MODELING OF ELECTROCHROMIC GLAZING SWITCHING CONTROL STRATEGIES IN MICRO-DOE-2.1E

Maria Corsi, Radu Zmeureanu and Paul Fazio[*]

Summary

This paper aims to advance the knowledge related to the simulation of electrochromic glazing switching control. First, a critical evaluation of existing control strategies currently available in the DOE-2.1E program was performed to study the effect of several driving variables on the cooling load of an existing large office building. Second, the present capabilities of the DOE-2.1E program were expanded using the Functional Values approach which enables the user to introduce new algorithms (e.g., control strategies) without recompiling the program. Third, the effect of switching time was studied for the building's perimeter zones. Since electrochromic windows will affect both building energy consumption and visual quality, the optimization of the switching time was formulated as a multi-objective problem with two conflicting objectives (energy and visual quality). The Pareto optimum solutions are shown for different weighting coefficients applied to the energy performance and visual quality. General rules for switching were then extracted from the results, and will be used in future work to formulate the basis of an optimized switching strategy to be analyzed using the DOE-2.1E program.

Key words: Electrochromic windows, energy analysis, office buildings, computer modeling

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1. INTRODUCTION

Electrochromic coatings are part of a family of chromogenic materials whose solar-optical properties can be switched from a transmissive state to a reflective or absorptive state over the solar spectrum thereby providing greater control of solar gains and daylight transmittance [1]. These advanced coatings generally consist of five layers: an electrochromic layer, an electrolyte or ionic conductor and a counter-electrode are sandwiched between transparent conductors [2]. The transmittance of the electrochromic layer can be changed from a bleached state to a colored state by applying a low voltage across the transparent conductors causing ions to move from the counter-electrode to the electrochromic layer. The coating is returned to its original state by reversing the voltage. Control of the coating properties can be linked to a building energy management system such that a glazing on which the coating has been applied can respond to a broad range of conditions such as climate, building operation, time of day or season. In contrast, conventional glazings (e.g., clear, reflective, tinted) do not offer optimum solar control capabilities since their properties remain static over the broad range of environmental conditions.

The first computer simulation studies on the use of electrochromics compared the solar-optical properties of three types of idealized electrochromic glazings, whose properties were made to switch over different regions of the solar spectrum (visible, infrared, and the entire solar spectrum), and also addressed the differences between reflecting and absorbing electrochromics [3]. Computer simulations were also performed using the DOE-2 program for commercial buildings located in hot climates in order to quantify the potential energy savings incurred by using idealized electrochromic glazings [2,4]. In these studies, the control objective was to maintain adequate illuminance levels in the perimeter zones, while other control strategies were not explored.

Recent research work addresses some issues related to switching control strategies for commercial and residential buildings [5-8]. Such studies compared the energy performance of buildings resulting from the use of several existing models of control strategies incorporated within the DOE-2 program. It was found that a control strategy based on illuminance levels offered the best annual energy performance for commercial buildings, compared with control based on cooling load or total incident solar radiation. Selkowitz et al. [9] concluded that the maximization of energy savings for cooling, heating and lighting would require a predictive control strategy to account for building characteristics such as thermal mass. Lee and Selkowitz [6] have studied the feasibility of using a complex predictive control strategy by comparing the performance of narrow-band and broad-band electrochromic glazings (the narrow-band electrochromic has a lower range of shading coefficient than the broad-band electrochromic) controlled by illuminance levels to a theoretical optimum envelope and lighting system. They concluded that simple strategies are suitable for the narrow-band electrochromic, while a predictive control strategy would improve the energy performance of the broad-band electrochromic.

Two main issues must be addressed in order to successfully model the impact of electrochromic glazings in large commercial buildings: (i) the selection of an appropriate switching control strategy must be based on careful study of the relationships between the driving variables for switching, glazing properties (e.g., solar and visible transmittance, solar heat gain coefficient) and building characteristics (e.g., thermal mass, window-to-wall ratio, internal loads, type of HVAC system and schedule of operation), and (ii) determination of the set-points for switching or of the optimum switching times (when to initiate switching to the colored state and when to return the glazing to its bleached state). Ultimately, the control strategy will have a direct impact on the potential energy savings resulting from control of solar gains and will also affect occupant visual comfort.

In a previous paper, Corsi et al. [10] evaluated the global parameters characterizing the performance (e.g., solar and visible transmittance, U-value, and solar heat gain coefficient) of several types of double glazed windows, including one which incorporated an experimental electrochromic coating developed at the University of Moncton, New Brunswick (Canada). The evaluation was performed using the APPLIED FILM LAMINATOR [11] and WINDOW 4.1 [12] public domain computer programs along with the corresponding spectral data files of the glazing types.

This paper aims to advance the knowledge related to the simulation of electrochromic glazing switching control. First, a critical evaluation of existing control strategies currently available in the DOE-2.1E program [13] was performed to study the effect of several driving variables on the cooling load of an existing large office building. Second, the present capabilities of the DOE-2.1E program were expanded using the Functional Values approach which enables the user to introduce new algorithms (e.g., control strategies) without recompiling the program. Third, the effect of switching time was studied for the building’s perimeter zones. Since electrochromic windows will affect both building energy consumption and visual quality, the optimization of the switching time was formulated as a multi-objective problem with two conflicting objectives (energy and visual quality). The Pareto optimum solutions are shown for different weighting coefficients applied to the energy performance and visual quality. General rules for switching were then extracted from the results, and will be used in future work to formulate the basis of an optimized switching strategy to be analyzed using the DOE-2.1E program.

2. PROPERTIES OF THE EXPERIMENTAL ELECTROCHROMIC COATING

Spectral reflectance and transmittance data at normal incidence were obtained for the bleached and colored states of an experimental electrochromic coating developed at the University of Moncton under contract with the Department of Natural Resources Canada [14,15]. The measured data is for a coating applied to a 1 mm clear glass substrate. The APPLIED FILM LAMINATOR program was used to extrapolate these data to a glass-coating thickness of 6 mm. The visible transmittance of the resulting electrochromic glazing can be switched from 57.3% in the bleached state to 20.5% in the colored state, while the solar transmittance switches from 37.8% to 10.4% (Figure 1). A double glazed window incorporating the electrochromic coating on the inside surface of the outside pane and a 6 mm clear glazing as the inside pane, separated by an air gap of 12.7 mm was then defined.

Corsi et al. [10] have used the WINDOW 4.1 computer program to compare the performance of this electrochromic window relative to seven conventional window types as well as two idealized electrochromic windows (Figure 2). The shading coefficient of the experimental electrochromic window varies from 0.44 in the bleached state to 0.19 in the colored state. By comparison, the shading coefficient of a double glazed bronze/clear window remains constant at 0.58. Generally, the experimental electrochromic window maintains a higher ratio of visible transmittance to shading coefficient than most of the commonly used conventional windows (e.g., double clear, bronze/clear, reflective/clear, clear/Low-e), thereby transmitting a greater proportion of visible gains than solar gains.

3. EVALUATION OF EXISTING ELECTROCHROMIC GLAZING CONTROL STRATEGIES

The solar-optical properties of the experimental electrochromic window were imported from the WINDOW 4.1 program into the existing window library of the DOE-2.1E energy analysis program, which was then used to study the effect of driving variables for switching on the heat extraction rate of perimeter zones (evaluated within the SYSTEMS block of the program). A computer model of an existing seven storey office building located in Laval, Quebec, developed with the MICRO-DOE-2.1E program [16], was used to perform this evaluation. A typical floor consists of a 27 m x 21.6 m core zone (the longer dimension runs East-West) surrounded by four perimeter zones 3.7 m deep, oriented along the four cardinal directions. The window-to-wall ratio is 0.62. The initial building model was modified to include continuous dimming lighting controls in order to maximize the benefits of natural daylighting in the perimeter zones. The combination of daylighting and electric lighting system was required to maintain a minimum illuminance level of 500 lux.

Currently, modeling of electrochromic glazing control in the DOE-2.1E program is possible through the selection of one of eight driving variables for switching as well as the corresponding high and low set-points: (i) outdoor drybulb temperature, (ii) total incident solar radiation, (iii) direct incident solar radiation, (iv) total solar radiation transmitted through the glazing in the bleached state, (v) direct solar radiation transmitted through the glazing in the bleached state, (vi) total solar radiation incident on a horizontal plane, (vii) total space cooling load at the previous hour (estimated by the LOADS block of the program), and (viii) illuminance levels. With the exception of the last driving variable, selection of the set-points is not straightforward as it requires an analysis of the dynamics between the driving variables and their effect on the controlled variables (i.e., the solar gain and the extraction rate). For example, there are some problems with the use of control variables (ii, iii and vii) in commercial buildings. A control model based on solar radiation transmitted through the glazing in the bleached state would make it impossible to correctly measure the driving variable once the glazing is no longer in its bleached state. Therefore, one can expect a cyclic switching between bleached and colored states. On the other hand, a control model which uses the space cooling load as the driving variable does not inherently account for the time lag between the occurrence of peak solar gains and the peak cooling load. In some previous studies the electrochromic glazing was automatically switched from the bleached state to the colored state whenever the total space load was greater than zero

[5,7,8]. However, the cooling load is due to several components such as solar gains and internal gains due to people, equipment, and lighting, yet only the solar gains component can be controlled using electrochromics. Since the space cooling load is usually greater than zero during summer months, regardless of whether solar gains are substantial or not, the glazing will remain in a permanently colored state.

In the present study, simulations were first performed with the electrochromic window in its bleached state in order to study the effect of the outdoor drybulb temperature and total incident solar radiation on the extraction rate of the perimeter zones. A plot of hourly values of outdoor drybulb temperature and the extraction rate of the South perimeter zone is shown in Figure 3 for the month of July. It can be seen that there is no correlation between the cooling load and outdoor drybulb temperature for the commercial building studied. Exterior temperature would primarily affect conduction heat gains; however, the U-value of the window is not affected by the state of the electrochromic glazing studied. Therefore, control by outdoor temperature would not be an effective strategy for this building. Furthermore, if the U-value can be changed when the state of the electrochromic glazing is switched, the performance of this type of control strategy would depend on the contribution of conduction gains to the extraction rate relative to the contribution of solar gains. For example, the conduction gains do not contribute significantly to the extraction rate of the building studied, as shown in Figure 4. Thus, one would expect lower energy savings from a control strategy based on outdoor drybulb temperature, compared with one that is based on solar radiation. It is also worth noting, the time delay between the maximum solar gains (at 12:00) and the maximum extraction rate (14:00) due to the thermal mass of the building (Figure 4).

The largest component of the extraction rate for the building studied is due to glass solar gains; therefore, a control strategy based on solar radiation is likely to be the most effective option. The relationship between the total incident solar radiation and the ratio (RGC) of solar gain to the extraction rate is shown in Figure 5. It can be seen that the maximum ratio RGC occurs several hours before the occurrence of the peak solar gain. For the South orientation, the maximum ratio occurs at 10:00 a.m. while the peak solar gain occurs at noon. Tentatively, at this stage of the research it can be concluded that the potential for thermal storage of solar radiation is greatest when the ratio RGC has the maximum value. Therefore, in order to reduce the peak cooling load, switching of the electrochromic glazing can potentially start when the maximum ratio RGC occurs. This ratio incorporates the effect of solar radiation and thermal lag, and the feasibility of its use in a switching control algorithm will be studied in future work.

Relationships which link the driving variables for switching to the extraction rate, such as those described above, can facilitate an initial selection of appropriate set-points for the existing control strategies. However, in order to capitalize on the full benefits of electrochromic glazings, qualitative performance parameters such as visual quality must also be assessed.

4. OPTIMIZATION OF THE SWITCHING TIME

4.1 Background

The switching times of the electrochromic glazing are defined here as the time (t_1) at which the glazing is switched from the bleached state to the colored state and the time (t_2) at which the glazing is returned to its bleached state. The difference between t_2 and t_1 will determine the switching duration, that is the total number of hours that the glazing will remain in its colored state. It will directly influence the energy savings resulting from reduction in solar gains, as well as the amount of daylight that is transmitted to the interior space and the corresponding visual quality. Generally, one can assume that the longer the switching duration, the greater the energy savings could be, whereas the visual quality is decreased since the glazing is in the colored mode for an extended period of time. In addition, the time at which switching is initiated will also influence the amount of energy savings. Thus, a gain in one objective (i.e., to maximize energy savings) results in a loss in the other objective (i.e., to maximize visual quality). The optimization of the switching times can therefore be formulated as a multi-objective model with two conflicting objectives. The solution of such an optimization problem is termed a Pareto optimum, and represents a set of feasible solutions to the problem, rather than a single optimum point [17]. A move away from the Pareto optimum results in a loss or gain in the value of the objectives. Furthermore, many Pareto optima are possible depending on the weighting factors that are applied to each objective, representing the decision maker's priority on each objective.

4.2 Definition of optimization objectives

Visual quality within the indoor environment can be characterized by several performance indices such as Disability Glare Factor, Visual Comfort Probability, Luminance Ratios, Color Rendition Index, and Color Preference Index. Although detailed studies of the effect of electrochromic windows on some of the above indices could be performed using available lighting simulation programs, such a detailed analysis is beyond the scope of the present study. For the purposes of this research, the visual quality (VQ) is considered to be comprised of two terms which account for access to views and provision of natural lighting:

$$VQ = \alpha \cdot AV + \beta \cdot DIF$$

where AV = Access to Views, based on the assumption that occupants prefer a clear access to views of the external environment during working hours

DIF = Daylight Illuminance Factor, based on the assumption that natural lighting is preferred by occupants over artificial electric lighting.

Each component can take a value between 0 and 1, and α and β are the weighting factors related to each component. For this study, α and β were selected as 0.9 and 0.1, respectively. A sensitivity analysis will be performed in future work to assess the influence of the weighting factors on the results.

Conceptually, the “clearness” of the view, during the working hours, can be expressed by the visible transmittance of the window, relative to a clear double glazed window which is considered to provide the clearest possible view:

$$AV = \frac{N_1 * T_{vis\_bleached} + N_2 * T_{vis\_colored}}{N_{TOT} * T_{vis\_double\_clear}}$$

where N_1 = number of hours the electrochromic glazing is in the bleached state during the working hours

N_2 = number of hours the electrochromic glazing is in the colored state during the working hours

$N_{TOT} = N_1 + N_2$, total working hours in the day (from 8:00 to 17:00, for a total of nine hours)

$T_{vis\_bleached}$, $T_{vis\_colored}$ = visible transmittance of the window, at normal incidence, in the bleached and colored states, respectively

$T_{vis\_double\_clear}$ = visible transmittance of a reference clear double glazed window.

The Daylight Illuminance Factor (DIF) describes the extent to which a specified illuminance level (e.g., 500 lux for offices) can be met by natural lighting rather than electric lighting:

$$\mathrm{DIF} = 1 - \frac{(500 - \mathrm{DI})}{500}, \; \textit{if } DI \leq 500 \; lux$$

$$\mathrm{DIF} = 1, \; \textit{if } DI > 500 \; lux$$

where DI = Daylight Illuminance level.

The objective function representing energy savings (EER) is calculated as the reduction in the extraction rate (ER) of the perimeter zone due to switching of the glazing, relative to the electrochromic window that is maintained in its bleached state:

$$ERR = \frac{ER_{\text{bleached state}} - ER_{\text{switched state}}}{ER_{\text{bleached state}}}$$

Since both the Extraction Rate Reduction (ERR) and Visual Quality (VQ) objectives are dimensionless, they can be combined into a composite objective function by applying weighting coefficients:

$$\text{Objective} = w_1 \cdot ERR + w_2 \cdot VQ$$

where w_1 and w_2 can be varied to reflect the importance given by the designer to each objective function; $w_1 + w_2 = 1.0$.

4.3 Optimization methodology

The approach used to optimize the glazing switching times is illustrated in Figure 6. First, two Functional Values routines were developed and coupled with the window description of the computer model in order to study the effect of switching time on the energy savings and the visual quality. The first routine affects the program's solar gain calculations loop of the selected window, while the second routine affects the corresponding daylighting calculations. Two main conditions were imposed through these routines: (i) the switching start and stop times, and (ii) switching was only allowed when direct solar radiation was incident on the surface. The routines alter the switching factor (SWFAC), an internal variable of the program which describes whether the electrochromic glazing is in the bleached or the colored state. The long-term goal of developing these routines was to create a structure allowing for a more complex switching algorithm to be later incorporated in the MICRO-DOE-2.1E program.

Three sets of simulations were then performed to isolate the impact of switching the South, West and East perimeter zone windows for the month of July. For the South zone, t_1 and t_2 were varied from 8:00 to 17:00 (when direct solar radiation is present) in increments of one hour. For the West zone, direct solar radiation is present on the surface from 12:00 to 20:00, yet there are important solar gains between 17:00 and 20:00 which affect the extraction rate of the zone. However, since the occupancy period ends at 17:00, the visual quality is not of concern beyond this hour, and the cooling load can be reduced by maintaining the electrochromic glazing in the colored state from 17:00 to 20:00. Therefore, t_1 was varied from 12:00 to 16:00, while t_2 remained fixed at 20:00. For the East zone, the opportunity exists to reduce the extraction rate by maintaining the glazing in the colored state from 4:00 and 8:00 during which the visual quality is not of concern. Hence, t_1 remained fixed at 4:00, while t_2 was varied from 8:00 to 12:00.

The visual quality and extraction rate reduction relative to the bleached mode of the electrochromic window were then calculated for each simulation, and the Pareto feasible solutions of t_1 and t_2 were determined. The weighting coefficients, w_1 and w_2, in the composite objective function were varied from 0 to 1 in increments of 0.1 in order to study their effect on the overall value of the objective function.

4.4 Pareto feasible solutions of t_1 and t_2

Examples of Pareto feasible solutions of t_1 and t_2 for the South perimeter zone are shown in Figures 7 and 8. The optimum values of t_1 and t_2 are defined here as those times which lead to a composite objective function value within 5% of the absolute maximum, and the possible combinations of t_1 and t_2 are represented by the area limited by thick contour lines. Since the DOE-2.1E program uses an hourly time step for the calculations, the resulting Pareto optimum solutions are presented using integer variables. When full priority is given to the visual quality component of the composite objective function (i.e., $w_1=0$ and $w_2 = 1$), the optimum switching duration should not exceed a maximum of two hours, and switching from bleached to colored mode could occur at any time between 8:00 to 15:00 (Figure 7). Essentially, the glazing will be controlled such that it will remain in the bleached mode for the longest possible duration in order to ensure a maximum visual quality. In Figure 8, the EER and VQ objectives are given equal weights, and most switching times are feasible except for some extremes. If however, full priority is given to the extraction rate reduction, the maximum switching duration is required, which limits the set of feasible solutions to the following three: (i) from 8:00 to 15:00, (ii) from 8:00 to 16:00, and (iii) from 9:00 to 16:00. Essentially, the glazing will be controlled such that it will remain in the colored mode for the longest possible duration in order to ensure maximum energy savings.

The Pareto feasible solutions of the switching start time t_1 for the West perimeter zone are shown in Figure 9 for the full range of weighting coefficients. Those solutions with a value of objective function within 5% of the absolute maximum are located between the thick lines. When equal priority is given to both the extraction rate reduction and the visual quality (w_1=w_2=0.5), all values of t_1 are feasible. If the designer decides that a higher priority should be given to the visual quality (w_1=0.1, w_2=0.9), the switching start time could occur at any time between 15:00 and 16:00. Conversely, if a higher priority is given to energy savings (w_1=0.8, w_2=0.2), then the switching start time could occur between 12:00 and 13:00.

CONCLUSIONS

Electrochromic windows enable the dynamic control of solar-optical properties, thereby affecting solar heat gains as well as lighting quantity and quality. New technologies and building materials such as electrochromic windows must therefore be assessed in terms of their impact on both energy savings and quality of the indoor environment. In this paper, the switching time of an experimental electrochromic glazing was optimized based on a multi-objective model of the conflicting performance criteria (energy savings and visual quality). Future work will concern the following: (i) development of an optimized switching strategy to be coupled with the MICRO-DOE-2.1E program by using the two routines mentioned above, (ii) assessment of the potential impact of electrochromic windows on the performance of commercial buildings in terms of climate, building size and internal loads, compared with some conventional window types (e.g., double clear, bronze/clear, reflective/clear).

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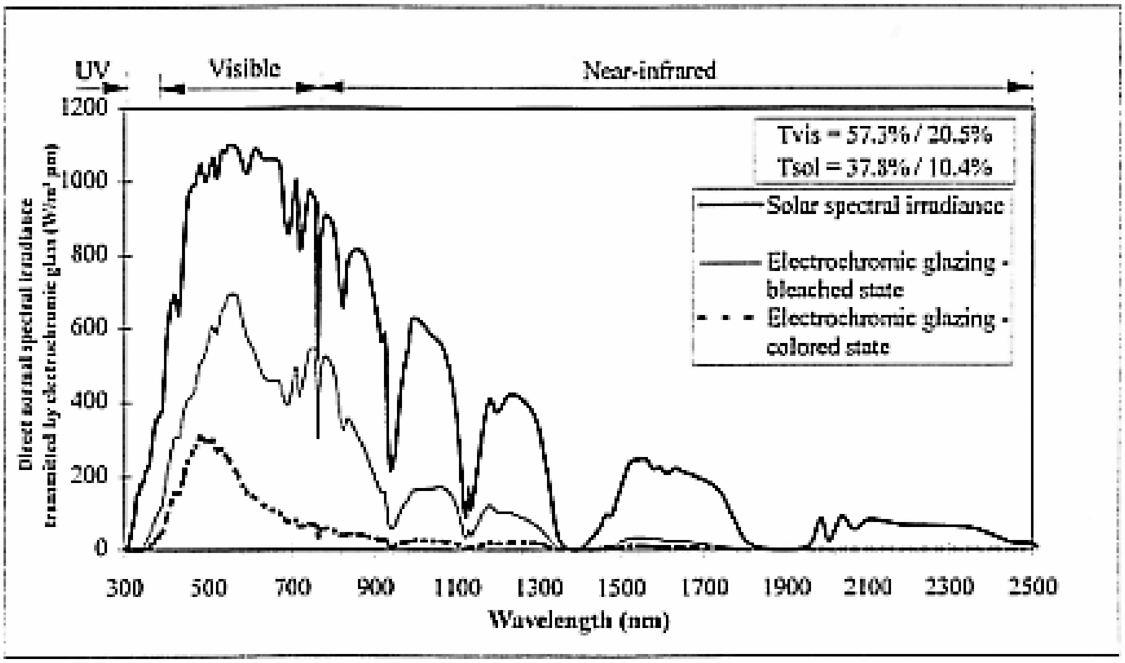

Figure 1. Spectral transmittance of the experimental electrochromic coating applied on a 6 mm thick clear glass substrate, determined using APPLIED FILM LAMINATOR.

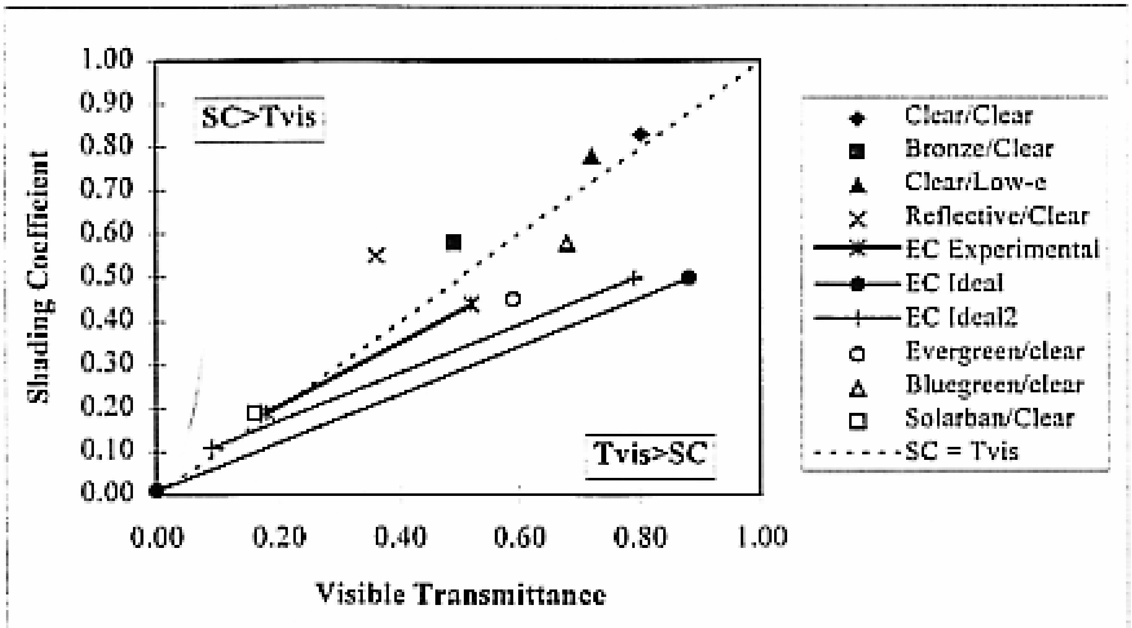

Figure 2. Shading Coefficient vs. Visible Transmittance of the window types evaluated using WINDOW 4.1.

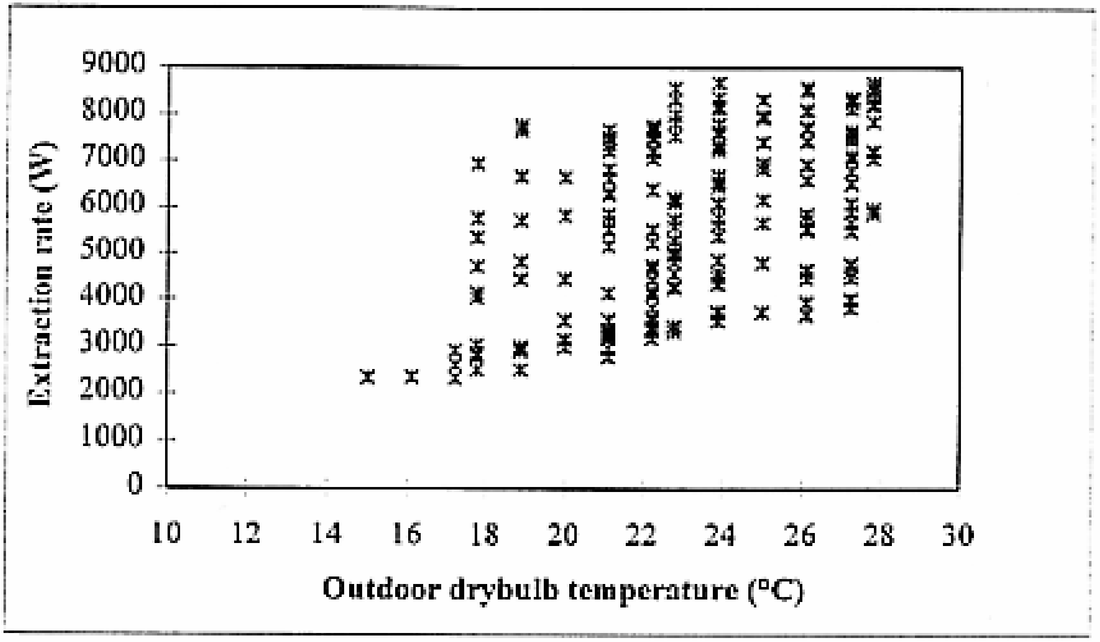

Figure 3. Relationship between the extraction rate and the outdoor drybulb temperature for the South perimeter zone for the month of July.

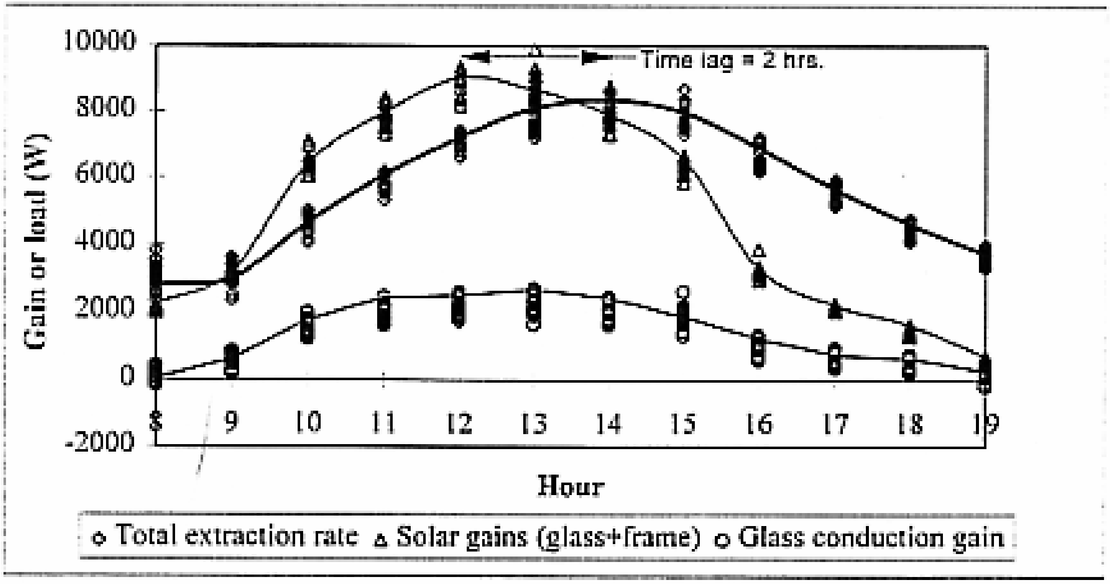

Figure 4. Comparison of solar gains, glass conduction gains and extraction rate for the South perimeter zone for the month of July.

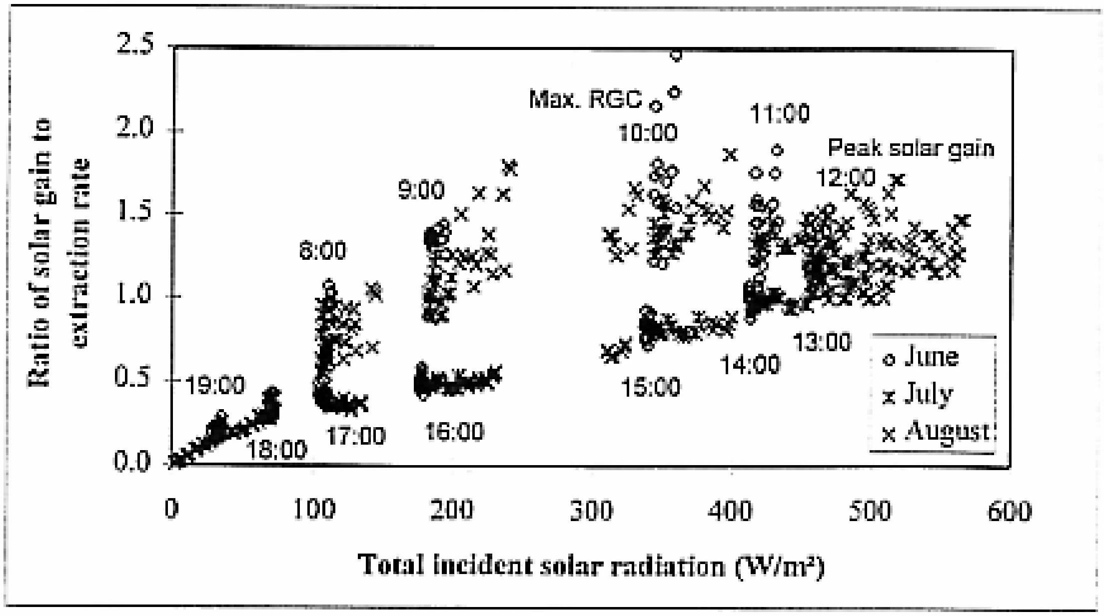

Figure 5. Relationship between the ratio of solar gain to extraction rate and the total incident solar radiation for the South perimeter zone.

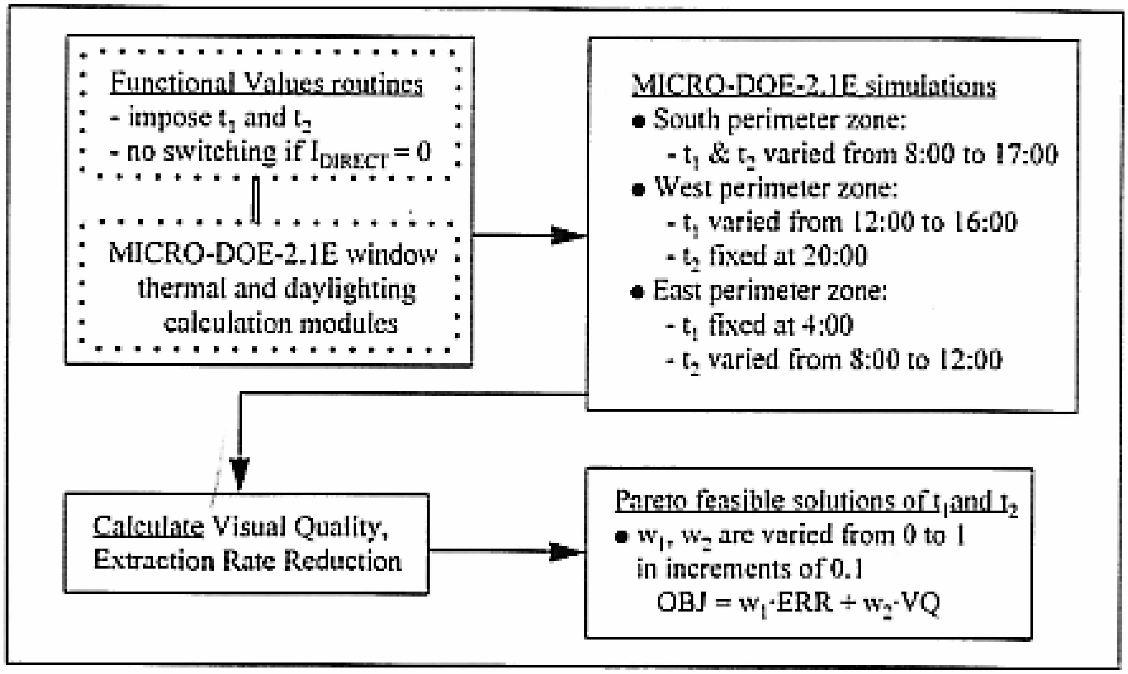

Figure 6. Approach used to optimize the switching times of the electrochromic glazing.

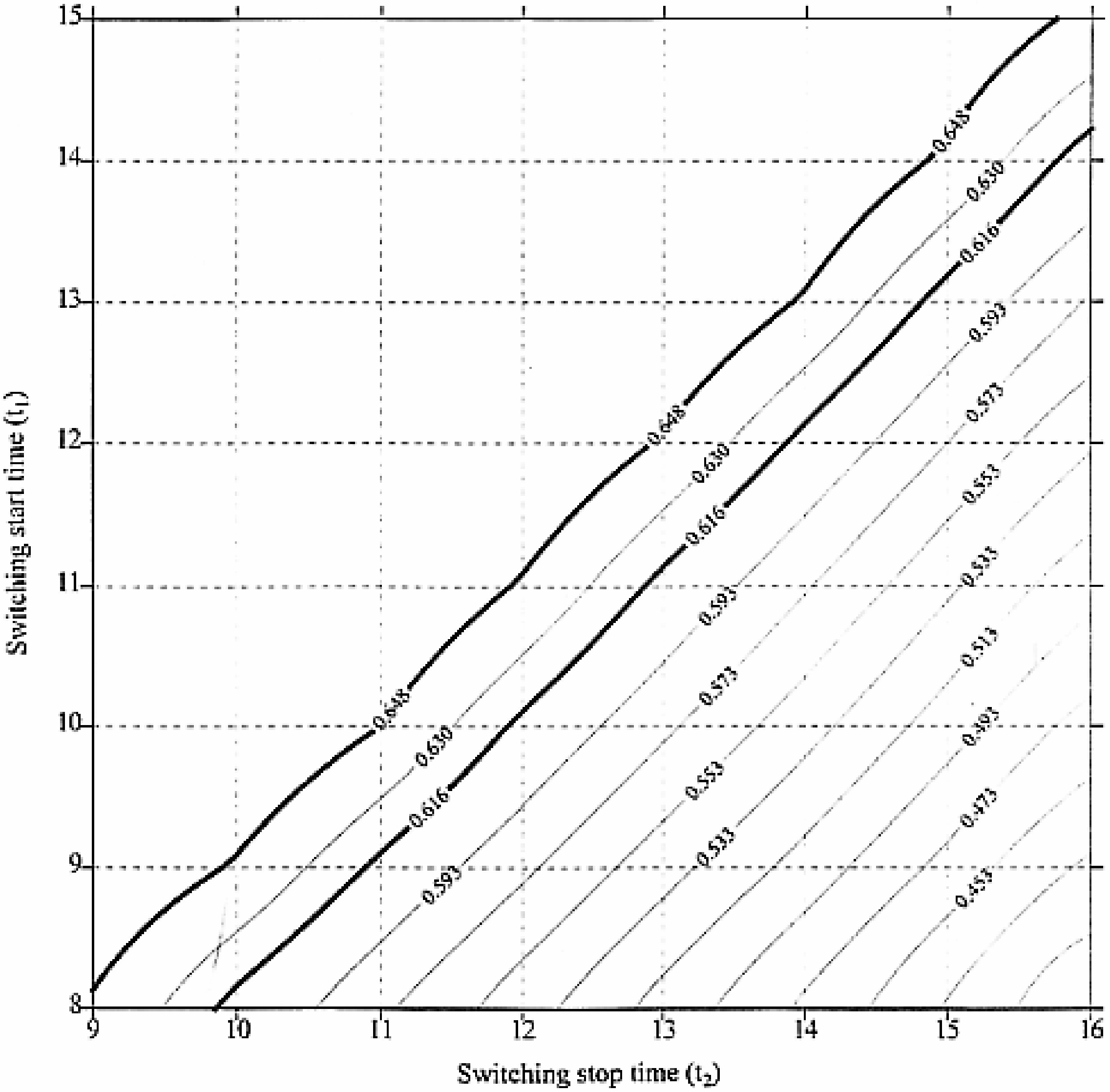

Figure 7. Pareto feasible solutions of t_1 and t_2 for the South perimeter zone when full priority is given to the visual quality (i.e., Objective=0·ERR+1·VQ).

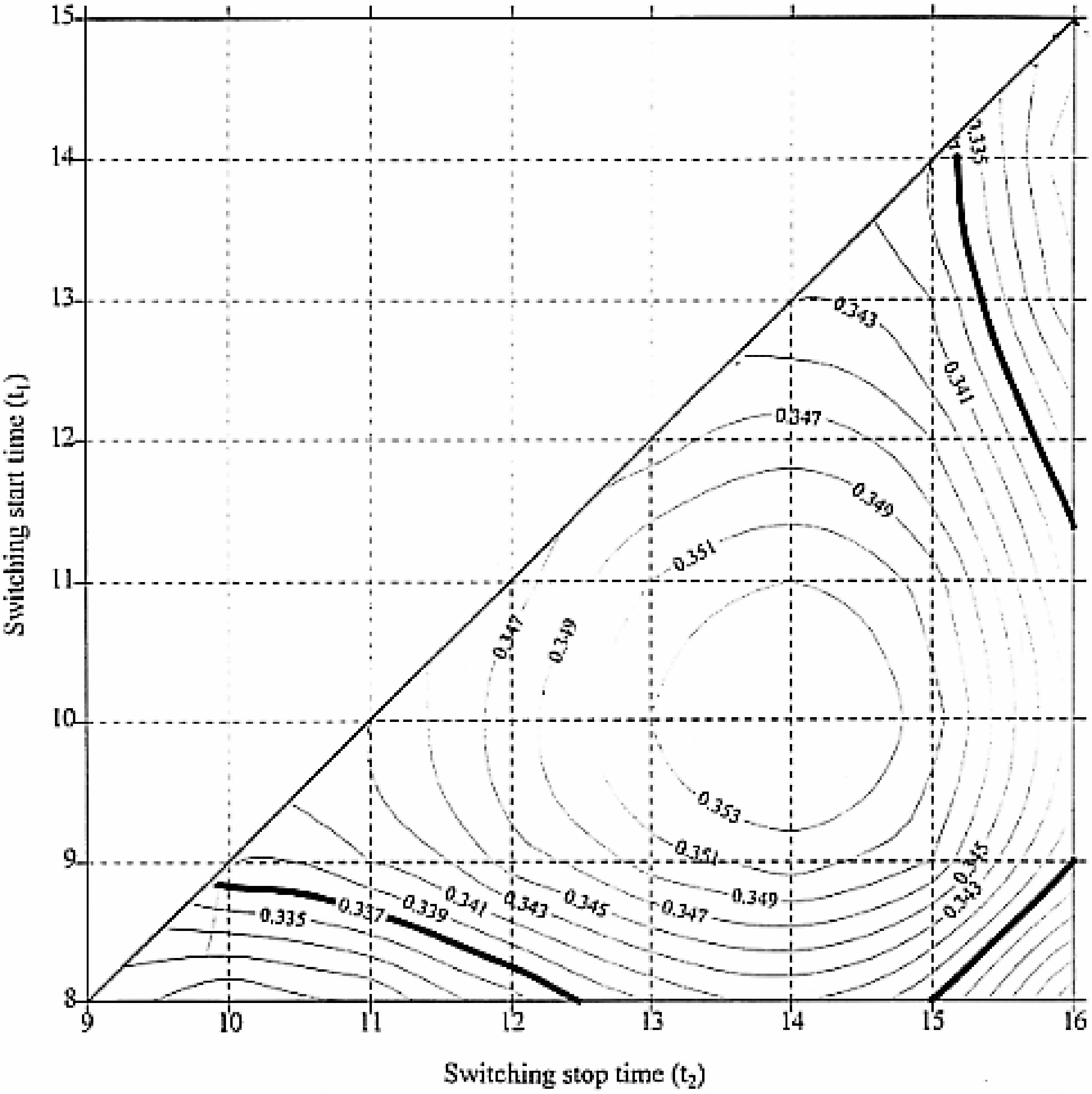

Figure 8. Pareto feasible solutions of t_1 and t_2 for the South perimeter zone when equal priority is given to both objectives (i.e., Objective=0.5·ERR+0.5·VQ).

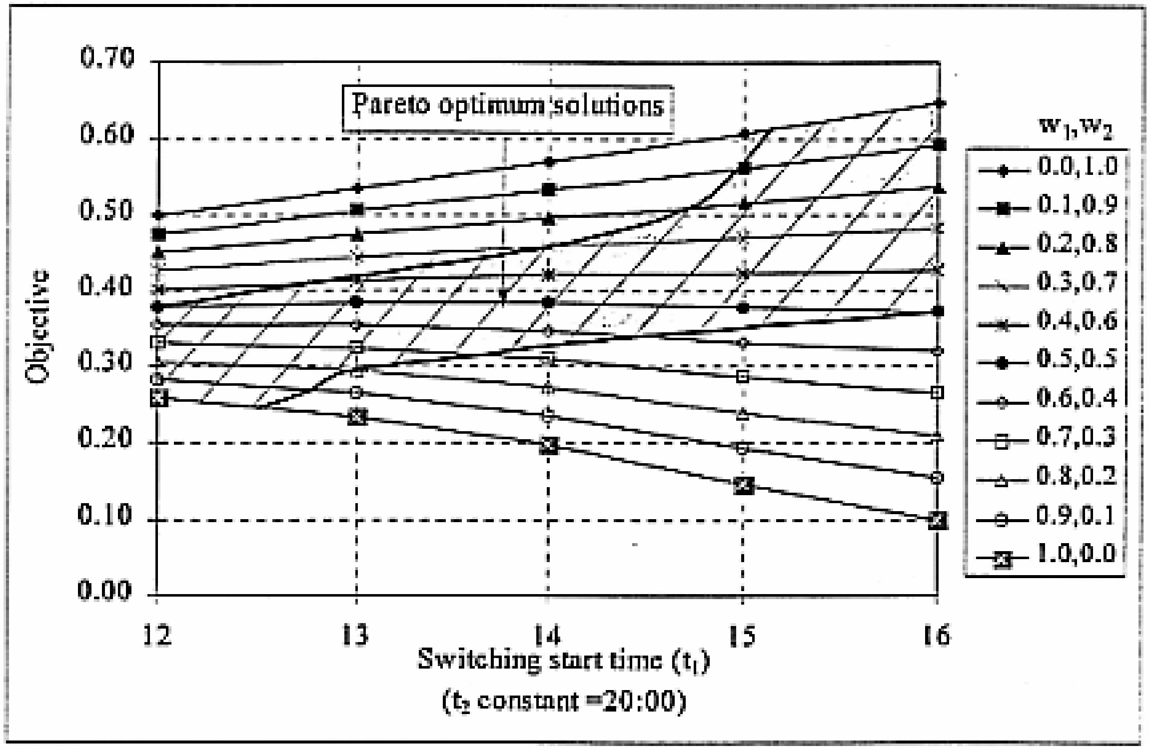

Figure 9. Pareto feasible solutions of t_1 for the West perimeter zone.