EVALUATING INTERIOR NIGHT LIGHT EXFILTRATION THROUGH COMMERCIAL BUILDING FACADES
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FACADE PERMEABILITY

Humanity's need for shelter and desire to develop its aesthetic have produced enclosures which range from rigid to ephemeral. Facade design and engineering continue to expand, and while vernacular shelters retain their validity amidst new materials and methods, the primary role of the building facade remains the same: to mitigate exterior conditions to promote comfortable interior conditions. It is the duty of the architect, engineer, and facade consultant to regulate the permeability of the building envelope to allow appropriate infiltration and protect the contents of a building from the potentially damaging consequences of daylight.

Facade permeability is most commonly studied in terms of light infiltration, by which sunlight enters the glazed area of a building facade, heating the interior. In the case of new commercial construction, the facade assembly is placed under simulated scrutiny and becomes a major factor in the estimation of electrical loads necessary for maintaining occupant comfort. Its measurable influence on costly energy-dependent systems has perhaps prevented equal consideration of facade exfiltration. The inverse ability for the facade to allow light to escape a building interior is becoming more relevant as research continues in the realm of light pollution and health.

CITIES AT NIGHT

While facade exfiltration has been extensively studied in regards to thermal inefficiency, it is important to consider the inverse path of light from a building's lit interior after dark. Though beautiful, a visible skyline draws attention to potentially significant light losses from building interiors. Accounting for variable lighting strategies and patterns of illumination, it is unclear how much light is escaping through a building facade after dark. What is very clear is light in the environment which directly or indirectly emits from man-made sources fundamentally recognized as light pollution. Forms of light pollution include unintentional light trespass across property lines, sky glow, which veils astronomic bodies, and glare which is often disorienting or uncomfortable.[1]

The presence of excess light in the night sky as light pollution is a problem currently being researched to great lengths by professionals in the natural and atmospheric sciences, medicine, ecology, astronomy, landscape and lighting design. Despite cross-disciplinary interest, little research exists to quantify interior night light exfiltration through glazed facades. While research into the effects of light

pollution on humans continues steadily, many critical studies have looked to buildings as the source of disorientation for migrating birds. The extensive study of bird strikes, or bird-window collisions, concerns the attraction of birds to various properties of building facades, which often results in injury or fatality. While the causes and frequency of bird strikes are vastly complex, a dangerous relationship has been established between tall commercial buildings and birds migrating over urban areas.[2] Acknowledging the fatal relationship between birds and buildings, researchers have introduced the concept of mitigation at the building facade. Strategies such as glazing frit patterns, films, and awnings have been proposed to reduce bird attraction to the "beacon effect" caused by interior lighting.[3] Many of these studies have developed innovative techniques for measuring light loss through building facades. An analysis of these studies was useful in developing a methodology that could communicate lighting results within the architectural context, utilizing metrics common to the building and engineering disciplines. Illuminance, which defines luminous flux density arriving at a surface, is a metric typically used by lighting engineers to analyze appropriate light levels within a space. Luminance, which references to the total amount of luminous flux density leaving a projected surface in a given direction, is closely tied to discomfort glare analyses performed by building scientists.[4] Applying accessible and affordable software and measurement tools, *illuminance* and *luminance* values can be accurately measured or simulated to understand interior light loss propagation in the urban environment.

METHOD

The analysis of an existing case study was imperative to understanding exfiltration and validating an accurate digital model. The validated model was used to approximate
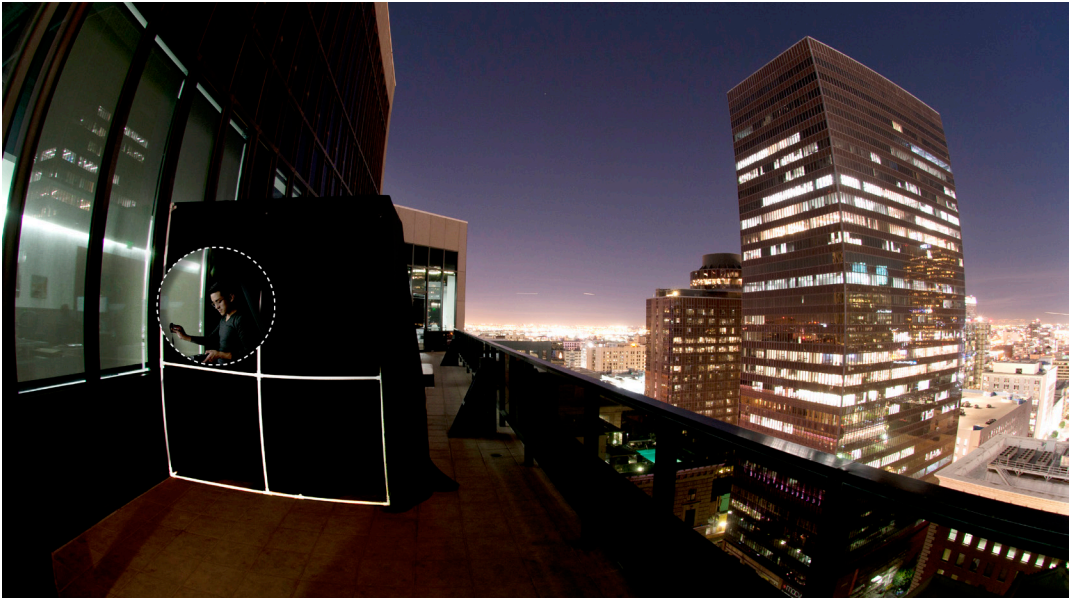
real world and speculative shading scenarios. The totality of the project consisted of three phases. The first captured illuminance and luminance data via physical experiment. In the second phase, Rhinoceros 5.0 with DIVA 3D modeling software were used to replicate the building case study in detail and simulate the existing exfiltration phenomena. The results of the data processing stage confirmed the ability of the DIVA-for-Rhino plug-in to accurately simulate reality. The third phase included digital modeling of various facade shades and the accurate simulation of their potential to reduce unwanted light loss.

Photometric analyses were conducted after dark during business hours on the exterior terrace of a commercial office tower in downtown Los Angeles. Photos were taken at a shielded vantage point 1m from the facade using a Nikon D300 with a fisheye lens. The camera's automatic bracketing feature was enabled and a remote shutter button was used to minimize movement of the camera once in place. The resultant photographs were saved in .HDR
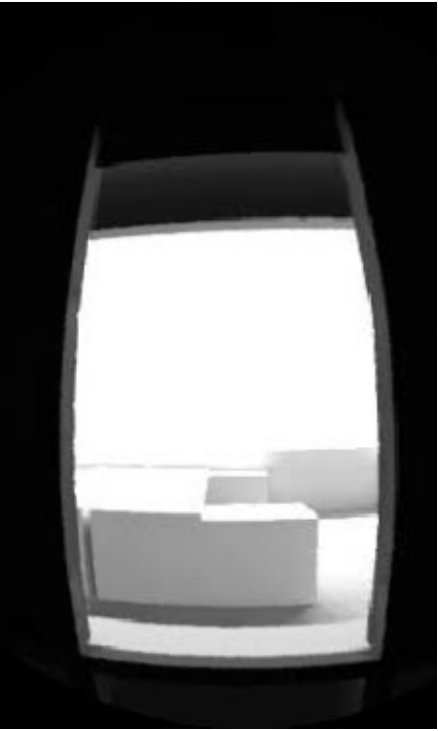
format after minimal processing. The resultant High Dynamic Range file was then converted to false color for analysis in hdrScope, a utility developed by Viswanathan Kumaragurubaran in collaboration with Mehlika Inanici at the University of Washington, Seattle.[5] The concentration of various colors in a false color rendering helps identify useful information regarding the intensity and distribution of light in a test space.

CASE STUDY ANALYSIS

Illuminance measurements were taken with a NIST certified EXTECH 407026 lux/foot-candle light meter at predetermined calculation points. The calculation points were demarcated with a temporary grid of monofilament line following the capture of luminance photos at vertical planes 1m and 2m from the facade plane. Several additional illuminance measurements were taken at the interior and exterior facade glazing planes for use in digital model validation. Figure 1 is a composite image of the *data collection area* in place on the case study terrace.

VALIDATION

The digital modeling procedures in the data processing phase required advanced knowledge of Rhinoceros 5.0 and the DIVA-for-Rhino simulation plug-in. The description of the digital environment was made simple by the results of the visual survey and site measurements. The definition of surfaces and their properties was accomplished in Rhinoceros while the definition of the light source properties, calculation of surface luminances, and transformation of surface radiometric properties for display, were specified using the integrated DIVA user interface. Simulation conditions which replicated physical testing methods were conducted to achieve illuminance measurements and luminance renderings capable of being compared seamlessly.

The accuracy of illuminance calculations was evaluated by comparing peak values at each calculation plane. The peak values were recorded with respect to the source plane and offered reliable data regarding the reduction and distribution of light through the glazing material. Averaged illuminance values, though useful when comparing multiple reduction strategies, would convey an incomplete understanding of light distribution. Luminance, which is often useful for describing thresholds of discomfort glare, was evaluated by comparing peak measurements labeled by the DIVA-for-Rhino wxfalsecolor utility. Figure 2 combines a fisheye image of the facade with the corresponding rendering of the digital model. The accuracy of the simulated peak luminance to the measured case study values was described as a percentage.

REDUCTION TESTING

With the understanding that the case study building reflected a non-standard open office plan indirectly lit by an unconventional lighting strategy, a second "shoebox model" was developed to test light level reductions. This model, illustrated in Figure 3, incorporates conventional office spaces located on the lower levels of the same case study building.

The square boundary of the space was modeled spanning four facade glazed panels of identical dimensions to the case study building, for an overall dimension of 3.7m x 3.7m. The floor to ceiling height, in comparison to the open office, was modeled lower at 3.5m. As with the case study simulation model, the surface directional vectors were oriented to the interior light sources. The *reduction testing* process required advanced knowledge of Rhinoceros 5.0 and the DIVA-for-Rhino simulation plug-in as well as a working knowledge of WINDOW 7.4 and Optics6.

Many software variables were identified and manipulated in order to conduct accurate testing. Though simulations were conducted after dark, weather files were nonetheless required for testing with DIVA. The .epw format weather file was sourced from a weather station located on the roof of the test building located in downtown Los Angeles.

The calculation planes utilized for the *reduction testing* phase were specified similarly to those modeled in the first and second phases with few adjustments. An additional horizontal calculation plane was added at the upper boundary of the tested facade geometry. This "sky" plane and the corresponding "ground" plane at the lower boundary were chosen to host calculation points which would determine direct light leak contributions to uplight and light trespass, respectively. Between these planes, three calculation planes divided the facade glazing units equally. These planes correspond

to the upper and lower halves of the window. The point grid distributed nodes evenly along each glazed facade unit width and included a much denser net of points in the array spanning 2m from the facade. These grids, with the simulated light levels shown on a color scale, are numbered 0-4 in Figure 3.

Reduction testing was dependent on the accurate definition of digital shading devices for use in DIVA's Radiance simulations. Though relatively simple to define manually, custom Radiance materials were "crosschecked" using several free software tools developed by the Lawrence Berkeley National Laboratory. The use of WINDOW 7.4 allowed the virtual construction of custom facade glazing systems via a friendly user interface. The software analyzed daylight and heat transmission through complex shading systems well outside the scope of night time analysis. The result was a Visible Light Transmittance factor that was included in the glazing definition.

Optics6 also analyzed digital facade assemblies utilizing an extensive database of films and coatings, resulting in highly complex optical features. Additionally Optics allowed custom facade constructions to be exported as text-based Radiance material definitions, which could be utilized in various ways to simulate night light loss through the facade. To adopt the more conventional lighting strategy used in the case study's lower-level office spaces, a commercial troffer was selected for use in *reduction testing*. Lighting analysis models sourced from the manufacturer were loaded into the Rhinoceros model for simulation.

A baseline "unglazed" condition was simulated for comparison with various facade shading materials substituting the glazing layer. These were then compared to one another and ranked in terms of their reduction potential.

RESULTS

Peak illuminance values are colored in red for the illuminance maps in Figure 4. Though diagrammatic in nature, the maps allow a viewer to understand patterns in the distribution of light loss outside the facade plane. These maps represent the five stacked calculation planes (Planes 0-4) used for illuminance measurements at a building's exterior. The window plane was modeled at the left of the map. For reference, the map on the far left illustrates the unglazed base case to which the other maps can be compared. The calculated maximum and minimum illuminance results are also noted under each map. These strategies reflect marginal reductions in light levels arriving at the horizontal calculation planes. It is important to note the distribution of spill light exceeds the boundaries of the 2m calculation grid for each of these conditions.

ILLUMINANCE

Reductions in illuminance were analyzed by comparing the maximum lux values at each calculation plane, which are summarized in Figure 4.

The graph in Figure 6 compares illuminance reductions by shading type. The vertical axis can be read as the window plane with subdivisions representing the stacked calculation Planes 0-4. The horizontal axis quantifies average illuminance values at each calculation grid. For reference, the results of the unglazed condition are plotted with a dashed line at the far right.
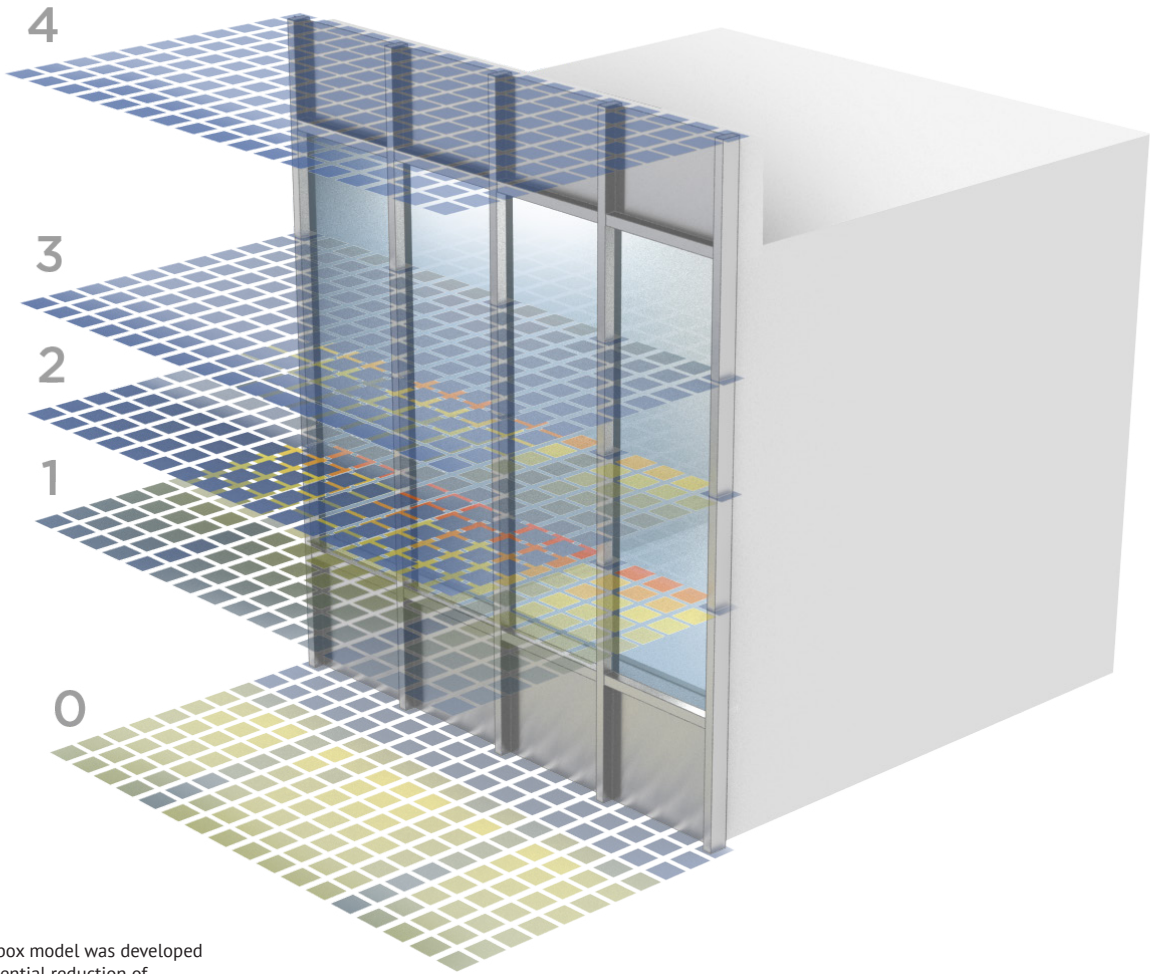

FIGURE 3
A digital shoebox model was developed to test the potential reduction of unwanted light loss through various facade makeups. Horizontal calculation grids represent light levels arriving upon a hypothetical ground plane (Plane 0), lower window region (Plane 1), window midline (Plane 2), and upper window region (Plane 3), as well as direct skyward contributions (Plane 4).
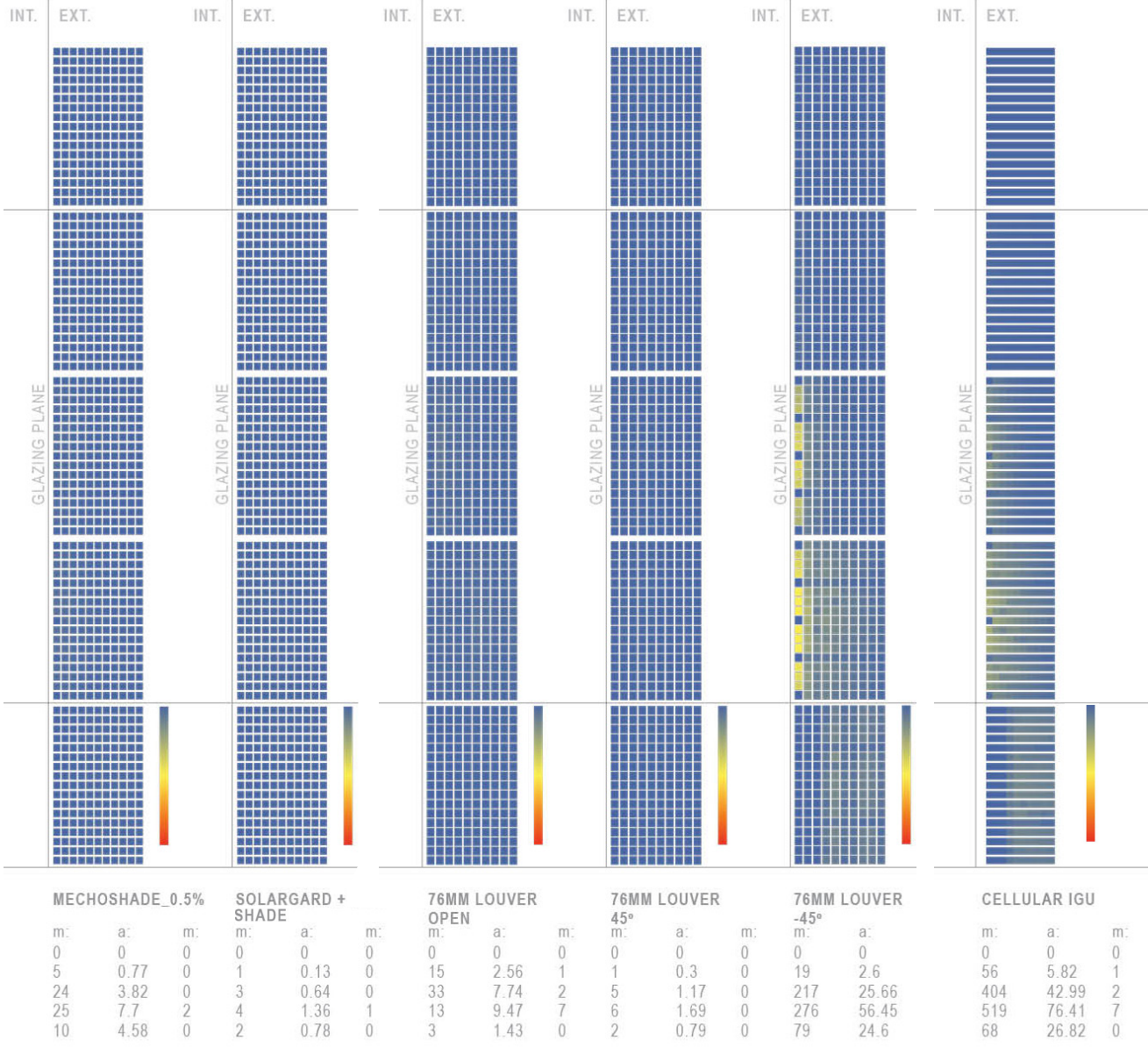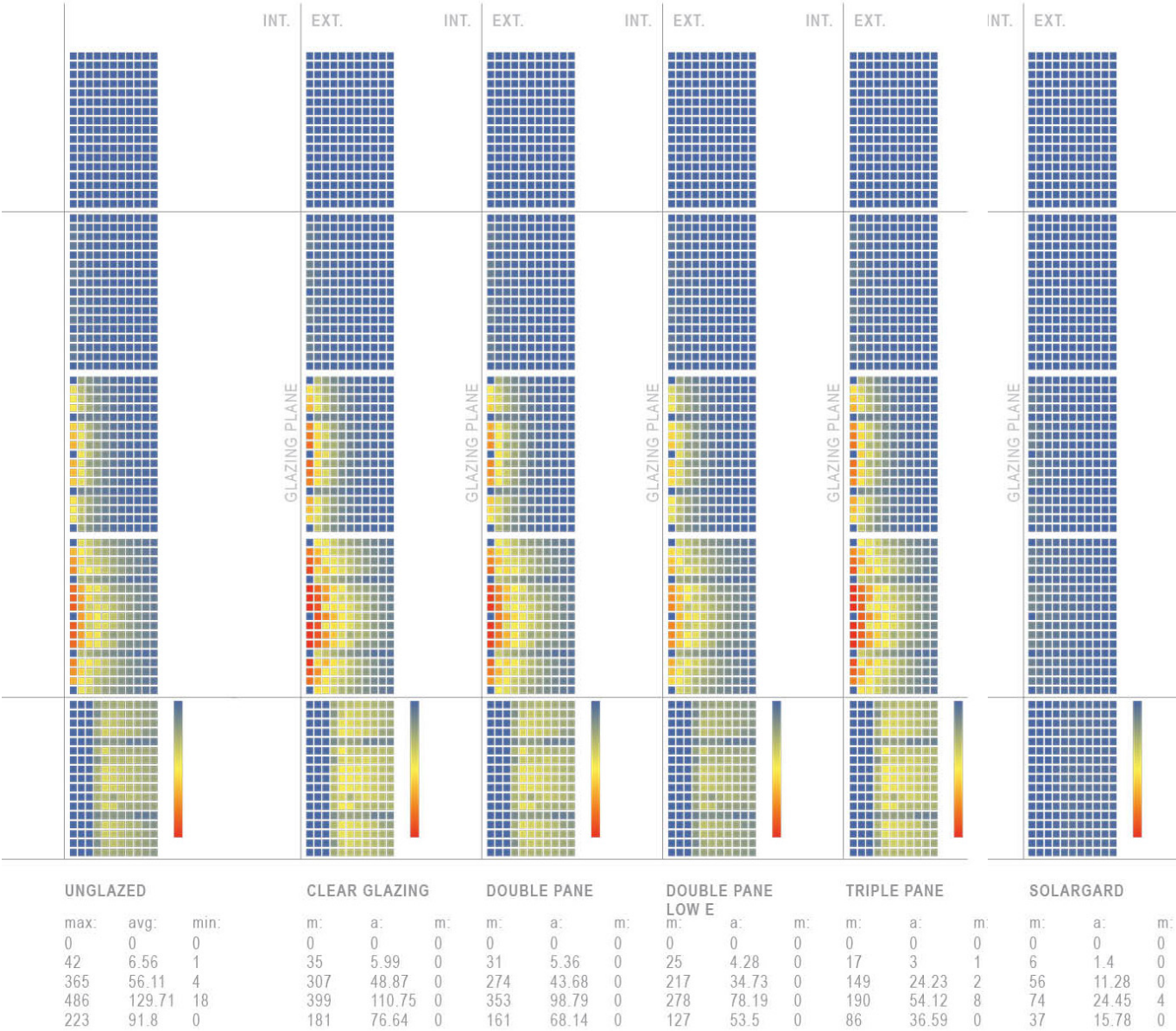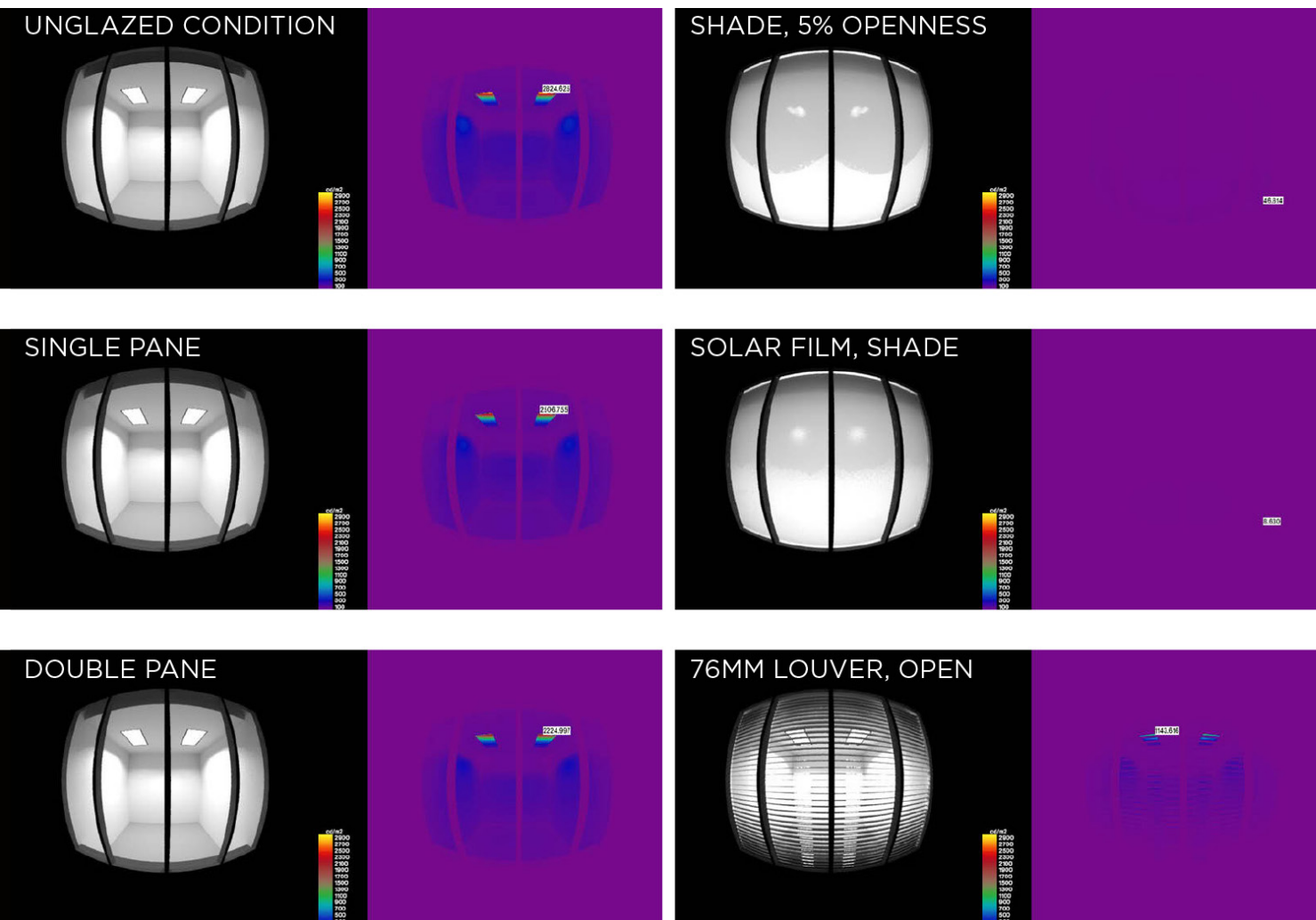
FIGURE 4
Illuminance maps illustrate interior light losses through various facade makeups. It is important to note the concentration of high light levels at the lower window region's simulation grid (Plane 1), originating at the glazing plane.

Left panel:

UNGLAZED			CLEAR GLAZING			DOUBLE PANE			DOUBLE PANE LOW E			TRIPLE PANE			SOLARGARD		
max:	avg:	min:	m:	a:	m:	m:	a:	m:	m:	a:	m:	m:	a:	m:	m:	a:	m:
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	6.56	1	35	5.99	0	31	5.36	0	25	4.28	0	17	3	1	6	1.4	0
365	56.11	4	307	48.87	0	274	43.68	0	217	34.73	0	149	24.23	2	56	11.28	0
486	129.71	18	399	110.75	0	353	98.79	0	278	78.19	0	190	54.12	8	74	24.45	4
223	91.8	0	181	76.64	0	161	68.14	0	127	53.5	0	86	36.59	0	37	15.78	0

Right panel:

MECHOSHADE_0.5%			SOLARGARD + SHADE			76MM LOUVER OPEN			76MM LOUVER 45°			76MM LOUVER -45°		CELLULAR IGU		
m:	a:	m:	m:	a:	m:	m:	a:	m:	m:	a:	m:	m:	a:	m:	a:	m:
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0.77	0	1	0.13	0	15	2.56	1	1	0.3	0	19	2.6	56	5.82	1
24	3.82	0	3	0.64	0	33	7.74	2	5	1.17	0	217	25.66	404	42.99	2
25	7.7	2	4	1.36	1	13	9.47	7	6	1.69	0	276	56.45	519	76.41	7
10	4.58	0	2	0.78	0	3	1.43	0	2	0.79	0	79	24.6	68	26.82	0

FIGURE 5
Luminance images are rendered conventionally and in false color, with peak luminance values called out in cd/m^2

LUMINANCE

DIVA simulation was used to test the potential for luminance reduction using facade shading materials. Measured using false color maps rendered at 1m from the facade, the data showed significant reductions in peak luminance. The rendered images in Figure 5 approximate luminous "hot spots" in the scene with a color scale which accompanies each image. The use of a fisheye perspective approximates potential views from an observer above or below the window's midplane.

The graph in Figure 7 compares peak luminance in Candela/m^2 by shading type and plots the corresponding reduction percentage of the unglazed condition.
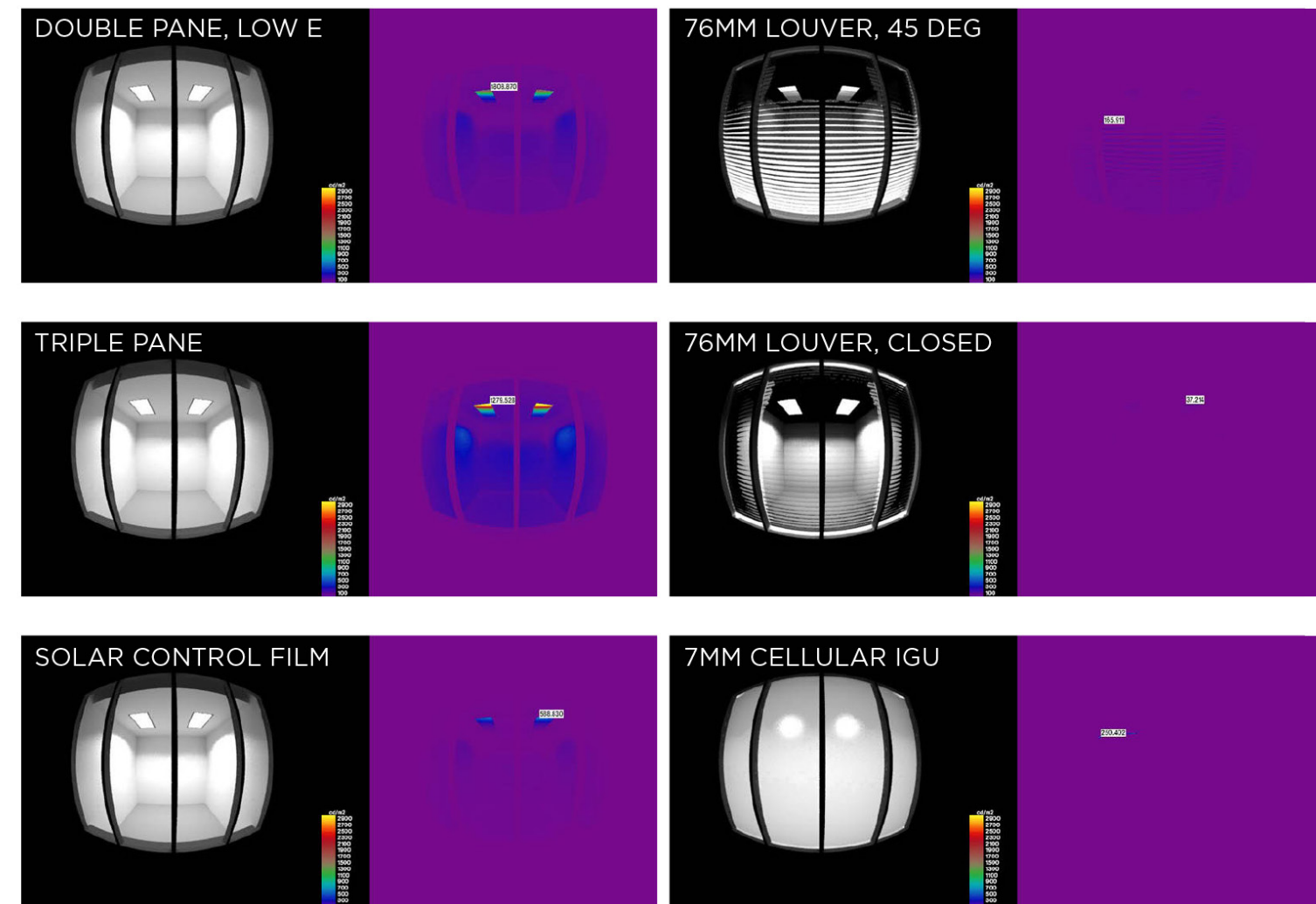
AVERAGE ILLUMINANCE BY FACADE TREATMENT

Legend:
- SOLAR GARD FILM
- MECHOSHADE
- SHADE + FILM
- LOUVERED BLIND OPEN
- LOUVERED BLIND 45
- LOUVERED BLIND CLOSED
- CELLULAR IGU
- SINGLE PLANE CLEAR
- DOUBLE PANE CLEAR
- TRIPLE PANE
- UNGLAZED CONDITION

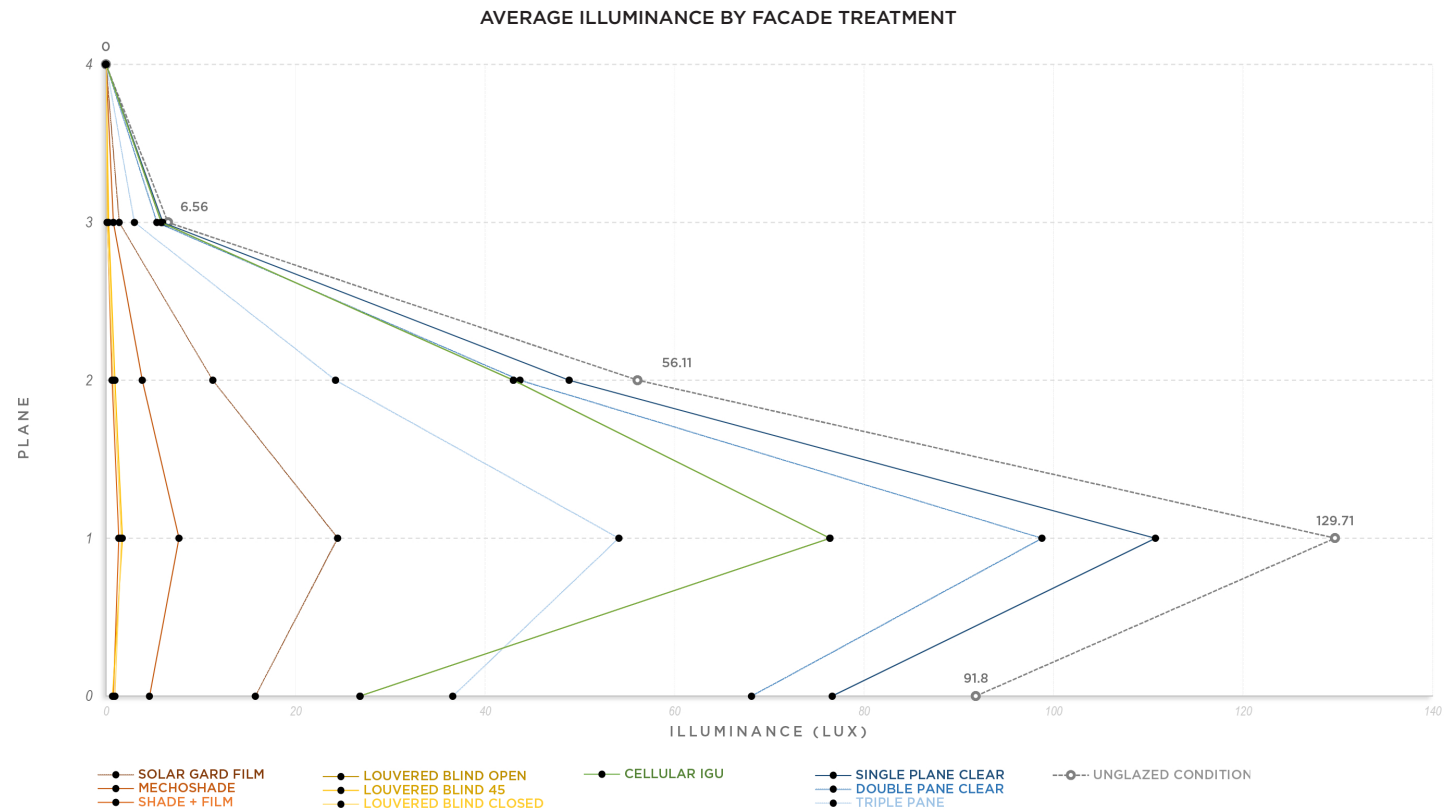## LUMINANCE REDUCTION AT 1M FROM FACADE BY SHADING TYPE

∧
FIGURE 6
Comparison of average illuminance value by facade condition.

⌐
FIGURE 7
Comparison of peak luminance values by facade condition and the reduction potential as a percentage.

FINDINGS

The findings which document the reduction of light levels due to facade treatments support the initial research hypothesis. It was found that conventional facade shading strategies modeled in Rhinoceros 5.0 and analyzed in DIVA could have a significant impact in reducing exterior light levels in the form of illuminance and luminance measurements. Although these results describe a limited sampling of the total simulated conditions, they illustrate potentially large light level reductions due to slight variations in glazing makeup, window treatment, and orientation of an internal shade structure. These twelve facade simulations represent endless opportunities for light reduction testing if a variety facade conditions are used simultaneously. The reduction potential of facade shading systems may be used strategically by designers to effectively reduce urban sources of illumination which contribute to light pollution.
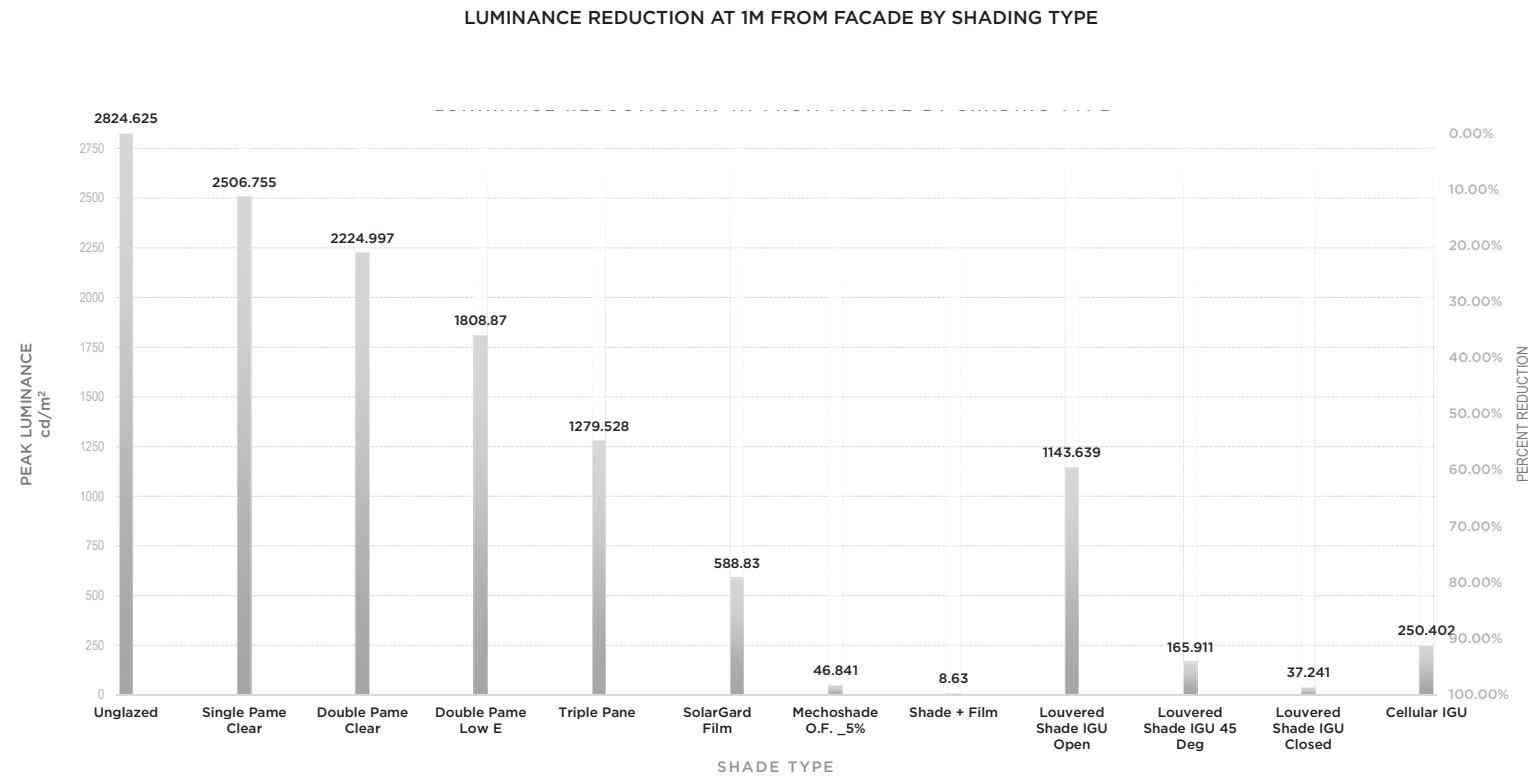
CONCLUSION

Interior night lighting, whether an indication of occupied or unoccupied spaces, creates iconic identities for commercial buildings sharing an urban skyline. But this vista also conceals the ecological, cultural, and astronomical consequence of insensitive lighting design. Various disciplines have identified the relationship of the built environment to light pollution, offering motivations for reductions in light loss. Despite these motivations, cities have continued to brighten with harmful effects. Designers require a toolset which is developing just as rapidly to combat these effects. Designers may see the building facade as a membrane which must be designed for exfiltration of night lighting as much as infiltration of daylighting, with the possibility of shading strategies which are sensitive to lighting conditions of day and night. Accurate digital analysis of interior night light leak coupled with facade information may be a useful tool for estimating and implementing necessary reductions. With research supporting the light leak reduction potential of conventional facade treatments, designers can make influential decisions managing light for interior and exterior environments, and ultimately dim the damaging effects of an inevitably bright future.

ENVIRONMENTAL

FROM BILLET TO BUILDING

EVALUATING INTERIOR NIGHT LIGHT EXFILTRATION THROUGH COMMERCIAL BUILDING FACADES

[1] Boyce, P. R. (2014). Human Factors in Lighting. Third edition. Boca Raton: CRC Press/Taylor and Francis

[2] Parkins, K. L., Elbin, S. B., & Barnes, E. (2015). Light, Glass, and Bird—Building Collisions in an Urban Park. Northeastern Naturalist 22 (1): 84–94.

[3] Machtans, C., Wedeles, C., & Bayne, E. (2013). A First Estimate for Canada of the Number of Birds Killed by Colliding with Building Windows. Avian Conservation and Ecology 8 (2): 6.

[4] Schiler, M. (1992). Simplified Design of Building Lighting. Parker-Ambrose Series of Simplified Design Guides.

[5] Kumaragurubaran, V. (2012). High Dynamic Range Image Processing Toolkit for Lighting Simulations and Analysis. Retrieved April 25, 2016, from http://search.proquest.com/docview/1034738463

TOWARDS A PASSIVE HOUSE CURTAINWALL

[1] City of New York Inventory of New York City's Greenhouse Emissions, April 2016, by Cventure LLC, Cathy Pasion, Mikael Amar, and Yun Zhou, Mayor's Office of Sustainability, New York, 2016

MATERIAL

ARCHITECTURALLY EXPOSED STRUCTURAL STEEL FACADES

EMERGING MATERIAL APPLICATIONS