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Daylighting and energy analysis of multi-sectional facades

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Abstract

Previous studies on dynamic facades have focused on a single type of section/shading, investigating its properties or control in order to improve comfort or reduce energy use for lighting and air-conditioning. Multi-sectional dynamic façade concepts are able to balance daylight provision and energy use reduction versus maintaining comfort levels. However, the overall potential of such systems needs to be investigated in an integrated manner. A typical multi-sectional facade consists of a top section, representing the non-viewing (daylighting) part, a main middle (viewing) section and a spandrel section. The top section can transmit daylight deeper into the space and the middle section should provide direct outside view (or privacy) and protect from glare and sunlight. The two sections may have different areas, glazing properties, and shading types and control options. This paper investigates the concept and quantifies the impact of combinations of solar protection and light redirecting devices. The analysis includes two climates and two orientations to serve as a preliminary study to assist in design guidelines for multi-sectional façades.

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Keywords: Dynamic facades; Shading; Light-redirect devices; Daylighting; Energy.

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1. Introduction

Previous studies on dynamic facades focused on a single type of shading on the facade. However, the balance between daylight maximization, reduction in energy use, glare protection, and outside view is difficult to achieve with standard facades employing single shading systems (even with dynamic operation). Automated roller shades may or may not result in this balance depending on many factors, including glazing properties, room size, etc [1]. Light-redirecting systems can bring more daylight into the space but they can also result to glare or overheating if not carefully controlled [2, 3]. Multi-sectional dynamic facades serving multiple functions are efficient solutions. Each section serves one or more functions (e.g. glare protection, daylight provision, SHGC reduction etc.) to compensate each other’s weakness. The concept is not new; however, systematic integration of new facade technologies and synchronization of system controls has not been achieved.

In a typical “three-section facade", the bottom part is opaque (spandrel), simply satisfying the thermal resistance requirements for the considered location. The middle (viewing) section provides view to the outside and the top

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(daylighting) section aims to deliver extra daylight. Both sections should have some kind of solar protection system to prevent glare and control excessive solar gains. Figure 1 shows the concept and the difference between a standard façade and a multi-sectional façade. In the standard configuration, shades need to close to protect from glare, reducing daylight availability. On the contrary, the top session of a multi-sectional façade can still provide useful daylight (glare restrictions remain). For deeper spaces, systems capable of transmitting or redirecting light more effectively are desired (e.g., venetian blinds, light shelves, redirecting coatings or films [5], laser cut panels [6], nano- , micro-, and mini-blinds [7]). For the middle session, the most common designs are roller shades and venetian blinds that can be easily overridden by occupants. Other advanced options include shades with variable transmittance along their height, or switchable and semi-transparent PV windows. A few studies have focused on the advantages of multi-sectional facades with roller shades and venetian blinds [8-12], showing that light-redirecting system can provide evener indoor daylight distribution, but in some cases can lead increased glare sensation.

To accomplish better performance and avoid glare issues, various factors should be considered in the design of a multi-sectional façade, such as the properties, the size, and the control of each individual device and their synchronized operation –since their combined effect will determine indoor conditions and energy use. Integrated solutions with combined system design and control features are a necessity for this complex problem. Errors in estimation of performance indices may result in incorrect selection of fenestration properties/control and reduced performance. Such an oversight in the early design stage could have significant effects on the energy consumption, cost and indoor comfort conditions during the lifetime of the building. Theoretically, this concept should have superior performance compared to standard facades, but the actual benefits and savings have not been systematically quantified. This paper investigates the impact of the combinations of three solar protection and light redirecting devices (light shelves, roller shades, and venetian blinds) in an integrated manner. In this way, it serves as a preliminary study to assist in future design multi-sectional façade guidelines.

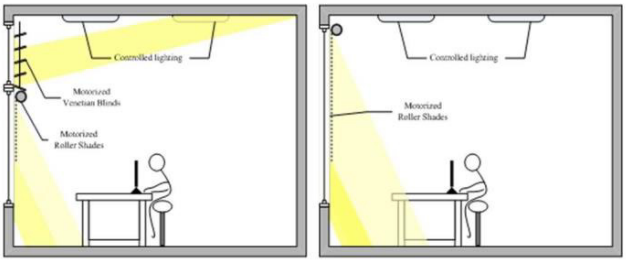

Figure 1. Multi-Sectional Façade (left); Traditional façade (right)

2. Methodology

2.1. Integrated Thermal and Daylighting Model and Design Factors

The daylighting model implements a hybrid ray-tracing and radiosity method [13]. Direct sunlight transmitted through the (simple/complex) fenestration system is tracked with the ray-tracing module, while the radiosity module computes interior diffuse reflections and final illuminance distributions. Detailed glazing properties are imported from WINDOW, and detailed angular roller shade properties are computed using a validated-semi-empirical model [14] embedded in the newest version of EnergyPlus. The annual visual discomfort frequency is used to evaluate the risk of visual discomfort based on two vertical illuminance criteria ($E_{v,\ beam} < 1000$ lux or $E_{v,\ total} < 2670$ lux), avoiding limitations of daylight glare probability [15]. The simulation program, written in Matlab, performs daylighting and thermal simulations in sequence. Solar radiation distribution and internal heat gains from electric lights, generated in daylighting module, are passed into the thermal calculation module, which implements a 1-D implicit finite difference thermal network approach to predict the transient thermal behavior including non-linear conduction, convection, and radiation. Each surface is represented as a node. Surfaces with high thermal mass are divided into at least three layers (control volumes). Convective heat transfer coefficients and thermal modeling in shading cavities are based on

EnergyPlus and ISO15099 [16]. The integrated model results include hourly or sub-hourly and annual heating and cooling load, surface temperatures, interior illuminance and luminance distributions, and respective annual metrics. The model has been extensively used and is validated with full-scale experimental measurements, and with EnergyPlus and Radiance/DAYSIM for various shading scenarios [1, 13, 17].

Roller shades provide view through open-weave fabrics and control. Openness factor refers to the "open" percentage of the shading fabric, which allows a visual connection to the outside, and direct light transmission. Visible transmittance and openness factor strongly both influence indoor daylight conditions and visual comfort. We have recommended different openness factors and visible transmittance values for different locations, orientations and glazing properties [15] to assure that the annual visual discomfort frequency is less than 5% when the shades are closed. Other factors, such as reflectivity and absorptance, are important for controlling solar heat gain. For warm climates, fabrics with high front reflectivity are recommended. Managing daylight and glare with roller shades is challenging, since daylight redirection is not possible and advanced shading control algorithms are necessary in conjunction with occupant overrides [17]. Light transmission and redirection from the top section depends on the system type, properties and control. The ability of venetian blinds to redirect light depends on the reflectivity and the specularity of the slats. Any downward beam illuminance may create glare problems: even with "cut-off angle" control, there will be a second downward reflection originating from the bottom surface of slats –this can be solved if the bottom surface has low specularity/ reflectivity. Light redirection controls for venetian blinds have been proposed in [2]. This study considers motorized interior light shelves as an option. The concept of light-shelf and blinds are similar, but the light shelf does not create multiple downward reflections. The redirected light hits the ceiling and is reflected into the room. In a multisectional façade, the length of the light-shelf should be at least equal to the height of the top section. The effects of light-redirecting devices on cloudy days are greatly reduced due to the lack of direct light and the glare risks are small. The other challenge is the synchronization of operation (control coordination) of the two shading devices in the two sections. These should be controlled independently to maximize benefits, but in reality the control of one affects the other since interior conditions are affected. Since light-redirecting devices contribute to daylight provision, the logic followed here is to first select the properties, control type and set point of the top section, and then adjust the properties and control of the middle section to accommodate the design of the top part in an integrated manner.

2.2. Case Study Description

A series of cases was studied through simulation to investigate the concept. The analysis was done for a medium-size perimeter office space (12 m × 12 m × 3 m high) with one exterior façade (67% window-to-wall ratio). The work plane height is 0.8 m. The reflectance of ceiling, vertical walls and floor are 80%, 50% and 20% respectively. A high performance glazing system with high visible transmittance (64%) and low solar transmittance (25%) was selected to avoid excessive solar heat gain, imported from WINDOW. The installed lighting power density is 10 W/m^2 in the company of continuous dimming control, and other equipment gains were 5 W/m^2 (working hours are 9am-5pm). The work plane illuminance set point is 500 lux. A 12 x 12 grid on the work plane is used for daylighting calculations.

Four scenarios listed in Table 1 have been studied. Scenarios 1 and 2 are baseline cases for comparing standard and multi-sectional façade concepts. The properties and controls listed in Table 1 were selected using parametric studies as follows: (i) the key rule imposed was the annual visual discomfort frequency- parameter combinations that caused discomfort frequency greater than 3% were eliminated (three occupant locations have been evaluated for that purpose - 0.91m, 1.83m, 2.74m from the window) and (ii) then the final selection was based on the rank of continuous daylight autonomy (cDA). The shading controls were based on the results of previous studies. "Effective illuminance" control is a work plane protection control that refers to moving roller shades to positions resulting in work plane illuminance less than 2000 lux (up to 1m from the window). A window sensor set point is used, corresponding to that value. For venetian blinds, the light-redirect control enables redirection of light to avoid direct light on the occupant seated near the windows [2]. Fig. 2 shows representative light transmission profiles.

Table 1. Façade Properties and Controls used in Simulation

	Shading Type	Properties	Control
Scenario 1	No Shading	-	-
Scenario 2	Roller Shades (2 m)	Transmittance = 5% Openness Factor = 1% Front Reflectivity=70%	Effective illuminance control Setpoint = 2500 lux
Scenario 3	Roller Shades (1.1 m)	Same as Scenario 2	Effective illuminance control Setpoint = 1500 lux
	Blinds (0.9 m)	Slat Front Reflectivity = 80% Slat Front Specularity = 80% Slat Back Specularity = 0% Slat Width/Gap Height = 5 cm	Low-profile angle: cut-off angle control High-profile angle : light-redirect control Darkness override = 3000 lux
Scenario 4	Roller Shades (1.4 m)	Same as Scenario 2	Effective illuminance control Setpoint = 2500 lux
	Light Shelf (0.6 m)	Shelf Reflectivity = 80% Shelf Specularity = 80% Shelf Length = 1 m	Low-profile angle: cut-off angle control High profile angle: light-redirect control Darkness override = 3000 lux

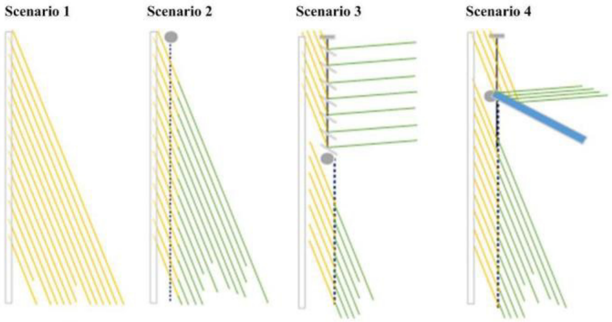

Figure 2. Distribution of transmitted light (and solar radiation) for 4 Scenarios (12:00pm, June 21st)

3. Simulation Results

3.1. Daylight Autonomy

A warm climate (Miami) and a cold climate (Chicago) were used to demonstrate results for the different scenarios. Fig. 3 presents the continuous daylight autonomy of Scenarios 2, 3, 4 for a south-facing office in Chicago. The average cDA of ***Scenario 1*** is 84% but the annual visual discomfort frequency reaches 75% even at 2.74 m away from the window (the "no shading" Scenario is not realistic and is only used for reference). Among the other three scenarios (designed to keep visual discomfort frequency less than 3%), scenario 4 (roller shades + light shelf) has the highest continuous cDA – 64.61%, which is 24% higher than ***Scenario 2*** (roller shades only). Scenario 4 has better performance than Scenario 3 because of more efficient light-redirection for that geometry. Fig. 3 also shows that the multi-sectional façade cases (both blinds and light shelf cases) benefit the occupants by generating a more even light distribution of and improve the overall interior visual environment.

3.2. Energy Savings

To calculate the site energy consumption, we assume that the COP of the cooling system (electric) is 3.4 and the efficiency of the heating system (gas) is 0.8. The site energy use is then converted to source energy use using typical conversion factors for the US (3.25 for electricity and 1.1 for natural gas). Fig. 4 shows the source energy consumption for the different cases in Miami and Chicago. Using roller shades as a baseline, the major energy savings from multisectional façades come from lighting. The differences in heating and cooling between the 3 scenarios are small, due to the control logic followed to maximize daylight without causing glare. The cooling energy consumption of the two multi-sectional façade Scenarios is slightly lower than the baseline, because the reduced internal heat gains from lighting have a higher impact on cooling load than the additional transmitted solar gains.

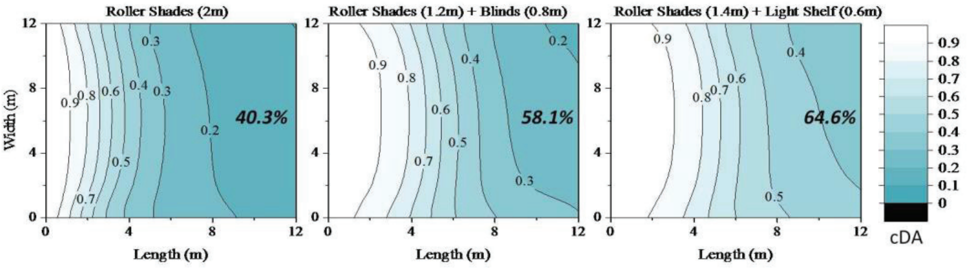

Figure 3. Daylight Autonomy of Three Different Shading Scenarios (Chicago, south façade)

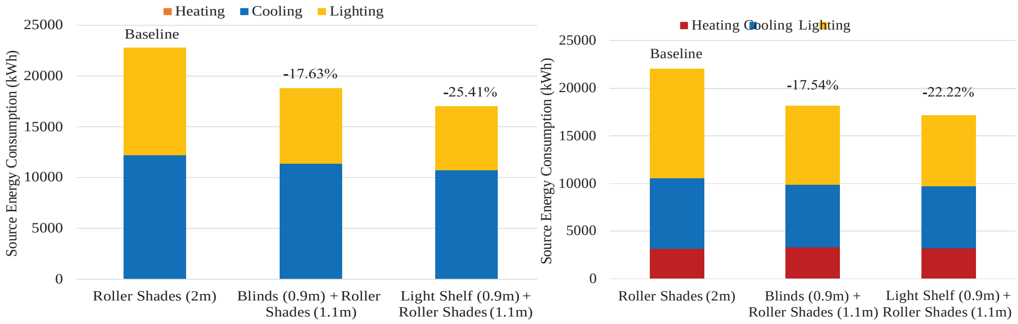

Figure 4. Source energy consumption for a south office in Miami (left) and Chicago (right) with the different multi-sectional façade Scenarios

3.3. Location and Orientation

The efficiency of a light-redirect device relies on the amount and the profile angle of direct light, depending on location and orientation. Fig. 5a shows the annual work plane illuminance levels in a south facing office in Miami and Chicago for Scenario 4, at a point located 10 m away from the windows. Miami benefits from light redirection from February (lower latitude) and Chicago from March. High solar angles in Miami during the summer result in less available daylight (but also lower solar gains). Fig. 5b compares the work plane illuminance in a south- and a west-facing office, both in Miami, to show the impact of orientation.

4. Conclusion

This paper studies the concept of multifunctional facades with dynamic light redirecting devices in the top section. We first identified what kind of sectional combinations are the most beneficial, flexible and realistic, including roller shades, venetian blinds and light-shelves. The integrated thermal and daylighting model shows the benefits of multifunctional façade concepts. The most significant benefit comes from lighting energy savings, also associated with the reduction of cooling load due to the decrease in internal heat gain. Dynamic control is a key factor when considering multi-functional facades. The control algorithms developed for single components can be applied, but the individual set points need to be modified to maximize daylight and avoid glare. Further studies will focus on the "control coordination" between different sections. A model-based control would be a good solution and the embedded optimizer needs to consider more variables when different sections are automatically controlled, depending on outside conditions and occupant comfort preferences.

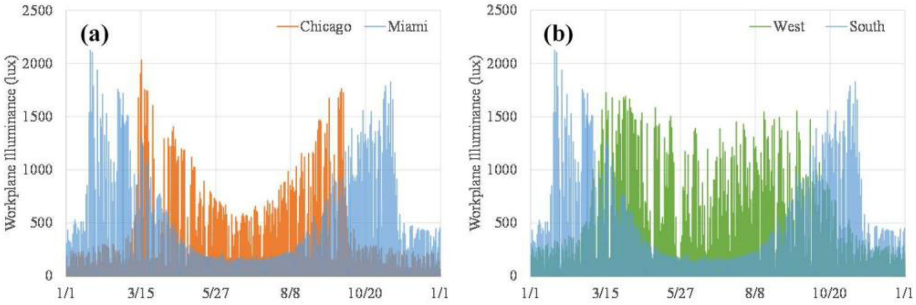

Figure 5. The impact of multi-sectional façade Scenario 4 on annual work plane illuminance: (a) south façade, 10 m away from windows in Miami and Chicago (b) south and west façade, 10 m away from windows in Miami

Table 2. Source energy consumption and continuous Daylight Autonomy for the different cases in Miami and Chicago

	Source Energy Consumption (kWh)				**Continuous Daylight Autonomy**			
Location/ Orientation	**Miami/ South**	**Chicago/ South**	**Miami/ West**	**Chicago/ West**	**Miami/ South**	**Chicago/ South**	**Miami/ West**	**Chicago/ West**
No Shading	14378	13007	15279	14108	84.3%	88.0%	74.2%	80.5%
Roller Shades (2m)	22780	22019	22582	21623	40.3%	66.2%	37.3%	41.6%
Blinds (0.9m) + Shades (1.1m)	18764	18158	19888	19561	58.1%	72.1%	41.7%	48.8%
Light Shelf (0.9m) + Shades (1.1m)	16991	17127	19321	19140	64.6%	79.4%	48.8%	55.6%

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