

# Intelligent Skins: Daylight harvesting through dynamic light-deflection in office spaces

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## ABSTRACT:

The building envelope is the critical interface between the occupants and the outdoors. This surface has the ability to be interactive; it can incorporate intelligent features, activated by sensors that respond in real time to a change in environmental conditions. A kinetic façade could use simple movements of louvers, complex transformable panels, or even variable material characteristics such as transparency or reflectivity that react to stimuli.

Daylight harvesting is one area where a kinetic façade can be used to help achieve lower energy consumption in office buildings while also mitigating some of the negative impacts of introducing natural lighting into a building including uneven distribution of day lighting, illumination levels above or below the recommended range, and excessive heat gain affecting thermal comfort. This paper provides a brief insight on the primary author's current thesis work regarding light-deflection techniques. It explains the objectives of the research work and documents simulation runs for the first phase of performance analysis including initial modelling and analysis of a parametric panel system. Although these initial studies focus on relatively simple geometries, it is intended that the method of analysis will be applied to increasingly complex forms to demonstrate that a kinetic façade system can be both aesthetically compatible to complex geometries and contribute to better energy performance of a building.

The study focuses on investigating the effectiveness of light deflection in dynamic secondary skin layer in terms of daylighting performance, quality and quantity, in south-facing indoor spaces using a set of performance criteria. A simple example was developed and simulations run to see if the performance criteria could be achieved using Rhino as a modelling tool, Grasshopper as a parametric interface, DIVA for daylight evaluation, and Galapagos for problem solving.

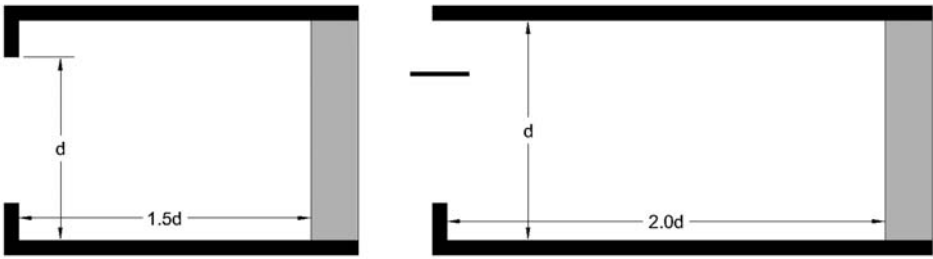
The authors hypothesize that the integration of light deflection techniques in an intelligent dynamic panel system allows for the enhancement of daylight harvesting, quantity and quality, inside south-facing spaces.

**KEYWORDS:** kinetic façade, daylight harvesting, interactive architecture, intelligent skin, building envelope

## INTRODUCTION

In the United States, lighting accounts for almost 30%-25% of total electrical energy use and in the commercial sector up to 37% (Phillips 2004, 38). Electric lighting also has an indirect effect on cooling loads in spaces, and as a rule of thumb, each unit of electric light requires an additional one-half unit of electricity for space conditioning. Lighting efficiency, in terms of less electrical consumption in buildings, can be improved by simply using less artificial light and taking advantage of available natural light. This is an obvious statement, but ironically, although the use of glass in office buildings has become an iconic element in the architecture profession, interior lighting has not always improved.

Typically, the daylight depth in a room with an untreated opening is about one and a half times the distance from the window head to the floor (O'Connor 1997). A typical window head is at 2.20m, which results in a 3.30m room depth of daylight area, given the previous ratio (figure 1). One method that allows for better daylighting efficiency is redirecting light either into or out of the space, commonly referred to as light-deflection. Often the primary use of these devices was to block daylight from entering the interior space. Light deflectors block light by re-directing it away from the occupants' line of sight, protecting inhabitants from glare and heat gain from direct sunlight. Light shelves and other techniques can be used for both light deflection and daylight harvesting. Using the example in figure 1, light deflection techniques, such as light shelves, can increase the penetration ratio up to twice as much, giving a larger room depth of 4.40m with daylight.



**Figure 1:** The figure on the left shows the depth of daylight in case of untreated window opening while the right figure shows the extended depth up to two times using light shelves.(O'Connor 1997)

The introduction of the light redirection technology can have a great impact on the performance of facades in optimizing daylighting. Light deflection devices have been proven to efficiently increase the performance of daylighting in interior spaces, by redirecting light deep into the space minimizing the undesirable effect of direct sunlight and the use of electric lighting. While these techniques have the same objective of increasing the amount of daylight in interior spaces, they are not suitable for every building. Daylight problems are mostly treated individually where system customization is sometimes required. The customization does not have to be major alteration of an existing technology, but could be a minor addition that makes the system fit within the design problem and context. These systems are usually referred to as passive daylight systems; they allow for better lighting inside the spaces while being static. While passive systems enhance the performance, they lack the flexibility of adapting to changing outdoor conditions. For example, light shelves are stationary, but the incident angle of sunlight is changing with the sun's path making the shelf effective on certain times and days and ineffective for the rest of the year or under different sky conditions. Given the limitation of passive systems, designers started adopting active control systems that led to introducing kinetic techniques in the profession.

The purpose of the daylight deflection, besides protection against glare, is to control the intensity, direction, and distribution of light. This can be achieved by controlling the amount of light penetrating through the building envelope and reflecting unnecessary light back to the outdoor environment. In his book, Koster mentions that the efficiency of daylight deflection system is directly related to these factors: the type of the deflector, physical properties of the deflector, location of the system in the building, and mounting position relative to the space (Koster 2004). He also discusses the main purpose of using light deflection techniques-- they should provide protection against solar heat and glare and control the supply of light, thereby improved indoor illumination. The advantage of light-deflection techniques over solar shading is the ability of working as a control layer and strengthening low daylighting levels, specifically at the back of a space.

"In practice, the shading systems are closed during periods of the largest solar gains (direct solar radiation), darkening the interior and resulting in a need for artificial lighting. This is a waste of energy that could be avoided, especially since the total electrical energy for lighting is transformed into heat that must be removed in summer by an energy-intensive interior cooling system." (Koster 2004, 80)

This statement addresses the need of exploiting light deflection and controlling light penetrating into the space. Instead of possessing one function, efficiency requires shading devices to minimize solar heat gain and control light by blocking it or bouncing it off appropriately into the spaces, without wasting free solar energy and consuming more electric light.

Architecture is experiencing a demand for responsive-based designs, where the occupants' comfort level is being achieved through the use of smart systems. Integrating light deflection techniques into an intelligent envelope system of the building is the main goal of this study. Intelligent features may add more control layers to a kinetic system by gathering data, interpreting its impact, and reacting appropriately to unforeseen circumstances, whether environmental or occupants' behaviour.

## OBJECTIVE

An optimum visual environment in office spaces through the use of daylight is crucial for employees' comfort, productivity, and morale (Dasgupta 2003). Visual comfort and potential energy efficiency is addressed through five main parameters: light level (illuminance), luminous distribution, glare, light penetration depth, and direct sunlight. An intelligent dynamic light-deflection system should provide daylight levels over a range of possible sky conditions (including clear, variable, and overcast), be within a recommended range, have an even distribution of daylight inside the space, and allow deep penetration of daylight beyond the typical one and half times or two times ratio explained earlier (O'Connor 1997). In the context of this study, the quality of light is defined as the acceptable luminous distribution of daylight on the working plane and the penetration of light for more than two times the window header height. The quantity of light is referred to as the illumination levels on the same working plane.

The objective of this tool is integrating daylighting performance into the early design stage of the project. While the main objective is providing a tool that simulates daylighting at different times and compiles an actuation scenario for a secondary skin, it can be used to find an optimal solution for a static louvers skin that enhances daylighting for as many days of the years. The tool is intended to enhance the process of designing kinetic facades that respond to daylighting and enhances the indoor luminous environment.

## METHODOLOGY

The study focuses on investigating the effectiveness of light deflection in a dynamic secondary skin layer in terms of daylighting performance, quality and quantity, in south-facing indoor spaces using the performance standards discussed earlier. The proposed approach involves exploring independently actuating louvers on a secondary skin layer in combined schemes. There are infinite possibilities of combined skin configuration for intelligent-kinetic louvers system; each louver may have its own tilt angle. Therefore, the best approach for this study is using parametric software that automatically generates as much possibilities as the designer desires.

A simple example was developed in search for indoor luminous conditions that fit performance criteria. This was done using Rhino as a modelling tool, Grasshopper as a parametric interface, DIVA for daylight evaluation, and Galapagos for problem solving.

*Rhino* (<http://www.rhino3d.com/>) is a 3d NURB-based modeling program. Until relatively recently, it has not been easily used in conjunction with simulation software. Now DIVA-for-Rhino supports a series of performance evaluations including links to Radiance, Daysim, and Evalglare (Rheinhardt et. al., 2010).

*Grasshopper* (<http://www.grasshopper3d.com/>) is a free, graphical algorithm editor tightly integrated with Rhino's 3d modeling tools. It is possible to integrate pseudo-environmental effects such as sun and wind to dynamically change form. Sun systems have also been developed for it to achieve accurate sun shadow simulations, and two-way connections to and from Ecotect have been demonstrated.

*DIVA* is a Rhino plugin for daylighting simulation. The plugin runs a commonly used simulation engine, RADIANCE, and it can be directly run from the Grasshopper interface through using a pre-built component provided through Harvard GSD (SD)2 website. This component allows data exchange between DIVA and Rhino, and uses Rhino as an interface for showing the results and the visualization. DIVA calculates illumination levels, daylight factors, glare, and provides visualizations in the form of calculation grid diagrams and renderings.

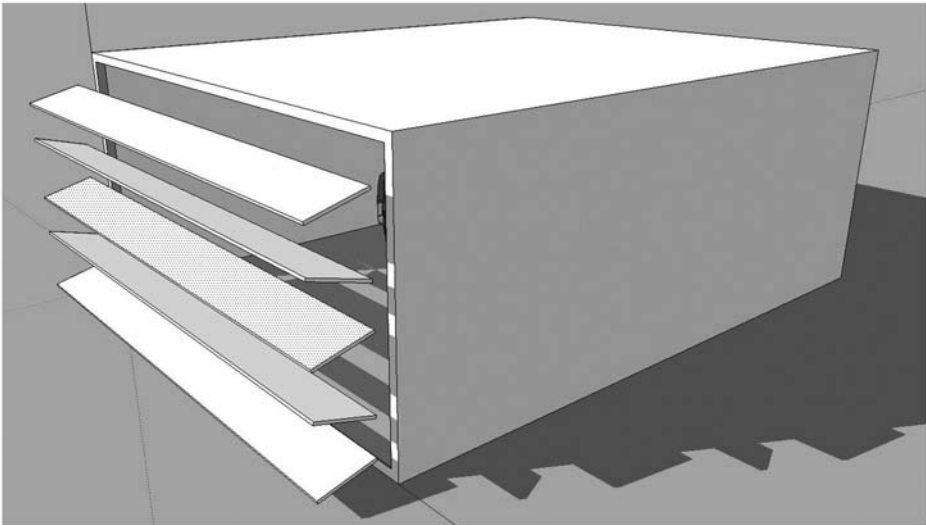
Adding to the efficacy of the experiment, a genetic algorithm has been incorporated into the definition to enable a search of the best skin configuration at specific dates and times, or under different sky conditions. A genetic algorithm works by searching for an optimal solution under certain parameters and conditions. For example, a single desired solution might be acceptable indoor illumination levels; parameters might include tilt, depth, and number of louvers; and given inputs could be latitude, sky condition, and time constraints. Changes in any of these parameters trigger the system to run and find an optimal configuration for the skin to maintain the desired luminous environment.

*Galapagos* is a genetic algorithm feature that is used for problem solving cases within Grasshopper. It creates an evolutionary generic loop that populates generations of possible solutions with random individuals based on the predefined criteria. The system couples similar possible solutions together and then finds a best fit solution which may end up being a locally optimal solution in some cases. *Galapagos* is intended to be used in this study to find the best possible tilt angles of the louvers' configuration for certain times of the day. However, *Galapagos* will be running off a pre-defined set of parameters, leaving only the calculation for this tool. For all simulations, data will be documented for June 21st (summer solstice), December 21st (winter solstice), and March 21st (equinox), each at 9:00 am, 12:00 pm, and 4:00 pm.

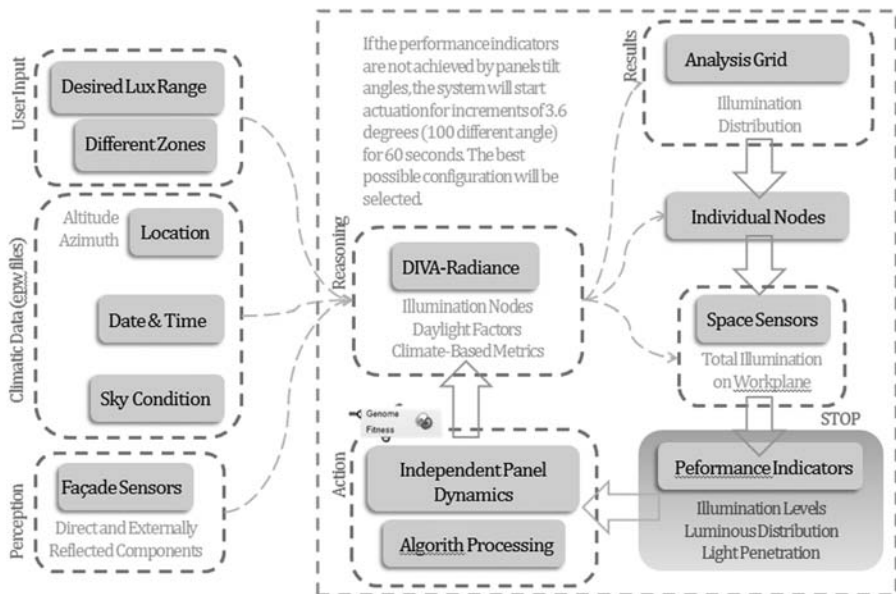
Integrating *Galapagos* and *DIVA* into one algorithm extends the capabilities of basic daylighting simulation by not just calculating a single answer to a set of givens, but trying to discover what set of parameters gives the "best" solution to the problem. Although the algorithm's objective is to search for an optimal solution, it does not necessarily find the best possible solution. It may present a solution that is found to be relatively better than others. *Galapagos* operation is single-numerical value dependent, which means the performance criteria should be translated to a single numerical value. For example, if the performance criteria require the sum of all nodes to be 1800 Lux as an average illuminance value, *Galapagos* will run to find solutions that give either a value close to 1800 or a value that is far away from this number. In our case study, a solution that maximizes the number to be close enough to the fitness numerical value is desired.

Although it is possible to create and test extremely complex geometry with these software tools, a very simple test case was established to verify that that method would actually work. As will be discussed later, problems did develop even with the base case. The simple base case is a series of louvers arranged horizontally above each other, divided into two sets each actuated independently. Figure 2 shows the combined configuration of the louvers where three louvers are in shading position, and the other two louvers are in a harvesting position to deflect light further into the interior space. This configuration is intended to spread light more evenly inside instead of concentrating the light in certain zones.

The interior space is divided into four different zones each with nine light sensors/calculation points. The sensors measure the illumination levels on the workplane and illustrates it graphically in the form of on-screen readings in Rhino viewports. *DIVA* also allows the user to extract the readings in the form of numerical values that can be used again in the simulation loop.



**Figure 2:** The figure shows the independent tilt angles of the exterior louvers.



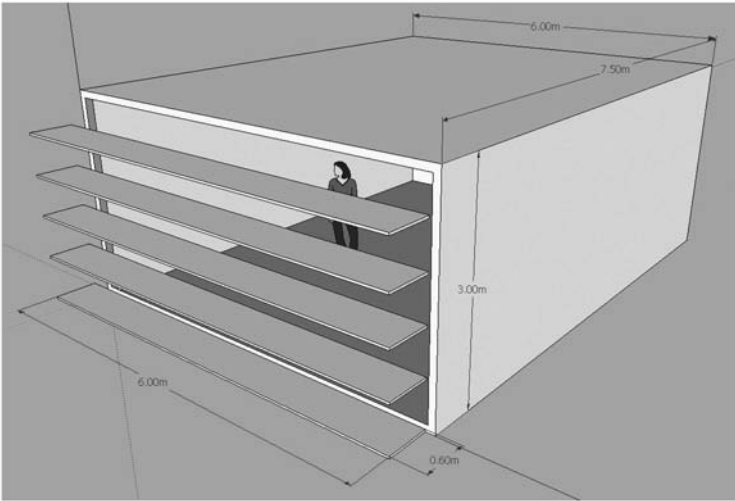
**Figure 3:** The figure shows the specification of the proposed system together with the data workflow.

The proposed system is intended to have three main inputs: user, climate, and sensors (figure 3). All inputs are processed through DIVA/Radiance, and then results are shown in the form of analysis grids. Using Grasshopper, readings are extracted separately and matched against the pre-defined acceptable conditions. If these readings match the acceptable ranges, the system will stop the calculation process. If they do not match the performance criteria, the system will repeat the calculation process until the best possible tilt angle is found. The panels have been set to rotate in increments of 3.6 degrees, one hundred possible angles.

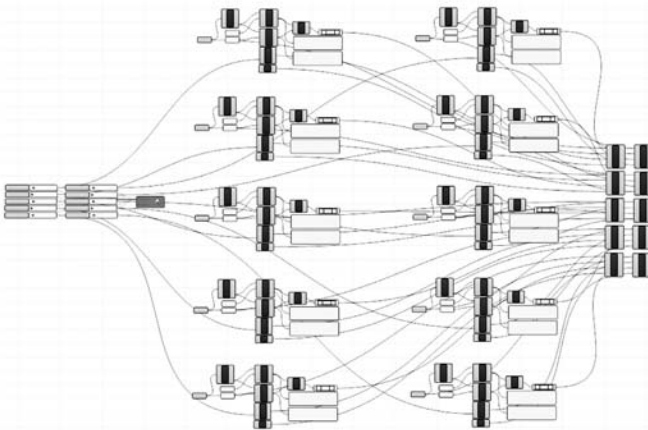
The DIVA definition in Grasshopper calculates and provides the sensors' illumination readings. If they go outside of the recommended range, it will order the panels to move in certain angle increments until a minimum of three of the zones fall within the recommended range. An angle increment is to be set for actuation as well as a maximum time for searching for the best tilt angle. For example, if the allowed maximum calculation time is 5 minutes, the five large panels will actuate to find the best angles that achieve the best illumination level inside the space. If this angle is not found in 5 minutes, the system will choose the best possible calculated configuration to bring illumination level closest to the recommendation.

## SIMULATION CRITERIA

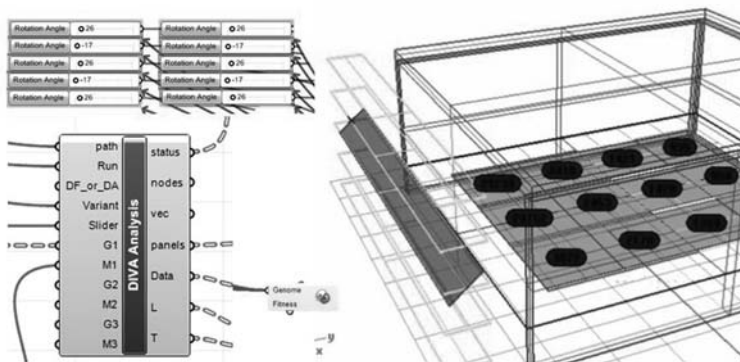
There are infinite possibilities of combined skin configuration for intelligent-kinetic louvers system since the proposed system depends on independent angle control, where each louver may have its own tilt angle. Therefore, the best approach for this study is using parametric software that automatically generates as much possibilities as the designer desires. In order to speed the process (and due to some software limitations that did not allow for the full range of tilt to be studied), it was decided not to adjust each louver at a specific tilt angle but to use some results from another study. In 2005, a MIT student explored the independent blind angle control for venetian blinds and its impact on ceiling illuminance. Using physical models, she was able to establish conclusions for light-reflection on the upper surface of venetian blinds. In her research, she presented three equations for three variables: incident angle, reflected angle, and blind tilt-angle. These equations are useful in determining the reflected angle, which consequently gives hints about where the light is going into the space. The tilt angles that McGuire used for testing were 26° & -17°, 52° & 41°, and 30° & 60° (McGuire 2005).



**Figure 4:** The figure shows the dimensions of the office space used in the simulation.



**Figure 5:** The figure shows part of the Grasshopper definition that illustrates the ten louvers with the angle sliders on the left hand side.



**Figure 6:** The figure shows the interior calculation grid/sensors with one of the louvers rotating to adjust the quality and quantity of the daylight inside the space.

The modelled space in Rhino has dimensions of 6m width, 7.5m depth, and fully-glazed height of 3.0m (figure 4). This office space has been divided into four main zones: two close to the window opening and two at the back of the space. The interior surfaces have been assigned reflectance of 80% for ceiling, 50% for walls, and 20% for floor. The secondary skin panels have reflectance of 90%. The opening has been assigned generic doubled glazed material with 72% visual transmittance. Because of its sunny weather and daylight availability, Los Angeles has been chosen to be the location of the test and this south-facing office space.

Initially, the louvers system has been divided into five main louver levels where each level has two louvers (figure 5 and figure 6). It is intended to control each of the ten louvers independently with different tilt angles. However, at this point of the study and for quick simulation runs, each two louvers on the same level are similarly treated with the same rotation angle.

The analysis method is dependent on three main qualities of daylighting: illuminance, luminous distribution, and light penetration.

## ILLUMINANCE

Different organizations recommend different light levels of illuminance for office spaces. The recommended illumination levels according to the Illuminating Engineering Society of North America (IESNA) for a typical office space is 200-500 lux (IES North America 2000). The NRC Institute for Research in Construction recommends levels of 400 – 500 lux for typical office work (National Research Council Canada). In terms of daylight factor, the recommended percentage is 2% – 5% (IES North America 2000). This study targets a level of 300-500 lux taking into account that values not less than 200 lux and higher than the recommended range may be acceptable in some areas of the space, under certain conditions.

## LUMINOUS DISTRIBUTION

For better visual environment, the IESNA recommends that, within the occupant's field of view, the ratio between the maximum and minimum illuminance should not exceed 1:10 (IES North America 2000). However, the NRC Institute for Research in Construction recommendation exceeds that of IES and goes up to 1:20 (National Research Council Canada), providing an acceptable argument for this high contrast, like highlighting certain object on the working plane. Sometimes due to high contrast, the occupant perceives parts of the space as dark which in reality actually has sufficient light levels. Maintaining this ratio prevents the false perception of light level inside spaces. Within the framework of this study, ratios up to 1:20 will be acceptable.

## LIGHT PENETRATION

Untreated window openings allow light penetration one and a half times the distance from the floor to window head. Incorporating a light shelf extends the ratio up to twice the distance (figure 1). Within the context of this study, the target is for two and a half times this vertical distance with the use of light deflection devices.

## SIMULATION RESULTS

The simulation has been run once with no secondary skin – just the glazing – and three times with different tilt angles (figures 7, 8 and 9 described in the four coming sections). In the first two runs, the panels were in shading positions with two different angles in each case, while in the third run, the panels were in combined position with another two different angles. All other factors, otherwise previously noted, have been fixed for fair comparison. For all simulation runs, the time and date have been set to August 21, 12:00pm. Initially and until the Grasshopper definition is fully developed, the tilt angles' selection has been manually simulated, taking into consideration that in the future the definition will select the angle based on pre-defined parameters. Although disappointing that that tilt angles had to be manually adjusted, when the software bug is fixed, refinements to the solution set will be made.

In the following three sections, a diagram is repeated many times as an explanation to the simulation runs (figures 7, 8 and 9). The green text on the left side of the figures is a diagram legend for the calculation grid plan view. It is divided into four legends based on the number of grids inside the space. First text legend refers to the lower left grid. Second text legend refers to lower right grid. Third text legend refers to upper right grid. Fourth text legend refers to upper left grid.

### SHADING CONFIGURATION (30 AND 60 DEGREES)

The exterior panels have been tilted to 30 and 60 degrees in a shading configuration (figure 7). With this configuration, the simulation showed a 50:50 result; the front two zones are overlit while the back zones are within the acceptable daylight factor range (figure 7). The high-angle sun emits light that is reflected by the panels and intensively deflected into the front portion of the space. Light is bounced off the 30 degrees panels, reflected on the back surface of the 60 degrees ones, and deflected into the front half of the space. Given the performance indicators mentioned in section 1.1, these results are not acceptable; thus the tilt angles are not successful in achieving good daylighting quality and quantity inside the space.

### SHADING CONFIGURATION (52 AND 41 DEGREES)

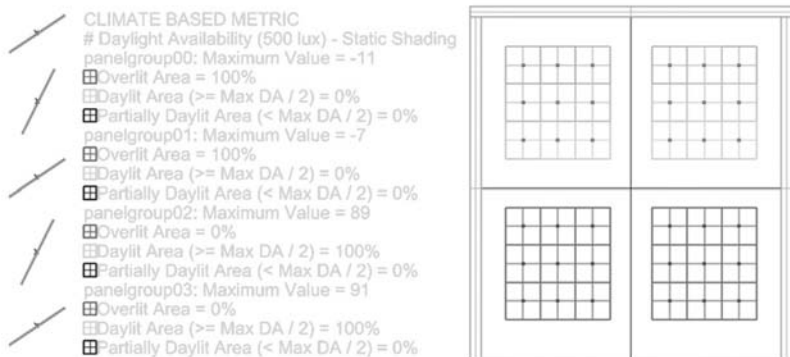
The simulation has been repeated with another set of tilt angles – 52 and 41 degrees – in a shading configuration. The results were more promising than the first run (figure 4). The overlit area is less, which means less light deflection is concentrated in the front zone. However, a partially daylit area showed in the back portion of the space. The upper right zone is relatively the best zone in this run where no overlit areas are present and only 22% of the zone is partially daylit. Though this run shows better results compared to the previous case, it is still far away from the research objective which targets even distribution of acceptable lighting levels inside the space.

### COMBINED CONFIGURATION (26 AND -17 DEGREES)

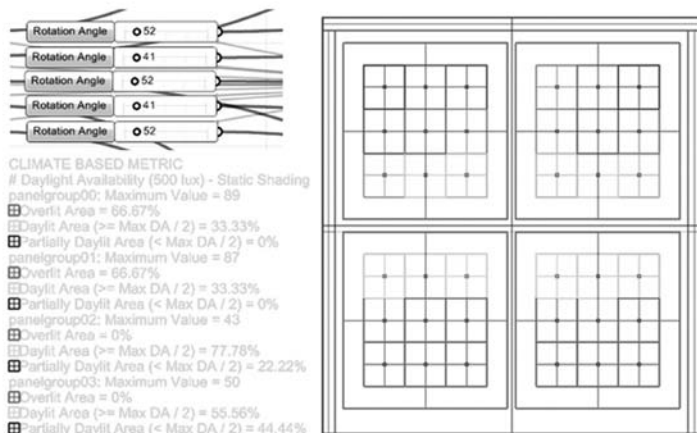
This run is different from the previous ones. The panels are set to combined configuration; panels 1, 3 and 5 are tilted to 26 degrees in a shading configuration that blocks more light from penetrating into the space, and panels 2 and 4 are tilted to -17 degrees in a harvesting position that deflects more daylight into the space. This skin configuration makes use of some of the light and blocks the unnecessary portion. The sunlight hitting the harvesting panels is deeply deflected into the space to maintain illumination levels within the desired range. Light is partially blocked by the 26 degrees panels, falls on the -17 degrees louvers, and deeply deflected into the back of the space. So, intense light is blocked from over-illuminating the front of the space and the back of the space get more light which makes it fall within the desirable range. Unlike the previous runs, this configuration overcame the partially daylit areas at the back of the space and minimized the overlit area at the front of the space by putting 33% of each of the front zones in the acceptable daylight factor range.

## SIMULATIONS' CONCLUSION

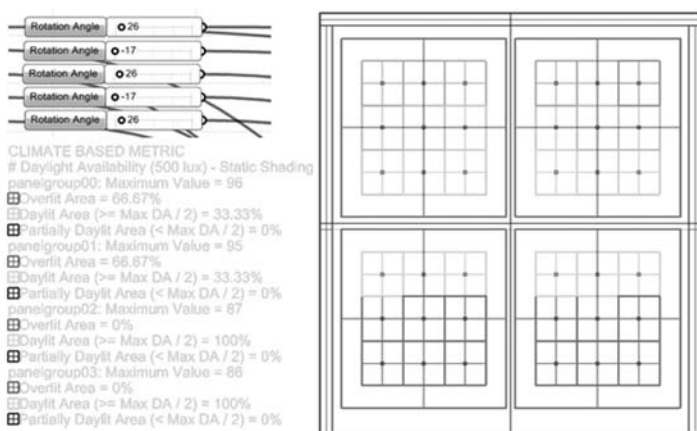
The results for the three simulation runs are part of the first simulation phase of the primary author's current thesis work. By comparing the previous three tilt angle configurations, the combined configuration of -17 and 26 degrees is, so far, the most successful and has more potential for better performance. When comparing the three cases against each other, the 30-60 degrees configuration has a 50:50 performance; half of the space is within the acceptable range and the other half is overlit. As the tilt angles are changed to 52 and 41 degrees there is better distribution of daylight inside the space but the space is still over lit at the front of the space and partially lit at the back of the space. The combined configuration of 17 and 26 tilt angles optimizes daylight inside the space; it increases the percentage of daylight zones and minimizes the overlit areas. Figure 10 shows the illumination levels in Lux for each of the three configurations in addition to the base case with static horizontal louvers. The static horizontal louvers case and the 60-30 degrees case showed almost equal results in



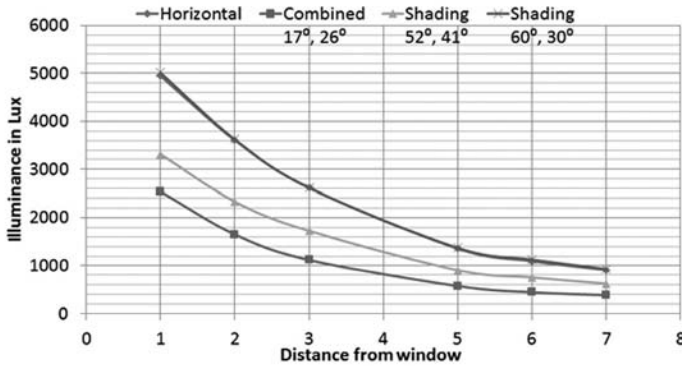
**Figure 7:** The figure shows the daylight factor results of panel configuration in shading position with angles of 30 and 60 degrees. The image on the right shows a top view of the interior space enclosing four independent calculation grids located on the work plane.



**Figure 8:** The figure shows the daylight factor results of panel configuration in shading position with angles of 52 and 41 degrees.



**Figure 9:** The figure shows the daylight factor results of panel configuration in shading position with angles of 26 and -17 degrees.



**Figure 10:** The figure shows illumination levels chart for four panel configurations including the base case with static horizontal louvers.

illumination levels. It is intended to proceed further by simulating the results of louvers that move every 15 minutes with a fixed louver system.

### OPPORTUNITIES AND LIMITATIONS

At this early stage of the study, the algorithm is not fully developed; thus using this methodology as a design tool presents some opportunities and limitations. This tool presents a single solution for the design problem through the use of horizontal rotating louvers, which is definitely not the best solution for low solar altitudes. However, it would not be difficult to change the geometry and parameters in Grasshopper for other design ideas. The extensibility of this algorithm makes it open to the integration of more variables into the process as the tool develops. This opportunity allows designer to customize the input parameters according to the real project's experiences. Thus, designers can test numerous attributes against each other and decide on the changes that achieve the most desirable luminous environment, in terms of cost, aesthetics, and/or materials.

As for daylighting, there are many other different attributes that were not covered in this example. Only three attributes were studied: the illumination levels, luminous distribution (contrast ratio), and the penetration depth of daylighting into the back of the space. More aspects like glare, surface brightness, surrounding urban context – resulting in externally reflected components – could be explored in future studies.

Future work includes finishing the Grasshopper definition and defining the constraints for the Galapagos problem solving simulation. The most important and challenging part of this phase is extracting individual readings for each sensor/calculation point and linking it to the parameters for the Galapagos run where it will only be used for the running a large number of solutions and finding the best based on the constraints. Then the skin will be divided into four zones and each enable to act independently to adjust the maximum possible area inside the space in terms of daylighting – quality and quantity. It is intended to test the applicability of the system on complex geometry and assess its performance on such forms against regular ones. It is also planned to provide animation for the panels' actuation that shows instant illumination changes on the work plane. This visualization would be useful in providing the designer with a quick scenario of the dynamic process and its impact of the quality of day lighting.

### CONCLUSION

Daylighting is a variable natural force that changes due to the sun's apparent movement in the sky. A fixed louver system would only be efficient during certain times of the day, while a dynamic system would be able to respond to variable environmental conditions. Independent rotation of the louvers in a secondary skin system is one kind of performance-based dynamic system. The use of independent tilt angles for secondary skin panels have strong potential for achieving better daylighting performance. The combined configuration of shading and harvesting positions showed strong potential for successfully achieving the objective of the study. It is capable of directing more

useful light into the back of a space and at the same time blocking strong light levels at the front of the room, thus resulting in optimizing the quality and quantity of daylight in interior spaces.

By providing reliable fast-calculating algorithm and comprehensive visualization in the form of animation, the proposed workflow presented in this paper extremely contributes to the ability of the designer to account for daylighting performance during the design phase. It enables the designer to account for changing conditions of natural forces, specifically the sun. The use of DIVA component in Grasshopper brings the analysis tool to native modelling software, Rhino. This minimizes the use of many interfaces and experiencing disconnection in data exchange between multiple software programs, thus increasing the analysis process speed and minimizing possible errors.

An original intent of the study was to demonstrate that a kinetic façade could be used in harmony with complex parametric design to provide better performance without compromising the intent of the designer. Although this objective was set aside for future work, the authors still maintain that it is critical that more research is initiated at the intersection of innovative architectural design and building science. The resultant performance based design solution must also be compatible with the designer's aesthetic. High performance buildings should also be beautiful buildings.

## ACKNOWLEDGEMENTS

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