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DEVELOPMENT OF A COMPARISON-BASED CONTROL STRATEGY OF ELECTROCHROMIC GLAZING FOR THE MANAGEMENT OF INDOOR LIGHTING AND ENERGY EFFICIENCY

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ABSTRACT

The daylight performance of buildings can be controlled by using electrochromic (EC) glazing as the tint of the EC glass can be altered by the application of an electrical voltage. One issue, however, is the selection of the strategy to control the tint level and obtain appropriate daylight and the least energy consumption. A new control strategy is proposed, which consists of comparing the simulated performances of all possible EC states and selecting the most appropriate at all times. The new strategy is compared to two commonly used strategies to show its ability to improve both lighting performance and energy efficiency.

INTRODUCTION

Windows are critical components of building envelopes as the U-value and solar transmittance of windows, which are generally significantly higher than that of the enclosing walls, may lead to issues related to heating, cooling and comfort (Karlsson et al., 2000). At the same time, windows provide natural light, which is beneficial to occupants (Burpee et al., 2009). Accordingly, finding the optimum trade-off between lighting performance and energy efficiency is an important design goal. Smart glazing materials are capable of switching their solar transmittance as a response to external stimuli such as temperature, sun exposure and electric voltage. Therefore, incorporating them in the building envelope provides the opportunity to improve lighting performance and energy consumption.

This study examines the incorporation of electrochromic (EC) glazing into buildings. An EC glass can change its transmission properties when an electric voltage is applied on the glass. Several commercial products exist on the market, which can vary their visible transmittance (VT) back and forth between 70% (clear state) and 1% (dark state) in minutes.

It is crucial to control EC windows as efficiently as possible in order to gain the most from their ability to affect lighting performance and energy consumption. This study focuses on the development of a new control strategy, called Comparison-Based Strategy (CBS), which consists of comparing the lighting and energy performance of each possible EC state using numerical simulation and objectively selecting the most appropriate at every hour of the year.

A number of studies present control strategies based on various setpoints such as visual comfort (e.g. illuminance level) and energy measures (e.g. heating and cooling loads). The criteria for evaluating the strategies were based on energy efficiency (Warner et al. 1992, Karlsson et al. 2000, Karlsson, 2001, Lee et al. 2004, Jonsson and Roos 2010a, 2010b). Other studies added more specific visual comfort metrics to their control techniques such as window luminance and glare (Gugliermetti and Bisegna 2003, Platzer 2003, Assimakopoulos et al. 2007, Lee and Tavil 2007, Sbar et al. 2012, Fernandes et al. 2013). Although these strategies have shown improvements in performance, there remains a need for developing a strategy, which depends on the instantaneous comparison of lighting performance and energy efficiency criteria. The goal of this study is to develop and evaluate a control strategy that uses numerical simulation results for both lighting performance and energy performance corresponding to the various states of the EC, and compares the performances of each case to select the best scenario in real time, hence the name Comparison-Based Strategy (CBS). Two variants of the strategy, referred to as CBSa and CBSb, are presented based on tradeoff preferences between criteria. The variants of CBS are compared to two commonly used strategies, which are based on solar radiation and illuminance as described in Karlsson et al. (2000), and Lee et al. (2004), respectively.

The remainder of this paper includes four sections. The first section presents the methodology describing the new control strategy and the corresponding algorithm. The new control strategy is then applied to an example building and the results are compared with those obtained with the two commonly used strategies. Finally, a parametric study for illustrating the characteristics of the strategy is presented.

METHODOLOGY

The new strategy is based on the instantaneous comparison of the performance of all scenarios, referred to as Basic Scenarios (BS), corresponding to all states of the EC and artificial light. In this research, numerical simulations are obtained using two commercial software, namely DIVA-for-Rhino (Solemma LLC, 2017) for lighting simulation and EnergyPlus™ (DOE and NREL, 2016) for energy consumption. The implementation of the control strategy is programmed in MATLAB® (Mathworks, 2015). Since the analyses of lighting performance (DIVA) and energy consumption (EnergyPlus) are completely independent from each other, all numerical simulations, corresponding to all Basic Scenarios, are run independently and all results are stored in a database that can be accessed by the controller (MATLAB).

For explaining the development of the numerical models, an example 1000-sqft building, shown in Figure 1, is used. The application focuses on the largest room (375 sqft), which includes a South-facing façade with five windows equipped with EC glass and a West-facing regular glass door. Each of the other four rooms includes a regular glass window. A porch provides shading on the West façade and is modeled as a 28-ft-long and 12.5-ft-wide overhang. Simulations of light and energy were performed for the mild climate of Anderson, South Carolina, based on the corresponding weather file available from the United States Department of Energy Library. Figure 2 shows the plan of the model and the selected room.

Figure 2. Plan of the model showing the main room, the table, and the sensor location in red

Daylight Simulation with DIVA-for-Rhino

The 375-sqft room (shown in Figure 3) is modeled in DIVA-for-Rhino with the commonly used surface reflectances of 0.2, 0.5, and 0.7 for the floor, walls, and ceiling, respectively. A table with a surface reflectance of 0.5 is located in the middle of the room and the horizontal illuminance is simulated at the center of the table. The visible transmittance (VT) of the EC glass is assumed to be 58% when the EC is OFF (i.e., clear) and 10% when it is ON (i.e., tinted). The West door is made of glass with a VT of 60%. The reflectances of the bottom surface of the overhang and the ground are 0.7 and 0.2, respectively.

In this paper, lighting performance is measured by the amount of light (i.e., horizontal illuminance in Lux) received at the center of the table in the main room. The Illuminating Engineering Society of North America (IESNA) recommends various target values around 400 Lux for typical office tasks (DiLaura et al., 2011). In this research, we lump these target values into a desired range defined by a lower threshold value ITH1 = 300 Lux and an upper threshold value ITH2 = 500 Lux. Outside of this range, the space is considered either too dark (i.e., below 300 Lux) or too bright (i.e., above 500 Lux). Note that these threshold values may be changed to accommodate other tasks if needed.

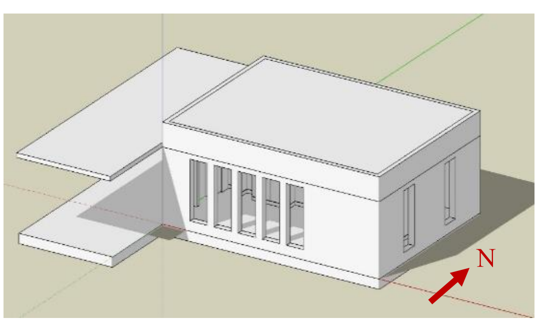

Figure 1. 1000-sqft building with EC windows on South façade and porch on West side

Figure 3. Interior space of the DIVA model

Figure 4 (a) shows the results of the simulated illuminance at the center of the table for seven days of summer for various VT values. As expected, the illuminance is significantly lower when EC is in darker states.

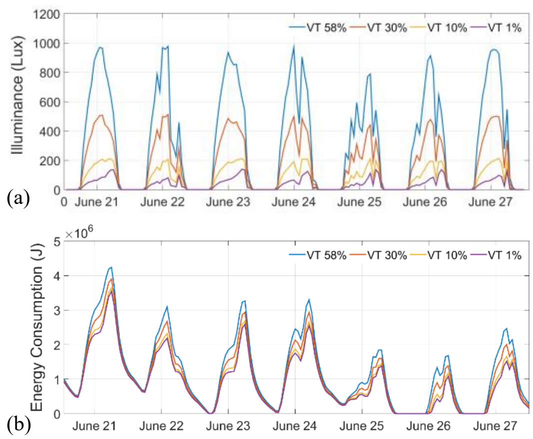

Figure 4. Simulated results for a week in the summer: (a) illuminance at the center of the table; (b) cooling energy for the whole building

Energy Consumption Simulation with EnergyPlus™

For the energy consumption simulation, the entire building is modeled with EnergyPlus™. A default heat-pump HVAC system is considered for heating and cooling the building with setpoint temperatures of 76ºF (24.4ºC) in summer and 72ºF (22.2ºC) in winter. Figure 4 (b) illustrates the results of hourly energy consumption for a week in the summer. As expected, the energy consumption is smaller when the EC is tinted. Note that during the winter the energy consumption would be smaller when the EC is OFF since the heat gain would provide passive heating.

Artificial Light

In this paper, we assume that the user is able to supplement daylighting with artificial light, referred to as AL, with an illuminance of 100 Lux at the center of the table when AL is ON and 0 Lux when AL is OFF. This value is then added to the level of horizontal daylight illuminance computed by DIVA to represent the total illuminance when AL is ON (Grondzik & Kwok, 2015).

The electrical power of the LED light is assumed to be 10W. The thermal energy emitted to the space by the LED bulbs is neglected. However, the electrical energy consumption of the LED bulbs is included by converting it to an equivalent thermal energy using the coefficient of performance of the heating and cooling system (assumed to be 3.0 in this paper) and then added to the total energy calculation.

Note that the artificial light could be implemented dynamically in the numerical simulations. However, the whole process would require twice as many numerical output files in the database without significant added benefit.

Basic Scenarios

As mentioned earlier, it is assumed that the EC has two possible tint levels when the EC is either OFF or ON. As a result, four Basic Scenarios (BS1 to BS4) correspond to the four possible combinations of the two levels of EC and the two levels of AL. The characteristics of the four BS's are shown in Table 1. The Basic Scenarios are simulated numerically for all working hours (i.e., 8:00AM to 6:00PM) seven days per week during the whole year.

Table 1. Description of Basic Scenarios

Basic Scenario	EC	AL	VT	SHGC(1)	AL Illuminance (Lux)
BS1	OFF	OFF	58%	0.40	0
BS2	ON	OFF	10%	0.13	0
BS3	OFF	ON	58%	0.40	100
BS4	ON	ON	10%	0.13	100

(1) SHGC: Solar Heat Gain Coefficient

Comparison-Based Strategy (CBS)

The Comparison-Based Strategy (CBS) was developed in this research to control the EC and the AL for selecting, at each hour, among the four basic scenarios, the best basic scenario that provides optimum horizontal illuminance at the point of interest and energy consumption. Two variants of CBS are developed. The algorithm of the first variant, CBSa, is shown in Figure 5. The strategy can be described simply as follows.

For each working hour, determine the number, N, of BS's that provide illuminance between 300 and 500 Lux. If N = 0, select the BS that has the lowest illuminance above 500 Lux. If no BS exist with illuminance above 500 Lux, select the BS that has the highest illuminance below 300 Lux. If N > 0, select the BS that consumes the least energy.

The variant CBSa shown in Figure 5 places priority on selecting a BS with illuminance above 500 Lux before selecting a BS below 300 Lux when there is no BS in the desired range. The variant CBSb is the opposite. It is defined by switching the order of the statements and placing priority on selecting a BS below 300 Lux before selecting a BS above 500 Lux when no BS fall in the desired range. The corresponding statement becomes:

If N = 0, select the BS that has the highest illuminance below 300 Lux. If no BS exist with illuminance below 300 Lux, select the BS that has the lowest illuminance above 500 Lux.

Note that the algorithm is formulated to accommodate any illuminance threshold values. In a real-life application, the user (e.g., building owner, designer, or occupant) would select these threshold values for a given building.

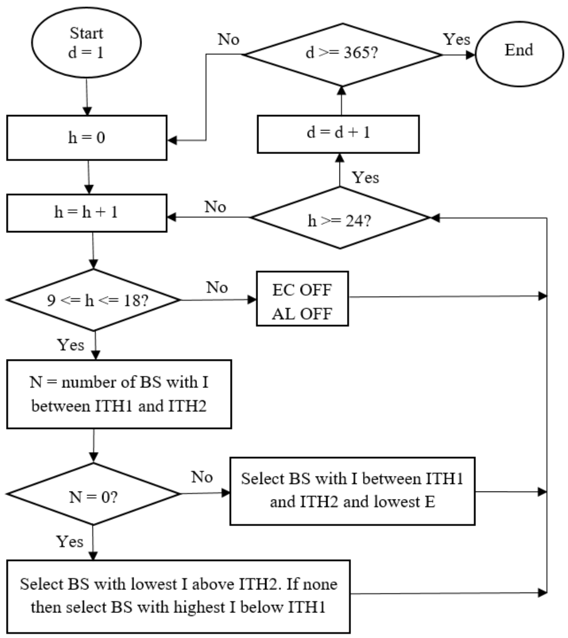

Figure 5. Algorithm of CBSa (h = clock time, d = number of days, ITH1 = lower illuminance threshold, ITH2 = upper illuminance threshold, I = horizontal illuminance (Lux), E = Energy consumption (J))

Comparison of CBS with Existing Control Strategies

The new control strategy is compared to two existing control strategies, referred to as the Solar Strategy (SS) and the Illuminance Strategy (ILL), which are commonly used for their simplicity of implementation.

Solar Strategy

The Solar Strategy (SS) is based on the use of an unobstructed façade sensor that measures the outdoor vertical Incident Solar Radiation Rate (ISR) at the center of the South wall. For the purpose of this research, the ISR is obtained from the EnergyPlus™ output. The EC and AL states are then selected at each hour of the simulation based on ISR. The strategy can be described as follows. If ISR is smaller than a pre-defined threshold value, TH1 = 100 W/m^2, then turn the artificial light ON (i.e., EC OFF, AL ON). If ISR is greater than TH1 and smaller than a second pre-defined threshold value, TH2 = 200 W/m^2, then turn AL OFF (i.e., EC OFF, AL OFF). Finally, if ISR is greater than TH2, turn EC ON (i.e., EC ON, AL OFF). Note that the threshold values of 100 and 200 W/m^2 are arbitrary values that must be optimized such that they provide the most appropriate indoor illuminance level at the point of interest and lowest energy consumption based on the climate and building orientation.

Illuminance-Based Strategy

The Illuminance-based strategy (ILL) is solely based on the hourly horizontal illuminance at the indoor point of interest (i.e., center of the table) and does not consider energy consumption in managing the EC states. The decision for choosing the EC and AL states aims to keep illuminance within specific thresholds. In a given hour (noted h), the controller checks the illuminance level of the previous hour, noted I_{h-1}. If I_{h-1} is within the desired predefined range (i.e., ITH1 < I_{h-1} < ITH2), the controller turns both EC and AL OFF. If I_{h-1} is not within the desired range, the controller selects the scenario that is the closest to the desired range. For example at hour h = 11, assume that EC is ON, AL is OFF, and I_{10} is 100 lux. Since I_{10} is lower than the desired range, the controller decides to turn EC OFF and AL ON at the next hour to compensate for the lack of light. Take another example where EC is OFF, AL is ON, and I_{10} is 700 lux. In this case, since I_{10} is higher than the desired range, the controller decides to turn EC ON and AL OFF at the next hour to make the room darker.

Note that, similarly to the SS strategy, the thresholds used in ILL have to be optimized for any application based on the climate and building orientation. The optimization is done using an optimization process that tries to find the most appropriate thresholds for reaching the best illuminance levels throughout the year.

DISCUSSION AND RESULT ANALYSIS

In this section, we compare the performance of CBSa and CBSb with SS and ILL. The main distinction between these strategies is the type of information used to make a decision on the EC and AL states. SS and ILL make decisions based on the exterior incident solar radiation and interior illuminance measured by sensors, respectively, without knowing with certainty whether or not the selected state is the optimum at all times. CBS is fundamentally different from SS and ILL since the decision is exclusively based on the comparisons of the numerically predicted performances of all possible case to determine with certainty which state is optimum at all times.

As mentioned above, the CBS algorithm is based on three illuminance ranges: below 300 Lux, between 300 and 500 Lux, and above 500 Lux. However, for the purpose of evaluating and comparing the four control strategies (CBSa, CBSb, SS, and ILL), five ranges must be defined:

Range 1 (R1): I < 100 Lux, undesirable (too dark);
Range 2 (R2): 100 Lux < I < 300 Lux, acceptable;
Range 3 (R3): 300 Lux < I < 500 Lux, desirable;
Range 4 (R4): 500 Lux < I < 1000 Lux, acceptable;
Range 5 (R5): I > 1000 Lux, undesirable (too bright).

Note that five ranges are not used in the control strategies, they are only used in the comparison of the strategy. Five ranges are needed, as opposed to only three, to make the distinction between acceptable and undesirable situations when the desirable range cannot be achieved.

In this research, a single point of interest (i.e., at the center of the table in the middle of the main room) is considered for evaluating lighting performance, which is sufficient to illustrate the proposed control strategy. However, several points within the space could be considered and an average value could be used to provide a more representative distribution of light throughout the space.

Figure 6 shows the number of hours where the illuminance, I, falls in each of the five ranges of interest for the four strategies. In general, CBSa and CBSb reveal a better lighting performance than SS and ILL since they are able to maintain the illuminance within the desired range (R3) 58% of the working hours compared to 17% for SS and ILL.

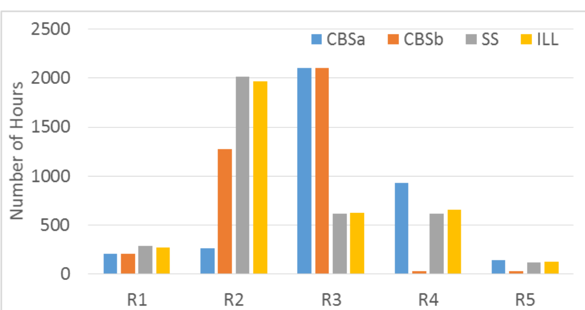

Figure 6. Number of hours for CBSa, CBSb, SS, and ILL categorized by illuminance ranges

It can also be observed that CBSa keeps the illuminance in R2 7% of the time and in R4 26% of the time. This is due to the fact that CBSa gives priority to brighter conditions whenever it cannot find a scenario within the desired range R3. Alternatively, CBSb keeps the illuminance in R2 34% of the time and in R4 only 1% of the time. This is expected since CBSb prioritizes dark over bright conditions as long as they are acceptable.

In terms of energy consumption, it can be observed from Figure 7 that SS is the most efficient strategy. CBSa, CBSb and ILL are 5%, 1%, and 2% less energy efficient than SS, respectively. Despite this, we can still conclude that CBSa and CBSb are more efficient strategies in terms of lighting performance since they provide 241% more hours in the desired illuminance range for an increase of only 5% and 1% in annual energy consumption.

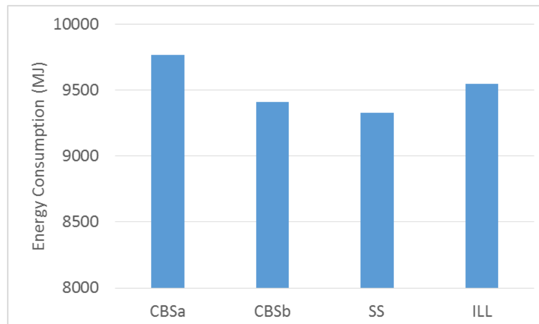

Figure 7. Annual energy consumption for CBSa, CBSb, SS, and ILL

Figure 8 illustrates the breakdown of the strategies by basic scenarios (BS). The BS that corresponds to natural lighting (i.e., EC OFF, AL OFF) account for only 5% to 20% of the time. The most commonly used BS is using artificial light (i.e., EC OFF AL ON) which accounts for 60% to 65% of the time for the four strategies.

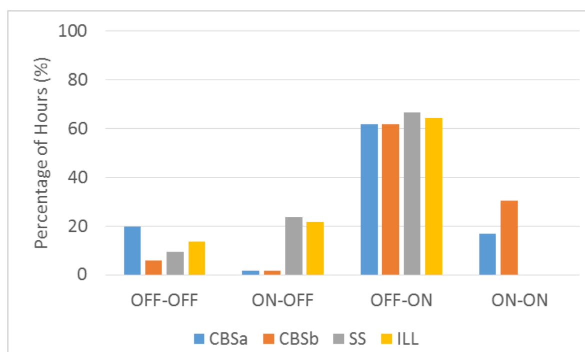

Figure 8. Number of hours corresponding to EC and AL states (e.g., "ON-OFF" means "EC ON, AL OFF")

The most interesting aspect shown in Figure 8 is the difference between CBSa/CBSb and SS/ILL. Contrary to SS and ILL, CBSa and CBSb use EC ON AL ON for a significant number of hours. This basic scenario is counter-intuitive since it corresponds to the dark state of EC, which prevents natural light from entering the room, and compensates with artificial light. This example suggests that CBSa and CBSb are able to identify and select basic scenarios that would not be selected otherwise even though they are beneficial overall. This is due to the fact that the electrochromic glass is assumed to have only two states which corresponds to 58% visibility transmittance when EC is OFF and 10% visible transmittance when EC is ON. In future work, the electrochromic glass will have four states, i.e., 58%, 30%, 10%, and 1% visible transmittance values, which will provide higher resolution and is expected to allow CBSa and CBSb to find scenarios that fall in the desired range without activating the electrochromic glass and artificial light simultaneously. Similarly, the artificial light will also include several illuminance levels such as 100, 200, and 300 Lux in order to provide more versatility.

PARAMETRIC STUDY

This section discusses the performance of the strategies with the effect of EC darkness, climate, and season.

Effect of EC Darkness

The previous results assume that the two-state EC varies its visible transmittance from 58% for the clear state to 10% for the dark state. In this section, two additional cases for the visible transmittance of the dark state are considered: 30% and 1%. Note that, in all cases, the visible transmittance of the clear state is 58%. Many other combinations of clear and dark states could be considered. However, these selected combinations are sufficient to illustrate the effect on the strategies.

The results of the three cases for CBSa and CBSb are compared to SS and ILL and graphically shown in Figure 9 and Figure 10.

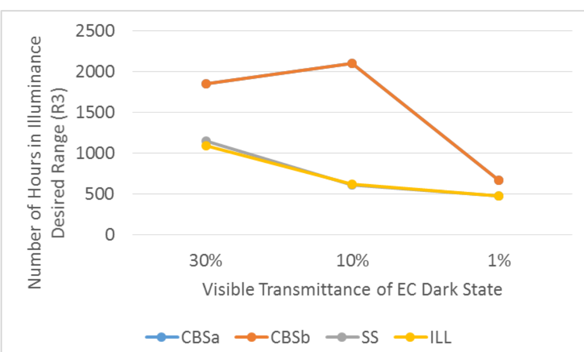

Figure 9. Number of hours in the desired illuminance range (R3) for three different VT's of EC dark state

The results show that the strategies perform differently for different levels of tint. In all cases, CBSa and CBSb provide significantly more hours in the desired range 3 than SS and ILL. For SS and ILL, the number of hours in the desired illuminance ranges decreases as the visible transmittance of the dark state decreases from 30% to 1%. In other words, a darker tint of EC makes it increasingly difficult for the strategies to provide the illuminance in the desired range R3. With the exception of CBSa, all strategies increase the energy efficiency as the visible transmittance of the dark state decreases. This is possibly due to the reduced heat gain in the summer without compromising the beneficial heat gain in the winter.

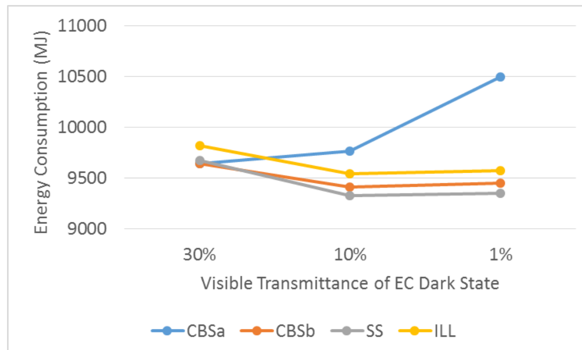

Figure 10. Comparison of energy consumption for three different VT's of EC dark state

Effect of Climate

Three different climates are considered. Miami, FL is a hot climate where any heat gain is mostly detrimental. Anderson, SC is a mild climate with approximately equal heating and cooling loads, where any heat gain through the windows is beneficial in the winter and detrimental in the summer. Bismarck, ND is considered a cold climate, where any heat gain through the windows is mostly beneficial.

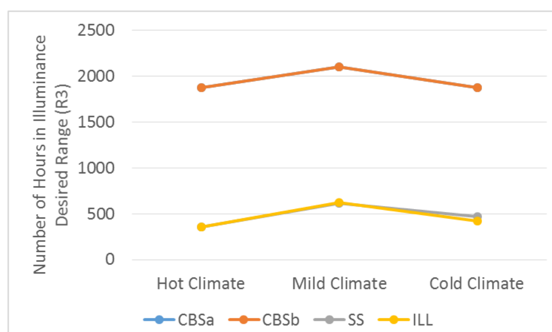

Figure 11. Number of hours in the illuminance desired range (R3) for three different climates

As seen in Figure 11 and Figure 12, the higher performance of CBSa and CBSb compared to SS and ILL seems to be independent of the climate. The number of hours in the desired range is significantly greater for

CBSa and CBSb while maintaining the same overall energy consumption.

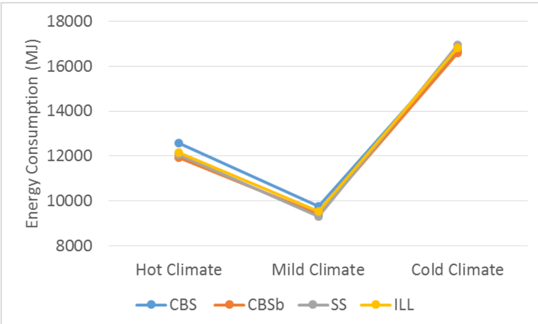

Figure 12. Energy consumption for three different climates

Effect of Season

The effect of season is studied in the mild climate of Anderson, SC for EC tint levels of 58% and 10%. We observe from Figure 13 and Figure 14 that, in all seasons, CBSa and CBSb provide the highest number of hours in the desired range 3. It should be noted that CBSa and CBSb provide more hours of the desired range in colder months.

In terms of energy consumption, it can be observed from Figure 14 that in each season, the strategies consume approximately the same amount of energy when compared with each other.

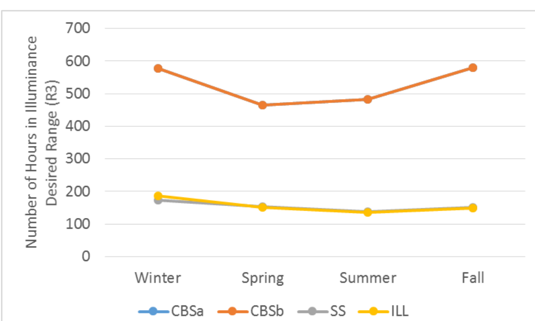

Figure 13. Number of hours in the illuminance desired range (R3) for the four seasons

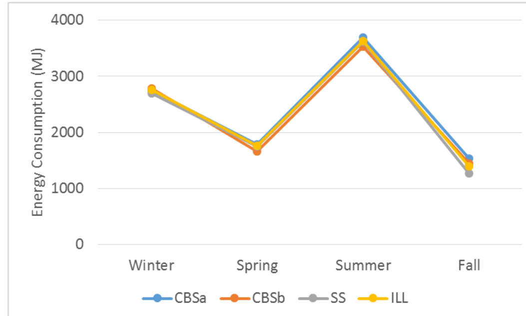

Figure 14. Energy consumption for the four seasons

CONCLUSION

Prior work has reported the benefits of using electrochromic glazing in buildings for improving energy efficiency and lighting performance. Yet, finding the best control strategy for getting the most out of the glass potential remains an important question. The control strategies proposed in the literature are mostly dependent on one aspect for changing the tint level such as interior light levels or outdoor radiation. In this study, two variants of a new strategy, called the Comparison-Based Strategy (CBSa and CBSb), are developed based on the instantaneous comparison of different scenarios defined by the tint level of the EC glass and the use of artificial lighting. The performance of each scenario is defined by two numerically computed criteria. The first criterion is to maximize the number of hours when the indoor illuminance at a point of interest falls in desired and/or acceptable predefined ranges. The second criterion is to minimize the annual energy consumption of the building. The performance criteria are simulated numerically using DIVA and EnergyPlus™ for all scenarios and stored in a database that can be accessed by the algorithm for comparing scenarios and selecting the most appropriate for each hour of the year. CBSa and CBSb are compared to two commonly used strategies available in the literature. In order to make a fair comparison, the parameters of both strategies were selected such that both perform at their best. It is shown that CBSa and CBSb provide better illuminance performance compared to the other strategies with no or little increase in energy consumption. However, some limitations, which will be addressed in future work, are worth noting. Although the amount of light, i.e., illuminance, is an important component of visual comfort, other aspects such as glare and luminance ratios are important quantities that should be considered. Since the research presented in this paper is focused exclusively on numerical analysis, the practical implementation of this new strategy in an actual building should be demonstrated, in particular using outdoor sensors that provide instantaneous weather conditions in order to extract the appropriate information from the numerical database. The usability of CBS and the impact of building occupation on the performance is a significant research question and will be addressed in future work. A future study could also be based on physical experimentation with and without human subjects to validate the quantification of lighting performance when using the proposed EC control strategy.

NOMENCLATURE

AL	Artificial light
BS	Basic scenario
E	Energy consumption (J)
EC	Electrochromic glass
I, I_h	Horizontal illuminance (Lux) at hour h
ILL	Illuminance-based strategy
ISR	Incident solar radiation rate (W/m^2)
ITH1	Lower illuminance threshold (Lux)
ITH2	Upper illuminance threshold (Lux)
CBS	Comparison-based control strategy
SHGC	Solar heat gain coefficient
SS	Solar strategy
TH1	Lower solar radiation threshold (W/m^2)
TH2	Upper solar radiation threshold (W/m^2)
VT	Visible transmittance

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