Building Envelope:
Performance optimisation processes for a daylight responsive architecture

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ABSTRACT: Traditional shading design principles guide the vertical and horizontal orientation of fins, louvres and awnings being applied to orthogonal planar façades. Due to doubly curved envelopes characterising many contemporary designs, these rules of thumb are now not always applicable. Operable blinds attempt to regulate the fluctuating luminance of daylight and aid in shading direct sunlight. Mostly they remain closed, as workers are commonly too preoccupied to continually adjust them so a reliance on electrically powered lights remains a preference. To remedy these problems, the idea of what it is to sustainable enclose space is reconsidered through the geometric and kinetic optimisation of a parametric skin, with sunlight responsive modules that regulate interior light levels. This research concludes with an optimised design and also defines some unique metrics to gauge the design’s performance in terms of, the amount of exterior unobstructed view, its ability to shade direct sunlight and, its daylight glare probability.

Keywords: Daylight, Glare, Simulation, Radiance, Parametric Design

INTRODUCTION
The necessity to utilise natural light in the interior of buildings is strongly supported by numerous health benefits, energy saving and environmental factors [1]. Traditional design principals guide the vertical and horizontal orientation of shading devices for buildings with east, west and equatorial façades [2]. However there is little research that contributes to the knowledge of shading systems suited to contemporary architecture, characterised by double curved surfaces. A research through design process and state of the art software is utilised to model and simulate the performance of a daylight responsive skin suited to hot climate double curved façades. The system being optimised is an operable envelope, which regulates the amount of light transmitted from the exterior to the interior of the building over the course of the day.

Findings from the research conclusively support the performance of the two resultant designs and also give an insight to the characteristics associated with shading devices suited to double curved façades. The methodology developed, establishes unique metrics for performance measurements. The process consists of an evidence-based approach to design evolution, where each iterative design decision responds to the findings from the former measured results. The skin system is parametrically modelled to simulate the automated response the independently moving panels have to the changing daylight conditions over the course of a day. An initial design is tested through computational simulations, to evaluate its performance and to gain an understanding of where improvement can be made.

METHOD
Interior and Workplace Lighting standards state, commercial lighting levels should be 160 Lux for background environments and 320 Lux for task lighting [3]. Therefore the aim of the skin system is to regulate the internal mean natural light levels at 240 Lux over the course of the day, which is the midpoint between these two lighting levels. Further to this, the system being designed also needs to be suitable for a surface that has a double curvature so that it is a feasible resolution to the issues associated with shading organic building façades. An operable panel system has been devised as the most appropriate design response due to its ability to shade whilst maintaining an external view.

Five iterations of the design are generated sequentially through performance analysis, via the computational simulation. Both summer and winter solstices are selected as simulation days to test the full range in sun altitudes. Analyses are performed at seven hourly increments between 9am and 3pm to evaluate the system’s performance over the course of the day. In total, five design iterations are tested, resulting in 210 calculations. This number is compounded by the kinetic function of the individually responsive panels. The complexities in modelling this system are most clearly represented through quantifying the amount of panel
angle variations. For example the third, fourth and fifth skin iterations consist of modules containing four individually moving panels. As these modules are arrayed 300 times over the testing surface, the complete skin consists of 1,200 individually responsive panels. To simulate a design at the 7 hourly increments over the two solstices, the system requires the control of over 16,000 individual panel angle variations.

**Parametric Automation**

Due to this degree of complexity, an approach that automates the movement of the skin’s response to the sun’s position is required. Parametric software is utilised to produce an algorithm that controls the response each individual panel has to the sun’s changing position in the sky, over the course of the day. As well as controlling this movement, the algorithm also simultaneously measures the performance of the design. The package used to create these parameters is Grasshopper, which is a graphical algorithm editor, that is tightly integrated with McNeel’s Rhinoceros 3D. The algorithm gives the designer a highly refined degree of control over the system. The 1,200 individual panel’s sensitivity to sunlight can be fine-tuned with the adjustment of a numerical value, to achieve the desired internal lighting levels. This tuning process occurs through utilising Radiance illuminance simulations as a direct feedback loop, in order to achieve the desired interior mean Lux of 240.

The algorithm developed for this research utilises a node that moves along a curve in the modelling environment, which has an associative relationship to the rotation of the skin’s panels. As the curve in space is defined as a sun path, with an equatorial orientation, the node traveling this path simulates the movement of the sun. Additionally Geco components for Grasshopper are utilised to create a live link between McNeel’s Rhinoceros 3D and Autodesk’s Ecotect to define the sun path. These components are supplementary plugins for Grasshopper, developed by Ursula Frick and Thomas Grabner, the directors of UTO at the University of Innsbruck [4]. To measure the performance of the daylight responsive system, three metrics have been defined. Existing methods sourced from the literature have been adapted specifically to suit the performance measurement of this daylight responsive system. A pavilion is modelled as a testing space to simulate how the five module options perform, arrayed over the double curved façade. Specific material surface reflectivity is assigned to the various elements of the pavilion (Table 1).

<table>
<thead>
<tr>
<th>Substrate Surface</th>
<th>Reflectivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceiling</td>
<td>80%</td>
</tr>
<tr>
<td>Floor</td>
<td>20%</td>
</tr>
<tr>
<td>Walls</td>
<td>50%</td>
</tr>
<tr>
<td>Skin Panels</td>
<td>35%</td>
</tr>
</tbody>
</table>

**Area of External View**

Studies by Hartig et al. show that having access to an external view has been an associative factor of good health and well-being [5]. Therefore the ability for the skin to achieve a high degree of external view is a vitally important aspect in understanding the design’s performance. To derive the most appropriate method for determining the amount of external views, an occupant would receive, research on window to wall ratios by Xing Su et al. is investigated [6]. Due to the double curvature of the pavilion’s façade, a flattening process is required to measure the area of external unobstructed view. Planar area calculations are performed on the elevated projections of the skin, which are represented as a percentage that correlates to the amount of unobstructed view received by the occupant (Figure 1).

**Direct Sunlight Shading**

It is commonly known that in hot climates it is desirable to avoid direct sunlight entering an internal space as it increases the building’s heat gain, meaning it is more reliant on cooling systems [7]. Therefore the ability for the skin to shade the space is a vitally important aspect in understanding the design’s performance. In order to measure this performance, area calculations are again conducted utilising an additional projection method. To simulate the shadows generated from the skin, an outline of its geometry is projected onto the internal floor at a vector direction based on the sun’s rays at the given testing time. Following this, area calculations of the floor and projected geometry are...
performed to generate a percentage of the amount of floor area illuminated by direct sunlight (Figure 2).

**Daylight Glare Probability**

Glare is a subjective condition that is experienced by a high contrast in light, which can cause irritation, fatigue and headaches [8]. Therefore the skin system’s ability to reduce the glare perceived by building occupants is also of vital importance. Jan Weinold and Jens Christoffersen at the Fraunhofer Institute for Solar Energy Systems devised a new method for analysing glare, known as Daylight Glare Probability (DGP) [9]. DGP is able to gather data on the complexities of glare as the method computes the directional properties associated with light. To analyse the DGP a virtual camera with a 180 degree fish eye lens is positioned inside the pavilion 1700mm from the ground, to replicate an occupants perspective (Figure 3).

From this camera location a simulation takes place, using Evalglare, a programme that uses the DGP algorithm to compute the probability of glare. Evalglare also produces a High Dynamic Range image, which serves as an instrument to visually determine the location of the glare source (Figure 4).

The results from DGP are represented as a percentage, which can be categorised using the index depicted in the table below (Table 2).

<table>
<thead>
<tr>
<th>DGP Rating</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imperceptible</td>
<td>30%</td>
<td>34%</td>
</tr>
<tr>
<td>Perceptible</td>
<td>35%</td>
<td>49%</td>
</tr>
<tr>
<td>Disturbing</td>
<td>40%</td>
<td>44%</td>
</tr>
<tr>
<td>Intolerable</td>
<td>45%</td>
<td>60%</td>
</tr>
</tbody>
</table>

**RESULTS**

The following section of the paper displays elevations of the five iterative skin types. Graphs illustrate the performance results of each of the iterations according to the three performance metrics. The reasons for each of the sequential design iterations in the optimisations process are also discussed. The following five skin systems are successful in maintaining a mean interior Lux of 240 over the course of the day, for both summer and winter solstices.
Figure 5: Skin Type 'x' Option One

Figure 6: Skin Type 'x' Option Two

Figure 7: Skin Type 'y' Option Three

Figure 8: Skin Type 'y' Option Four

Figure 9: Skin Type 'z' Option Five
Skin Type ‘x’ Option One
This first option’s design consists of quadrilateral modules with and average size of 350mm by 350mm (Figure 5). These panels pivot on their upper edge meaning they are asymmetrical in their pivot function. The results show that as the skin regulates a mean internal Lux of 240, the area of external view reduces during the middle of the day. The graphs show a large trough in performance, for both summer and winter with a maximum area of external view of 38% in winter at 3pm and a minimum of 10% in summer at 12pm. The maximum direct sunlight that enters the space is 2% occurring at 3pm in winter, with a minimum of 1% occurring at 11am in summer. Additionally DGP increases during the middle of the day for summer with a maximum of 31% occurring in between 11am and 12pm, while conversely it decreases during the middle of the day for winter with a minimum of 23% at 12pm. The aim for the next iteration is to reduce the trough in performance of area of external view, for the middle of the day.

Skin Type ‘x’ Option Two
For this option the quadrilateral modules have been increased in length by 1.8 times (Figure 6). This iteration achieves a maximum area of external view of 35% at 3pm in summer and a minimum of 8% at 12pm in summer. This increase in panel length has flattened the performance trough in its area of external view over the course of the day. However, the results show that this trough has been flattened not by an overall increase in view, but by decreasing the amount of view at the beginning and end of the day. The maximum direct sunlight that enters the space occurs again at 3pm in winter, with 4% and the minimum occurring at 12pm in summer, with no direct sunlight entering the space. This iteration successfully reduces the amount of DGP, with a maximum of 30% occurring at 12pm in summer and a minimum of 22% occurring between 11am and 12pm in winter. The next skin iteration implements a new type of panel system.

Skin Type ‘y’ Option Three
This third system’s modules have each been subdivided into four right angle triangles that pivot symmetrically on the modules outer edges (Figure 7). The new category of Type ‘y’ has been established, due to the significance of the change in design. This new type has a less drastic trough, in the area of external view over the course of both summer and winter solstice days. Although its maximum area of external view is not as high as the previous iteration, with a maximum of 23% occurring at 3pm in winter, there is an increase in minimum with 10% occurring at 12pm in summer. The maximum direct sunlight that enters the space occurs again at 3pm winter with 4% and the minimum occurring again at 12pm in summer with 1% direct sunlight entering the space. Additionally the DGP has been reduced, with a maximum of 29% occurring at 12pm in summer and a minimum of 21% occurring between 11am and 12pm in winter. The aim for the next skin iteration is to improve the area of external view.

Skin Type ‘y’ Option Four
With this iteration, the triangular shaped modules have been raised at the centre to from pyramids that project from the façade when in the closed state (Figure 8). This iteration performs as it aims to, as it improves the area of external view with a maximum of 25% occurring at 3pm in summer and a minimum 8% occurring also in 12pm summer. It has been discovered that this increase in view has been achieved due to self-shading caused by this skin’s undulation. One unexpected outcome of this iteration is its ability to reduce the amount of direct sunlight entering the space with a maximum occurring again at 3pm in winter, with 3% and a minimum of no direct sunlight entering the space at 3pm in summer. An unfortunate side effect linked with the increase in area of external view is an increase in DGP, with a maximum of 30% occurring at 12pm in summer and a minimum of 23% occurring at 11am in winter. The aim for the next iteration is to reduce the amount of DGP.

Skin Type ‘z’ Option Five
This iteration is based on the previous type with pyramidal shaped modules. However a surface curvature has been incorporated into the panels of this design (Figure 9). The new category of Type ‘z’ has been established, due to the significance of the change in design. Unfortunately this design has reduced the amount of external view with a maximum of 17% occurring at 3pm in summer and a minimum of 9% occurring at 12pm, also in summer. The maximum direct sunlight that enters the space is 7% occurring at 3pm in summer, with a minimum of 1% direct sunlight entering the space at 10am in also summer. As glare can be caused by a high contrast in light, the aim of the curvature in the panel system is to reduce DGP, through a gradient of light reflectance, caused by the varying degrees of incident angles. Unfortunately the curvature is not successful in reducing glare, with a maximum DGP of 33% occurring between 11am and 1pm in summer and a minimum of DGP of 23% occurring at 11am in winter.

**DISCUSSION**
This section compares the five skin options against each performance criteria, as a means to generate discussion and draw conclusions associated with the design changes.
Area of External View

Option One offers its occupants the most consistent amount of external view over the course of the solstice days, with an average of 22% in summer and an average of 30% in winter. Over the course of the solstice days, Option Five is the worst performer, with an average of 14% in summer and an average of 12% in winter.

Direct Sunlight

From the five design iterations, all offer the space a high degree of shading, allowing very little direct sunlight to enter the space. Option Four performs the best out of the five options, in terms of its ability to shade direct sunlight. In summer, it allows an average of 0.5% of direct sunlight into the space. Conversely in winter, it shades the space from an average of 1% of direct sunlight over the course of day. Option Five is the worst performer, shading the space from an average of 2% in summer and an average of 2% in winter.

Daylight Glare Probability

All of the five iterations in a worse case scenario achieve a DGP, which is lower than what is classified in imperceptible in Table Two. However, there is still a degree of variation in the performance of the iterations. Option Three, offers the lowest average of DGP over the course of the solstice days. In summer, Option Three has an average DPG of 27% and average of 22% occurring in winter. Conversely Option Five has the worst average performance in terms of DGP. Option Five, has an average of 32% in summer and an average of 25% in winter.

CONCLUSION

By utilising a research through process, this paper contributes knowledge of shading systems suited architecture characterised by double curved surfaces. In conclusion, Skins Type ‘x’ which are quadrilateral in shape, are most appropriate for vertical applications as they pivot from their top edge. Conversely, Skins Type ‘y’ and ‘z’ are suitable for both vertical and horizontal applications as their modules are symmetrical pivot function. Additionally it is noted that the difference in pivot function between Skins Type ‘x’ and Skins Type ‘y’ and ‘z’, results in a change in trend for their area of external view.

Skins Type ‘x’ provides the highest average area of external views, with the largest range in performance over the course of both summer and winter solstice days. Conversely Skins Type ‘y’ and ‘z’ do not provide as much area of external view in the morning and afternoon but provide more consistency over the course of the day. As Skins Type ‘x’ provides the highest performance in views in the morning and afternoon, it is recommended that this type would be most suitable for a buildings typology such as housing. The consistency in performance of Skins Type ‘y’ and ‘z’ suggests that they are most appropriate for a building typology such as an office, which is occupied during these times.

The reason for this differentiation in trend between performances, in access to view comes back to the notion of geometrical function. This is best explained in traditional terms as, Skins Type ‘y’ and ‘z’ open, they function as both a vertical and horizontal shading system. This is due to the fact that they create a three dimensional projection from the façade. Alternatively, Skins Type ‘x’, when in their open position, only functions as horizontal shading systems as they can only create a two dimensional projection from the façade. This also explains their high degree of view variance. As they are limited in their capacity to self-shade, their only response to direct sunlight is to radically shift towards their closed state, decreasing the external view.

This process is successful as it develops two optimised skin types for double curved façades of buildings situated in hot climates. Skin Type ‘x’ Option One and Skin Type ‘Y’ Option Three have the highest overall performance for each from the three types. The two types are suitable for different building typologies, with Skin Type ‘y’ Option Three being the highest overall performer. This research also develops a unique set of metrics and a parametric algorithm that controls the complexities of the system as it responds to the sun’s changing position. These metrics and algorithm may serve as a valuable instrument for future research in furthering the development of daylight responsive systems in architecture.

REFERENCE