EVALUATION OF THE POTENTIAL IMPACT OF ELECTROCHROMIC WINDOWS ON THE ENERGY PERFORMANCE OF COMMERCIAL BUILDINGS

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ABSTRACT

Evaluation of the Potential Impact of Electrochromic Windows
on the Energy Performance of Commercial Buildings

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Electrochromic windows appear to be the most promising emerging technology to improve building performance as they provide greater control of solar gains; they have a potentially significant impact on the indoor visual environment and energy requirements of commercial buildings. The research work presented in this thesis, which is accomplished using computer simulation, proposes to undertake an engineering evaluation of the performance of electrochromic glazings and to advance knowledge in the field by developing a new model to simulate their control. First, the performance of an experimental electrochromic coating is compared relative to conventional glazing types. The APPLIED FILM LAMINATOR and WINDOW 4.1 computer programs are used to evaluate the global parameters characterizing window performance (solar and visible transmittance, U-value, and solar heat gain coefficient). A critical evaluation of existing control strategies is performed using DOE-2.1E to study the effect of several driving variables for switching on the cooling load of an existing large commercial building. The present capabilities of the DOE program are expanded using the Functional Values approach in order to study the effect of the electrochromic glazing switching time for the building's perimeter zones. Since electrochromic windows affect both building energy consumption and visual quality, the optimization of the switching time is

formulated as a multi-objective model with two conflicting objectives (energy and visual quality). Pareto optimum solutions are shown for different weighting coefficients applied to both objectives. This approach constitutes the basis of an automated optimized electrochromic glazing switching strategy that is developed and incorporated in the DOE-2.1E program.

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CHAPTER 1
INTRODUCTION – PERSPECTIVES ON ELECTROCHROMICS

> *"It is our belief that electrochromic coatings and "smart windows" are going to be important subjects in the research on materials for energy efficiency and solar applications for several years to come."*
>
> *Svensson and Granqvist, 1985 [1]*

Glazing in commercial buildings is increasingly required to meet multiple, and often conflicting, performance objectives, namely [2,3,4]: (i) minimize solar gains to reduce cooling energy consumption and peak electric demand, (ii) transmit daylight to reduce lighting energy consumption and electric demand, (iii) improve occupant visual comfort by minimizing glare and providing access to clear views of the exterior, (iv) maintain thermal comfort by minimizing heat losses, and (v) reduce heating energy consumption by utilizing solar gains for passive solar heating. The ideal glazing must therefore be able to respond to a wide range of conditions in order to achieve the various energy and comfort objectives. Conventional glazings, such as clear, reflective, and tinted, offer limited control of the above performance criteria since their properties remain static over the broad range of environmental conditions. Therefore, often, one performance criteria is met at the expense of another. The level of intelligence and adaptability that is required to achieve the performance objectives is possible through dynamic control of the glazing's solar-optical properties. The U.S. Department of Energy has announced that the highest priority in research is currently in the field of dynamic envelopes, of which electrochromic glazings are expected to play a significant role [5].

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 [6]. These advanced coatings generally consist of five layers, as shown in Figure 1-1 (although other configurations are possible): an electrochromic layer, an electrolyte or ionic conductor and a counter-electrode are sandwiched between transparent conductors [2].

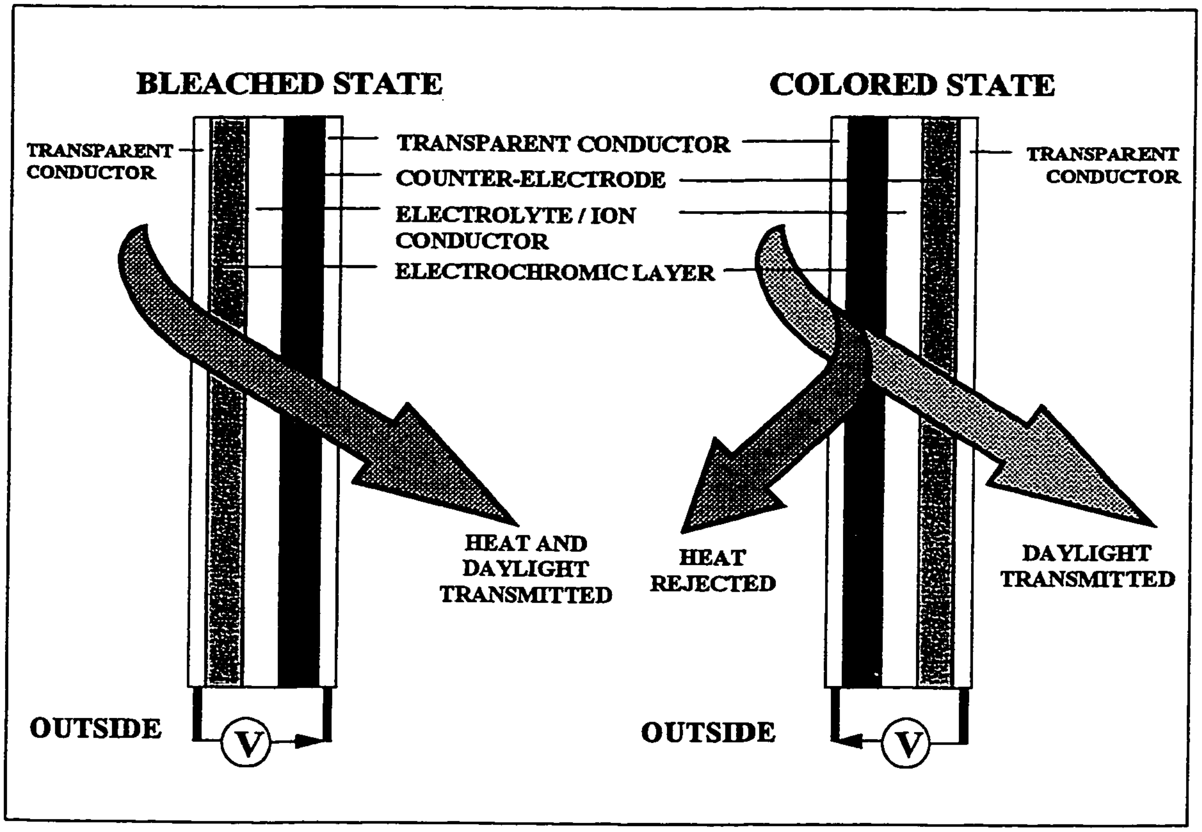

Figure 1-1. Typical layers of an electrochromic coating. [7]

The transmittance of the electrochromic layer can be varied between a bleached state and a colored state by applying a small voltage across the transparent conductors. An electrochemical reaction ensues with the simultaneous injection of ions and electrons; ions are shuttled from the counter-electrode to the electrochromic layer by means of the ionic conductor [1,8,9]. The reaction is reversible, so the coating is returned to its original bleached state by reversing the voltage. In this case, ions are withdrawn from the electrochromic layer and transferred to the counter-electrode. Taking tungsten oxide (WO_3) as an example, the reaction can be written as follows (Figure 1-2) [8,9]:

$$WO_3 \text{ (transparent)} + xH^+ + xe^- \leftrightarrow H_xWO_3 \text{ (blue)}$$

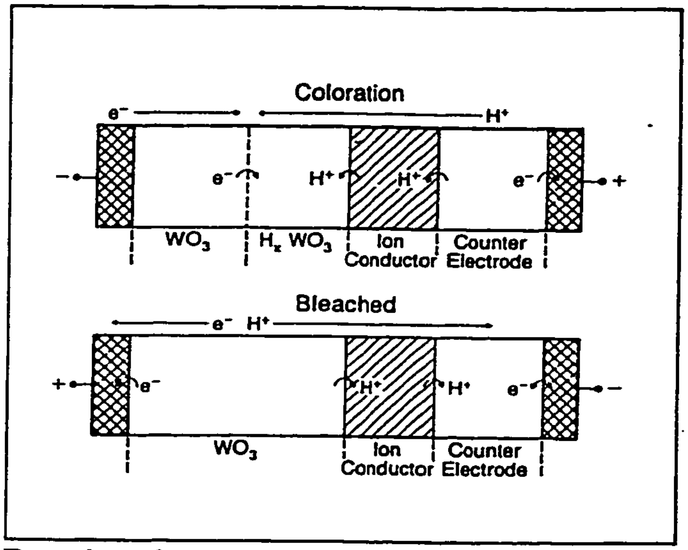

Figure 1-2. Reactions in tungsten oxide during coloration and bleaching. [9]

A more general form of the reaction in electrochromic coatings can be written as [10]:

$$\underset{\text{bleached state}}{EC^{n} + y\,CE^{m}} \leftrightarrow \underset{\text{colored state}}{EC^{n-a} + y\,CE^{m+(a/y)}}$$

where EC is the electrochromic layer and CE is the counter-electrode.

Two configurations are possible for electrochromic coatings [11]:

(i) the five-layer design, where the entire electrochromic coating is applied to one glass substrate, and one surface of the coating therefore remains exposed; with this design, the exposed transparent conductor imparts a low thermal emittance to the electrochromic glazing.

(ii) the laminated two-layer design is considered, where half the coating (i.e., transparent conductor and electrochromic layer) is applied to one glass substrate, while the other half (i.e., counter electrode and transparent conductor) is applied to another glass substrate. The two components are then laminated together using the electrolyte as an adhesive, which is usually a polymer. In this design, the electrochromic coating does not inherently possess low-e properties, but this can be achieved by applying a low-e coating to one of the exposed substrate surfaces.

The electrochromic coating can be applied to the glass substrate and then incorporated into a double-glazed insulated glass unit [12]. This advanced window technology facilitates true building intelligence since control of the coating properties can be linked to a building energy management system. An electrochromic window can therefore respond to a broad range of conditions such as climate, building operation, time of day or season. In this manner, a switching control algorithm can be implemented to minimize heating, cooling and electric lighting loads while optimizing the quality of the visual environment (greater access to views, glare control and provision of natural lighting).

1.1 HISTORY OF THE DEVELOPMENT OF ELECTROCHROMIC COATINGS

Research in the field of electrochromic coatings is primarily concentrated along two main directions: (i) materials science, in which the main issues are: the study and development of the various components that comprise an electrochromic coating (also known as an electrochromic device), the development of an electrochromic device that meets requirements for solar-optical properties, durability and cost-effectiveness, the examination of device structure and configuration, the development of device fabrication techniques, and the characterization of solar-optical properties; and (ii) performance assessment within the context of their application in buildings, cars, sunglasses, and airplanes; this area of research is concerned with assessing the energy, comfort (glare, lighting) and economic impacts of electrochromic coatings, and also addresses issues related to performance modeling, control of solar-optical properties, device implementation and operation.

It is beyond the scope of this research to present an exhaustive and detailed review of the materials science perspective. Greater emphasis will be placed on the second category, on how these coatings could affect building performance, since this subject is more relevant to the context of this thesis.

Electrochromism was first discovered in the early 1970's and its application was recognized chiefly for the development of small digital information displays. Consequently, the main research emphasis was on studying and developing electrochromic coatings with fast switching properties; however, these information displays were soon abandoned in favor of liquid crystal displays (LCD) which offered better response times. It was not until the mid 1980's that the development of electrochromic coatings began to flourish anew as researchers recognized their potential to modulate natural light and solar gain in building windows and as well as for uses such as sunglasses and automotive rear-view mirrors to control glare. [6,13]

Researchers such as Lampert [9] and Truong and Mehra [14] were among the first to review previous research on electrochromic materials and to place it in the context of large-area applications such as windows; they also discussed the technical challenges in developing devices for this purpose. A new set of requirements for the development of electrochromic devices emerged as a result of the shift in application from display device to window: the device would need to be transmissive rather than opaque in the bleached state, intermediate switching between the bleached and colored states was essential, slower switching speeds became acceptable, a longer device lifetime was required, and the temperature response also became an important issue. Chevalier and Chevalier [4] also added that device lifetime depends on the coating's ability to withstand environmental factors such as exposure to ultra-violet radiation, extremes in temperature, and humidity. Furthermore, the cycling from the bleached state to the colored state could affect the coating's properties and hence the long-term device performance. The coating's thermal and mechanical properties are also important factors, as the electrochromic window in its colored state must be able to withstand increased temperatures due to absorbed solar radiation, and any crack or delamination of the adhesive bond between each layer of the coating and between the coating and the glass substrate would result in poor performance. The requirements of electrochromic devices for application in windows are summarized in Table 1-1 below:

Table 1-1. Summary of requirements for electrochromic devices applied to windows. [2]

τ_{solar} - bleached	50% to >70%
τ_{solar} - colored	<10% to 20%
$\tau_{visible}$ - bleached	50% to >70%
$\tau_{visible}$ - colored	<10% to 20%
Switching voltage	1-5 volts
Optical memory	1-24 hours
Switching time	1-60 sec.
Cyclic lifetime	>10k-1M cycles
Lifetime	5-20 years
Operating temperature	-30° to 70°C if protected or 0° to 70°C

According to Mathew et al. [12] of the Optical Coating Laboratory (California), windows for residential applications are usually required to last 10 to 20 years, while for commercial buildings window lifetime must be between 20 to 40 years. Therefore, they recommended that electrochromic windows have a lifetime of 10 to 40 years, depending on the application. Furthermore, based on surveys of end-users, it was indicated that they would prefer a switching time of less than one minute, but a maximum of five minutes would be acceptable. Users also prefer the window to have neutral colors.

Materials for electrochromic devices can be classified as organic, inorganic or polymeric, and can be either liquid or solid. The most widely researched materials for the electrochromic layer are the inorganic transition metal oxides, namely, tungsten oxide, WO_3, iridium oxide, IrO_x, and nickel oxide, NiO [1,6,8]. Tungsten oxide is considered to have the greatest potential for device development and has therefore received the most research attention.

The overall cost and effectiveness of the electrochromic device is determined by the transparent conductors as they represent the largest cost of the electrochromic device [6]. These should possess high transparency and be very conductive. The typical material used is indium tin oxide, In_2O_3:Sn, (ITO) [15].

The ionic conductor or electrolyte can be in solid or liquid form. The ionic conductivity of the material will influence the switching speed of the electrochromic device. In general, liquid devices perform better than solid-state ones in terms of switching speed as the ions are more mobile. The most common liquid electrolyte is based on H^+ protons in water; however, this may cause some electrochromic materials to corrode. Electrolytes such as Li^+, Na^+, K^+ in solvent are preferred. A disadvantage of liquid electrolytes is that they incur stability problems at the interface with the counter-electrode and electrochromic layers [9]. Furthermore, potential leakage, freezing and thermal degradation are other problems commonly associated with liquid electrolytes [14]. Solid-state devices are therefore preferred for window applications [9,14] as they are more stable; however, they possess a lower ionic conductivity than liquid electrolytes and therefore incur longer switching times. The most commonly used ions are Li^+, Na^+, Ag^+ or H^+ [6,8,14]. Solid polymer electrolytes, particularly polyethylene oxide (a-PEO), have also been gaining much research interest due to their high ionic conductivity, temperature performance and variety in coloration [6,8,13]. Lithium based polymers are also being explored for window applications [6,15].

The ion storage layer, or counter-electrode, presents both technical and cost challenges in electrochromic device development. The counter-electrode can also be an electrochromic material provided that it complements the active electrochromic layer; in this case, if coloration occurs by the injection of ions into the electrochromic layer, the material is cathodic, whereas if coloration occurs by rejection of ions, the material is anodic [1,6,15]. One of the most important requirements of the ion storage material is that it must match the charge capacity of the electrochromic material [6], and it is currently a limiting factor on the performance of WO_3 devices [16]. The problem with many ion storage materials is that they undergo progressive degradation which eventually hampers the bleaching and coloration cycle [17]. Here too, polymers have gained significant research interest. The most promising polymer electrodes are based on polyorganodisulfides which do not deteriorate significantly; Lawrence Berkeley Laboratory has patented a group of compounds based on this polymer material [17]. It is claimed that the charge capacity of the polymer can be adjusted to match that of the electrochromic layer [18].

The over 1800 patents on electrochromic components [17] are evidence that research and development in the area of electrochromics is strong and growing. Several research and government sponsored initiatives have been established in order to facilitate and accelerate the commercialization of electrochromic products, ranging from windows, sunglasses, sunroofs and rear-view mirrors. Granqvist et al. [15,19] have grouped the possible applications of electrochromic coatings into four main areas (Figure 1-3):

(i) the information display (Figure 1-3(a)), which is created by incorporating a white pigment in the coating and can be applied to signs and labels

(ii) the variable reflectance mirror (Figure 1-3(b)), which is obtained when a transparent electrode is replaced by a mirror. This device is used in cars and trucks as anti-glare rear-view mirrors.

(iii) the smart window, which can change from transmitting to absorbing (Figure 1-3(c))

(iv) a surface with variable thermal emittance (Figure 1-3(d)).

The Asahi Glass Co. in Japan installed close to 200 prototype tungsten oxide electrochromic windows, with a size of 0.4 x 0.4 m, in the Seto Bridge Museum, as well as 50 prototypes in the Daiwa House [2,8]. The transmittance range of the window is from 70-75% in the bleached state to 10% in the colored state [20].

In Canada, researchers at the University of Moncton developed a solid-state experimental electrochromic coating, for application in windows, under contract with the Department of Natural Resources Canada (CANMET) [21,22]. The solar transmittance of the tungsten oxide based coating can switch from 52% to 13%, while the visible transmittance switches from 60% to 21% [21].

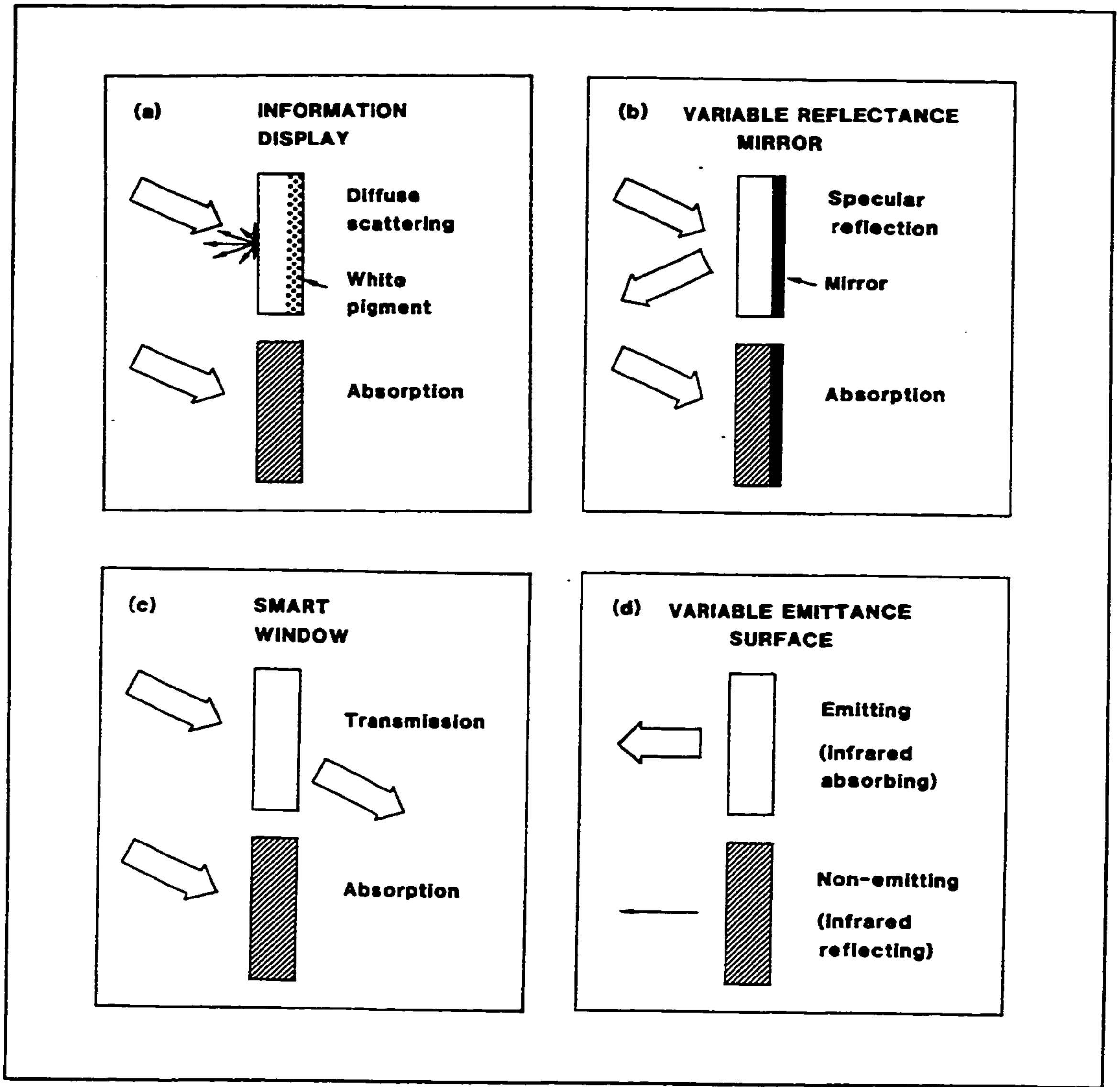

Figure 1-3. Applications of electrochromic coatings. [19]

Researchers at INRS - Énergie et Matériaux (Quebec, Canada) developed and tested three laminated two-layer solid-state electrochromic devices, also under contract with CANMET. During the course of their work, the researchers developed new polymer electrochromic and electrolyte materials, as well as new coating and laminating techniques with the aim of reducing production costs and increase long-term stability of the electrochromic devices. They were successful in scaling up their prototypes from a size of 10 x 10 cm to a size of 35 x 35 cm. [23]

Researchers at the Ontario Research Foundation [24] developed a solid-state electrochromic heat-mirror device based on crystalline tungsten oxide. The device relies on reflectance modulation to switch in the near-infrared region of the solar spectrum.

The International Energy Agency (IEA) initiated a major research effort in January 1992 with the creation of Task 18, Advanced Glazing Materials for Solar and Building Applications, under the agency's Solar Heating and Cooling Program. Over 60 researchers from 15 countries were involved. The main objectives of this five year effort were to: (i) develop advanced glazing materials in order to achieve substantial benefits in terms of energy savings and environmental impact, (ii) perform in-depth studies of material properties and performance, and (iii) undertake technology transfer by providing technical information on materials, energy and environmental assessments as well as the use of design tools. Task 18 was divided into two subtasks; Subtask A, the Modeling and Control Strategies Project, relied on computer simulation in order to evaluate energy and comfort benefits of advanced glazings applied to residential and commercial buildings in different climates, examine glazing control strategies, establish performance criteria and examine the range of application of these avanced glazing technologies. DOE-2, WINDOW 4 and FRAME are among some of the computer tools that were used to meet the objectives of Subtask A. The activities related to objective (ii) were grouped in Subtask B, the Case Study Projects. The advanced glazings under study included chromogenic materials (electrochromic and thermochromic), aerogels, low-e coatings, transparent insulation, evacuated glazings, light transport devices and holographic media. [25,26,27,28] To date, Lawrence Berkeley Laboratory in the United-States is the only organization to have published information on the performance of electrochromic glazings within the context of IEA activities [25].

In 1995, the U.S. Department of Energy launched the "Electrochromics Initiative" which provides a cost-sharing arrangement with industry in order to develop prototype electrochromic windows [8,29].

Benson and Branz [30] at the National Renewable Energy Laboratory (NREL), have developed a photovoltaic (PV) - powered electrochromic window covering produced on a flexible polymer substrate, to be used in retrofit applications in buildings. The window covering, which is to be applied to the inside surface of an existing window, is claimed to provide a lower cost alternative to saving energy without the expense of replacing existing windows. From a building owner's perspective, the risks associated with implementing a new technology would also be reduced since the covering could easily be removed if it does not perform according to expectations. Recently, NREL was seeking to negotiate license agreements with companies in the U.S. to commercialize PV-powered electrochromic windows and sunglasses [31].

Both NREL and LBL are examining the use of electrochromic glazings for car windows to reduce heating and cooling loads in vehicles. The reduced loads would result in downsized equipment, as well as reductions in fuel consumption, vehicle weight and cost. [32,33]

Rearview mirrors are presently the most commercially available electrochromic item [8]; their success stems from the smaller size and shorter life span requirements compared with building windows. The reflectance of the rearview mirrors automatically adjusts to reduce glare due to headlights from other cars. Electrochromic mirrors developed by Gentex possess two sensors, one which measures the ambient light level, another which measures glare. The dimming of the mirror's reflectance is a function of the glare level; the reflectance of the Gentex mirror switches from 80% to 7% [34]. Donnelly and Gentex are the two main producers of electrochromic mirrors and their clients include General Motors, Ford, Chrysler, Mercedes-Benz, Nissan, Toyota, Honda, Rolls Royce, among others [35,36,37].

The successful commercialization of small-scale electrochromic products demonstrates the significant advances that researchers have made from a materials science perspective. However, according to Chevalier and Chevalier [4] there remain some major challenges to be addressed before electrochromic devices can be successfully implemented in buildings. These challenges include:

(i) optimizing the individual materials that comprise an electrochromic device

(ii) improving the electrical operation of the devices such that switching time is reduced

(iii) improving, or developing, large-scale coating deposition and production techniques such that the switching time of the device is within acceptable limits, the expected solar-optical properties are achieved, and that the device is protected against environmental degradation

(iv) ensuring satisfactory performance of the device for the given application, particularly when the device is scaled from prototype size to actual size, and considering the effect of switching from transmitting to absorbing on the glazing temperatures

(v) studying their impact on the thermal interactions that occur in occupied spaces.

NREL has performed accelerated life testing of several prototype electrochromic windows developed by U.S. manufacturers. Tracy et al. [38] have identified three main degradation mechanisms in electrochromic windows: elevated temperature, illumination, and continuous cycling. The effect of these degradation mechanisms on the electrochromic window include: (i) cosmetic defects such as the presence of color streaks in the bleached state, the presence of bleached areas in the colored state, and lack of uniform coloration, and (ii) degradation of the contrast ratio, defined as the ratio of the transmittance in the bleached and colored states of the window at a wavelength of 550 nm. These are factors that must be addressed by product manufacturers to ensure the stability and durability of their windows.

Selkowitz et al. [16] have also noted that while researchers have undertaken extensive efforts to develop marketable electrochromic windows, they have often done so without sufficiently addressing issues related to building performance. Indeed, fewer studies exist on the energy performance aspects of electrochromic windows, than on the material development. These studies are discussed in the following sections of this chapter.

1.2 MODELING THE SOLAR-OPTICAL PROPERTIES OF ELECTROCHROMIC GLAZINGS

The first computer simulation studies on the use of electrochromics in buildings 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 [2,39]. The studies also addressed the differences between reflecting and absorbing electrochromics, as well as the impact of the position of an electrochromic glazing within a double-glazed window configuration. Although overall building energy performance was not addressed in the evaluation, the study from Reilly et al. [39] was the first to provide general guidelines on the performance aspects of electrochromic windows using the shading coefficient and visible transmittance as performance indicators. The WINDOW 3.1 program was used to perform the analysis. It was modified to calculate the solar optical properties of the windows, wavelength by wavelength, based on glazing spectral data; the program then determined the weighted average, or integrated, properties over the solar spectrum. The authors found that a reflecting electrochromic window has a lower shading coefficient than an absorbing electrochromic; however, the differences between the two are reduced if the electrochromic glazing for either type is used as the outer pane of the window, since absorbed solar radiation will mainly flow outward (thus reducing heat gain to the space). The exception occurs when the non-electrochromic glass layer is highly absorbing, such as green glass, in which case the electrochromic glazing should be positioned as the inside layer of the double-glazed window. The position of the reflecting electrochromic glazing had very little impact on the shading coefficient of the double-glazed window;

whereas, it was recommended that the absorbing electrochromic glazing always be placed on the outside in order to reduce heat gain to the space and thus obtain a lower shading coefficient for the overall window. Furthermore, the performance of an electrochromic glazing could be improved or altered by incorporating a spectrally selective coating in the double-glazed window, so that for example, an electrochromic glazing that switches over the solar spectrum can be made to perform as a glazing which switches over the visible region.

The advent of advanced glazings and complex window systems has raised several issues concerning performance modeling and the calculation of window solar heat gain. Window radiant solar heat gain is comprised of two components: (i) one due to the incident solar radiation which is directly transmitted through the window into the space, and (ii) one due to the solar radiation which is absorbed by the window, and is re-radiated to the space [3]:

$$q_i = E_i\,(\tau_{sol} + N_i\,\alpha_{sol}) = E_i \cdot SHGC \qquad (1.1)$$

where q_i = total solar heat gain, W/m²

E_i = solar irradiance, W/m²

τ_{sol} = solar transmittance of a single glazing

α_{sol} = solar absorptance of a single glazing

N_i = fraction of absorbed solar radiation that flows inward

SHGC = Solar Heat Gain Coefficient, representing the portion of incident solar radiation that passes through the glazing and becomes heat gain.

It can be seen from equation 1.1 that the Solar Heat Gain Coefficient depends on the solar transmittance and absorptance, both of which vary as a function of wavelength and incidence angle of solar radiation. The SHGC therefore also depends on wavelength and incidence angle. It is convenient at this point to define the Shading Coefficient, SC, which is the ratio of the SHGC of a window under study to the SHGC of a reference clear single glazing with normal incidence solar transmittance of 0.86, reflectance of 0.08, and absorptance of 0.06 [3]:

$$SC = \frac{SHGC}{0.87} \tag{1.2}$$

The main advantage of using the SC is that it remains constant over changes in incidence angle and solar spectrum, provided that the glazing of interest exhibits similar angular properties as the reference glazing. This is true of single and double glazed clear windows and some single glazed tinted windows. Thus, the ASHRAE Shading Coefficient method has traditionally been used to determine window solar gain using the following relationship [3]:

$$q_i = SC \times SHGF \tag{1.3}$$

where SHGF = Solar Heat Gain Factor, representing the solar heat gain through a 3 mm reference clear single glazing. This quantity is obtained from tables in the ASHRAE Handbook of Fundamentals [3] for various latitudes, orientations, and time of day.

McCluney [40] used the WINDOW 4 program to determine the sensitivity of the SHGC to changing value of incidence angle for a variety of window systems. He found that the

SHGC, and hence the SC, remain constant for incidence angles upto 40°. However, he also noted that:

> "peak summertime solar gains occur with east- and west-facing windows at angles of incidence ranging from about 25 to 55 degrees....for north- and south-facing glazings, peak summertime solar gains occur at angles of incidence greater than the range of relative SHGC constancy....Angles of incidence important for annual energy performance calculations range from 5 to more than 80 degrees for east- and west-facing windows and for horizontal glazings. The range is only slightly reduced for south-facing windows. For north-facing windows, the direct-beam solar gains are small and their angles of incidence range from 62 to 86 degrees."

Therefore, in the case of spectrally selective glazings, advanced coatings and complex window systems, whose solar optical properties are heavily spectrally and angular dependent, the SC no longer remains constant and this method produces significant inaccuracies in calculating solar gain. As a result, McCluney [40,41] has recommended that the Shading Coefficient method of calculating solar gain be discarded for advanced glazings. The SHGC method has been proposed, in the ASHRAE Handbook of Fundamentals, as a replacement to the SC method; the equation to calculate solar gain therefore becomes [3]:

$$q_i = \int E_{i\lambda}(\tau_{s\lambda} + N_i\,\alpha_{s\lambda})\,d\lambda = \int E_{i\lambda}\,SHGC_{\lambda}\,d\lambda \qquad (1.4)$$

where the subscript "s" refers to the property of the window system, and λ represents the wavelength or solar spectral distribution. The SHGC must therefore be determined on a wavelength by wavelength basis. This method is known as the "spectrally based method" and is the procedure recommended by ASHRAE, the National Fenestration Rating

Council and the Canadian Standards Association [3,40]. Furthermore, the WINDOW 4.1 computer program [42,43] was recommended as a tool to perform the above calculations, given that it has the ability to perform the spectrally and angular based calculations of the solar optical properties of window systems; moreover, it is highly used by industry in the U.S. [40].

In calculating the angular solar optical properties of coated glazings, the WINDOW 4.1 program assumes that the glazing behaves as a 3 mm clear glass when the solar transmittance is greater than 0.65, and behaves as a 3 mm bronze glass when the solar transmittance is less than or equal to 0.65 [42]. Klems et al. [44] have validated the accuracy of these assumptions by comparing measured values of SHGC of spectrally selective windows with those calculated using WINDOW 4.1.

The solar optical properties of windows provide performance indices that allow a simple and quick comparison of different window types. However, as a final step in evaluating the performance of windows, ASHRAE recommends that a whole building energy analysis be performed in order to determine the window's annual energy performance. The hourly energy simulation would therefore include the effects of interactions between the building systems (e.g., envelope, lighting, HVAC), building type, orientation, and occupancy [3]. For accuracy of the calculations, here too it is recommended that the window solar gain be determined using the SHGC as it accounts for the dependency on incidence angle [41]. WINDOW 4.1 facilitates the above process by providing an interface with the DOE-2.1E energy analysis program [45], which is the most widely used energy analysis program in North America and has been extensively validated. An output file containing the window's thermal and angular dependent solar optical properties can be exported from the WINDOW 4.1 program and be integrated within the existing window library of the DOE-2.1E program. The interface is currently only available with the DOE-2.1E program.

The DOE-2.1E program currently offers three methods to calculate the solar gain through windows [45,46,47]: (i) based on the ASHRAE Shading Coefficient method, (ii) the user can select a window from a very small library of generic coated (reflective coating only) and uncoated single and multiple glazed windows; the library contains precalculated angular properties, or (iii) the user can select a window from a library of 200 windows which was created using the WINDOW-4 program and spectral data provided by glazing manufacturers. Reilly et al. [47] have used DOE-2.1E to compare the Shading Coefficient method (i) and the detailed method (iii) of calculating the solar gain for a South-facing window on a clear day in June in Chicago. Considering a wind speed of 3.3 m/s, at peak conditions (i.e., noon), it was found that the SC method underpredicted the solar gain by at most 10% for a single reflective glazing, and overpredicted the solar gain by a maximum of 17% for a double glazed clear window. If no wind is assumed (0 m/s), the SC method underpredicted the solar gain by up to 35% for the reflective glazing, and by 12% for the clear window. The authors attribute the discrepancies with the SC method to two main reasons:

(i) the angular transmittance of the glazings studied differs from the transmittance of the reference glazing

(ii) the solar gain of the studied glazings was primarily due to absorption, yet the reference glass has a low absorptance.

1.3 STUDIES ON THE POTENTIAL ENERGY SAVINGS OF ELECTROCHROMIC WINDOWS IN BUILDINGS

Much of the work concerning the energy impacts of electrochromic windows in buildings originates from the Lawrence Berkeley National Laboratory (U.S.A.). Researchers there have primarily used the WINDOW program to determine angular dependent solar-optical properties of electrochromic windows and the DOE-2.1E energy analysis program to determine the whole building energy performance due to the use of these windows. Earlier studies [2,48] regarding the energy impacts of electrochromic windows in commercial buildings were based on idealized coating properties, generally performed for prototypical buildings located in cooling dominated climates (e.g., California), and based on straightforward control strategies, i.e., the electrochromic glazing was only controlled to maintain an adequate illuminance level in the space. These studies were mainly geared towards establishing the potential energy performance thresholds for electrochromic windows in order to justify further development work. It is important to note that the benefits of electrochromic windows extend beyond savings in heating and cooling energy consumption and in peak electricity demand; these windows can be applied in conjunction with a daylighting scheme (i.e., light dimming controls) in order to reduce lighting electricity consumption and improve the visual environment through glare control. Researchers have begun to broaden the scope of the window performance requirements to include visual and thermal comfort criteria as technically feasible and cost-effective electrochromic windows approach commercialization. This has also led them to explore other control strategies.

Selkowitz et al. [49] cited 60% savings in cooling and lighting energy for the perimeter zones of a building located in a hot climate, and a 50% reduction in peak electric demand. They further claim that savings due to downsized HVAC systems and chillers could offset the initial cost of electrochromic windows by 10 to 20%. According to Warner et al. [48], since electrochromic windows inherently control solar gain, operable shading devices would potentially no longer be required resulting in additional investment cost savings of approximately $55/m^2$ to $108/m^2$ (U.S.).

Lampert and Granqvist [2] compared the energy impacts of several window types for a commercial building located in a cooling-dominated climate, including: (i) one electrochromic window which was controlled to maintain illuminance levels to 538 lux (τ_{vis} = SC = 0.8 in the bleached state), (ii) a photochromic window whose transmittance varied linearly as a function of total incident solar radiation (τ_{vis} = SC = 0.8/0.2), (iii) and (iv) a high transmission glazing with and without shades (τ_{vis} = 0.78, SC = 0.8), and (v) a low transmission glazing without shades (τ_{vis} = 0.07, SC = 0.18). In terms of monthly cooling energy consumption, the electrochromic window outperformed all other window types and the low transmittance window was the second best performer. In terms of total energy consumption (lighting, heating, cooling, fans and miscellaneous electrical use), again, the electrochromic window outperformed all other window types, followed by the photochromic window. The results showed that the low transmittance window was the poorest performer during winter months, while the high transmittance window without shades resulted in the highest total energy consumption during the summer months. Of all window types, the electrochromic window also resulted in the lowest peak electric demand and could reduce the chiller size by 12% compared to a building with a low transmittance window, and by 36% compared to a building with unshaded clear glass.

Warner et al. [48] compared the peak demand and energy savings potential of five window types for a commercial building located in a hot climate (California). The windows studied included (Table 1-2): tinted, reflective, spectrally selective, an idealized broad-band electrochromic, where the transmittance can switch over the entire solar spectrum, and an idealized narrow-band electrochromic, where the transmittance can switch only in the visible region of the spectrum and is minimum in the infrared region, resulting in a lower range of shading coefficient than the broad-band electrochromic. Both electrochromic windows were controlled to maintain an illuminance level of 538 lux in the perimeter zones.

Table 1-2. Summary of window properties used by Warner et al. [48]

Window type	τ_{vis}	SC
Tinted	0.38	0.54
Reflective	0.10	0.20
Spectrally selective	0.37	0.30
Broad-band electrochromic	0.70/0.09	0.84/0.26
Narrow-band electrochromic	0.50/0.11	0.71/0.09

The researchers found that the use of the narrow-band electrochromic window resulted in the lowest annual electricity consumption and peak demand for perimeter zones compared with all other window types, and could reduce the chiller size (allocated to the perimeter zones) by 20% compared with a daylit building with tinted windows. Other conclusions that could be drawn from the results include:

- In terms of annual lighting electricity consumption for the West perimeter zone, at window-to-wall ratios (WWR) between 0.3 and 0.6, the electrochromic windows used in conjunction with a daylighting scheme (i.e., lighting controls) resulted in 65% energy savings compared to a non daylit building. Furthermore, at a WWR of 0.3, the electrochromics resulted in 22% lower lighting energy consumption than tinted or spectrally selective windows, and 55% lower relative to reflective windows. When electrochromic windows were used, the lighting energy consumption remained stable at WWR above 0.3.
- When the narrow-band electrochromic window was used, the annual cooling electricity consumption remained rather constant when the WWR was above 0.2, whereas cooling energy increased with increasing WWR for the other window types. The same trend was observed for the total annual electricity consumption in perimeter zones. This means that greater window sizes can potentially be used with electrochromic windows and it would not result in a cooling energy penalty.
- The use of electrochromic windows in the North perimeter zone did not produce a significant advantage over conventional window types in terms of cooling energy consumption.
- A simple economic analysis was performed, comparing the impact of the narrow-band electrochromic windows in a daylit building with the impact of tinted windows in a non-daylit building, both at a WWR of 0.6. The incremental cost of the electrochromic windows was estimated at \$270/m^2 glass area more than conventional glazings initially; however, the incremental cost could be reduced to \$160/m^2 glass area more than conventional windows with mass production (dollar amounts are in

U.S. currency). Considering mass production, the use of electrochromic windows would result in total annual energy cost savings of $27/m^2$ glass area and a payback of 6 years. If the cost savings due to reduced peak energy demand, chiller size reductions and incentive programs were considered, the payback reduced to 3.2 years.

Enermodal Engineering [20] used the ENERPASS energy analysis program to assess the energy performance of commercial buildings with electrochromic windows (SC=0.8, τ_{vis}=0.71/0.1) relative to clear (τ_{vis}=0.71) and tinted windows (τ_{vis}=0.1) for two Canadian climates (Toronto, Ontario and Winnipeg, Manitoba) as well as a hot climate in the United States (Los Angeles, California). Two separate electrochromic glazing control strategies were simulated: (i) based on room temperature, where the electrochromic glazing was switched to the colored state when the room temperature exceeded the cooling set-point of 24°C, and (ii) based on illuminance level. The results for Toronto showed that the temperature controlled electrochromic window resulted in a greater reduction of the peak cooling demand; savings of 150 W/m² glass area were reported relative to clear windows and 40 W/m² glass area relative to tinted windows. In terms of lighting discomfort, which was defined in terms of the percentage of the time that the illuminance level exceeds the desired amount, the illuminance level controlled electrochromic window did not produce any discomfort, while the temperature controlled window produced lighting discomfort 10% of the time. For reference, clear windows produced discomfort 80% of the time, while tinted windows 50% of the time.

Sullivan et al. [50] used the DOE-2.1E program to study the energy performance of a prototypical office building located in two cooling-dominated climates (Phoenix, Arizona and Miami, Florida) and one heating-dominated climate (Madison, Wisconsin); the impact of six double glazed electrochromic windows from three different manufacturers was studied. Each window incorporated a real prototype electrochromic coating as the outer pane and either a high-transmittance low-e glazing or a spectrally selective low-e glazing as the inner pane. Switching of the electrochromic layer was controlled to maintain an illuminance level of 538 lux in the perimeter zone. The study does not permit an effective comparison of the performance of the electrochromic windows since the switched-state properties of the windows were almost the same for each window (SHGC=0.10-0.11, SC=0.12-0.13, and τ_{vis}=0.05-0.08); hence, only small differences in lighting, cooling and fan energy performance are noted. However, there are significant performance differences between the electrochromic windows and conventional tinted, reflective and spectrally selective windows. Considering the total electricity consumption of a building in Phoenix, for a West-facing window and a WWR of 0.6, the use of electrochromic windows resulted in savings of 28 kWh/m^2 floor area (24%) compared to conventional reflective windows and a savings of 90 kWh/m^2 floor area (53%) compared to conventional tinted windows. Lighting electricity consumption for the electrochromic windows was the same in Phoenix and Miami. Other conclusions that could be drawn from the study include:

- Peak electric demand for all electrochromic window types for the building located in Phoenix was approximately 65 W/m^2 at a WWR of 0.6; at this WWR, the use of electrochromic windows resulted in 50% savings compared to tinted windows, 30% relative to spectrally selective windows, and 20% relative to reflective windows.

- The authors recommended that an electrochromic window with high bleached state visible transmittance be used for small window-to-wall ratios, since the savings due to daylighting are greater than the increase in cooling energy consumption.
- Considering a West-facing electrochromic window in Madison during the heating season, a window that was maintained in its bleached state to maximize the solar gains resulted in approximately 40% lower heating energy consumption compared with a window that is controlled based on illuminance level. While the authors recommended that the window remain in its bleached state during the heating season, they concluded that glare control of the electrochromic window may be required.

Lee and Yoon [51] used DOE-2.1E to compare the energy performance of a three story commercial building located in South Korea due to aluminum frame electrochromic, bronze, heat mirror and low-e windows. However, the windows were selected from the existing window library of the DOE-2.1E program and the switching control strategy for the electrochromic window was not specified.

1.4 EXISTING STUDIES ON CONTROL STRATEGIES

Recent research work addresses some issues related to switching control strategies for commercial and residential buildings [25,52,53,54,55]. Such studies compared the energy performance of buildings resulting from the use of several existing models of control strategies incorporated within the DOE-2.1E program.

Sullivan et al. [25,52] studied the effect of three electrochromic glazing switching control strategies on the cooling, lighting and total electricity consumption and peak demand of a commercial building located in Blythe, California. The double glazed electrochromic windows studied were prototypes under development and included both absorptive and reflective electrochromic glazings combined with either clear or low-e glazings. An idealized, reflective electrochromic window was also defined. Window properties are summarized in Table 1-3.

Table 1-3. Summary of window properties used by Sullivan et al. [25,52]

Window type	τ_{vis}	SC
Tinted (grey)	0.38	0.54
Reflective	0.13	0.20
Low-e (tint)	0.38	0.35
Electrochromic glazings		
Clear absorptive	0.76/0.14	0.85/0.21
Clear reflective	0.73/0.14	0.73/0.20
Low-e absorptive	0.66/0.10	0.57/0.18
Low-e reflective	0.64/0.12	0.54/0.18
Idealized	0.65/0.00	0.67/0.06

Three switching control strategies were simulated: (i) based on daylight illuminance, where the window properties were controlled to maintain an illuminance level of 538 lux, (ii) based on incident total solar radiation, where the properties were varied linearly as a function of the high and low solar radiation set points; the window was maintained in the bleached state when the total incident solar radiation was less than 63 W/m², while three colored state set-points (i.e., high set-points) were studied: 189 W/m², 315 W/m², and 630 W/m², and (iii) based on the presence of a cooling load, i.e., the window was switched to the colored state if the cooling load from the previous hour was greater than zero (no intermediate switching occurred). No indication was provided as to how the set-points were selected. It was found that the control strategy based on illuminance levels offered the best annual energy performance for commercial buildings; this is because the savings due to daylighting are substantial, compared to the increase in cooling energy with increasing WWR. Control by space load was the worst performer compared to the other control strategies. Although this strategy resulted in the lowest cooling energy consumption, daylighting benefits were lowest because the window was almost always in its fully colored state, whereas, intermediate switching occurred with the other strategies. The authors concluded that space load control would be an effective strategy in buildings that do not have a daylighting scheme. The performance of a control strategy based on incident solar radiation depended on window size. For small window sizes (i.e., WWR < 0.35), the authors recommended that a larger range of set-points be used in order to maximize the daylighting benefits. For larger window sizes, the increase in cooling has a greater impact on energy consumption than lighting energy reductions; therefore a small set-point range is more appropriate in order to reduce solar gains. The peak electricity consumption was the same for all three control strategies; this is because the electrochromic windows have similar switched state properties and are in the colored state during peak conditions.

Sullivan et al. [25,53] studied the impact of three electrochromic glazing control strategies on the energy performance of a single-story house for two locations, Miami, Florida and Phoenix, Arizona. Six electrochromic window types and three low-e conventional types were considered. Four of the electrochromic windows consisted of a reflective electrochromic glazing combined with either an idealized low-e or idealized low-e and spectrally selective glazing. Window properties are summarized in Table 1-4.

Table 1-4. Summary of window properties used by Sullivan et al. [25,53,55]

Window type	τ_{vis}	SC
Low-e (clear)	0.77	0.75
Low-e (clear)	0.70	0.51
Low-e (tint)	0.41	0.33
Electrochromic windows		
Reflective, idealized low-e	0.65/0.16	0.67/0.27
Reflective, idealized spectrally selective low-e	0.65/0.16	0.55/0.24
Reflective, idealized low-e	0.65/0.08	0.67/0.20
Reflective, idealized spectrally selective low-e	0.65/0.08	0.55/0.18
Highly reflective, idealized low-e (future window type)	0.65/0.06	0.67/0.15
Highly reflective, idealized low-e (future window type)	0.65/0.00	0.67/0.06

The three electrochromic switching control strategies were based on: (i) incident total solar radiation; the window was maintained in the bleached state when the total incident solar radiation was less than 63 W/m², while three colored state set-points (i.e., high set-points) were studied: 189 W/m², 315 W/m², and 630 W/m², (ii) the presence of a space cooling load, where the window is either in its bleached state or its colored state, and (iii) outside air temperature, with a low set-point of 25.6°C, the same as the cooling set-point temperature, and a high set-point of 32.2°C at which the window would be in its fully colored state. Control by space load resulted in the best performance. Performance due to total solar radiation and outdoor temperature control depended on the range of set-points. For the former, a smaller set-point range resulted in lower energy consumption. Performance of the outdoor temperature control strategy depended on the selection of the high set-point, which according to the authors, should be correlated with the weather conditions and is therefore location-dependent. The authors do not recommend the use of this strategy.

Sullivan et al. [55] studied the impact of three electrochromic glazing control strategies on the energy performance of a commercial office building located in a heating-dominated climate, Madison, Wisconsin. This was one of the few studies that examined the annual heating energy performance of the building. Only the six electrochromic window types shown in Table 1-4 were considered in the study. The three electrochromic switching control strategies were based on: (i) daylight illuminance, where the window properties were controlled to maintain an illuminance level of 538 lux, (ii) incident total solar radiation, where the properties were varied linearly as a function of the high and low solar radiation set points; the window was maintained in the bleached state when the total incident solar radiation was less than 63 W/m^2, while three colored state set-points (i.e., high set-points) were studied: 189 W/m^2, 315 W/m^2, and 630 W/m^2, and (iii) the presence of a cooling load. The authors concluded that heating energy consumption was lowest when the cooling load control strategy was used. Since there is no cooling load during the heating season, the electrochromic windows essentially always remain in their bleached state, thus allowing solar gains to heat the zone, which in turn reduces the heating energy consumption. The next best performing control strategy was based on incident solar radiation with the broadest range of set-points (63-630 W/m^2); again, this is because it allows maximum benefit from solar heat gains during the heating season. However, the authors acknowledge that glare problems may arise from maintaining the window in its bleached state.

According to Selkowitz et al. [16], 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 [54] have studied the feasibility of using a complex predictive control strategy rather than one that is based on instantaneous measurements of the driving variables for switching (example, illuminance level). They compared the performance of an automated venetian blind system and of narrow-band and broad-band electrochromic glazings controlled by illuminance levels to a theoretical optimal dynamic system designed to minimize electricity consumption of the lighting system and minimize the solar gains. 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. The narrow-band electrochromic achieved 80% to 90% of the optimum energy performance for all orientations; therefore, predictive control strategies would not improve the performance by much. On the other hand, it was found that predictive controls could improve the performance of both the broad-band electrochromic and the venetian blind system by 35% to 40%.

While the main objective of the above studies has been to quantify the potential energy savings resulting from the use of electrochromic windows, researchers have also pointed to the necessity of exploring the impact on other performance issues such as occupant visual and thermal comfort as these factors directly affect worker productivity [16]. According to Selkowitz et al. [16], "the problem is made more difficult in that it is not a simple 'engineering optimization' problem but rather one that includes tradeoffs between energy savings and subjective human response." Lee and Selkowitz [54] also discussed the issue of mutiple control strategies, where different strategies can be used on an hourly, monthly or seasonal basis, and multiple performance criteria (i.e., energy savings, visual and thermal discomfort) are considered. They claim that developing a strategy based on multiple performance criteria is a particularly laborious process because the conflicting nature of some criteria means that it is difficult to fully satisfy all criteria. They acknowledge that further work is required in these areas, and add that "the resolution of multiple performance criteria will affect the realized energy performance of dynamic envelope and lighting systems and should therefore be investigated with as much care as predictive control algorithms." Selkowitz et al. [16] have performed preliminary assessments of the impact of electrochromic glazings on both thermal and visual comfort. Fanger's comfort model was used to determine the percentage of people dissatisfied (PPD) due to transmitted direct solar radiation through electrochromic, reflective and grey tinted glazing, while the glare index was used as a basis to evaluate visual comfort. At present however, existing energy analysis software do not provide an electrochromic glazing control strategy that is based on subjective performance. Furthermore, there are currently no models which optimize glazing operation for both energy savings and comfort and address the tradeoffs between the two. Therefore, such models have yet to be developed.

Moek et al. [56] used the lighting visualization program, RADIANCE, to assess the visual quality performance of an electrochromic glazing (τ_{vis} = 0.88/0.08), a clear glazing

(τ_{vis} = 0.88) and a tinted glazing (τ_{vis} = 0.41) in an office building located in Phoenix, Arizona. Visual quality was defined in this study in terms of:

(i) illuminance levels, where a maximum workplane illuminance of 500 lux is recommended for offices with visual display terminal (VDT) screens,

(ii) visual comfort as determined by luminance ratios, where for a VDT luminance of 85 cd/m^2, the luminance of all room surfaces within peripheral view should not exceed 850 cd/m^2 (i.e., a luminance ratio of 10:1). The maximum recommended luminance ratio between paper tasks and the VDT screen is 3:1, as well as between the task and adjacent dark surroundings.

(iii) VDT visibility near windows; while no method exists to evaluate this criteria, contrast and visibility depend on the ratio of task luminance to background luminance (the higher, the better), and

(iv) privacy.

The electrochromic glazing was controlled to maintain a workplane illuminance of 500 lux determined by two photosensors, one placed at the front of the office area, and one at the rear. The performance of the glazing types with respect to the above-mentioned criteria is summarized and compared in Table 1-5. It is noted that the electrochromic glazing generally offers better control of the required visual parameters, and outperforms the clear and tinted glazings. The authors comment that a visual transmittance of 0.01 for the colored state of the electrochromic glazing would ensure the required privacy, glare control, and constant daylight levels; however, this would increase the energy consumption for electric lighting to compensate for the resulting significant decrease in daylight levels. They also mention that occupants may be dissatisfied due to reduced access to clear views of the exterior. It is interesting to note that the authors qualitatively discussed the trade-offs between the visual quality and energy consumption, although they do not suggest an approach to quantify or study these trade-offs more in-depth.

Ultimately, technical, economic and performance issues will all be contributing factors towards the market acceptance and success of electrochromic windows. Lampert [8] summarizes the main issues concerning researchers as being "the cost of the glazing, the trade-offs between cost and benefit, and cost and lifetime". While definite cost figures are not yet available, recent estimates place the cost of electrochromic windows between \$100-1000 US\$/m^2, while companies have set cost limits from \$100-250 US\$/m^2 [6,8]. Coating production techniques will have a major impact on overall cost; however, researchers at the Optical Coating Laboratory are confident that "solid-state monolithic electrochromic coatings can be manufactured in much the same was as low-emissivity coatings are presently produced", thus reducing costs [12].

Table 1-5. Summary of results comparing visual performance of an electrochromic glazing with conventional glazings. [56]

Criterion	Performance of electrochromic glazing	Performance of clear and tinted glazings
Illuminance levels	Glazing is capable of maintaining workplane illuminance of 500 lux on sunny and overcast days. Levels are greatly exceeded under direct sun. Levels are not sufficient at rear area of space during overcast winter conditions. A $\tau_{vis} = 0.01$ in the colored state is recommended to meet the allowable level in the front zone under direct sun.	Illuminance levels exceed recommended maximum. Levels vary depending on daylight availability.
Visual comfort	A $\tau_{vis} = 0.05$ is necessary to meet recommended luminance ratio of 10:1, and a $\tau_{vis} = 0.016$ is necessary to meet luminance ratio of 3:1 under direct sun for glare control.	
VDT Visibility (for Aug. 21 peak clear sky conditions)	Ratio of task luminance to background luminance from 8:00 - 16:00: 17 - 48 for the electrochromic controlled by the sensor at the rear of the zone 30 - 48 for the electrochromic controlled by the sensor at the front of the zone.	Ratio of task luminance to background luminance from 8:00 - 16:00: 7 - 16 for the clear glazing 13 - 28 for the tinted glazing Provide poor to moderate visibility.

1.5 CONCLUSIONS

Several observations and issues emerge from the existing body of literature on the topic of electrochromic coatings and windows:

(i) The strong research efforts on the materials science aspect of electrochromic coatings is noted, while few publications address their performance in buildings. This latter area of research is still young as demonstrated by the small number of publications that originate principally from Lawrence Berkeley Laboratory.

(ii) Earlier research demonstrated the energy performance thresholds of idealized electrochromic windows, which was useful in justifying the long-term development of electrochromic coatings. However, in order to achieve this objective, the scope of the research was necessarily narrow: one single performance criterion was studied, that of energy savings, and one single electrochromic switching strategy was considered, based on illuminance levels.

(iii) Eventually, researchers began to study the effect of other switching strategies; however, they utilized only some of the strategies that are currently available in DOE-2.1E. Furthermore, guidelines on the systematic application of these existing strategies have not yet been developed, particularly regarding the selection of appropriate set-points for a given building application and climate.

(iv) The main area where the research has not advanced significantly is in the assessment of the combined impact of electrochromic windows on energy savings and other factors such as visual quality and thermal comfort. As the commercialization of electrochromic windows began to become a reality, researchers alluded to multiple performance criteria. However, while research in this area is recommended in several studies, there currently exists no methodology to address the effect of combined performance criteria. Consequently, no new tools have been developed and incorporated into existing energy analysis software to address this issue.

(v) There exists a need to develop enhanced computer models of electrochromic glazing switching control strategies that address the tradeoffs between subjective performance factors and the quantitative impacts such as energy savings. Furthermore, the model should support the creation of more complex strategies that include a combination of driving variables for switching and enable users to optimize glazing operation. The current scope of research can therefore be broadened to develop approaches and tools that facilitate the assessment and implementation of combined performance criteria.

1.6 SCOPE AND OBJECTIVES OF THE THESIS

The general objectives of the present research are twofold: (i) to undertake a detailed evaluation of the performance of electrochromic glazings, and (ii) to advance knowledge in the field by developing new models to simulate their control.

The objectives are achieved using computer simulation (Figure 1-4). Three public domain computer programs, APPLIED FILM LAMINATOR [57], WINDOW 4.1, and MICRO-DOE-2.1E, are used to evaluate the complex interactions between building systems, thermal phenomena and the properties of the electrochromic glazings. The work described in this thesis is based on the spectral data of an experimental electrochromic coating developed at the University of Moncton.

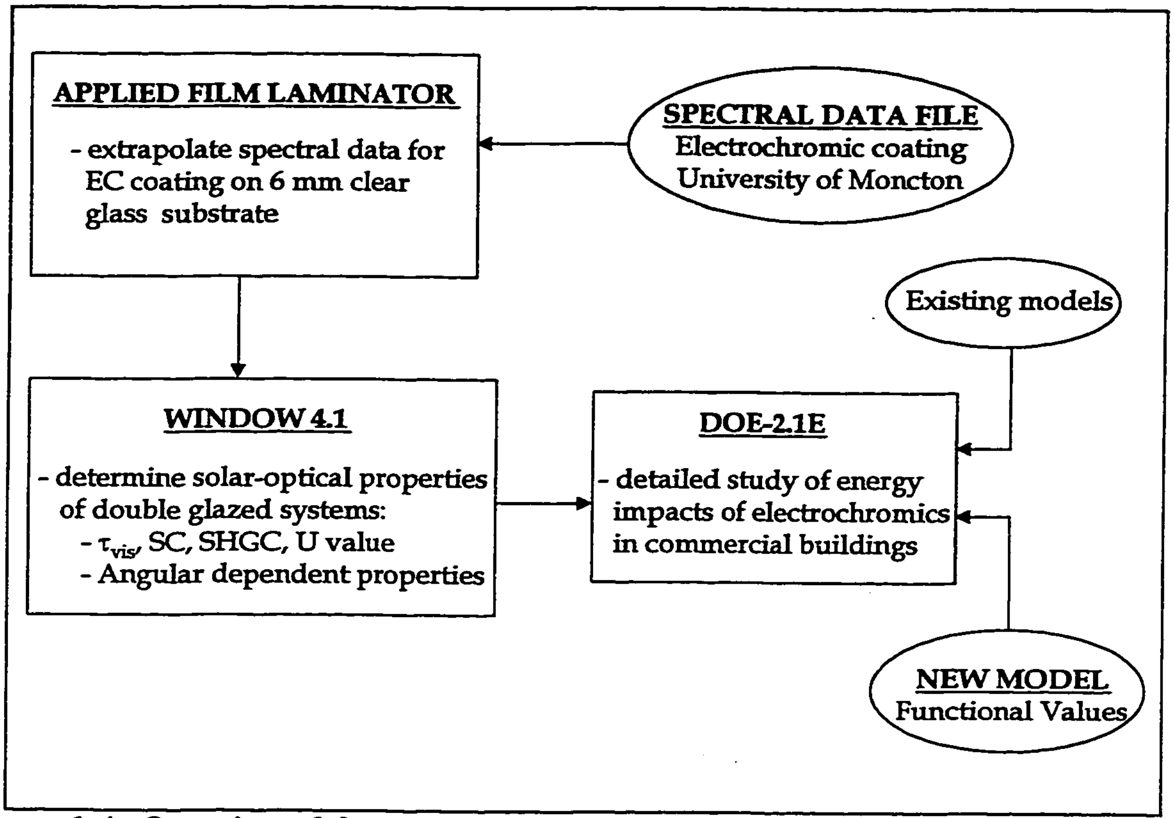

Figure 1-4. Overview of the approach used to accomplish the thesis objectives.

The emphasis of the first objective is to develop an approach to model a glazing which incorporates the experimental electrochromic coating and to study the main influencing factors for switching the properties of the coating from the bleached state to the colored state. The work can be divided into the following sub-objectives:

(i) model a glazing which incorporates the experimental electrochromic coating and determine its solar-optical properties

(ii) characterize and compare the properties of several types of double glazed windows including one which incorporates the experimental electrochromic glazing

(iii) perform a critical evaluation of several existing models of electrochromic glazing control strategies that are available in the DOE-2.1E energy analysis program and provide insight on their application and selection of set-points.

The knowledge obtained during first objective is then used to develop a new model to control the switching of the electrochromic window such that it optimizes energy savings and visual comfort. The emphasis here is to:

(i) address the trade-offs between the two conflicting objectives

(ii) couple the model with the DOE program using the program's Functional Values approach

(iii) apply the model to evaluate the whole building performance of an existing commercial building resulting from the use of electrochromic windows.

1.7 OVERVIEW OF THE THESIS

This thesis consists of six chapters. An overview of the state-of-the-art research on electrochromic coatings was presented in this chapter, Chapter 1, with a particular emphasis on their application in buildings. The main issues governing the modeling and performance assessment of electrochromic windows are discussed.

In Chapter 2, the integrated solar-optical properties of the experimental electrochromic coating are determined, and a double glazed window incorporating the coating is modeled. The performance of this electrochromic window is then compared relative to several conventional window types based on their properties.

An in-depth analysis of existing electrochromic glazing control strategies, that are available in the DOE-2.1E energy analysis program, is presented in Chapter 3. An existing large commercial building is used as a case study, and the impact of several driving variables for switching of the electrochromic glazing on the extraction rate of perimeter zones is studied. This chapter provides valuable conclusions on the applicability of the existing control strategies, as well as their limitations.

A new procedure to optimize the switching operation of the electrochromic window was developed and is presented in Chapter 4. This unique approach considers two conflicting performance objectives: energy consumption reduction and improvement of the visual quality. The switching strategy was formulated as a multi-objective optimization problem with conflicting objectives. Pareto optimum solutions are developed which demonstrate the trade-offs between both objectives. The procedure was coupled with DOE-2.1E using the Functional Values approach.

The feasibility of using electrochromic windows in commercial buildings is studied in Chapter 5. The impact of the conventional and electrochromic windows on the whole-building performance of an existing commercial building is determined and compared. The application of electrochromic windows and the resulting whole-building performance in two different climates is also evaluated.

The conclusions and main contributions of this work are presented in Chapter 6. Opportunities for further work are also discussed.

CHAPTER 2
CHARACTERIZING THE PROPERTIES OF AN EXPERIMENTAL ELECTROCHROMIC COATING

The work described in this thesis is based on the spectral data of an experimental electrochromic coating that was developed at the University of Moncton. A thorough analysis of the impact of electrochromic glazings on the energy performance of buildings begins with the determination of the coating's total, or integrated, solar-optical properties and the modeling of a glazing which incorporates the coating. Of particular interest is the performance of the electrochromic glazing relative to conventional glazing types that are currently used in commercial buildings. Corsi et al. [58] used two public domain computer programs to perform this evaluation. This chapter describes how the APPLIED FILM LAMINATOR program was used to model a 6 mm thick glazing which incorporates the experimental coating. Then, the WINDOW 4.1 program was used to evaluate 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 incorporates the experimental electrochromic glazing.

2.1 DESCRIPTION OF THE EXPERIMENTAL COATING

Spectral reflectance and transmittance data, measured at normal incidence, were obtained for the bleached and colored states of an experimental, monolithic solid-state electrochromic coating developed at the University of Moncton, New Brunswick

(Canada), under contract with CANMET of the Department of Natural Resources Canada [21,22] (Figure 2-1). The data was supplied courtesy of Dr. Vo-Van Truong, head of the Thin Films Research Group in the Department of Physics, University of Moncton. The coating consists of the following sequence of layers:

1 mm clear glass substrate / ITO / $Li_x V_2O_5$ / $LiBO_2$ - LiF / WO_3 / ITO / MgF_2

where: ITO = indium tin oxide as the transparent conductors

$Li_x V_2O_5$ = lithium vanadate as the ion storage medium

$LiBO_2$ - LiF = lithium borate - lithium fluoride as the ionic conductor

WO_3 = tungsten oxide as the electrochromic layer

MgF_2 = magnesium fluoride as an outer layer which serves to protect the coating from ambient humidity

Truong et al. [21] have studied the effect of temperature, humidity and exposure to ultraviolet radiation on the performance and stability of the coating. Their tests on earlier coating prototypes revealed that the transparent conductor is susceptible to degradation due to exposure to humidity. This prompted the researchers to add the protective MgF_2 layer.

It is important to note that the spectral data of the experimental electrochromic coating included the presence of a 1 mm thick clear glass substrate. This 1 mm coating-substrate is referred to as the "electrochromic coating" throughout this thesis.

In this chapter, the analysis of the performance of the electrochromic coating is based on several performance indices (visible transmittance, shading coefficient, solar heat gain coefficient, U-value); these indices are described in section 2.1.2. The performance evaluation is divided into two parts:

(i) first, it was necessary to determine the coating's integrated solar-optical properties and to extend the spectral data of the 1 mm coating to a common glass thickness of 6 mm. Researchers at Lawrence Berkeley Laboratory recommended the use of the APPLIED FILM LAMINATOR program to model the 6 mm coating-substrate [59], hereafter referred to as the "electrochromic **glazing**".

(ii) second, a double glazed window which incorporates the experimental electrochromic glazing was defined, along with several conventional window types and two idealized electrochromic windows. The WINDOW 4.1 program was used to determine the solar-optical and thermal properties of these windows based on spectral data of the individual glazing layers. Window performance was then compared based on the indices that are described in section 2.1.2.

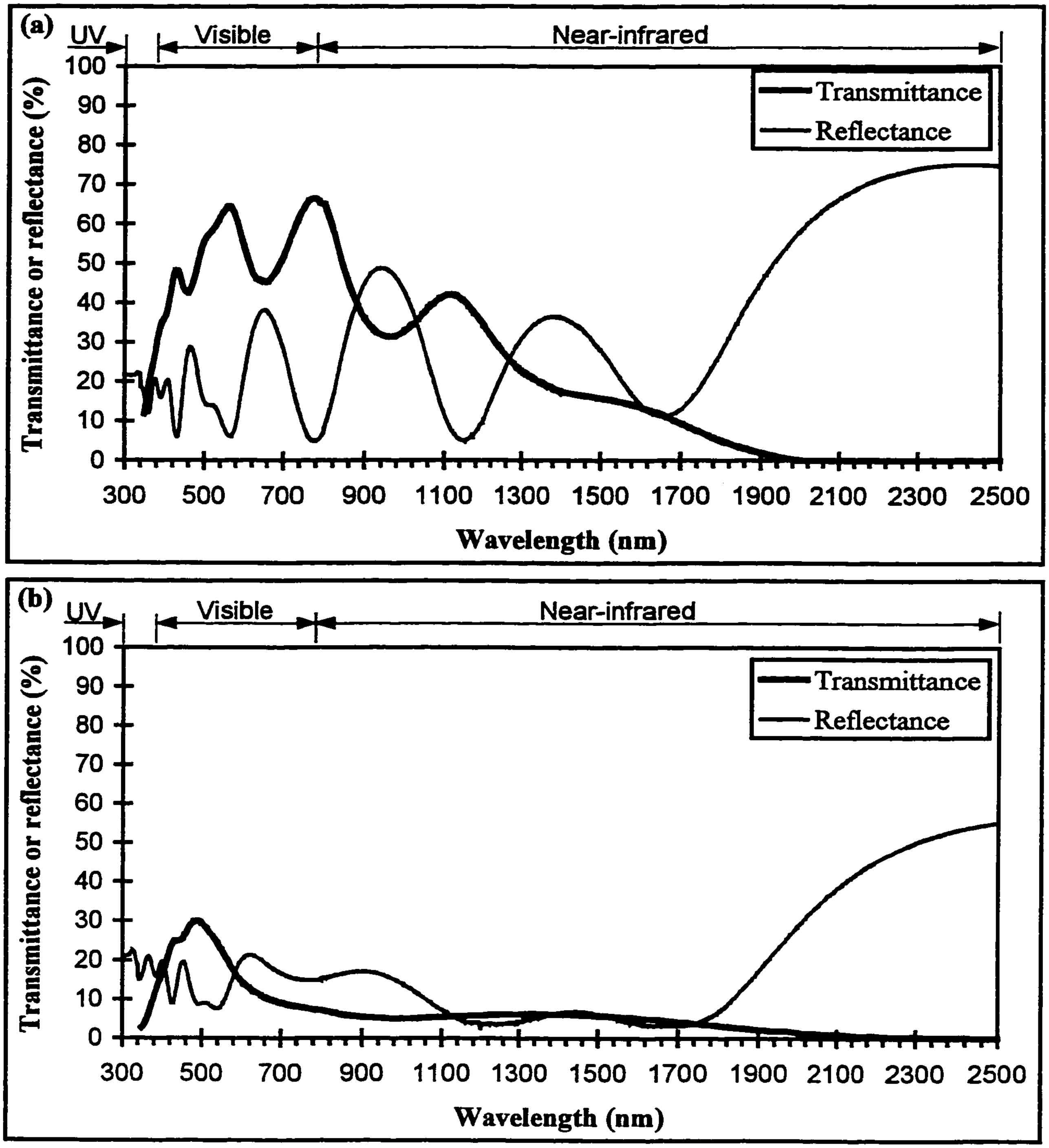

Figure 2-1. **Spectral transmittance and reflectance data of the experimental electrochromic coating in the (a) bleached state, and (b) colored state.**

2.1.1 Determining the solar-optical properties - background

Measurements of transmittance, reflectance and absorptance are dependent on wavelength and incidence angle. Given a set of spectral data ($R_\lambda=\tau_\lambda$, ρ_λ, or α_λ) at a specific incidence angle, the total or integrated solar-optical property (R_s) is determined as the weighted average response using the solar spectral irradiance as the weighting function [60]:

$$R_s = \frac{\int_0^\infty R_\lambda \, E_\lambda \, d\lambda}{\int_0^\infty E_\lambda \, d\lambda} \tag{2.1}$$

where: E_λ = solar spectral irradiance, W/m²·μm. This quantity can be obtained from standard ASTM E 891-87 [60] for air mass 1.5

λ = wavelength, μm.

It was discussed in Chapter 1 that ASHRAE, the National Fenestration Rating Council (NFRC) and the Canadian Standards Association recommend that the solar-optical properties of advanced glazings and complex window systems be calculated using the "spectrally based method", i.e., on a wavelength-by-wavelength basis. Both ASHRAE and the NFRC recommend the use of the WINDOW 4.1 program to perform these calculations; this program was therefore selected to calculate the performance indices of the double glazed windows that are described in this thesis.

The heat transfer through a window system is determined as the area-weighted average of the heat transfer through the centre-of-glass, edge-of-glass, and frame components of the window. The heat transfer across the centre-of-glass is modeled in WINDOW 4.1 as a one-dimensional process; based on the climatic data as boundary conditions, a steadystate energy balance is performed at the centre node of each window layer to calculate the temperature at these nodes, and subsequently at the glazing surfaces. These temperatures are then used to calculate the conductive, convective and radiative heat fluxes leaving the layer surfaces. Detailed equations for the centre-of-glass calculations are provided in Arasteh et al. [43]. The absorptance and solar-optical properties of the window layers influence the heat transfer. For window systems with multiple glazing layers, WINDOW 4.1 considers the transmittance through each layer, the front and back reflectance from each layer and the solar absorptance in each layer. These quantities are calculated wavelength-by-wavelength using recursive relationships that account for the internal reflections within the window system, and the total properties are then computed using equation 2.1 [43]. Heat transfer through the edge-of-glass is characterized as two dimensional, and the WINDOW 4.1 program provides generic correlations, determined using finite element modeling techniques, which calculate the edge-of-glass U-values as a function of other glazing properties such as centre-of-glass U-value and spacer material [42,43]. Heat transfer through the window frame is one-dimensional; WINDOW 4.1 provides typical U-values of generic frames that were determined experimentally. Alternatively, more accurate edge-of-glass and frame U-values can be determined using the FRAME computer program, and then be imported in WINDOW 4.1 [42].

The WINDOW 4.1 program determines the solar and thermal performance indices (SC, SHGC, τ_{vis}, U-value) of window systems defined by the user. The program possesses libraries of window components, including glazings, gas fills, frames and dividers. The glass library contains spectral data of several glazing types that are supplied by manufacturers. An advantage of this program is that users can also add their own spectral data files. A spectral data file is required for each glazing layer in the window system when the spectrally based calculations are performed ("multi-band model"); otherwise, the program calculates the performance indices using the integrated solar-optical properties of the glazing layers ("single band model"). The latter method is less accurate, particularly for advanced windows that are spectrally selective. WINDOW 4.1 calculates the performance indices for the entire window system defined by the user as well as individually for the centre-of-glass, frame and dividers. Angular calculations of the solar-optical properties are also performed. Another advantage of the program is that it allows users to export window thermal and solar-optical data and integrate them within the existing window library of the DOE-2.1E energy analysis program. [42]

WINDOW 4.1 currently does not offer the capability to model films or coatings applied on glass substrates. Lawrence Berkeley Laboratory offers the APPLIED FILM LAMINATOR program for this purpose; it is currently a stand-alone program that will be incorporated with the WINDOW 4.1 program as of the next release [61]. APPLIED FILM LAMINATOR calculates the solar-optical properties of a combined coating-glass substrate based on spectral data of the individual components. The main advantage of this program is that it is compatible with WINDOW 4.1, i.e., the format of the input spectral data files is similar to WINDOW 4.1, and the output spectral data file of the newly defined coated glazing can be imported into the WINDOW 4.1 glass library. According to Finlayson et al. [61], the errors between average properties calculated using

APPLIED FILM LAMINATOR and measured values are generally not more than 0.5%; the specified tolerances are 1% for transmittance values and 2% for reflectance values.

2.1.2 Window performance indices

The solar spectrum consists of three main regions: ultra-violet (0 nm to 380 nm), visible (380 nm to 780 nm) and near-infrared (780 nm to 2500 nm). Approximately 47% of the solar energy consists of visible light, while the remaining energy in the ultra-violet and near-infrared regions contributes only heat to the space [3]. Ideally, therefore, glazings for cooling-dominated buildings would be required to maintain a high transmittance in the visible region in order to provide benefits from natural lighting, while minimizing the transmittance in the other regions to reduce solar gains. There are several performance indices that can be used to compare window types relative to one another and to help designers in making initial design decisions. In this respect, it must be noted that these indices provide a measure of "instantaneous" performance under specific conditions and they do not account for building performance as a whole [3]. In this chapter, the analysis of the performance of the electrochromic coating is based on instantaneous performance indices such as visible transmittance, shading coefficient, solar heat gain coefficient, and U-value. These indices are described below.

Overall heat transfer coefficient, U-value ($W/m^2 \cdot °C$): The ASHRAE Handbook of Fundamentals [3] defines the U-value as representing "the rate of thermal heat transfer through fenestration in the absence of sunlight, air infiltration, and moisture condensation"; i.e., it is the heat transfer rate due to conduction and convection caused by a temperature difference between the outdoor and indoor environments. The overall heat transfer coefficient includes the effect of the window frame (U_f), center-of-glass (U_{cg}), and edge of glass (U_e), and is calculated as the area weighted average of the U-value of each component [3]:

$$U_o = \frac{U_{cg}A_{cg} + U_{eg}A_{eg} + U_f A_f}{A_{tot}} \quad (2.2)$$

The centre of glass U-value of a double glazed window is determined as [62]:

$$U_{cg} = \frac{1}{(1/h_o)+(1/h_g)+(1/h_i)} \quad (2.3)$$

where: h_o and h_i = exterior surface and interior surface heat transfer coefficients, respectively, W/m²·K

h_g = combined convective and radiative heat transfer coefficient for the air gap, W/m²·K.

Solar Heat Gain Coefficient, SHGC: was previously defined in Chapter 1; this term represents the portion of incident solar radiation that passes through the glazing and becomes heat gain. It accounts for two components: (i) solar radiation which is directly transmitted to the space, and (ii) solar radiation which is absorbed by the window that is re-radiated to the space [3]:

$$SHGC = \tau_{sol} + N_i\, \alpha_{sol} \quad (2.4)$$

Shading Coefficient, SC: was also described in Chapter 1 as the ratio of the SHGC of a window under study to the SHGC of a reference clear single glazing [3].

Visible Transmittance, τ_{vis}: refers to the glazing transmittance in the visible region of the solar spectrum, from 380 nm to 780 nm. The transmittance in this region is weighted with the photopic response of the human eye.

Luminous Efficacy Constant, Ke: is the ratio of visible transmittance (τ_{vis}) to shading coefficient (SC), and provides a measure of the heat content of transmitted daylight [63]. Given that the shading coefficient is being replaced by the solar heat gain coefficient, a new performance index is described in the 1997 ASHRAE Handbook of Fundamentals [3]: the light-to-solar-gain ratio (LSG), defined as the ratio of τ_{vis} to SHGC. A glazing which possesses a high LSG is recommended for buildings in hot climates as well as for commercial buildings with high internal loads [3].

Energy Rating (ER): The Energy Rating is a measure of overall window performance considering the effects of solar heat gains, conductive heat losses and heat losses due to infiltration [64]. Canadian Standard CSA-A440 requires the calculation of this performance rating for vertical windows in heated homes. The average Energy Rating for all Canadian climates and all orientations is determined as [64]:

$$ER = 72.2\ SHGC_w - 21.9\ U_w - 0.54 \left(\frac{L_{75}}{A_w}\right) \tag{2.5}$$

where: ER = energy rating, W/m²

$SHGC_w$ = solar heat gain coefficient of the window, dimensionless

U_w = overall heat transfer coefficient of the window, W/ m²·°C

L_{75} = window air leakage rate at a pressure difference of 75 Pa, m^3/hr

A_w = total area of the window, m²

The ER is calculated for standard window sizes and window types (i.e., fixed, operable) for specific environmental conditions (T_{out} = -18°C and T_{in} = 21°C). A positive ER value indicates that the solar gains exceed the heat losses and therefore contributes to heating the house. A negative ER value indicates that heat losses exceed the solar gains. Although this performance index is intended for residential use only, it is used here merely to provide a qualitative comparison of window thermal performance; the same window size and environmental conditions have been used for each window type. The effects of infiltration have been neglected in this study. For cooling-dominated buildings (i.e., commercial buildings), it is recommended that the U-value and SHGC be used as indicators of thermal performance [65].

2.1.3 Preparation of the spectral data files for use in APPLIED FILM LAMINATOR and WINDOW 4.1

The wavelength range for the spectral reflectance and transmittance data of the experimental electrochromic coating was from 300 nm and 350 nm (respectively) to 2500 nm, at one nanometer increments, for a total of 2150 to 2200 data points. Recall that APPLIED FILM LAMINATOR and WINDOW 4.1 both have similar spectral data file formats. The preparation of the spectral data files for use in both programs involved the following three steps:

(i) First, it was necessary to reduce the number of spectral data points to 450 or less, which is the maximum number that WINDOW 4.1 can accept.

(ii) The spectral data file must include a header specifying the units, glazing thickness, glazing conductivity, thermal infrared hemispherical transmittance (t_{ir}), and thermal infrared hemispherical emittance, for the coating or glazing front and back (e_f and e_b). The last two properties must only be specified if the spectral data is supplied to 2500 nm; otherwise the programs calculate these two properties if the spectral data is supplied to 25000 nm.

(iii) The spectral data must be reported at normal incidence according to the following format [42]: wavelength, transmittance, front reflectance, back reflectance

Note that front and back surfaces refer to the outward surface and inward surface, respectively, and that the coating can be on either surface depending on whether the electrochromic glazing is placed as the outer or inner pane of a double glazed window (Figure 2-2). The reflectance data that was supplied by the University of Moncton was for the coating side. In the absence of other data, and given that the thickness of the coating-substrate is only 1 mm, it was assumed that the reflectance of the front and back surfaces were equal.

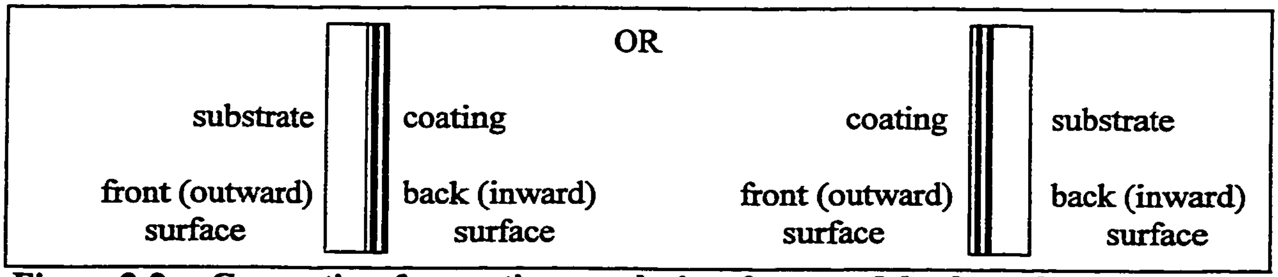

Figure 2-2. Convention for coating or glazing front and back surfaces. [adapted from ref. 57]

For the first step, i.e., to reduce the total number of data points to a maximum of 450, the SPECPACK utility program that is supplied with WINDOW 4.1 was used. SPECPACK performs a linear interpolation between data points that are on a line, thereby eliminating the intermediate points. The user must specify an interpolation tolerance. Given that the original spectral data file was much bigger than WINDOW 4.1 could process, it was necessary to divide each data set for the bleached and colored states of the experimental coating into data subsets at different wavelength ranges, containing less than 450 data points each; otherwise SPECPACK could not be used. SPECPACK was then applied to each subset at tolerances of 0.5%, 1% and 2% in order to determine the lowest possible tolerance to produce an overall maximum of 450 points. The resulting subsets that had been compressed with SPECPACK were then recombined into one spectral data file to cover the full wavelength range from 300 nm to 2500 nm. For the bleached state, a tolerance of 0.5% produced a total of 421 data points, while for the colored state, a tolerance of 2% produced a total of 443 points.

The header data is summarized in Table 2-1. The emittance of the substrate side was specified as 0.84, which corresponds to the emittance of uncoated glass, as specified in the WINDOW 4.1 manual [42]. The emittance of the coating side was specified as 0.08, corresponding to the emittance of a low-e film, which is feasible for solid-state electrochromic coatings [11]. Furthermore, the electrochromic glazings in the existing DOE-2.1 window library also possess the same coating-side emissivity as a low-e coating. Regarding the thermal infrared hemispherical transmittance, according to the WINDOW 4.1 manual, "all glass products have a thermal infrared hemispherical transmittance of 0.0" [42].

Table 2-1. Summary of electrochromic coating properties used in APPLIED FILM LAMINATOR analysis

Property	Value
Glazing thickness [mm]	1.00
Glazing conductivity [W/m-K]	0.90
Thermal infrared hemispherical transmittance (t_{ir})	0.00
Thermal infrared hemispherical emittance - front (e_f)	0.84
Thermal infrared hemispherical emittance - back (e_b)	0.08

2.1.4 Solar-optical properties of the electrochromic coating and glazing - use of APPLIED FILM LAMINATOR

The APPLIED FILM LAMINATOR program was used to determine the spectral data of a 6 mm glazing which incorporates the experimental electrochromic coating. The program offers two choices for modeling the 6 mm thick electrochromic glazing: (i) the 1 mm electrochromic coating-substrate can be considered as a film (i.e., coating only) which is applied onto a 5 mm clear glass substrate, or (ii) it can be considered as a 1 mm coated substrate whose properties can be extrapolated to a 6 mm glass thickness. The second method is applicable to the experimental coating since the data includes the presence of a clear glass substrate; however, both methods were examined.

The input data required by the program depends on the modeling approach that is used. If modeling approach (i) is used, the program requires the following data as input: (1) the normal spectral transmittance and reflectance of the clear glass substrate, and (2) the normal spectral transmittance of the coating, and the reflectance of the exposed surface of the coating (front) as well as the reflectance of the coating surface that comes into contact with the substrate of the coating (back), since the front and back reflectances are generally not equal for most films [61]. If modeling approach (ii) is used, the program requires: (1) the normal spectral transmittance and reflectance of the clear glass substrate which is of the desired thickness, and (2) the normal spectral transmittance and front and back reflectance of the coated glazing whose properties are to be extrapolated to the desired substrate thickness. The clear glass substrate was selected from the Libbey Owens Ford database of spectral data files from the WINDOW 4.1 library. APPLIED FILM LAMINATOR graphs the spectral data of the selected components (substrate and film) as well as of the resulting coated glazing. The integrated properties of these components are also shown on-screen and the spectral data of the resulting coated glazing can be saved to a file which can then be imported into the WINDOW 4.1 glass library.

Using APPLIED FILM LAMINATOR, it was found that the integrated visible transmittance of the experimental electrochromic coating switches from 0.583 (58.3%) in the bleached state to 0.208 (20.8%) in the colored state, representing a range in transmittance of approximately 3:1. It has been reported that most electrochromic coatings have a visible transmittance range between 2:1 and 4:1 and a maximum bleached state transmittance between 50 and 80% [16]. The visible reflectance of the experimental coating switches from 0.149 (14.9%) to 0.127 (12.7%). The solar transmittance switches from 0.415 (41.5%) to 0.11 (11.0%), while the solar reflectance switches from 0.251 (25.1%) to 0.146 (14.6%). Two important observations can be made from these properties and from Figure 2-1: (i) the coating can be classified as a broad-band electrochromic since the change in transmittance and reflectance from the bleached to the colored states occurs over the entire solar spectrum, rather than within a specific region (i.e., visible or near-infrared); reductions in both natural lighting and solar gain can therefore be expected when the coating is switched to the colored state, and (ii) the sum of the integrated solar transmittance and reflectance in the colored state is approximately 0.26; i.e., the absorptance is 0.74 (compared to the bleached state absorptance of 0.67); since the transmittance and reflectance decrease from the bleached state to the colored state, the absorptance therefore increases indicating that the coating can be classified as an absorbing type. According to Granqvist [19] electrochromic materials are more commonly of the absorbing type.

The resulting spectral data of the electrochromic glazing for the bleached and colored states are shown in Figures 2-3(a) and 2-4(a) for the case where the coating was extrapolated to a thickness of 6 mm. It can be seen in Figures 2-3 and 2-4 (b), (c) and (d), that there is no difference in the transmittance and film side reflectance values for both the bleached and colored states between the two modeling approaches, while the substrate side reflectance for the extrapolation approach is slightly higher than the lamination approach in the 2000-2500 nm wavelength range.

The properties of the original 1 mm electrochromic coating-substrate, the clear glass substrate and the resulting electrochromic glazing are summarized in Table 2-2. It can be noted that the solar and visible transmittance of the 6 mm thick electrochromic glazing are slightly less than the values for the 1 mm thick electrochromic coating-substrate; the visible transmittance can be switched from 57.3% to 20.5%, rather than 58.3% to 20.8% (for the 1 mm coating), while the solar transmittance can be switched from 37.8% to 10.4% (compared to 41.5% to 11.0% for the 1 mm coating).

Table 2-2. Properties of electrochromic coating, glass substrate and electrochromic glazing.

	τ_{vis}	τ_{sol}
1 mm electrochromic coating-substrate	58.3% / 20.8%	41.5% / 11.0%
6 mm clear glass substrate	89.0%	78.9%
6 mm electrochromic glazing	57.3% / 20.5%	37.8% / 10.4%

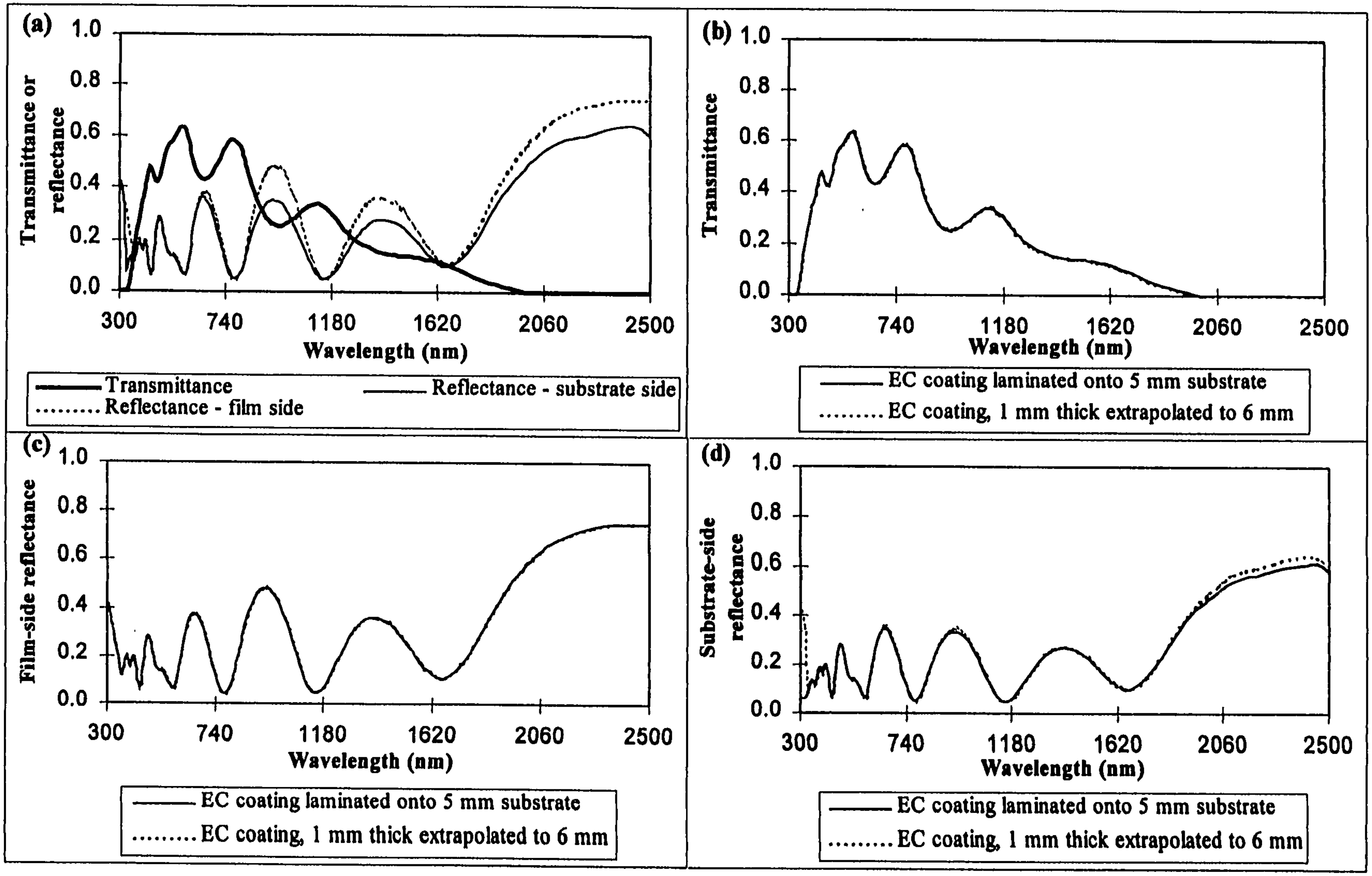

Figure 2-3. **(a) Transmittance and reflectance data of electrochromic coating (bleached state) extrapolated to a thickness of 6 mm, (b) comparison of transmittance values between laminated coating (5 mm) and extrapolated results, (c) comparison of film-side reflectance, (d) comparison of substrate-side reflectance.**

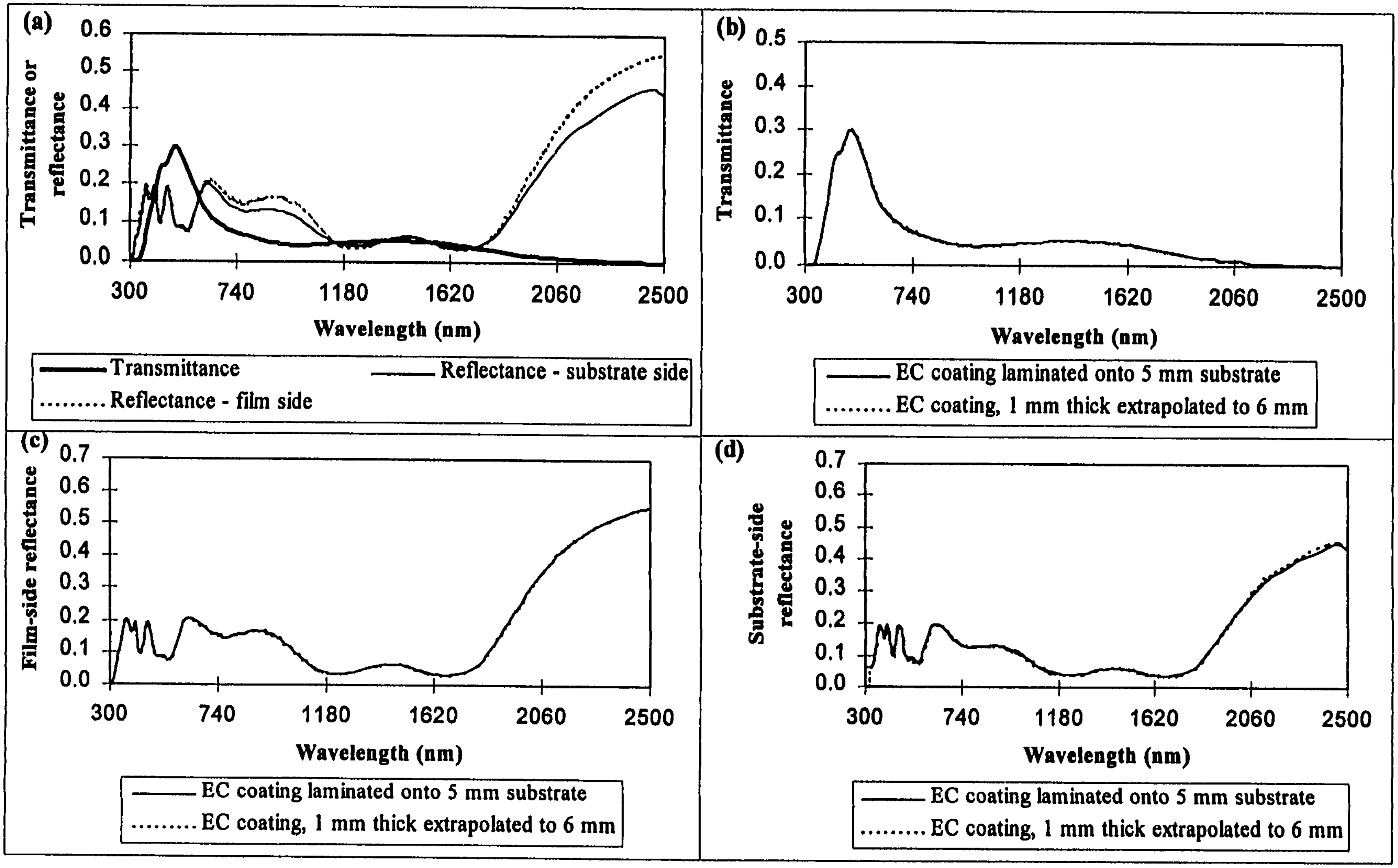

Figure 2-4. **(a) Transmittance and reflectance data of electrochromic coating (colored state) extrapolated to a thickness of 6 mm, (b) comparison of transmittance values between laminated coating (5 mm) and extrapolated results, (c) comparison of film-side reflectance, (d) comparison of substrate-side reflectance.**

The impact of the experimental electrochromic glazing on incident solar irradiance (for air mass 1.5) is illustrated in Figure 2-5, which shows the resulting spectral transmittance of the experimental electrochromic glazing for the bleached and colored states.

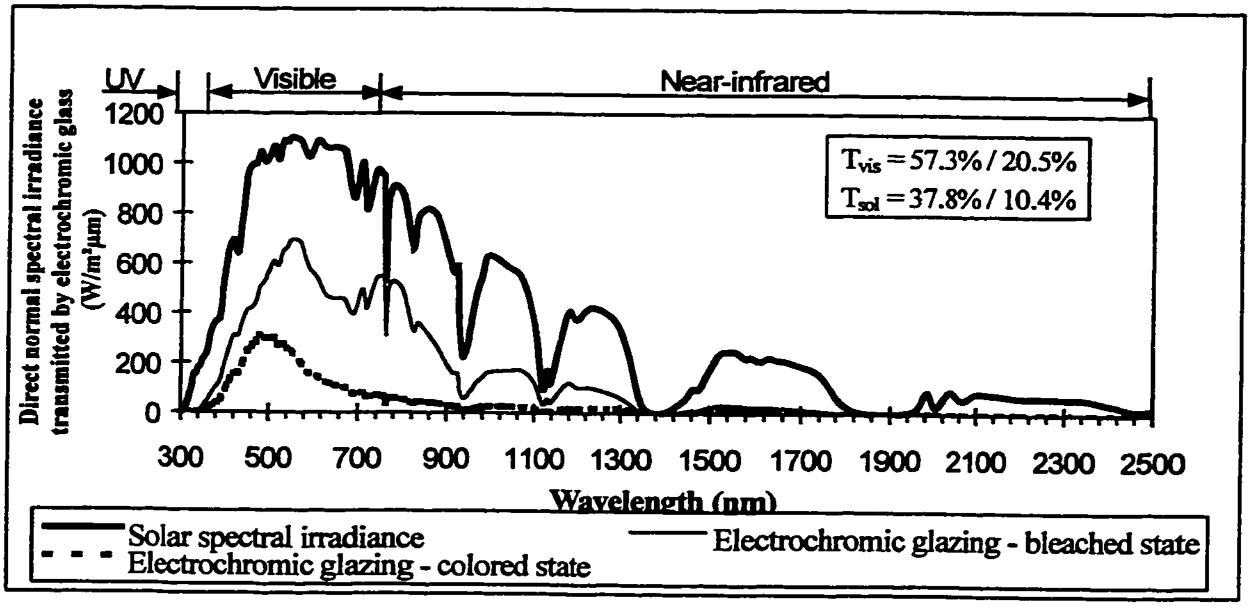

Figure 2-5. Spectral transmittance of the 6 mm thick experimental electrochromic glazing.

As a final discussion of the characteristics of the experimental electrochromic coating, recall the requirements of electrochromic devices that were described in Chapter 1. The electrochromic coating must meet certain performance characteristics if it is to be considered suitable for applications in windows. The characteristics of the experimental coating, as detailed by Truong et al. [21] or determined using APPLIED FILM LAMINATOR, are compared in Table 2-3 with the required characteristics described by Lampert and Granqvist [2]. Most of the characteristics of the experimental coating fall within the required range, with the exception of the solar transmittance in the bleached state and the time that it takes for the glazing to reach its fully colored state (i.e., the switching speed). While the development of a protected, monolithic solid-state electrochromic coating was successful, the researchers acknowledge that the high cost of fabrication and the high switching speed are two main factors which hinder immediate commercialization of the present coating.

Table 2-3. Characteristics of the experimental electrochromic coating compared with the required characteristics of electrochromic coatings for window applications.

	Required characteristics [2]	Experimental coating (1) [21]
τ_{sol} - bleached	50 - 70%	41.5%
τ_{sol} - colored	10 - 20%	11.0%
τ_{vis} - bleached	50 - 70%	58.3%
τ_{vis} - colored	10 - 20%	20.8%
Switching voltage	1 - 5 volts	3 volts
Optical memory	1 - 24 hours	8 hours
Switching speed	1 - 60 sec.	7.5 minutes
Cyclic lifetime	>10k-1M cycles	3k (2)
Lifetime	5 - 20 years	N/A
Operating temperature	-30 to 70°C (protected) and 0 to 70°C	tested between room temperature and 60°C

Notes:

(1) Transmittance values were calculated using APPLIED FILM LAMINATOR. Remaining characteristics were obtained from reference [21].

(2) No significant changes in coating properties were observed after 3000 cycles.

2.1.5 Idealized electrochromic coatings

In buildings where the cooling load is dominant, the ideal window should have low solar heat gain properties (SC, SHGC), yet also possess a high visible transmittance such that a daylighting strategy could be used to reduce electric light loads. The question arises as to how high or how low must the solar-optical properties of the electrochromic glazing be in order to maximize performance and is it justifiable to pursue development of coatings with "better" properties. The characteristics and performance of the experimental electrochromic glazing must therefore be compared with other electrochromic glazings whose properties are close to the limits of solar and light control performance. Two idealized electrochromic coatings were therefore defined whose properties were allowed to switch in the visible region only (380 nm - 770 nm wavelength range). Hence, the transmittance of the first idealized electrochromic coating switches from 100% to 0% in the visible range, representing the maximum limits for switching (Figure 2-6 (a)). The visible transmittance of the second idealized coating switches from 90% to 10%, representing a more realistic switching range (Figure 2-6 (b)). In both cases, the transmittance of the idealized coating in the colored state was maintained constant at the minimum visible transmittance value throughout the entire solar spectrum (300 nm - 2500 nm). APPLIED FILM LAMINATOR was then used to determine the spectral data for 6 mm thick glazings which incorporate the idealized electrochromic coatings, following the procedure described in the previous section.

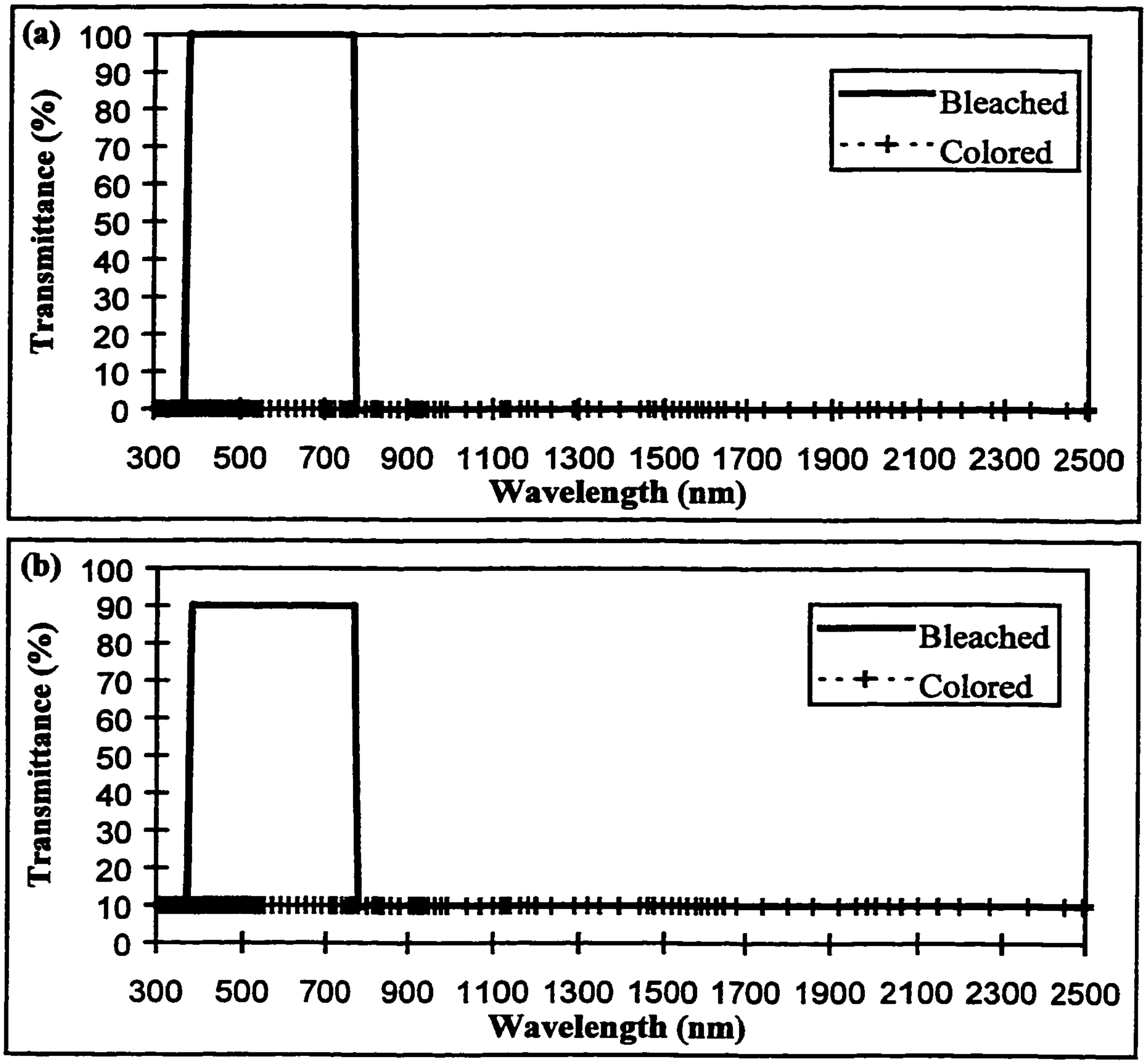

Figure 2-6. Idealized electrochromic coatings. (a) represents a coating with the maximum possible switching range, (b) represents a coating with a more realistic switching range.

2.2 CHARACTERISTICS OF DOUBLE-GLAZED WINDOWS

The WINDOW 4.1 program was used to evaluate the global parameters characterizing the performance of several types of double glazed windows. First, a total of 10 glazing types were selected, including the experimental electrochromic glazing, the two idealized electrochromic glazings, and seven conventional glazings which are described in section 2.2.1 (i.e., clear, reflective, low-e, bronze, and other tints). Second, double-glazed windows were defined and the corresponding glazing spectral data files were used in the WINDOW 4.1 program to determine the most important solar-optical properties for energy calculations (e.g., visible transmittance, U-value, solar heat gain coefficient, etc.). Third, the relative performance of the selected windows was compared based on the indices that were described in section 2.1.2.

2.2.1 Conventional glazings

The spectral transmittance of the seven conventional glazings, available in the WINDOW 4.1 library of spectral data, is compared in Figure 2-7 and the integrated transmittance is summarized in Table 2-4. Clear glazing possesses the highest transmittance in both the visible and near-infrared regions; therefore, it would result in the greatest daylighting benefits, but also the greatest solar heat gains. Low emissivity glazing maintains a high visible transmittance, but reduces the solar transmittance by 19% compared to the clear glazing. Reflective glazing, on the other hand, substantially reduces the visible transmittance (by 56%) but reduces the solar transmittance by approximately 37%. Among the tinted glazings, bronze glass reduces both solar gains and visible light by approximately 38%. The Bluegreen and Evergreen tinted glazings offered by Libbey Owens Ford are relatively new tints which are designed to maximize visible light transmission while reducing the solar gains. Bluegreen glass transmits a higher amount of daylight and solar gains that the Evergreen glass. The Solarban glazing possesses the lowest transmittance of all the glazings selected; therefore, it will significantly reduce the solar gains, but will also result in highly reduced daylighting benefits.

Table 2-4. Integrated transmittance of 6 mm thick glazings studied.

	τ_{vis}	τ_{sol}
Clear	0.890	0.792
Bronze	0.547	0.496
Reflective	0.390	0.501
Low-e	0.804	0.639
Evergreen	0.658	0.328
Bluegreen	0.757	0.488
Solarban	0.173	0.098
EC-bleached	0.573	0.378
EC-colored	0.205	0.104

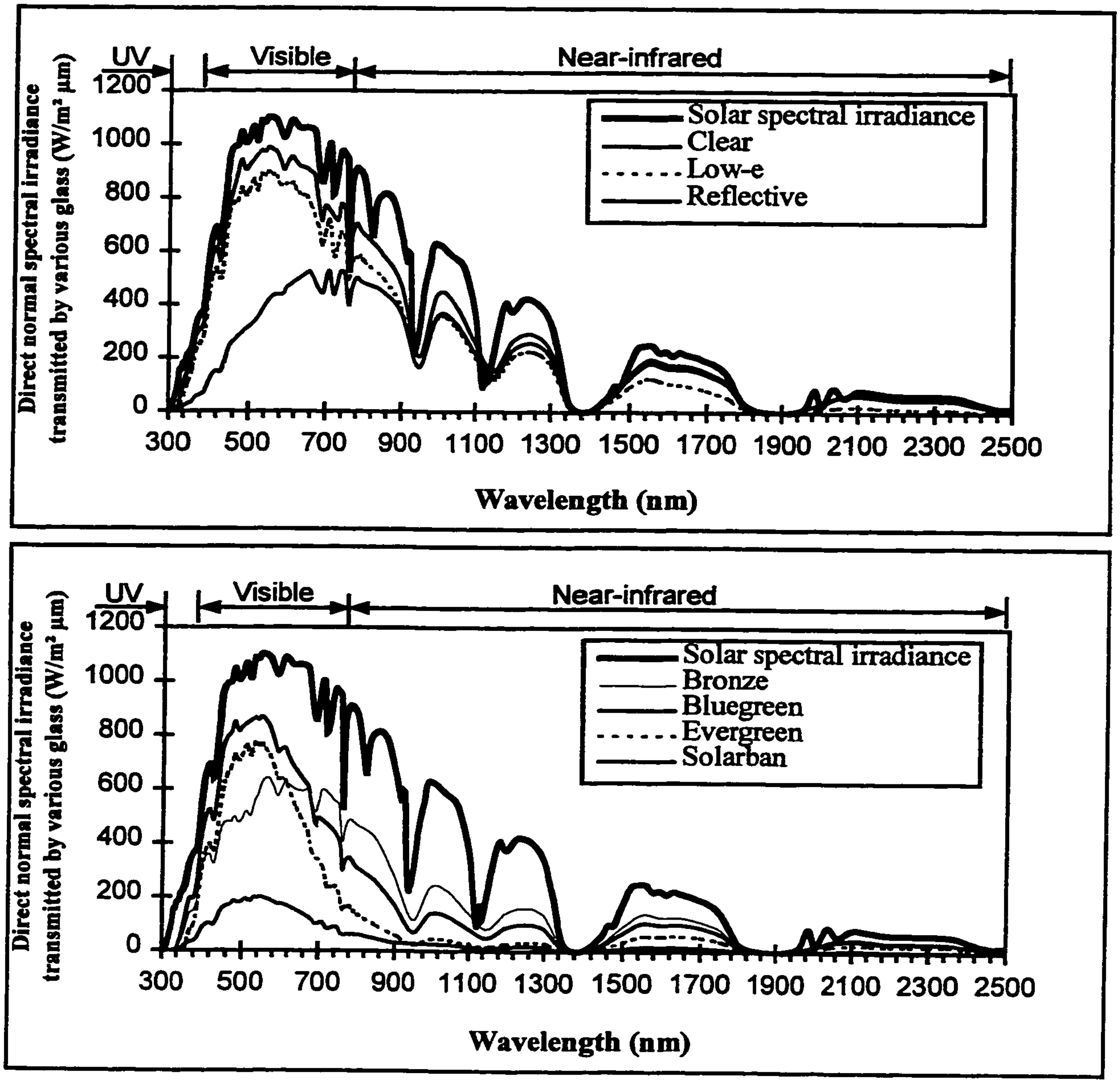

Figure 2-7. Spectral transmittance of 6 mm thick conventional glazings.

2.2.2 Defining the double glazed windows in WINDOW 4.1

Three main steps were used to define the double glazed windows in the WINDOW 4.1 program. First, the spectral data files of the experimental and idealized electrochromic glazings were imported from APPLIED FILM LAMINATOR into the existing Glass

Library of the WINDOW 4.1 program. The Glass Library was then updated in order to include the spectral data files of the conventional glazing types that were selected for this study, otherwise the calculations would be performed using the "single-band" approach. Spectral data for conventional glazings were obtained from the existing library in the WINDOW 4.1 program, which were supplied by glazing manufacturers.

Second, the centre-of-glass component was defined in the Glazing System Library for each of the 10 windows to be studied. The double glazed windows were defined layer by layer, starting with the outside layer, followed by a 12.7 mm air gap, and the inside layer. With the exception of the low-e glazing, all conventional and electrochromic glazings were defined as the outer layer, and the inner layer was defined as a 6 mm clear glazing. For the experimental electrochromic glazing, the effect of using the glazing as the inner layer was also studied and is discussed in section 2.2.3. Note that the Glazing System Library enables the user to perform calculations of the angular solar-optical properties of the glazing system. This option was used for the present study.

Third, the program's main screen was used to specify the remaining components of the windows (frame, edge). The main screen of the WINDOW 4.1 program allows the user to design and analyze a window system which includes all components such as frames, dividers, and glazing. The user must first enter general information regarding the size, tilt, and environmental conditions. The user must then define or select the window components from the respective libraries including frame, glazing system (centre-of-glass), and dividers (if any). Since the final analysis of the selected window types will be performed in the DOE-2.1E program, window specifications such as size and frame type were defined similar to windows in the existing DOE-2.1E window library for consistency. These specifications for the selected windows are summarized in Table 2-5. No dividers were specified for the windows.

Table 2-5. WINDOW 4.1 specifications of the selected window types.

Specification	Defined	Comments
Window type	Picture	Refers to fixed window type
Tilt	90°	Vertical window
Size	Fixed BB	Size was selected for consistency
Width	1219.20 mm	with windows in the existing
Height	1828.80 mm	DOE-2.1E window library.
Units	SI	--
Frame type	3	Refers to an aluminum frame. The U-value is from the 1989 ASHRAE Handbook of Fundamentals. [42]
Edge Correlation	1 class 1	Existing correlations represent edge-of-glass U-values as a function of center-of-glass U values. "1 class 1" refers to an aluminum spacer material [42].

The corresponding spectral data files were used in WINDOW 4.1 to determine the most important solar-optical properties for energy calculations, namely: shading coefficient (SC), solar heat gain coefficient (SHGC), visible transmittance (τ_{vis}), and thermal conductance (U value).

Window performance was evaluated at standard ASHRAE summer conditions for solar heat gain calculations and NFRC/ASHRAE winter conditions for calculation of window U value (Table 2-6).

Table 2-6. Summary of weather conditions used in the WINDOW 4.1 analyses. [42]

		Outside temp (°C)	Inside temp (°C)	Wind speed (m/s)	Wind direction	Direct solar radiation (W/m²)	T_{sky} (°C)	E_{sky}
Winter	U value	-17.8	21.1	6.7	Windward	0.0	-17.8	1.0
Summer	Solar	31.7	23.9	3.4	Windward	783.0	31.7	1.0

Notes:

T_{sky} = effective sky temperature; the WINDOW 4.1 default value is the same as the outside temperature and represents a cloudy sky. The WINDOW 4.1 manual recommends that the default value be used for U-value calculations. [42]

E_{sky} = effective sky emissivity; default value of 1.0 also represents a cloudy sky and indicates that T_{sky} is equal to the outside temperature. [42]

2.2.3 Impact of coating placement within double-glazed window

There are two possibilities for the placement of the electrochromic glazing within the double glazed window: (i) the electrochromic glazing can either be placed as the outer pane, or (ii) it can be placed as the inner pane. Considering surface 1 as the outermost surface of the glazing system, the electrochromic coating can therefore either be placed on surface 2 or on surface 3 (Figure 2-8).

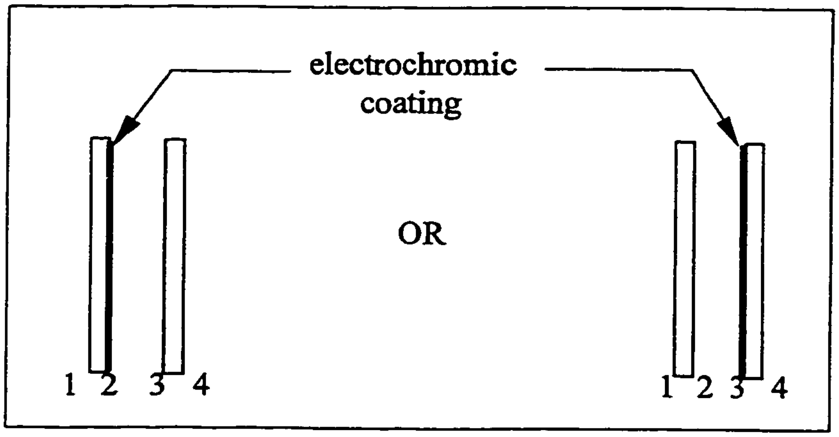

Figure 2-8. Possible placement of electrochromic coating within the double glazed window.

The impact of coating placement on the angular calculations of SHGC are shown in Figure 2-9 (a) and (b) for the bleached and colored states of the experimental electrochromic double glazed window.

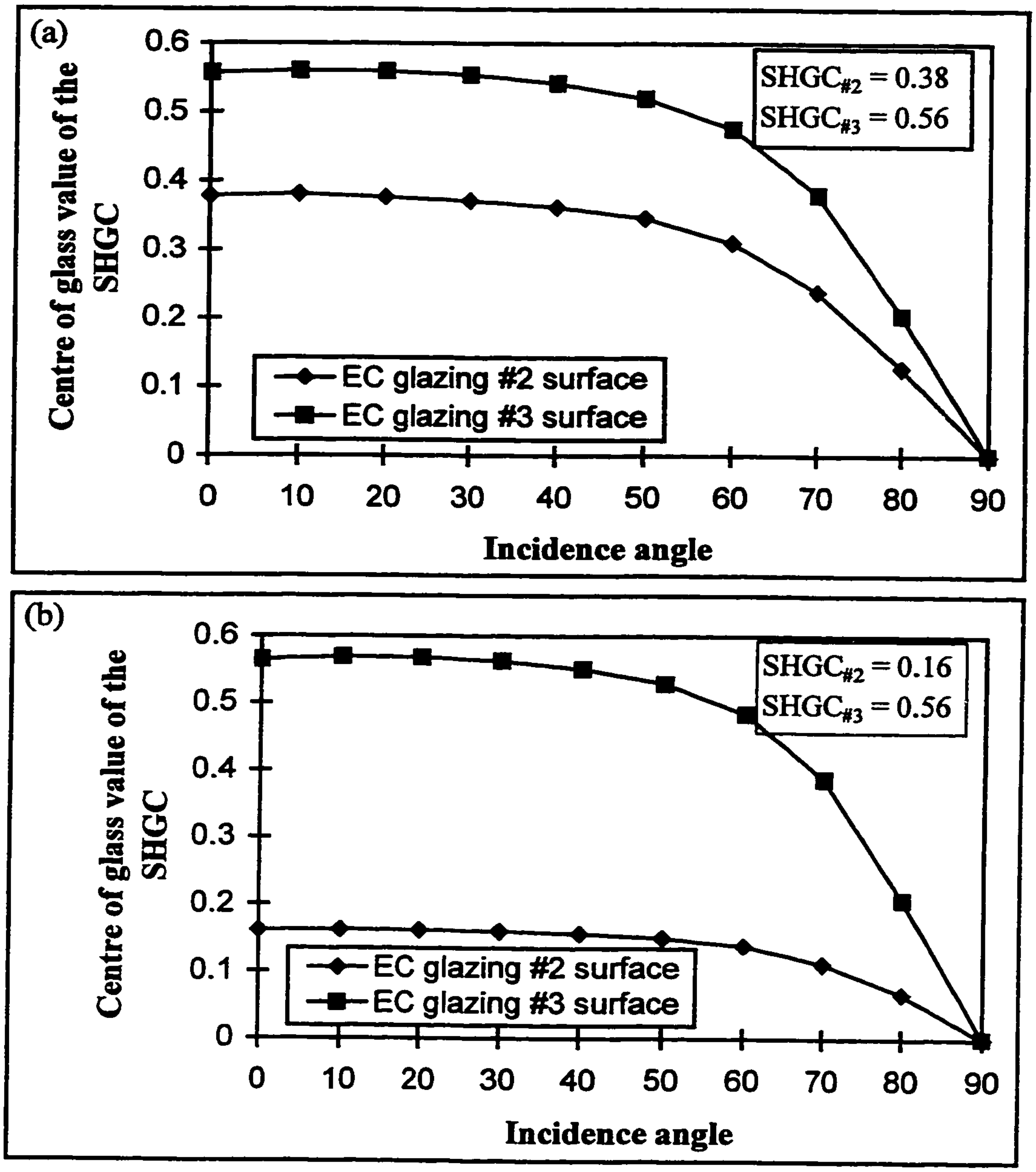

Figure 2-9. Impact of coating placement on the angular and integrated values of the solar heat gain coefficient for the (a) bleached and (b) colored states of the experimental electrochromic window.

Note that when the electrochromic coating is placed on surface 3, there is no change in the angular or integrated values of the SHGC between the bleached and colored states (0.56 in both cases). When the coating is placed on surface number 2, the SHGC is reduced from the bleached to the colored state (from 0.38 to 0.16, respectively). Given that the electrochromic glazing is of the absorbing type, the absorbed solar radiation can be transmitted outside when the glazing is placed as the outer pane. These conclusions are consistent with the findings of Reilly et al. [39] that were described in Chapter 1, section 1.2. The researchers had recommended that absorbing type electrochromic glazings be placed as the outer layer in order to reduce the solar heat gain properties.

2.2.4 Relative comparison of window properties - results and discussion

The centre-of-glass properties of the selected glazings, as calculated by WINDOW 4.1, are presented in Table 2-7. The windows are grouped in five classes in terms of shading coefficient values from a minimum of 0.20 to a maximum of 0.83. Note that conventional glazings for windows of type F and J had been selected to attain similar solar gain properties (SC and SHGC) as the experimental electrochromic window (type G) in its bleached and colored states, respectively.

Table 2-7. Centre-of-glass properties of the selected glazings, as calculated by WINDOW 4.1

SC range	Window ID	Glazing Type (Outside pane/inside pane)	SC	SHGC	τ_{vis}	Ke (τ_{vis}/SC)	LSG (τ_{vis}/SHGC)	U value (W/m² °C)	Energy Rating (W/m²)
0.78 - 0.83	A	Clear/clear	0.83	0.72	0.80	0.96	1.11	2.74	-8.02
	B	Clear/low-e	0.78	0.67	0.72	0.92	1.07	1.96	5.45
0.55 - 0.58	C	Bronze/clear	0.58	0.50	0.49	0.84	0.98	2.74	-23.91
	D	Bluegreen/clear	0.58	0.50	0.68	1.17	1.36	2.74	-23.91
	E	Reflective/clear	0.55	0.47	0.36	0.65	0.77	2.74	-26.07
0.45 - 0.50	F	Evergreen/clear	0.45	0.38	0.59	1.31	1.55	2.74	-32.57
0.26 - 0.32 (0.50/0.01)	G	EC_experimental (avg.)	0.32	0.27	0.35	1.09	1.29	1.78	-19.49
		(bleach/colored)	0.44/0.19	0.38/0.16	0.52/0.18	1.18/0.95	1.37/1/13	1.78	-11.55/-27.43
	H	EC_IDEAL2 (avg.)	0.31	0.26	0.44	1.42	1.69	1.78	-20.21
		(bleach/colored)	0.50/0.11	0.43/0.09	0.79/0.09	1.58/0.82	1.83/1.0	1.78	-7.94/-32.48
	I	EC_IDEAL (avg.)	0.26	0.22	0.44	1.69	2.00	1.78	-23.10
		(bleach/colored)	0.50/0.01	0.43/0.01	0.88/0.00	1.76/0.00	2.05/0.0	1.78	-7.94/-38.26
< 0.20	J	Solarban560-20S/clear	0.19	0.17	0.16	0.84	0.94	2.73	-47.51

The Energy Rating index and the Luminous Efficacy Constant, Ke, can provide a qualitative assessment of windows in cold climates, as shown in Figure 2-10. The figure can be divided into four quadrants. Window properties in quadrants I and II (i.e., when Ke > 1.0 or τ_{vis} > SC) would provide daylighting benefits with reduced solar heat gains; window properties in quadrants II and III (i.e. ER > 0) incur greater solar gains than conductive heat losses and would likely be suitable for passive solar buildings or narrow plan buildings where the envelope has a greater impact on heating energy consumption. Windows in quadrants I and IV would be appropriate for large commercial buildings where solar gains and internal heat gains comprise the major components of the cooling load, and conductive heat losses do not have a significant effect on energy consumption. Overall, the experimental electrochromic window maintains a higher Ke ratio than four out of six of the commonly used conventional window types which were considered for this study, thereby transmitting a greater proportion of visible gains than solar gains. The broader switching range of the idealized electrochromics means that lower Energy Rating indices are expected when they are in their fully colored states compared with the experimental electrochromic; however, this can be addressed by limiting the switching range of the glazing during the winter season.

A comparison of window performance based on the shading coefficient and visible transmittance is shown in Figure 2-11. The electrochromic windows as well as the evergreen and bluegreen windows outperform the other conventional windows. These windows would therefore yield daylighting benefits with reduced solar heat gain. The idealized electrochromic windows in their bleached state are the overall best performers, having the highest ratio of τ_{vis} to SC compared to all other window types. They may however incur glare problems; however, again, this may be addressed by limiting their switching range. The remaining conventional windows would provide a greater proportion of heat gains than daylighting benefits, with clear double glazed windows being the greatest provider of solar gains and visible gains.

In terms of thermal performance (Figure 2-12), the low-e window is the only net energy provider compared to all window types. Comparing the electrochromic windows, the smaller switching range of the experimental electrochromic window limits the heat losses, mainly because it possesses a higher SHGC in the colored state than the idealized electrochromic windows. The electrochromic windows have the lowest U-value compared to the conventional windows; radiative heat losses are reduced for the electrochromic coatings (idealized and experimental) since they possess the same emissivity as a low-e coating. The thermal performance of the experimental electrochromic window is expected to be better than the conventional window types since it possesses a lower U-value, thereby reducing conductive heat losses in winter, and a lower SHGC (with the exception of window type J), thereby reducing the solar gains in summer.

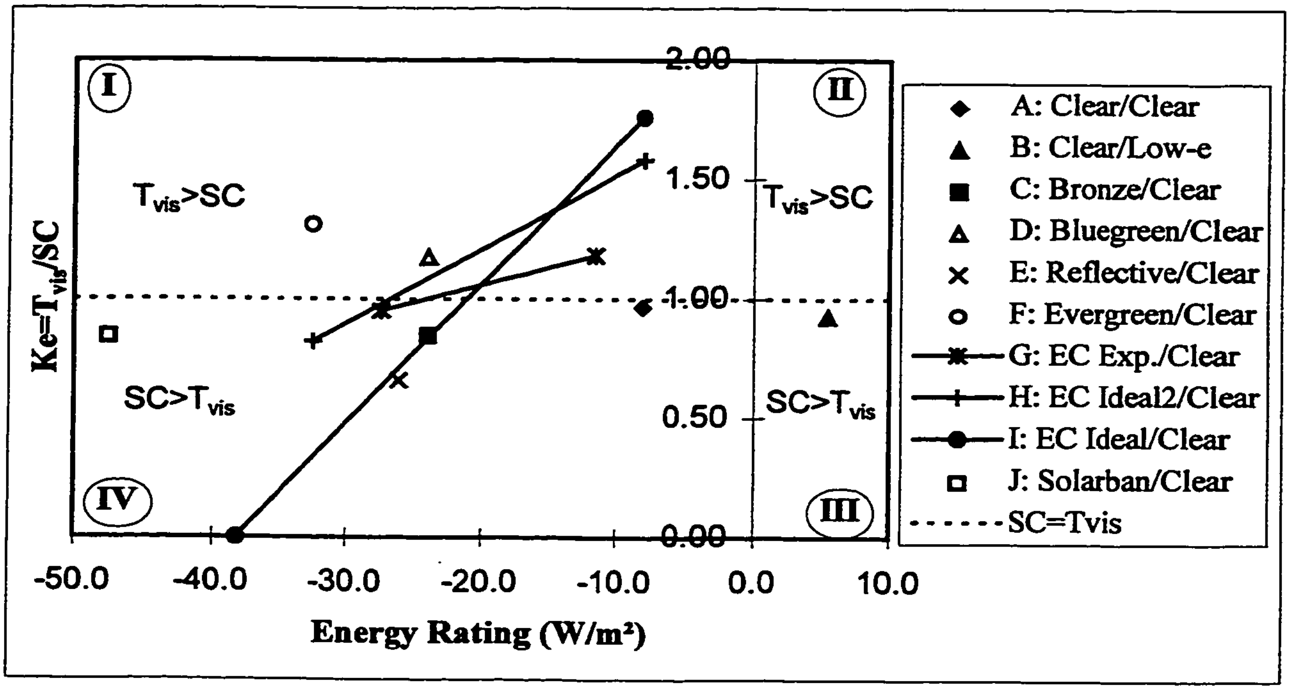

Figure 2-10. Qualitative comparison of window performance based on luminous efficacy and Energy Rating.

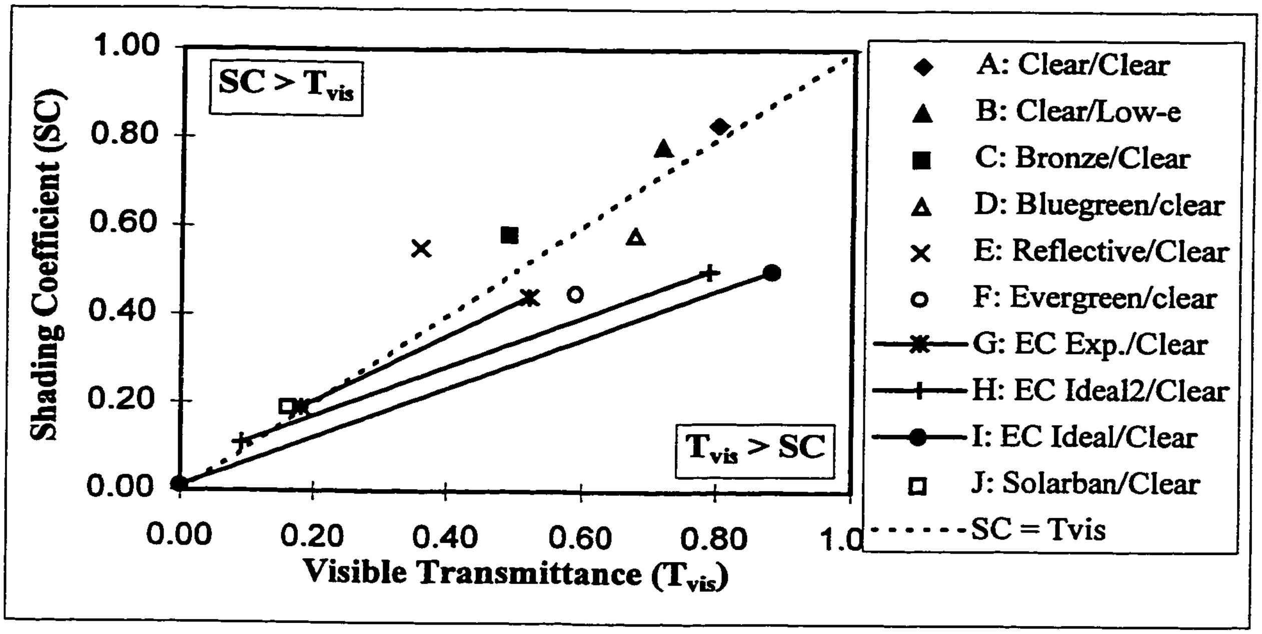

Figure 2-11. Comparison of window types based on shading coefficient and visible transmittance.

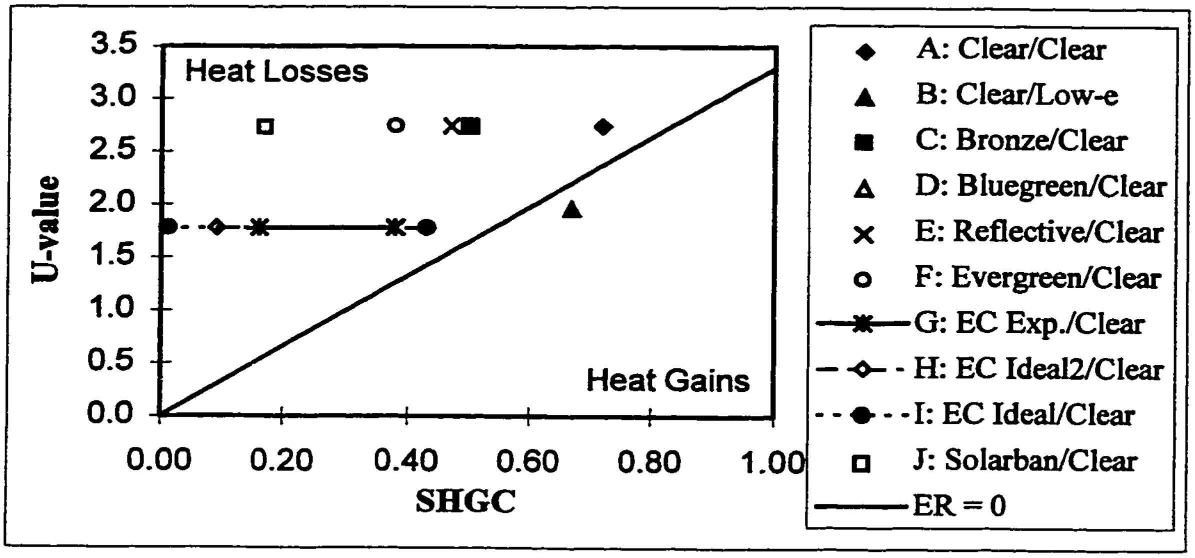

Figure 2-12. Comparison of window types based on U-value and Solar Heat Gain Coefficient.

2.3 CONCLUSIONS

This chapter demonstrated a detailed step-by-step procedure for modeling an experimental electrochromic coating and window using two public domain computer programs, APPLIED FILM LAMINATOR and WINDOW 4.1. The objective was to determine the solar optical properties of a glazing that incorporates the experimental coating, a double glazed window that incorporates the experimental electrochromic glazing, and several conventional double glazed windows. Some important conclusions regarding the experimental electrochromic coating were made as a result of this modeling experience:

(i) the coating is classified as a broad-band electrochromic whose properties can switch over the entire solar spectrum

(ii) the coating is classified as absorbing, rather than reflective, when it switches to the colored state

(iii) within a double glazed window configuration, the absorbing electrochromic coating is best placed as the inner layer of the outer glazing pane of the window, which ensures that the SHGC of the window is reduced when the coating is switched to the colored state, and that absorbed solar radiation is directed outside.

The emphasis of this chapter is on the relative performance of the electrochromic window compared to conventional window types, based on performance indices that are independent of interactions that occur between all the systems and conditions in a building. A complete performance assessment requires the whole building energy performance to be studied.

These indices can facilitate an initial selection of windows, particularly conventional windows whose properties remain static; however, in the case of electrochromic windows, the performance depends on the switching control strategy, as well as the solar optical properties. This chapter therefore provides an idea of the possible limits of performance for electrochromic windows, but the dynamic operation of the electrochromic window must be considered in a more in-depth analysis. To this end, the next step in the evaluation is to gain an understanding of the driving variables that cause switching to occur and their impact on building conditions and cooling loads. This evaluation is presented in Chapter 3.

CHAPTER 3
CRITICAL EVALUATION OF EXISTING ELECTROCHROMIC GLAZING CONTROL STRATEGIES

The application of an appropriate strategy to control the switching of electrochromic glazings requires an analysis of the complex interactions between glazing properties, the driving variables for switching, the controlled variables, as well as building characteristics and operation. It was seen in the literature review (Chapter 1) that the existing control strategies, which are available only in the DOE-2.1 energy analysis program, were used in past studies to assess the potential energy savings in prototypical office buildings. While these studies were important in that they helped establish performance limits of ideal and actual electrochromic windows, there are practical limitations associated with some of the existing switching models. Furthermore, the studies were based on a direct application of various strategies and did not provide guidelines on the selection of appropriate switching set-points. A more in-depth analysis is provided in this chapter.

The main objectives of this chapter are to: (i) evaluate the effectiveness of existing electrochromic glazing control models considering their impact on the heat extraction rate of an existing seven-storey commercial building located in Laval, Quebec, which was used as a case study, (ii) provide insight on the application of the existing strategies and selection of switching set-points, and (iii) explore alternative approaches to initiate switching of the electrochromic glazing. The chapter begins with a brief description of the existing DOE-2.1E control strategies and of the building that was used as a case study in the evaluation. Several energy simulations were performed in order to study the relationships between the driving variables for switching of the glazing properties and the heat extraction rate of the perimeter zones of the existing commercial building [58]. Conclusions are drawn as to the applicability of existing strategies.

3.1 EXISTING MODELS OF CONTROL STRATEGIES

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 [46]:

(i) outdoor drybulb temperature

(ii) total solar radiation incident on the glazing

(iii) direct solar radiation incident on the glazing

(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)

(viii) illuminance level at a reference point in the zone.

The user must specify the following information in the LOADS module of the input file in order to apply the control strategy: the driving variable, the high and low set-points used for switching (except for driving variable viii), a switching schedule to define when switching of the glazing is permitted throughout the day and year, and the codes of the electrochromic window in its bleached and colored states, as available in the program's window library. The program interpolates between the bleached state and colored state properties of the electrochromic glazing when the value of the driving variable is between the specified low and high set-points. A switching factor, SWFAC, which is used in the program's window thermal and daylighting calculations, is defined as follows for the partially switched state: [46]

$$\text{SWFAC} = \frac{(\text{Value of control variable}) - (\text{Low set-point})}{(\text{High set-point}) - (\text{Low set-point})}$$

where, SWFAC = 0.0, if the electrochromic glazing is in the bleached state, and 1.0 if the glazing is in the colored state.

Otherwise, the glazing remains in its bleached state when the driving variable is less than the low set-point, or in the colored state when the driving variable is greater than the high set-point, as illustrated in Figure 3-1. The glazing is in an intermediate, or partially switched, state when the driving variable is between the high and low set-points.

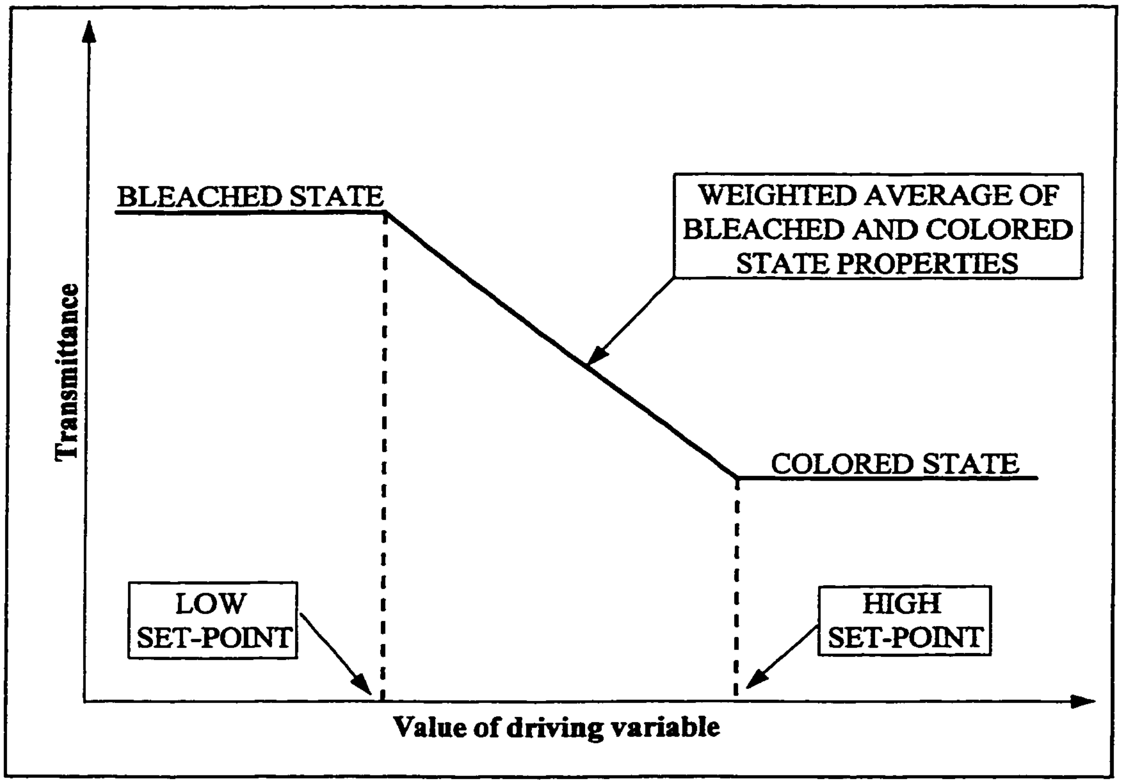

Figure 3-1. DOE-2.1E control concept for electrochromic glazing. [46]

3.2 LIMITATIONS OF EXISTING CONTROL MODELS

Except for control based on illuminance levels, driving variable (viii), 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, such as the solar gain and the heat extraction rate.

There are some problems with the use of control variables (iv), (v) and (vii) in real commercial buildings. If the sensor is located inside the building:

(1) 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 the bleached and colored states.

(2) A control model that 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 [25,52,53,55]. The underlying assumption was that the solar gains were the largest contributors to the cooling load so all other loads were neglected; therefore, a set-point of zero was intended to indirectly prevent all solar gains from being transmitted into the space. In reality however, the cooling load is due to several components including solar gains, as well as internal gains due to people, equipment, and lighting. It is only the solar gains component that can be controlled using electrochromics. With this type of strategy, the glazing will remain in a permanently colored state, regardless of whether solar gains are substantial or not, since the space cooling load is usually greater than zero during summer months. It would be more convenient to determine a base cooling load that includes the effect of lighting, equipment, and people; then, switching could be initiated when the cooling load exceeds the base amount as this would be attributed to the effect of solar gains.

3.3 DESCRIPTION OF THE EXISTING COMMERCIAL BUILDING

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 program, which was then used to study the effect of driving variables for switching on the heat extraction rate of perimeter zones of the existing commercial building. The "heat extraction rate" is evaluated within the SYSTEMS block of the program, and differs from the "cooling load," which is calculated within the LOADS block. The cooling load is defined in the DOE user's manual [45] as: "the rate at which heat must be removed from the space to maintain space air temperature at a ***constant*** value." The extraction rate, on the other hand, "is the rate at which heat is removed from the ***conditioned*** space." In other words, the operation of the HVAC control system is taken into account. Therefore, the heat extraction rate more accurately represents the actual building operation and is the quantity of interest throughout this thesis.

The computer model of the building was initially developed by Pasqualetto [66], and was modified for the purposes of the present research in order to isolate the impact of electrochromic windows on energy and lighting electricity consumption specifically in the perimeter zones. A brief description of relevant building details follows. The building, located in Laval, Quebec, comprises 10 410 m² floor area and consists of seven floors of office space and an underground garage. The ground floor consists of a restaurant, a bank and the lobby. Each floor from one to seven was modeled as five zones: 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 occupancy density was estimated as 25.8 m²/person on the first and seventh floors and 30.7 m²/person on floors two to six. Power densities for lighting and equipment were defined as shown in Table 3-1.

Electricity is the only source of energy in the building. Heating is provided along the perimeter by electric baseboard heaters for the period between September 15 and May 1. The heating set-point is 20°C. The office tower is served by a central VAV HVAC system having a total air flow capacity of 38 200 L/s. The cooling set-point is 23°C and the cooling system operates from 7:00 to 23:00 for the period between April 15 and October 15. The restaurant and bank are each served by a rooftop HVAC unit.

Table 3-1. Summary of power densities defined in DOE building input file.

	Power density (W/m²)			
	Lighting		Equipment	
	Core	Perimeter	Core	Perimeter
First floor	30.99	30.99	6.99	6.99
Floors 2-6	15.49	12.37	5.38	5.38
Seventh floor	23.24	23.24	5.38	5.38

The following modifications were made to the initial building model for the purposes of the present research:

(1) The revised building model includes perimeter daylighting with continuous dimming lighting controls for the fluorescent lamps. Workplane illuminance was to be maintained

at 538 lux, which is the recommended illuminance level for offices. The lighting reference point for daylighting and glare calculations was located along the centerline of each zone, at 2/3 the depth of the zone (i.e., 2.47 m), as recommended in the DOE-2.1E Supplement [46], and at a height of 0.76 m from the floor (representing the desk height). Glare calculations were performed for a view parallel to the window.

(2) The windows, which in the original model were sloped downwards by 10° to reduce solar gains, were oriented in a vertical position for the present work. The window height is 1.67 m and the width spans the entire facade. The window-to-wall ratio, WWR, is calculated as 0.62. The windows of the office floors, restaurant, bank and lobby were originally specified as having a shading coefficient of 0.38. These were replaced, for the office floors only, by the experimental electrochromic window whose bleached state and colored state properties were integrated into the existing DOE window library.

(3) The single central VAV system was replaced by two central VAV systems, one serving the perimeter zones and another serving the core area.

3.3.1 Control by outdoor drybulb temperature

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 of the existing commercial building. The typical meteorological year (TMY) for Montreal was used in the simulation. A plot of hourly values of outdoor drybulb temperature and the extraction rate of the South perimeter zone is shown in Figure 3-2 for the month of July.

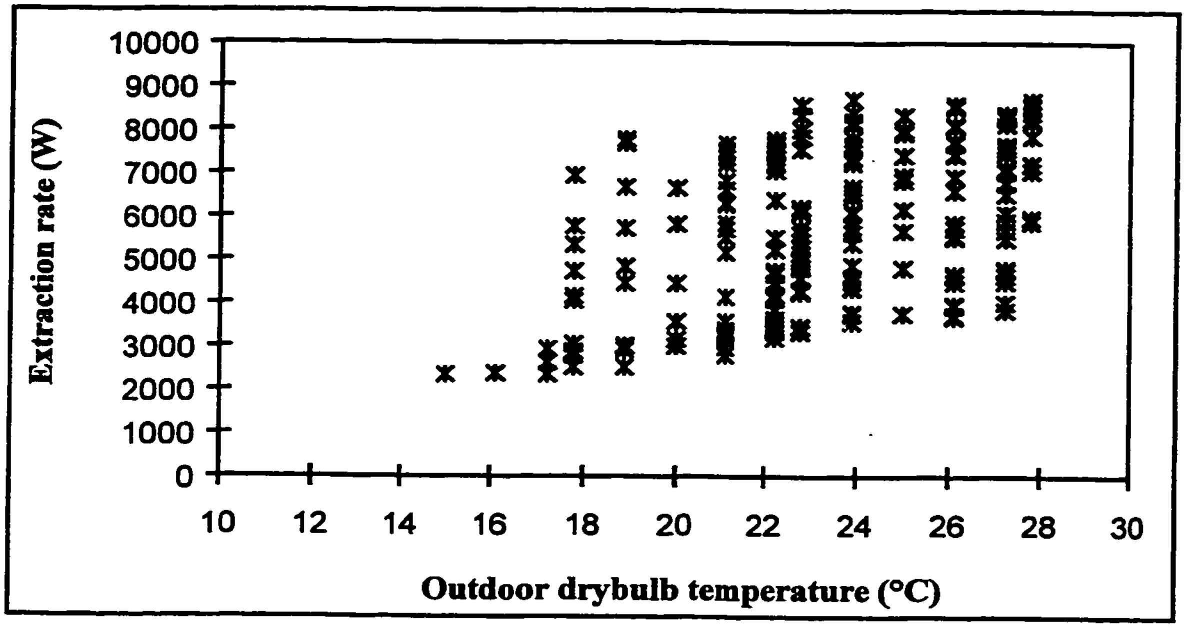

Figure 3-2. Relationship between the outdoor drybulb temperature and the total extraction rate for the South perimeter zone for the month of July.

It can be seen that there is no correlation between the cooling load and outdoor drybulb temperature for the commercial building studied. Plots for the East and West orientations yield similar results and need not be shown here. 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 3-3. Therefore, control by outdoor temperature would not be an effective strategy for this building. 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. Similar observations can be made for the East and West perimeter zones (Figure 3-4). Moreover, since there is no clear correlation between the extraction rate and the outdoor air temperature, the switching set-point can only be selected in an arbitrary way.

It is also worth noting from Figures 3-3 and 3-4, the time delay between the occurrence of maximum solar gains and the occurrence of maximum extraction rate due to the thermal mass of the building. It was found that for the South and West orientations, the time lag is approximately 2 to 2.5 hours, while for the East orientation, the time lag is approximately 0.5 hour. Furthermore, the hour of occurrence of the peak solar gain and peak extraction rate is different for each orientation. Therefore, in order to maximize the energy savings, a switching control sequence (switching start time and stop time) should be adapted for each perimeter zone. Note that in this study, it was assumed that switching does not have a time delay.

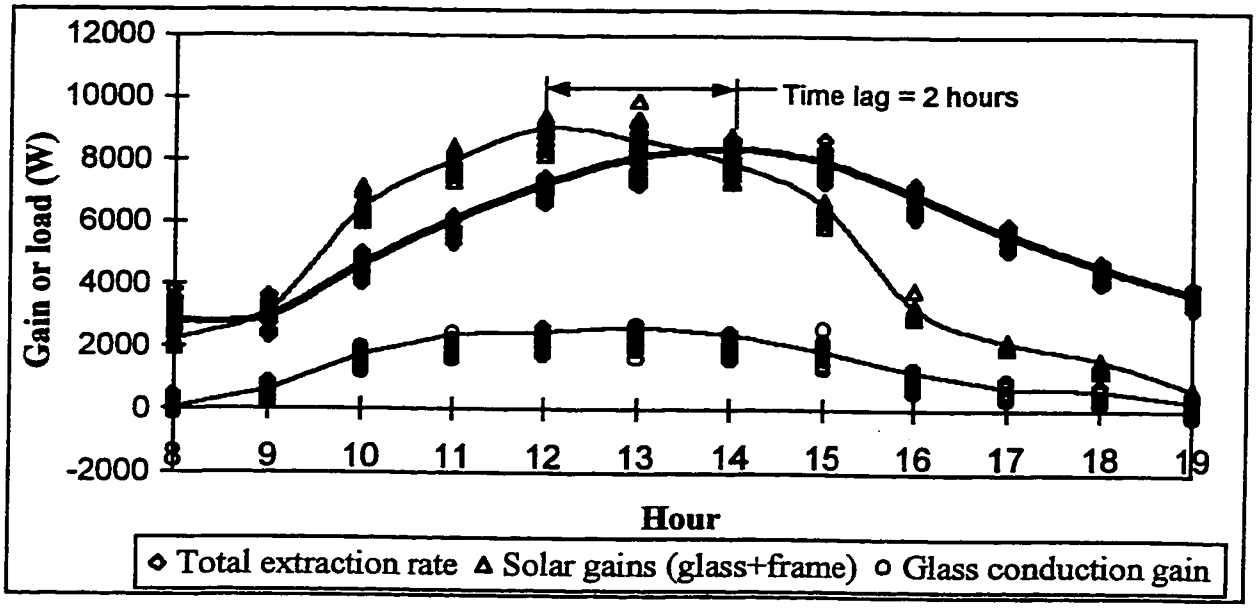

Figure 3-3. Comparison of solar gains, glass conduction gains, and extraction rate for the South perimeter zone for the month of July.

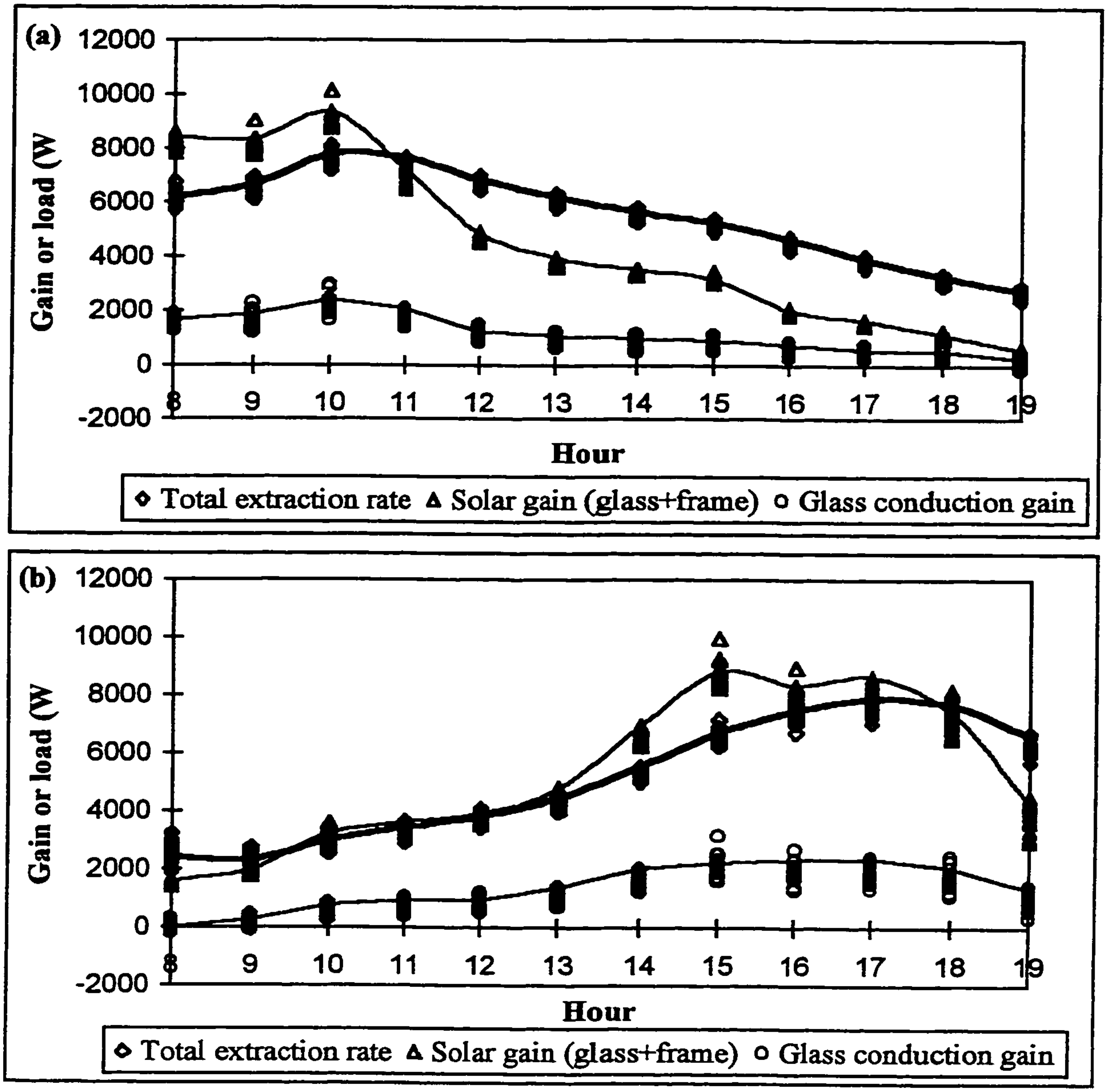

Figure 3-4. Comparison of solar gains, glass conduction gains, and extraction rate for the: (a) East perimeter zone, and (b) West perimeter zone, for the month of July.

3.3.2 Control by solar radiation

Table 3-2 shows the ratio of solar gains to extraction rate for each perimeter zone considering simulation results for the month of July. Note that for the North orientation, since solar radiation is primarily diffuse a relevant comparison cannot be made with the ratio of the other orientations. 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. As discussed at the beginning of section 3.3, a strategy based on transmitted solar radiation would not be applicable in practice; therefore, the focus in the present section is on the incident solar radiation.

Table 3-2. Ratio of solar gains to extraction rate for each perimeter zone for the month of July.

Perimeter zone	Ratio of solar gains to extraction rate
South	77.4%
East	81.7%
West	85.2%
North	Not applicable

The main issue in applying this strategy is the determination of the high and low set-points for switching. Since the extraction rate, i.e., the controlled variable, is related to incident solar radiation, i.e., the driving variable, it is necessary to understand the relationship that exists between the two, as illustrated in Figure 3-5 for the South perimeter zone. Plots for the East and West perimeter zones are similar and need not be presented here.

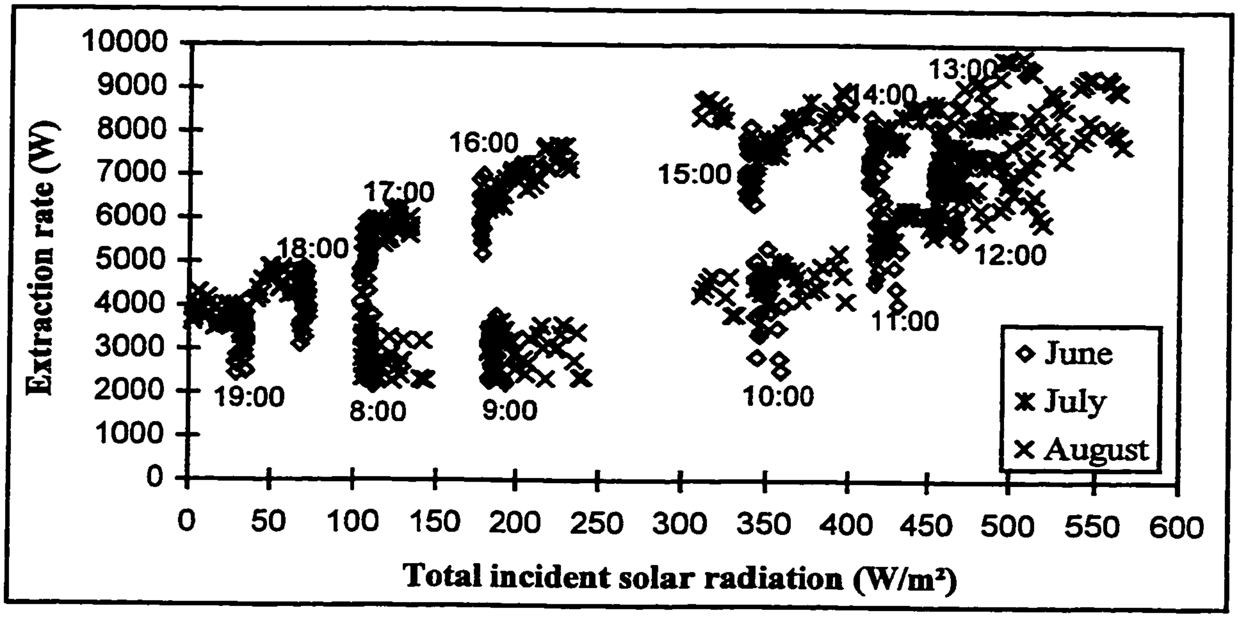

Figure 3-5. Relationship between the heat extraction rate and the total incident solar radiation for the South perimeter zone.

The obvious trend is that the extraction rate increases during the morning hours as the incident solar radiation increases, peaks at 14:00 and then decreases in the afternoon hours as the solar radiation decreases. The incident solar radiation peaks at noon, and it can be seen from the graph that there is a two hour time lag between the occurrence of peak solar radiation and the peak extraction rate. However, an appropriate choice of set-points is not evident simply by studying the chart as several questions can be raised:

- what is the impact of a particular choice of set-points on the extraction rate?
- should the glazing be switched at the occurrence of peak solar radiation or before? If so, how long before?
- for how long should the glazing remain in the colored state, i.e., at what point is it no longer effective, in terms of incremental energy savings, to maintain the glazing in the colored state?

Answers to the above questions cannot be obtained directly from the chart. Therefore, it is worthwhile exploring new indices that can provide a more direct method to determine the set-points for switching of the electrochromic glazing.

Figures 3-3 and 3-4 show during which hours the solar gains have the greatest impact on the cooling load. Taking the South perimeter zone as an example, it can be seen that the solar gains exceed the extraction rate during the morning hours from approximately 9:00 a.m. to 13:30. In physical terms, it signifies that during these hours there is a high potential for thermal storage of solar radiation. Beyond the point where the solar gains and the extraction rate cross, at 13:30, the extraction rate exceeds the solar gains, indicative of the thermal lag effect, where stored energy is released into the space. Therefore, in order for a switching control strategy to be effective in reducing the peak extraction rate, it would be more appropriate to switch the electrochromic glazing at some point in the morning hours in order to reduce the amount of energy stored. It is therefore the relationship between the solar gains relative to the extraction rate that can provide an indication of the possible set-points. A plot of the ratio of solar gain to the extraction rate (RGE) versus the incident solar radiation is shown in Figure 3-6 for the South perimeter zone and Figure 3-7 for the East and West zones.

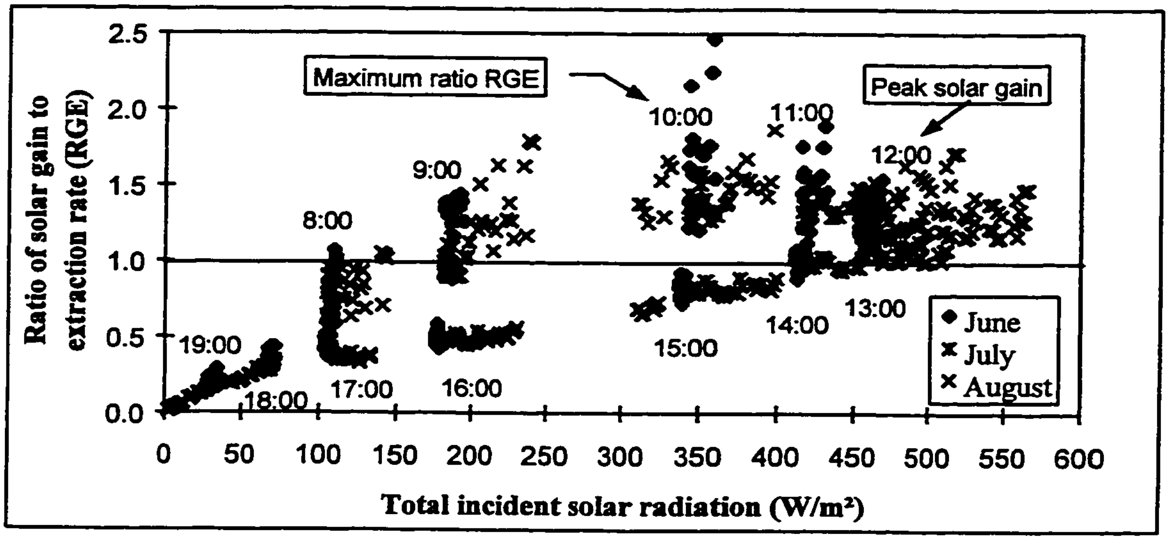

Figure 3-6. Relationship between the ratio of solar gain to extraction rate (RGE) and the total incident solar radiation for the South perimeter zone.

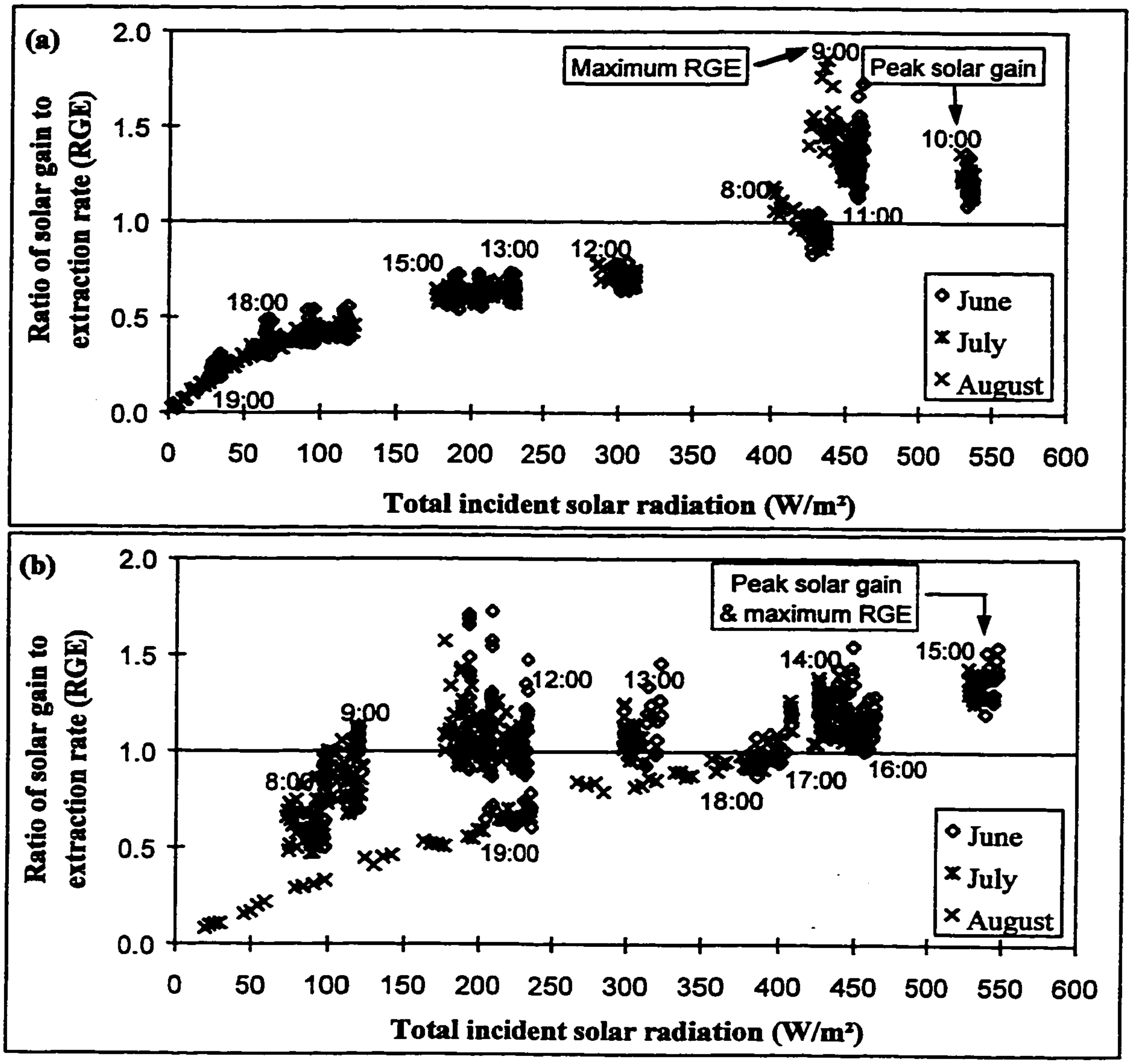

Figure 3-7. Relationship between the ratio of solar gain to extraction rate (RGE) and the total incident solar radiation for the: (a) East and (b) West perimeter zones.

The maximum ratio RGE occurs before the occurrence of the peak solar gain. For the South orientation, the maximum ratio occurs at 10:00-11:00 a.m. while the peak solar gain occurs at noon; for the East orientation, it was found that the maximum ratio occurs at 9:00 a.m., one hour before the occurrence of the peak solar gain. For the West orientation it seems that the maximum ratio occurs when the solar gains are maximum. It can be concluded that the potential for thermal storage of solar radiation is greatest when the ratio RGE has the maximum value. Therefore, in order to reduce the peak extraction rate, switching of the electrochromic glazing can potentially start when the maximum ratio RGE occurs. An RGE of 1.0 indicates that the solar gains are equal to the extraction rate; beyond this point, the solar gains decrease, and the amount of energy storage also decreases. This point can therefore potentially represent the time at which the glazing can be returned to the bleached state. Since this index incorporates both the effect of solar radiation and thermal lag, the feasibility of its use in a switching control algorithm merits further study.

A preliminary assessment of the validity of the above conclusions was made. The performance due to the following five control strategies were compared, including one based on the RGE index:

(i) the electrochromic glazing was switched to the colored state at the hour of occurrence of the peak extraction rate: 14:00 for the South orientation, 10:00 for the East orientation, and 17:00 for the West orientation. The glazing was returned to the bleached state when the direct incident solar radiation was zero.

(ii) the electrochromic glazing was switched to the colored state one hour before the occurrence of the peak extraction rate.

(iii) the electrochromic glazing was switched to the colored state two hours before the occurrence of the peak extraction rate.

(iv) the DOE-2.1E SPACE-LOAD control was used. In order to apply this strategy, the base cooling load was determined, that excludes the effect of solar gains. However, it was not possible to completely isolate the cooling load from the effects of solar gain, particularly for the South and East orientations. This is because for these orientations, solar gains are present before the cooling system is in full operation. The set-point for switching was determined based on a plot of the cooling load (from the LOADS block) versus total incident solar radiation for each orientation. The following set-points were then used in the simulation: 22.4 W/m^2 for the South orientation, 15.4 W/m^2 for the East and 18.6 W/m^2 for the West.

(v) switching was based on the RGE index. The electrochromic glazing was switched to the colored state at the hour of occurrence of the maximum RGE, which was obtained from Figures 3-6 and 3-7. The glazing was returned to the bleached state at the hour when RGE = 1.0. Therefore, switching start and stop times for each orientation were specified as follows: for the South 10:00 and 14:00, East 9:00 and 11:00, West 15:00 and 18:00.

DOE's Functional Values feature was used to develop a routine that would impose the switching start and stop time of the glazing. The routines are described in detail in Chapter 4.

Simulations were first run with the electrochromic glazing in the bleached state, the results of which were used to determine the percentage reduction in the extraction rate due to switched state results for the above five cases. The resulting reductions in the extraction rate are shown in Figures 3-8, 3-9 and 3-10 for the South, East and West perimeter zones, respectively.

Comparing the results of the first three switching cases, it is clear that greater energy savings occur when the glazing is switched earlier than at the hour of occurrence of the peak extraction rate (i.e., cases (ii) and (iii)). Control by space load (iv) is the overall best performing strategy for each orientation with over 30% reduction in the extraction rate. Note however that the approach presented here for applying control by space load is different than the approach used by other researchers in previous studies. In this chapter, the set-points for switching were selected based on the relationship between solar gains and the cooling load. Other researchers however did not isolate the solar component of the cooling load; rather the glazing was switched whenever a cooling load was present in the space, regardless of whether solar radiation was a significant component of the load. The strategy based on the RGE index (v) is the second best performer for the South orientation with savings between 25 and 28%. However, switching based on this index did not perform as well for the East and West orientations. For the East orientation, the RGE index for switching slightly underperforms switching that is initiated one hour before the occurrence of the peak extraction rate (strategy (ii)). This is expected, since both strategies cause the electrochromic layer to switch from the bleached state to the colored state at 9:00. The difference is that for strategy (ii) the glazing is in the colored state for a longer period of time than for strategy (v), thereby causing a greater reduction of solar heat gains to the space. For the West orientation, the performance of strategy (v) is similar to the performance of strategy (iii) where the glazing is switched to the colored state two hours before the occurrence of the peak extraction rate. This can be expected since both strategies cause the glazing to be switched to the colored state at 15:00. Further work is necessary to improve the RGE index as a basis for switching.

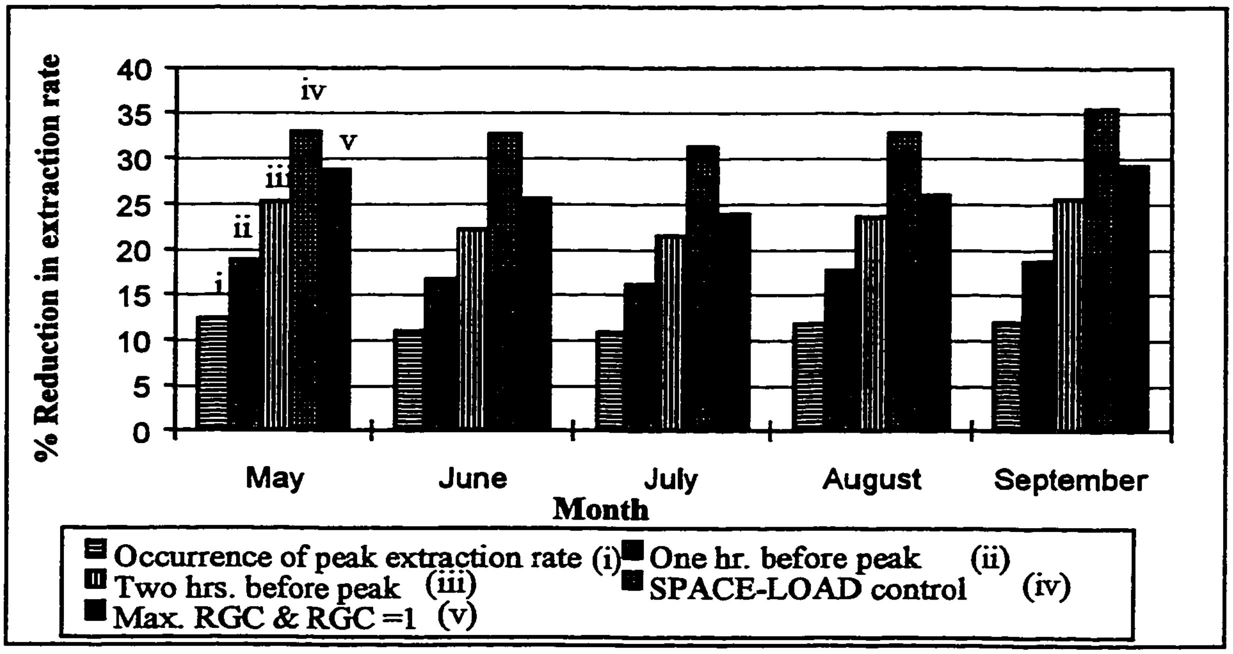

Figure 3-8. Percentage reduction in extraction rate due to various switching strategies, South perimeter zone.

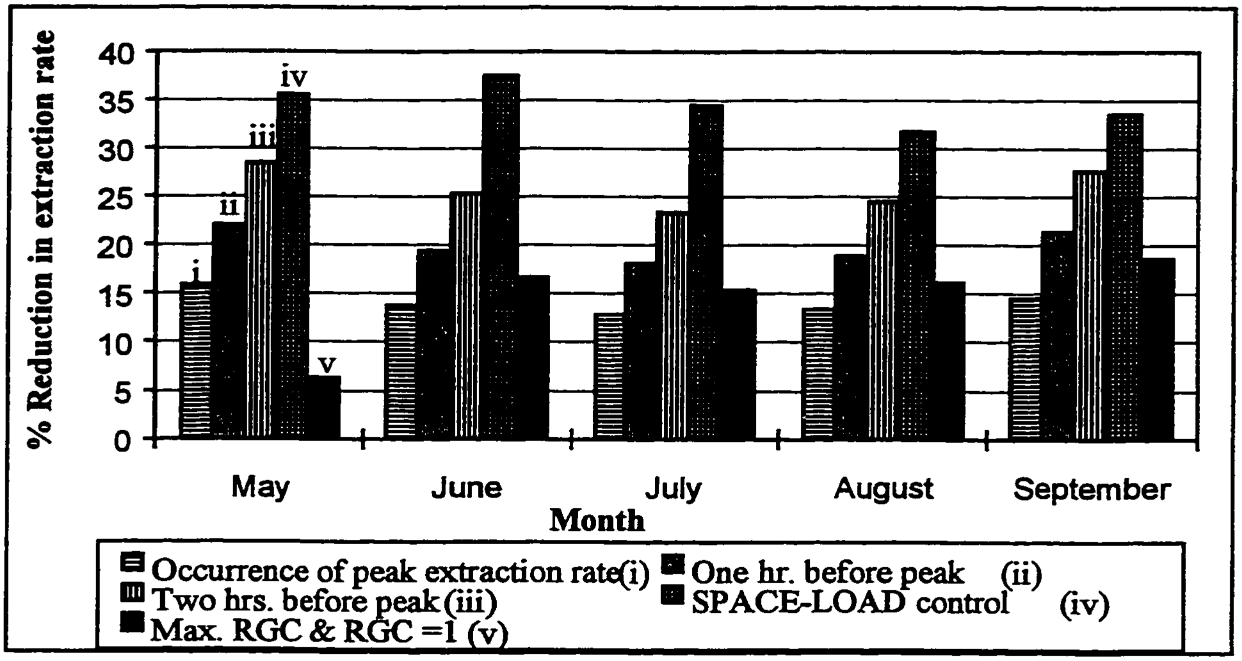

Figure 3-9. Percentage reduction in extraction rate due to various switching strategies, East perimeter zone.

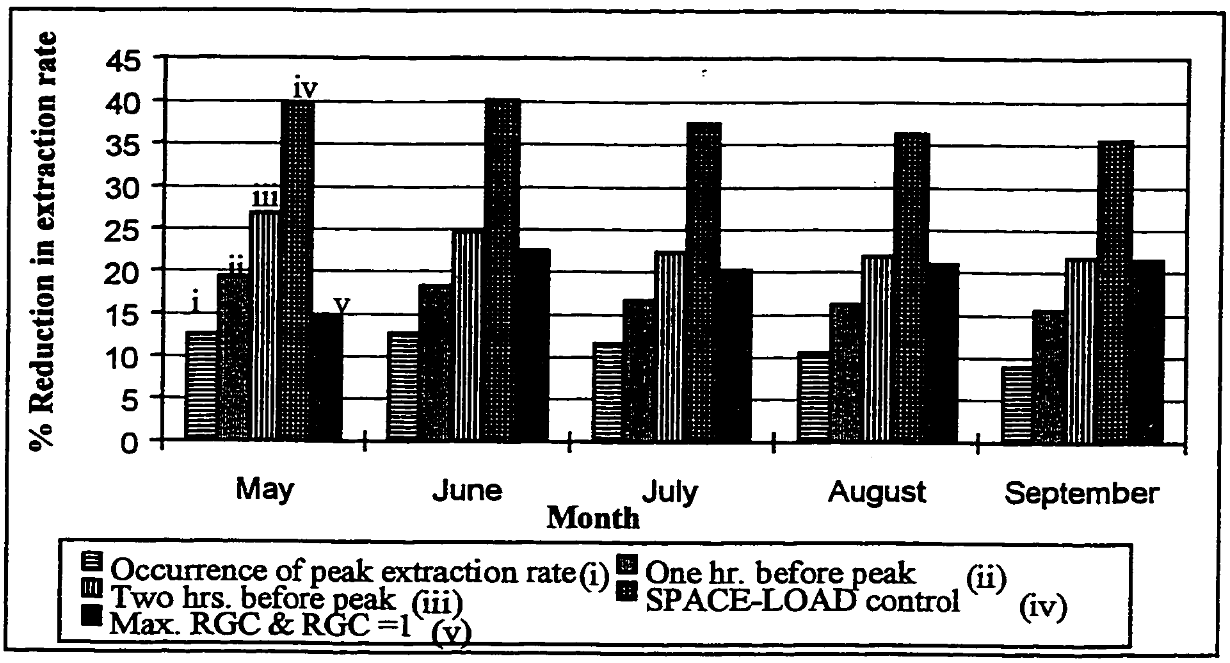

Figure 3-10. Percentage reduction in extraction rate due to various switching strategies, West perimeter zone.

3.4 CONCLUSIONS

Three 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), (ii) the determination of the set-points for switching, and (iii) the switching duration. Although existing models of electrochromic glazing control strategies can be used to perform a preliminary evaluation of the potential energy savings due to these advanced windows, their application is not straightforward and can provide misleading results.

The emphasis to date has been on the energy savings potential of electrochromic windows, but ultimately, the control strategy used will have a direct impact on the potential energy savings resulting from control of solar gains and will also affect occupant visual comfort. Therefore, in order to capitalize on the full benefits of electrochromic glazings, qualitative performance parameters such as visual quality must also be assessed. These issues are addressed in Chapter 4.

CHAPTER 4
A PROCEDURE TO OPTIMIZE THE SWITCHING TIME OF THE ELECTROCHROMIC GLAZING

Electrochromic windows enable the dynamic control of solar-optical properties, thereby affecting solar heat gains as well as lighting quantity and quality. They must therefore be assessed in terms of their impact on both energy savings and quality of the indoor environment in order to capitalize on their full potential. Selkowitz et al. [16] indicated that "the problem is made more difficult in that it is not a simple 'engineering optimization' problem but rather one that includes tradeoffs between energy savings and subjective human response to lighting quality." It was seen in Chapter 3 that existing models of switching control can only facilitate an assessment of the potential energy savings and do not address subjective factors. New models are therefore required to address the conflicting nature of these two objectives and provide designers with a means to optimize the operation of these windows.

The main objective of this chapter is to advance the knowledge related to the simulation of electrochromic glazing switching control through the development of a new procedure [67] that: (i) introduces performance indices to evaluate energy and subjective parameters, (ii) accounts for the necessary tradeoffs between energy and visual quality, and (iii) optimizes the switching operation of electrochromic windows based on these tradeoffs.

First, 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. Two functions were developed to provide a structure to change the state of the electrochromic glazing based on the time of day. The effect of switching time was then studied for the perimeter zones of the existing commercial building that was described in Chapter 3. 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 performance objectives, demonstrating the associated tradeoffs. Finally, the body of work presented in this chapter was synthesized, and culminated in the development of an automated optimized switching strategy that was coupled with the MICRO-DOE-2.1E program.

4.1 BACKGROUND

The switching times of the electrochromic glazing are defined in this work as follows: (i) the time t_1 at which the glazing is switched from the bleached state to the colored state, and (ii) 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. Figure 4-1 qualitatively shows the relationship between the visual quality and the energy savings as the switching time of the electrochromic glazing is increased. 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 [68]. Many Pareto optima are possible depending on the decision-maker's priority on each objective.

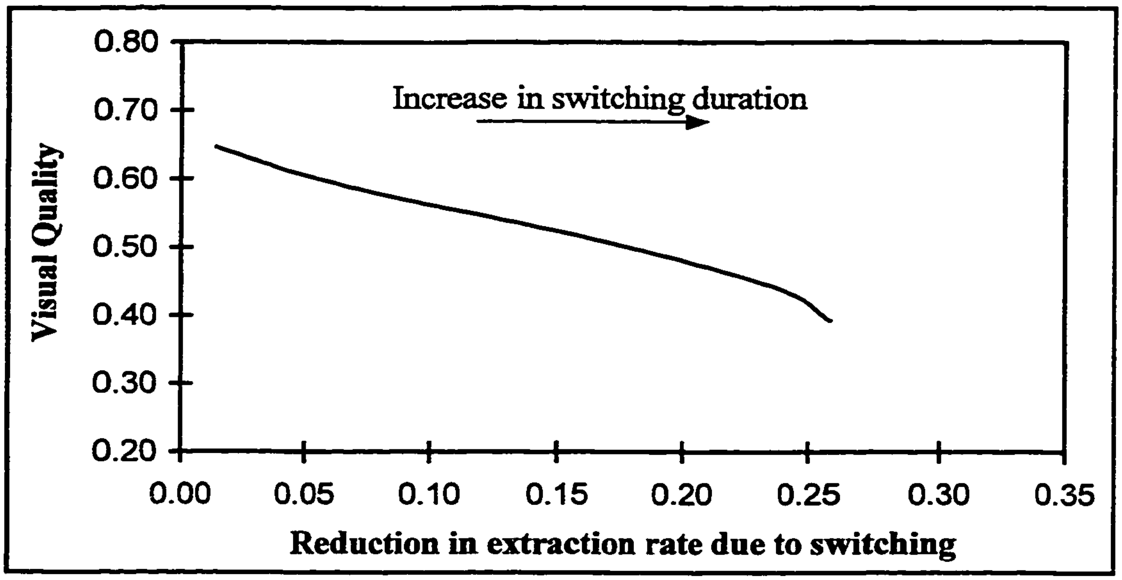

Figure 4-1. Variation of visual quality and reduction in extraction rate as the switching duration of the electrochromic glazing is increased.

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:

$$VQ = \alpha \cdot AV + \beta \cdot DIF \tag{4.1}$$

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 ($\alpha + \beta = 1$).

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:

$$AV = \frac{N_1 \bullet \tau_{vis\_bleached} + N_2 \bullet \tau_{vis\_colored}}{N_{TOT} \bullet \tau_{vis\_double\_clear}} \tag{4.2}$$

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)

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

$\tau_{vis\_double\_clear}$ = visible transmittance, at normal incidence, of a reference clear double glazed window.

The Daylight Illuminance Factor (DIF) describes the extent to which a specified illuminance level (e.g., 538 lux for offices) can be met by natural lighting rather than electric lighting, as shown in Figure 4-2:

$$\mathrm{DIF} = 1 - \frac{(538 - \mathrm{DI})}{538}, \; if\, DI \leq 538\, lux$$

(4.3)

$$\mathrm{DIF} = 1, \; if\, DI > 538\, lux$$

where: DI = Daylight Illuminance level at the reference point in the perimeter zone.

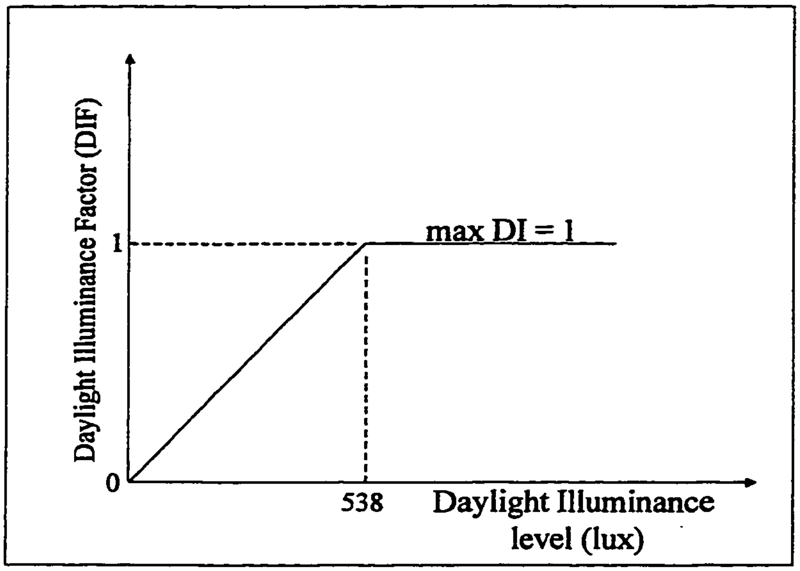

Figure 4-2. Concept for assigning values to the Daylight Illuminance Factor.

The objective function representing the Extraction Rate Reduction (ERR) is calculated as the reduction in the extraction rate of the perimeter zone due to switching of the glazing ($ER_{switched\ state}$), relative to the extraction rate when the electrochromic window is maintained in its bleached state ($ER_{bleached\ state}$)

$$ERR = \frac{ER_{bleached\ state} - ER_{switched\ state}}{ER_{bleached\ state}} \qquad (4.4)$$

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

$$OBJECTIVE = w_1 \cdot ERR + w_2 \cdot VQ \qquad (4.5)$$

where w_1 and w_2 represent the weighting coefficients and can be varied to reflect the importance given by the designer to each objective function; $w_1 + w_2 = 1$.

4.3 OPTIMIZATION METHODOLOGY

The approach used to optimize the glazing switching times is illustrated in Figure 4-3. The enumeration approach is used as a first step towards understanding the optimization process. First, two Functional Values routines were developed and coupled with the window description of the building computer model in order to study the effect of switching time on the energy savings and the visual quality. 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 16:00 (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 extraction rate 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 17:00, 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 to 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.

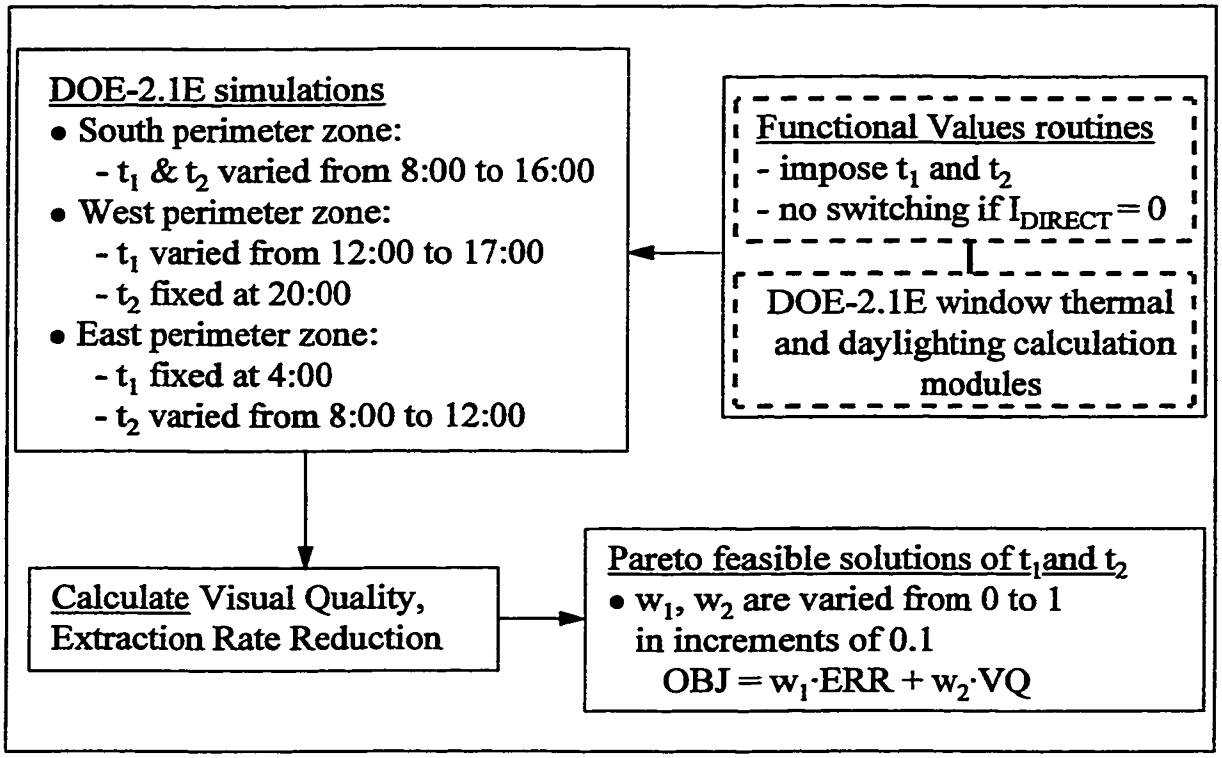

Figure 4-3. Approach used to optimize the switching times of the electrochromic glazing.

In performing the calculations, the following points apply:

- Equation 4.2 can be rewritten as:

$$AV = \frac{(9 - \sum_{8:00}^{17:00} SWFAC) \bullet \tau_{vis\_bleached} + (\sum_{8:00}^{17:00} SWFAC) \bullet \tau_{vis\_colored}}{9 \bullet \tau_{vis\_double\_clear}}$$

where, the SWFAC variable, from the DOE-2.1E hourly report variable list, is used to determine the number of hours that the glazing is in the bleached and colored states during the working hours. Since a SWFAC value of 1 represents the glazing in the colored state, the sum of SWFAC values between the hours of 8:00 and 17:00 represents the number of hours that the glazing is in the colored state.

- The daylight illuminance (DI) used in calculating the Daylight Illuminance Factor (DIF) is the value of the RAYDIL hourly variable in the DOE-2.1E program.
- The Access to Views objective is calculated on a daily basis. The Daylight Illuminance Factor is calculated on an hourly basis, and an average value is then calculated for the working day. An average value for each objective is then calculated for the entire month of July.
- For this study, α and β, i.e., the weighting coefficients for the AV and DIF terms used in calculating the Visual Quality (equation 4.1) were selected as 0.9 and 0.1, respectively. Based on a daylighting analysis using LUMEN-MICRO, for a cloudy day and for different cubicle configurations, it was found that the illuminance level due to daylight far exceeded the required level of 538 lux even when the electrochromic glazing was in the colored state. Since the DIF term would not have a significant impact on the overall results, for this study greater importance was given to the AV component.
- The extraction rate is taken as the monthly sum of the DOE-2.1E SYSTEMS hourly variable QNOW.
- The weather file for the year 1992 recorded at Dorval airport, Montreal, was used in the DOE-2.1E simulations.

4.3.1 Description of the functional values routines

The Functional Values approach, available in DOE-2.1E, enables users to introduce new functions which alter or replace the LOADS and SYSTEMS algorithms without recompiling the program [46]. The functions are similar to FORTRAN subroutines, and the user must specify the variables to be calculated as well as the access point within the LOADS and SYSTEMS calculations loops where the new function is to be introduced.

The first function that was developed affects the program's solar gain calculations loop of the selected window (subroutine CALWIN), while the second function affects the corresponding daylighting calculations in the program's DINTIL subroutine. Both functions are called from within the window description of the building in the LOADS module of the input file, as shown below:

```
ZONE-7-WI = WINDOW
        GLASS-TYPE = EC-BLEACH
        GLASS-TYPE-SW = EC-COLOR
        SWITCH-CONTROL = NO-SWITCH
        SWITCH-SCH = SW-SCHED
        X = 0
        Y = 0
        HEIGHT = 5.48
        WIDTH = 113
        FUNCTION = (*SW_STH*,*NONE*)
        WINDOW-SPEC-FN = *STH_ILL* ..
```

where SW_STH is the function that affects the solar gain calculations for windows in the South perimeter zones, and STH_ILL is the function that affects the daylighting calculations, also for windows facing South. The SWITCH-CONTROL command is used to specify the type of control strategy that is available in DOE-2.1E (as presented in section 4.1); NO-SWITCH was used since switching was determined by the functional values routines. The structure of the **FUNCTION** command, shown above, e.g., FUNCTION = (*function_name*,*NONE*), ensures that calculations in the SW_STH routine are performed before the CALWIN routine is executed. The entry point of the function in DOE's CALWIN subroutine is shown in Figure 4-4. The **WINDOW-SPEC-FN** is used strictly to affect daylighting, and its entry point in DOE's DINTIL subroutine is presented in Figure 4-5. A copy of both functions is included in Appendix A.

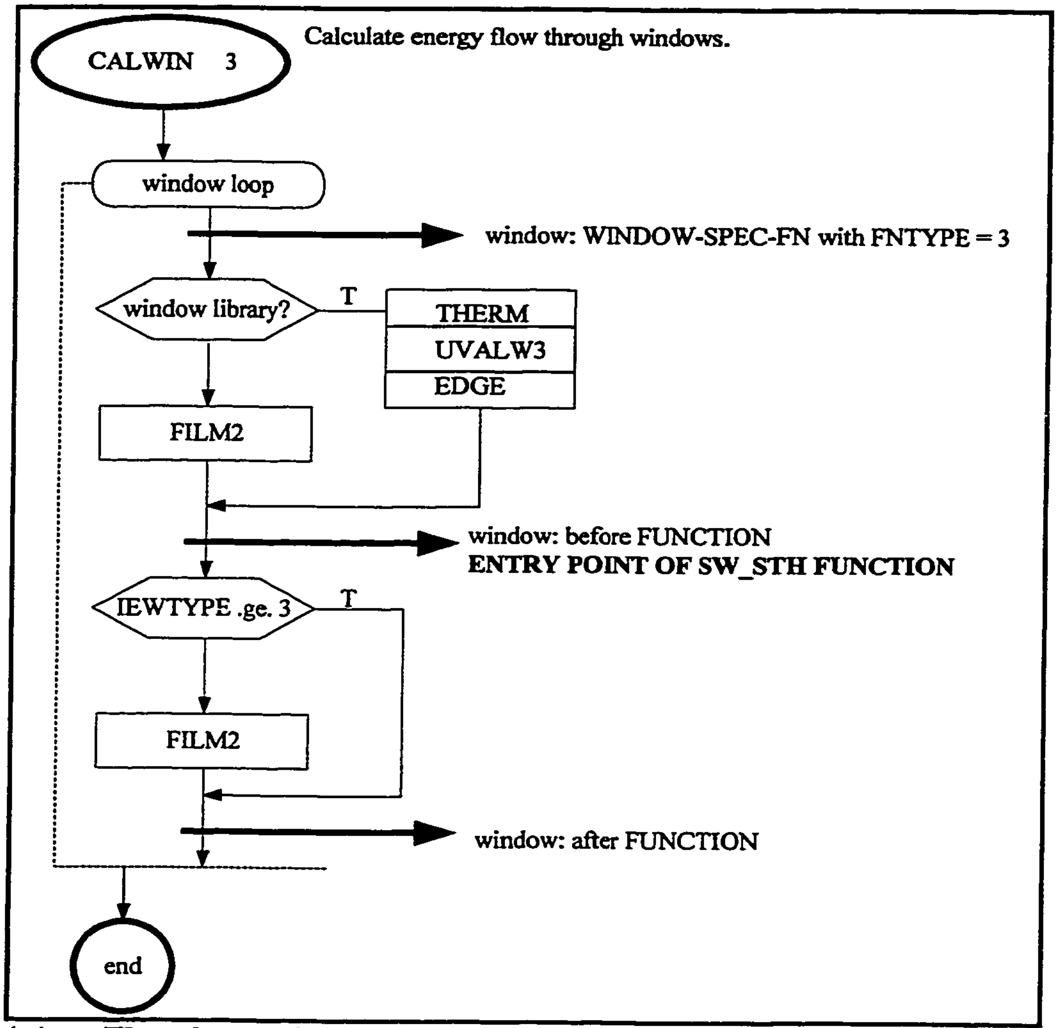

Figure 4-4. Flowchart of DOE-2.1E CALWIN subroutine [46] showing entry point for the developed function, SW_STH.

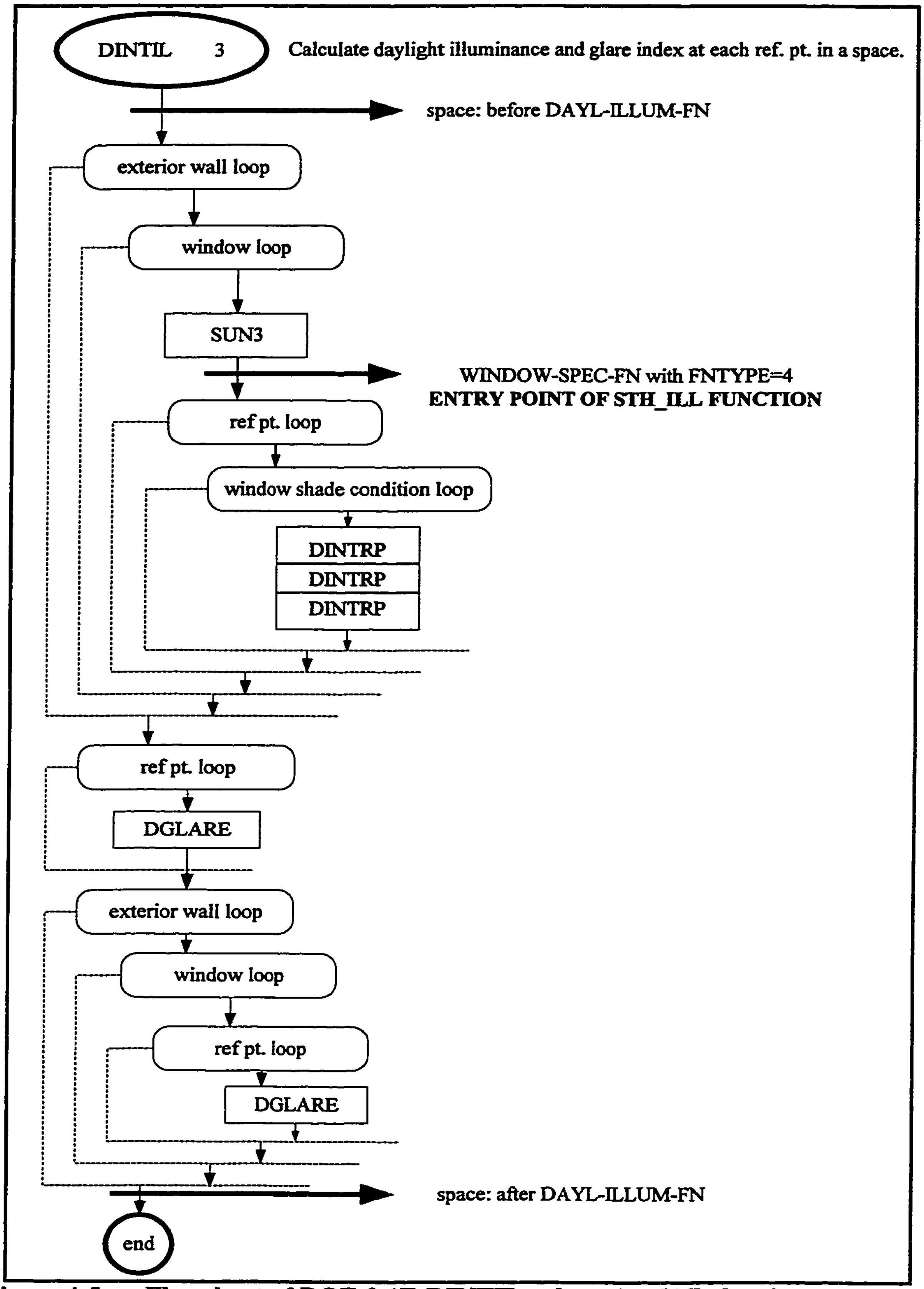

Figure 4-5. **Flowchart of DOE-2.1E DINTIL subroutine [46] showing entry point for the developed function, STH_ILL.**

Two main conditions were imposed through these routines: (i) the switching start and stop times, i.e., t_1 and t_2, which are stored in text files labeled orientation.tim for each orientation (e.g., south.tim), and (ii) switching was only allowed when direct solar radiation was incident on the surface (QDIR>0.0001). Switching was permitted during weekdays only (ISCDAY = 2 to 6) and from May to September (IMO = 5 to 9). The routines alter the switching factor (SWFAC). In this research, SWFAC could only take values of 0.0 or 1.0; in other words, the electrochromic glazing could either be in the bleached state (SWFAC = 0.0) or the colored state (SWFAC = 1.0) with no intermediate switching (Figure 4-6).

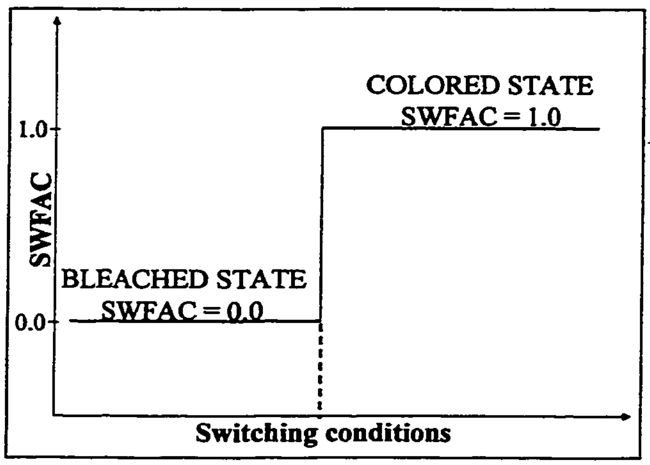

Figure 4-6. Switching mode of the electrochromic window.

4.4 PARETO FEASIBLE SOLUTIONS OF T_1 AND T_2

Figure 4-7 shows the conflicting nature of the relationship between the visual quality and the energy savings as the switching time of the electrochromic glazing is varied in the South perimeter zone of the commercial building studied. Note how maximum energy savings are achieved when the switching duration is longest; however, the visual quality is minimum. For example, when t_1=8:00 and t_2 = 16:00, a 28% reduction in extraction rate is achieved due to switching and the visual quality is almost 40%. However, when t_1=8:00 and t_2 = 9:00, the energy savings are less than 5% but the visual quality is 65%.

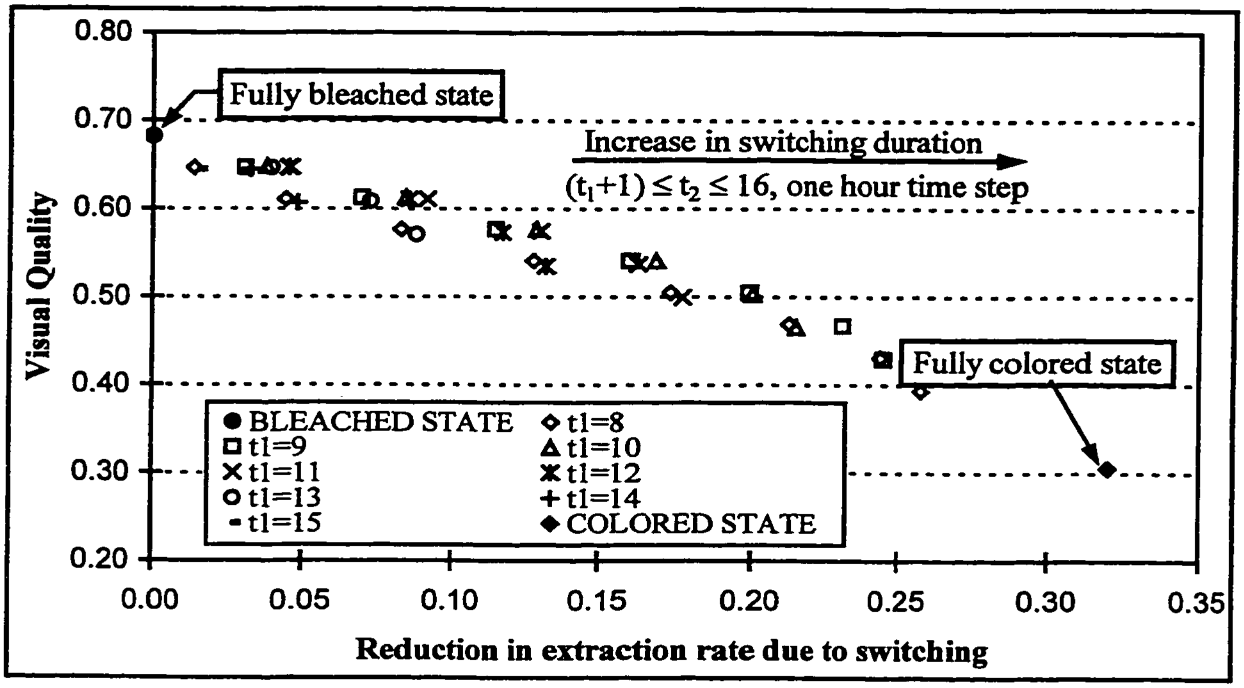

Figure 4-7. Variation of visual quality and reduction in extraction rate as the electrochromic glazing is switched from the bleached state to the colored state at different switching times. Values shown are for the South perimeter zone, for the month of July.

Examples of Pareto feasible solutions of t_1 and t_2 for the South perimeter zone are shown in Figures 4-8 to 4-12 for several different values of the weighting coefficients. The remaining figures, along with a table of the results, are included in Appendix B for reference. 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 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 $w_2 = 1$, Figure 4-8), switching from bleached to colored mode could occur at any time between 8:00 to 15:00, and the optimum switching duration should not exceed a maximum of two hours. 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 4-9, the ERR objective is assigned a weighting coefficient of 0.3, while the VQ objective is assigned a weighting coefficient of 0.7. Comparing Figures 4-8 and 4-9, it can be seen that the range of feasible solutions of t_1 and t_2 broadens as both weighting coefficients move towards a value of 0.5. In Figure 4-10, the ERR and VQ objectives are given equal weights, and most switching times are feasible except for some extremes. The set of feasible switching times becomes more restrictive as greater priority is given to the extraction rate reduction, as shown in Figure 4-11, where ERR has a weight of 0.7. If full priority is given to the extraction rate reduction (Figure 4-12), 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.

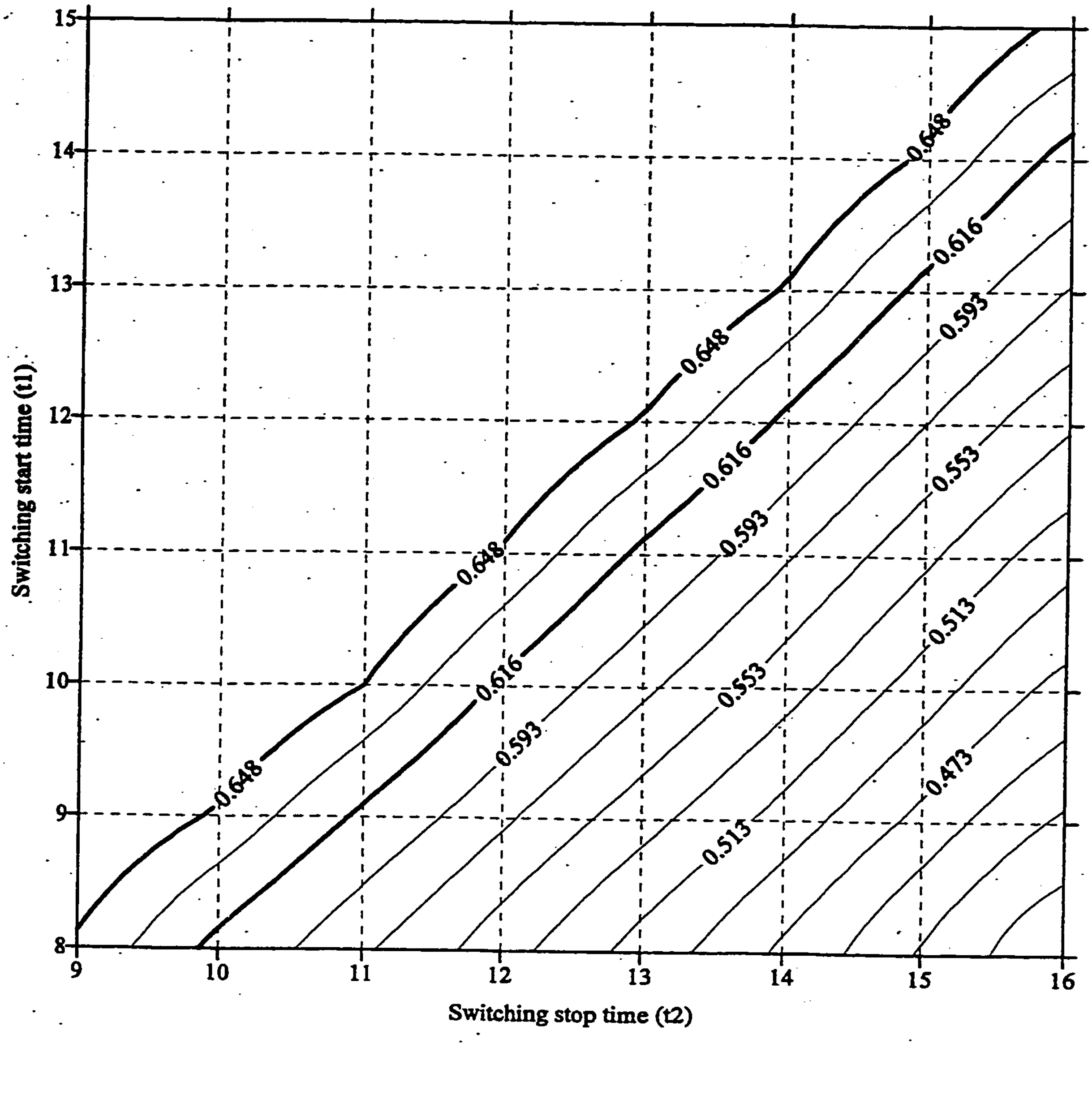

Figure 4-8. Pareto feasible solutions of t_1 and t_2 for the South perimeter zone when full priority is given to the visual quality, OBJECTIVE=0·ERR+1·VQ.

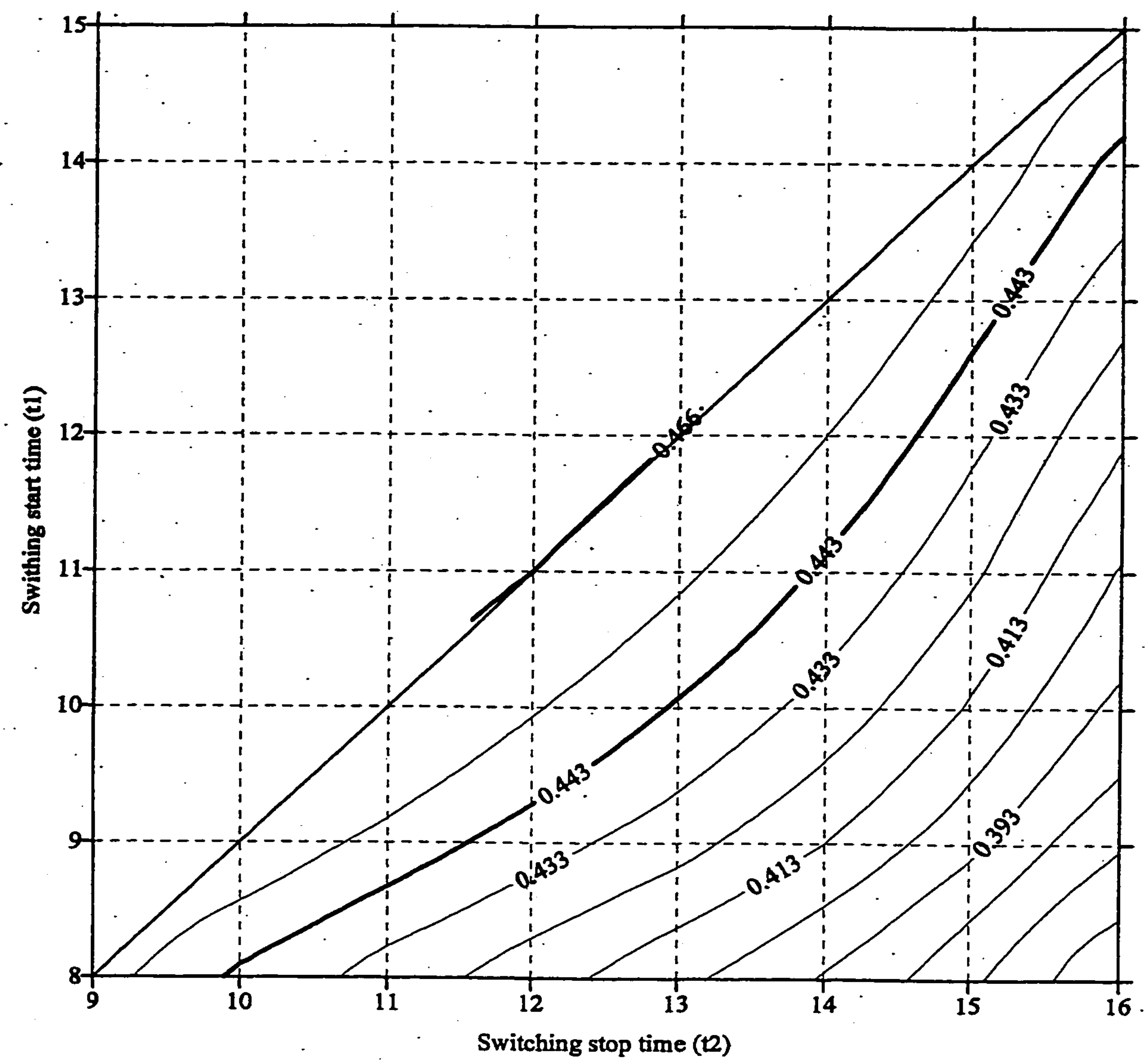

Figure 4-9. Pareto feasible solutions of t_1 and t_2 for the South perimeter zone when OBJECTIVE=0.3·ERR+0.7·VQ.

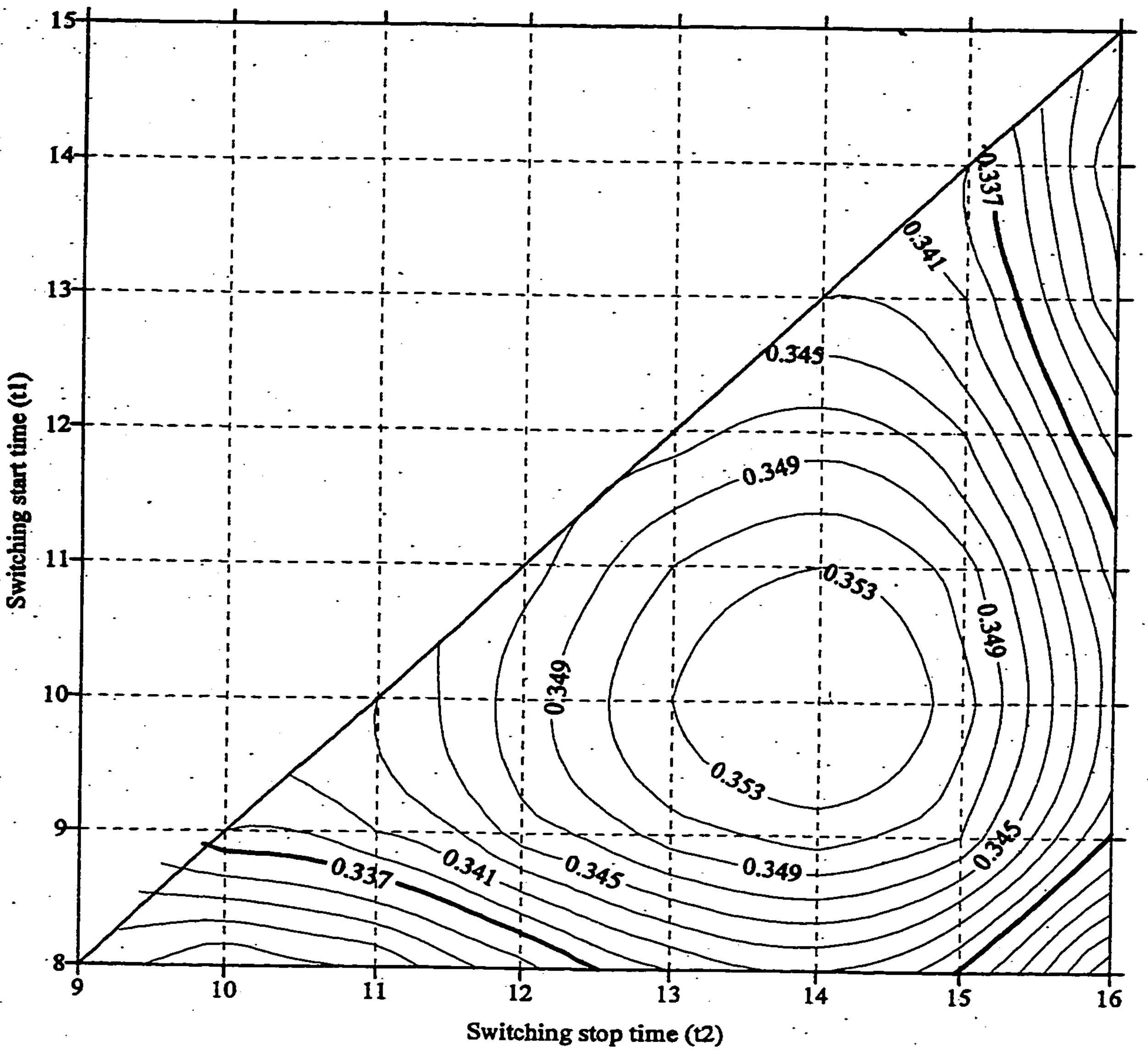

Figure 4-10. Pareto feasible solutions of t_1 and t_2 for the South perimeter zone when equal priority is given to both objectives, (i.e., OBJECTIVE=0.5·ERR+0.5·VQ).

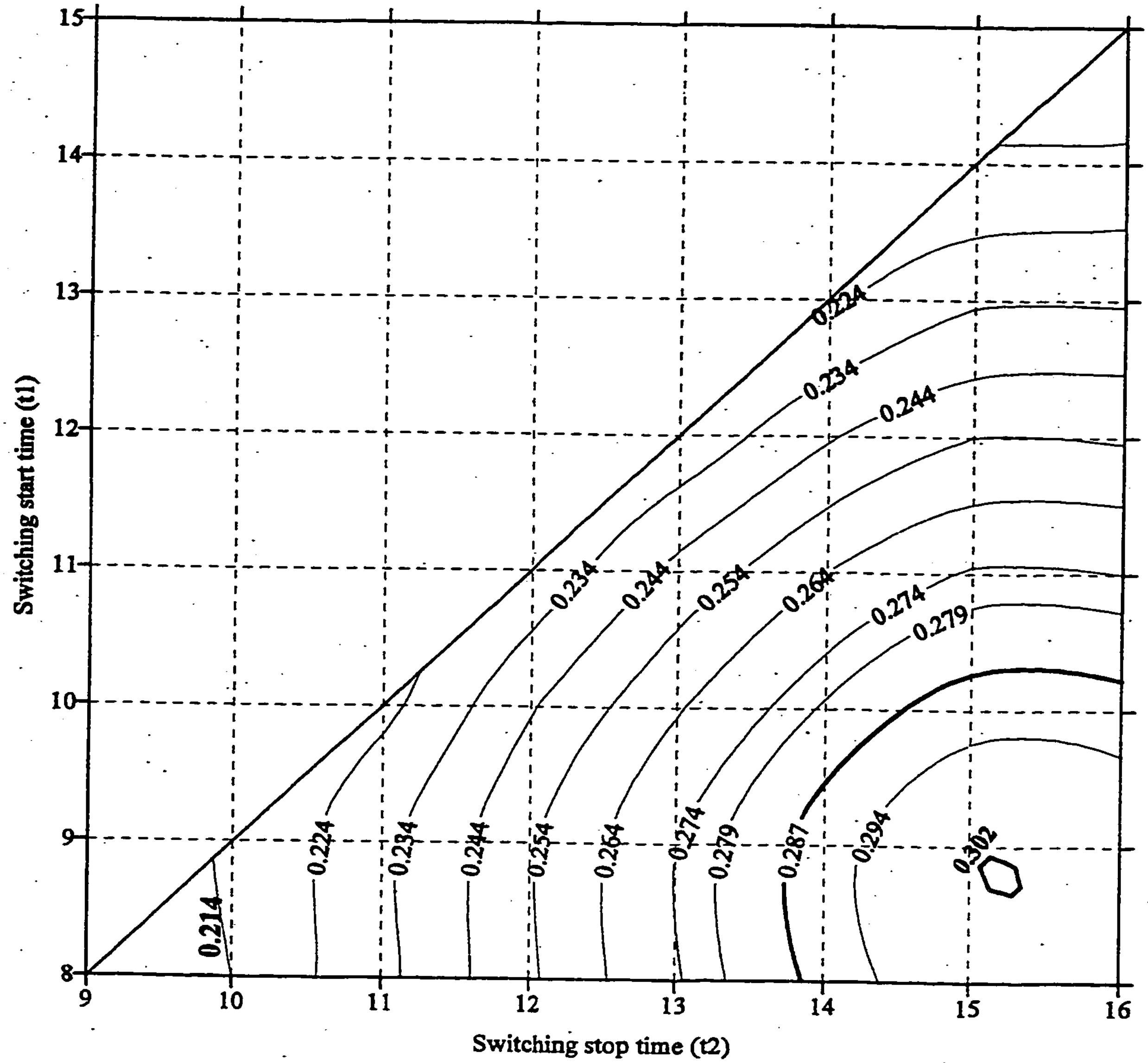

Figure 4-11. Pareto feasible solutions of t_1 and t_2 for the South perimeter zone when OBJECTIVE=0.7·ERR+0.3·VQ.

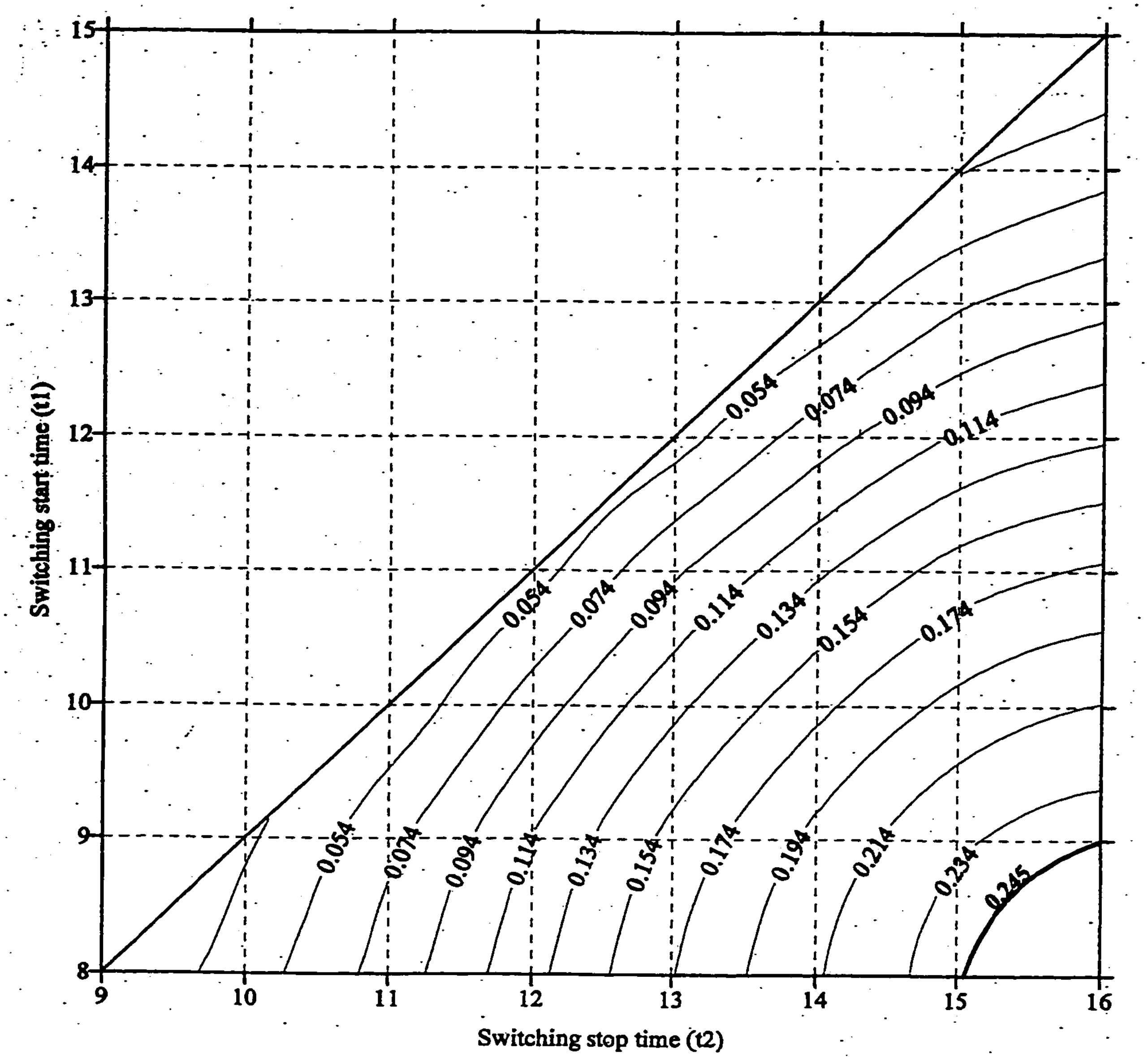

Figure 4-12. Pareto feasible solutions of t_1 and t_2 for the South perimeter zone when full priority is given to the extraction rate reduction (i.e., OBJECTIVE=1·ERR+0·VQ).

The Pareto feasible solutions of the switching start time t_1 for the West perimeter zone are shown in Figure 4-13 for the full range of weighting coefficients. Those solutions with a value of objective function within 5% of the absolute maximum are located in the shaded area between the thick lines. When equal priority is given to both the extraction rate reduction and the visual quality (e.g., 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 (e.g., 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 (e.g., w_1=0.8, w_2=0.2), then the switching start time could occur between 12:00 and 13:00.

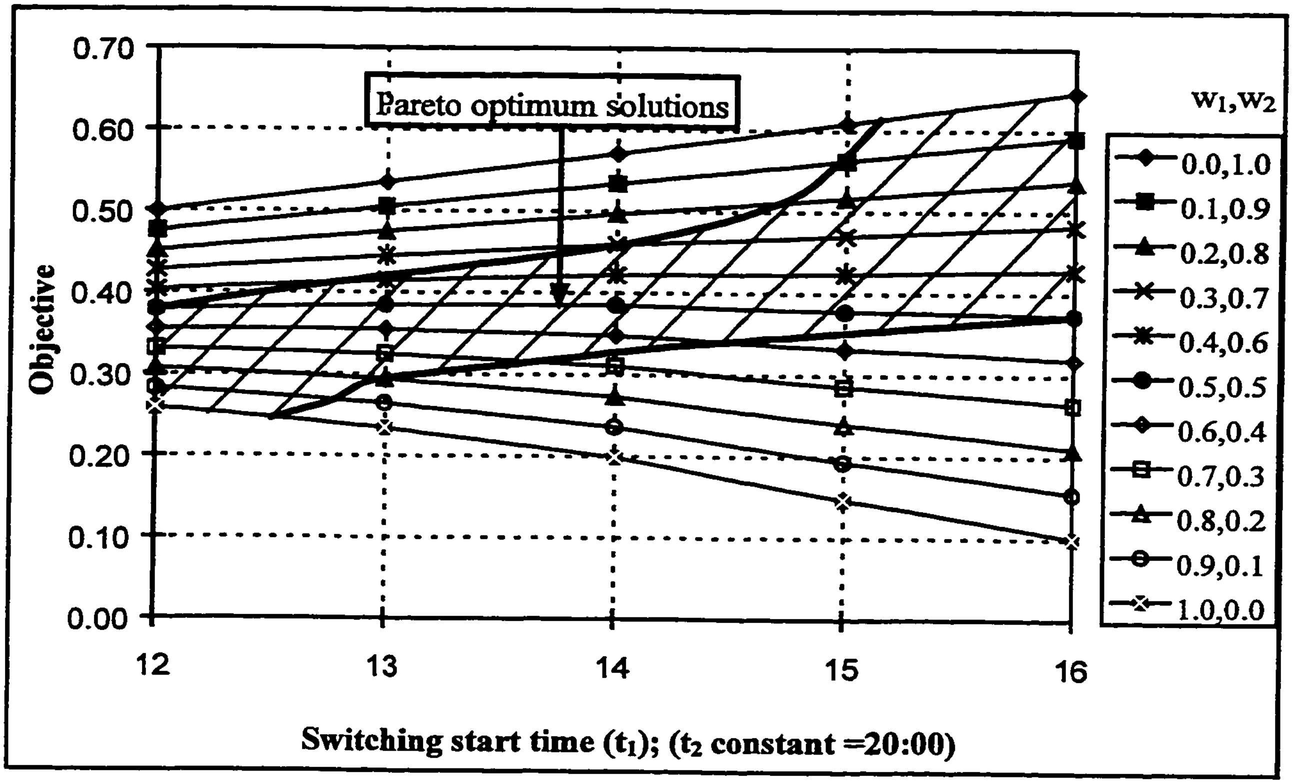

Figure 4-13. Pareto feasible solutions of t_1 for the West perimeter zone for the full range of weighting coefficients.

The Pareto feasible solutions of the switching stop time t_2 for the East perimeter zone are shown in Figure 4-14 for the full range of weighting coefficients. Those solutions with a value of objective function within 5% of the absolute maximum are located in the shaded area between the thick lines. All values of t_2 are feasible when equal priority is given to both the extraction rate reduction and the visual quality (e.g., w_1=w_2=0.5). If a higher priority is given to the visual quality (e.g., w_1=0.1, w_2=0.9), the switching stop time could occur at any time between 8:00 and 9:00, thereby maintaining the electrochromic window in the bleached state for the entire duration of the working day. Conversely, if a higher priority is given to energy savings (e.g., w_1=0.8, w_2=0.2), then the switching stop time could occur between 11:00 and 12:00.

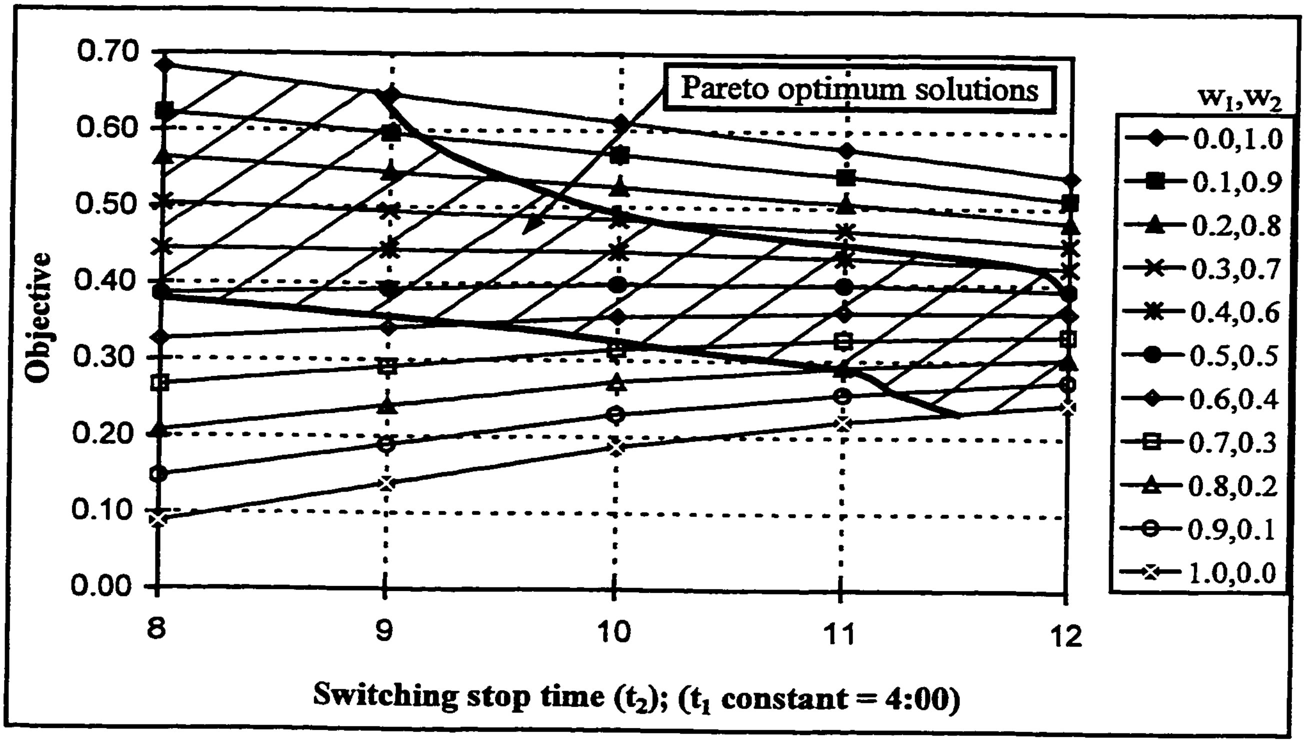

Figure 4-14. Pareto feasible solutions of t_2 for the East perimeter zone for the full range of weighting coefficients.

4.5 A PROCEDURE TO AUTOMATE THE OPTIMIZATION PROCESS

The long-term goal of developing the functional values routines described in section 4.3.1 was to create a structure allowing for a more complex switching algorithm to be incorporated in the MICRO-DOE-2.1E program. The process of determining the optimum switching times of the electrochromic glazing for given weighting coefficients was consolidated into an automated optimized switching strategy. This was achieved through the creation of several FORTRAN programs to perform the required calculations and a batch file which links the programs with the MICRO-DOE-2.1E energy simulations.

The following general conditions apply to the switching strategy:

- Switching was only permitted on a typical floor of the commercial building studied since the main quantity of interest is the optimum switching start and stop times. The optimum times would subsequently be applied for each floor to study the whole-building impact of electrochromic windows, which is the subject of Chapter 5.
- In the previous sections, the impact of switching time was isolated for each perimeter zone. However, for the present work, the functional values routines were applied to all three perimeter zones for each simulation in order to account for the thermal interactions between zones. Therefore, for any given combination of switching time, the objective function was first calculated separately for each perimeter zone, and then an area weighted average of the individual objective function values was taken in order to obtain one single value of the objective function.

- The energy simulations were performed for the entire cooling season from May 1st to September 30th, and the monthly results were averaged to obtain one value for the cooling season.

An overview of the structure and data flow of the optimized strategy is presented in Figure 4-15. The entire process is run by a batch file, called OPTIM.BAT, which loops the switched state simulations and calculations until all combinations of switching times are exhausted for each orientation. A description of each component of the strategy follows the figure and a copy of the FORTRAN programs is included in Appendix C.

First, a DOE-2.1E energy simulation is run with the electrochromic window in the bleached state. The main quantity of interest for this simulation is the total monthly extraction rate for each perimeter zone, calculated from the hourly values. The simulation results are saved in the BLEACHED.SIM file. CLEANCLR is a program written in FORTRAN that reads the data from BLEACHED.SIM and extracts the monthly sum values of the extraction rate for each perimeter zone. Data is then saved to the file EXT_CLR.DAT.

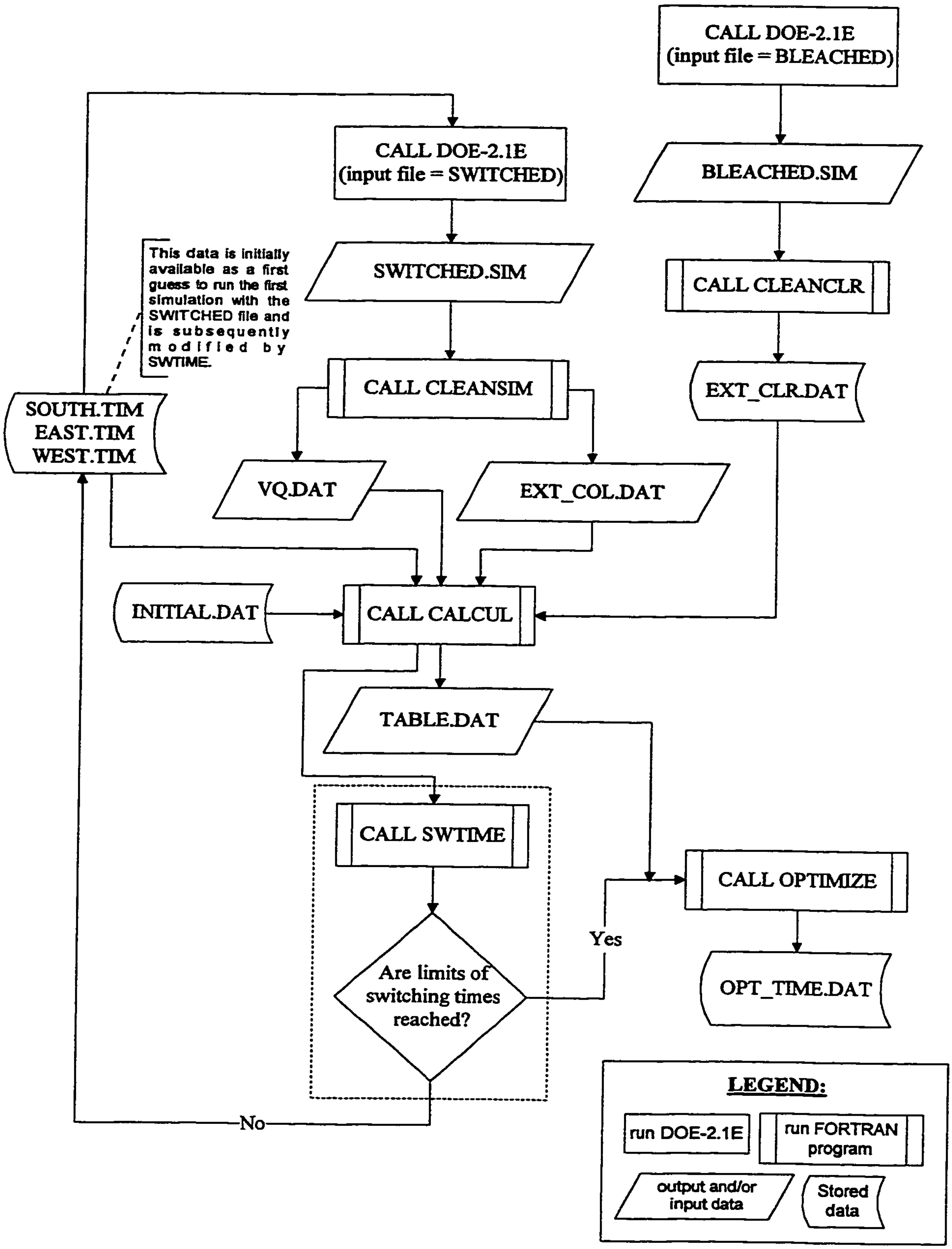

Figure 4-15. Overview of the structure and data flow of the optimized switching strategy that is run by the batch file OPTIM.BAT.

Simulations are then performed with the electrochromic window in the colored or switched, state, the results of which are saved to SWITCHED.SIM. The switching times, t_1 and t_2, of the electrochromic window are stored in three separate files, SOUTH.TIM, EAST.TIM and WEST.TIM. Initially, these files contain the first guess of the switching times, which in this study was simply specified as the extremes in switching. The functional values routines were structured with an INCLUDE statement, which allows data to be read from stored files and therefore enables the user to vary the simulation parameters, in this case the switching times.

The CLEANSIM program reads the data that is stored in the SWITCHED.SIM file and extracts the data that is required to calculate the visual quality and extraction rate reduction performance criteria. The extracted data is saved to two new files: (i) VQ.DAT, which contains the hourly values of SWFAC and the daylight illuminance levels for the South, East and West perimeter zones, and (ii) EXT_COL.DAT, which contains the monthly sum value of the extraction rate for each perimeter zone.

The CALCUL program calculates the performance indices for each perimeter zone that are used to determine the optimum switching time of the electrochromic glazing, namely: Access to Views, Daylight Illuminance Factor, Visual Quality, Extraction Rate Reduction, and OBJECTIVE. Finally, the area weighted average of the perimeter zone objective functions is determined in order to obtain the overall value of the objective function for the given switching times. Results of the CALCUL program calculations for each simulation are saved in the file TABLE.DAT. The file INITIAL.DAT contains the normal incidence visible transmittance of the clear double glazed window and of the electrochromic window in the bleached and colored states, which are used to calculate Access to Views. The file also contains the weighting coefficients used to calculate the Visual Quality and the objective function, which are pre-defined by the user.

The SWTIME program is called after each simulation, and selects the next set of switching times for each orientation and checks if these are within the specified limits of switching. If they are within limits, then another iteration is performed. At present, all combinations of switching times are explored using the enumeration approach. In other words, all combinations of switching times for the West zone are exhausted first, while the switching times for the South and East zones remain fixed from simulation to simulation. When the limits of switching are reached for the West zone, the switching time for the East zone is decreased by one hour, while the switching times for the South zone remain fixed and simulations are then performed until the limits of switching are again reached for the West zone. The process continues until all the limits of switching are reached for the East zone, then the switching time for the South zone is varied by one hour and the cycle continues. When the limits of switching are reached for the South zone, it means that all combinations of switching times have been exhausted and the OPTIMIZE program is called. For this case study, a total of 900 simulations were performed. These simulations were performed in batch mode on six Pentium machines as each simulation required approximately 1.5 to 2.0 minutes to complete.

The OPTIMIZE program reads the value of the average objective function for each combination of switching time, obtained from the TABLE.DAT file, and then finds the maximum value. The maximum value of the average objective function is retained as well as those values within 5% is of the absolute maximum. The corresponding optimum switching times for each perimeter zone are then stored in a separate file called OPT_TIME.DAT.

In the future, the SWTIME algorithm will contain the optimization algorithm for the selection of the switching times t_1 and t_2 to be evaluated in the next iteration.

4.5.1 Application of the optimized strategy

The optimized switching strategy was applied for the experimental electrochromic window when:

$$\text{OBJECTIVE} = 0.8 \cdot \text{ERR} + 0.2 \cdot \text{VQ}$$

The Pareto feasible solutions that lead to a value of the objective function within 5% of the absolute maximum, when the perimeter zones are considered individually, are shown in Table 4-1. Taking the South perimeter zone as an example, the switching start time t_1 can be either 8:00 or 9:00, while the switching stop time t_2 can be either 15:00 or 16:00. The electrochromic window can therefore feasibly be in the colored state from six to eight hours, depending on the switching times.

Table 4-1. Pareto feasible solutions when perimeter zones are considered individually (OBJECTIVE = 0.8·ERR + 0.2·VQ).

	South	East	West
t_1	8:00-9:00	4:00	12:00 -13:00
t_2	15:00 - 16:00	11:00 - 12:00	20:00
Duration	6 to 8 hrs	7 to 8 hrs	7 to 8 hrs

If the integrated impact of all three zones is considered, the value of the objective function that is used to determine the final optimum switching times is based on an area weighted average of the value of the objective function of each perimeter zone. The range of optimum switching times generally increases by only one hour, as shown in Table 4-2. Furthermore, a given switching time for one orientation must correspond with specific switching times for the other two orientations if the objective function is to be maximized, within 5%, according to the integrated effect of all three zones. For example, an optimum switching time of 10:00 - 15:00 for the South orientation must be coupled with a switching time of 4:00 - 12:00 for the East orientation, and a switching time of 12:00 - 20:00 or 13:00 - 20:00 for the West orientation. Alternatively, an optimum switching time of 10:00 - 15:00 for the South orientation can also be coupled with a switching time of 4:00 - 11:00 for the East orientation, and a switching time of 12:00 - 20:00 for the West orientation. The above switching times would produce a value of the average objective function that is within 5% of the maximum average value. Note that while the switching times are optimized with respect to the average value of the objective function which accounts for the integrated effect of all zones, this may, in some cases, result in slightly less than optimum operation of the windows in the individual zones. However, given that the difference in possible switching times is only one hour, the average value of the objective function can be used as a basis to determine the optimum switching times of the electrochromic window, rather than considering the effect of individual zones.

Table 4-2. Pareto feasible solutions when the integrated impact of all three zones is considered (OBJECTIVE = 0.8·ERR + 0.2·VQ).

	South	East	West
t_1	8:00 - 10:00	04:00	12:00 -14:00
t_2	14:00 - 16:00	10:00 - 12:00	20:00

4.6 CONCLUSIONS

In this chapter, a new electrochromic glazing switching strategy was developed based on a multi-objective model of two conflicting performance criteria, namely energy savings and visual quality. The model inherently accounts for the tradeoffs between the two performance criteria through the application of weighting coefficients that reflect the importance that is assigned to both objectives. The heart of the model consists of two functional values routines that were developed and coupled with the DOE-2.1E energy analysis program; these routines affect the DOE program's window thermal and daylighting calculations.

The effect of switching time of the experimental electrochromic window was studied for the South, East and West perimeter zones of the commercial building, and the Pareto feasible solutions were shown for a range of weighting coefficients. It was seen that is the visual quality is given a higher priority, the switching duration is limited to a few hours in order to maintain the window in the bleached state for much of the working day. If equal priority is assigned to both the energy and visual quality objectives, most or all switching times are feasible. The switching times become more restrictive as higher priority is given to the energy savings in order to maintain the window in the colored mode as long as possible.

An optimized switching strategy was also developed which automates the entire process of determining the optimum switching times of the electrochromic glazing for given weighting coefficients. The procedure is run by a batch file that creates the links between several FORTRAN programs that perform the required calculations, the various input and output data, and the DOE-2.1E energy analysis program. The automated strategy facilitates the selection of Pareto optimum switching times and provides a structure for future model enhancements.

CHAPTER 5
WHOLE-BUILDING ANALYSIS - COMPARISON OF WINDOW PERFORMANCE

The main objective of this chapter is to study the feasibility of utilizing electrochromic windows for commercial building applications. Specifically, the MICRO-DOE-2.1E energy analysis program was used to evaluate the impact of the experimental electrochromic window on the performance of the existing commercial building, and the results were compared to the whole-building performance due to the conventional windows and idealized electrochromic window that were described in Chapter 2. This evaluation was performed relative to the performance of double glazed clear windows [69]. In this work, building performance is characterized in terms of five main parameters: (i) visual quality, (ii) reduction in the heat extraction rate of the perimeter zones, (iii) reduction in total electricity consumption, and (iv, v) reduction in electricity consumption for fans and chillers. A further comparison of whole-building performance was made based on two different climates: Montreal, Quebec (Canada), and Phoenix, Arizona (U.S.A.).

5.1 DESCRIPTION OF THE TWO CLIMATES

Montreal is characterized by a hot and humid summer, while Phoenix is hot and dry. The direct normal solar irradiation, or solar intensity, provides an indication of the solar gain patterns for both climates, as shown in Table 5-1. Only solar data is presented in

Table 5-1, because it was shown in Chapter 3 that an electrochromic switching strategy based on incident solar radiation would be most effective for the building studied. Recall that it was also shown that there is no correlation between the outdoor temperature and the heat extraction rate of the building studied, while other variables for switching could not be implemented in practice.

Table 5-1. Direct normal solar intensity for Montreal and Phoenix. [3]

	Montreal		Phoenix	
	Direct Normal Solar Intensity (W/m^2)			
	Daily Total	Peak	Daily Total	Peak
May	11044	887	10712	903
June	11185	871	10608	884
July	10729	863	10376	878
August	10030	870	10046	894
September	9130	893	9790	934
Latitude	45° 28' N		33° 26' N	

Note: Solar data is based on a clear day.

From Table 5-1, it can be determined that the daily total solar intensity in Phoenix is generally from 3% to 5% lower, from May to July, than in Montreal, while the peak solar intensity is from 1.5% to 4.6% higher. This can be attributed to the relative position of the sun for the two climates. The solar altitude is the angle between the line to the sun and the horizontal; it is dependent on the local latitude, the solar declination and the apparent solar time as expressed by the following equation [3]:

$$\sin \beta = \cos L \cdot \cos \delta \cdot \cos H + \sin L \cdot \sin \delta \tag{5.1}$$

where β = solar altitude, degrees

L = local latitude, degrees North

δ = solar declination, i.e., the position of the sun at solar noon relative to the equatorial plane; $-23.45° \leq \delta \leq 23.45°$

H = hour angle = 0.25(number of minutes from local solar noon), degrees

The solar declination is expressed as:

$$\delta = 23.45 \cdot \sin\left(360 \cdot \frac{284 + n}{365}\right) \tag{5.2}$$

where n = day of year

Local time must be converted to Apparent Solar Time (AST) in order to calculate the hour angle:

$$AST = LST + ET + 4(LSM - LON) \tag{5.3}$$

where LST = local standard time

ET = equation of time (shown below), minutes

LSM = local standard time meridian, degrees

LON = local longitude, degrees West

$$ET = 9.87 \cdot \sin\left(4\pi \cdot \frac{n - 81}{364}\right) - 7.53 \cdot \cos\left(2\pi \cdot \frac{n-81}{364}\right) - 1.5 \cdot \sin\left(2\pi \cdot \frac{n-81}{364}\right) \tag{5.4}$$

Using the above equations, the solar altitude on June 21 at noon is approximately 78° at 33°N latitude in Phoenix and 68° at 44°N latitude in Montreal. Given that the sun is in a lower position in Montreal than in Phoenix, the incidence angle between the direct beam and the normal to the vertical surface is smaller and therefore slightly higher values of total direct normal solar intensity can generally be expected.

5.2 APPROACH OVERVIEW

The whole-building performance due to double glazed clear windows serves as a basis for comparison between the window types that were described in Chapter 2 (Table 2-7). The simulation of the energy performance of the large existing office building was first performed using the double glazed clear window (type A), and subsequently using the experimental electrochromic window (type G), the idealized electrochromic window (type H), and the remaining conventional window types (B to F, and J). Since one of the objectives was to evaluate the reduction of energy consumption for cooling, the simulation period was defined from May 1 to September 30, which corresponds to the present operation of the chillers. Outside this period, cooling is provided through "free-cooling". The assessment of the impact of electrochromic windows in the commercial building studied was evaluated only for perimeter zones, which is where windows could have a direct influence on building performance.

In this work, building performance is characterized in terms of five main parameters: (i) visual quality, (ii) reduction in the heat extraction rate of the perimeter zones, (iii) reduction in total electricity consumption, (iv) reduction in electricity consumption for fans, and (v) reduction in electricity consumption for chillers. The first two parameters are combined into the objective function as described in section 4.2, where for the present study OBJECTIVE = 0.8·ERR + 0.2·AV for all window types studied. Furthermore, recall that the perimeter zones are served by a separate central VAV system thereby allowing the impact of parameters (ii) to (v) to be isolated from the core zone.

Given that the visible transmittance at normal incidence of each conventional window type is always a constant value, equation 4.2 for determining the Access to Views can be rewritten as follows:

$$AV = \frac{\tau_{vis\_window}}{\tau_{vis\_double\_clear}} \qquad (5.1)$$

where τ_{vis_window} = visible transmittance, at normal incidence, of the conventional window.

Therefore, AV will be a constant value throughout the year for conventional windows, while for electrochromic windows, the value of AV depends on the state of the window and can therefore vary from day to day.

Since the building performance is determined relative to double glazed clear windows, equation 4.4 for determining the Extraction Rate Reduction can now be considered as follows:

$$ERR = \frac{ER_{double\_clear} - ER_{window}}{ER_{double\_clear}} \qquad (5.2)$$

where: ER_{double_clear} = Extraction rate of the perimeter zone when double glazed clear windows are used

ER_{window} = Extraction rate of the perimeter zone when the either conventional or electrochromic windows are used.

5.2.1 Switching times of the electrochromic windows

The switching times of the electrochromic windows that were used in the energy simulations were determined using the optimization procedure described in section 4.5. It is interesting to note the differences in feasible solutions of the switching times between the experimental and idealized electrochromic windows and the climate (Table 5-2). For the case where the extraction rate reduction and the visual quality are assigned a weighting coefficient of 0.8 and 0.2, respectively, the experimental electrochromic window in Montreal possesses the least number of combinations of Pareto feasible solutions. The range in switching times is therefore most restrictive for the experimental electrochromic window in Montreal. For the idealized electrochromic window located in Montreal, the range in both t_1 and t_2 increases by one hour for the South orientation, yet remains the same for the East and West orientations. The experimental electrochromic window in Phoenix has the broadest range in t_1 compared to the same window in Montreal, and also has the highest number of combinations of feasible solutions.

Table 5-2. Comparison of Pareto feasible solutions when the integrated impact of all three zones is considered, according to electrochromic window type and climate (OBJECTIVE = 0.8·ERR + 0.2·VQ).

Climate	Window type	Time	South	East	West
Montreal	Experimental EC (43 combinations)	t_1	8:00 - 10:00	4:00	12:00 -14:00
		t_2	14:00 - 16:00	10:00 - 12:00	20:00
	Idealized EC (65 combinations)	t_1	8:00 - 11:00	4:00	12:00 -14:00
		t_2	13:00 - 16:00	10:00 - 12:00	20:00
Phoenix	Experimental EC (89 combinations)	t_1	8:00 - 12:00	4:00	12:00 -15:00
		t_2	13:00 - 16:00	10:00 - 12:00	20:00

An explanation for the above observations may be found by examining some of the actual values of the parameters used to calculate the value of the objective function (Table 5-3). Comparing the experimental and idealized electrochromic windows in Montreal, it can be seen that the values of the calculated parameters are generally higher for the idealized electrochromic window. This can be attributed to the higher switching range in both visible transmittance and solar heat gain coefficient of the idealized window. Since the bleached state visible transmittance of the idealized electrochromic window is 38% higher than the bleached state visible transmittance of the experimental window, the access to views and daylight illuminance factors will both tend to be greater. Furthermore, since the switched state value of the solar heat gain coefficient of the idealized electrochromic window is 44% lower than the experimental window, greater energy savings can be expected for the idealized window.

Table 5-3. Comparison of parameters used to calculate the value of the objective function, according to electrochromic window type and climate.

Window	Zone	AV	DIF	VQ	ERR	OBJ
Experimental Electrochromic, Montreal	South	0.381	0.996	0.443	0.261	0.297
	East	0.534	0.992	0.580	0.241	0.309
	West	0.498	0.997	0.548	0.238	0.300
Idealized Electrochromic, Montreal	South	0.431	0.953	0.483	0.387	0.406
	East	0.755	0.996	0.780	0.367	0.449
	West	0.678	0.998	0.710	0.359	0.429
Experimental Electrochromic, Phoenix	South	0.324	1.000	0.391	0.179	0.222
	East	0.509	1.000	0.558	0.210	0.280
	West	0.462	1.000	0.516	0.217	0.277

Note - t_1 and t_2 are as follows for all cases:

South: 9:00 - 16:00 East: 4:00 - 11:00 West: 13:00 - 20:00

Comparing the performance of the experimental electrochromic window between Montreal and Phoenix, it can be seen from Table 5-3 that results for Phoenix tend to be lower than those for Montreal. The value of the objective function is from 9% to 31% lower (West and South orientations, respectively) for Phoenix than Montreal. This is largely due to the reduced energy savings (i.e., ERR) for a building located in Phoenix, which is expected since the direct solar intensity is lower in Phoenix than in Montreal. Two conclusions can be made based on the above observations: (i) the reduced energy savings in Phoenix may indicate that an electrochromic window with lower switched state solar properties than the experimental electrochromic window may be more appropriate for this climate in order to reduce the solar gains, or (ii) other factors, such as outdoor temperature, may be a larger contributor to the cooling load rather than solar gains, although switching of the electrochromic window does not affect conduction thermal gains. A re-examination of the driving variables for switching of the electrochromic window is required in order to account for the differences in climate and to verify the validity of the above conclusions. Furthermore, electrochromic windows whose U-value can be modified from the bleached state to the colored state also need to be studied.

The optimum switching times of the electrochromic windows that were used in the energy simulations were selected from the set of Pareto feasible solutions and are summarized in Table 5-4.

Table 5-4. Optimum switching times of the experimental and idealized electrochromic windows that were used in the simulation of whole-building performance.

Perimeter zone	Switching times	
	Start time (t_1)	Stop time (t_2)
South	9:00	16:00
East	4:00	11:00
West	13:00	20:00

5.3 RESULTS

5.3.1 Evaluation for Montreal

The window performance, considering the Montreal climate, based on both energy and visual quality objectives (i.e., the objective function) is compared in Figures 5-1 to 5-3 for the South, East and West perimeter zones of the commercial building. The experimental electrochromic window outperforms the double glazed clear window by approximately 52% to 54% on a seasonal basis. The better performance of the electrochromic window is due: (i) to a lower shading coefficient (0.44 for the electrochromic window compared with 0.83 for the double glazed clear window), and (ii) to the switching from bleached to colored mode. For this particular case, each factor improves the overall performance by approximately 26%.

The idealized electrochromic window (type H) outperforms all window types, followed by the Solarban/clear window (type J) and by the experimental electrochromic window. All three window types outperform the double glazed clear window by 50% to 61%. As explained in section 5.2.1, the broader switching range of the idealized window's solar-optical properties results in better energy and visual performance. Upon closer examination of the visual quality and extraction rate reduction components, it was determined that the Solarban/clear window results in 16% to 21% greater energy savings than the experimental electrochromic window; however, the visual quality is from 38% to 54% lower than the electrochromic window. Since the extraction rate reduction is given the higher priority in the objective function, with a weighting factor of 0.8, the Solarban/clear window results in a higher value of the objective function. Furthermore, although the Solarban/clear window possesses the same solar heat gain properties (i.e., SC and SHGC) as the colored state of the experimental electrochromic window, the fact that solar-optical properties of the electrochromic window are variable, results in comparatively lower energy savings. This is attributed to the bleached state properties of the electrochromic window, where the values of SC and SHGC are higher than those for the Solarban/clear window. Hence, when the electrochromic window is in the bleached state, the solar gains are higher than those due to the Solarban/clear window and the corresponding energy savings are lower.

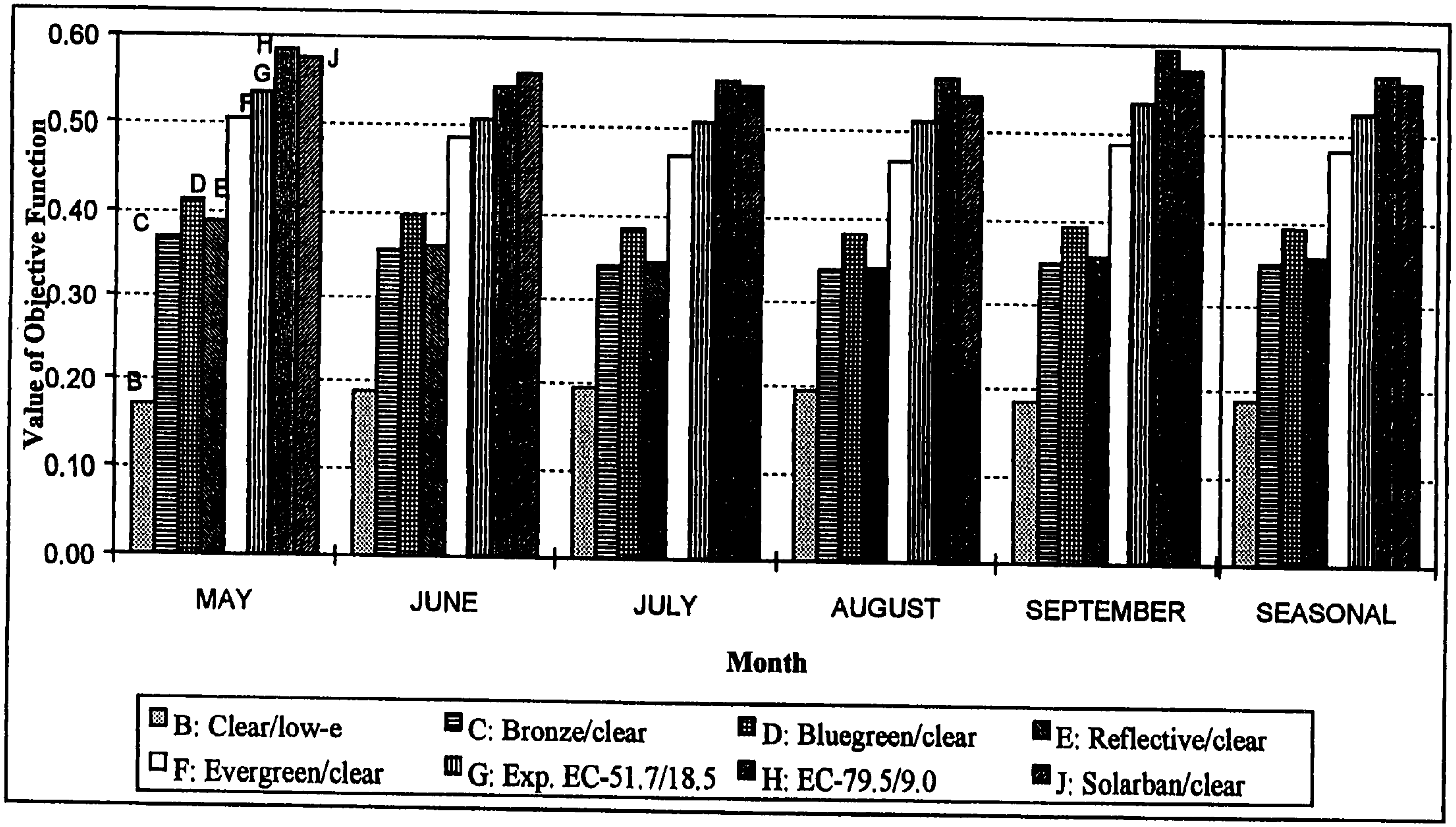

Figure 5-1. **Comparison of the overall energy and visual performance of the window types studied relative to the double glazed clear window for the South perimeter zone, Montreal climate (OBJECTIVE = 0.8·ERR + 0.2·VQ).**

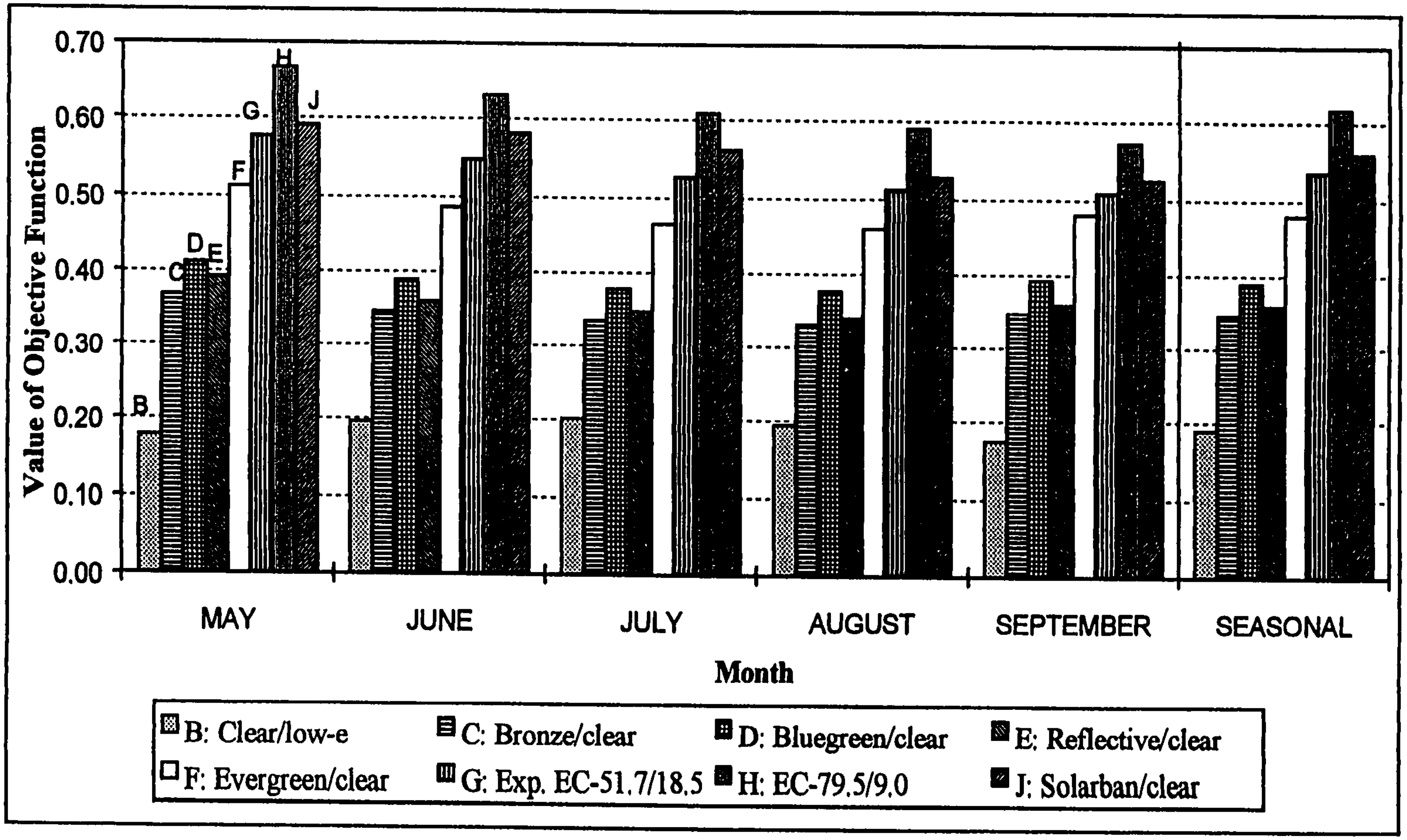

Figure 5-2. **Comparison of the overall energy and visual performance of the window types studied relative to the double glazed clear window for the East perimeter zone, Montreal climate (OBJECTIVE = 0.8·ERR + 0.2·VQ).**

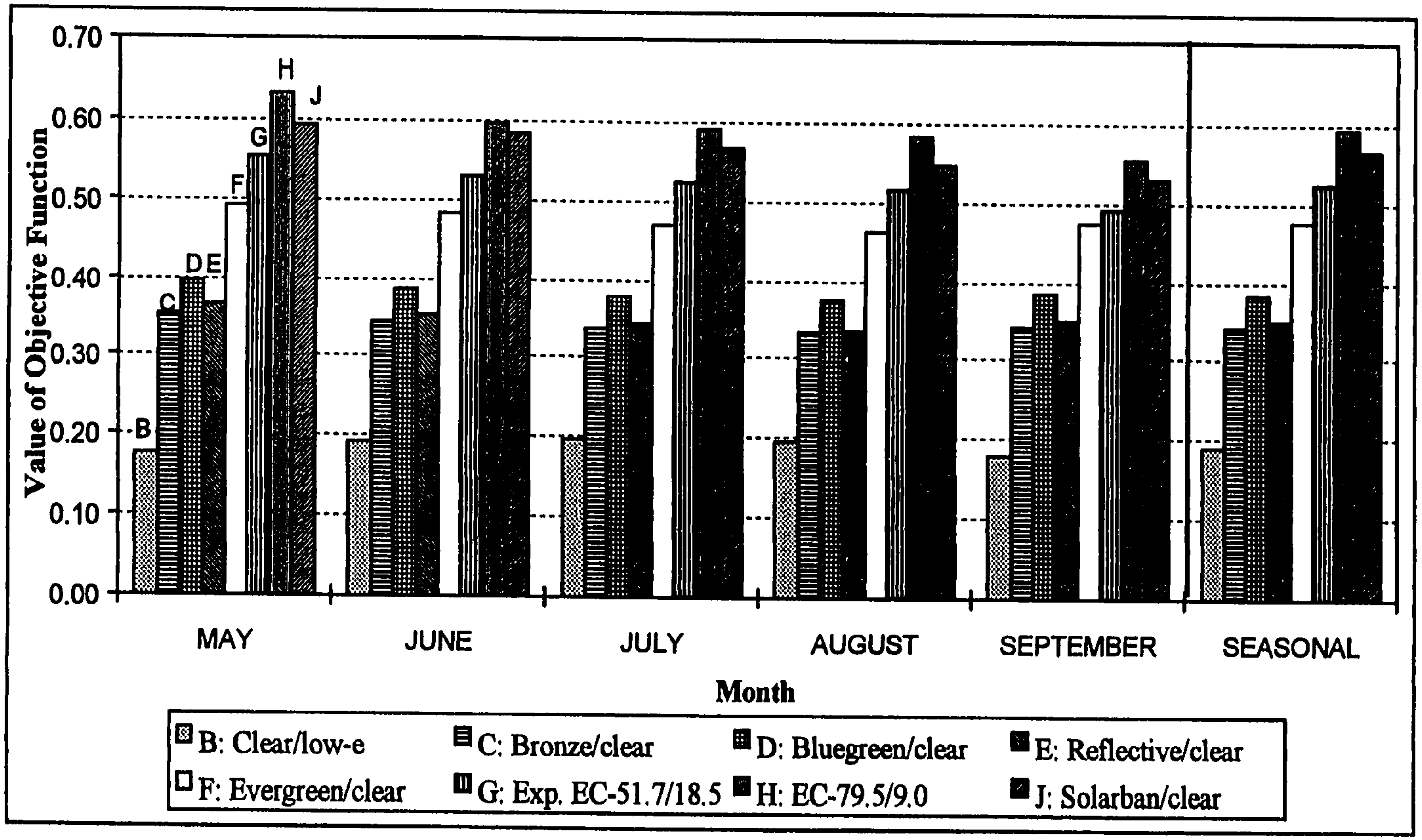

Figure 5-3. **Comparison of the overall energy and visual performance of the window types studied relative to the double glazed clear window for the West perimeter zone, Montreal climate (OBJECTIVE = 0.8·ERR + 0.2·VQ).**

The savings in electricity consumption relative to the double glazed clear window are shown in Figures 5-4 to 5-6. When the experimental and idealized electrochromic windows are used, the electricity consumption for the VAV fans is reduced by 18%, while the seasonal electricity consumption of the chillers serving the perimeter zones can be reduced by 42%, and the total electricity consumption of the perimeter zones is reduced by 24%. In terms of fan electricity consumption, the experimental electrochromic window outperforms all other window types, which generally reduce the consumption by 12% to 15%. The use of Solarban/clear windows reduces the seasonal chiller electricity consumption by 54% thereby outperforming all other window types. The use of electrochromic windows results in slightly lower chiller energy savings compared with the Solarban/clear window; however, the electrochromic windows offer a significantly better performance advantage in terms of the visual quality.

Since the Solarban/clear window possesses the same solar heat gain properties as the experimental electrochromic window in the colored state, it is expected that the energy performance for both windows would be similar, with the Solarban/clear window having a slight performance advantage. However, in terms of fan electricity consumption, the Solarban/clear window results in lower energy savings than the experimental electrochromic window, particularly for the months of May and September (Figure 5-4). The reason for this discrepancy can be determined by examining hourly values of the zone temperature, extraction rate and fan air flow rate for a typical day, as shown in Tables 5-5 and 5-6. The zone temperature set-point for cooling is 22.8°C ± 1.1°C, while the thermostat setting for heating is 20.0°C ± 1.1°C. Although, the fans are scheduled to operate between 7:00 and 23:00, they will also operate when the zone temperature falls below the heating set-point range or above the cooling set-point range. It can be seen from Table 5-5 that when Solarban/clear windows are used, the zone temperature falls below the thermostat setting for heating from 1:00 to 23:00. Since the SHGC of the Solarban/clear window is quite low at a value of 0.17, the zone does not benefit from sufficient solar gains that would otherwise raise the zone temperature. Therefore, the system fans must be turned on. For the case of the experimental electrochromic window (Table 5-6), given that the state of the window alternates between the bleached state (SHGC= 0.38) and the colored state (SHGC=0.16) depending on the hour and incident solar radiation, solar gains will be admitted into the zone to a greater extent than with Solarban/clear windows. The zone temperatures are therefore within the prescribed limits throughout the day. Fan energy consumption is therefore higher when Solarban/clear windows are used compared with the electrochromic window.

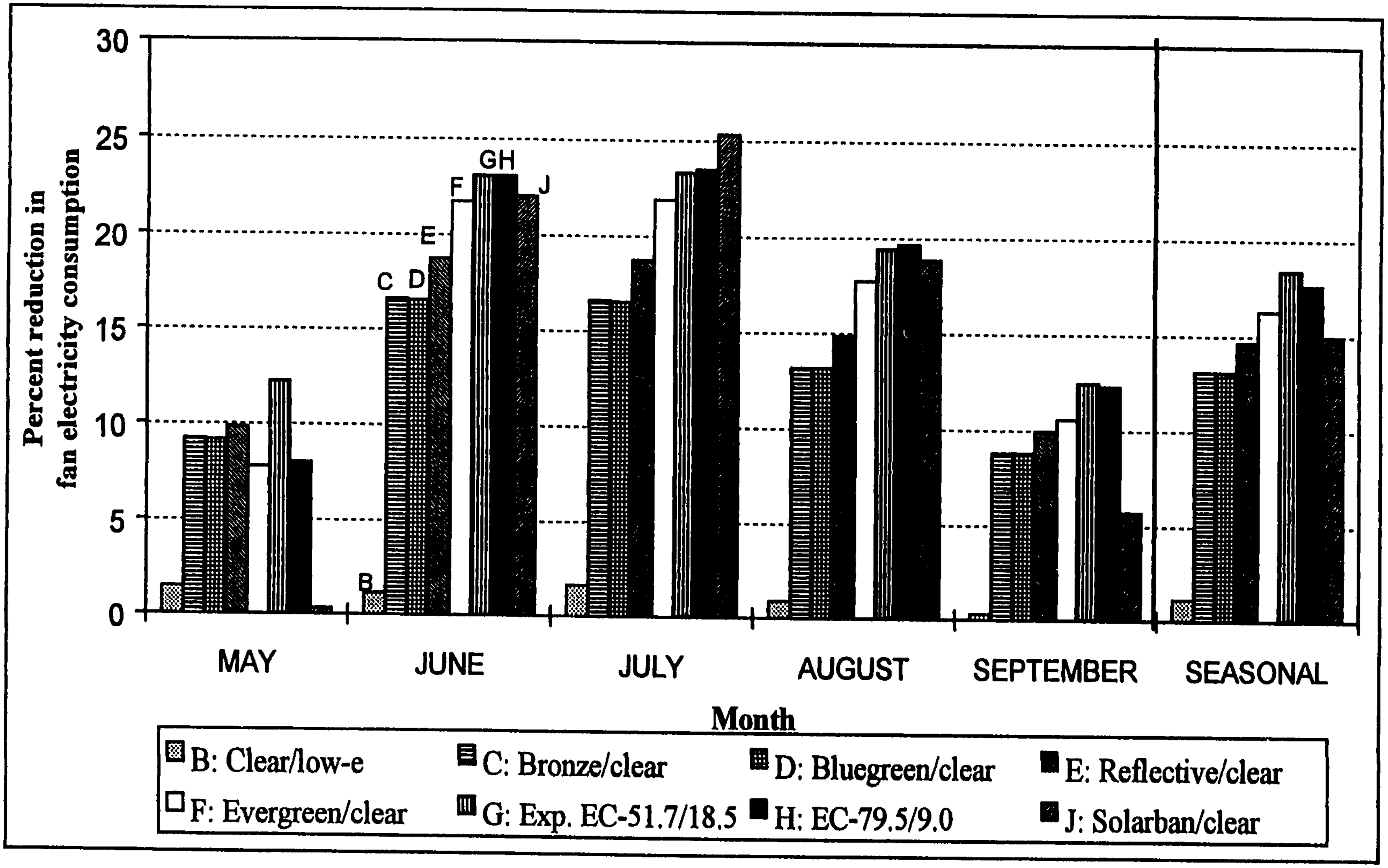

Figure 5-4. Percent reduction in fan electricity consumption of the perimeter zones due to the windows studied, relative to double glazed clear windows, Montreal climate.

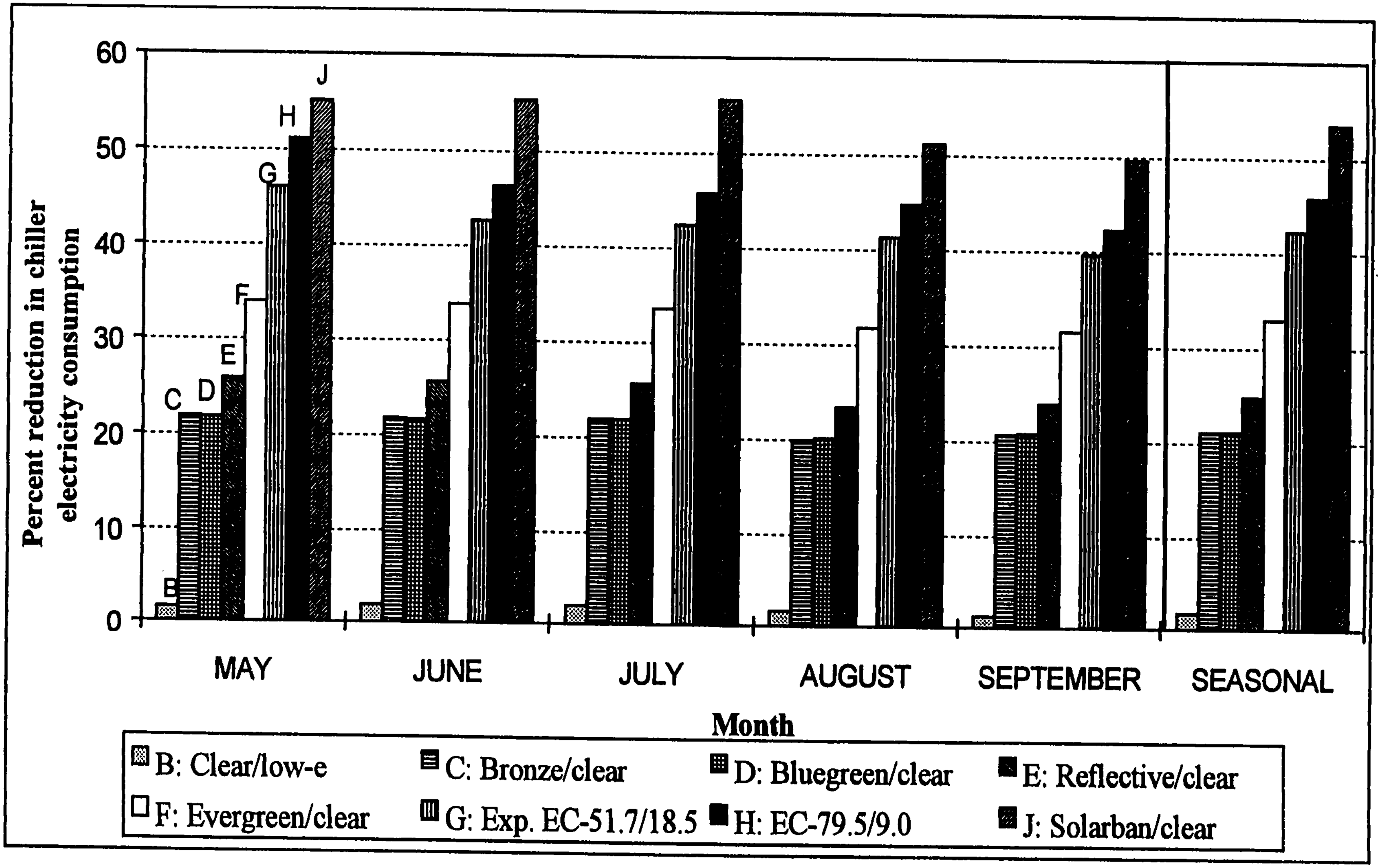

Figure 5-5. Percent reduction in chiller electricity consumption of the perimeter zones due to the windows studied, relative to double glazed clear windows, Montreal climate.

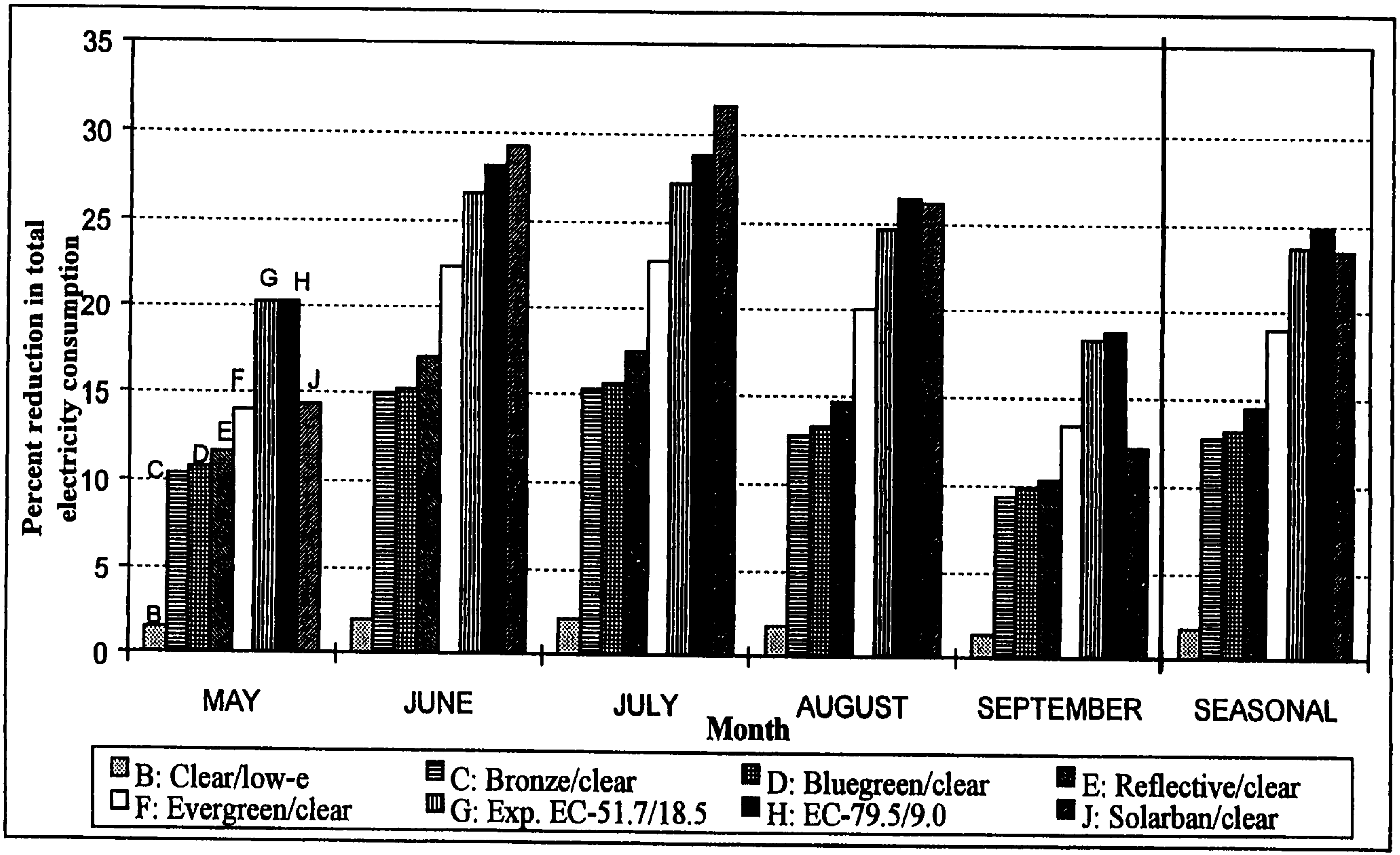

Figure 5-6. **Percent reduction in total electricity consumption of the perimeter zones due to the windows studied, relative to double glazed clear windows, Montreal climate.**

Table 5-5. Hourly extraction rate (South zone) and total perimeter fan electricity consumption on May 16, when Solarban/clear windows are used.

	Solarban/clear window			
Date & hour	Zone temp. (°C)	Extraction rate (W)	Air flow rate (L/s)	Fan electricity consumption (kWh)
516 1	17.5	1460.52	4241.44	39.33
516 2	17.1	1306.05	4241.44	39.33
516 3	16.7	1159.80	4241.44	39.33
516 4	16.4	1078.61	4241.44	39.33
516 5	16.1	956.39	4241.44	39.33
516 6	15.9	947.89	4241.44	39.33
516 7	15.8	965.18	4241.44	39.33
516 8	16.1	1041.97	4241.44	39.33
516 9	16.8	1158.33	4241.44	39.33
51610	17.7	1342.40	4320.24	39.33
51611	18.6	1542.88	4290.04	39.33
51612	19.6	1751.57	4241.44	39.33
51613	20.4	1959.37	4241.44	39.33
51614	21.1	2120.58	4325.44	39.33
51615	21.1	2175.10	4314.11	39.33
51616	20.9	2150.77	4487.77	39.33
51617	20.6	2084.82	5234.79	39.33
51618	20.4	2008.03	5534.44	39.33
51619	20.4	1991.61	4841.22	39.33
51620	20.3	1990.15	4447.19	39.33
51621	19.9	1945.30	4288.63	39.33
51622	19.4	1861.48	4241.44	39.33
51623	19.6	802.80	4241.44	39.33
51624	19.7	0.00	0.00	0.00
Total	--	35802	101223	905

Table 5-6. Hourly extraction rate (South zone) and total perimeter fan electricity consumption on May 16, when experimental electrochromic windows are used.

	Experimental electrochromic window			
Date & hour	Zone temp. (°C)	Extraction rate (W)	Air flow rate (L/s)	Fan electricity consumption (kWh)
516 1	20.4	0.00	0.00	0.00
516 2	20.2	0.00	0.00	0.00
516 3	20.1	0.00	0.00	0.00
516 4	19.9	0.00	0.00	0.00
516 5	19.8	0.00	0.00	0.00
516 6	19.7	0.00	0.00	0.00
516 7	18.9	1785.57	4260.79	39.33
516 8	19.3	1792.89	4394.80	39.33
516 9	19.8	1910.72	4967.22	39.33
51610	20.6	2060.79	5008.75	39.33
51611	21.2	2200.01	4737.88	39.33
51612	22.0	2343.63	4620.37	39.33
51613	22.3	3057.03	4733.63	39.33
51614	22.3	3686.90	5430.63	39.33
51615	22.3	3400.25	6274.85	39.33
51616	22.3	2834.28	6781.67	39.33
51617	22.1	2393.75	6368.29	39.33
51618	21.8	2337.47	6435.30	39.33
51619	21.7	2297.61	5630.71	39.33
51620	21.6	2282.66	5206.94	39.33
51621	21.2	2237.23	4466.06	39.33
51622	20.7	2148.42	4241.44	39.33
51623	21.4	0.00	0.00	0.00
51624	21.2	0.00	0.00	0.00
Total	--	38769	83559	629

Note that there is no significant difference in performance between the idealized and experimental electrochromic windows in terms of energy savings (Figures 5-4 to 5-6) and for the stated objective function (Figures 5-1 to 5-3). The main differences occur with respect to the visual quality, where the idealized electrochromic window outperforms the experimental window by 9% for the South perimeter zone, 34% in the East zone, and 30% in the West zone. However, these performance differences are not evident in the overall value of the objective function since: (i) the area-weighted average performance of all three zones is considered (as described in section 4.5), and (ii) the extraction rate reduction is the dominant factor in the value of the objective function since the visual quality is given a relatively lower priority (0.2). Therefore, for the particular case studied, it can be concluded that it may not be cost-effective to improve the solar-optical properties of the experimental window for what would amount to a small performance improvement.

5.3.2 Evaluation for Phoenix

The seasonal performance, in Phoenix, of three window types relative to the performance of the double glazed clear window, is presented in Figures 5-7 and 5-8 based on the optimization objective function and the savings in electricity consumption, respectively. The following three window types were selected for this evaluation: (i) reflective/clear (window type E), (ii) experimental electrochromic (type G), and (iii) Solarban/clear (type J). Considering the objective function (Figure 5-7), the experimental electrochromic window outperforms the double glazed clear window by approximately 45% to 50% on a seasonal basis, which is slightly less than the performance in Montreal (i.e., 52% to 54%).

This difference in performance between the two climates is due to the reduced savings in the extraction rate in Phoenix. Note that the experimental electrochromic window slightly outperforms the Solarban/clear window, whereas the reverse is true for the Montreal climate.

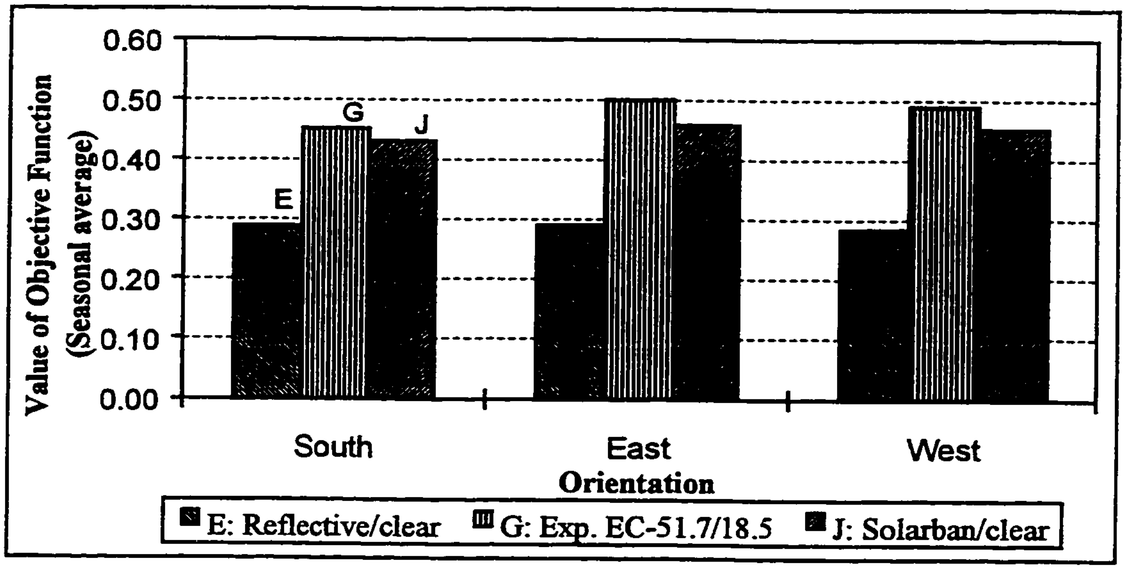

Figure 5-7. Comparison of the overall energy and visual performance of the window types studied relative to the double glazed clear window, Phoenix climate (OBJECTIVE = 0.8·ERR + 0.2·VQ).

In terms of savings in the electricity consumption related to the perimeter zones (Figure 5-8), the use of the experimental electrochromic window results in a 37% reduction in chiller electricity consumption compared with the double glazed clear window and a 31% reduction in both fan electricity consumption and total electricity consumption. There is a very small performance difference between the electrochromic window and the Solarban/clear window.

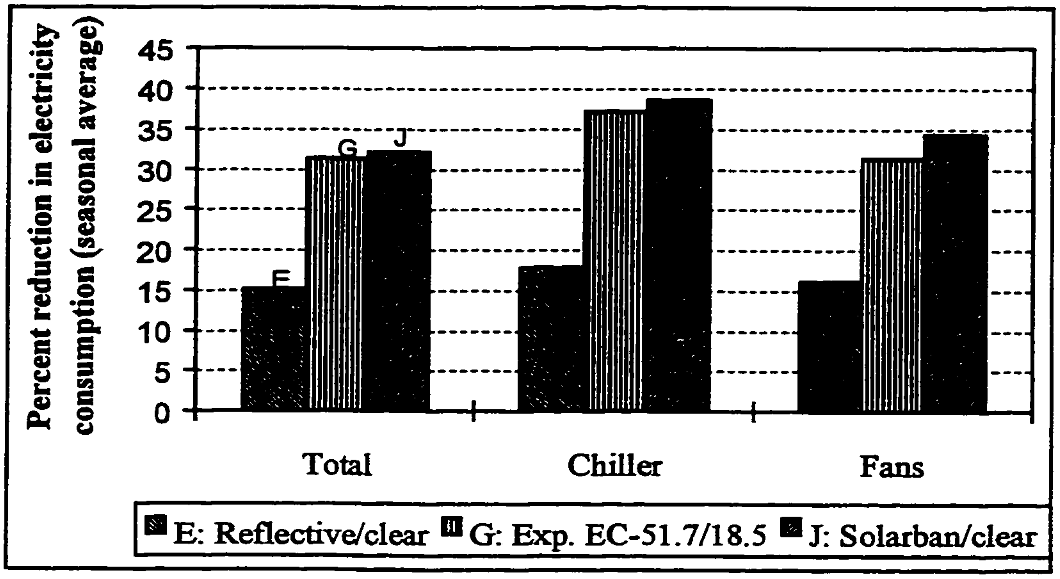

Figure 5-8. Percent reduction in electricity consumption of the perimeter zones due to three window types relative to the double glazed clear window, Phoenix climate.

5.4 CONCLUSIONS

The impact of the experimental electrochromic windows on the performance of the commercial building studied was assessed in this chapter. The results were compared with the performance due to several conventional window types as well as an idealized electrochromic window. The impact of two different climates was also studied, namely, Montreal, Quebec (Canada), and Phoenix, Arizona (U.S.A.).

It was found that the experimental electrochromic window had the least number of Pareto feasible solutions of the switching times for the Montreal climate, while the range in switching times increases by 51% for the idealized electrochromic window. This difference is due to the wider range of solar-optical properties of the idealized window;

however, an important observation in this study is that there is no significant performance difference between the electrochromic windows studied for the Montreal climate. This conclusion indicates that further expensive improvements in the solar-optical properties of the experimental electrochromic window are not required in order to increase the energy and visual performance.

The experimental window in Phoenix resulted in the least restrictive combinations of switching times. Savings in the extraction rate are diminished in this climate, indicating that the properties of the experimental electrochromic window may require improvements. Further research is required to examine the driving variables for switching in this climate and determine the optimum properties of the window.

The results of this study show that electrochromic windows have a significant potential to reduce energy consumption of commercial buildings in both climates. Considering the Montreal climate, in terms of the objective function, the experimental electrochromic window outperformed the double glazed clear window by over 50% and compares favorably with the performance of the idealized window and the Solarban/clear window. The experimental window also substantially reduces the chiller electricity consumption in the perimeter zones by 42%. While the performance of the window in the Phoenix climate is slightly below the performance in Montreal, the performance difference compared with the Solarban/clear window is negligible.

The use of electrochromic windows in commercial buildings can be recommended for both climates as they result in significant energy savings compared to the majority of conventional window types. They have the added important benefit of improving visual quality. Furthermore, unlike conventional windows, the properties of the electrochromic window can be switched to suit a variety of conditions and seasons, such that they can always be operated to maximize energy reduction and visual quality throughout the year.

CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

The research work presented in this thesis exposed the main factors that influence the performance of electrochromic windows in commercial buildings. The need for new approaches and tools to optimize the switching operation of electrochromic glazings was identified and a new model was developed.

6.1 GENERAL CONCLUSIONS

The literature review in the field of electrochromic coatings revealed that research efforts have historically primarily been aimed at improving the materials that compose the electrochromic coating to ensure its long-term durability and technical performance. While a major application of these coatings is in smart windows for buildings, comparatively fewer studies exist on the assessment of their impact on building energy performance. In these studies, researchers have used simplified existing models of control strategies available in the DOE-2.1E program to establish energy performance thresholds of electrochromic windows. However, guidelines for the selection of an appropriate control strategy and its set-points for switching have not been developed. Furthermore, the complex issue of evaluating the performance of electrochromic windows based on combined multiple and conflicting performance criteria, such as reduction of energy consumption and improvement of visual quality, has not been addressed by researchers. Consequently, no models and tools exist to address multiple performance criteria, demonstrate the trade-offs between these conflicting criteria, and optimize the switching of the electrochromic glazing.

The first part of the research work presented in this thesis consisted of undertaking a detailed evaluation of the performance of electrochromic glazings. The starting point for this work was the spectral transmittance and reflectance data of an experimental electrochromic coating. The APPLIED FILM LAMINATOR program was used to model a 6 mm glazing which incorporates the electrochromic coating. By studying the corresponding solar-optical properties of the electrochromic glazing, it was possible to classify the coating as a broad-band electrochromic whose properties switch from the bleached state to the colored state over the entire solar spectrum. The coating was further classified as an absorbing electrochromic.

The WINDOW 4.1 program was then used to evaluate the indices that characterize the performance of window systems. A total of ten double glazed windows were defined, including one which incorporates the experimental electrochromic glazing, seven conventional window types and two idealized electrochromic windows. A relative comparison of the performance of these window systems was performed based on indices that are independent of the interactions that occur between building systems. Although it was shown that electrochromic windows generally outperform conventional windows, it was determined that the dynamic operation of the window and the switching strategy are important factors that influence its overall performance. A deeper basis for performance analysis of electrochromic windows was therefore explored.

An in-depth critical analysis of existing control strategies that are currently only available in DOE-2.1E, was performed by studying the relationships between the driving variable for switching, and the controlled variable, such as solar gains and the extraction rate. The DOE program was used to evaluate the effect of several switching strategies on the extraction rate of the perimeter zones of an existing commercial building located in Montreal. A strategy based on outdoor drybulb temperature would not be appropriate for the building studied as it was shown that there was no correlation between this variable and the extraction rate. The largest component of the extraction rate is due to solar gains and it was determined that a control strategy based on incident solar radiation would be most appropriate for the building studied.

Two main conclusions emerged from the first part of the study: (i) the selection of an appropriate switching control strategy must be based on careful study of the relationships between the glazing properties (transmittance, solar heat gain coefficient), the driving variables for switching, and the building characteristics (thermal mass, size, internal gains, window-to-wall ratio), and (ii) the optimum switching duration of the electrochromic glazing is an important factor that influences the overall performance.

The second objective of the research work was to develop a new model to simulate the switching control of electrochromic glazings. The present capabilities of the DOE program were expanded using the Functional Values approach. The use of this approach to develop electrochromic glazing control strategies was pioneered in this research. Two functions were developed to control the glazing's switching time; these functions were coupled with the DOE-2.1E program using the Functional Values approach. Since electrochromic windows will affect both building energy consumption and visual comfort, the optimization of the switching time was formulated as a multi-objective model with two conflicting objectives. The Pareto optimum solutions were shown for different weighting coefficients applied to the energy performance and quality of view demonstrating the trade-offs between the two objectives. An optimized switching strategy was developed which automates the process of determining the optimum switching times of the electrochromic glazing for given weighting coefficients.

The optimizing procedure described above was applied to evaluate the impact of the experimental electrochromic window on the whole-building performance of the commercial building for two climates, Montreal, Canada, and Phoenix, U.S.A. The results were compared to the whole-building performance due to the conventional window types. The results showed that electrochromic windows could significantly reduce the electricity consumption (total, chillers and fans) in the perimeter zones.

6.2 CONTRIBUTIONS

The contributions of the research work presented in this thesis are summarized below:

Characterization of the solar-optical properties of a real electrochromic coating

A step-by-step approach to model the solar-optical properties of an experimental electrochromic coating using the APPLIED FILM LAMINATOR program was presented. The solar-optical properties of a glazing that incorporates the coating were characterized and the coating was classified as a broad-band absorbing electrochromic.

Performance analysis of electrochromic and conventional window types based on global performance indices

Graphs of global performance indices (U-value, visible transmittance, shading coefficient, solar heat gain coefficient) for ten window types were presented, comparing the expected performance of the experimental and idealized electrochromic windows relative to conventional window types. The graphs show how the switching range of the solar-optical properties of the electrochromic windows can affect their performance.

Critical review of existing models of electrochromic glazing control strategies

An in-depth analysis of existing control models available in DOE-2.1E was performed, based on a systematic study of the driving variables for switching and their impact on the extraction rate of a the perimeter zones of an existing commercial building. The evaluation revealed the main issues related to their applicability to the particular building, the feasibility of their implementation and determination of set-points.

<u>Development of a new model to optimize the switching time of the electrochromic glazing using the Functional Values approach</u>

Two functions were developed to provide a structure to change the state of the electrochromic glazing based on the time of day. The use of the Functional Values feature of DOE-2.1E for this purpose was pioneered in this research. The optimization of the switching time was modeled as a multi-objective problem with two conflicting objectives: extraction rate reduction and visual quality. A performance parameter, access to views, was defined. Curves of Pareto optimum solutions for combinations of switching times for different weighting coefficients applied to the performance objectives clearly demonstrate the trade-offs between the two conflicting objectives. This is the first electrochromic switching model in DOE-2.1E that addresses multiple performance criteria and the trade-offs between them.

A major advantage of this model is that it provides a framework for the introduction of more elaborate switching control strategies and optimization procedures. Furthermore, the objective function defining the overall performance of the electrochromic window can be easily expanded to include other criteria.

<u>Development of a procedure to automate the optimization process</u>

The automated process includes the developed switching functions and a series of FORTRAN programs to retrieve and process DOE results as well as perform the optimization. A batch file links the programs with the DOE-2.1E energy simulations.

Evaluation of the feasibility of using electrochromic windows for commercial building applications

The switching model that was developed was applied to determine the whole building performance when the experimental electrochromic window is used. A comparison to conventional window types was made. A further comparison of whole-building performance was made based on two climates.

6.3 OPPORTUNITIES FOR FURTHER RESEARCH

Research on the performance of electrochromic windows is still young and there are many opportunities to explore, particularly in the area of control strategies for switching of the glazing properties. Some suggestions for improvements to the model presented in this thesis and for further work are presented below.

Improvements to the switching model developed in this work

1. Examine the impact of intermediate switching. The work presented in this thesis assumed that the electrochromic glazing was only switched between two states: bleached and colored. Intermediate switching between these two states was not permitted. Allowing intermediate switching would increase the level of complexity of the optimization, as the solar-optical properties of the window become important factors in the overall objective function.

2. <u>Customize the optimized switching strategy to the winter season.</u> The model presented in this work was developed and applied to optimize the switching operation of the electrochromic window during the summer season (i.e., cooling season). In order to customize the model for the winter, or heating season, the performance objectives would be different. Namely, the objective would be to maximize the solar gains to heat the perimeter zones (or minimize heating energy consumption). This would require that the glazing remain in its bleached state for longer periods of time; however, minimizing glare would be the conflicting performance objective in this case.

3. <u>Incorporate glare as a criteria in the definition of visual quality.</u> The area of visual quality assessment of windows is beginning to receive research attention. Glare control is one aspect of visual quality. A term for glare could be included in the equation for visual quality that was developed in this work, and could be in the form of a penalty function for when glare levels are exceeded in the space.

4. <u>Perform a sensitivity analysis of the weighting coefficients that are used in the visual quality objective function.</u> In the present work, the access to views component of the visual quality was given a weight of 0.9 and the Daylight Illuminance Factor was given a weight of 0.1. It can be noted from Table B-1 in Appendix B that the value of the Daylight Illuminance Factor is virtually 1.0 for all cases of switching times as well as for the bleached and colored states of the electrochromic glazing. Both the glazing's visible transmittance and the window size will influence the value of DIF. Since the visible transmittance of the experimental electrochromic window is low in the colored state, one

would expect a lower value of DIF. However, given that the window-to-wall ratio of the building studied is quite high at 0.62, a greater quantity of light is transmitted into the space and daylight saturation likely occurs. The DIF was therefore assigned a weight of 0.1 in order to reduce the factor's influence on the Visual Quality. It would be more appropriate to perform a sensitivity analysis to assess the influence of the weighting factors on the results. Furthermore, the daylighting performance should be correlated with window size.

5. Improve the switching time algorithm. At present, the switching time optimization algorithm employs the enumeration approach to select the switching time for the next iteration. This is an inefficient process that can be improved by exploring the use of more efficient search techniques such as genetic algorithms.

6. Replace the basis for switching in the optimization algorithm with other driving variables. Presently, the switching of the electrochromic window is based on the time of day in the developed algorithm. More complex conditions for switching should be explored, as should other driving variables that can be measured in practice such as incident solar radiation.

Other areas to explore

7. Extend the whole building performance analysis of electrochromic windows to other building types and conditions. In this work, the feasibility of using electrochromic

windows was studied for a large commercial building where the core has a greater impact on overall energy consumption. Other building sizes and conditions should be examined. For example, in narrow plan office buildings the envelope would have a greater impact on the thermal interactions and on the heating and cooling loads. Relationships between the building size, climate, internal load level, glazing properties, window-to-wall ratio, and driving variables for switching can be developed such that these relationships can provide quick, simple rules of thumbs for designers to estimate the impact of electrochromic windows for their building type and climate.

8. Re-evaluate energy code requirements for window size. Most energy codes impose a limit on window size; however, given that thermal impact of electrochromic windows can be dynamically modified, larger window sizes may be acceptable without limiting the performance. The current limits on window size should be re-evaluated.

9. Explore the use of predictive control strategies. To date, the controls aspect (hardware, algorithms) of electrochromic windows has largely been unexplored. This is consequently the most significant area where research opportunities can flourish. Adaptive, learning control algorithms could be developed that can learn the characteristics of building conditions and operation and switch the electrochromic glazing according to the most appropriate driving variable.

10. Validate new control algorithms using an outdoor test cell or environmental chamber. This in fact represents the logical next step in studying the implementation of

various control algorithms and validating their performance under real conditions. Pennisi et al. [70] are using an outdoor test cell to measure the daylight performance and thermal conductance of an experimental electrochromic window. The authors however do not elaborate on the switching strategy they use to control the window.

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APPENDIX A

FUNCTIONAL VALUES ROUTINES

```
FUNCTION  NAME = SW_STH ..

ASSIGN

    IMO = IMO
    IDAY = IDAY
    IHR = IHR
    ISCDAY = ISCDAY
    QDIR = QDIR
    SWFAC = SWFAC ..

CALCULATE ..

    SWFAC = 1.0
    ##include  south.tim
    IF ((IMO.LT.5).OR.(IMO.GT.9)) GO TO 9
        IF ((ISCDAY.LT.2).OR.(ISCDAY.GT.6)) GO TO 14
        IF (QDIR.LE.0.0001) GO TO 12
            IF ((IHR.GE.T1).AND.(IHR.LE.T2)) SWFAC = 0.0

12        CONTINUE
14        CONTINUE

9   CONTINUE

    END

END-FUNCTION ..
```

```
FUNCTION  NAME = STH_ILL ..

ASSIGN

     FNTYPE = FNTYPE
     IMO = IMO
     IDAY = IDAY
     IHR = IHR
     ISCDAY = ISCDAY
     RDIR = RDIR
     VTS = VIS-TRANS-SEL
     VT = VIS-TRANS
     MWIPRPSW = MWIPRPSW
     SWFAC = SWFAC ..

CALCULATE ..

     IF (FNTYPE.NE.4) RETURN

     SWFAC = 1.0
     ##include  south.tim
     IF ((IMO.LT.5).OR.(IMO.GT.9)) GO TO 20
          IF ((ISCDAY.LT.2).OR.(ISCDAY.GT.6)) GO TO 22
          IF (RDIR.LE.0.0001) GO TO 23
               IF ((IHR.GE.T1).AND.(IHR.LE.T2)) SWFAC = 0.0
               VTSW = ACCESS(MWIPRPSW+147)
               VTS = SWFAC*VT + (1.0 - SWFAC)*VTSW

23          CONTINUE


22          CONTINUE

20   CONTINUE

     END

END-FUNCTION ..
```

APPENDIX B

PARETO FEASIBLE SOLUTIONS FOR THE SOUTH PERIMETER ZONE

Table B-1. Details of the components of the objective function and Pareto feasible solutions of optimum switching times for different values of the weighting coefficients.

t1	t2	AV	DIL	VQ	ERR	Overall objective function: OBJECTIVE = w1*ERR + w2*VQ										
						s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11
8	16	0.326	0.998	0.393	0.258	0.393	0.380	0.366	0.353	0.339	0.325	0.312	0.298	0.285	0.271	0.258
8	15	0.368	0.999	0.431	0.244	0.431	0.412	0.394	0.375	0.356	0.337	0.319	0.300	0.281	0.263	0.244
8	14	0.410	0.999	0.469	0.212	0.469	0.443	0.418	0.392	0.366	0.341	0.315	0.289	0.264	0.238	0.212
8	13	0.450	0.999	0.505	0.173	0.505	0.472	0.438	0.405	0.372	0.339	0.306	0.273	0.240	0.206	0.173
8	12	0.490	0.999	0.541	0.128	0.541	0.499	0.458	0.417	0.376	0.334	0.293	0.252	0.211	0.169	0.128
8	11	0.530	0.999	0.576	0.082	0.576	0.527	0.478	0.428	0.379	0.329	0.280	0.231	0.181	0.132	0.082
8	10	0.567	0.999	0.610	0.044	0.610	0.554	0.497	0.441	0.384	0.327	0.271	0.214	0.158	0.101	0.044
8	9	0.607	0.999	0.646	0.014	0.646	0.583	0.520	0.457	0.393	0.330	0.267	0.204	0.140	0.077	0.014
9	16	0.366	0.999	0.429	0.245	0.429	0.411	0.392	0.374	0.355	0.337	0.319	0.300	0.282	0.263	0.245
9	15	0.408	1.000	0.467	0.231	0.467	0.443	0.420	0.396	0.373	0.349	0.325	0.302	0.278	0.255	0.231
9	14	0.450	1.000	0.505	0.199	0.505	0.474	0.444	0.413	0.383	0.352	0.322	0.291	0.260	0.230	0.199
9	13	0.490	1.000	0.541	0.160	0.541	0.503	0.465	0.427	0.388	0.350	0.312	0.274	0.236	0.198	0.160
9	12	0.530	1.000	0.577	0.115	0.577	0.530	0.484	0.438	0.392	0.346	0.300	0.253	0.207	0.161	0.115
9	11	0.569	1.000	0.612	0.069	0.612	0.558	0.504	0.450	0.395	0.341	0.287	0.232	0.178	0.124	0.069
9	10	0.607	1.000	0.646	0.031	0.646	0.585	0.523	0.462	0.400	0.339	0.277	0.216	0.154	0.093	0.031
10	16	0.406	0.999	0.465	0.215	0.465	0.440	0.415	0.390	0.365	0.340	0.315	0.290	0.265	0.240	0.215
10	15	0.448	1.000	0.503	0.200	0.503	0.473	0.442	0.412	0.382	0.352	0.321	0.291	0.261	0.231	0.200
10	14	0.490	1.000	0.541	0.169	0.541	0.503	0.466	0.429	0.392	0.355	0.317	0.280	0.243	0.206	0.169
10	13	0.530	1.000	0.577	0.129	0.577	0.532	0.487	0.442	0.398	0.353	0.308	0.263	0.219	0.174	0.129
10	12	0.569	1.000	0.612	0.084	0.612	0.560	0.507	0.454	0.401	0.348	0.295	0.243	0.190	0.137	0.084
10	11	0.609	1.000	0.648	0.038	0.648	0.587	0.526	0.465	0.404	0.343	0.282	0.221	0.160	0.099	0.038

Table is continued on following page.

Table B-1. Details of the components of the objective function and Pareto feasible solutions of optimum switching times for different values of the weighting coefficients. (CONTINUED)

t1	t2	AV	DIL	VQ	ERR	Overall objective function: OBJECTIVE = w1*ERR + w2*VQ										
						s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11
11	16	0.443	0.999	0.499	0.177	0.499	0.467	0.435	0.402	0.370	0.338	0.306	0.274	0.241	0.209	0.177
11	15	0.485	1.000	0.537	0.163	0.537	0.499	0.462	0.425	0.387	0.350	0.312	0.275	0.237	0.200	0.163
11	14	0.527	1.000	0.575	0.131	0.575	0.530	0.486	0.441	0.397	0.353	0.308	0.264	0.219	0.175	0.131
11	13	0.567	1.000	0.611	0.091	0.611	0.559	0.507	0.455	0.403	0.351	0.299	0.247	0.195	0.143	0.091
11	12	0.607	1.000	0.646	0.046	0.646	0.586	0.526	0.466	0.406	0.346	0.286	0.226	0.166	0.106	0.046
12	16	0.483	0.999	0.535	0.132	0.535	0.495	0.454	0.414	0.374	0.334	0.293	0.253	0.213	0.173	0.132
12	15	0.525	1.000	0.573	0.117	0.573	0.527	0.482	0.436	0.391	0.345	0.299	0.254	0.208	0.163	0.117
12	14	0.567	1.000	0.611	0.085	0.611	0.558	0.505	0.453	0.400	0.348	0.295	0.243	0.190	0.138	0.085
12	13	0.607	1.000	0.646	0.045	0.646	0.586	0.526	0.466	0.406	0.346	0.286	0.226	0.166	0.106	0.045
13	16	0.523	0.999	0.571	0.088	0.571	0.522	0.474	0.426	0.378	0.329	0.281	0.233	0.184	0.136	0.088
13	15	0.565	1.000	0.609	0.072	0.609	0.555	0.501	0.448	0.394	0.341	0.287	0.233	0.180	0.126	0.072
13	14	0.607	1.000	0.646	0.040	0.646	0.586	0.525	0.464	0.404	0.343	0.282	0.222	0.161	0.100	0.040
14	16	0.563	0.999	0.607	0.048	0.607	0.551	0.495	0.439	0.383	0.327	0.272	0.216	0.160	0.104	0.048
14	15	0.605	1.000	0.645	0.033	0.645	0.583	0.522	0.461	0.400	0.339	0.277	0.216	0.155	0.094	0.033
15	16	0.605	0.999	0.644	0.016	0.644	0.582	0.519	0.456	0.393	0.330	0.267	0.204	0.141	0.079	0.016
COLORED		0.232	0.974	0.306	0.320	0.306	0.307	0.309	0.310	0.311	0.313	0.314	0.315	0.317	0.318	0.320
BLEACHED		0.647	1.000	0.682	0.000	0.682	0.614	0.546	0.478	0.409	0.341	0.273	0.205	0.136	0.068	0.000

<u>Legend:</u>

s1 = 0.0·ERR+1.0·VQ
s2 = 0.1·ERR+0.9·VQ
s3 = 0.2·ERR+0.8·VQ
s4 = 0.3·ERR+0.7·VQ
s5 = 0.4·ERR+0.6·VQ
s6 = 0.5·ERR+0.5·VQ
s7 = 0.6·ERR+0.4·VQ
s8 = 0.7·ERR+0.3·VQ
s9 = 0.8·ERR+0.2·VQ
s10 = 0.9·ERR+0.1·VQ
s11 = 1.0·ERR+0.0·VQ

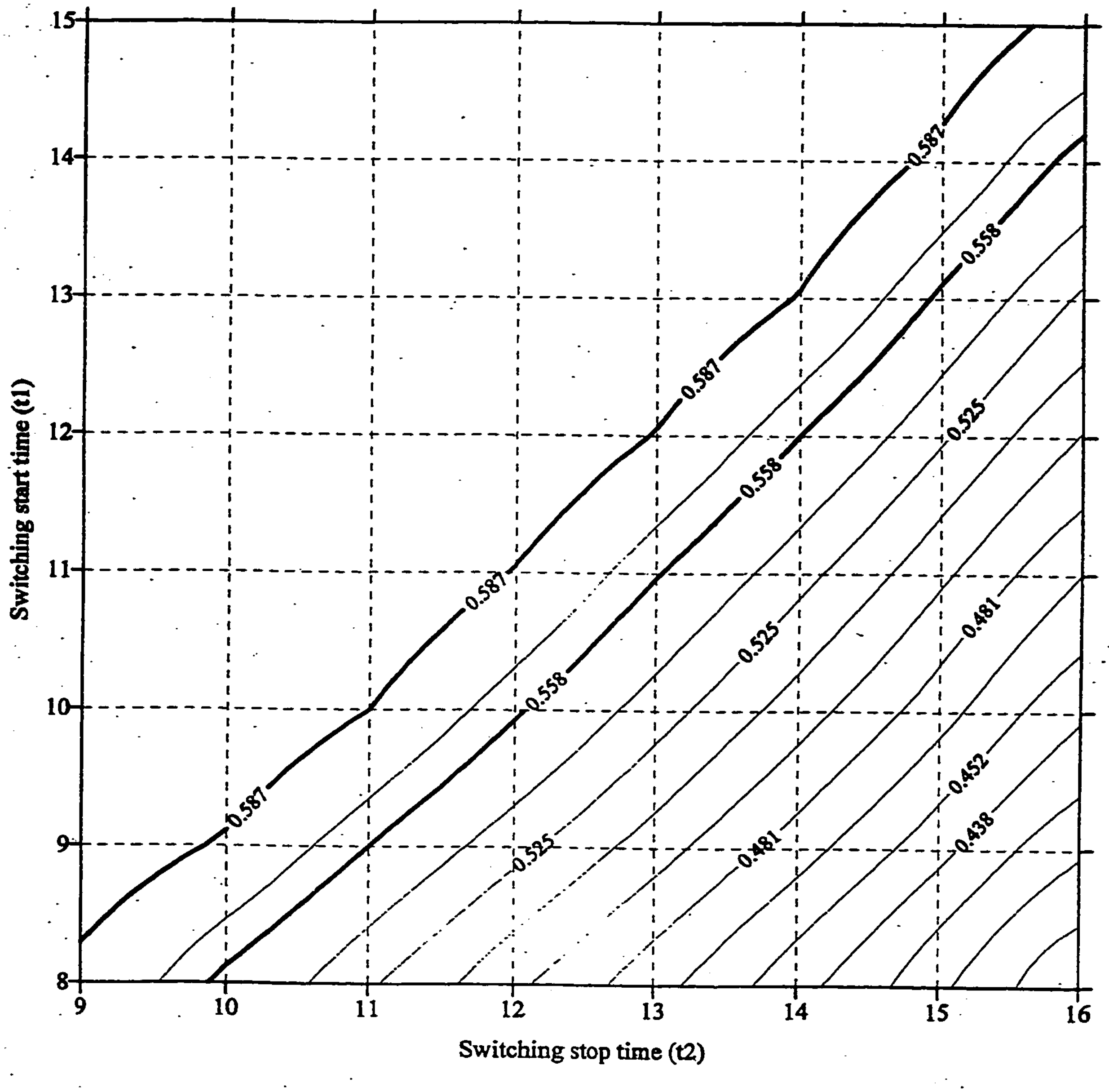

Figure B-1. Pareto feasible solutions of t_1 and t_2 for the South perimeter zone when OBJECTIVE=0.1·ERR+0.9·VQ.

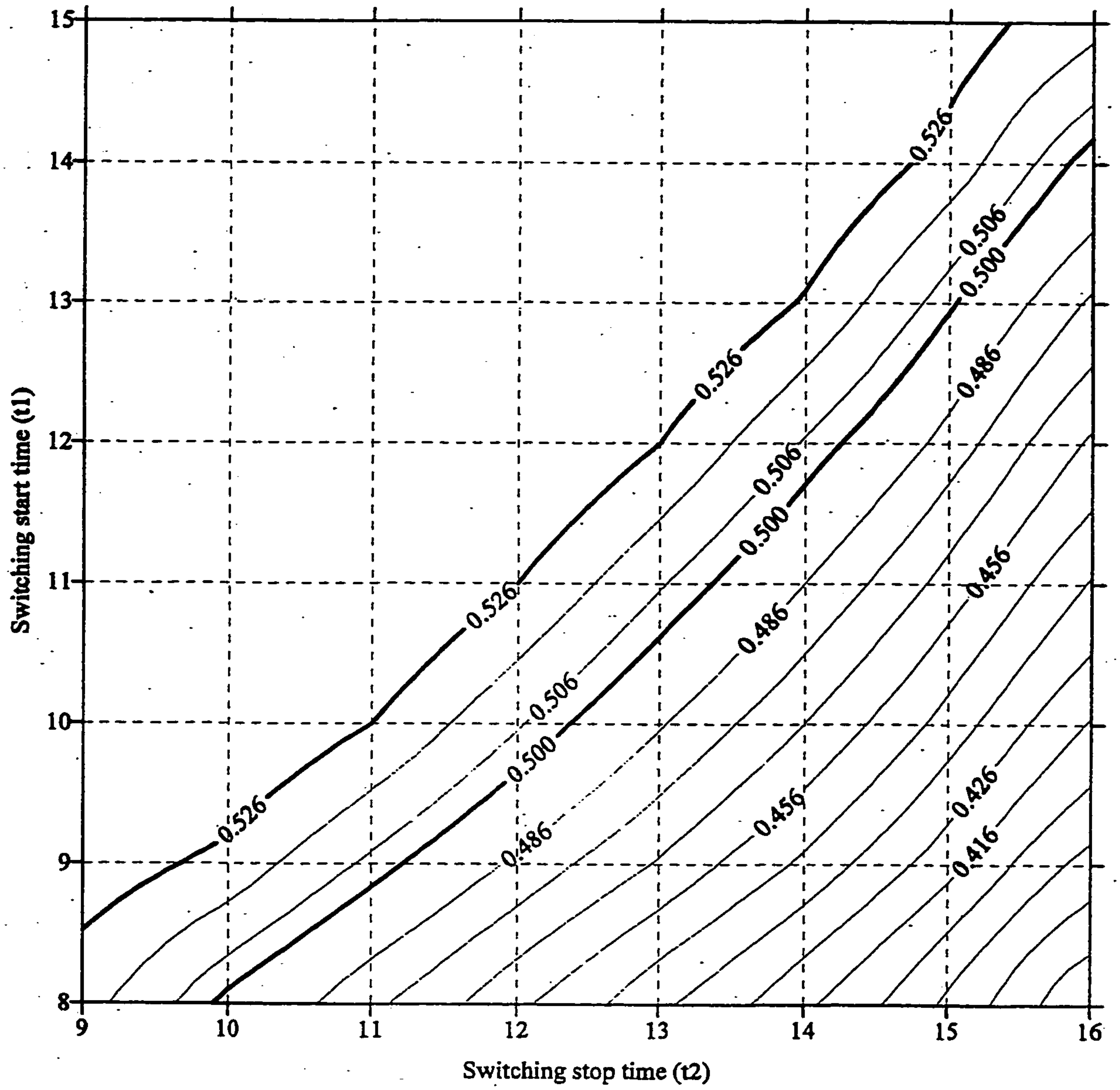

Figure B-2. Pareto feasible solutions of t_1 and t_2 for the South perimeter zone when OBJECTIVE=0.2·ERR+0.8·VQ.

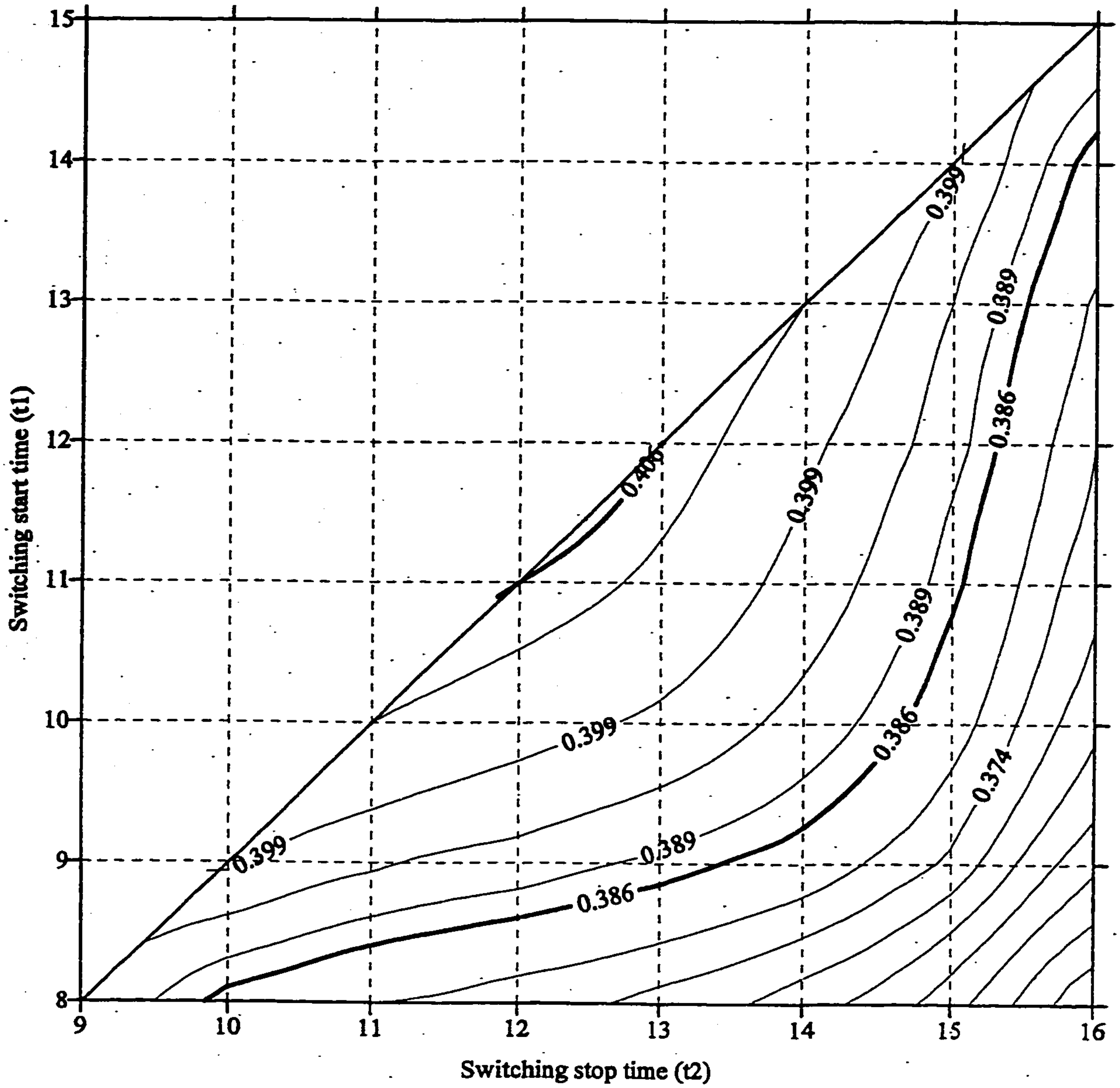

Figure B-3. Pareto feasible solutions of t_1 and t_2 for the South perimeter zone when OBJECTIVE=0.4·ERR+0.6·VQ.

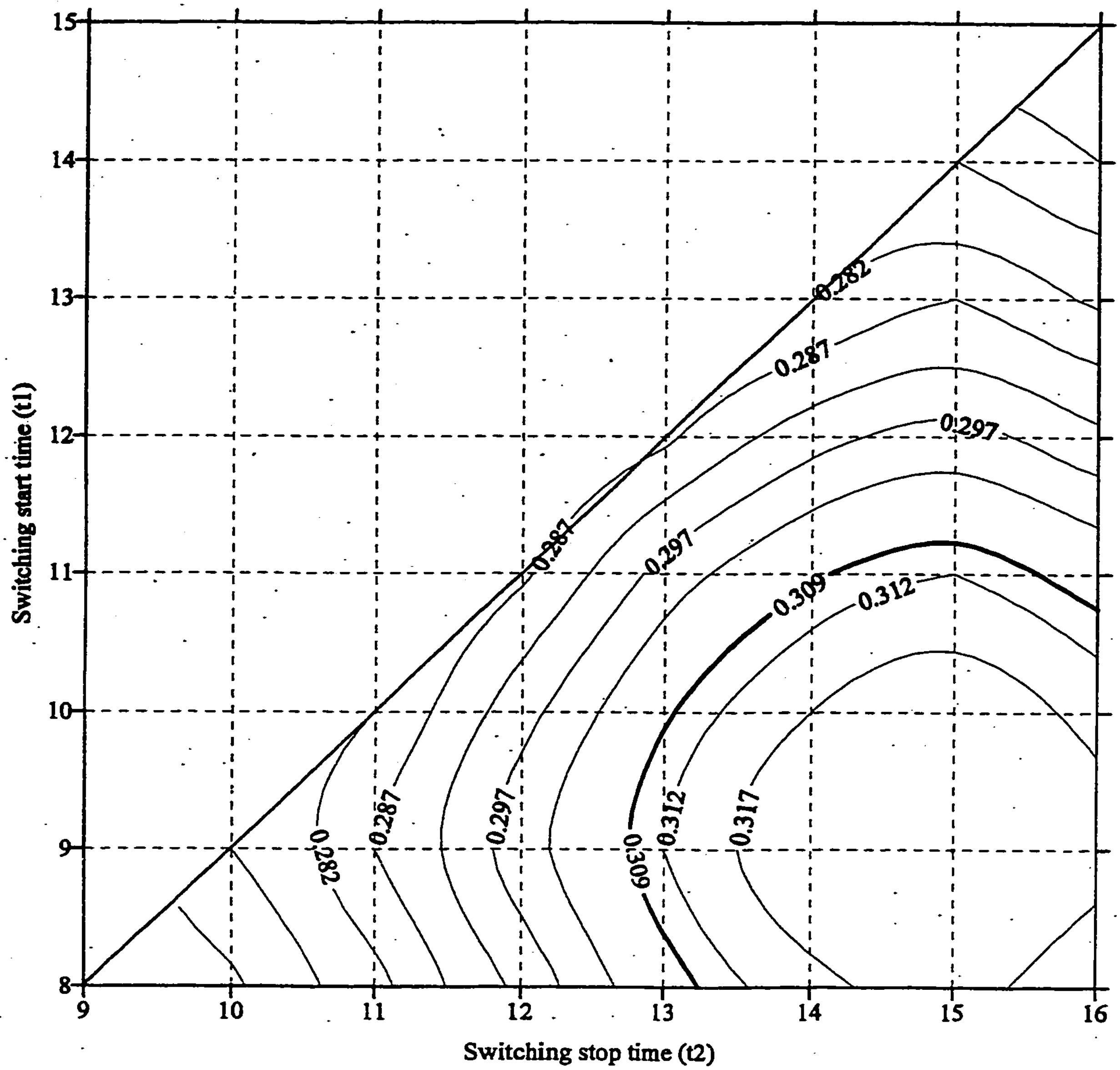

Figure B-4. Pareto feasible solutions of t_1 and t_2 for the South perimeter zone when OBJECTIVE=0.6·ERR+0.4·VQ.

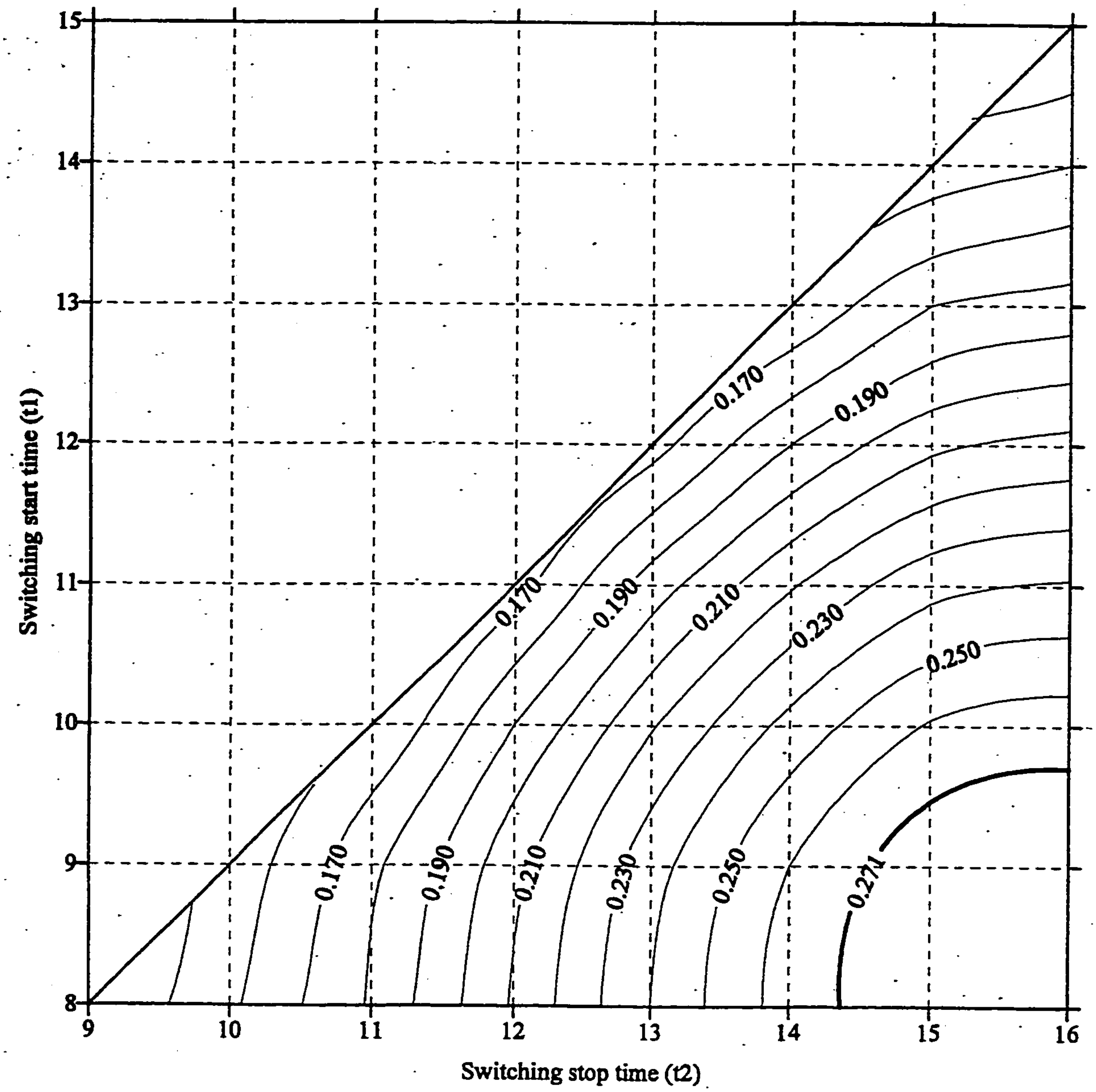

Figure B-5. Pareto feasible solutions of t_1 and t_2 for the South perimeter zone when OBJECTIVE=0.8·ERR+0.2·VQ.

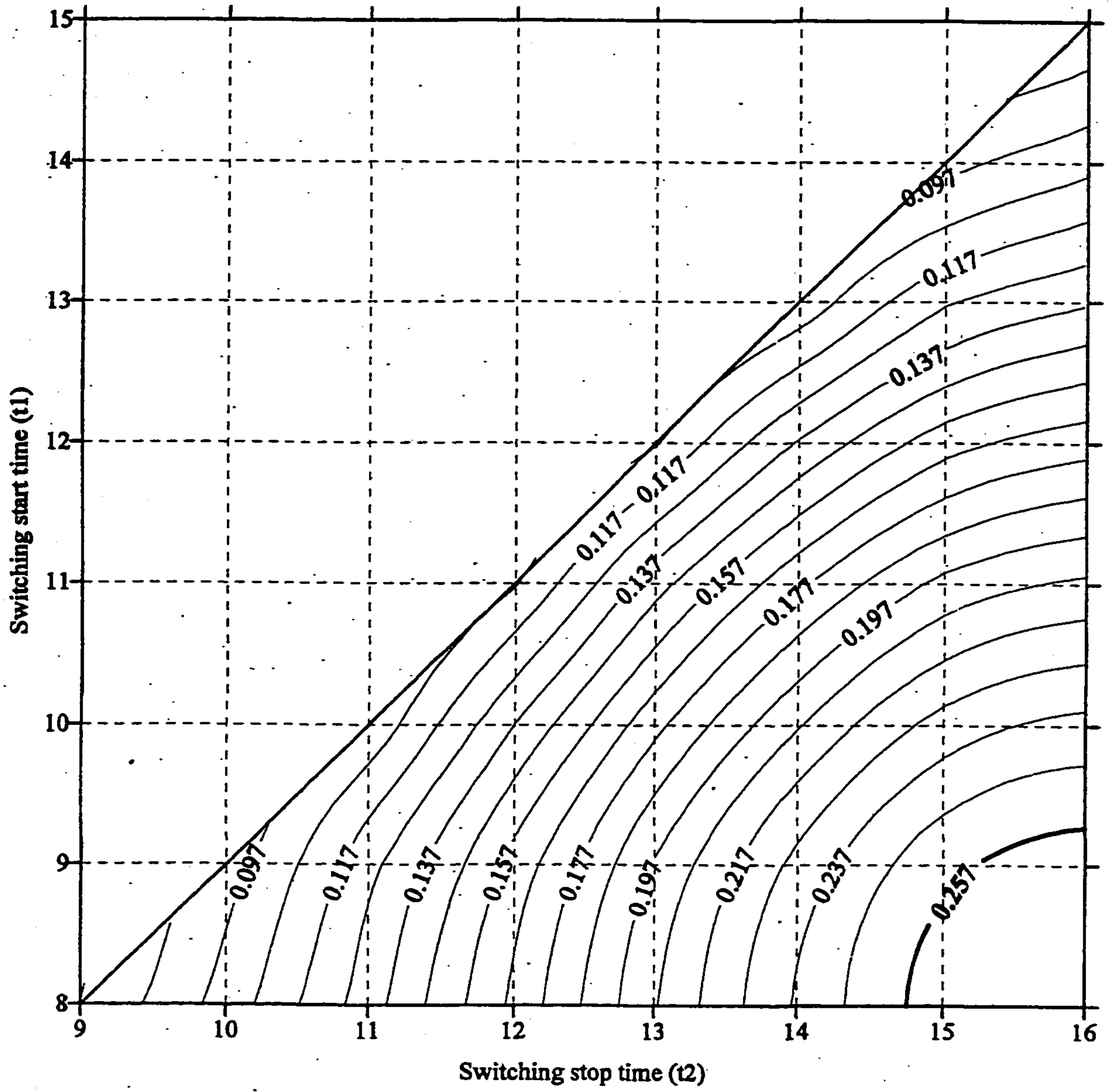

Figure B-6. Pareto feasible solutions of t_1 and t_2 for the South perimeter zone when OBJECTIVE=0.9·ERR+0.1·VQ.

APPENDIX C

PROGRAMS FOR THE AUTOMATED OPTIMIZED SWITCHING STRATEGY

OPTIM.BAT

```
rem * Maria Corsi, M.A.Sc. student, Centre for Building Studies
rem * June 20, 1997.
rem * ********************************************************************* *
rem * This batch file automates the procedure to optimize the switching     *
rem * time of the electrochromic glazing. It comprises batch routines to    *
rem * run DOE, as well as calls to FORTRAN programs which calculate the     *
rem * required performance criteria and select the next switching time.     *
rem * ********************************************************************* *
@echo off
rem * * * BATCH FILE FOR DOE SIMULATION, GLAZING IN BLEACHED STATE * * *
SET FILENAME=BLEACHED
DEL INPUT2.TMP
DEL INCOPY.TMP
DEL CTRL.TMP
DEL STDFIL.TMP
DEL OUTPUT.
COPY %filename% INPUT2.TMP
COPY INPUT2.TMP INCOPY.TMP
DOEBDL
COPY OUTPUT  %filename%.BDL
COPY MONT92.QC   WEATHR.TMP
DOESIM
COPY OUTPUT  %filename%.SIM
rem COPY %filename%.* D:\MARIAC\RESULTS
rem [END OF A RUN]
CLEANCLR
: 8
rem * * * BATCH FILE FOR DOE SIMULATIONS, GLAZING IN SWITCHED STATE * * *
SET FILENAME=SWITCHED
DEL INPUT2.TMP
DEL INCOPY.TMP
DEL CTRL.TMP
DEL STDFIL.TMP
DEL OUTPUT.
COPY %filename% INPUT2.TMP
COPY INPUT2.TMP INCOPY.TMP
DOEBDL
COPY OUTPUT  %filename%.BDL
COPY MONT92.QC   WEATHR.TMP
DOESIM
COPY OUTPUT  %filename%.SIM
rem COPY %filename%.* D:\MARIAC\RESULTS
rem [END OF A RUN]
rem
CLEANSIM
```

```
CALCUL
SWTIME
DEL VQ.DAT
DEL EXT_COL.DAT
if not errorlevel 1 goto 8
COPY TABLE.DAT D:\MARIAC\RESULTS
D:
cd MARIAC\RESULTS
OPTIMIZE
```

CLEANCLR.FOR

```
      PROGRAM CLEANCLR

* July 3, 1997.

* ****************************************************************** *
* This program reads data from the DOE simulation output file,       *
* BLEACHED.SIM (where the electrochromic window is maintained in the *
* bleached state), and extracts the monthly SM value of the extraction *
* rate for the South, East and West perimeter zones.  The resulting  *
* data is saved to the file EXT_CLR.DAT                              *
* ****************************************************************** *

      CHARACTER*132 LINE

      OPEN (UNIT=1,FILE='BLEACHED.SIM',STATUS='OLD')
      OPEN (UNIT=2,FILE='EXT_CLR.DAT',STATUS='NEW')

      DO WHILE (1)

      READ (1,'(A)',END=32000) LINE

      IF (LINE(1:7).EQ.'REP-HR7') THEN
            CALL EXT_SM(LINE)
      ENDIF

      END DO

32000 CONTINUE

      CLOSE (UNIT=1)
      CLOSE (UNIT=2)


      END

* ****************************************************************** *
* This subroutine writes the monthly SM values of the extraction rate *
* for each perimeter zone.                                           *
* ****************************************************************** *

      SUBROUTINE EXT_SM(LINE)

      CHARACTER*132 LINE

      DO WHILE (2)
      READ (1,'(A)',END=3000) LINE
      IF (LINE(2:16).EQ.'MONTHLY SUMMARY') THEN

            DO WHILE (3)
            READ (1,'(A)',END=4000) LINE
```

```
            IF (LINE(5:6).EQ.'SM') THEN
                  WRITE (2,'(A)') LINE(11:48)
            ELSEIF (LINE(2:15).EQ.'YEARLY SUMMARY') THEN
                  GO TO 10
            ELSE
15                CONTINUE
            ENDIF

            END DO

      ENDIF

      END DO

3000  CONTINUE
4000  CONTINUE
10    CONTINUE

      RETURN
      END

* ********************************************************************** *
```

CLEANSIM.FOR

```
      PROGRAM CLEANSIM

* June 27, 1997.

* ******************************************************************** *
* This program reads data from a DOE simulation output file and        *
* extracts the data that will be used in calculating the visual quality*
* and extraction rate reduction performance criteria.  The "cleaned" or*
* extracted date is saved to two new files: (i) VQ.DAT, which contains *
* the hourly values of SWFAC and Illuminance for the South, East and   *
* West perimeter zones; and (ii) EXT_COL.DAT, which contains the       *
* monthly SM value of the extraction rate for the South, East and West *
* perimeter zones.                                                     *
* ******************************************************************** *

      CHARACTER*132 LINE

      OPEN (UNIT=1,FILE='SWITCHED.SIM',STATUS='OLD')
      OPEN (UNIT=2,FILE='VQ.DAT',STATUS='NEW')
      OPEN (UNIT=3,FILE='EXT_COL.DAT',STATUS='NEW')

* ******************************************************************** *
* DESCRIPTION OF FILES AND VARIABLE                                    *
* =================================                                    *
* SWITCHED.SIM = DOE-2.1E simulation output file for the electrochromic*
*                window in the switched (colored state)                *
*                                                                      *
* VQ.DAT = FORTRAN output file which contains hourly values of SWFAC   *
*          and daylight illuminance for the South, East and West       *
*          perimeter zones                                             *
*                                                                      *
* EXT_COL.DAT = FORTRAN output file which contains the monthly sum     *
*               value of the extraction rate for the South, East and  *
*               West perimeter zones.                                  *
*                                                                      *
* LINE = represents one line of data in the SWITCHED.SIM file          *
* ******************************************************************** *

      DO WHILE (1)

      READ (1,'(A)',END=32000) LINE

* ******************************************************************** *
* The following loop prints out the value of SWFAC and daylight        *
* illuminance between the hours of 9:00 and 17:00 (DOE time - i.e.     *
* actual time is from 8:00 to 17:00.  These represent the working      *
* day.                                                                 *
* ******************************************************************** *
```

```
      IF ((LINE(1:2).GE.' 5').AND.(LINE(1:2).LE.' 9')) THEN
             IF (LINE(1:1).EQ.'-') GO TO 5
             IF ((LINE(5:6).GE.' 9').AND.(LINE(5:6).LE.'17')) THEN
                    WRITE (2,'(A)') LINE
             ENDIF
 5           CONTINUE
      ENDIF

      IF (LINE(1:7).EQ.'REP-HR7') THEN
             CALL EXT_SM(LINE)
      ENDIF

      END DO

32000 CONTINUE

      CLOSE (UNIT=1)
      CLOSE (UNIT=2)
      CLOSE (UNIT=3)


      END

* ******************************************************************* *
* This subroutine writes the monthly SM values of the extraction rate
*  for each perimeter zone.
* ******************************************************************* *

      SUBROUTINE EXT_SM(LINE)

      CHARACTER*132 LINE

      DO WHILE (2)
      READ (1,'(A)',END=3000) LINE
      IF (LINE(2:16).EQ.'MONTHLY SUMMARY') THEN

             DO WHILE (3)
             READ (1,'(A)',END=4000) LINE

             IF (LINE(5:6).EQ.'SM') THEN
                    WRITE (3,'(A)') LINE(11:48)
             ELSEIF (LINE(2:15).EQ.'YEARLY SUMMARY') THEN
                    GO TO 10
             ELSE
15                  CONTINUE
             ENDIF

             END DO

      ENDIF

      END DO

3000  CONTINUE
```

```
4000  CONTINUE
10    CONTINUE

      RETURN
      END

* ******************************************************************** *
```

CALCUL.FOR

```
      PROGRAM CALCUL

* July 4, 1997.

* ******************************************************************** *
* This program calculates the performance indices used to determine the*
* optimum switching time of the electrochromic glazing.  The following *
* indices are calculated: (i) Access to Views (based on hourly value of*
* the DOE SWFAC variable), (ii) Daylight Illuminance Factor (based on  *
* DOE hourly values of the daylight illuminance at reference point 1)  *
* (iii) Visual Quality (based on AV and DI), (iv) Extraction Rate      *
* Reduction (based on monthly sum values of the extraction rate in the *
* South, East and West perimeter zones, (v) Objective function value   *
* (based on VQ and ERR), and finally (vi) Average objective function   *
* (area weighted average for the three zones).                         *
* The calculations cover the entire cooling season from May 1st to     *
* Sept. 30th.                                                          *
* ******************************************************************** *


      REAL TVISCLR,TVISCOLR,TVISDBCL,A1,A2,W1,W2,A_SOUTH,A_EAST,
     /A_WEST,A_TOT,AV_MO_S,AV_MO_E,AV_MO_W,DI_MO_S,DI_MO_E,DI_MO_W,
     /T1_SOUTH,T2_SOUTH,T1_EAST,T2_EAST,T1_WEST,T2_WEST,VQ_SOUTH,
     /VQ_EAST,VQ_WEST,ERR_S,ERR_E,ERR_W,OBJ_FN_S,OBJ_FN_E,OBJ_FN_W,
     /AVG_OBJ

      INTEGER TOT_HRS,IRC

      OPEN (UNIT=2,FILE='VQ.DAT',STATUS='OLD')
      OPEN (UNIT=3,FILE='INITIAL.DAT',STATUS='OLD')
      OPEN (UNIT=4,FILE='TABLE.DAT',STATUS='NEW',IOSTAT=IRC)
      OPEN (UNIT=5,FILE='EXT_CLR.DAT',STATUS='OLD')
      OPEN (UNIT=6,FILE='EXT_COL.DAT',STATUS='OLD')
      OPEN (UNIT=7,FILE='SOUTH.TIM',STATUS='OLD')
      OPEN (UNIT=8,FILE='EAST.TIM',STATUS='OLD')
      OPEN (UNIT=9,FILE='WEST.TIM',STATUS='OLD')

* ******************************************************************** *
* DESCRIPTION OF DATA FILES:                                           *
* ========================                                             *
* VQ.DAT = DOE-2.1E simulation output file containing the data to be   *
* read in this Fortran program (hourly values of SWFAC and daylight    *
* illuminance for each orientation.)                                   *
*                                                                      *
* INITIAL.DAT = data file containing: visible transmittance of electro-*
* chromic window in clear and colored states, TVIS of clear double     *
* glazed window, weighting coefficients used in calculating Visual     *
* Quality and Objective Function.                                      *
*                                                                      *
* TABLE.DAT = output file of this FORTRAN program containing summary of*
```

```
* switching time, AV, DI, VQ, and value of objective function for each *
* orientation and for each combination of switching times.             *
*                                                                      *
* EXT_CLR.DAT = contains extraction rate of each perimeter zone due to *
* electrochromic windows that are maintained in the clear state only.  *
*                                                                      *
* EXT_COL.DAT = contains extraction rate of each perimeter zone due to *
* electrochromic windows that are switched to the colored state at     *
* specified T1 and T2.                                                 *
*                                                                      *
* SOUTH.TIM, EAST.TIM and WEST.TIM = contain the current run value of  *
* T1 and T2 for each orientation.                                      *
* ******************************************************************** *
*                                                                      *
* DESCRIPTION OF VARIABLES USED IN THE MAIN PROGRAM AND IN SUBROUTINES:*
* GENERAL NOTE: "_?" = _S, _E, or _W, to indicate the orientation      *
* ==================================================================== *
*                                                                      *
* A_SOUTH,A_EAST,A_WEST = area of the perimeter zone                   *
* A_TOT = total area of the perimeter zones, where switching occurs    *
*                                                                      *
* TVISCLR = visible transmittance of the electrochromic glazing        *
*           in the clear (bleached) state                              *
* TVISCOLR = visible transmittance of the electrochromic glazing       *
*            in the colored state                                      *
* TVISDBCL = visible transmittance of the double glazed clear window   *
*                                                                      *
* A1 = weighting coefficient for AV in the calculation of VQ           *
* A2 = weighting coefficient for DI in the calculation of VQ           *
* W1 = weighting coefficient for ERR in the calculation of OBJ_FN      *
* W2 = weighting coefficient for VQ in the calculation of OBJ_FN       *
*                                                                      *
* T1_SOUTH,T2_SOUTH                                                    *
* T1_EAST,T2_EAST      = switching start and stop time for each        *
* T1_WEST,T2_WEST        perimeter zone                                *
*                                                                      *
* TOT_HRS = total number of hours in the working day                   *
*                                                                      *
* Variables used for the calculation of Access to Views:               *
* ====================================================                 *
* HRS_CLR_? = number of hours that the electrochromic glazing is in the*
*             clear state                                              *
* HRS_COL_? = number of hours that the electrochromic glazing is in the*
*             colored state                                            *
*                                                                      *
* SWFAC_?(DAY,HOUR) = hourly value of the variable SWFAC (switching    *
*                     factor from the DOE simulation output, for each  *
*                     orientation                                      *
* SWFACSM?(DAY) = the daily sum of the SWFAC variable                  *
* AV_SOUTH(DAY),AV_EAST(DAY),AV_WEST(DAY) = Access to Views calculated *
*   for each day and each orientation                                  *
* SUM_AV_? = variable used in DO loop to sum the daily AV values       *
* AV_MO_? = Access to Views performance factor for the month (avg.)    *
*                                                                      *
```

```
* Variables used for the calculation of Daylight Illuminance Factor    *
* ================================================================     *
*                                                                      *
* ILLUM_?(DAY,HOUR) = illuminance at ref. pt. for the (day,hour) -     *
*                     value read from DOE simulation output file       *
*                                                                      *
* DI_SOUTH(DAY,HOUR)                                                   *
* DI_EAST(DAY,HOUR)      = hourly value of Daylight Illuminance for the *
* DI_WEST(DAY,HOUR)        day in question                             *
*                                                                      *
* DI_SUM_S(DAY) = variable used in DO loop to sum the hourly values of *
*                 DI_SOUTH,_EAST,_WEST(DAY,HOUR) to obtain total for   *
*                 the day                                              *
* DI_AV_?(DAY) = Average DI for the day                                *
* SUM_DI_? = variable used in DO loop to sum the average daily DI      *
*            values to be used in calculation of monthly average       *
* DI_MO_? = Daylight Illuminance performance factor for the month(avg.)*
*                                                                      *
* VQ_SOUTH,_EAST,_WEST = Visual Quality for each orientation (avg.     *
*                        for month)                                    *
*                                                                      *
* Variables used for the calculation of Extraction Rate Reduction      *
* ==============================================================       *
* ER_CLR_? = extraction rate of the perimeter zone when the electro-   *
*            chromic window is in the bleached state (monthly SM value)*
* ER_COL_? = extraction rate of the perimeter zone when the electro-   *
*            chromic window is in the switched state (for given t1,t2) *
*            (monthly SM value)                                        *
* ERCLRT_? = total of each ER_CLR_?                                    *
* ERCOLT_? = total of each ER_COL_?                                    *
* ERR_? = Extraction Rate Reduction in the perimeter zone, due to      *
*         switching at given t1,t2                                     *
*                                                                      *
* OBJ_FN_? = objective function for each orientation                   *
* AVG_OBJ = area weighted average of the objective function            *
* DAY = day number                                                     *
* DAYCOUNT = day counter                                               *
* DAYCT_2 = day counter                                                *
* ******************************************************************** *

      IF (IRC.NE.0) THEN
            OPEN (UNIT=4,FILE='TABLE.DAT',STATUS='OLD',ACCESS='APPEND')
      ENDIF

      READ (3,11) TVISCLR,TVISCOLR,TVISDBCL,A1,A2,W1,W2
11    FORMAT (3(F5.3,2X),3(F4.2,2X),F4.2)

* Area of the perimeter zones of the Laval building

      A_SOUTH = 1212.0
      A_EAST = 996.0
      A_WEST = 996.0
      A_TOT = A_SOUTH + A_EAST + A_WEST
```

```
      READ (7,12) T1_SOUTH,T2_SOUTH
12    FORMAT (11X,F5.2)
      READ (8,13) T1_EAST,T2_EAST
13    FORMAT (11X,F5.2)
      READ (9,14) T1_WEST,T2_WEST
14    FORMAT (11X,F5.2)

      TOT_HRS = 9

      CALL VIEWS(TOT_HRS,TVISCLR,TVISCOLR,TVISDBCL,AV_MO_S,AV_MO_E,
     / AV_MO_W)
      REWIND (UNIT=2)
      CALL DAY_ILL(TOT_HRS,DI_MO_S,DI_MO_E,DI_MO_W)

* Calculation of Visual Quality

      VQ_SOUTH = A1*AV_MO_S + A2*DI_MO_S
      VQ_EAST = A1*AV_MO_E + A2*DI_MO_E
      VQ_WEST = A1*AV_MO_W + A2*DI_MO_W

      CALL EXTRACT(ERR_S,ERR_E,ERR_W)

* Calculation of Objective function for specified weighting factors

      OBJ_FN_S = W1*ERR_S + W2*VQ_SOUTH
      OBJ_FN_E = W1*ERR_E + W2*VQ_EAST
      OBJ_FN_W = W1*ERR_W + W2*VQ_WEST

      AVG_OBJ = (OBJ_FN_S*A_SOUTH + OBJ_FN_E*A_EAST + OBJ_FN_W*A_WEST)
     / /A_TOT

      WRITE (4,15) T1_SOUTH,T2_SOUTH,AV_MO_S,DI_MO_S,VQ_SOUTH,ERR_S,
     / OBJ_FN_S,T1_EAST,T2_EAST,AV_MO_E,DI_MO_E,VQ_EAST,ERR_E,OBJ_FN_E,
     / T1_WEST,T2_WEST,AV_MO_W,DI_MO_W,VQ_WEST,ERR_W,OBJ_FN_W,AVG_OBJ
15    FORMAT (F5.2,1X,F5.2,5(1X,F5.3),2(1X,F5.2),5(1X,F5.3),2(1X,F5.2),
     /  6(1X,F5.3))

      CLOSE (UNIT=2)
      CLOSE (UNIT=3)
      CLOSE (UNIT=4)
      CLOSE (UNIT=5)
      CLOSE (UNIT=6)
      CLOSE (UNIT=7)
      CLOSE (UNIT=8)
      CLOSE (UNIT=9)

      END

* ******************************************************************* *

      SUBROUTINE VIEWS(TOT_HRS,TVISCLR,TVISCOLR,TVISDBCL,AV_MO_S,
     / AV_MO_E,AV_MO_W)

* The following routine reads the hourly SWFAC for each day, calculates
```

```
* the Access to Views performance factor for that DAY, and then
* calculates the average AV factor for the entire cooling season.

      REAL TVISCLR,TVISCOLR,TVISDBCL,SWFACSMS(31),SWFACSME(31),
     /SWFACSMW(31),SUM_AV_S,SUM_AV_E,SUM_AV_W,SWFAC_S(31,24),
     /SWFAC_E(31,24),SWFAC_W(31,24),AV_SOUTH(31),AV_EAST(31),
     /AV_WEST(31),AV_MO_S,AV_MO_E,AV_MO_W

      INTEGER  HRSCLR_S(31),HRSCLR_E(31),HRSCLR_W(31),HRSCOL_S(31),
     /HRSCOL_E(31),HRSCOL_W(31),TOT_HRS,DAY,DAYCOUNT,HOUR

      DAYCOUNT = 0
      SUM_AV_S = 0.0
      SUM_AV_E = 0.0
      SUM_AV_W = 0.0

      DO WHILE (60)

      READ (2,16,END=200) DAY
16    FORMAT (2X,I2)
      BACKSPACE (UNIT=2)

      SWFACSMS(DAY)  = 0.0
      SWFACSME(DAY)  = 0.0
      SWFACSMW(DAY)  = 0.0

      DAYCOUNT = DAYCOUNT + 1

      DO 35 J = 9,17

            READ (2,17,END=250) DAY,HOUR,SWFAC_S(DAY,HOUR),
     /      SWFAC_E(DAY,HOUR),SWFAC_W(DAY,HOUR)
17          FORMAT (2X,I2,I2,7X,F4.2,2(18X,F4.2))

            SWFACSMS(DAY)  = SWFACSMS(DAY)  + SWFAC_S(DAY,HOUR)
            SWFACSME(DAY)  = SWFACSME(DAY)  + SWFAC_E(DAY,HOUR)
            SWFACSMW(DAY)  = SWFACSMW(DAY)  + SWFAC_W(DAY,HOUR)

35    CONTINUE

      HRSCLR_S(DAY)  = 9 - SWFACSMS(DAY)
      HRSCOL_S(DAY)  = SWFACSMS(DAY)
      AV_SOUTH(DAY)  = (HRSCLR_S(DAY)*TVISCLR + HRSCOL_S(DAY)*TVISCOLR) /
     / (TOT_HRS*TVISDBCL)

      HRSCLR_E(DAY)  = 9 - SWFACSME(DAY)
      HRSCOL_E(DAY)  = SWFACSME(DAY)
      AV_EAST(DAY)  = (HRSCLR_E(DAY)*TVISCLR + HRSCOL_E(DAY)*TVISCOLR) /
     / (TOT_HRS*TVISDBCL)

      HRSCLR_W(DAY)  = 9 - SWFACSMW(DAY)
      HRSCOL_W(DAY)  = SWFACSMW(DAY)
      AV_WEST(DAY)  = (HRSCLR_W(DAY)*TVISCLR + HRSCOL_W(DAY)*TVISCOLR) /
     / (TOT_HRS*TVISDBCL)
```

```
      SUM_AV_S = SUM_AV_S + AV_SOUTH(DAY)
      SUM_AV_E = SUM_AV_E + AV_EAST(DAY)
      SUM_AV_W = SUM_AV_W + AV_WEST(DAY)

      END DO

200   CONTINUE
250   CONTINUE

      AV_MO_S = SUM_AV_S / DAYCOUNT
      AV_MO_E = SUM_AV_E / DAYCOUNT
      AV_MO_W = SUM_AV_W / DAYCOUNT

      RETURN
      END

* ********************************************************************* *

      SUBROUTINE DAY_ILL(TOT_HRS,DI_MO_S,DI_MO_E,DI_MO_W)

* The following routine reads the hourly Daylight Illuminance for each
* day, calculates the Daylight Illuminance factor for each hour,
* averages it for the day and then calculates the average DI factor for
* the entire cooling season.

      REAL SUM_DI_S,SUM_DI_E,SUM_DI_W,DI_SUM_S(31),DI_SUM_E(31),
     /DI_SUM_W(31),ILLUM_S(31,24),ILLUM_E(31,24),ILLUM_W(31,24),
     /DI_SOUTH(31,24),DI_EAST(31,24),DI_WEST(31,24),DI_AV_S(31),
     /DI_AV_E(31),DI_AV_W(31),DI_MO_S,DI_MO_E,DI_MO_W

      INTEGER  DAY,DAYCT_2,J,HOUR,TOT_HRS

      SUM_DI_S = 0.0
      SUM_DI_E = 0.0
      SUM_DI_W = 0.0

      DAYCT_2 = 0

      DO WHILE (7500)

      READ (2,18,END=300) DAY
18    FORMAT (2X,I2)
      BACKSPACE (UNIT=2)

      DI_SUM_S(DAY) = 0.0
      DI_SUM_E(DAY) = 0.0
      DI_SUM_W(DAY) = 0.0

      DAYCT_2 = DAYCT_2 + 1

      DO 34 J=9,17

             READ (2,19,END=350) DAY,HOUR,ILLUM_S(DAY,HOUR),
```

```
     /        ILLUM_E(DAY,HOUR),ILLUM_W(DAY,HOUR)
 19           FORMAT (2X,I2,I2,3(16X,F6.1))

              IF (ILLUM_S(DAY,HOUR).LE.50.0) THEN
                 DI_SOUTH(DAY,HOUR) = 1.0 - ((50.0 - ILLUM_S(DAY,HOUR))
     /                                / 50.0)
              ELSEIF (ILLUM_S(DAY,HOUR).GT.50.0) THEN
                 DI_SOUTH(DAY,HOUR) = 1.0
              ENDIF

              IF (ILLUM_E(DAY,HOUR).LE.50.0) THEN
                 DI_EAST(DAY,HOUR) = 1.0 - ((50.0 - ILLUM_E(DAY,HOUR))
     /                               / 50.0)
              ELSEIF (ILLUM_E(DAY,HOUR).GT.50.0) THEN
                 DI_EAST(DAY,HOUR) = 1.0
              ENDIF

              IF (ILLUM_W(DAY,HOUR).LE.50.0) THEN
                 DI_WEST(DAY,HOUR) = 1.0 - ((50.0 - ILLUM_W(DAY,HOUR))
     /                               / 50.0)
              ELSEIF (ILLUM_W(DAY,HOUR).GT.50.0) THEN
                 DI_WEST(DAY,HOUR) = 1.0
              ENDIF

              DI_SUM_S(DAY) = DI_SUM_S(DAY) + DI_SOUTH(DAY,HOUR)
              DI_SUM_E(DAY) = DI_SUM_E(DAY) + DI_EAST(DAY,HOUR)
              DI_SUM_W(DAY) = DI_SUM_W(DAY) + DI_WEST(DAY,HOUR)

 34      CONTINUE

         DI_AV_S(DAY) = DI_SUM_S(DAY) / TOT_HRS
         DI_AV_E(DAY) = DI_SUM_E(DAY) / TOT_HRS
         DI_AV_W(DAY) = DI_SUM_W(DAY) / TOT_HRS

         SUM_DI_S = SUM_DI_S + DI_AV_S(DAY)
         SUM_DI_E = SUM_DI_E + DI_AV_E(DAY)
         SUM_DI_W = SUM_DI_W + DI_AV_W(DAY)

         END DO

 300     CONTINUE
 350     CONTINUE

         DI_MO_S = SUM_DI_S / DAYCT_2
         DI_MO_E = SUM_DI_E / DAYCT_2
         DI_MO_W = SUM_DI_W / DAYCT_2

         RETURN
         END
```

```
* ******************************************************************** *

      SUBROUTINE EXTRACT(ERR_S,ERR_E,ERR_W)

* The following routine calculates the Extraction Rate Reduction
* performance factor.

      REAL ER_CLR_S,ER_CLR_E,ER_CLR_W,ER_COL_S,ER_COL_E,ER_COL_W,ERR_S,
     /ERR_E,ERR_W,ERCLRT_S,ERCLRT_E,ERCLRT_W,ERCOLT_S,ERCOLT_E,ERCOLT_W

      ERCLRT_S = 0.0
      ERCLRT_E = 0.0
      ERCLRT_W = 0.0

      ERCOLT_S = 0.0
      ERCOLT_E = 0.0
      ERCOLT_W = 0.0

      DO WHILE (800)

      READ (5,20,END=400) ER_CLR_S,ER_CLR_E,ER_CLR_W
20    FORMAT (F10.1,2(5X,F10.1))

      READ (6,21,END=450) ER_COL_S,ER_COL_E,ER_COL_W
21    FORMAT (F10.1,2(5X,F10.1))

      ERCLRT_S = ERCLRT_S + ER_CLR_S
      ERCLRT_E = ERCLRT_E + ER_CLR_E
      ERCLRT_W = ERCLRT_W + ER_CLR_W

      ERCOLT_S = ERCOLT_S + ER_COL_S
      ERCOLT_E = ERCOLT_E + ER_COL_E
      ERCOLT_W = ERCOLT_W + ER_COL_W

      END DO

400   CONTINUE
450   CONTINUE

      ERR_S = (ERCLRT_S - ERCOLT_S) / ERCLRT_S
      ERR_E = (ERCLRT_E - ERCOLT_E) / ERCLRT_E
      ERR_W = (ERCLRT_W - ERCOLT_W) / ERCLRT_W


      RETURN
      END

* ******************************************************************** *
```

SWTIME.FOR

```
      PROGRAM SWTIME

* July 3, 1997.

* ******************************************************************* *
* This program selects the next T1,T2 and checks whether they are     *
* within the specified upper/lower limits for each orientation.       *
* ******************************************************************* *

      REAL T1_MIN_S,T1_MAX_S,T2_MAX_S,T1_MIN_E,T2_MIN_E,T2_MAX_E,
     /T1_MIN_W,T1_MAX_W,T2_MAX_W,T1_SOUTH,T2_SOUTH,T1_EAST,T2_EAST,
     /T1_WEST,T2_WEST

      OPEN (UNIT=2,FILE='SOUTH.TIM',STATUS='UNKNOWN')
      OPEN (UNIT=3,FILE='EAST.TIM',STATUS='UNKNOWN')
      OPEN (UNIT=4,FILE='WEST.TIM',STATUS='UNKNOWN')

* ******************************************************************* *
* SOUTH.TIM, EAST.TIM, WEST.TIM: contain T1 and T2 for each orientation*
* STATUS = UNKNOWN allows to read and write from and to the same file  *
* without an error message occurring (as would be the case if STATUS   *
* were defined as 'OLD' or 'NEW')                                      *
* ******************************************************************* *

      T1_MIN_S =  9.00
      T1_MAX_S = 16.00
      T2_MAX_S = 16.00
      T1_MIN_E =  5.00
      T2_MIN_E =  9.00
      T2_MAX_E = 12.00
      T1_MIN_W = 13.00
      T1_MAX_W = 17.00
      T2_MAX_W = 20.00

* ******************************************************************* *
* The above variables represent upper and lower limits of T1 and T2   *
* for each orientation.  Note that for the East orientation, T1 can   *
* vary from 13:00 to 17:00 while T2 remains fixed at 20:00 (to benefit *
* from energy savings from 17:00 to 20:00 without loss in visual      *
* quality performance).  For the West orientation, T1 remains fixed at *
* 5:00, while T2 can vary from 9:00 to 12:00.  The MIN/MAX times      *
* generally represent the hours where DIRECT solar radiation is       *
* incident on the surface.                                            *
* ******************************************************************* *

* Read the previous T1 and T2 for each orientation from the data files.

      READ (2,11) T1_SOUTH,T2_SOUTH
11    FORMAT (11X,F5.2)
```

```fortran
      READ (3,12) T1_EAST,T2_EAST
12    FORMAT (11X,F5.2)

      READ (4,13) T1_WEST,T2_WEST
13    FORMAT (11X,F5.2)

      REWIND (UNIT=2)
      REWIND (UNIT=3)
      REWIND (UNIT=4)

* Hierarchy: all combinations of switching time for the west orientation
* are exhausted first while T1 and T2 for the south and east remain
* fixed. When T1_WEST exceeds the T1_MAX_W (ie. 17:00), then T2_EAST is
* decreased by one hour, and the cycle begins again. When all
* combinations of switching time for the east orientation are exhausted,
* then T1_SOUTH is increased by 1 hour, and the cycle begins again.
* This continues until T1_SOUTH reaches T1_MAX_S (i.e. when all
* combinations of switching time for the south orientation are
* exhausted.

      IF ((T1_WEST.GE.T1_MIN_W).AND.(T1_WEST.LE.T1_MAX_W)) THEN
            T1_WEST = T1_WEST + 1.00
      ENDIF

      IF (T1_WEST.GT.T1_MAX_W) THEN
            T2_EAST = T2_EAST - 1.00
            T1_WEST = T1_MIN_W
      ENDIF

* Note above that T1 and T2_SOUTH remain the same.

      IF (T2_EAST.LT.T2_MIN_E) THEN
            T2_SOUTH = T2_SOUTH - 1.00
            T1_WEST = T1_MIN_W
            T1_EAST = T1_MIN_E
            T2_EAST = T2_MAX_E
      ENDIF

* Note above that T1_SOUTH remains the same.

      IF (T2_SOUTH.LT.T1_SOUTH) THEN
            T1_SOUTH = T1_SOUTH + 1.00
            T2_SOUTH = T2_MAX_S
            T1_EAST = T1_MIN_E
            T2_EAST = T2_MAX_E
            T1_WEST = T1_MIN_W
            T2_WEST = T2_MAX_W
      ENDIF

      IF (T1_SOUTH.GT.T1_MAX_S) THEN
            STOP 1
      ENDIF

      WRITE (2,14) T1_SOUTH
```

```
14    FORMAT (6X,'T1 = ',F5.2)

      WRITE (2,15) T2_SOUTH
15    FORMAT (6X,'T2 = ',F5.2)

      WRITE (3,16) T1_EAST
16    FORMAT (6X,'T1 = ',F5.2)

      WRITE (3,17) T2_EAST
17    FORMAT (6X,'T2 = ',F5.2)

      WRITE (4,18) T1_WEST
18    FORMAT (6X,'T1 = ',F5.2)

      WRITE (4,19) T2_WEST
19    FORMAT (6X,'T2 = ',F5.2)

      CLOSE (UNIT=2)
      CLOSE (UNIT=3)
      CLOSE (UNIT=4)

      END
```

OPTIMIZE.FOR

```
      PROGRAM OPTIMIZE

* ****************************************************************** *
* June 25, 1997.                                                     *
* This program reads the value of the average objective function for *
* each combination of switching time (from the file 'TABLE.DAT') and *
* then finds the maximum value.  The corresponding optimum switching *
* times for the South, East and West perimeter zones are then stored *
* in a separate file.                                                *
* ****************************************************************** *

      REAL AVG_OBJ,MAX_OBJ,FIV_PCT

      CHARACTER*132 LINE

      OPEN (UNIT=1,FILE='TABLE.DAT',STATUS='OLD')
      OPEN (UNIT=2,FILE='OPT_TIME.DAT',STATUS='NEW')

* ****************************************************************** *
* DESCRIPTION OF VARIABLES AND FILES                                 *
* ==================================                                 *
* AVG_OBJ = area weighted average of the objective function value of *
*           each perimeter zone                                      *
* MAX_OBJ = maximum value of AVG_OBJ                                 *
* LINE = represents the entire line of data in the input file        *
*                                                                    *
* TABLE.DAT = output file from the CALCUL.FOR program which contains *
*             the monthly average values of the performance indices  *
*             for each orientation and for each combination of switch- *
*             ing time                                               *
* OPT_TIME = contains the Pareto optimum switching times based on a 5% *
*            range from MAX_OBJ                                      *
* FIV_PCT = a value of 5% away from MAX_OBJ                          *
* ****************************************************************** *


* The following loop sets the first value of AVG_OBJ in the file as the
* maximum objective function value.  If each subsequent value of AVG_OBJ
* is greater, then it is retained as the maximum value.

      READ (1,10) AVG_OBJ
10    FORMAT (126X,F5.3)

      MAX_OBJ = AVG_OBJ

      DO WHILE (1)

      READ (1,11,END=250) AVG_OBJ
11    FORMAT (126X,F5.3)
```

```
      IF (AVG_OBJ.GT.MAX_OBJ) THEN
            MAX_OBJ = AVG_OBJ
      ENDIF

      END DO

250   CONTINUE

      FIV_PCT = MAX_OBJ - MAX_OBJ*0.05

      REWIND (UNIT=1)


* In the following loop, the value of AVG_OBJ is read from the file, and
* if it is equal to the value of MAX_OBJ, then the entire line of data
* is read and saved to the file OPT_TIME.DAT.

      DO WHILE (2)

      READ (1,12,END=350) AVG_OBJ
12    FORMAT (126X,F5.3)

      IF ((AVG_OBJ.GE.FIV_PCT).AND.(AVG_OBJ.LE.MAX_OBJ)) THEN
             BACKSPACE (UNIT=1)
             READ (1,'(A)') LINE
             WRITE (2,'(A)') LINE
      ENDIF

      END DO

350   CONTINUE

      CLOSE (UNIT=1)
      CLOSE (UNIT=2)

      END
```