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MODELING AN ELECTROCHROMIC WINDOW USING A MULTI-CRITERIA CONTROL STRATEGY

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ABSTRACT

Electrochromic (EC) glazing products have the ability to actively control solar transmission based on low voltage input. While this technology has been around for several years, the default options to model EC glazing in current simulation tools is still limited and often does not allow a full evaluation of multi-state EC products with predictive controls. Given a growing interest from the design community for incorporating EC glazing in high performance and net zero energy buildings, this paper will present a methodology for modeling a commercially available multi-state EC product with the actual control logic using EMS and compare the results with the default modeling approach.

INTRODUCTION

Incorporating glass in buildings presents a unique set of challenges for designers who want to improve thermal comfort and utilize more natural light while reducing energy use. A new range of adaptive glazing technologies are now available that can help balance both energy use and indoor comfort (Beatens et al. 2010) without compromsing the visual connection to outdoors. Such glazing products improve energy efficiency through tunable transmittance of solar energy and visible light. This type of glazing is often called "smart" or "intelligent" and is based on chromogenic materials (Granqvist et al. 2018) with electrochromic (EC) materials currently being the most widely studied and important option (Granqvist 2014). EC windows allow solar transmisison to be changed in a controlled and reversible manner using low voltage electric current (Deb 2000). EC windows could reduce peak electric loads significantly in commercial buildings and provide added daylighting benefits as well as improve comfort and enhance productivity in homes and offices (Lee et al. 2004).

In order to evaluate the performance of state-of-the-art and innovative adaptive glazing technologies such as EC windows, it is important to rely on whole building performance simulation (BPS) tools that are able to accurately reproduce their dynamic behavior when integrated at the building level. While EC technology has been around for several years, the options to model EC glazing in most BPS tools is limited to two tint states, using at most one or two control inputs such as incident solar radiation, indoor illuminance etc. However, most commercially available EC windows have more than 2 tint states and typically use a combination of predictive and reactive controls to manage tints. Hence there is a potential gap between typical modeling options and actual product controls.

Given a growing interest from the design community for incorporating dynamic glazing in high performance and net zero energy buildings, this paper will address this gap by modeling a multi-state EC product in EnergyPlus (UIUC, LBNL 2017a) using the Energy Management System (EMS) feature to replicate the extact control algorithm. This will provide a more realistic estimate of the energy savings with such a product, when modeled close to its expected behavior in a real building. The EMS results will be evaluated against the default 2-tint state EC Modeling option available in EnergyPlus (E+). A mid-rise commercial office building with standard Low-E glazing and manual roller shades will be used as a reference baseline across three distinct climate zones. While this paper references a specific EC product with four tint states, the intention is to demonstrate to the reader the flexibility of EMS for modeling various control stategies with any number of tint states.

TECHONLOGY OVERVIEW

Electrochromic Glazing Product

View Dynamic Glass (VDG) is a commercially available EC glazing product that is manufactured as Insulating Glass Units (IGU) in sizes up to 10ft x 6ft. It typically consists of an argon filled IGU with a 6 mm clear outer lite having a EC coating on surface 2 and a 6 mm clear inner lite. A VDG IGU has four tint states with Tvis typically varying from 1% to 60% and SHGC varying from 9% to 40% for the darkest to clearest tint states. Tint state selection is fully automated and controlled by a set of algorithms collectively called Intelligence® (a registered trademark of View, Inc.). By default, it consists of three functional modules in order of priority.

Module A - Direct Glare Control

- Ensure there is no direct sun penetration beyond a specified indoor distance and within specified view angles of an occupant

Module B - Heat Load Control

- When glare is not a concern ensure that transmitted solar gain is below a specified threshold

Module C – Weather/Daylight Control

- Use site-specific real time data from a roof mounted photosensor array to select a lighter tint state under overcast and cloudy conditions

Each module will independently propose a tint state at a given interval (typically every 10 mins) with a "final" tint state being passed to the IGU based on a preset decision hierarchy between the three modules. Tint state selections with Modules A & B are already pre-determined for a given IGU, based on window orientation, building geometry and site location for clear sky conditions. These two modules constitute the "predictive" aspect and decide the tint states for clear sunny days for each IGU, well before the sun can cause direct glare or excess solar gain at a certain time in the day. Module C is the "reactive" component of this system and uses data from a roof mounted photosensor array to track solar radiation intensity and maps that to preset thresholds for overcast conditions. This allows the algorithm to correctly override the typically darker tint state selections that would result from clear sky conditions alone. This combination of predictive and reactive components makes Intelligence® an effective control system over a 100% model-based or 100% sensor-based system. The system also allows for user overrides via a web app or wall switch and can be connected to a BMS using BACnet over IP.

Default EC Modeling options in E+

EC glazing can be modeled in E+ as a shading device, classified as SwitchableGlazing. This control essentially "switches" the glass construction for a window between two fixed states – fully clear and fully tinted, based on a user defined control type and setpoint such as Incident Solar = 200W/m^2. A limitation here is that only any 2-tint states can be modeled at one time with no intermediate states.

E+ offers up to 16 different switching control types (UIUC, LBNL 2017b) including incident solar radiation, outdoor temperature, daylight illuminance etc. Past studies have shown that EC control options based on daylight illuminance (Sullivan et al. 1994) or solar radiation (Corsi et al. 2000) show the best energy savings. A control option based on daylight illuminance however is a sensor-based system that can only "react" to changing light levels inside a space. In real world applications this implies that the window will start tinting only after there is a high enough light level to cause glare and an occupant will likely experience discomfort until the tint transition is complete. This control type does not align with the predictive ability of Intelligence®. Hence, for this paper only the incident solar based control was used as the default alternative.

Modeling with EMS

In real world applications an Energy Management System (EMS) is a dedicated computer that can handle complex algorithms to control a building's energy-related systems. The EMS feature in E+ has been developed to simulate many such novel control algorithms that are not possible with the previous generation of BPS programs. A programming language called EnergyPlus Runtime Language (Erl) is used to describe the control algorithms. E+ interprets and executes Erl programs as the energy model is being run. The EMS feature offers a Sensor object that reuses standard E+ output variables to provide a general way of obtaining a wide variety of input data. A counterpart EMS actuator object act as the conduit by which Erl programs control and overide the behavior of EnergyPlus components such as surface constructions, thermostat setpoints, internal shades etc. (Ellis et al. 2007)

METHODOLOGY

This paper evaluates a 4-tint state EC product with a multi-criteria control algorithm modeled using the EMS feature in E+. The EMS program setup and validation is first discussed in depth, followed by a review of annual energy savings of the EMS approach over the default option available in E+. A reference case with Low-E glass and shades is also used to compare energy savings with VDG for a midrise commercial office.

ENERGY MODEL SETUP

Glazing Model

Four ways to model vertical fenestration are offered in E+. The Full Spectral Model (FSM) is the preferred, 'benchmark' method of Modeling windows in E+, because it accounts for the wavelength-by-wavelength optical interactions between glass layers (Lyons et al, 2010). In addition, the FMS is based on full, peer-reviewed IGDB spectral data. Full Spectral IDF files for VDG were exported from LBL Window (LBNL 2017) for a standard dual pane IGU configuration. Figure 1 shows IGU properties calculated for each Tint state. A dual pane IGU with PPG Solarban60 Low-E coating was used as reference glazing along with 3% Openess Factor fabric shades. The shades are fully down whenever incident beam solar is > 50 W/m^2 & daylight glare index > 22. Shades are assumed to stay down the rest of the day but are reset to fully-up position again the next morning. The shade control was setup in this manner using an

EMS program to mimic the typical operation of manual interior shades in office buildings.

View Standard Dual IGU	Environmental Condition	U Value Btu/Hr-ft2-F	SHGC	Tvis
Tint 1	NFRC 100-2010	0.289	0.443	0.621
Tint 2	NFRC 100-2010	0.289	0.28	0.413
Tint 3	NFRC 100-2010	0.289	0.104	0.056
Tint 4	NFRC 100-2010	0.289	0.087	0.011

Figure 1 IGU properties by Tint State (Window v7.6)

Building Model

The DOE Medium Office 90.1 2010 prototypes for Phoenix, Chicago and San Francisco were used as the starting point for the building models (PNNL, DOE. 2018). The building is oriented along the cardinal directions, with the longer sides facing North-South (Figure 2).

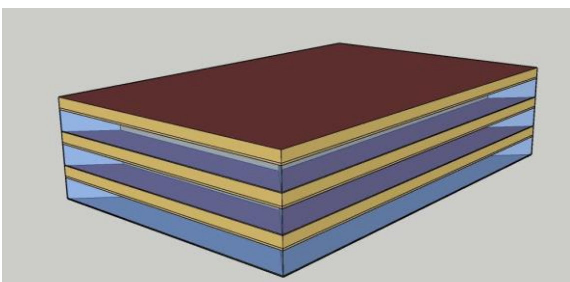

Figure 2 Prototype Building (Longer sides facing N-S)

The following modifications were made to the original DOE medium office models

- Add floor to ceiling curtainwall glazing- gross WWR increased to 65%
- ShadowCalculation method set to TimestepFrequency in order to compute the sun positions at each time step
- window frame conductance adjusted for frame area not explicitly modelled
- 100% of perimeter zones (15 ft) controlled by daylight sensors
- Simulation Timestep = 6 (Every 10 mins)

2-tint Switching Control

For the 2-tint model, the default construction for each window is Tint 1. The ShadingControl Object is assigned the Tint 4 construction, which is applied to a window, whenever the incident solar radiation is > 150 W/m^2. Sullivan et all. 1994, recommend a range of 63-190 W/m^2 as the control setpoints for high WWR buildings. Since only a single setpoint value can be entered in E+, a value close to the middle of the range was used.

EMS SETUP FOR 4-TINT STATE MODEL

Surface Construction State

An actuator that is useful for modeling dynamic technologies such as EC windows is available in E+. These actuators are called – Surface - and have a control type - Construction State - which allows EMS to assign and override the default construction assigned to the component (UIUC, LBNL 2017c). Each window object is assigned one actuator, used in conjunction with a ConstructionIndexVariable object. This input object is used to create and fill a global Erl variable with the value that points to the specific construction named in the object. The Erl variable is what gets assigned to the construction-state actuator's variable to override the default construction assigned to a surface. In this case the default construction assigned is Tint 1 which is the clearest EC state. The other 3 construction objects represent the darker tint states with Tint 4 being the darkest.

EMS program Structure

Intelligence® was replicated by converting the exact control logic to an EMS program. This program is executed by E+ before the zone loads are calculated. This calling point is appropriate since the construction state (tint state) of the window will affect the thermal loads in the zone, which need to be determined before computing the HVAC loads. The Erl code is setup to mimic the decision flow that drives Intelligence® in terms of the 3 functional modules - direct glare, heat load and weather control.

Module A - Direct Glare Control

The objective of this module is to determine at each time step (for sun up hours) if the sun is within a defined angular range of a given facade orientation and if the sun penetration on the floor (measured perpendicular to the façade) is exceeding a user defined maximum value called Penetration Depth (PD).

At runtime the EMS program first checks if the current timestep solar azimuth is within a precalculated azimuth range, based on window width and the positions of the two extreme most occupants facing a façade (Figure 3). These are considered critical azimuth angles for that façade, within which glare might occur.

However, once the sun is within the critical angular range it is necessary to also determine if the timestep PD is sufficient to reach the occupant or not (Figure 4). Assuming the maximum allowable PD to be 5ft, in floor layout terms this essentially means there is a 5ft perimeter area around the facade where there is no permanent occupant and no chance of direct glare. The PD can be adjusted to suit specific furniture layouts and can varied for different rooms on the same floor.

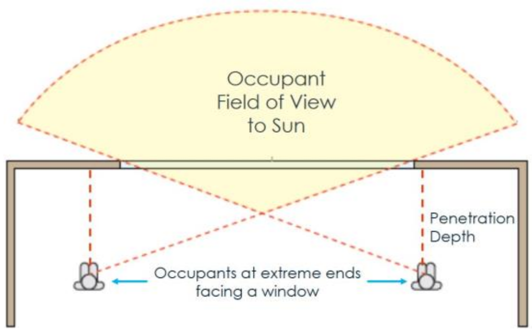

Figure 3 Critical Azimuth Angle Range

At each timestep the current PD is calculated based on the window height and solar altitude angle and compared against the maximum set PD. If the max PD is exceeded, then the module will propose Tint 4 or else Tint 1. The PD parameter can be adjusted to account for work plane height or eye height as per occupant preference.

Figure 4 Direct Sun Penetration Depth

Module B - Heat Load Control

The Heat Load module is designed to ensure that whenever direct glare is not a problem the transmitted solar gain through VDG is always below a pre-set threshold for that window orientation and location. The threshold for a given façade orientation is set to the maximum annual incident clear sky radiation x 0.21. For example, if the maximum incident clear sky radiation is 800 W/m^2 on a south facing window, the maximum transmitted radiation will not be allowed to exceed (800 x 0.21) 168 W/m^2 at any given time in the year. At each time step the EMS program will iteratively evaluate the SHGC of each tint state times the current timestep clear sky incident radiation on a window and select the lightest tint state that will meet the solar transmission threshold.

Clear sky incident radiation values for each of the four cardinal directions were calculated using the ASHRAE Clear Sky Tau Model (ASHRAE 2017) and read back to E+ via a Schedule: File object. The clear sky radiation values could have also been calculated at each timestep by incorporating the ASHRAE equations using Erl, but for this paper the values were generated externally.
This module does not use the incident radiation values already calculated by E+ using TMY3 data, because its purpose is to determine tint states for "theoretical" clear sky conditions only, while the TMY3 data is already adjusted for weather conditions such as cloud cover and can't provide just the clear sky data.

Module C – Weather/Daylight Control

This module mimics the function of the roof mounted photosensor array that is installed at each VDG site. It can override the tint state decision of the previous two modules and assign a clearer state based on total solar radiation levels reported in the TMY3 file.
Typically, a radiation level < 200 Watts/m^2 is used as an indicator of an overcast sky while values above 400 Watts/m^2 are indicative of clear sky conditions. These radiation values have been determined by site measurements at actual VDG installs. This EMS module uses two sensors to access the Site Direct and Site Diffuse solar radiation recorded in the TMY3 file.

Final Tint State Selection

The final IGU tint state selection at each timestep is determined based on a rule which first considers the maximum of the tint states returned by Modules A & B to cover for glare & radiation under clear sky conditions. That max value is then compared to the tint state returned by Module C, which is checking for cloud cover. The lower of the two is the final tint state. The window construction actuator for each window in the E+ model is then assigned the appropriate construction (tint state). The reader should note that in this modeling exercise the windows with the same façade orientation have been assigned the same tint state since there is no shading from surrounding buildings and each window is identical in size. However, the tint state for each EC window in an E+ model can be managed independently with EMS.

EMS VALIDATION

All relevant EMS variables were extracted from the eplusout.eso file and analyzed for expected tint state outputs according to the three functional modules. For the sake of brevity, EMS outputs for only a single day for a south facing window in Phoenix, AZ have been shown. This date (Oct 3rd) was found to have non-uniform sky conditions across the day, allowing for the demonstration of a range of tint states.

Figures 5 - 8 show how each EMS module made tint state selections and how the "Final" tint state was selected for the south window on Oct 3rd.

Module A - Direct Glare Control

On Oct 3rd, the sun rises and sets entirely on the south side and the solar altitude angle is low enough to ensure that the PD at each timestep is greater than an assumed max of 5 ft (1.52 m) all day. As a result, Mod A simply outputs Tint 4 for all hours (Figure 5) from sunrise to sunset.

Module B - Heat Load Control

Mod B selects the lightest tint state that will keep the "theoretical" transmitted clear sky radiation below a threshold, which is 180 W/m^2 (857 * 0.21) for the south façade in this case. It simply follows the clear sky radiation curve and steps up and down through the tint states (Figure 6). Tint 2 is sufficient for most of the day except between noon to 1 pm when the transmitted radiation crosses the threshold and Tint 3 is output.

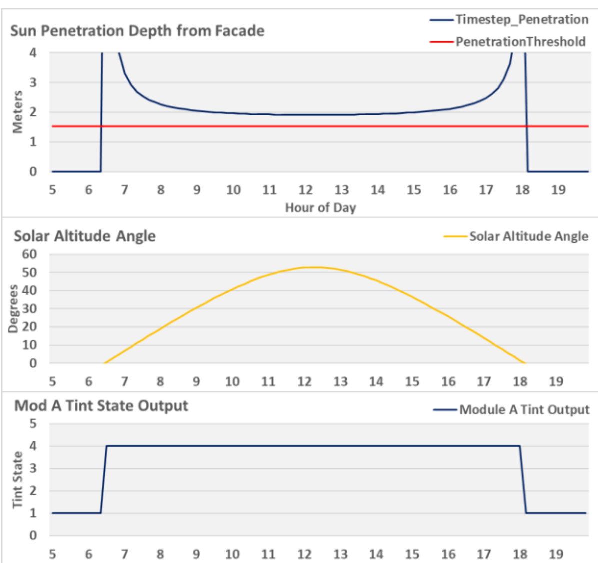

Figure 5 Mod A Validation – Oct 3(south window)

Module C – Weather/Daylight Control

Mod C tracks the total horizontal solar radiation as provided in the TMY3 file. On Oct 3rd, the radiation level rises steeply from 7 am to 9 am (Figure 7) and mostly stays above 400 W/m^2 until 2 pm, resulting in an output of Tint 4, except around 10 am to 11am when there is a drop. After 2 pm, the radiation level starts reducing and Mod C outputs Tint 3 until about 3 pm and then Tint 2 until sunset.

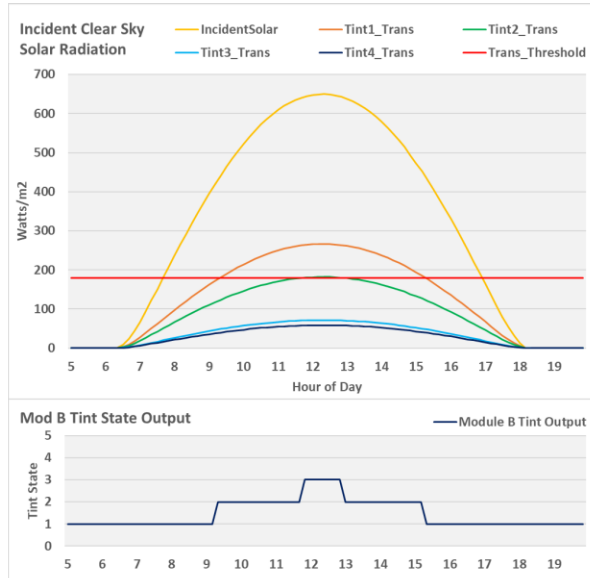

Figure 6 Mod B Validation - Oct 3(south window)

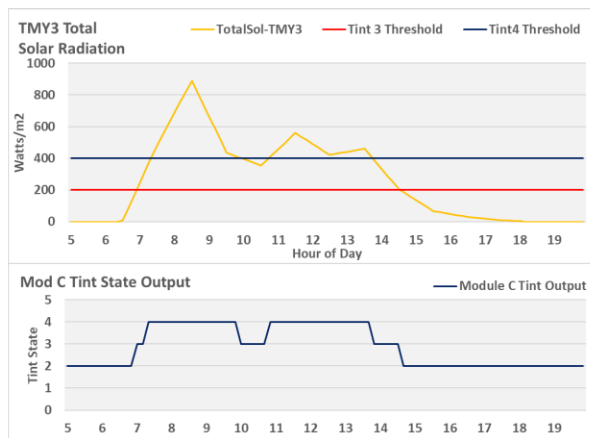

Figure 7 Mod C Validation Oct 3rd

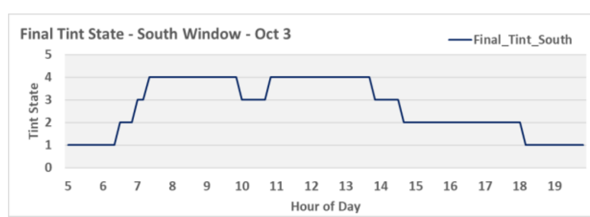

Figure 8 Final Tint State Output Oct 3rd (south window)

Final Tint State Selection

The final tint state selection for the South façade on Oct 3rd is mainly driven by Mod A from 8 am to 2 pm due to the low sun altitude and high radiation values, except whenever Mod C outputs a lower tint state based on a dip in the total solar radiation values in the TMY3 file. The final tint state output (Figure 8) is essentially the Mod C tint state output (Figure 7) superimposed on the Mod A tint state output (Figure 5). Incidentally, on Oct 3rd Mod B does not play a role in the final tint selection since the max of Mod A and B is always Tint 4 and glare control has a higher priority over radiation control. For this location, Mod B does play a role for clear sunny days in March and September when the sun is high enough to not penetrate beyond the 5 ft PD but still exceeds the transmitted radiation threshold.

RESULTS & DISCUSSION

Tint State Schedules

The timestep (every 10 mins) tint state selections made by E+ are added for the whole year and shown in Figure 9 as annual schedules. These charts shows the % of time (out of all annual sun-up hours) a window is in each tint state. Only the South and West facing window data is shown here. The tint state schedules for the three cities are shown as three columns.The Rows are aligned with a specific EC control option for VDG. For the 4-tint models two Penetration Depth (PD) options – 1ft and 5ft have been compared. PD is used to determine how often VDG needs to select Tint 4 to control for glare, based on sun penetration from the façade. The smaller the PD, the greater the need for Tint 4 under clear sky conditions.

Comparing the tint schedules of the 2-tint model with the 4-tint 1ft PD model shows a similar magnitude of Tint 4 usage. Since the SHGC for Tints 3 & 4 are very close it is reasonable to add up the % values for those two tints for the 4-tint 1ft PD model and compare that to the Tint 4 % value for the 2-tint model. Now the Tint 4 % values are even closer. This confirms that the default 2-tint solar control option is effectively the same as the 4-tint EMS model when occupants are sitting within 1 ft of the façade. As the PD threshold increases the use of the Tint 1 & 2 goes up, since higher sun angles don't penetrate far enough inside the space to require Tint 4 or 3. However this also depends on the site weather conditions. Among the three cities, Phoenix with its greater number of clear sunny days uses more of Tint 4 and Tint 1, implying that the EMS is simply using Mod A to make a glare or non-glare decision based on clear sky conditions, with less inputs from Mod C for weather overrides. Conversely, due to the greater frequency of cloud cover in SFO and Chicago, a much higher use of the lighter tint states can be observed. This implies that Mod C is now playing a more dominant role in driving the EMS to override the tint selections made by Mod A/B assuming clear sky conditions. This confirms that the EMS program is correctly selecting the tint states based on weather conditions such as clear or cloudy sky and the subsequent annual energy use prediction will be closer to actual VDG performance for a given location.

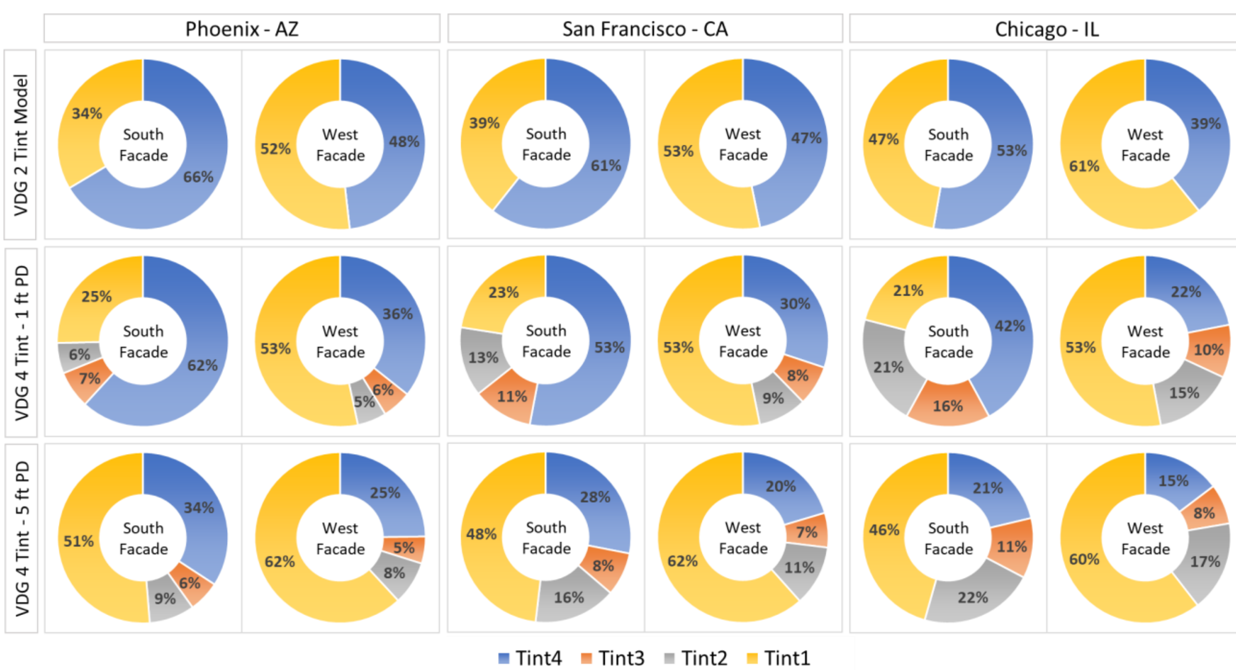

Figure 9 Annual Tint State Schedule (% of Annual Sun-Up Hours)

Annual Energy Use

Figure 10 presents the Energy Use Intensity (EUI) delta by end-use for the 4-tint EMS models over the default 2-tint model as a baseline. As observed from the tint schedules in Figure 9, when the PD increases from 1 to 5 ft the % time in Tint 4 reduces and the lighter tint states with higher Tvis are utilized more. This leads to lower lighting energy use compared to the 2-tint model (negative kBtu/sft values) but at the cost of higher HVAC energy use (cooling/heating/fans) leading to a net energy penalty. This general trend is observed in all the three cities.

In a cooling dominated location like Phoenix the savings from reduced lighting usage is not enough to offset the increased HVAC energy use due to solar gain. Hence the 4-tint 1ft PD model which uses Tint 4 the most shows the smallest net energy penalty over the 2-tint model. In SFO however, the cooler climate tips the balance in favor of lighting energy use over HVAC energy use. Here the 4-tint models perform slightly better than the 2-tint model due to greater lighting energy savings. Finally, in Chicago the increased HVAC energy use again outweighs the lighting savings with the 4-tint models for a net energy penalty compared to the 2-tint model.

One point to note here is that in all cases the heating energy use is going up with a higher usage of the lighter tint states. This might appear to be counter-intuitive since the lighter tint states have higher SHGC and in theory should allow more passive heating. However, with darker tint states the electric lighting power goes up producing more internal heat gain from the fixtures as defined in the DOE prototype models. This heat gain is helping to offset the space heating energy use. On the other-hand whenever the EMS program selects a lighter tint state its typically due to overcast conditions in the TMY3 or the sun is not on the façade. This implies that the incident radiation levels are low and hence the potential for passive heating during those hours is not as effective as the constant internal heat gain from electric lights.

Figure 11 shows the % annual energy savings for the VDG models over the LowE with manual shades baseline case. It should be noted that the savings delta between the 4-tint and 2-tint models for each city is within ± 1.5%. This is an acceptable delta given the fact that the 2-tint model is achieving energy savings by simply reducing HVAC cooling loads with a greater usage of Tint 4, without consideration for lighting energy use or annual daylight autonomy. The 4-tint EMS models on the other hand show comparable energy savings by balancing the HVAC and lighting energy use, with a greater proportion of lighter tint states (Figure 9) typically prefered by occupants.

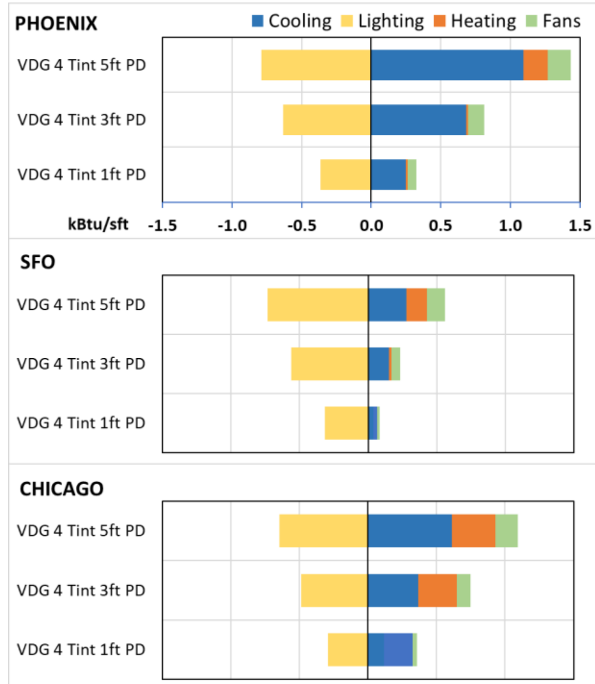

Figure 10 EUI delta for VDG 4-tint EMS Models over default 2-tint model

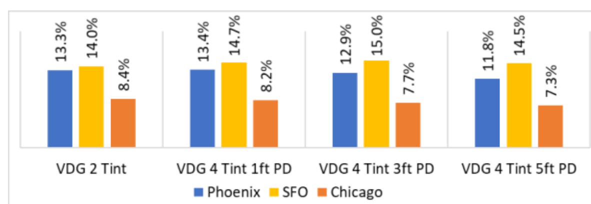

Figure 11 Annual Energy Savings over LowE+Shades

CONCLUSION

Based on the results for the 3 locations, this paper shows that EC glazing with a multi-criteria control strategy can provide annual energy savings by using an appropriate selection of tint states based on time of day, local weather, building geometry and interior layout. This paper also demonstrates from a modeling standpoint that such a control algorithm can be fully incorporated in E+. The default 2-tint model is found to be functionally equivalent to the 4-tint EMS model only when occupants are seated very close to the façade, requiring the glazing to mostly switch between the 2 extreme tint states with minimal use of intermediate states. The 2-tint model should be used only for this type of scenario to estimate total energy use without end-use breakdown. If a project needs separate estimates of energy end-uses such as lighting and HVAC, then a multi-state EC model should be adopted. Also, if E+ outputs are going to be used for thermal and daylight analysis, then a multi-state model must be used to get an accurate annual tint schedule for all tint states. Lastly, an EMS model is needed for performing calibrated simulation exercises for buildings that have multi-state EC products installed. However, in that case it is recommended to use actual site weather data instead of historic TMY3 data so that the E+ model tint state predictions match up with the actual on-site EC glazing behavior.

STUDY LIMITATIONS

This study was focused on demonstrating the modeling methodology of a multi-state EC product using annual energy end-use savings as the key metric. While the outputs from the 4-tint EMS models show a balanced mix of light & dark tint states a more detailed analysis in terms of glare, annual daylight availability and thermal comfort is needed to make any direct conclusion regarding occupant satisfaction. This study also did not look at peak demand reduction and HVAC sizing with EC vs LowE glazing. The author intends to address these topics in subsequent papers by utilizing the multi-state EC modeling methodology described in this study.

ACKNOWLEDGMENT

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NOMENCLATURE

BPS	Building Performance Simulation
DOE	Department of Energy
E+	EnergyPlus
EC	Electrochromic
EMS	Energy Management System Feature in E+
Erl	EnergyPlus Runtime Language
IDF	EnergyPlus Input Data File
IGDB	International Glass Data Base
IGU	Insulating Glass Unit
PD	Penetration Depth of Direct Sun on floor
SHGC	Solar Heat Gain Coefficient
Tvis	Visible Transmittance
VDG	View Dynamic Glass

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