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Development of a façade retrofit performance guide using climate-based analysis including dynamic façade systems

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ABSTRACT

The impact of static and dynamic façade systems and components on daylight performance and energy use in perimeter building zones has been addressed in previous studies, but there are limited sources of information for comprehensive façade retrofit guidelines.

This paper presents the development of a façade retrofit performance guide for perimeter office spaces in North America. An integrated thermal- lighting simulation tool, validated with experimental results and verified advanced tools, is used to calculate annual energy performance indices and daylighting metrics for perimeter spaces in different climates. The tool flexibility allows parallel investigation of several parameters (window-to-wall ratio, glazing optical and thermal properties, shading properties and controls) and evaluation of performance indices such as dynamic daylight metrics, site and source energy use for air-conditioning and lighting, and peak demand, as well as human comfort.

A guide tool with a simple interface was also developed to help designers and architects make appropriate decisions about façade systems and components. A highlight of this tool is the ability to model and produce results for dynamic façade systems for which the daylighting and thermal performance is difficult to assess using simplified tools or publicly available software. The powerful engine can be also used to establish multivariate correlations for evaluating the combined impact of façade design decisions.

1. INTRODUCTION

Façade is an important factor in building design and retrofit considering its significant impact on daylighting performance and energy use, especially for buildings with large perimeter zones. Modern building facades consist of static and dynamic components including various types of glazing, insulated envelope and controllable shading attachments. Their impact on building performance has been addressed in previous studies: some investigated the variation of building energy consumption as function of glazing types and window size (Shen and Tzempelikos, 2012, 2013; Tsikaloudaki et al., 2012; Kim et al., 2012); others evaluated the energy savings potential from shading control and properties (Nielsen et al., 2011, Reinhart and Wienold, 2011); and a few studies were committed to develop new shading control strategies (Tzempelikos and Shen, 2013a, 2013b; Chan and Tzempelikos, 2013).

Ghisi and Tinker (2005) concluded that the best window-to-wall ratio for lighting energy savings depends on room configuration and local climate. Tzempelikos and Athienitis (2005) calculated the impact of dynamic exterior shading on lighting and cooling energy demand for a typical office space and showed that a minimum window-to-wall ratio of 30%-40% is required to satisfy daylighting requirements without significantly increasing heating and cooling needs. A similar study was performed for Amsterdam (Ochoa et al., 2012) reporting that window-to-wall ratio between 50% and 70% are most appropriate for all orientations. Goia et al. (2013) showed that the optimal configuration is achieved when the glazed façade percentage is between 35% and 45% of the total façade area regardless of the orientation. Shen and Tzempelikos (2012, 2013) investigated the balance between daylighting benefits and energy requirements in perimeter private office spaces with interior roller shades taking into account glazing properties, shading properties and control together with window size, climate and orientation. The study showed that window and shading properties play an important role for different orientations. Nevertheless, for several commonly used window products and automated shades, windows occupying 30%-50% of the façade can actually result in lower total energy consumption than smaller or larger windows, both for the climate of Chicago and Los Angeles. A recent study conducted for Helsinki, London and Rome (Jin and Overend, 2014) also emphasized the importance of glazing type and window size based on the whole-life cost and comfort analysis for a cellular office room and an open-plan office floor. In an earlier study of the same researchers' (Jin et al., 2011), they searched an optimal solution with 70% window-to-wall ratio as the façade design option of best whole-life value.

Both advanced whole building simulation software and simplified tools were used in existing literature to help designers at the early design stage in evaluating the potential impact of façade design and control decisions. Among these few tools, EnergyPlus (EnergyPlus, 2007) and ESP-r are too complicated for designers to use because they all require very detailed information about the building and equipment. Some simplified tools emphasize on intelligent facades including energy and comfort criteria (Ochoa and Capeluto, 2009; Hellstrom et al., 2007) and others focus on performance-driven design exploration for daylighting (Gagne et al., 2011).

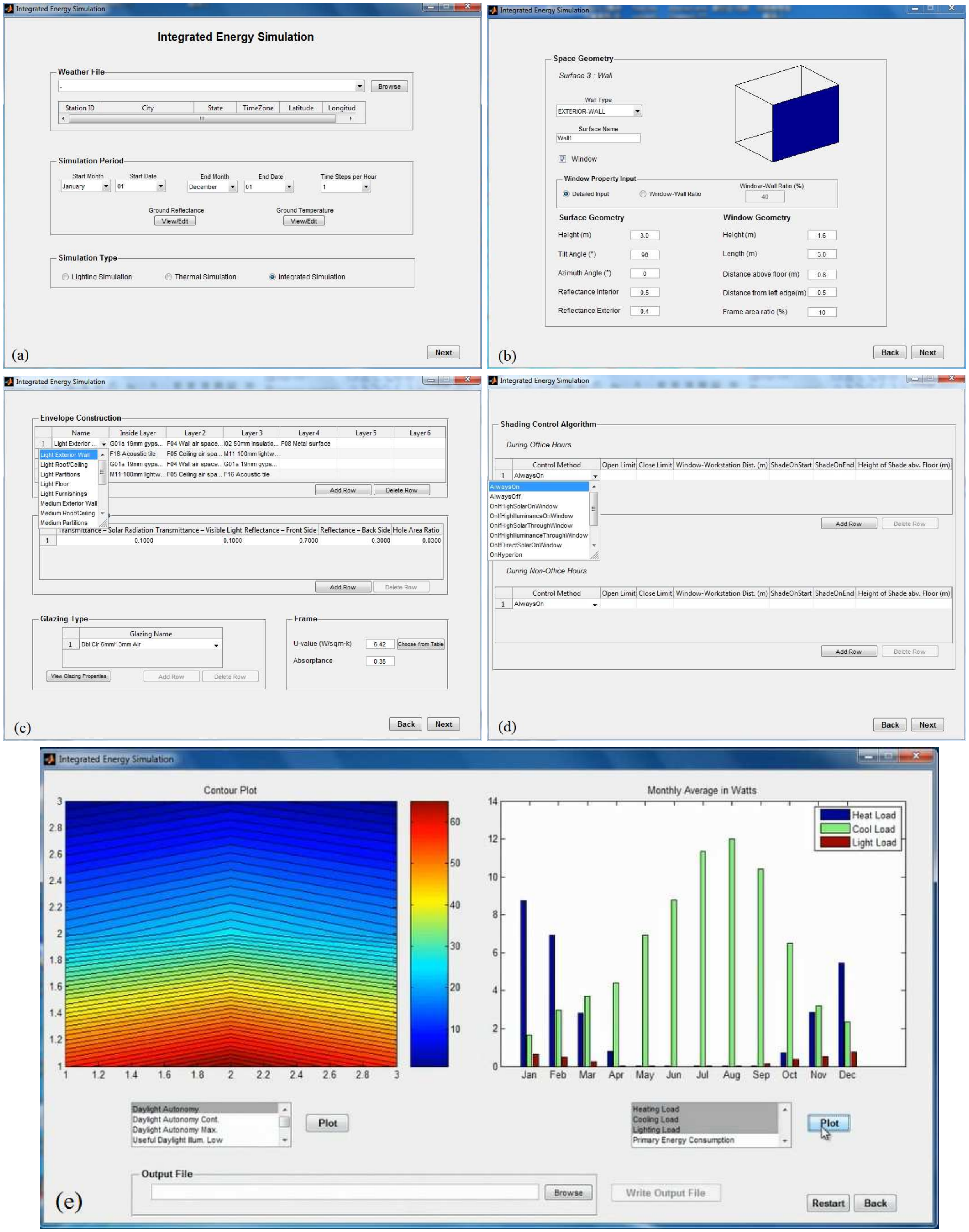
In the above mentioned studies, only simple control strategies with either open or closed shades positions were investigated. Recently, Shen and Tzempelikos (2013a, 2013b) studied shading control methods that move shades to intermediate positions and reported significant energy savings potential in space total source energy consumption. Such advanced shading control strategies are comparatively new with limited data. Also, it is not surprising that different conclusions were drawn in previous literature, given the different studied locations and climates. Comprehensive climate-based façade design and retrofit guidelines are urgently needed but without adequate sources of information.

This paper presents the development of a façade design and retrofit performance guide for perimeter office spaces in North America. An integrated thermal-lighting simulation tool, validated with experimental results and verified advanced tools, is used to calculate annual energy performance indices and daylighting metrics for perimeter spaces in different climates. The model flexibility allows parallel investigation of several parameters (window-to-wall ratio, glazing optical and thermal properties, shading properties and controls) and evaluation of performance indices such as dynamic daylight metrics, site and source energy use for air-conditioning and lighting, and peak demand, as well as human comfort. A guide tool with a simple interface was also developed to help designers and architects make appropriate decisions about façade systems and components. A highlight of this tool is the ability to model and produce results for dynamic façade systems for which the daylighting and thermal performance is difficult to assess using simplified tools or publicly available software. The powerful engine can be also used to establish multivariate correlations for evaluating the combined impact of façade design decisions.

2. THE TRANSIENT THERMAL-LIGHTING TOOL

2.1 Interface introduction

The transient thermal-lighting tool is developed based on a previous study (Shen and Tzempelikos, 2012). It has a user-friendly interface and combines high accuracy and rapid calculation speed. Figure 1 shows some of the elements and screenshots of the interface.



Integrated Energy Simulation

Weather File: -

Station ID	City	State	TimeZone	Latitude	Longitud

Simulation Period

Start Month: January
Start Date: 01
End Month: December
End Date: 01
Time Steps per Hour: 1
Ground Reflectance
Ground Temperature

Simulation Type

○ Lighting Simulation ○ Thermal Simulation ● Integrated Simulation

Space Geometry

Surface 3 : Wall

Wall Type: EXTERIOR-WALL
Surface Name: Wall1
☑ Window

Window Property Input

● Detailed Input ○ Window-Wall Ratio
Window-Wall Ratio (%): 40

Surface Geometry		Window Geometry	
Height (m)	3.0	Height (m)	1.6
Tilt Angle (°)	90	Length (m)	3.0
Azimuth Angle (°)	0	Distance above floor (m)	0.8
Reflectance Interior	0.5	Distance from left edge(m)	0.5
Reflectance Exterior	0.4	Frame area ratio (%)	10

Envelope Construction

	Name	Inside Layer	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
1	Light Exterior ...	G01a 19mm gyps...	F04 Wall air space...	I02 50mm insulatio...	F08 Metal surface		
		F16 Acoustic tile	F05 Ceiling air spa...	M11 100mm lightw...			
		G01a 19mm gyps...	F04 Wall air space...	G01a 19mm gyps...			
		M11 100mm lightw...	F05 Ceiling air spa...	F16 Acoustic tile			

Light Exterior Wall
Light Roof/Ceiling
Light Partitions
Light Floor
Light Furnishings
Medium Exterior Wall
Medium Roof/Ceiling
Medium Partitions

	Transmittance – Solar Radiation	Transmittance – Visible Light	Reflectance – Front Side	Reflectance – Back Side	Hole Area Ratio
1	0.1000	0.1000	0.7000	0.3000	0.0300

Glazing Type

	Glazing Name
1	Dbl Clr 6mm/13mm Air

Frame

U-value (W/sqm·k): 6.42
Absorptance: 0.35

Shading Control Algorithm

During Office Hours

	Control Method	Open Limit	Close Limit	Window-Workstation Dist. (m)	ShadeOnStart	ShadeOnEnd	Height of Shade abv. Floor (m)
1	AlwaysOn						

AlwaysOn
AlwaysOff
OnIfHighSolarOnWindow
OnIfHighIlluminanceOnWindow
OnIfHighSolarThroughWindow
OnIfHighIlluminanceThroughWindow
OnIfDirectSolarOnWindow
OnHyperion

During Non-Office Hours

	Control Method	Open Limit	Close Limit	Window-Workstation Dist. (m)	ShadeOnStart	ShadeOnEnd	Height of Shade abv. Floor (m)
1	AlwaysOn						

Daylight Autonomy
Daylight Autonomy Cont.
Daylight Autonomy Max.
Useful Daylight Illum. Low

Heating Load
Cooling Load
Lighting Load
Primary Energy Consumption

Output File

Figure 1: Elements and screenshots of the interface for the thermal-lighting façade analysis tool

The tool accepts TMY3 file in the format of .csv as weather input to start a simulation. Users can go to website (http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/) to download weather files for various locations. The tool allows customization for simulation period, calculation time step and switch among lighting simulation, thermal simulation and integrated simulation. Space geometry is defined by editing the surface dimensions and checking if the surface contains a window. A window can be defined by entering specific dimensions or by just determining a window to wall ratio. Users need to edit the surface properties, determine if the surface is an exterior or interior surface and may edit the surface name (Figure 1 (b)). Building envelope can be defined by selecting every material from the material library and then combine them into constructions or just selecting one option from the pre-defined constructions (Figure 1 (c)). The embedded envelope library contains all the materials covered in ASHRAE_2005_HOF_Materials. Also it is very convenient to add new items in the envelope material library, glazing library and shading library since they are all in .csv formats. Shading control strategies include simple open/closed control; advanced shading control strategies with intermediate shade positions developed in previous studies (Tzempelikos and Shen, 2013a, 2013b) are all integrated in the thermal-lighting tool. It is also allowed to edit the sensor grid for lighting and daylighting calculations. After all these settings are set, the user needs to determine the office hours, lighting control methods and then run the simulation. The tool can generate annual summary results and allows users to review results in graphs and tables. Detailed simulation results can also be viewed in .csv file to a determined location on disk.

2.2 Simulation methodology

The main simulation theory employed behind the interface includes the Perez et al. model (1990), the radiosity method and a finite different thermal network approach. The lighting simulation consists of four steps: use TMY3 illuminance data and the Perez et al. model to predict exterior illuminance incident on the façade; calculate the transmitted illuminance into space in terms of angular glazing properties and angular shading properties (beam to beam, beam to diffuse properties); calculate the interior light fluxes and illuminance values after inter-reflections using a radiosity-based method with tracking of directly sunlit areas; and calculate the daylight metrics and electric lighting requirements. The entire calculation is completed for each time step for a pre-selected grid on the work plane surfaces. If continuous dimming control is deployed, the electric light power (E_L) needed to maintain the target (set point) illuminance (usually 500 lux for office space) on the work plane (e.g. 0.8m above floor) is calculated from Eq. (1) if the daylight levels, E_i, are lower than the illuminance set point E_s.

$$E_L = \frac{P_L \cdot A}{E_s} \cdot \frac{\sum (E_s - E_i)}{n} \tag{1}$$

where P_L is the lighting power density, A is the work plane area, and n is the number of calculation points on the work plane. The required electric lighting power for all the grid points at each time step is averaged to obtain the overall electric lighting load, which is then used to calculate the heat gains (convective and radiative) from electric lighting in the thermal simulation at the same time step.

The thermal simulation uses the implicit finite difference thermal network approach to predict the transient thermal response of the studied space. One dimensional energy flow through envelope is assumed and non-linear heat transfer coefficients are simulated for interior and exterior convection and radiation at each calculation time step (EnergyPlus, 2007). Each surface of the studied space is represented with at least two surface nodes: three additional thermal nodes will be added for the surface if it has a mass layer. Solar radiation absorbed by each node and heat gains to the air node by convection (due to window-shade gap airflow, equipment, occupant and electric lighting) are represented by appropriate modified input sources; heat storage in thermal mass is represented by capacitances. Heat balance nodal equations are solved simultaneously to determine the node temperatures and energy flows between all connected nodes at each time step. The energy balance equation for a node (i) with thermal storage is shown in Eq. (2):

$$C_i \frac{T_{i,p} - T_{i,p-1}}{\Delta t} = \sum \left(\frac{T_{j,p} - T_{i,p}}{R_{ij,p}} \right) + S_{i,p} \tag{2}$$

where T is temperature, p is the time step, j represents all nodes connected to node i, R_{ij} is total thermal resistance between nodes i and j, C_i is the capacitance of the node i (product of specific heat, density and volume), and S_i is total heat input to node including lighting heat gain resulting from the daylighting simulation. For the convective heat transfer and airflow inside the glazing-shading cavity, a model based on pressure-balance method is used (ISO 15099, EnergyPlus 2007).

3. CLIMATE-BASED FAÇADE DESIGN AND RETROFIT ANALYSIS

3.1 Selection of representative locations

In order to perform a climate-based study across the US, 15 locations representing the different climate zones and population centers in the climate zones were selected as representatives (Table 1). They are the 15 out 16 locations selected for commercial building reference model locations (Torcellini et al., 2008) (Alaska was not considered). The selection of the reference model locations is based on Briggs et al.'s climate zone classification system (2003) for DOE and ASHRAE Standard 90.1-2004. An important characteristic of their classification is that they tend to run in east-west bands across US; subdivisions for moist, dry and marine divide these bands. As part of this effort, a set of typical locations were developed based on their representativeness in each climate zone; population or number of buildings were not considered. As a balance of the representativeness of the climate and the number of buildings in each climate zone, a revised set of locations were selected as the reference model locations. For example two locations were selected for climate zone 3B because they represent different climates within in one zone. These sub-climate zones are designated as 3B-CA for the California coast and 3B-other for the remaining part of the climate zone 3B.

Table 1: Selected locations representing different climate zones and population centers in the climate zones

Number	1	2	3	4	5	6	7	8
Climate Zone	1A	2A	2B	3A	3B-CA	3B-other	3C	4A
Representative City	Miami, Florida	Houston, Texas	Phoenix, Arizona	Atlanta, Georgia	Los Angeles, California	Las Vegas, Nevada	San Francisco, California	Baltimore, Maryland
Number	9	10	11	12	13	14	15	
Climate Zone	4B	4C	5A	5B	6A	6B	7	
Representative City	Albuquerque, New Mexico	Seattle, Washington	Chicago, Illinois	Denver, Colorado	Minneapolis, Minnesota	Helena, Montana	Duluth, Minnesota	

3.2 Evaluated façade variables and performance metrics

There are many space parameters that affect the perimeter building performance with regards to the visual and thermal environment and energy consumption. Based on previous sensitivity studies (Shen and Tzempelikos, 2013; Heiselberg et al., 2009), space orientation, window size, glazing type, lighting system control and shading properties are important factors. However, the orientation is not a factor that can be fully controlled. In addition, the advanced shading control strategies presented in recent studies (Tzempelikos and Shen, 2013a; Shen and Tzempelikos, 2013b, 2014) are not considered. So the present analysis is performed for each main orientation investigating the lighting and energy performance in terms of window size, glazing type, shading type and control, and lighting system control. Energy performance is evaluated as source energy consumption of four different aspects: lighting, heating, cooling and total consumption. For lighting environment evaluation, three metrics are evaluated: *i*) daylight autonomy (DA), an annual measure of how often a minimum work plane illuminance requirement (e.g. 500 lux for office spaces) can be met by daylight alone; *ii*) continuous daylight autonomy (DAcon), which considers partial credit to time steps when the daylight illuminance lies below the light level setpoint and *iii*) time ratio of annual working hours when work plane illuminance at least at one inspected point exceeds the recommended light level (e.g. 2000 lux for office spaces, E_{wp} > 2000 lux).

3.3 Case study of a private office space

The climate-based analysis is performed for a perimeter office space with one exterior façade with window(s) (intermediate floor) – the other surfaces are in contact with conditioned interior spaces that have the same indoor air temperature as the studied space (heat storage in these surfaces and the convection heat transfer between them and air are still considered). The space dimensions are 4 m wide by 4 m deep by 3 m high. It has typical masonry (brick) wall and interior roller shades. The interior surface reflectances of the floor, ceiling and walls are 45%, 80% and 50% respectively. The exterior surface absorptance of external wall is 60%. Total thermal resistance of the opaque section of exterior façade is 3.5 m^2K/W. The space is occupied from 8:00 am to 6:00 pm with occupant density of 0.11 p/m^2 and leased sensible heat of 76 W each people. The installed lighting power density is 10 W/m^2 and the load factor for other internal equipment is assumed as 5.4 W/m^2. Air conditioning is operating throughout the whole year, with variable temperature set points for office time (heating: 22 ^oC, cooling: 24 ^oC) and non-office time (heating: 18 ^oC, cooling: 26.6 ^oC). In this study, it is assumed that heating consumes natural gas (efficiency is 0.8) and cooling consumes electricity (COP is 3.5). The conversion factors for natural gas and electricity to source energy are 1.047 and 3.34 respectively. A grid with dimensions of 1 m × 1 m is used for work plane illuminance calculation; the working area is 0.5m from all vertical surfaces and the work plane surface is 0.8m above floor.

The following façade variables are considered in this study: three window sizes (expressed as window to wall ratio), two glazing types, two types of roller shades and two lighting control strategies. More specifically, this paper presents the impacts of:

- Three window sizes: 2.2m × 1.64m (length × height), 2.8m × 2.142m and 3.35 × 2.51m with respective window-to-wall ratios (WWR) of 30%, 50% and 70%.
- Two types of glazing as described in Figure 2.
- Two types of roller shades with their angular properties shown in Figure 3. The only difference in the properties of the two types of roller shades are their reflectance: one has a high reflectance of 77% (Shade-I) on the exterior side while the other one has a lower value of 40% (Shade-II). Their interior reflectance are the same as 5% as well as their openness of 4%.
- Continuously dimming-off lighting control and no lighting control (fully on) conditions.
- Two shading control strategies: *i*) Open/closed control based on the amount of incident solar radiation on façade: shades automatically close when incident solar radiation exceeds 200 W/m^2 during daytime and close at night; *ii*) Effective illuminance control (Shen and Tzempelikos, 2014) based on solar geometry and sky conditions: shades move automatically to a position that prevents direct sunlight on the work plane surface (partially open). Correlations between effective illuminance transmitted through window and work plane illuminance were also used to control work plane illuminance below 2000 lux for office spaces.

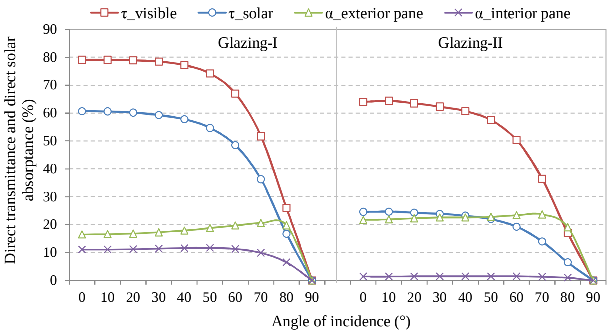


Figure 2: Glazing angular properties: visible and solar beam transmittance, exterior and interior pane absorptance for the two studied types of glazing

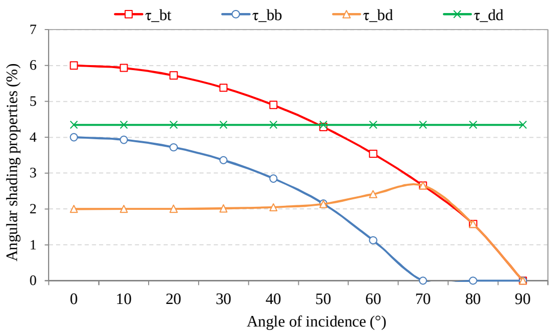


Figure 3: Angular properties of the studied roller shades: τ_bt is beam-total transmittance, τ_bb is beam-beam transmittance, τ_bd is beam-diffuse transmittance and τ_dd is diffuse-diffuse transmittance

3.4 Results and analysis

The daylighting and energy analysis is performed for the selected representative locations considering all space variable combinations mentioned above. In total, 15120 cases were studied and presented in 1008 geographical contour graphs. In this section, only representative results are shown. Figure 4 shows the daylighting performance for the case with 50% WWR window facing south; Glazing –II and Shade-I are used in this case; the Open/closed control (Control-I) is compared with the Effective illuminance control (Control-II) in the figure as well.

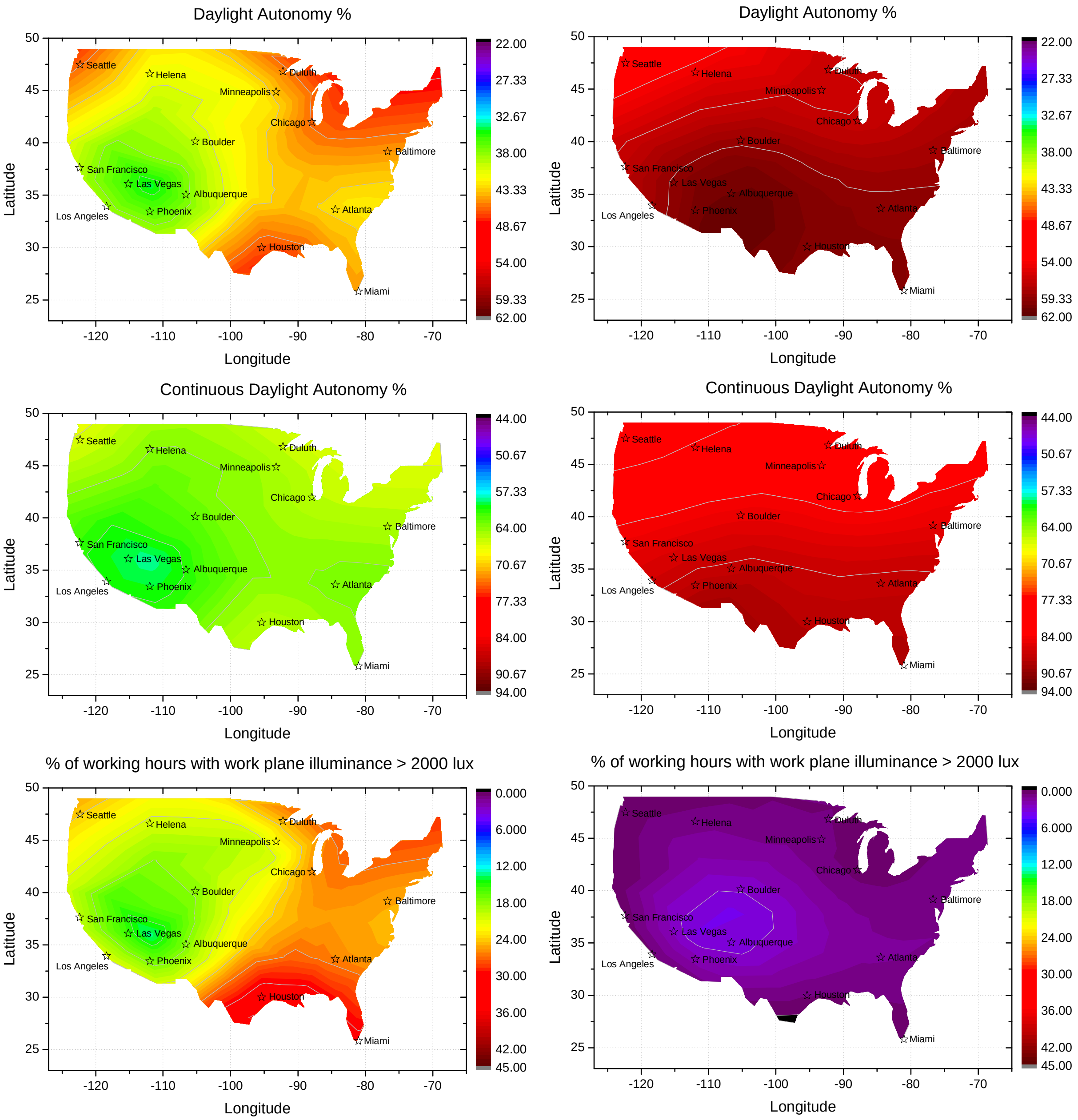


Figure 4: Daylighting performance for the case with 50% WWR window facing south, Glazing –II and Shade-I when Control-I (left column) and Control-II (right column) are employed.

As shown in Figure 4, Control-II performs better than Control-I in terms of daylight utilization. With Control-I, geometrical distribution of daylight autonomy and continuous daylight autonomy present the opposite trend to the distribution of solar energy resources. This is because that the control strategy closes shades depending on the incident solar radiation only, therefore locations with higher solar radiation have less time during working hours with open shades. On the contrary, the daylight autonomy and continuous daylight autonomy distributions across US follow the distribution of solar radiation resources with Control II: the values roughly vary along with latitudes. The difference in shading operations well explains the different daylighting performance distributions with the two shading control strategies (Table 2). The shading operations show larger difference among the representative locations when Control-I is employed, while Control-II results in smaller difference in shading operations among the locations. One point worth noticing is that, although the annual time-area percentage of working time when shades are partially open for Control-II is lower than Control-I, Control-II has higher time-area percentage of unshaded windows in winter and lower in summer. Comparing the two shading strategies, Control-II results in daylight autonomy values about 6% to 25% higher than Control-I. As for continuous daylight autonomy values, Control-II is about 11% to 30% higher than Control-I. The most significant advantage of Control-II over Control-I in terms of daylighting performance is manifested by inspecting how often it happens that work pane illuminance exceeds the recommend value of 2000 lux during working hours. With Control-I, the percentage of working hours when work plane illuminance exceeds 2000 lux ranges from 13% to 32% across US, which is higher than the condition under Control-II (generally below 5% for the presented case).

Table 2: Annual time-area percentage of unshaded window (direct outside view) for the case with 50% WWR window facing south, Glazing-II and Shade-I (%)

Representative City	Miami, Florida	Houston, Texas	Phoenix, Arizona	Atlanta, Georgia	Los Angeles, California	Las Vegas, Nevada	San Francisco, California	Baltimore, Maryland
Control-I	42.04	45.08	25.81	38.52	34.29	29.20	34.49	42.34
Control-II	33.33	34.62	26.30	32.43	29.55	28.02	28.66	32.99
Representative City	Albuquerque, New Mexico	Seattle, Washington	Chicago, Illinois	Denver, Colorado	Minneapolis, Minnesota	Helena, Montana	Duluth, Minnesota	
Control-I	28.75	51.49	46.84	35.25	41.73	35.26	44.75	
Control-II	28.43	35.72	34.07	30.48	32.47	25.83	32.37	

Based on the daylighting performance shown in Figure 4, it is expected to have a lower lighting energy consumption with Control-II, if lighting control is considered. Corresponding to the difference in lighting heat gain results from different electric lighting requirements and shading operation, the source energy consumption for heating and cooling are not the same either. Table 3 compares the source energy consumption for lighting, heating and cooling for the presented case under the condition that the lighting system is continuously dimmable.

Table 3: Source energy consumptions on lighting (L), heating (H) and cooling (C) for the case with 50% WWR window facing south, Glazing-II, Shade-I and continuously dimming-off lighting control (kWh/m^2·y)

Representative City		Miami, Florida	Houston, Texas	Phoenix, Arizona	Atlanta, Georgia	Los Angeles, California	Las Vegas, Nevada	San Francisco, California	Baltimore, Maryland
L	Control-I	45.49	43.66	52.12	46.82	50.66	53.08	49.97	44.43
	Control-II	14.05	14.84	14.28	15.62	17.39	18.17	19.26	18.76
H	Control-I	0	2.40	0.35	8.55	0.04	3.01	0.46	20.18
	Control-II	0	2.48	0.34	8.68	0.04	3.01	0.44	20.25
C	Control-I	89.49	69.33	112.24	55.44	53.94	87.55	35.87	41.85
	Control-II	83.38	63.62	105.25	49.86	48.31	81.85	30.91	37.14
T	Control-I	134.97	115.39	164.71	110.82	104.64	143.64	86.29	106.45
	Control-II	97.43	80.94	119.88	74.17	65.75	103.04	50.62	76.16
Representative City		Albuquerque, New Mexico	Seattle, Washington	Chicago, Illinois	Denver, Colorado	Minneapolis, Minnesota	Helena, Montana	Duluth, Minnesota	
L	Control-I	50.85	42.27	43.80	46.96	44.94	46.98	43.43	
	Control-II	15.32	27.16	21.63	19.13	21.98	24.50	22.30	
H	Control-I	13.05	15.23	40.38	27.23	54.46	41.59	72.60	
	Control-II	13.18	14.59	40.72	27.49	54.76	41.53	73.53	
C	Control-I	56.01	25.08	32.61	40.18	31.06	30.04	18.56	
	Control-II	50.42	21.62	28.64	35.76	27.22	26.15	15.43	
T	Control-I	119.92	82.58	116.79	114.37	130.45	118.61	134.59	
	Control-II	78.92	63.37	90.99	82.38	103.97	92.19	111.26	

*T is total source energy consumption including source energy consumption on lighting, heating and cooling.

As listed in Table 3, the lighting source energy consumption with Control-I shows high values ranging from 42 kWh/m^2·y to 54 kWh/m^2·y, comparing to the much lower values with Control-II ranging from 14 kWh/m^2·y to 27 kWh/m^2·y. For heating source energy consumption, shading control strategies do not show a significant impact: Control-I results in higher lighting heat gains; Control-II allows more solar radiation transmitted into space in winter, thus results in very similar heating energy use. However, for cooling source energy consumption, the higher lighting heat gain and more solar radiation transmitted into space results in higher values for Control-I. Total source energy consumption is the best indicator in energy performance evaluation. As listed in Table 3, for the studied case, Control-II outperforms Control-I for all the representative locations in US.

The above discussion only compares between two different shading control strategies. A more complete comparison of total source energy consumption among different space options is shown in Figure 5.

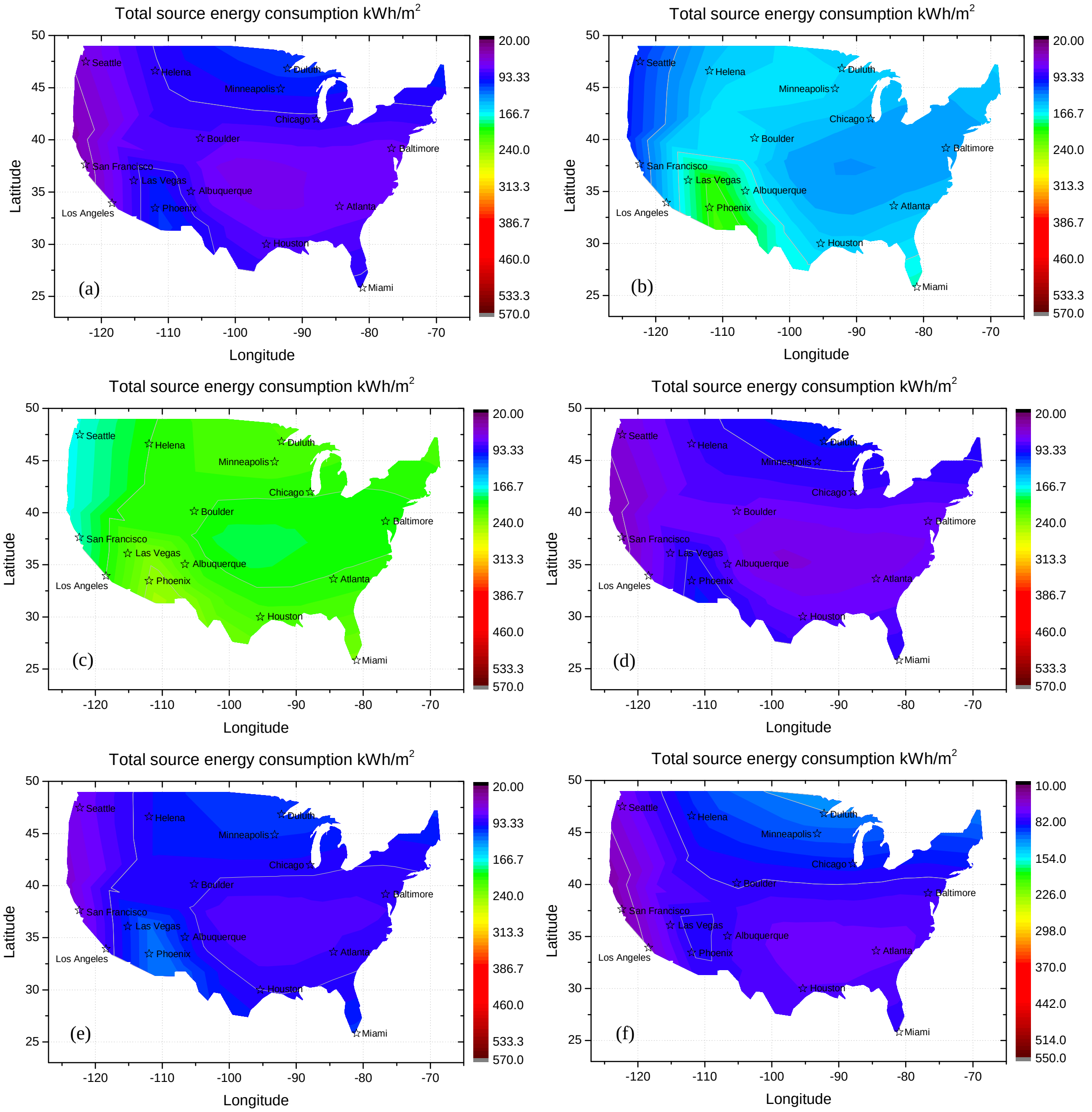


Figure 5: Total source energy consumption for the cases listed in Table 4

Table 4: Case description for Figure 5

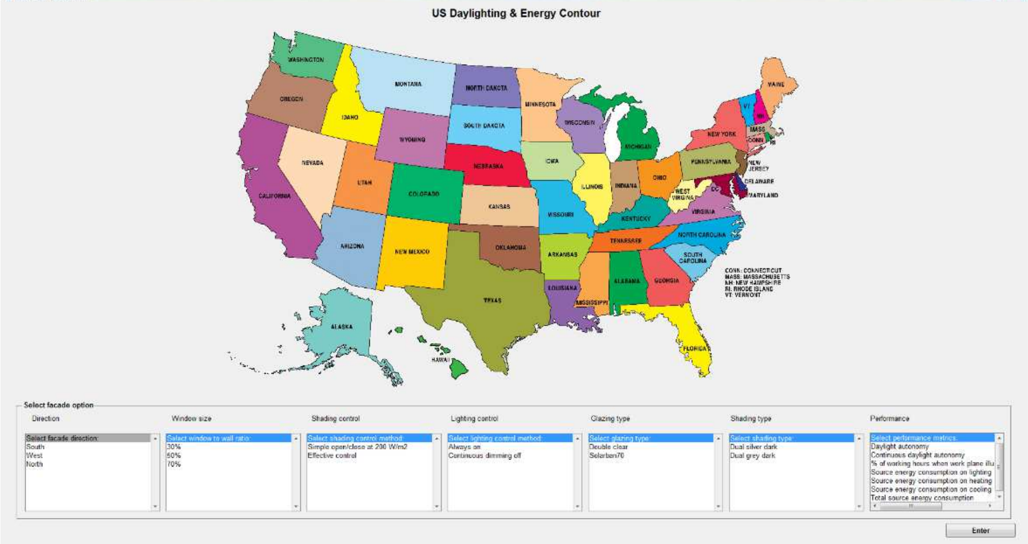
Case No.	Orientation	WWR (%)	Glazing	Shade	Shading control	Lighting control
(a)	South	50	Glazing-II	Shade-I	Control-II	Dimming
(b)	South	50	Glazing-I	Shade-I	Control-II	Dimming
(c)	South	50	Glazing-II	Shade-I	Control-II	Fully on
(d)	South	30	Glazing-II	Shade-I	Control-II	Dimming
(e)	South	50	Glazing-II	Shade-II	Control-II	Dimming
(f)	West	50	Glazing-II	Shade-I	Control-II	Dimming

Glazing properties have a significant impact on total source energy consumption in all locations. Comparing between Figure 6 (a) and Figure 6 (b), Glazing-I results in higher consumption than Glazing-II; the increase in total source energy consumption varies for different locations because of the complex combined influence of climate, shading operation and interactions among lighting, heating and cooling requirements. Dimming control for lighting saves a great amount of energy: for most locations over 50% of the total source energy are saved. The important role that window size plays in total source energy consumption does not emerge in the presented cases: comparing Figure 6 (d) with Figure 6 (a), the numbers are similar because of the small difference in window size and high glazing quality. A decrease in shading exterior reflectance from 77% to 40% generally increases the total source energy consumption in all studied locations by 1.8 kWh/m^2·y to 21 kWh/m^2·y. This can be explained from two aspects: the decrease lowers the effective transmittance of glazing-shading system (inter-reflection weakened) which eventually results in increase in lighting energy consumption; and the decrease in exterior reflectance increases cooling energy consumption. Finally, the impact of orientation can be examined by comparing Figure 6 (f) with Figure 6 (a). The compared orientations (west and south) outperform each other at different locations, for example, in Minneapolis west is better than south.

The discussion in this section only covers a small portion of possible space options. The numberless combinations cannot be compared to achieve optimal building performance although an exhaustive study can provide a meaningful guide for façade retrofit options. Also, an optimization study is useful to provide a target façade option for different representative locations.

4. THE FAÇADE GUIDE TOOL

As mentioned in above section, there are in total 1008 geographical contour graphs comparing daylighting and energy performance considering different orientations, window sizes, glazing types, shading properties, shading controls and lighting controls across the US. The huge amount of data is difficult to use by designers and professionals, so we developed a viewer (tool) to organize the data and facilitate utilization of the data. The viewer is user-friendly, as illustrated in Figure 6. Users can customize the data they want to see by selecting different options of space conditions and performance metrics. Multiple options under one list can be selected at the same time to show several contours together and compare between them.



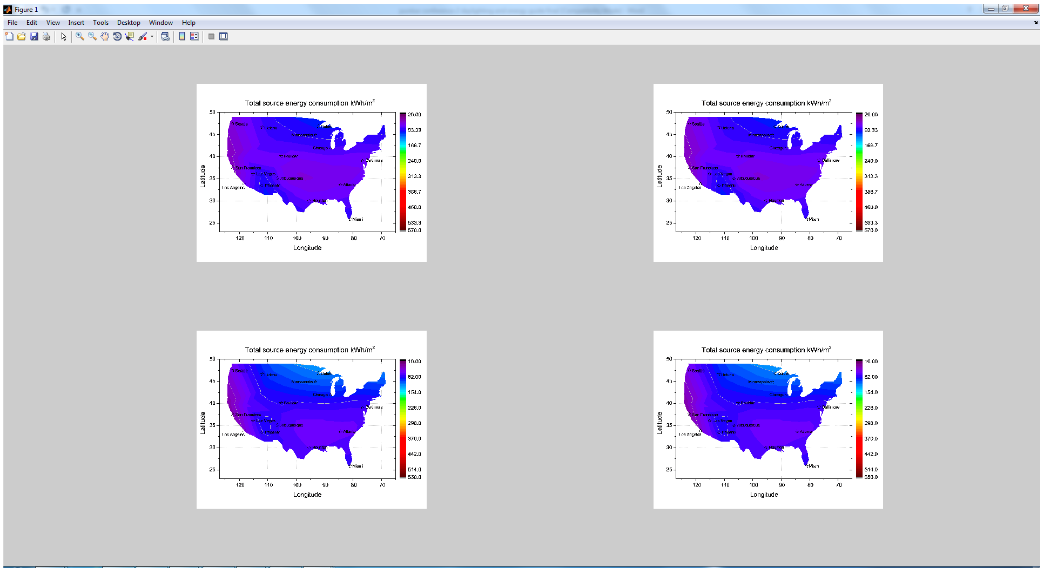


Figure 6: Screenshots of the interface for the viewer

5. CONCLUSIONS

This paper presents the development of a façade retrofit performance guide using climate-based analysis including dynamic façade systems. A transient daylighting-thermal tool is used for daylighting and energy performance analysis. Fifteen locations across US are selected as representatives considering different climate zones and the number of buildings in each climate zone. A private office space was used as a cast study. Daylighting and energy performance considering different orientation, window size, glazing type, shading properties, shading control and lighting system controls were presented as geographical contour graphs. A reviewer was also developed to organize the huge amount of data and facilitate building designers and professionals to be informed of building performance resulting from different space design and operation options.

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