Designing for Irradiated Shade

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Irradiated Shade is an ongoing project that develops a means of uncovering, representing, and designing for the unseen dangers of ultraviolet radiation within conditions of apparent shade—a growing yet under-explored threat to cities, buildings, and bodies. The project leverages its position in the US-Mexico borderlands, a vital testing ground in which physiological effects of solar radiation are rendered upon vulnerable populations. This paper will discuss: the design context, considerations for ultraviolet (UV) radiation as a complex design problem, the limits of existing design tools to address conditions of UV at a building scale, and the development of custom architectural design tools to improve the ability to visualize and combat UV exposure. The paper introduces an algorithmic drawing technique capable of mapping the built environment from the perspective of UVB scatter, producing spherically-projected sky dome maps indicating the risk of UVB exposure in a particular location to *sensitize* designers to this hidden danger. [1]

DESIGN CONTEXT: AN INVISIBLE THREAT

Particularly high ultraviolet radiation exposure levels map closely to the geography of the US-Mexico border.[2] Urban populations living along and south of the border face significant health risks due to increased exposure levels over the next several decades.[3] Binational urban environments spanning the international border, like the study area of El Paso-Ciudad Juarez, are particularly vulnerable to high levels of diffuse solar radiation. Yet their fragmented jurisdictional and regulatory frameworks pose significant challenges to urban planners and designers seeking to collect and visualize accurate, complete, and contiguous datasets.[4]

Despite its impact on human health and urban environments, ultraviolet radiation is largely under-considered in architectural design efforts at the building scale. This is due, in part, to the difficulty of seeing, sensing, measuring, and perceiving ultraviolet radiation in a built environment, as well as the general lack of sufficient architectural tools and workflows to represent, visualize and simulate its complex behavior. As such, the "invisibility" of ultraviolet radiation is both literal and disciplinary. That is, the phenomenon is rendered "invisible" to human faculties of perception and investigation, and is "invisible" as a design concern for a majority of architects and designers.

To better understand the literal "invisibility" of ultraviolet radiation, it is helpful to assess whether protection from ultraviolet radiation correlates with visible phenomena, namely shade and shadow. While the visible presence of shade and shadow clearly indicate whether an area will be protected from direct light and solar exposure, there is not a similar visible indicator that sufficiently signals protection from ultraviolet exposure. By comparing a traditional photograph, capable of recording wavelengths of light along the visible spectrum, and an ultraviolet photograph capturing only the UV spectrum, we can observe a distinct lack of correspondence between shaded areas and areas with low UV intensity. By capturing the invisible UV wavelengths, ultraviolet photographs reveal that high UV values often appear continuously across areas otherwise protected from visible wavelengths by shade and shadow. This disjunction between shade as a visible phenomenon and UV exposure as a hidden threat is amplified when light and radiation is 'scattered' in an environment. "Scatter" can increase with high degrees of atmospheric particulate, or high amounts of reflectivity on surfaces within an urban environment. Both conditions are common features of urbanized desert environments, like the study area. Because of this, in the borderland, even in apparent shade, the body is exposed to harmful, scattered UVB radiation, creating conditions of *irradiated shade*.

Despite the lack of precise correlation between shade and protection from ultraviolet exposure, shaded areas are often falsely assumed to offer high degrees of protection against UV. The falsity of "safe shade" complicates efforts to protect human health from ultraviolet exposure within shade, as additional protective measures such as protective clothing, headwear, sunscreen, or limited exposure time may be reduced with the assumption of adequate protection. The human body's sensitivity to thermal comfort may further this false sense of security within conditions of high ultraviolet exposure. Studies have noted that heat-stress is a more reliable initiator of a protective response for organisms exposed to UVB radiation than the radiation itself. This is problematic within *irradiated shade*, as a higher degree of thermal comfort may not initiate the appropriate protective response, leading

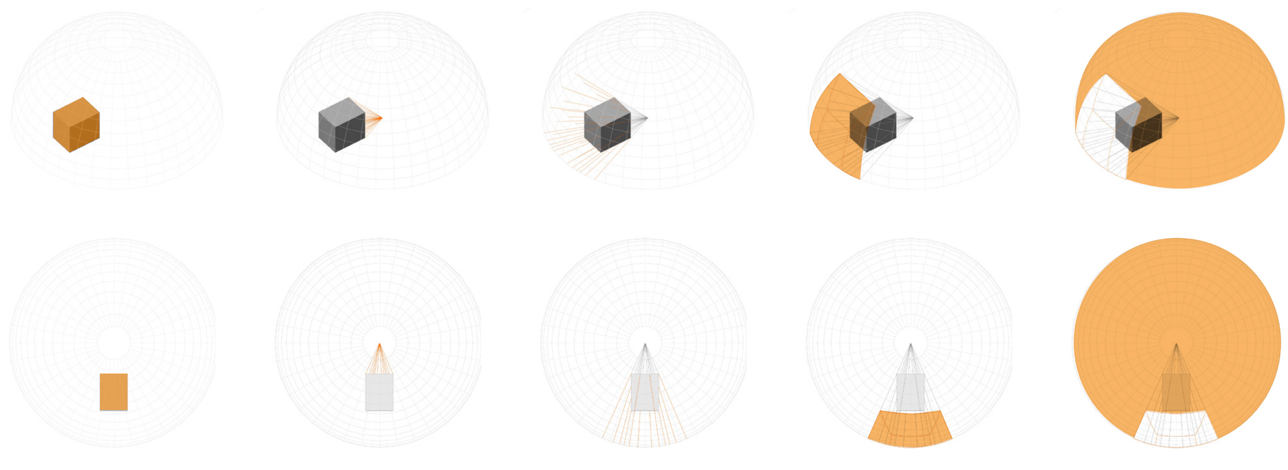

Figure 1. Spherical Projection Algorithm. Image Credit: POST-Project for Operative Spatial Technologies

to skin damage, eye damage, and the inhibition of the immune system of users of public shade.

As we have seen, urban UV exposure is a near-invisible, and non-senseable phenomenon, escaping our view while eluding and even confusing our senses. But perhaps more concerning is the relative invisibility of the topic in architectural discourse, design culture, and pedagogy. We need to promote fluency in design for an irradiated urban atmosphere if we hope to combat the deleterious health impacts experts predict will increase in the coming decades. To counteract these conditions, our design research team has developed a suite of complementary representational tools and workflows at both the urban and building scale to uncover the hidden, *non-senseable*, dangers of UVB radiation within conditions of apparent shade. Our work at the urban scale has included the production of "shade surplus," "shade deficit," and "irradiated shade" maps of the study area to help *sensitize* planners and designers to these conditions. This paper will focus on our efforts to introduce computational workflows and representational techniques enabling analyses and designs capable of increasing protection from UV exposure at the building scale.

UV RADIATION AS A COMPLEX DESIGN PROBLEM

The workflows and techniques presented here consider UV radiation as a complex design problem, building on the science of ultraviolet exposure, as well as spatial logics, translating the most relevant spatial metrics for use in intuitive and interactive design environments. An overview of the major metrics and terms particular to ultraviolet radiation and design provide a basis for further elaboration.

The effectiveness of a shade structure in combatting UV radiation (UVR) can be measured by evaluating the UV *protection factor* (PF) of a given design. Optimizing this metric would appear first to be a seemingly familiar matter of calibrating architectural geometry to the sun's position in the sky. The *protection factor* is measured by comparing the UV index value of a horizontal plane exposed to full sun with the UV index value of a horizontal plane beneath the overhead shade structure. A PF of 15, equating to 94% protection from direct solar radiation,[5] is considered "effective shade."[6] Especially when considering *direct solar radiation*, the PF can be increased by blocking solar exposures with overhead surfaces. Designers seeking to maximize the reduction of direct radiation will often study sun angles and shadow locations to calibrate shadow coverage of areas they wish to protect.

But static geometric analyses cannot account for the full range of ultraviolet exposure conditions, especially when the effects of *diffuse solar radiation* are taken into consideration. As radiation is absorbed, scattered, and reflected through the atmosphere, and potentially under a shade canopy, a simple shadow study will no longer directly correlate to PF values. Environmental and atmospheric factors can increase or reduce the PF dramatically. As the solar zenith angle (SZA) changes throughout the day, and throughout the year, PF values change as well. High sun angles can increase the diffuse radiation levels, while low sun angles in winter months can allow radiation to travel further under an overhead canopy. Increased cloud cover, atmospheric pollution, and particulate matter can all increase the available diffuse radiation values, while the reflectivity of the ground and other nearby surfaces can further amplify its effects. Designers must also understand and account for changing use conditions over time. A more accurate measure of effective or "safe" shade for a given structure can vary widely depending on the hours of intended use of the space, the estimated length of exposure, and frequency of use of a given space.

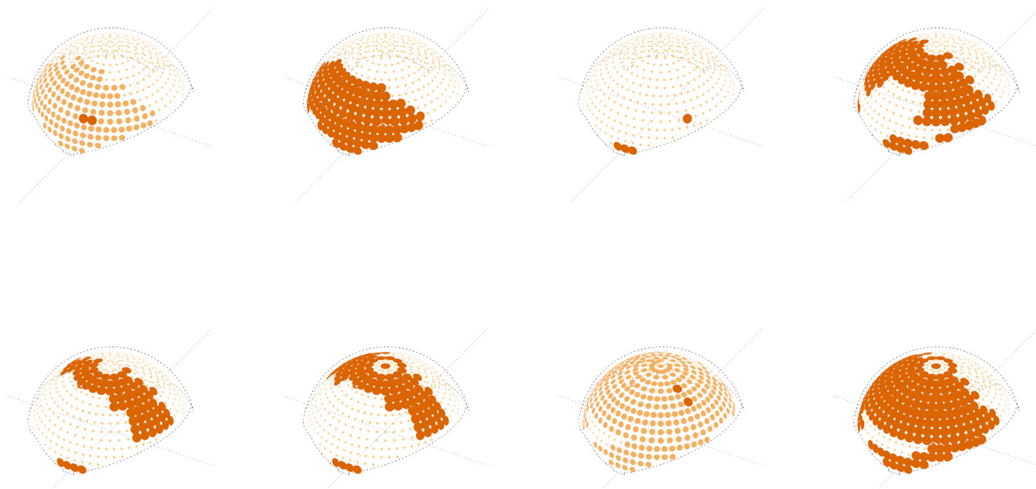

Figure 2. Skydome Diffuse Solar Radiation Mapping. Image Credit: POST-Project for Operative Spatial Technologies

For a shade structure design to provide effective protection against ultraviolet radiation, it must combat *both* the direct solar radiation and the diffuse solar radiation values. While horizontal surfacing above an occupied area can effectively combat direct radiation, vertical surfacing around the occupied area is most effective at blocking diffuse radiation, necessitating a hybrid, volumetric approach to more impactful and effective design solutions. To complicate matters further, the need for overhead structure and side enclosure changes over time. Over the course of any given day, the proportion of radiation attributed to direct solar radiation values compared to diffuse solar radiation values will oscillate, changing the primary design criteria for a shade structure. Just before, and just after solar noon, diffuse radiation is the primary design consideration, while at midday, direct radiation would have the largest impact on exposure. The "design space" for a shade structure optimized for protection against UV exposure is thus constantly shifting.

While the most effective shade structure solution would be a fully enclosed volume, this runs counter to the nature of shade structures themselves, which are often deployed as partial, mostly overhead enclosures to provide "just enough" protection to encourage use without the significant cost, or the limits to access or views that a full enclosure would entail. To optimize a shade structure design, therefore, one would need to simultaneously provide *maximal protection* and *maximal openings*, a seemingly contradictory charge. In other words, designing for irradiated shade would require the precise articulation of the largest possible openings, while ensuring that the openings will not significantly and adversely impact the amount of ultraviolet exposure. The *skyview*, or the amount of sky visible from a given observation point, is a critical variable in determining the protection factor.[7] High indirect exposure values correlate with high percentages of visible sky. The overall size of the shade structure, and the design of openings along sides can mitigate the *skyview*, and greatly impact the protection factor.

Shade, therefore, is not the discrete condition captured in ubiquitous urban and architectural "sun" and "shadow studies," which focus only on the visible, optical qualities of light and shadow. These solar logics flatten the complex, three-dimensional nature of ultraviolet radiation. Safe shade is contingent on the articulation of a shade enclosure that considers not only the provision of shade, but a minimized *skyview*, the particulars of which will depend largely on the nuances of the surrounding built environment. Designers must be empowered to observe and respond to a wider context than current representational tools allow.

LIMITS OF EXISTING DESIGN TOOLS

The analytical and generative architectural design tools, and forms of representation capable of addressing diffuse radiation and ultraviolet exposure at a building scale are currently limited. As we have seen, the design challenge is a complex and relational three-dimensional puzzle to solve. A robust approach would demand that we develop tools and representations that: closely consider the ability of the surrounding context to mask sky exposure, easily identify and address the most vulnerable exposures; and evaluate the performance of a given design to block diffuse radiation.

Most major 3D modeling platforms include robust interfaces for evaluating and visualizing the impact of the built environment only on the visible spectrum. Most designers have integrated these tools into their project development workflows, with sun chart and solar analyses now routine investigations to understand the impact of a design and its context on the availability of light and shadow. As we have

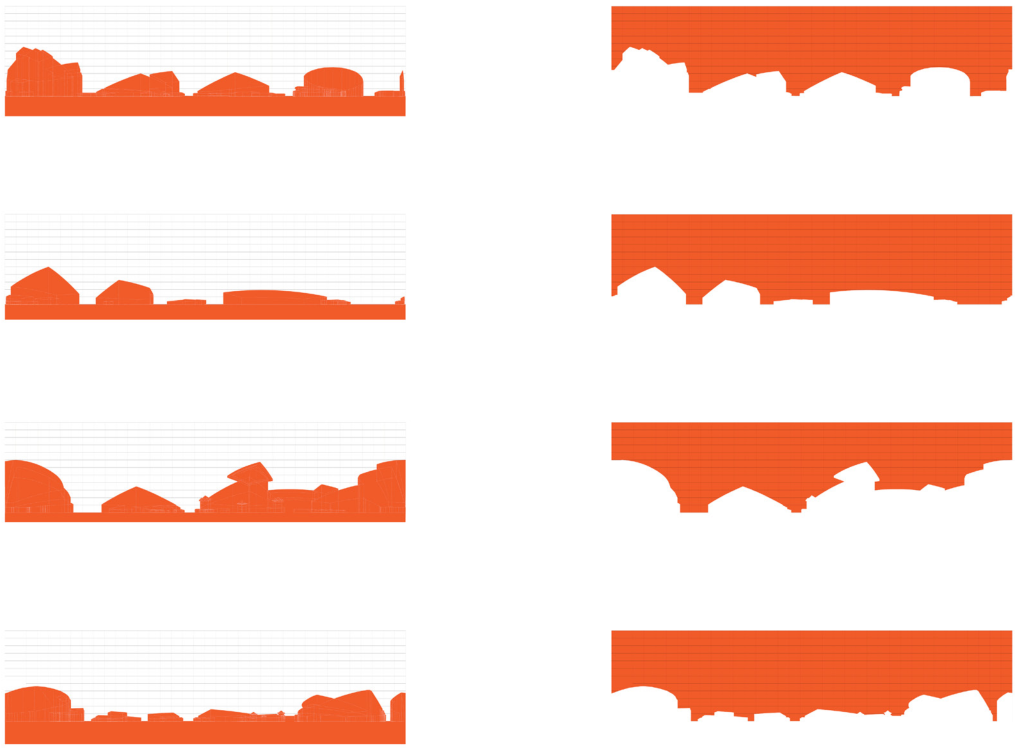

Figure 3. Sky Exposure Panorama Drawing from Cylindrical Projection Algorithm. Image Credit: POST-Project for Operative Spatial Technologies

seen, the recording of visible information from light and shadow studies will only ever closely approximate the condition of direct solar radiation.

The recording of visible information relies primarily on the linear projections of sun angles to ground planes or other occupied surfaces. The simple behavior of direct solar radiation translates to simple and straightforward representational techniques, aligned with legacies of orthographic projection. Designers seeking to calibrate the provision of shade or shadow, and increase the protection against direct solar radiation, can use orthographic, planimetric projections of rendered views, or even project sun angles to plans themselves, to quickly and effectively evaluate coverage.

Orthographic drawing has its limits for evaluating exposure to diffuse radiation, however. Instead of evaluating single linear directional trajectories, diffuse radiation must be considered entering a site from multiple directions simultaneously. To map and respond to this multidirectional onslaught we must imagine—and image—the site and building "in the round." A diffuse radiation analysis would need to capture the full three-dimensional construct around a given site by panning the full horizon. It must also consider the full range of trajectories above and below the site, looking from ground to the top of skydome simultaneously.

There exist a few drawing and imaging techniques capable of capturing this multi-dimensional and multi-directional phenomenon in a single, synthetic representation. But their use in architectural production is not common or readily supported within commonly-used architectural design software platforms, requiring further development of custom algorithms or plugins to support effective design evaluation and representation workflows.

CUSTOM TOOLS: CYLINDRICAL PROJECTION ALGORITHM

First, we consider the *panoramic drawing*, based on cylindrical projection technique. To produce and evaluate the *skyview* of a given environment, we have developed a *cylindrical projection algorithm* which takes a station point and a surrounding cityscape, including any proposed shade structure, as its inputs. Similar to perspective projection, the projection originates from an assumed observer's location, located at the station point. This station point serves as the center for a cylinder, which provides the surface and coordinate system against which the cityscape is projected. Projection lines are passed through each edge and corner of each building mass, as well as through intermediate points along each edge. These lines are extended until they intersect the cylinder, generating a series of intersection points, plotted on the cylinder. The coordinate location of each point on the cylindrical grid is then translated

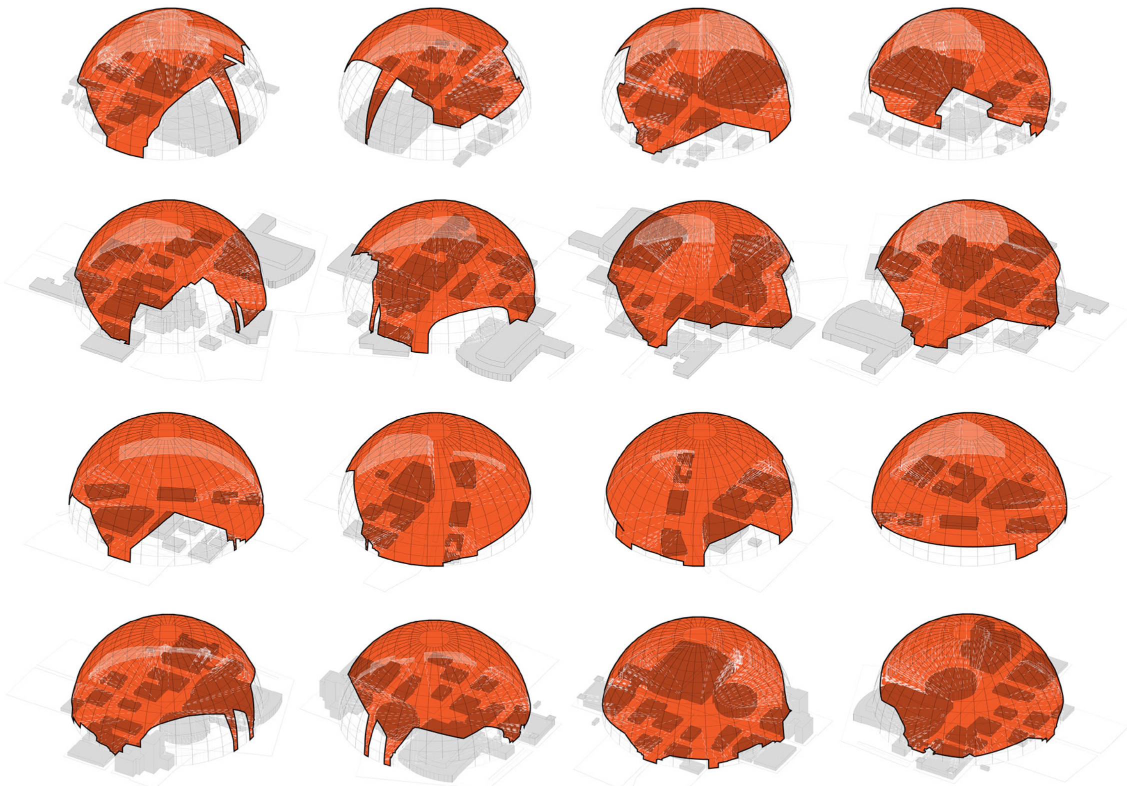

Figure 4. Sky Exposure 3D Mapping from Spherical Projection Algorithm. Image Credit: POST-Project for Operative Spatial Technologies

to a new coordinate location on a flattened, unrolled version of the cylinder, with the same coordinate system. The points are then used as inputs to reconstruct the edges of each feature of the cityscape. Horizontal edges appear curved against the unrolled cylinder.

This strategy creates a clear and concise translation of the complex three-dimensional reality of the site on a single, synthetic drawing, with some distortions and omissions that problematize its utility for our purposes. Since the cylinder unrolls into a rectangular surface, there is an immediate clarity to the vertical orientation of the skyview—the horizon line unrolls at the bottom, and higher elevations appear higher in the drawing. The mapping of the building areas obscuring the skyview allows for quick assessment of areas of likely overexposure and underexposure. The drawing allows for quick assessment of the cardinal and altitudinal orientations which provide the most protection from diffuse solar radiation, as well as the orientations that are most exposed.

Some issues with this technique include the graphic translation of cardinal orientation and the apparent and often arbitrary discontinuities in the constructed fabric and the atmosphere that results. The representational technique distorts the sky dome from its true proportions, especially at higher altitudes, were quadrants must be scaled horizontally to achieve a rectangular frame. This graphically emphasizes the upper levels of the atmosphere, which we have seen is most relevant to direct solar radiation, and minimizes the relative area of the 'skyline' building and other environmental components near the horizon, which are most impactful in blocking diffuse radiation. Since the cylinder is open above the station point, projections against it cannot collect any information immediately above the station point. Evaluators of the drawing must additionally contend with a "seam" in the environment along which the cylindrical projection is imagined to reconnect. Any close evaluations required near this seam, or across it, are hampered by the imposed graphic distance and may require adjusting the projection logic as the analysis progresses.[8]

CUSTOM TOOLS: SPHERICAL PROJECTION ALGORITHM

To remedy these distortions and make a more synthetic and fully three-dimensional mapping of the site context, we next consider a *hemispheric projection*, a technique already commonly deployed by researchers in multiple domains conducting analyses of solar radiation in urban environments. Hemispheric photographs are commonly used across a range of applications to capture multi-directional, synthetic images, including conditions near the horizon and overhead in every

Figure 5. Sky Exposure Catalog. Image Credit: POST-Project for Operative Spatial Technologies

cardinal direction.[9] By viewing the structure and surrounding site from a single, hemispheric perspective we can intuitively engage with the ability of the design to mask sky exposure. This approach makes a fully continuous representation possible, as the mapped skydome can be viewed planimetrically to show all cardinal directions and all altitudes at once. The plan view is not without its own representational distortions. The hemispheric plan overemphasizes the overhead portions of the skydome. The near-vertical elements of the hemisphere close to the horizon are minimized in the map, while the broad, near-horizontal faces of the upper quadrants of the dome appear with minimal distortion. Isometric views of the masked skydome present a clearer representation of the overall distribution of masked and exposed portions of the skydome. The *sky exposure catalog* collects results from every major street intersection within the study area. Additional trajectories for this work include the consideration of “remapping” the 2D representations within a 3D digital environment, using AR/VR tools to evaluate transformations in real-space and in real-time. The design research team is developing proposals for an *Irradiated Shade* pavilion prototype, a structure that protects users from UVB radiation while *sensitizing* them to the degree of UVB exposure within different locations in the project.

ENDNOTES

1. See Stephen Mueller. “Irradiated Shade: Mapping, Modeling, and Measuring Urban UVB Exposure.” ACADIA 2020 Distributed Proximities [Conference Proceedings] (forthcoming).
2. See Ersela Kripa and Stephen Mueller. “An Ultraviole(n)t Border.” e-flux architecture (Apr 2020). https://www.e-flux.com/architecture/at-the-border/325756/an-ultraviole-n-tborder/
3. See Kripa & Mueller (2020)
4. See Mueller (forthcoming).
5. Gies, Peter, and Christina Mackay. “Measurements of the Solar UVR Protection Provided by Shade Structures in New Zealand Primary Schools.” Photochemistry and photobiology 80, no. 2 (2004): 334-339.
6. Parisi, Alfio V., and David J. Turnbull. “Shade provision for UV minimization: a review.” Photochemistry and photobiology 90, no. 3 (2014): 479-490.
7. Parisi et al (2014).
8. As with any projected drawing, the spatial depth of elements captured by the projection is flattened to the drawing plane. As such, the technique does not make obvious the depth of each surrounding element from the observer. Whether and to what degree a plane captured in the projection recedes in view may be relevant in understanding the effectiveness of each face or mass in blocking likely diffuse trajectories. Given that the projection is computed from the digital model, this depth information can however be ascertained with further analysis and graphic refinement.
9. See, e.g., Chen, Liang, Edward Ng, Xipo An, Chao Ren, Max Lee, Una Wang, and Zhengjun He. “Sky view factor analysis of street canyons and its implications for daytime intra-urban air temperature differentials in high-rise, high-density urban areas of Hong Kong: a GIS-based simulation approach.” International Journal of Climatology 32, no. 1 (2012): 121-136.