DESIGN OPTIMIZATION OF A CONTEMPORARY HIGH PERFORMANCE SHADING SCREEN- INTEGRATION OF ‘FORM’ AND SIMULATION TOOLS

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ABSTRACT
This project is an attempt to integrate and evaluate the formal and ornamental desires of contemporary architecture with the pressing need to create designs that optimize energy and daylight performance.

With increased sophistication of digital tools to assess daylight and energy in buildings, a great potential exists to optimize the performance of contemporary building façades. This research study proposes a process for applying daylighting and energy analysis software to optimize the performance of a sun-shading screen based on Sculptor Erwin Hauer's design.

Through an iterative analysis of the south facing screen, daylight and energy performance of an interior test space is optimized through parametrically manipulating the opening size and module depth of the screen. Results are then compared to baseline spaces with 30% and 100% Window-to-Wall ratios (WWR) to understand the screen's relative performance gains. This analysis shows that the optimized screen manages to reduce annual energy use by 35 percent and 42 percent vis-à-vis the two baseline cases.

INTRODUCTION
The progression of style from traditional to modern architecture and now contemporary architecture has resulted in a deficiency of incorporating sustainable techniques in building design. Consequently, according to the U.S Energy Information Administration (EIA), lighting, cooling and heating are now responsible for the greatest amounts of energy consumption in the building sector; followed by water heating, ventilation, etc. (EIA, 2003).

As architecture continues to reinvent itself in the way form is created, the application of a building’s skin has shifted from pre-Modern notions of applied ornamentation, to the deliberate removal of ornamentation in Modernism (~1920s), and has re-emerged in Postmodernism (~1960) and present day architecture. The birth of the digital era has brought about tools that allow for parametric design of both organically- and geometrically-derived building skins. These skins however, largely tend to be an aesthetic expression of form (or ornament), and rarely address environmental conditions such as effective radiation control, daylighting or thermal comfort.

To that end, the ever present climatic crisis coupled with increased environmental regulations has created the necessity for increased integration of formal design with sustainable practices. As a result, the building skin, as both the building’s primary protection from the elements and as the Architect’s statement, must be addressed and better implemented into design to address increasingly complex sets of needs.

The building skin must perform the role of an environmental filter between interior and exterior conditions, while addressing and resolving a wide spectrum of issues such as technical performance, visual appearance, ventilation, assembly, etc. (Lovell, 2010). However, controlling the sun’s radiation and providing adequate daylight levels and views are a few of many important tasks that the skin must also perform. These issues, among others, are the focal point of this research study.

A survey of 177 design practitioners in 2007 indicated that the designers defined daylighting as “the interplay of natural light and building form to provide a visually stimulating, healthful and productive interior environment” while, engineers defined daylighting as “the use of fenestration systems and responsive electric lighting controls to reduce overall building energy requirements (heating, cooling, lighting)” (Galaisi & Reinhart, 2007). This study seeks to show that providing adequate daylight, creating a visually stimulating and healthful interior environment, as well as reducing overall energy consumption of buildings can be achieved by incorporating a well-designed and performative building skin.

With new complex building forms gaining popularity, semi-standardized shading devices such as louvers or overhangs are often disregarded due to the difficulty of integration of these forms with highly articulated contemporary building design. This poses the question: Is it possible to design an ornamental building skin that is simultaneously a performative shading device that also provides acceptable views to the outside?
METHODOLOGY

To integrate all aspects of architectural design, a comprehensive methodology is required to consider how a building looks and works; how it sustains the physical comfort of its occupants; how it fits within its context and climate; and what the design signifies to its occupants and community. Due to the hypothetical environment of this research study, only local climate and the formal language of design have been evaluated in detail.

Case Study: Intercircles

To understand the limitations and possibilities of transforming an ornamental design into a functional one, the Intercircles project by Erwin Hauer was chosen as a case study (Figure 1). Erwin Hauer is best known for his multivalent geometric architectural screens, developed between 1950 and 1959, inspired by the concept of infinity and continuous surfaces. This study sought to analyze this particular screen through a process of experimentation and parametric modulation. The typology was developed into novel mutations that maintained the aesthetics and language of the original prototype while proposing new performative functions. Intercircles allowed for the opportunity to explore the possibilities of modulating the screen walls to optimize porosity to control the quality and quantity of daylight transmission. Through this exploration, a system of units were developed whose geometric distortions produce varying degrees of porosity, and therefore daylight transmission.

Creation of Units: By closely examining Hauer’s complex screen, its pattern was reconstructed geometrically through the manipulation of different sized circles. The module consists of four smaller circles rotated along the Z-axis, which are placed around the perimeter of a larger circle (Figure 2). The unit module was created by constructing 1/8 of the surface and then mirroring and reflecting it 8 times around its edges (Figure 3). Each module was mirrored along its edge to create a larger screen (Figure 4).

The initial exploration of the geometry was executed in the Rhinoceros CAD environment. Rhinoceros (Rhino) is a stand-alone, commercial NURBS-based 3-D modeling tool, developed by Robert McNeel and Associates (McNeel, 2010). The realization of multiple parameters that control the surface geometry – such as the size of the circles, rotation of the circles, the placement of the smaller circles in relation to the bigger circle, etc. – required the geometry to be constructed in Grasshopper as a means to control each variable parametrically. Grasshopper is a graphical algorithm plug-in for Rhino which allows for parametric modeling and scripting (McNeel, 2010).

Although multiple parameters exist that control and vary the geometry, two were chosen for further exploration that affect aperture size and module depth. To understand their effect both on the geometry and their performance as measured by radiation control and available daylight, the size and
the rotation of the smaller circles were manipulated, as illustrated in Figure 5. To understand the modules' effectiveness as a shading device, the next step was to study how the variations would strategically respond to specific environmental conditions.

Environmental Conditions
A building's skin must respond to the particular environmental conditions of its location. For purposes of this case study, Boston, MA (42.3° N, 71.1° W) was chosen as the testing environment. The Boston-Logan Intl AP 725090 (TMY3) weather file was used for the lighting and energy simulations. A south facing, double glazed, open-plan office space was assumed as the test space. The test space measured 15'-0" (4.5 m) wide, 35'-0" (10.6 m) deep, by 15'-0" (4.5 m) high, and was assumed to have occupied hours from 8 AM to 5 PM. In studying the internal gains of an open office space modeled in DesignBuilder V4[2], a shading device is necessary to block most of the unwanted radiation, preferably from early-May to late-October (Figure 6) while maintaining a desired luminance level of 500 lux, recommended by IESNA (IESNA, 2000).

Changing the Parameters
The two chosen parameters produced 42 different module variations (Figure 7). However, not all 42 iterations were viable for further exploration. The elimination process considered isolating conditions of vectors extending beyond the given boundary, irregular surface behavior, as well as geometrically closed module apertures obstructing occupant views. Out of the 42 variations, 10 modules were selected for further exploration under the following three performance criteria: view, control of radiation, and interior illuminance levels (Figure 8).

View: View is defined here as the ability to have a visual connection to the outside. The visual field from a location in the room that is not entirely impinged upon by solid objects.

Due to angle rotation, each module provided different viewing conditions. Shallow angles provided a frontal direct view, whereas larger angles provided a more slanted indirect view (Figure 9).

Control of Radiation: To understand the behavior of each unit, all 10 modules were analyzed for radiation penetration through module apertures, using a gridded nodal surface placed directly behind each module in a south facing test space within the simulation environment. This simulation was performed using the DIVA plugin for the Rhinoceros CAD environment as a means to depict levels of radiation. The DIVA plug-in supports a series of performance evaluations by using validated tools including Radiance and Daysim (Reinhart, Jakubiec, Lagios, & Niemasz, 2011). DIVA was chosen so that all modeling and daylighting simulations could be carried out within Rhino.

The radiation level of the test surface within the test space without the screen over the entire year was measure at 847 kWh/m². Across all 10 modules, radiation levels within the test space over the entire year ranged from 299-507 kWh/m². This study produced data for total radiation levels as well as...
Daylight Penetration: To further understand the available daylight in the test space, Daylight Autonomy (DA), was measured by calculating the ‘climate based metric’ in DIVA, which uses Daysim for the back-end calculation. DA is defined as the “percentage of the occupied hours of the year where a minimum illuminance threshold is met by daylight alone (Reinhart & Walkenhorst, 2001).” Climate-based metric is the prediction of various radiant or luminous quantities using sun and sky conditions derived from standard meteorological datasets; the results are dependent both on the locale and the building orientation, in addition to the building’s composition and configuration (Mardaljevic, 2009).

The DA calculation measured the amount of daylight that penetrated each unit module falling on a horizontal surface which was placed directly behind the south facing screen at desk level (Figure 11). This exercise showed how module depth had a direct correlation to light quantities on the node surface. Shallow modules resulting from low angles of rotation allowed significant amounts of light close to the aperture, whereas the deeper modules with higher angles of rotation allowed deeper penetration of light into the room. These modules effectively acted as a light shelf. Therefore, to achieve adequate daylight penetration into the space, the modules required a minimum depth compared to the baseline design. Thus, the results of lighting levels were more successful through rotational variations as means to create a necessary depth, rather than through aperture size variation.

Choosing the Appropriate Modules

The goal of this research was to design and test an ornamental shading system that would both control the radiation and light levels and allow the inhabitants to have a view to the outside. The modules with the highest degrees of rotation allowed for deepest penetration of light into the space by redirecting daylight, as well as blocking undesirable
radiation during summer months. However, due to their depth, these modules obstructed views when standing close to the wall. Moreover, the modules may catch direct reflections from the sun causing glare. Therefore, it was necessary to place the deeper modules above six feet above finish floor (AFF) to minimize glare and maximize light penetration into the space. The modules with low angles of rotation performed similarly to a thin screen, and were ideal for maximizing views while maintaining a level of daylight control. The aperture sizes were homogenous which allowed for the eye to focus beyond the screen plane allowing for a uniform view out, and therefore were better options for the lower part of the screen wall (Figure 13).

Looking at the original picture of “Intercircles,” the circles appear to have a low rotational angle. If the entire screen consists of all low angles of rotation then there are no surfaces to redirect and reflect light deeper into the space. However, when the screen is a hybrid mix of modules – where the modules gradually deepen towards the ceiling, the space receives approximately 500 lux 100 percent of the occupancy time in a year (Figure 14).

![Figure 13](image1.png) **Figure 13** This image illustrates the benefit of the Hybrid Screen redirecting the light, as well as providing views to the outside

Daylight Calculation of the Screen

To understand the performance of the Ornamental Hybrid Screen, the 15’x35’x15’ (4.5 mx10.6 mx4.5 m) test space was equipped with four variants of south façade glazing: First, a 30 percent Window-to-Wall Ratio (WWR) was created with a single opening. Because daylight penetrates deeper into the space if openings are positioned closer to the ceiling, a second variant was created with a 30 percent WWR aperture evenly split into two openings – a clerestory aperture near the ceiling for light penetration, and a second centered on the wall as a vision window. Third, 100 percent glazed south façade was shaded by the test screen, and compared to a space with the fourth variant; an un-shaded 100 percent glazed south façade (Figure 15).

![Figure 14](image2.png) **Figure 14** (a) DA of the test space shaded with shallow modules, (b) DA of the same space shaded with the Ornamental Hybrid Screen

![Energy Calculation of the Screen](image3.png)

**Energy Calculation of the Screen**

Balancing useful daylight with harmful heat gain is critical in the design of appropriate shading devices, as the energy demand of a building is greatly influenced by solar radiation levels through apertures. Through comparative analysis, this research study sought to understand how to incorporate these criteria into the design process, to test the Ornamental Hybrid Screen’s ability to mitigate solar heat gain against the other three variants described above. However, simulating energy behavior of the test space posed a problem: the limits of digital construction for the screen in energy simulation software such as Design Builder and EnergyPlus. Directly creating a complex surface geometry is infeasible using the current energy simulation tools. In order to model the effect of the Ornamental Hybrid Screen on the energy consumption of the space, specific performance criteria of the Screen had to be measured using DIVA, including the screen’s shading coefficient and a yearly electric lighting schedule based on DA. The results were then synchronized with a thermal analysis performed in Design Builder linked with Energy Plus (Reinhart, 2010).

The shading performance of the screen was simulated with DIVA/Daysim every hour over the year by placing a vertical test surface directly behind the screen. In this study it was assumed that the occupants had the ability to open the screen (designed similar to a hinged shutter) in the winter months (preferably from November to April). The simulation measured light falling on the test surface with and without the screen as a shading device. The ratio of both values resulted in an hourly shading coefficient of the Ornamental Hybrid Screen (Figure...
To accurately measure the electric lighting demand of the test space, four sensors were located on the mid-line of the room in a linear fashion spaced 9'-0" (2.7 m) apart, 2'6"(0.8 m) AFF (Figure 17). The sensors were place in the occupant work area, starting approximately 8'-0" from the glazing. To optimize the work environment, the initial 8'-0" (2.4 m) buffer zone is designed for circulation and other non-task related programming to avoid shadows being cast on computers and work surfaces. Each sensor’s data generated by DIVA/Daysim was averaged to make an electric lighting schedule for the year.

For the thermal simulations, a second model was created in Design Builder and loaded with the analysis results listed above. The model was tested with the aforementioned Boston-Logan weather file, with a southern orientation, and exported as an IDF file for further analysis into Energy Plus. All thermal simulations were set up in DesignBuilder V4 [2] and run using EnergyPlus version 6.0 [0]. It was assumed that the space was bordered on five sides by analogous spaces. As a consequence, interior walls, floor and the ceiling were modeled as adiabatic surfaces. The exterior wall has a U value of 0.044 Btu/h-ft²-F (0.25 W/m²-K). Heating and cooling set points and setbacks were 20°C/15°C, and 23°C/26°C, respectively. The glazing was modeled as a double pane glass with Low-E coating and has a U value of 0.317 Btu/h-ft²-F (1.79 W/m²-K). The occupancy, lighting energy and the office equipment loads were 0.11 people/m², 25.0 W/m², and 10.8 W/m² respectively. The minimum fresh air requirements were set to 10.0 l/s-person. The photocell controlled dimming was also enabled. All thermal simulations were modeled in Design Builder and run using Energy Plus.

Consistent with prior tests, the Energy Plus simulation was measured four times: first with 30 percent WWR; second with 30 percent split WWR; third with 100 percent WWR shaded by the Ornamental Hybrid Screen; and lastly with 100 percent WWR without any shading device.

RESULTS

Daylight Autonomy: the 30 percent WWR received 24 percent DA, the 30 percent WWR Split received 26 percent DA, the Ornamental Hybrid Screen received 60 percent DA, and the 100 percent WWR received 71 percent DA (Figure 17). According to these results, the DA of the screened space is significantly higher than the 30% WWR spaces, almost as high as that of the un-shaded 100% WWR space.

Based on these results, electric lighting use would be the highest in all zones of the 30 percent WWR spaces due to lower levels of natural daylight, especially farther back in the space. Figure 18 illustrates the anticipated electric lighting energy use of each space.

After importing the DIVA/Daysim results into Design Builder, the energy simulation performed in Energy Plus revealed that the cooling energy consumption is the lowest in the space with the Ornamental Hybrid Screen. This was due to both the screen’s ability to block the undesirable radiation during summer months, and to the reduction of electric lighting needed throughout the year (Figure19).
To understand the overall energy consumption, the sum of energy requirements for lighting, cooling and heating were calculated for each scenario (Bourgeois, Reinhart, and Macdonald 2006). To analyze the total source energy use of each scenario, it was assumed that the test space used natural gas for heating and grid-purchased electricity for cooling and lighting. The EPA source-site ratio of 1.047 and 3.34 were used to calculate the total source energy use of each scenario (EPA, 2011). In this study, an assumed overall cooling coefficient of performance (CoP) of 3 and heating efficiency of 0.85 percent were used to convert space heating and cooling load into site electrical and natural gas energy consumption. Source-site ratios where then used to convert the site electrical consumption for lighting and cooling and gas consumption for heating into source energy.

The screened space consumed approximately 35 percent less source energy compared to the space with 30 percent WWR, and approximately 42 percent less source energy compared to the space with 100 percent WWR (Figure 20).

DISCUSSION

By studying the results of the simulation and testing, it was concluded that the Ornamental Hybrid Screen consisting of shallow and deep unit modules resulted in the most desirable lighting conditions. Although the solution was the best design in terms of performance, it was imperative to understand the constructability of the screen to understand economic feasibility. To construct the screen, a method for connecting multiple modules with different rotation angles was needed. This was solved by creating intermediate units that mediated between the changing angled modules (Figure 21).

There are numerous ways of constructing the unit modules in physical space. Two means of construction were chosen for testing: casting and robotic milling. Casting is a relatively simple and economically feasible process. Due to the complexity of the surface geometry, a two-part mold made of rubber (Smooth-On Oomoo-30) was constructed for ¼ of the surface geometry. Once the mold was created from 3d printed prototype, multiple unit modules were produced out of high density liquid plastic (Smooth-On smooth-Cast 300Q) in less than 20 minutes per piece (Figure 22).

The second method of construction explored the use of a 5-axis robotic arm with subtractive milling. The module was modeled in Mastercam software and cut from high-density foam (Figure 23).
In the author's opinion, a minimum of two different unit modules and a maximum of four different modules are needed to achieve desired lighting and energy results preferred in typical office buildings. The added complexity of multiple module variants is worth the extra effort, when it results in a better daylight space with lower energy use.

Clearly, additional research and design process would be required to understand screen performance on non-south facing façades, as well as to effectively deploy this screen on a building at scale, including issues of maintenance, relationship to glazing and structure.

**CONCLUSION**

The proliferation of digital tools has allowed architects powerful freedom to envision novel complex geometries, but too often at the expense of climatic performance measures. In light of this growing problem, this research project illustrates the potential for the contemporary design processes to fundamentally integrate building performance simulation with the architectural design process. As proved here, a building's shading device can be both a complex geometry that satisfies the immaterial aesthetic desires for ornament, while also fundamentally addressing building performance and interior user comfort.

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**REFERENCES**


