LIGHTING ENERGY SAVINGS POTENTIAL AND VISUAL COMFORT OF INTEGRATING ELECTROCHROMIC SMART WİNDOWS IN AN OFFICE BUILDING: A CASE STUDY IN ISTANBUL, TÜRKİYE

ELEKTROKROMİK AKILLI PENCERELERİN OFİS BİNASINA ENTEGRE EDİLMESİNİN AYDINLATMADA ENERJİ TASARRUFU POTANSİYELİ VE GÖRSEL KONFORU: İSTANBUL, TÜRKİYE'DEN ÖRNEK ÇALIŞMA

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ÖZET

Son yıllarda, tüm dünyada artan elektrik tüketimiyle enerji verimliliğinin önemi de artmaktadır. Artan bu enerji tüketimi içerisinde mimari yapılardaki enerji tüketim payı oldukça yüksektir. Bu çalışmada, aydınlatmaya harcanan enerji verimliliğini artırmak için akıllı bina aydınlatma kontrol modeli geliştirilmiş ve aydınlatma konforu ve enerji tasarrufu açısından en optimum durumun bulunması amaçlanmıştır. Çalışmada, kontrol edilebilir aydınlatması ve ışık geçirgenliği değiştirilebilen elektrokromik cam, geliştirilen kontrol algoritması ile kontrol edilerek aydınlatma konforu gereksinimleri karşılanmış ve %20'ye varan enerji tasarrufu sağlanmıştır. Sonuçlar, başarılı bir aydınlatma sistemine sahip olmak için yapay aydınlatma kaynağının oda içi ışık seviyesine bağlı olarak kontrol edilmesi gerektiğini göstermiştir. Ayrıca güneş ışınım şiddeti fazla olan bölge ve iklimlerde kontrol edilebilir lamba ile elektrokromik cam kullanılmasının sürdürülebilir enerji ve çevre hedefleri açısından daha önemli olduğu ortaya koymuştur.

Anahtar kelimeler: Akıllı bina, aydınlatma kontrolü, aydınlatma konforu, enerji tasarrufu, optimizasyon, elektrokromik cam.

ABSTRACT

The significance of energy efficiency has grown with the increasing electricity consumption worldwide in recent years. The share of energy consumption in architectural structures is relatively high due to this increasing energy consumption. In this study, a smart building lighting control model is developed to improve the energy efficiency of lighting and to find the optimum status regarding lighting comfort and energy saving. The controllable lighting and

electrochromic glass with variable light transmittance were controlled with the developed control algorithm to meet the lighting comfort requirements, and energy savings of up to 20% were obtained. The results show that to have a successful lighting system, the artificial lighting source should be controlled depending on the lighting level in the room. In addition, using controllable lamps and electrochromic glass in regions and climates with higher solar radiation intensity is crucial for sustainable energy and environmental goals.

Keywords: Smart building, lighting control, lighting comfort, energy saving, optimization, electrochromic window.

INTRODUCTION

Smart glass with adjustable light transmittance will play an essential role in the new energy-efficient buildings of the future. Thanks to smart glass, which can be controlled depending on various lighting factors, buildings will save on cooling and lighting costs (Gago et al., 2015; Tällberg et al., 2019). In addition, the workplace's lighting comfort has increased (Allen et al., 2017). Smart glasses are generally divided into three main categories: electrochromic (EC) glass, suspended particle glass, and liquid crystal glass (Wong & Chan, 2014).

Smart glasses with suspended particles can change the light transmittance from opaque to transparent with an alternating voltage applied to the glass via a cross-linked polymer component with polyhalite particles in a liquid suspension between two glass panels (Ghosh et al., 2015). Liquid crystal glasses with dispersed polymers are uniquely positioned in the market. This category includes composite materials, showing the advantages of solid polymer and liquid crystal materials (Cupelli et al., 2009). Thermotropic glasses also comprise a polymer gel layer between two glass panels. However, the gel layer changes from clear to cloudy depending on the temperature of the glass rather than the voltage applied to the glass (Inoue et al., 2008). Figure 5 details the internal architecture of electrochromic glass (Mardare & Hassel, 2019).

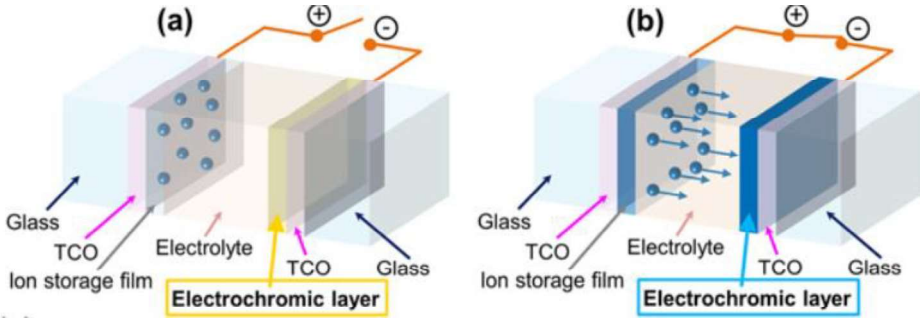


Figure 5. Electrochromic glass internal architecture (Mardare & Hassel, 2019)

EC glasses consist of five layers. Glass, electrolytes, two transparent conducting oxides, and electrochromic layers. When less than 5 V is applied between the electrodes, cations from the ion-storing layer are transported through the conductive thin film. The cations are then injected into the active layer with electrons provided by the external circuit. Still, the coloration can vary depending on the function of the type of cation used (Figure 5). A similar coloration occurs again for ions that leave the material during the transfer of ions from the ion storage layer to the electrochromic layer (Figure 5). If a reverse potential is applied, bleaching occurs, and the glass becomes transparent again. Overall, the electrochromic layer characterizes bleaching and coloring properties through redox reactions. The ion storage layer provides the necessary ion storage, maintaining the ion supply as needed. The electrolyte layer is an ion transport channel that guarantees rapid color change (Wu et al., 2023). However, all this requires that the electrochromic materials are highly transparent to visible light and that the switching voltage

range does not disturb the electrochemical stability. EC glasses retain their coloring properties under open circuit conditions and offer different coloring levels at intermediate voltages (Mardare & Hassel, 2019). The electric field caused by the voltage applied to EC glass can change the glass's optical and thermal properties. This allows the user to control light reflection, transmittance, absorption, and diffusion (Malekafzali Ardakan et al., 2017). This study develops a control method to improve the energy efficiency of lighting in smart buildings with integrated electrochromic glass. It evaluates the optimum case for lighting comfort and energy savings.

This paper is organized as follows: Section 1 contains the Introduction, including literature review and originality, while the test setup, materials, system design, flow chart, and scenarios are discussed in Section 2, Methodology. The performance analysis results, such as comparative analysis, cost-benefit relationship, and feasibility of the proposed scenario, are evaluated in Section 3 under the heading of Results.

METHODOLOGY

System Design (Block and Flow Diagram, Decision Tree Structure)

Test Bench

LDR and NTC in the sensor box are used to obtain ambient data in the system design. In this way, the circuit resistance is monitored by LDR depending on the intensity level of the light, and the resistance decreasing with increasing temperature is monitored by NTC. The collected data is transferred to the Arduino MEGA 2560 microcontroller. The control strategies developed in Python communicate with the microcontroller, allowing the system to be easily controlled remotely. In addition, the lighting parameters are saved to the SD card module at the end of each cycle. While a stepper motor controls the light transmittance of the EC glass, the desired driving voltage is provided by an AC voltage chopper using a potentiometer. Thus, EC and LED driver circuits were developed. The microcontroller controls the relevant driver via the power circuit. Finally, the block diagram of the test setup where the scenario-based test procedure is performed is shown in Figure 6.

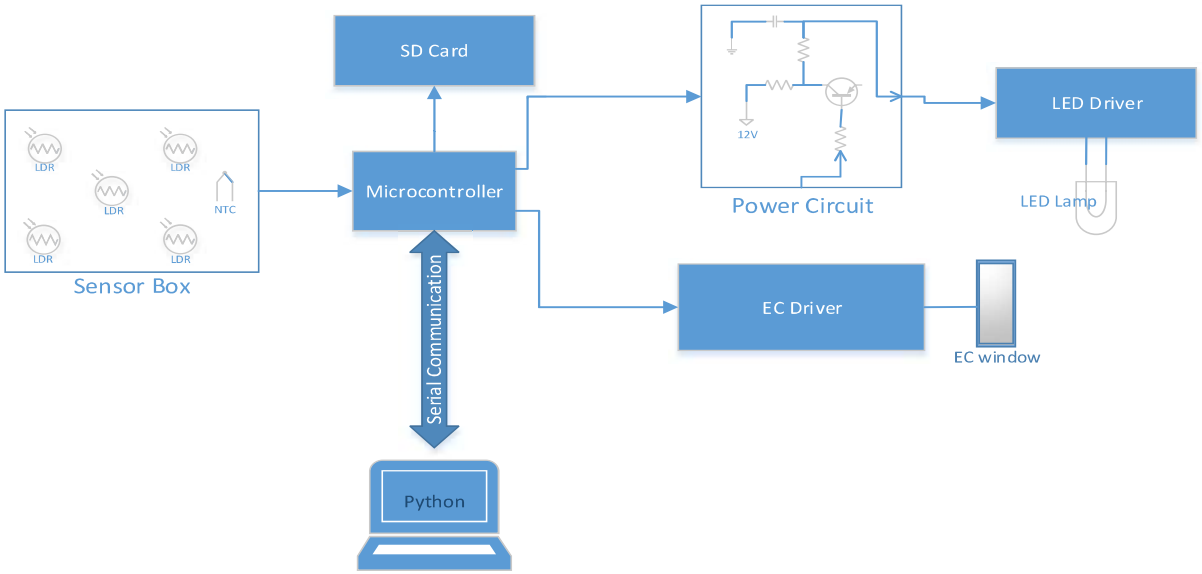


Figure 6. Test bench

Test Procedure of the Test Bench

After the test setup, one of the scenarios developed in Python (see Scenarios) is selected as a case, and the test is started. Considering the sunrise and sunset times, the start and end times of the tests are determined hourly, and the system runs only between these hours. After the start time, 10-bit values (between 0-1023) are obtained from the five LDRs in the sensor box. Under different irradiance conditions, the values read from the LDR and lux meter are compared with the corresponding values, and the polynomial regression method is performed on the obtained data. The lux values are obtained with an error of less than 10% with the help of the formulas obtained. After finding the lux values of these five points, the average lux is calculated using the corresponding values, and the uniformity factor is calculated based on Equation (13).

$$Uniformity = \frac{illumination_{min}}{illumination_{ave}} \tag{13}$$

Once the control algorithm is executed, the data calculated from the sensors at the end of each cycle and the dimmer percentages of the EC glass and LED lamp, if any, are stored on the SD card. This process is repeated until the end of the day. The system control strategy, written in the Python environment, uses a serial communication protocol to provide remote access to the data stored on the SD card at the end of the day. This allows Python to save the data collected during the day to the computer as an Excel file. The general flow of the test procedure is summarized in Figure 7.

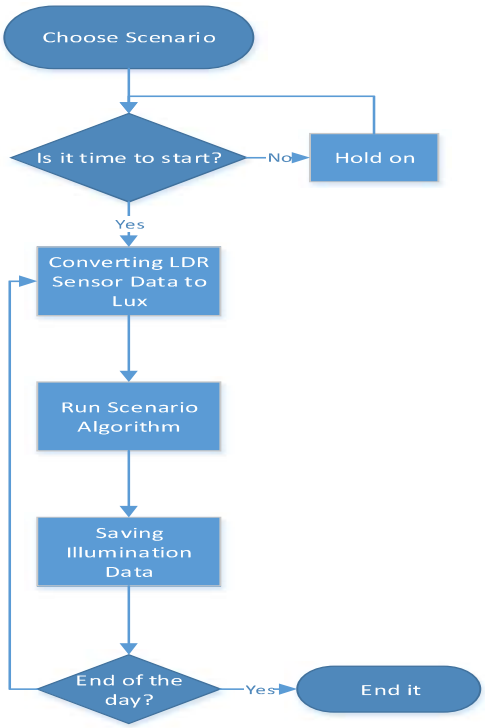


Figure 7. Test procedure of the test bench

Technical Details of the Test Bench

The test cell includes sensors, EC glass, and LED lamps. The rectangular prism-shaped test cell on the MDF base has dimensions of 45*40*30 cm. A window gap of 20*30 cm is left on the surface, considered as the front side of the chamber/room. IG80 and EC glass are placed in the relevant window opening based on the characteristics of the initial test situation, and the

test cell is operated. The location of the test cell is critical, considering the direct influence of solar radiation and weather conditions on the tests to be performed. While the results may vary depending on the change of location, there will be negligible differences in the results obtained for two days in the same area but under different weather conditions. Therefore, the experiments were conducted under similar weather conditions and in the same environment. Accordingly, the test was conducted at the Electrical Engineering Department of Yıldız Technical University, which has an average altitude of 90 m.

Besides the same ambient conditions, it is essential for the experiment's accuracy that the glass types to be tested have the same dimensions. When testing the two glass types, an equal size was chosen. IG80 glass, widely used in the market, serves the purpose of comparison. In contrast, the cost-benefit relationship of EC glass is evaluated based on the condition of the LED lamp. The window sizes and properties of IG80 and EC glass are explained in Table 2.

Table 2. Window size and specifications

Window type	Window-to-wall ratio	External wall area (m^2)	Window width (m)	Window height (m)	Light transmittance (%)
IG80	0.33	0.18	0.3	0.2	80
EC	0.33	0.18	0.3	0.2	2-60

On the other hand, the light transmittance can be adjusted by changing the voltage applied to the EC glass. An integrated driver model has been developed to adjust the light transmittance of the EC glass. A driver with a non-switching AC chopper is mainly preferred for this aim. Since the power consumption of the EC glass is low, a user-friendly voltage divider circuit with a potentiometer was designed. The NEMA17 stepper motor, driven by TB6560, is used for the driver's automatic control, and the motor is mounted on the potentiometer shaft with a coupling.

A 10W 70V DC Siobi Dimmer LED (Solar Light) is also installed on the chamber ceiling. Its purpose is to adjust the average illuminance level to 500 lx when the artificial lighting source is in use on the test bench, and there are no other light sources, such as sunlight. The LC1x30-E-AN, a crucial component in the system, powers the LED. However, it's important to note that the Arduino Mega2560 cannot provide the required 1-10 V range voltage by the LED driver. To overcome this, the microcontroller's 0-5 V voltage output is used with a simple power circuit to meet the LED's voltage requirements.

Scenarios

The best illumination method for the office environment is sought. Since the standard illuminance level and uniformity factor for the office environment are 500 lx and 0.8, these are set as reference levels. The proposed lighting method or scenario varies for different glass types and LED lamps. Finally, the scenarios realized in the study are explained in Table 3.

Table 3. Scenarios of the study

Scenario	Sub-scenario	Window type	LED	LED dimmer
1	A	IG80	Off	
	B		On	
2	C	EC	On	

When the LED lamp is off, the illuminance data for glass type IG80 is collected in sub-scenario A. Since there is no additional illumination in this sub-scenario, the main objective is to observe the sun's movement and determine the illuminance level of the test cell. In contrast, the cell in sub-scenario B is illuminated by an artificial light source in addition to sunlight. The test measures the energy expenditure and illuminance comfort of the office illuminated by an uncontrolled LED lamp. In sub-scenario C, the EC glass is tested. The LED is switched on as an artificial light source in addition to sunlight. The objective of using a permanent light source is to increase the illuminance of the test cell to the required level. On the other hand, the EC glass is meticulously controlled to maintain the illuminance level in the room at a comfortable level and to eliminate glare-causing radiation from the sun. The control algorithm or decision tree mechanism developed for EC glass is shown in Figure 8. If the ambient illuminance level is above the reference illuminance level, the EC dimmers and, therefore, the light transmittance of the glass are reduced. Otherwise, the EC dimmers, and hence, the light transmittance increases. The main objective is to provide lighting comfort.

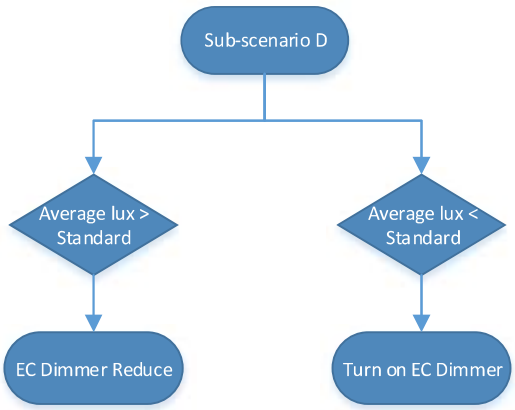


Figure 8. Decision tree of EC window considered in sub-scenario C

To maximize the energy from sunlight and reduce energy wastage, the LED lamp must be completely off or about to turn off before the EC dimmer is dimmed. Thus, if the ambient luminance level is above the reference value, the LED lamp is switched off first. If the required reference level still needs to be obtained, the light transmittance of the EC glass is reduced dimmer. The room's uniformity factor decreases as the EC glass's light transmittance decreases. Therefore, the uniformity factor must be higher than the reference value for the EC dimmer to be dimmed, and the control algorithm is run accordingly.

RESULTS

This section compares lighting comfort (average illuminance level and uniformity factor), energy savings (daily energy consumption), and dimmer percentages for the scenarios with and without LEDs, considering the control algorithms of different glass types. The illuminance level in sub-scenario A without LEDs as an artificial light source and with IG80 glass is only related to the illuminance level provided by sunlight. The lux values in the illuminance curve in sub-scenario B are high as the LED lamp is switched on uncontrolled, and the difference of 500 lux between the two sub-scenarios persists throughout the day. The illuminance values are lower in sub-scenario C as the light transmittance of the EC glass can be controlled even in the presence of LED lamps. It eliminates the highest illuminance values in sub-scenario B, especially during the day. However, it does not guarantee an entirely beneficial operation as the corresponding lux data exceeds the reference level. Even if IG80 glass is used, the most favorable control regarding the daily illuminance curve is provided in sub-scenario C, as LED lamp control is considered. Another service in ensuring lighting comfort is to keep the uniformity factor at the

required level. The uniformity factor in sub-scenario A, where only sunlight is considered, is below the required level (0.8) as expected, while in sub-scenarios B and C, where LED lamps are considered in addition to sunlight as an artificial light source, the uniformity factor is well above the required level. In addition to lighting comfort, another critical issue that concerns the consumer is the energy consumption caused by lighting and energy savings to reduce it. Energy consumption in sub-scenarios B and C, where the LED lamp is considered without a dimmer, is approximately equal. After comparing lighting comfort and energy savings, it is necessary to evaluate the relationship between dimmer levels with illuminance levels and energy consumption. The light transmittance of EC glass is low up to 17 hours in scenario C. However, it does not guarantee absolute lighting comfort as the illuminance level is above the reference level. After 5 pm, the light from the sun starts to decrease. Therefore, the light transmittance of EC glass increased again at the end of the day.

CONCLUSION

The test bench was modeled considering the office environment, and scenarios depending on the lighting method and glass type were considered in the study. The first scenario is divided into sub-scenarios considering only sunlight (A), sunlight, and LED without dimming (B) in the presence of IG80 glass. The second scenario assumes the reduction of the light transmittance of the EC glass (in sub-scenario C). Ambient temperature and irradiance data are collected with the help of a sensor box, while driver circuits are used to drive the EC glass and the LED. The control algorithms developed for the different scenarios communicate with the microcontroller via Python, and the data stored on the SD card is accessed remotely. An external power circuit is also used to adjust the output voltage level of the microcontroller for the LED driver. The main objective of the tests is to select the optimum lighting method that can provide lighting comfort and energy saving simultaneously. Sub-scenario A has no energy expenditure, while the lighting comfort (illuminance level and uniformity factor) is well below the standards in the region and climatic conditions where the tests were conducted. Although the uniformity factor offered by sub-scenario B is superior to the other scenarios, the illuminance level is well above the reference. Eventually, it became clear that to achieve a successful lighting method, the artificial light source should be controlled depending on the room's illuminance level. However, it is evident that in regions and climates with high solar radiation, the light transmittance of the EC glass needs to be adjusted or dimmed in addition to the LED lamp control.

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