MULTI-DIMENSIONAL ASSESSMENT OF HIGH-PERFORMANCE STATIC AND DYNAMIC GLAZING FOR ENVELOPE REFURBISHMENTS

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Abstract

The main aim of this paper is a multi-objective evaluation for envelope refurbishment with electrochromic glazing in a prototypical office room in Mannheim, Germany. Electrochromic glazing was compared to high-performance glazing with solar coating. The results showed that the high amount of embodied energy in electrochromic glazing could not be justified by the rather small savings of the operational energy. On the other hand, with a penalty-based control strategy, electrochromic glazing could improve visual comfort compared to static glazing with solar coating.

Introduction

The life cycle energy of buildings predominately comprises embodied energy (10-20 %) and operational energy (80-90 %) (Ramesh et al., 2010). One way to reduce operational energy in existing buildings is by optimizing their thermal envelope, which is often part of the refurbishment. However, embodied energy is expected to increase in energy-efficient buildings and can even exceed operational energy. Thereby, it is important to consider that the reduction of the operational energy does not occur through an unreasonable increase of the embodied energy.

Windows are responsible for a significant part of the building energy consumption, yet only 15 % of the windows in Europe included high-performance glazing in 2015 (European Commission, 2015). Since external shading cannot be installed in all types of façades, solar-coated (SC) or electrochromic (EC) windows can be used to achieve comfort and energy savings. Windows with solar coating let daylight pass through the glass while reducing the amount of the transmitted heat for protection against overheating. Additionally, a lower visible transmittance can help to reduce glare occurrences. Whether glazing is regarded as “solar control” depends on its solar transmittance: generally, glazing with a g-value below 0.5 qualifies as such (Wilson, 2004).

The role of windows is complex due to varying requirements for their performance at different times of the year, which call for adaptive properties. Unlike static windows, EC windows can dynamically modulate their spectral properties and adjust the level of solar and visible transmittance in response to electrical voltage. This is a considerable advantage because their properties can be controlled according to outdoor conditions.

Several publications investigated the reduction of operational energy through EC windows. Lee et al. (2012) reported that the automated electrochromic windows in a single, west-facing conference room in Washington DC reduced lighting energy by 91 %. Estimated annual energy savings and electricity peak demand were decreased by 48 % and 35 % respectively.

Belzer (2010) also reported that the lighting, cooling, and heating savings range between 15 % to 25 %, -3 % to 17 %, and -7 % to 15% respectively in small to medium offices at several locations in the US. The total savings of source energy range between 2 % to 7 %, depending on the window area, building location and orientation.

Cannavale et al. (2018) studied the energy and visual comfort performance in a simulated test room in Rome, Italy. The EC glazing with illuminance-based control saved 14 % of the annual energy consumption while guaranteeing the best use of daylighting in a confined space.

The embodied energy of EC glazing is often reported based on theoretical or laboratory findings instead of data provided by the existing EC glass manufacturers. Baldassarri et al. (2016) have conducted a “cradle-to-gate” energy and emissions analysis, in which they reported that the cumulative energy demand for conventional EC glazing excluding the framing was 2239 MJ-eq/m^2.

Papaefthimiou et al. (2006) have implemented the Energy Life Cycle Inventory analysis on a 40 x 40 cm prototype electrochromic window. The total primary energy for the production of the window unit was 2261 MJ. Considering that 9 % of the energy refers to the raw materials and the fabrication process of EC glazing, the cumulative energy demand excluding the framing was 1272 MJ-eq/m^2.

However, both studies were based on the laboratory production processes, whereas the process at the industrial scale can be very different and the embodied energy will be affected by the production rate.

The main objective of this paper is to introduce a multi-objective evaluation approach for building renovation for early decision-making. In this publication, we have compared the performance of EC glazing and the static glazing in regards to the operational, embodied energy and occupant comfort in a refurbished office room. To determine the embodied energy, environmental product declarations (EPDs) of the window manufacturers were used.

Theoretical office room

The theoretical office room in this study is located in Mannheim, Germany and is a lightweight construction with effective heat capacity of 47 Wh/(m²K). A large share of offices in Germany was built in the late 1980s and 1990s (Ecofys Germany GmbH, 2011). The average U-value of external walls in such offices is 0.85 W/m²K (Bundesministerium für Verkehr, Bau und Stadtentwicklung, 2011). The same value was used for the exterior south and west-facing walls of the pre-refurbished model of the theoretical office room. The German Building Energy Act prescribes that the thermal insulation of the exterior walls should not exceed 0.28 W/m²K in heated, non-residential buildings. In the refurbished model, this value was reached by adding external insulation to the exterior walls as the first measure of refurbishment. The rest of the surfaces in the room were assumed as adiabatic.

The second refurbishment measure is the exchange of windows. The window to wall ratio in the office room is 85 %, where the window covers 14 m² of the south-facing exterior wall. Such a large glazed façade is consistent with the architectural trends of the 1980s and 1990s. The U-value for glazing in German buildings built before 1994 is approximately 2.8 W/m²K (Fraunhofer-Informationszentrum Raum und Bau, 2011), a similarly high value was used for the original glazing in the base cases. For the exchange of the original window (Original), two windows were considered: a double glazing unit with solar coating and krypton gas filling (SC) and an EC double pane window with low-E coating and 90 % argon with 10 % air filling (EC). The overall window performance in table 1 was calculated by WINDOW 7.6.

Table 1: Properties of the glazing types

Glazing type	U_g W/(m²K)	SHGC	T_{sol}	T_{vis}	Shading state
Original	2.8	0.77	0.70	0.81	-
SC	1.1	0.31	0.23	0.38	-
EC					
Clear	1.3	0.43	0.29	0.44	S0
Low		0.21	0.07	0.12	S1
Middle		0.16	0.02	0.04	S2
Full		0.14	0.004	0.007	S3

The office room is designed for four occupants and has a floor area of 30 m². The usual work schedule of the building occupants in the prototypical office is Monday through Friday from 8:00 to 18:00.

Boundary conditions for operational energy

To simulate the operational energy of the office room TRNSYS software was used. For the simulation framework refer to (Ganji & Hoffmann, 2020; Ganji Kheybari et al., 2021). The basic air change (ventilation + infiltration) is 1.21 h^{-1} during the occupied hours and 0.24 h^{-1} during unoccupied hours (DIN 4108-2, 2013). For the increased ventilation, the simulation considers 3 h^{-1} for occupied hours when the indoor temperature is above 23 °C and higher than the outdoor temperature. For unoccupied hours and night ventilation, 5 h^{-1} was considered when the indoor temperature is above 21 °C and the daily average outdoor temperature is above 18 °C.

The setpoints for heating and cooling are 21 °C and 25 °C respectively with a setback of 3 K during unoccupied hours. The upper threshold was based on the comfort results obtained from the preliminary simulations.

Table 2: Boundary conditions in the office rooms

Item	Description	Additional details
Room geometry	Length = 6 m Width = 5 m Height = 3.3 m Window = 14 m² WWR= 85%	Open-plan office 3D geometry in Rhino
Internal gains	4 people (4 x 145 W) 4 computers (4 x 140 W) LED lighting (5 W/m²)	Daylight based control for artificial lighting in TRNSYS set-points: 300 - 500 lx
Infiltration	n = 0.24 h^{-1}	
Ventilation	Occupied: n =1.21 h^{-1}	Including infiltration
Increased ventilation	Occupied: n = 3 h^{-1}	T_{in}>T_{out} & T_{in}>23°C
	Unoccupied: n = 5 h^{-1}	$T_{out-avg24h}$>18°C & T_{in}>T_{out} & T_{in}>21°C
Heating /Cooling set-point temp	Heating = 21°C	Unoccupied: 18°C
	Cooling = 25°C	Unoccupied: 28°C

Heat pump and a chiller system were assumed for heating and cooling in this study. The annual average seasonal performance factor was considered COP = 4.2 for heating and COP = 4.0 for cooling to convert energy consumption of occupants to end-use energy (Miara, 2016).

Two control strategies and a static clear state were defined to operate the EC window:

Static clear state (NoCtrl) is used as the baseline condition. The EC window is never tinted in this state.

Rule-based control (Rad): classical control that is dependent on the incident global radiation on the facade. The top, middle and bottom window zones tint to [S3, S3, S0] configuration when the sensors register global radiation equal to or beyond 200 W/m². This threshold is prescribed for the installation of devices for sun protection for south-oriented windows in non-residential buildings (DIN 4108-2, 2013).

Penalty-based control (Pen): theoretical, multi-objective and predictive control that was generated according to the predefined priorities for energy, visual and thermal comfort parameters (Ganji Kheybari et al., 2021). Hourly results of all 64 tinting combinations have to be generated to identify the top-ranked combination with the minimum penalties. The priority for parameters such as minimal energy consumption, maximum thermal or visual comfort is applied by occupants. These priorities may vary according to the selected weighing fractions (ω) for each penalty (P). Penalty functions were defined for daylight glare probability index (P_{dgp}), useful daylight illuminance at every workplace ($P_{daylight}$), the usage of electric lighting ($P_{art.light}$), thermal discomfort (P_{pmv}) and finally, energy demand (P_{energy}). In this paper, the weighting fractions were assigned equally with the same priority in the total penalty function, which means that the priority is equal among energy savings, thermal and visual comfort provision.

$$Penalty_{\ total} = \begin{pmatrix} \omega 1 \times P_{\ dgp} + \omega 2 \times P_{\ daylight} \\ + \omega 3 \times P_{\ art.light} + \omega 4 \times P_{\ pmv} \\ + \omega 5 \times P_{energy} \end{pmatrix} \quad (1)$$

Table 3: Controls for EC glazing

Control strategies	Condition	EC tinting state [Top, Middle, Bottom zones]
Clear state (NoCtrl)	-	[S0,S0,S0] Clear
Control by radiation (Rad)	Radiation $_{global}$ < 200 W/m²	[S0,S0,S0] Clear
	Radiation $_{global}$ ≥ 200 W/m²	[S3,S3,S0] Fully tinted except for the bottom zone
Penalty based control (Pen)	Penalty-based algorithm	[var., var., var.] var: S0, S1,S2 or S3
		Thermal, visual and energy aspects with the same weighting fraction

Data collection for embodied energy

Initial embodied energy refers to the indirect energy that is consumed during the production of the materials and direct energy that is required to construct buildings (Stephan et al., 2011). Due to the lack of information about the energy required for the installation of EC windows and the complexities that might be associated with this process, the analysis was focused on indirect embodied energy only. This data is available in the environmental product declaration (EPD). For data collection, the German standardized database Ökobaudat reports various types of datasets for construction materials regarding their resource use and global ecological impacts. Since Ökobaudat does not contain datasets for glazing with solar coating or EC glazing, EPDs that were released by the glazing manufacturers were used instead (AGC Glass Europe, 2019; SAGE Electrochromics, 2020). The data in the analysis is presented as the yearly average, where the total embodied energy derived from the EPDs or Ökobaudat is divided over the net floor area and the building life span of 60 years.

Table 4: Quantities of the materials before and after refurbishment.

Material	Quantity		Total renewable and non-renewable energy (MJ)
	Pre-refurbish.	Refurbish.	
Plaster	1.17 m³		1141.90 per 1 m³
Insulation	6.67 m³	8.90 m³	533.40 per 1 m³
Concrete masonry (Wall)	7.36 m³		1494.50 per 1 m³
Gypsum	132.60 m²		68.20 per 1 m²
Ceramic	60.00 m²		121.30 per 1 m²
Precast concrete (Ceiling /Floor)	60.00 m² (20 cm thickness)		622.20 (20 cm) 808.86 (26 cm) per 1 m²
Glazing	14.00 m²		Original: 482.70 SC: 1318.70 EC: 9413.10 per 1 m²
Frame	15.20 m		636.70 per 1 m

Evaluation of occupant comfort

To assess thermal comfort the Predicted Mean Vote (PMV) was calculated. Clothing insulation was defined by the factors 0.5 or 1 clo, respective of the exterior temperature in summertime and wintertime. The metabolic rate was set to 1.2 met. Air velocity indoors was 0.1 m/s. Thermal comfort can be achieved when PMV is between +0.5 and -0.5 and PPD is kept below 10 % (Class B) (ISO 7730, 2005).

For visual comfort, useful daylight illuminance (UDI) and glare probability were analyzed. UDI expresses the percentage of the occupied hours when the horizontal illuminance is less than 3000 lux but greater than 300 lux. Hourly horizontal illuminance was processed for all the workplaces 75 cm above the ground level.

To predict the probability of glare, the simplified method was used in this paper by simulating vertical eye illuminance (Ev) at 120 cm height. A simulation was run for every glazing combination in Radiance lighting simulation tool. Glare experience was rated according to the following scale: acceptable glare (DGP < 0.35), perceptible glare (0.4 > DGP ≥ 0.35), disturbing glare (0.45 > DGP ≥ 0.4), intolerable glare (DGP ≥ 0.45) (DIN EN 17037, 2019).

Results

Figure 1 shows that the increase of thermal insulation in the exterior wall and the exchange of the window have substantially reduced heating and cooling energy. The highest reduction by approximately 17 kWh/(m²a) or 63 % is seen in the configuration with the EC window and penalty-based control. A comparable reduction was achieved by the window with solar coating (SC).

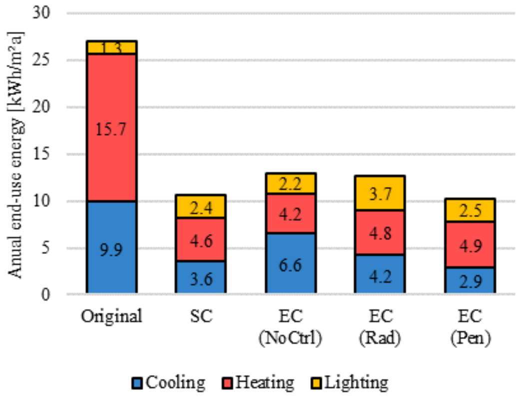

Figure 1: Operational end-use energy before and after refurbishment

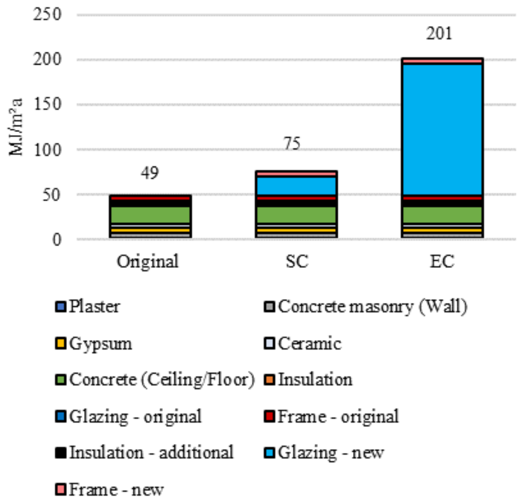

Figure 2: Embodied energy before and after refurbishment

The increase of thermal insulation and the replacement of the original windows with SC glazing and a frame increased embodied energy by 26 MJ/(m²a) in comparison to the room with the original windows. In the scenario with EC glazing, the increase in embodied energy was 152 MJ/(m²a). The embodied energy of EC glazing alone (146 MJ/(m²a)) exceeds the embodied energy of the rest of the materials in the office room, see Figure 2.

The primary energy factor of 1.8 was applied to convert end-use to primary energy (GEG 2020). After installing the window with solar coating and adding thermal insulation, the total primary energy was decreased from 224 MJ/(m²a) to 144 MJ/(m²a). It increased from 224 MJ/(m²a) to 268 MJ/(m²a) when the original glazing was replaced by EC with penalty-based control. Although this configuration reduced operational energy the most, this reduction did not compensate for the production burden of such glazing. The total primary energy in the office room with the best control strategy for EC glazing exceeds the variant with the solar-coated glazing by 1.9 times.

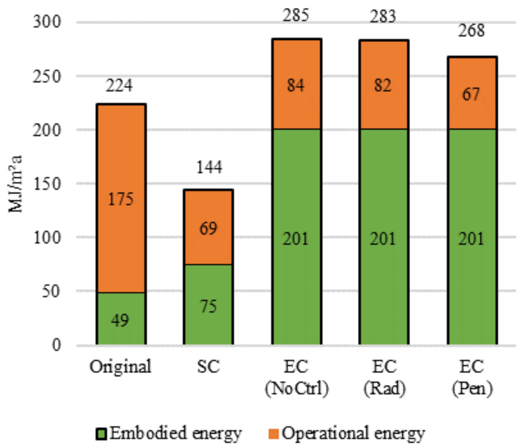

Figure 3: Primary energy before and after refurbishment

Hourly results of the individual local predicted mean vote (PMV) indicate that occupants felt neutral only 62 % of the occupied time in the pre-refurbished office room. After the refurbishment that included SC windows, the hours of thermal comfort increased to 88 %. In the configuration with the EC glazing and penalty-based control, thermal comfort was achieved for 89 % of the occupied hours.

Analysis of the useful daylight illuminance (UDI) indicates that there are too many "bright" hours (illuminance > 3000 lux) that are unwanted due to the risk of glare or overheating in rooms with the original and SC windows. EC window with penalty-based control provides the highest amount (86 %) of the occupied hours within the useful range of illuminance.

In the case of glare probability, only 53 % of the occupied hours are within the acceptable range in the pre-refurbished room. After renovation, the SC window increased the percentage of acceptable hours to 90 %, whereas the EC window with radiation and penalty-based control almost eliminated the possibility of glare (99%).

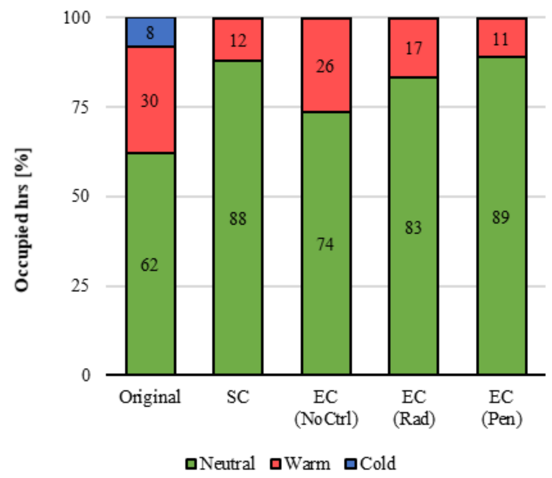

Figure 4: PMV before and after refurbishment

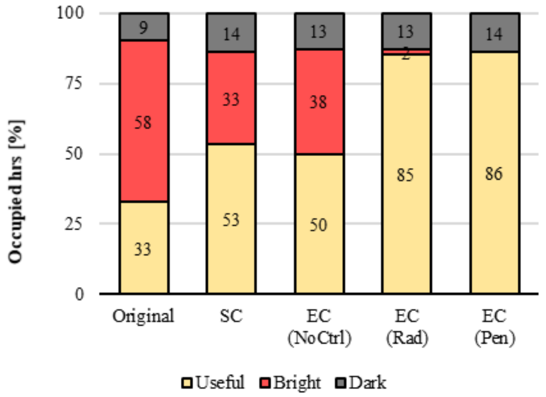

Figure 5: UDI before and after refurbishment

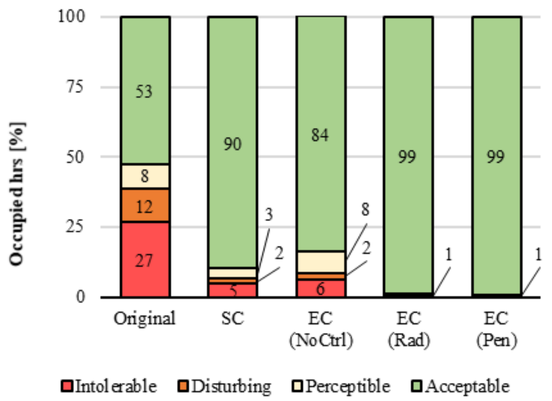

Figure 6: Glare before and after refurbishment

Discussion

In this paper, we have used a multi-objective evaluation approach to assess operational energy, embodied energy and occupant comfort in a refurbished prototypical office room in Mannheim, Germany. The refurbishment consisted of the addition of thermal insulation and the exchange of the original window to a SC or EC window. Two dynamic control strategies for EC windows were investigated: rule-based (incident radiation) and penalty-based (multi-objective prediction) controls.

The addition of insulation to the walls and exchange of the original window led to a drop in operational energy. EC window with penalty-based control decreased the operational energy the most, from approximately 27 kWh/(m²a) to 10 kWh/(m²a). The solar-coated window also led to similar savings reducing operational energy to 11 kWh/(m²a).

The embodied energy of the refurbished office room with EC glazing was 1.9 times higher in comparison to the refurbishment with SC glazing. The primary energy needed to manufacture the EC glazing was significantly higher in the EPD than what was reported previously in the literature. In consequence, the total primary energy of these variants was considerably higher than of those with the SC glazing.

As for the comfort criteria, the EC window could ensure the highest level of thermal comfort when controlled via penalty-based control. However, the percentage of occupied hours with neutral condition was only 1 % higher in comparison to SC window.

In terms of visual comfort, the variants with EC glazing performed better than the solar-coated glazing when useful daylight illuminance and glare probability were considered. The EC window with penalty based control kept 86 % of the occupied time within the useful daylight illuminance range, which was 33 % higher in comparison to the SC window. Additionally, there was no probability of glare in the room with the EC window for 99 % of the occupied time, while the SC window achieved this only for 90 % of the occupied time.

Summary

In this contribution, we have investigated different aspects of the electrochromic window for the refurbishment of largely glazed office rooms. The electrochromic window was found to reduce operational energy by 63 % in comparison to the original window and by only 3 % in comparison to the solar-coated window.

However, the office room refurbished with electrochromic glazing resulted in higher annual primary energy than that with static glazing with solar-coating when a 60-year life span was considered. This can be attributed to the high embodied energy of the electrochromic glazing unit that was based on the Environmental Product Declaration.

In terms of thermal comfort, the electrochromic glazing with a penalty-based control performed 1 % better than the static glazing with solar-coating.

Electrochromic windows significantly improved the occupants' visual comfort by increasing the hours of useful daylight illuminance by 33 % and reducing the probability of glare by 9 % in comparison to the static glazing with solar-coating.

Regarding the control strategy for electrochromic glazing, the penalty-based control performed better than the radiation-based control primarily with regards to the operational energy and thermal comfort.

According to our findings, the decision for window replacement would have to be based on the improvement of the thermal and predominately visual comfort because the savings of operational energy could not compensate for the high embodied energy of electrochromic glazing.

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