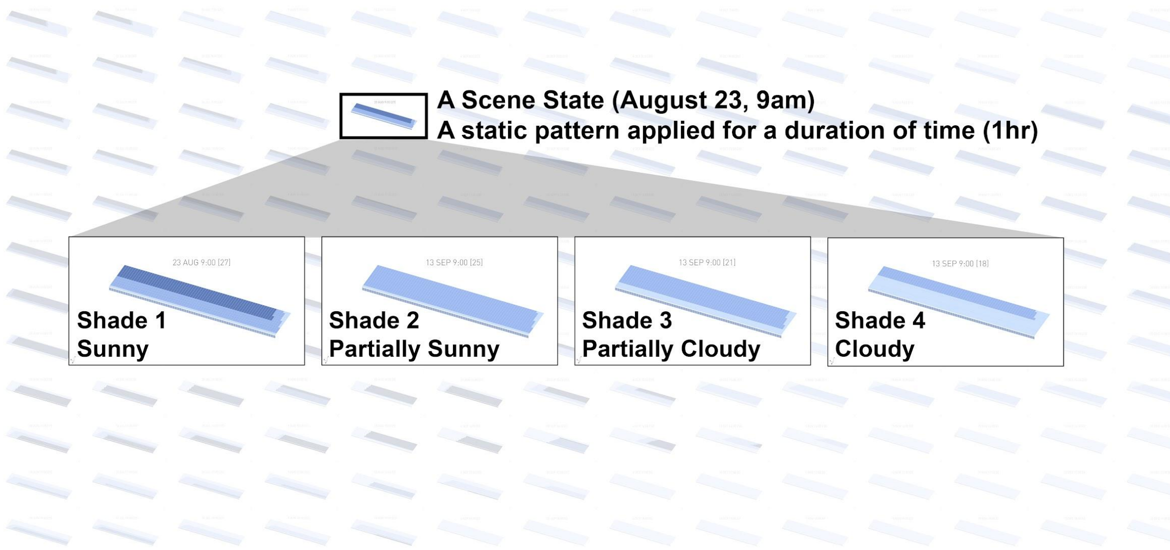

Figure 16C: At any given time, four tint-states are available to account for weather conditions

In total, 672 possible scene states were included in the final spreadsheet, accounting for 14 day-long “shows” of 12 hours each, with 4 weather conditions selectable at any moment. Data was organized with each cell comprising one column, and each hour per row. Four tabs were included, one for each weather level. Each cell contained a 0,1,2 or 3 - 0 equating to no tint, 3 for fully tinted. This spreadsheet was delivered to and absorbed into the Manufacturer’s control software for the installation.

4. Installation & Operation

The glazing and EC system were installed in the fall of 2017. Sage augmented their software to read the spreadsheet output, creating a simple data flow between the author and the installer. Commissioning was executed by the manufacturer both on-site and through remote monitoring.

The installed glazing is an Insulated Glass Unit (IGU) comprised of a laminated outboard lite containing the electrochromic tint material, cavity, and laminated inboard lite. The outboard laminated lite includes heat strengthened 3.9mm thick coated float glass with an interlayer of 0.9mm thick clear polymer interlayer for shatter resistance, followed by 2.2mm thick electrochromic variable tint material. A 21mm band of black ink obscuration material exists on surface #2 around the perimeter of each IGU. The cavity between lites is nominally 12mm filled with 90% argon/10% air, with desiccant along the sides to reduce moisture. The laminated inboard lite includes a polymer interlayer sandwiched between two pieces of clear float glass totaling 6mm. The total IGU thickness is 30mm. Each IGU contains a low voltage pig-tail for connection to the control system with wiring running through the mullion frames, operating at 5V DC or less (Sage Electronics, 2013).

Table 4: Glazing Characteristics

Additional performance Criteria	Untinted State (60% VLT)	Fully tinted (1% VLT)
U-value (Summer & Winter)	0.29	0.29
Solar Heat Gain Coefficient	0.42	0.09
Shading coefficient	0.48	.10

Glazing Characteristics from Construction Documents CSI Spec Section 088001 Special Function Glazing, section 1.11(Sage Electronics, 2013).

A quad-sensor (photocell) was installed on the roof to assess weather conditions from the four cardinal directions. However, during commissioning, the agent found it difficult to accurately measure ambient exterior light levels as direct light on the sensors in the morning and evening led to too much tint on the skylight. Instead, a 'SageGlass Interior Daylight Sensor 300-1053-001' (nominal 50mm in diameter with a 60deg field of view) was installed on a beam just below the skylight (Sage Electronics Inc, 2013). The glass tints and lowers the light hitting the sensor, but the system knows the tint level and back-calculates exterior lux on the glazing surface.

4.1 System Operation

Once commissioned, the system runs autonomously. On any given day, at 9 am, the aforementioned interior outward-facing sensor assesses the weather based on the normalized illuminance reading, directing the system to which of the four weather states to select, and transitions the skylight to that pre-calculated scene. Every 15 minutes, the sensor reports measured exterior illuminance to determine if cloud conditions have changed, requiring adjustment of the tint level. At 10 am, the next scene is instantiated, again with weather conditions accounted for, and so on and so forth. At 5pm the glass transitions back to clear, which remains until the following morning.

Image 1: Professional Photograph by Robert Benson

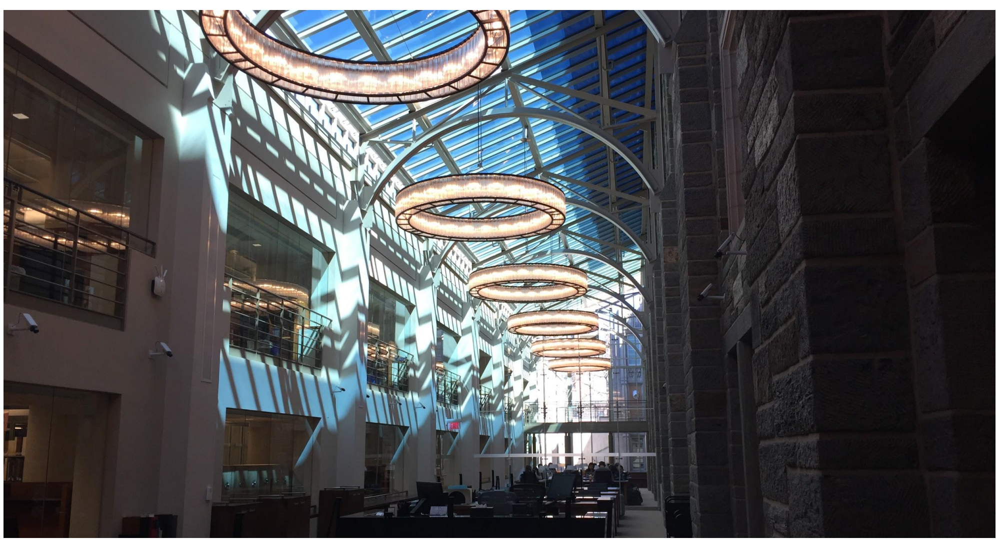

Image 2: Mid-afternoon photograph showing direct sun only shining on the north wall

4.2 Error Correction

The following spring after installation (2017), library staff noticed a "hole" where direct sun was penetrating a sensitive area at a specific time of day. Staff provided a sketch and note on a floor plan of where and when issues were present (Figure 21). It became clear that this 'hole' was formed for approximately 15 min at an edge between tinted and un-tinted cells. In the algorithm, solar vectors were calculated from the center points of each glazing cell; in this instance, the 'hole' was likely due to a mismatch between the calculated tint pattern and the movement of the sun at the extreme end of the particular pattern's 2-week use period. From this information, the author adapted the tint patterns, increasing tinting in adjacent cells, and provided an updated spreadsheet back to the manufacturer for reintegration. No further issues have since been identified.

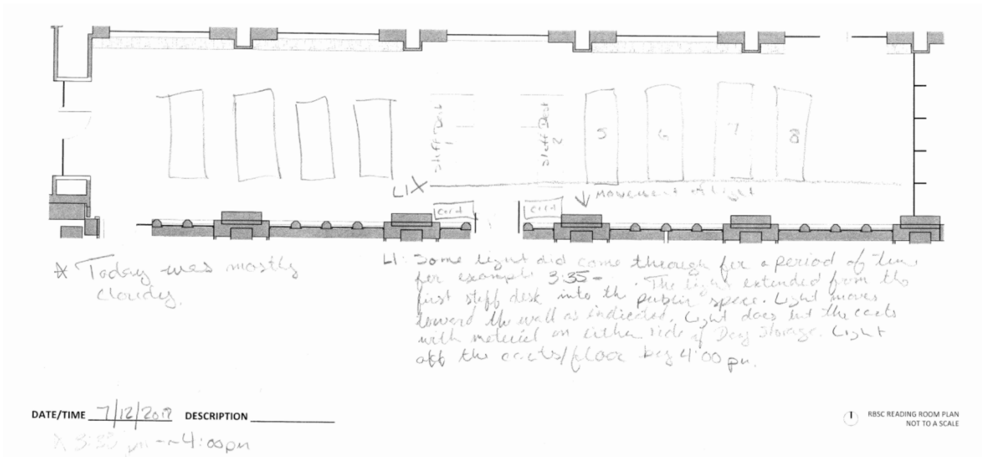

Figure 17: Sketch from occupants showing where the 'hole' occurred

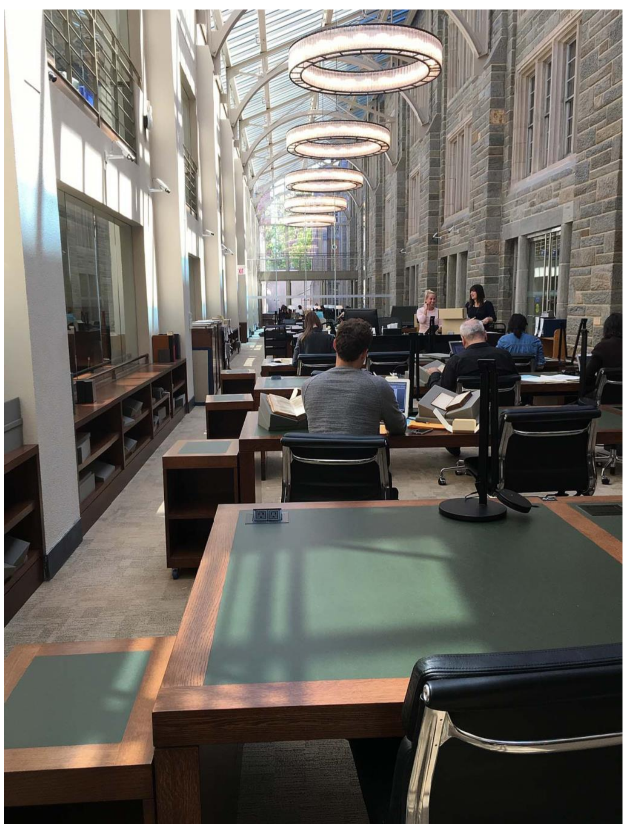

Image 3: Image provided by library staff showing the 'hole' direct-sun penetration

5. Discussion

This case study demonstrates the successful deployment of EC in a large skylit room, where the view is only a modified variant of the blue sky itself. As noted in the introduction, studies have shown a range of EC technology's limitations, notably its inability to fully shield direct sun and potential color shift when deeply tinted. A space with ample daylight access and the focus on minimal tinting, except when and where absolutely required, suggests less concern for circadian stimulus reduction, although further study with validated software able to assess circadian stimulus and field measurements would be required to confirm this hypothesis.

Given this use as a place to study rare books, color rendition is of particular interest. The TM-30 data reported in Section 3 shows that even in the lowest tint state, color rendition remains reasonably good with Gamut Index (R_g) = 89 and Fidelity (R_f) = 86. However, the relative chroma (R_{cs}) reports reduced color saturation (-14%) although still within 'typical values.' It's likely that red colors will appear less saturated and vibrant under full tinting. Although the east wall remained clear at all times to provide untinted daylight into the space and accounting for 15% of the room's exterior glazing, it is possible that during mid-summer lunchtime hours when the skylight is heavily tinted, the color rendition may drop in the western zone of the reading room. During these times, it is possible that researchers may rely on locally-provided task lighting to make up for the difference in color rendition, as well as a boost of illumination. The human eye has a great capacity for adaptation, and may simply adjust the white point to minimize any perceived reduction in color rendition. Future study and a Post-Occupancy Evaluation will be necessary to understand if the blue tinting is causing issues with users, although the author has received no complaints to date.

Additionally, although this case study did not prioritize energy use concerns, it is likely that the EC glazing contributes to reduced heating loads in the reading room as compared to other methods of solar control such as the originally installed screen or interior motorized shades; again, further research would be required to verify this hypothesis.

Regarding the level of photometric optimization, while this case study ultimately required the development of an algorithm able to quantify light levels at all times to meet the specific 500lux light level, in many future projects only "Geometric Heliotropism" may be needed for the successful use of EC technology. The technology's inherent ability to be programmed down to the individual cell suggests that, particularly in large skylit spaces, developing nuanced control scenarios that follow the sun could be a useful method for solar control that maximizes daylight access while shading specific zones within such spaces. For example, a large train hall such as New York City's Moynahan could employ electrochromic glazing with Geometric Heliotropism to selectively reduce direct sun on waiting room seating while keeping as much skylight clear as possible. In spaces such as this, limiting specific illuminance levels would be less critical than simply reducing solar gains and associated thermal and visual discomfort for occupants in a specific location in the space.

Table 5: Comparison of Baseline and Design Strategies

Iteration	Design Intervention	Pros	Cons
BASELINE: Existing Skylight & louver	Fixed VLT glazing with fixed louver - 7% VLT	Glazing required replacement due to ongoing leaking and thermal concerns. The louver could have remained if the space had not required specific light levels.	Did not meet the conservation threshold required by library faculty. No dynamic shading capabilities for peak solar hours
Design iteration 1: Architectural interventions	Reduced glazing area, translucent glazing at apex, & the addition of interior vertical baffles	Reduced solar penetration without requiring any dynamic control	Fundamentally altered the visual nature of the architecture; reduced solar penetration in winter months in order to meet maximum light levels in summer months
Design iteration 2: Glazing combinations	Various combinations of fixed VLT clear, translucent, and opaque glazing	Reduced solar penetration without requiring any dynamic control	Significantly reduced daylight in winter months in order to meet maximum light levels in summer months
Design Iteration 3: Geometric Heliotropism	EC glazing with geometrically defined control scenario to follow the sun and visually shade task plane at all times with minimum tinting	Dynamic solar control without moving parts; allows for tinting only the minimum amount of glazing necessary to reduce direct sun on task plane	Cannot meet specific light level thresholds without optimization.
Design Iteration 4: Photometric Heliotropism	Photometrically assessed EC heliotropic shade control with simplified solar obstruction geometry, meeting 500lux maximum at all times	Capable of meeting specific illuminance threshold at all times throughout the year.	Computationally complex; minimal potential uses beyond highly specific and regulated spaces

5.1 Future Post-Occupancy Evaluation

As of the publication of this manuscript the Reading Room has been occupied and in continual use for five (5) years. Anecdotal evidence suggests that the design has successfully met the client’s established criteria, as well as the perceptual experiences of its users. However, aside from the initial error-correction feedback early after installation, no full post-occupancy evaluation has been undertaken to confirm that the design actually meets all the specific criteria. It is the goal of this author to perform a post-occupancy evaluation in the future.

5.2 Meditation

This project provides a real-world application of optimization for a complex electrochromic glass layout in a highly controlled use case, yet under less constraining circumstances this project would likely never have occurred. The particular needs of a rare books reading room situated in a fully daylit atrium presented a unique and challenging opportunity to develop a new method for controlling daylight for sensitive materials and offered a chance to execute a fundamentally new and unique process for solar control that is perfectly tuned to its locale and adapted to the architecture. Here, in the almost cliche parlance of Louis Sullivan, "form follows function." The patterns created by the EC glazing are a constantly evolving expression of the exact daylight control needed at each moment.

Regarding the design process, the design tools and products in this case study offer the Daylighter's analog to digital fabrication, where the designer develops the design *and* produces the final product for the client from the same digital content. In this project, the parametric algorithm was developed as a projective representational tool - a means to create visualizations of the Geometric Heliotropism scheme that conveyed this concept to the client for approval. However, the Grasshopper algorithm ultimately took on a number of responsibilities, including visualizing each scene state, testing the illuminance of each scene iteration with Radiance, and exporting the result for each scene to a spreadsheet. This spreadsheet was then passed off to the EC glazing manufacturer, who used that code to drive the skylight controls. The design tool, therefore, became embedded in the installed control system.

Feedback from real-world use then provided feedback on the fidelity of simulations - to verify if the numerous assumptions and micro-decisions in fact contributed to an accurate control algorithm. A minor adjustment was required, from which the consolidated script was easily adjusted to accommodate the feedback. Granted, this feedback was limited and does not constitute a full post-occupancy evaluation, but it shows the capacity for the infrastructure to be adjusted through control sequences without major difficulties.

While the solar scene appears natural, like ever-evolving shadow patterns, design decisions were made and embedded into the algorithm that simulated this effect. The skylight is now essentially a low-resolution media display with 923 pixels; each pixel capable of 4 shades of blue, and with a transition time of 2-20 minutes. Visiting artists could be commissioned to produce a scene that runs during a particular event, program text to slowly scroll across the skylight, or even display the University's logo. On dark winter or gloomy overcast days, abstract geometric patterns could slowly morph over time to provide dynamic visual interest. The possibilities are quite literally infinite. This suggests a new medium for architecture - the capacities of high-performance facades able to be hybridized - producing both effect and aesthetic performative act.

The analytical approach to this project employed the most sophisticated algorithms available to the author at the time of development (2015-2016). Since that time, computation speeds have increased dramatically, and new tools such as advanced lighting analysis run on the GPU, or machine learning and AI have become commonplace in design research, all of which may offer more robust and streamlined approaches to developing a control design of this nature. In future research, machine learning algorithms with real-time AI-powered camera technology could potentially automate the patterning of the EC glazing to limit direct-sun penetration to the locations actually containing rare books (or other photosensitive artifacts) within the space, perhaps using beacons, AI cameras, or other technologies.

As buildings grow smarter, dynamic facades offer capabilities to respond to local climate conditions, control heat gain, and deliver comfortable as well as novel visual experiences. It's clear that electrochromic glazing technology has a bright future, in spite of its shortcomings. Latent within these systems are critical design decisions that must be made, reviewed, and tested. The design process does not always lend itself to easy access by many, placing the agency on those writing the codes and manipulating the models to responsibly deploy dynamic systems into the public realm.

Acknowledgments

Thanks to Robert (Bob) Osten and Keith Yancey at Lam Partners who secured the project and assisted in the design. Bob was critical in selecting glazing specifications in the early iterations, and both Bob and Keith, along with Jack Risser, provided support through the more computationally complex phases of the project. Thanks to Jason Donahue, Jonathon Baron, and Kristina Osborn at Shepley Bulfinch who brought in Lam Partners and had faith in our design proposals. Fredrick Fisher and Partners served as the Design Architect and supported the project development along with the client, James Wallace, Margaret Kehrer, and Darlene A. Dreyer, at Princeton University. Phil Spande and Helen Sanders at Sage Glass led the manufacturer to accept and deploy the technology, and Phil answered many questions on the technical functions of the system.Ahoo Malekafzali Ardakan, at Sant Gobain, also provided technical information and feedback. Finally thank you to Christoph Reinhart at MIT for sage advice and guidance on how to crack this nut, Jon Sargent, Alstan Jacubiec, and Holly Samuelson, for peer review, and Azadeh Omidfar Sawyer for constant collegiality and general support on all things daylighting.

Fisher Marantz Stone served as the Electric Lighting Designer on the project. Professional photography by Robert Benson.

The author has previously presented the project at DIVA Day 2017, IES Research Symposium 2022, and numerous academic guest lectures.

Declaration of Interest Statement

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The author holds no relationship with the manufacturer or University discussed in this paper.

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