Pre-design tools and procedures for efficient integration of smart windows

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Abstract

In this paper, design tools are proposed to architects, engineers and other building professionals involved in the pre-design stage of a project, in order to facilitate the integration of smart windows into the envelope. Smart window technologies can influence the building energy performance and the occupants' visual comfort. Therefore, it is of prime importance for building professionals to possess sufficient tools and knowledge to evaluate properly the pros and cons of smart windows. One of the aspects complicating the analysis is that the overall performance of smart windows is largely influenced by how they are operated, and by a variety of parameters such as the building features (thermal mass, etc.), the occupants, etc. A numerical model was developed to simulate the dynamic modeling of a zone, with a façade occupied by a smart window, and was coupled to an optimization toolbox to determine the optimal control of the opacity. This work thus helps to gain a better understanding of how smart window opacity states and their control affect the overall energy performance of buildings. Finally, modeling strategies as well as preliminary control guidelines to assess energy performance of buildings with smart windows are proposed based on this analysis.

1 Introduction

In early stage of building design, a good estimate of heating, cooling and lighting demands is required in order to assess the performance of the design. Nowadays, for environmental and economic reasons, enhanced building technologies are developed and integrated into designs to reduce energy consumption. Actually, many envelope components have evolved from previously passive (Sadineni et al. 2011) to active technologies often qualified of "smart" (Loonen et al. 2011).

Among these technologies, smart windows (Jelle et al. 2012) present opportunities to reduce building energy consumption by controlling solar heat gains. However, the complexity of heat transfer interactions in buildings can make optimal control of such technologies quite complex to reduce efficiently the energy consumption while maintaining at the same time occupants' comfort.

Research in the field of smart windows was initiated in the late 80s and early 90s by the Environmental Energy Division of the Lawrence Berkeley National Laboratory. At that time, results were presented mainly for idealized electrochromic (Reilly et al. 1991)(Selkowitz et al. 1994) windows and demonstrated a potential regarding energy loads reduction and the possibility to reduce the size of the mechanical systems. Later, the evolution of smart window technologies enabled the assessment of the performance of real electrochromic glazings in different climates and with different simple control strategies (Gugliermetti & Bisegna 2003). Results confirmed that real smart windows present energy consumption reduction opportunities and showed that better performances are obtained when daylight is maximized to achieve visual requirements. Today, research on smart windows is highly oriented towards more complex and efficient control strategies optimizing the trade-offs between solar gains and daylight requirements (Jonsson & Roos 2010). Despite the work conducted up to now, it is usually agreed that more research on smart window dynamics is required to develop more efficient predictive control strategies and to offer more simplified tools to architects and building designers, in order to truly benefit from the potential of these technologies.

This paper presents a model to simulate a perimeter zone with smart windows, and optimization results of the overall building energy consumption considering the control of the smart window and artificial lighting system. The objectives of this work are: 1- Increase the understanding of the effect on energy performance of relevant parameters related to design, control or climate, 2- Assess the relevance of advanced control on a smart window/artificial lighting combined system, 3- Develop tools (procedures) to evaluate properly smart window potential benefits and design strategies for building perimeter zones.

2 Methodology

Building model description

A building model was developed to calculate the overall energy consumption (i.e., heating, cooling and artificial lighting demands). Thus, the model considers a building located in Montreal, Québec, Canada, and is subdivided into a lighting model created in Matlab (Dussault et al. 2012) and a thermal model developed in TRNSYS. Both lighting and thermal considerations are based on previously validated models (Dussault et al. 2012)(Arnault 2012).

To limit computational time, the building model considers a single perimeter zone (5 m width × 5 m depth × 3 m height) maintained at a constant temperature (T_{in}=20°C) with a double glazed south façade and five interior adiabatic surfaces. The floor surface is a massive 0.254 m thick concrete slab and all other surfaces are modeled with non-massive materials. Surface and floor properties are presented in Table 1.

Table 1: Surface and floor properties

	Values	Units
Surface solar and IR emissivities		
$\varepsilon_{\mathbf{window}}$	0.84	-
$\varepsilon_{\mathbf{interior\ surfaces}}$	0.90	-
Floor slab properties		
$c_{\mathbf{p,floor}}$	837	J/kgK
$\rho_{\mathbf{floor}}$	2243	kg/m^3
$k_{\mathbf{floor}}$	1.73	W/mK

Since todays' architecture values building designs with highly glazed façades (Poirazis et al. 2008), the exterior wall is modeled with a window-to-wall ratio (WWR) of 1, even though it is known that buildings with WWR between 0.3 and 0.5 consume less energy (Tian et al. 2010)(Miyazaki et al. 2005) . Consequently, results presented with WWR=1 should be considered as an upper limit in terms of energy performance enhancement provided by smart windows since smaller WWR will reduce the influence of smart windows on the overall energy consumption.

The smart window considered in the model is a double pane insulated glass unit (IGU) electrochromic (EC) window with four possible states of opacity. The IGU has 6 mm thick glass panes and a 12.7 mm gap (90% argon/10% air). EC layer is located on surface 2 of the IGU (i.e. interior surface of the exterior glass pane). Table 2 presents center-of-glazing values for each state, obtained from the International Glazing DataBase (IGDB) via the Window6 software. Note that the simulation model actually uses detailed angular values of the glazing properties, but incident values are reported in Table 2 for the sake of comparison between the different states.

Table 2: Center-of-glazing properties of a smart window

Smart window states	U-Value W/m^2K	SHGC -	Tvis %	Tsol %
State 1 (S1) (bleached)	1.63	0.47	62.1	38.1
State 2 (S2)	1.63	0.17	21.2	8.6
State 3 (S3)	1.63	0.11	5.9	2.4
State 4 (S4) (fully tinted)	1.63	0.09	1.5	1.0

Internal gains are related to artificial lighting, occupancy and equipment. They are summarized in Table 3, with their radiative and convective fractions. Only sensible heat has been considered in the model.

Table 3: Internal gains

Gain types	Heat gains W/h	Convective fraction %	Radiative fraction %
Occupants (3)	219	30	70
Equipment	200	30	70
Light	200	41	59

As presented in Table 3, gains for occupants consider 3 occupants doing moderate office work (73W/h/occupant). Furthermore, lighting gains consider a heat-to-return percentage of 20% that is thus not accounted for in the energy balance.

The building lighting model calculates the illuminance distribution on interior surfaces of the building considering combined daylight and artificial light. In order to offer proper luminosity on the workplane, a sensor has been set in the middle of the room’s width and at two thirds of the room’s depth (from the glazed wall). The minimal required luminosity at the sensor is labeled WP_{req} and has been set to 500 lux (Dubois & Blomsterberg 2011) during occupancy hours. Although more visual comfort considerations could have been included, the aims of the ongoing research are more energy-oriented. Further studies will consider more exhaustive visual comfort models and their impacts on control strategies and building energy consumption.

To represent a typical transient variation of internal gains and lighting requirements in office buildings, schedules have been created. Figure 1 presents the schedule of occupancy and workplane light requirement for week days. The use of miscellaneous equipment follows the same pattern as occupancy. For simplicity, internal gains are set to zero at all time during week-ends.

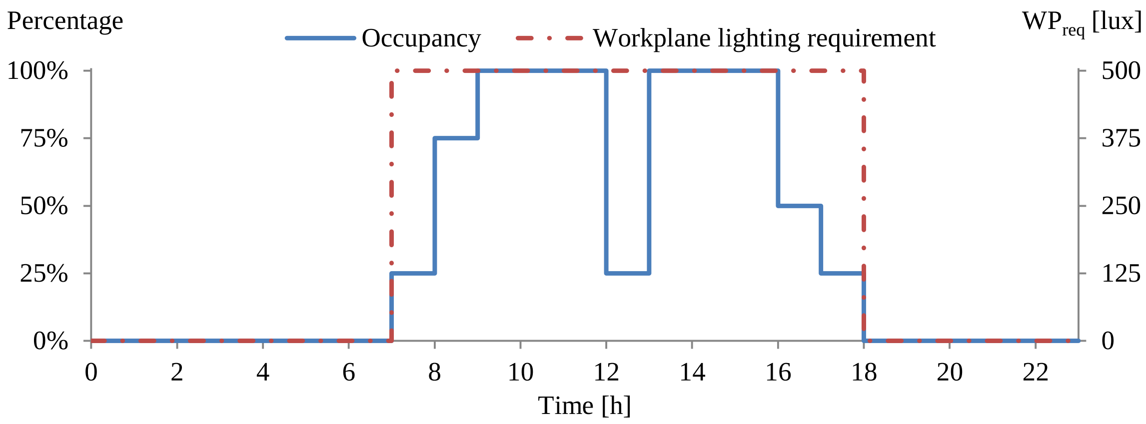

Figure 1: Week days schedule for occupancy and workplane lighting requirement

Control systems

The two building systems designed to control solar heat gains and lighting on the workplane are the smart window and the artificial lighting systems. Figure 2 illustrates the influence of the control systems on the overall energy consumption.

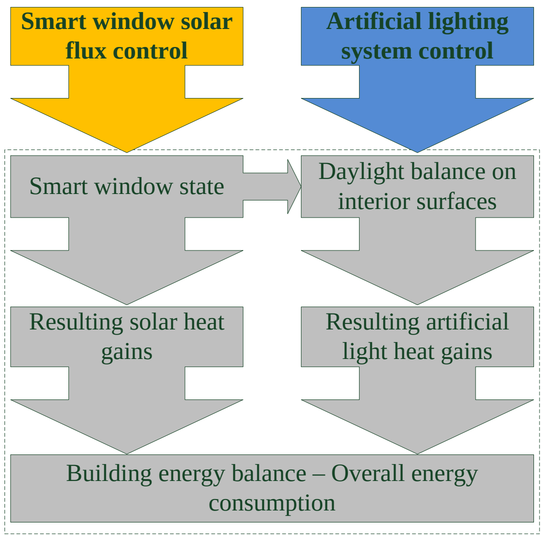

Figure 2: Systems control scheme

Many different control strategies could be used (Gugliermetti & Bisegna 2003) in order to achieve energy savings and visual comfort. To assess the relative effectiveness of different strategies, overall energy consumption results have been obtained considering the design control parameters presented in Table 4.

Table 4: Active systems control types

	Smart window	Artificial lighting
Control types	SW-1S	LCS1
	SW-4S	LCS2
		LCS3

In Table 4, there are two types of control for the smart window and three types for the artificial lighting. For the smart window, all control types begin with “SW” (standing for Smart Window) and are followed by a term “#S” defining the number of possible opacity states:

- 1S refers to a passive glazing, i.e. no control. The window remains at the same state (S1, S2, S3 or S4) during the entire simulation;
- 4S refers to four possible states, i.e. Clear, Fully tinted and two other intermediary states as presented in Table 2.

For the artificial lighting system, all control types begin with “LCS” (standing for Lighting Control System) and are followed by a number referring to the complexity of the control strategy:

- LCS1 refers to a basic artificial light control system always “On” during occupancy hours;
- LCS2 refers to an active control that can turn On/Off the lighting system depending on available daylight at the workplane sensor;
- LCS3 refers to an advanced artificial light control system that adjusts artificial light power to supply enough visible light at the workplane sensor during occupancy hours without over lighting (dimmer).

Simulation results presented in this paper were obtained by considering the 13 control strategy combinations of Table 5.

Table 5: List of control strategy combinations for simulations

Strategy combination #	SW	Light
1	SW-1S $_{State\ 1}$ (S1)	LCS1
2	SW-1S $_{State\ 2}$ (S2)	LCS1
3	SW-1S $_{State\ 3}$ (S3)	LCS1
4	SW-1S $_{State\ 4}$ (S4)	LCS1
5	SW-1S $_{State\ 1}$ (S1)	LCS2
6	SW-1S $_{State\ 2}$ (S2)	LCS2
7	SW-1S $_{State\ 3}$ (S3)	LCS2
8	SW-1S $_{State\ 4}$ (S4)	LCS2
9	SW-1S $_{State\ 1}$ (S1)	LCS3
10	SW-1S $_{State\ 2}$ (S2)	LCS3
11	SW-1S $_{State\ 3}$ (S3)	LCS3
12	SW-1S $_{State\ 4}$ (S4)	LCS3
13	SW-4S (optimization)	LCS3

The first strategy combination of Table 5 is the base case scenario considering a passive window having the properties of State 1 of the EC window, with lights “On” during all occupancy hours. This scenario has been set as the base case since it represents a typical perimeter building office with a passive low-e ($\varepsilon_{EC,layer}$=0.147) double insulated glazing unit with only manual control for light. Combinations 2 to 12 allow determining the optimal passive state as a function of the lighting strategy. Finally, combination 13 considers optimization runs (see the following section for details about the optimization procedure) that evaluate optimal hourly smart window states to minimize overall energy consumption with four possible SW states (States 1 to 4). Optimization runs consider a totally bleached SW state (State 1 in Table 2) between sunset and sunrise.

Optimization procedure

Before analyzing the behavior of a combined smart window/artificial lighting system, one must first determine which control gives optimal results. To obtain such control for active SW strategies (i.e., strategy 13 of Table 5), a genetic algorithm (Gosselin et al. 2009) has been used. This algorithm minimizes an objective function (in this case, the overall energy consumption) by evaluating a certain number (population) of different combinations (phenotypes) of the design variables (SW State at each time step). The initial population evolves generation by generation by keeping the phenotypes of a generation that give the best results and by creating the following generation from those phenotypes and newly created ones (children) by crossovers and mutations.

The design variables involved are thus the SW states at each simulated hour where sunlight is available. To minimize computational time, hourly artificial lighting variables have not been considered as design variables, but rather as values adjusted to meet requirements depending on the SW state, LCS and the lighting set point.

The objective function to minimize is the overall energy consumption (C_{OEC}), in Wh/m^2 of floor area, defined as:

$$Q_{Tot} = (Q_{Heat} + \frac{Q_{Cool}}{COP} + Q_{Light}) \quad (1)$$

where Q_{Heat} is the total energy consumed for heating in [Wh/m^2], Q_{Cool} is the total energy consumed for cooling in [Wh/m^2], COP is the coefficient performance of the cooling system and Q_{Light} is the total lighting energy consumption in [Wh/m^2].

Optimization parameters and convergence criteria used for the optimization runs are presented in Table 6.

Table 6: Parameters of the Genetic Algorithm

Number of phenotypes per generation	40	
Maximum number of generations	2000	
Number of generations with unchanged C_{OEC} value before convergence	250	
Proportion of children per generation	80	%
Children mutation probability	4	%
Number of chromosomal crossover	1	

3 Results

Effect of light control strategy with fixed opacity state

To integrate properly smart windows into building designs, one must first understand the behavior of each possible state of smart windows over a complete year. This way, the state leading to the lowest energy consumption could be determined for each season as a function of the lighting strategy.

Figures 3 to 5 present, for the artificial lighting controls LCS1, LCS2 and LCS3 respectively, the overall energy consumption for a typical day of each season for the four different fixed SW states (passive mode, i.e. no control is applied to the SW). These figures also present the approximate yearly behavior (average) for each state which is the average of the results for each typical day.

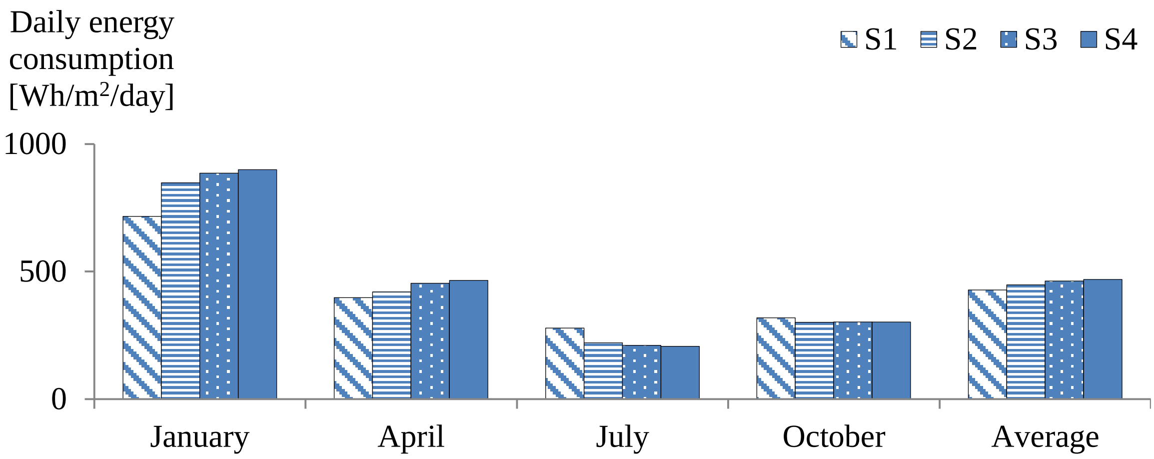

Figure 3: Effect of window passive opacity state on building loads with light control LCS1

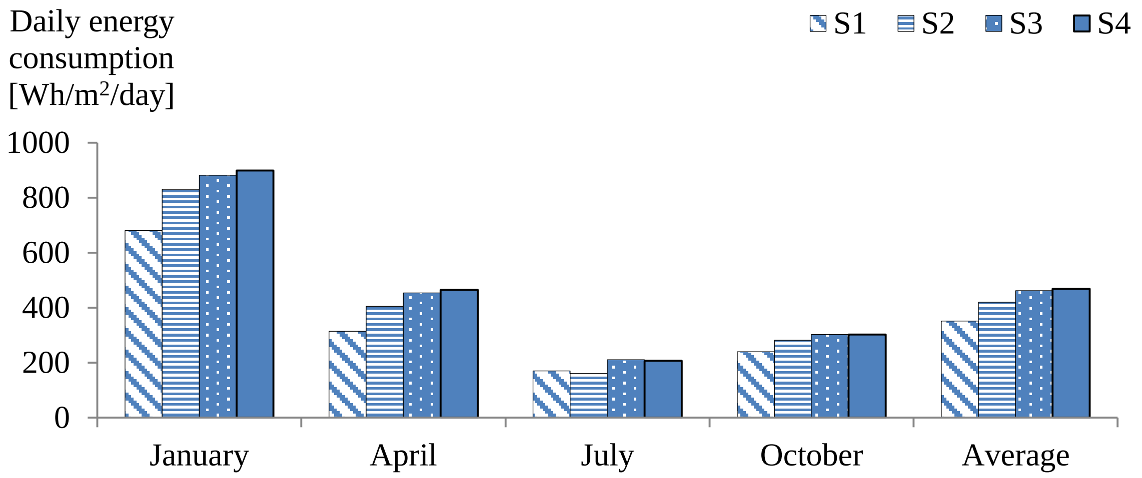

Figure 4: Effect of window passive opacity state on building loads with light control LCS2

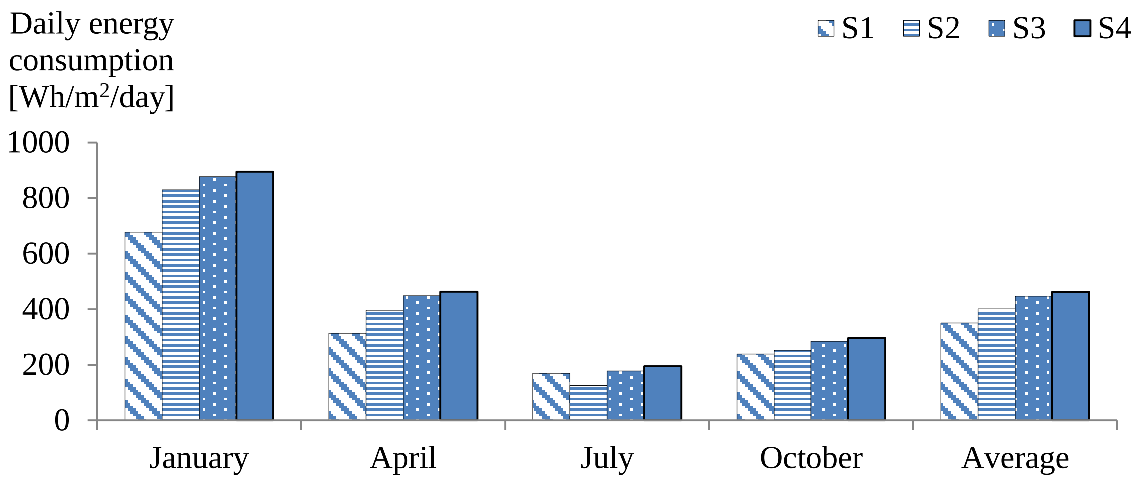

Figure 5: Effect of window passive opacity state on building loads with light control LCS3

From Fig. 3, we realize that a passive window with the sate S1 (clear state) combined with artificial lighting always on during office hours (LCS1) offers the lowest energy consumption values for January and April (where outside temperature values are lower, i.e.: mean daily temperatures around -13°C and 0°C, respectively) while passive windows with states S4 and S3 offer the lowest values for July and October (where outside temperature values are higher, i.e.: mean daily temperatures around 19°C and 8°C, respectively).

In Fig. 4, it is observed that the on/off control strategy (LCS2) for the artificial lighting system has the following effects compared to the situation with lights always turned on (LCS1): 1 – There are now changes for January and April, 2- The best passive state changes from S4 to S2 in July and from S3 to S1 in October. Figure 5 (with LCS3) exhibits similar trends compared to Figure 4 (LCS2).

Regardless of the lighting control strategy considered, Figs. 3, 4 and 5 show that even if different passive states are more adapted for different seasons, S1 seems to be the most appropriate state for a passive use on an annual basis for the building considered. To benefit from optimally varying window properties at all time, a building designer must integrate a smart window control to reduce energy consumption.

To assess the increase in performance associated to different controls, one could use the behavior obtained from those figures in a building simulation software to evaluate more precisely benefits of smart windows by dividing passive states by season. For example, if a designer is interested in a building with lighting control LCS1, he/she could run a simulation over a year using S1 for days of winter and spring seasons and S4 and S3 for summer and fall respectively. This procedure applied to the present building reduces the yearly energy consumption from 150.64 kWh/m^2 (S1-LCS1) to 143.71 kWh/m^2 ($S1_{winter\text{-}spring}$+$S4_{summer}$+$S3_{fall}$-LCS1), which corresponds to a reduction of about 4.6% only by considering a simplified control with four opacity changes per year. The same procedure applied for lighting control LCS3 reduces the yearly energy consumption from 118.16 kWh/m^2 (S1-LCS3) to 111.01 kWh/m^2 ($S1_{winter\text{-}spring\text{-}fall}$+$S2_{summer}$ –LCS3), which corresponds to savings of about 6.1%.

Effect of smart window control on building loads

The procedure presented in the previous section based on optimal seasonal SW states to approximate SW thermal performance could be followed for a particular project by building designers for a preliminary evaluation of potential savings. For designers interested to assess more precisely potential savings, a procedure taking into account more finely the modularity of smart windows should be elaborated. This section presents avenues that might offer solutions with this respect.

Figure 6 reports the results of a full hour-by-hour optimization of the SW opacity, combined with the advanced lighting control (LCS3). As presented in the previous section, S1 represents the most efficient passive state over a complete year for the building considered. For this reason, the three S1 results of the previous section are repeated in Figure 6 for the sake of comparison.

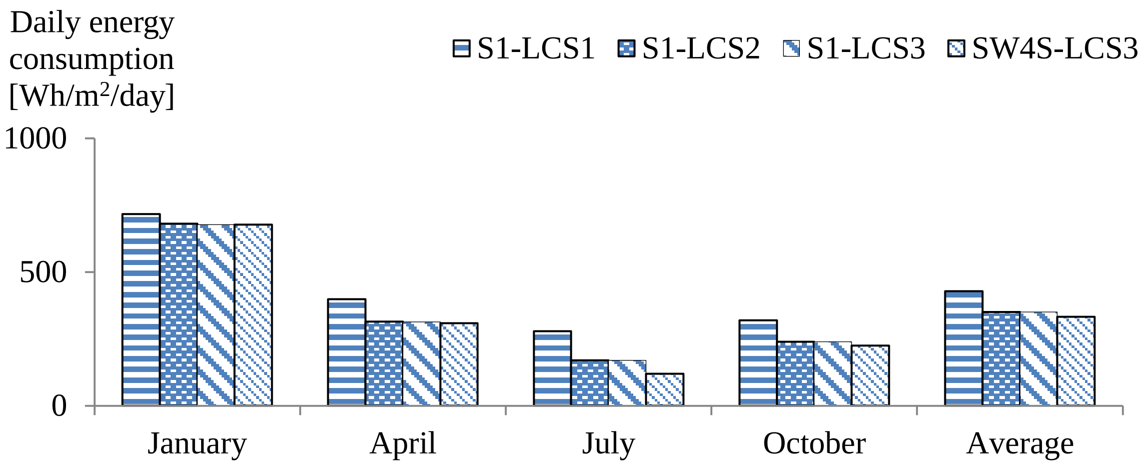

Figure 6: Effect of smart window opacity state control with lighting control LCS3 on building energy consumption compared to passive states

From Fig.6, we can observe that the hourly control (optimization) of the smart window brings more energy savings, with average reductions of the energy consumption of 22.3%, 5.2% and 4.9 % compared with S1-LCS1, S1-LCS2 and S1-LCS3, respectively.

Moreover, it is clear from Fig.6 that the highest energy consumption reduction is happening during the hot season (July) which corroborates results of other studies on the subject (Sullivan et al. 1996). In July, reductions of the energy consumption are 57%, 18% and 18% compared with S1-LCS1, S1-LCS2 and S1-LCS3, respectively. Savings for S1-LCS2 and S1-LCS3 are the same since daylight illuminance values on the workplane are higher than the required set point for all hours in both cases.

Compared to passive season control ($S1_{winter\text{-}spring\text{-}fall}$+$S2_{summer}$ –LCS3), hourly control optimization (SW4S-LC3) of the smart window brings average reductions of the energy consumption of about 1.8%, meaning that the simplified seasonal control approach could provide a fairly good estimation of smart window potential.

Figure 7 presents results for July of hourly opacity states optimized to reduce the overall energy consumption and its influences on cooling, heating and lighting loads compared to S1-LCS3 (best passive state over all seasons) and S2-LCS3 (best passive state for summer).

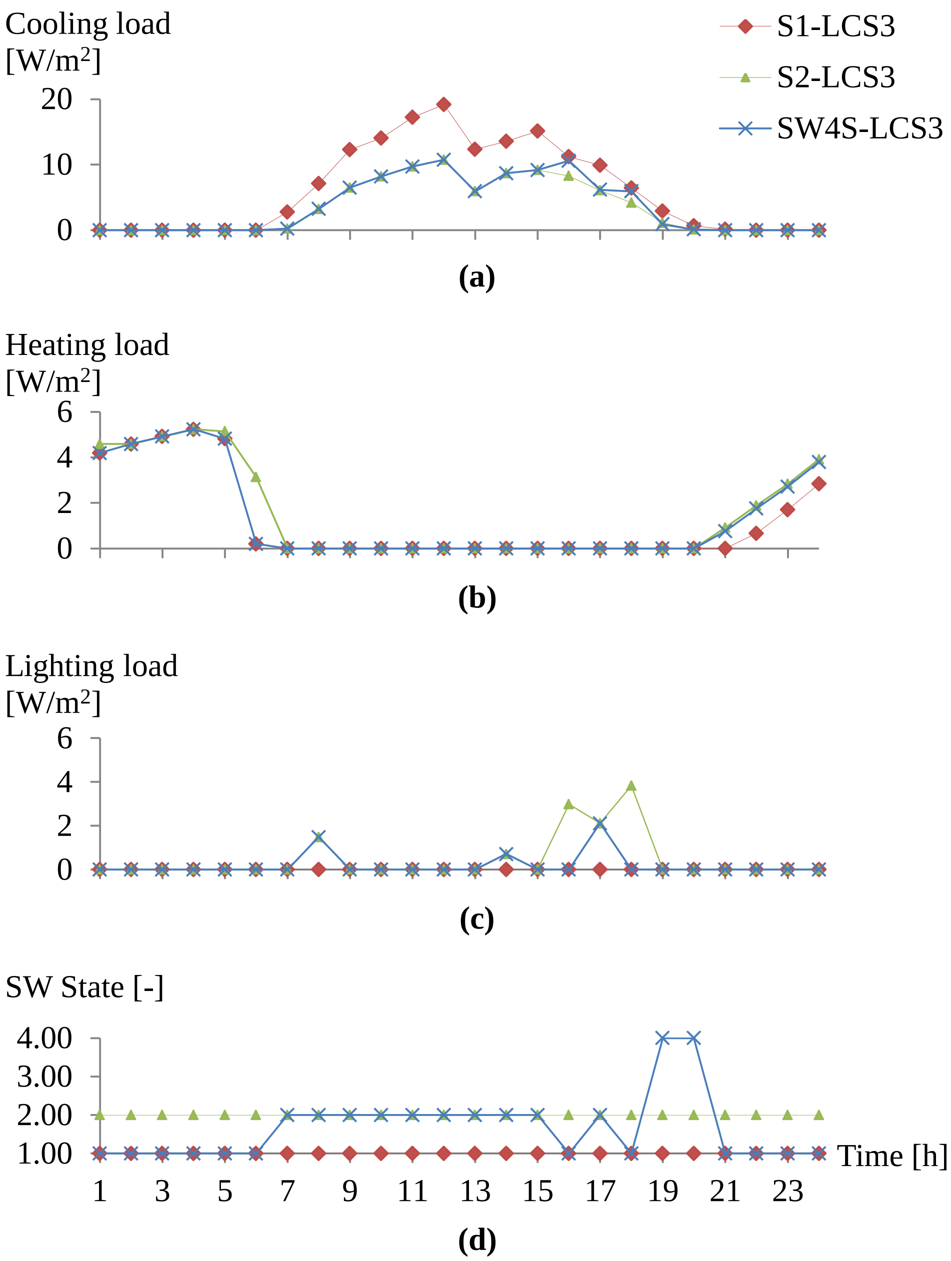

Figure 7: Hourly results for a typical day of July – a) Cooling loads, b) Heating loads, c) lighting loads and d) Smart window optimized opacity state

From Fig. 7, we can realize that the optimal hourly control of the smart window states (Fig. 7d) influences in a complex manner the cooling load (Fig. 7a). It is reduced due to lower solar heat gains at high opacity compared to S1-LCS3 and slightly increased due to higher solar heat gains (16h and 18h) compared to S2-LCS3. The heating load is also affected (Fig. 7b); it is increased slightly during evening and at night compared to S1-LCS3 due to the fact that the thermal mass of the floor slab has not received as much solar energy during the day. Compared to S2-LCS3, the optimal solution reduces heating due to higher solar heat gains. Furthermore, heating load results highlight the fact that a 24 hours period does not take into consideration the charging and discharging of the thermal mass for hours previous to the simulation start time. Finally, for the artificial lighting demand (Fig. 7c), some hours require additional artificial lighting since less daylight reaches the workplane compared to S1-LCS3.

Compared to S2-LCS3, less artificial lighting is required due to higher visible transmittance states at some hours.

From the results presented in this section, it is thus clear that an efficient hourly control of SW states provide higher savings than passive states. This being said, simple procedures shall be offered to building designers in order to roughly evaluate SW performance based on an optimal or nearly optimal control. The following guidelines are preliminary avenues that are proposed to address this need. They are based on the observations of optimized opacity such as that presented in Fig. 7. The following optimal SW behaviors can be noted:

- At night (solar radiation = 0 W/m^2) → Switch to state S1
- While $Q_{heating,S1} > 0$ → Switch to S1 to allow as much solar radiation as possible in the building
- While $Q_{cooling,S1} > 0$ AND Workplane lighting requirement = 0 lux → Switch to S4

Otherwise, i.e. when there is a cooling load at a given time ($Qcooling,_{S1} > 0$) and also a workplane lighting requirement larger than 0, the optimal state of the SW, S_{opt}, varies. Based on the optimization results, it was found that the best SW state was mostly correlated with the total solar irradiation incident on the window, G_{tot}. The approximate range of G_{tot} for which the optimal state is S1 is reported in the first line of Table 7, for each season. Similarly, the next lines of this table correspond to the range of G_{tot} for which the best state is S2, S3 or S4.

Table 7: Range of total façade incident solar radiation for which the best SW state is as indicated, during cooling hours with a lighting requirement of 500 lux.

Optimal SW state	**G_{tot} [W/m^2]**			
	Winter	Spring	Summer	Fall
S1	All values	0 - 225	0 - 100	0 - 110
S2	-	225 and over	100 and over	110 and over
S3	-	-	-	-
S4	-	-	-	-

Table 7 also reveals that the range of G_{tot} for which each state is optimal depends on the season considered. In other words, there are other aspects than just total solar incident irradiation to consider. For example, the indoor-to-outdoor temperature difference also affects to some respect which state is best at a given time.

Further studies will focus on the development of a more general correlation for the optimal state selection considering G_{tot}, the exterior-to-interior temperature difference, and internal gains. To ensure that the procedure and guidelines presented in this section are applicable to different building projects, annual simulations for different types of building, orientations and climates should be conducted. Further research will cover these elements.

4 Discussions and Conclusions

This paper presents thermal and daylight analysis results based on simulations for south perimeter building zones located in Montreal.

Considering an approach with passive opacity states (i.e., no optimized hour-by-hour changes of opacity), we determined the energy consumption as a function of the opacity state, the climate and the lighting strategy. The bleached state was better during cold exterior temperatures while darker states were preferred for warmer seasons. However, regardless of the selected artificial lighting control strategy, the bleached state is preferred to other darker passive states over an annual basis for climates as in Montreal. Considering these results, a preliminary design assessment procedure was proposed for designers. The procedure consists in calculating the building energy consumption with glazing properties for all passive states for a typical day of each season to evaluate which passive state is best (season by season). Then, a calculation combining these results could be performed, using the best selected passive state at each season to estimate total energy consumption with the integration of smart windows at a given season. Annual energy savings could thus be estimated compared to a base case building. It was found that this approach can provide a fairly good estimate of the SW performance on an annual basis.

To assess the relevance of advanced active SW control strategies, a genetic algorithm optimized hour-by-hour the opacity of a SW. Results have shown that optimal control is desirable mostly for warmer seasons and could offer savings between 5% and 22% compared to the best yearly passive state, depending on the artificial lighting strategy. Also, since the highest savings have been obtained for the summer, a more detailed results comparison have been made with the best yearly state (S1) and the best passive summer state (S2). It was shown that optimized control outperforms the passive state S1 mostly by reducing cooling loads and the passive state S2 mostly by reducing heating and lighting loads. Preliminary guidelines for control have been proposed based on the results of optimization. These guidelines consider the optimal state selection at each hour depending on heating or cooling conditions, lighting requirements and total solar radiation incident on the glazing.

As mentioned previously, reported results are relevant for South oriented perimeter zones of an office building, in a moderate climate. For different climates and/or façade orientations, one could follow the methodology presented in this article to obtain a relevant assessment of SW in terms of building energy consumption. Further studies will examine the influence of relevant building parameters (façade orientation, thermal mass, COP of systems, acceptable interior T° ranges, and other climates) on optimal results. More generic performance indicators and procedures will be developed for predesign of buildings with integrated SW.

5 Acknowledgements

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