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A multi-objective evaluation for envelope refurbishments with electrochromic glazing

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ABSTRACT

The main aim of this paper is a multi-objective evaluation of electrochromic (EC) glazing with consideration of operational and embodied energy including the impact of switchable glazing on visual and thermal comfort. Different criteria were evaluated for the refurbishment of a prototypical 30 m^2 office room in Mannheim, Germany. The room prototype was assumed as lightweight and heavyweight construction, where refurbishment strategies such as the addition of thermal insulation and the exchange of windows were investigated. For the window exchange, EC-glazing was compared to a high-performance glazing with solar coating. The EC-glazing was automated via a rule-based (incident radiation) and a penalty-based (multi-objective prediction) control strategy. Regarding operational energy, the EC-glazing performed slightly better than the glazing with solar coating. However, the results showed that the high amount of embodied energy in EC-glazings could not be justified by the rather small savings of the operational energy. On the other hand, with the penalty-based control, the EC-glazing improved visual comfort significantly in comparison to the static glazing with solar coating. The decision to replace the original glazing with an EC-glazing as opposed to a glazing with solar coating would have to be based on the improvement of occupants' comfort, due to an unjustifiable increase of embodied energy and marginal savings of operational energy.

1. Introduction

In the European Union (EU), buildings are responsible for nearly 40% of energy consumption and 36% of greenhouse emissions [1]. According to the European Commission, 35% of buildings in the EU are over 50 years old and only about 1% of the entire building stock is renovated [2]. Building renovation is a promising intervention because it can reduce total energy consumption and carbon emissions by 5–6% and 5% respectively [2] and can play a major role in the EU's goal of carbon neutrality by 2050.

Embodied energy (10–20%) and operational energy (80–90%) make up the biggest part of the life cycle energy in buildings [3]. One way to reduce operational energy in existing buildings is by optimizing their thermal envelope, which is often done as a part of the refurbishment. However, embodied energy is expected to increase in energy-efficient buildings and can even exceed operational energy [4,5]. This is noteworthy since the building energy efficiency class is usually evaluated based on the operational energy without consideration of the embodied energy in rating schemes like the "Energy Performance Certificate" [6]. 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 glass in 2015 [7]. Since external shading cannot be installed in all types of façades, solar-coated or electrochromic (EC) windows can be used to achieve comfort and energy savings. Windows with solar coating let daylight pass through the glass while at the same time reducing the amount of the transmitted heat for protection against overheating. Additionally, lower visible transmittance can help reduce glare experiences, although often at the expense of the increase in artificial lighting energy. Whether glazing is regarded as "solar control" depends on its solar transmittance: generally, glazing with a g-value below 0.5 qualifies as such [8].

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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 solar coated 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. However, one of the drawbacks of EC-windows is the blue tint of the glazing in the activated state that can distort the spectrum of the transmitted daylight.

Many studies have investigated the reduction of operational energy through EC windows. A study conducted by Lee et al. [9] investigated the automated electrochromic windows in a single, west-facing conference room in Washington DC. The lighting energy was reduced by 91% and the estimated annual energy savings and electricity peak demand were decreased by 48% and 35% respectively.

A study by Cannavale et al. [11] explored the energy and visual comfort performance in a simulated room in Rome, Italy. The study indicated that the EC glazing with illuminance-based control saved 14% of the annual energy consumption while ensuring the best use of daylighting.

Belzer [10] has concluded that in small to medium-sized offices at several locations in the US, the lighting, cooling, and heating savings range between 15% and 25%, −3%–17%, and −7% to 15% respectively. The total savings of source energy depend on the window area, building location and orientation but range between 2% and 7%.

On the other hand, the studies that investigated the embodied energy of EC glazing often report the results based on the theoretical or laboratory findings rather than using the data of the existing EC glass manufacturers. A “cradle-to-gate” energy and emissions analysis was done by Baldassarri et al. [11], in which they reported that the cumulative energy demand for conventional EC glazing excluding the framing was 2239 MJ-eq/m^2.

Energy Life Cycle Inventory analysis was conducted by Papaefthimiou et al. [12] on a 40 × 40 cm prototype electrochromic window. The total primary energy for the production of the window unit was 2261 MJ. However, 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.

It is noteworthy that both of the aforementioned studies were based on the laboratory production processes, whereas the process at the industrial scale will be affected by the production rate.

Although the increase in the embodied energy is unavoidable with the installation of EC-windows, it could be justified if the reduction of the operational energy is meaningful. Therefore, EC-windows must be operated efficiently via a control that aims to save energy while maintaining acceptable indoor conditions.

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.

2. Methodology of refurbishment

2.1. Main objective

In this publication, we compared the performance of a glazing with solar coating against an EC-glazing operated via different controls in refurbished lightweight and heavyweight constructions. For a broader comparison, we investigated the EC-glazing of two manufacturers that are currently available on the market (see section 2.4.2). Thus, operational energy, embodied energy of the materials and occupants’ comfort are regarded in this contribution.

Besides the improvement of the thermal insulation of the prototypical 30 m^2 office room, the study explores multiple glazing replacement scenarios for the refurbishment. The impact of the control strategy on the performance of EC-glazing was also examined. The office room prototype is presented as a lightweight and heavyweight variant to account for different possibilities of building construction. Fig. 1 illustrates the methodology for refurbishment for the prototypical office room and the evaluation criteria.

2.2. Prototypical office room

The prototypical office room used in this simulation-based study is fully glazed (south orientation) and located in Mannheim, Germany. It is designed for four occupants and has a floor area of 30 m^2(see Fig. 2). The usual work schedule of the building occupants in the prototypical office is Monday through Friday from 8:00 to 18:00. Their seats are arranged into two groups: group 1 (G1) and group 2 (G2). They are categorized according to their distance from the window. This is a necessary differentiation, as it is known that highly glazed facades can impact the thermal comfort of the occupants seated in the proximity of the transparent areas.

2.3. Construction types

The impact of the thermal mass was investigated to account for different types of constructions. Therefore, two base cases with different thermal mass are presented in this contribution. To calculate the thermal mass of both construction types, a simplified procedure according to DIN EN ISO 13786 Appendix A according to DIN 4108–2 was implemented. The construction with the effective heat capacity of 47 Wh/(K·m) was classified as the lightweight base case and 155 Wh/(K·m) as the heavyweight base case. The difference in thermal mass is attributed to the additional concrete in the floor and walls of the heavyweight construction (see figure A.2).

2.4. Refurbishment measures

Both construction types were considered as base cases in need of additional insulation and replacement of the original windows. Fig. 3 illustrates the methodology of refurbishment.

2.4.1. Thermal insulation

In Germany, there are 323,700 office and administrative buildings with a total floor space of 382.4 million square meters [13]. A large share of offices was built in the late 1980s and 1990s [14]. The average U-value of external walls in such offices is 0.85 W/m^{2}K [15]. Approximately the same values were used for the exterior walls in our pre-refurbished models. German Building Energy Act (GEG 2020) prescribes that the thermal insulation of the exterior walls should not exceed 0.28 W/m^{2}K in heated, non-residential buildings [6]. In the refurbished models, this value was reached by adding external insulation to the exterior walls. For the construction details see table A.1 in the Appendix.

The second refurbishment measure is the exchange of windows. The window to wall ratio in the office room is 85% and the window makes up 14 m^2 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 2.9 W/m^{2}K [16], a similarly high value was used for the original glazing in the base cases. For the exchange, three windows were considered: a double glazing unit with solar coating and krypton gas filling (U = 1.1 W/m^{2}K) and two EC-double pane windows with low-E coating and 90% argon with 10% air filling (U = 1.3 W/m^{2}K) from different manufacturers. Their properties are discussed in detail in section 2.4.2.

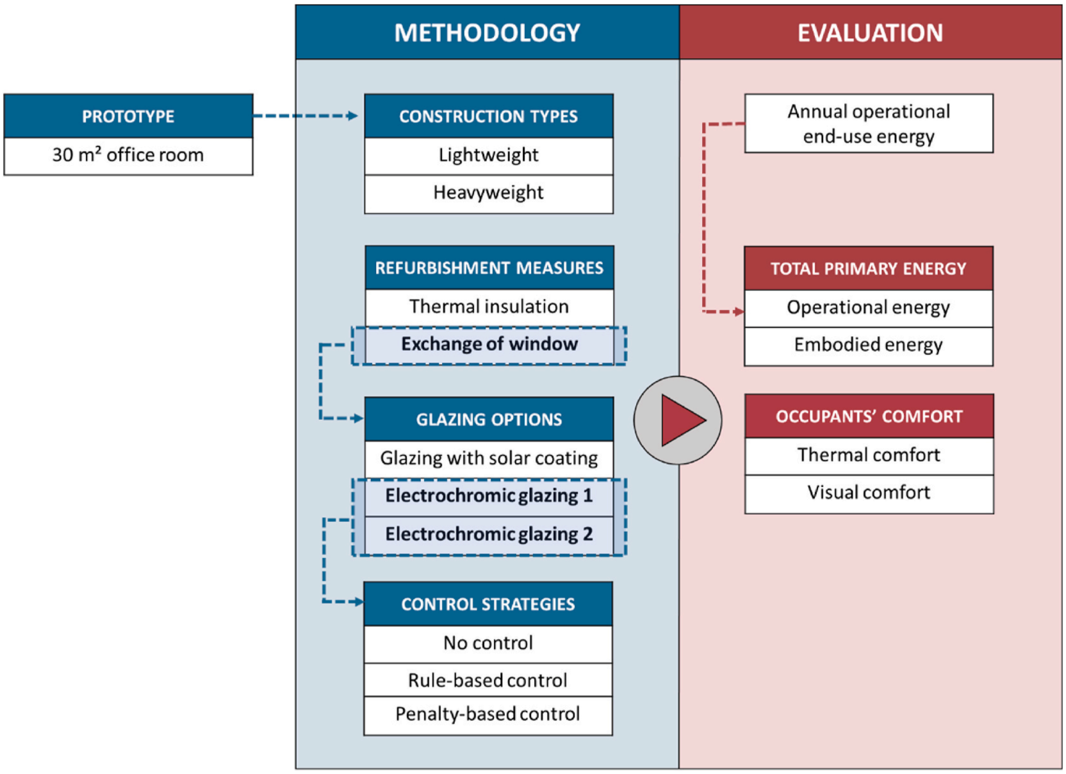

Fig. 1. Methodology for the refurbishment of the office room and the evaluation criteria.

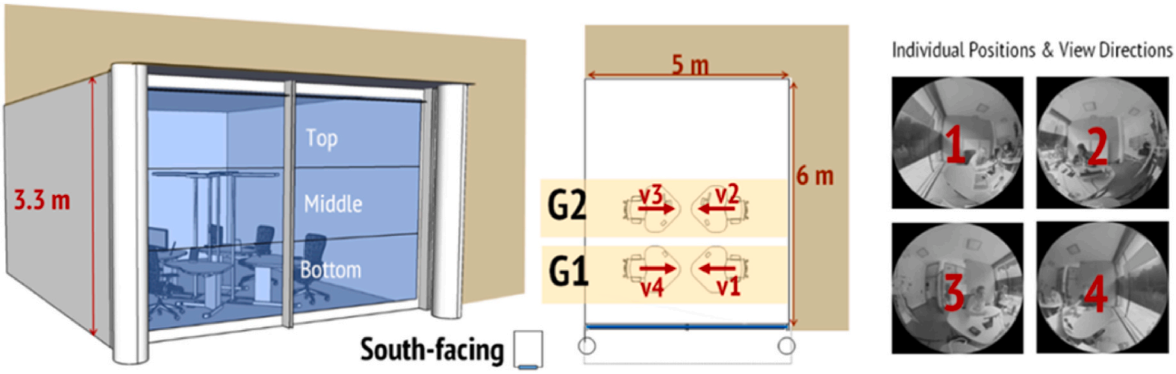

Fig. 2. Visual representation of the prototypical room and view directions.

2.4.2. *Glazing exchange*

As a part of the refurbishment, glazing with solar coating and two brands of EC-glazings that are currently available on the market were selected to replace the original old windows (see Table 1). For spectral transmittance of each glazing configuration, see figure A.3 in Appendix. The total area of the EC-glazing is divided into three zones: top, middle and bottom (refer to Fig. 2). Each zone can be controlled independently of another. This presents 64 possible configurations of EC-glazing with four levels of tinting.

Both EC-glazings, EC1 and EC2, can alter their solar and visible transmittance in four states: clear (S0), low tinted (S1), middle tinted (S2) and fully tinted (S3). SHGC considers primary and secondary solar heat gain and it is higher in EC2, meaning that it transmits more of the direct and absorbed heat into the space. SHGC is higher in all of the states of EC-window 2 by 5% in S0, 12% in S1 and S2, 7% in S3. For visible transmittance, the difference is higher by 13% in S1, 15% in S2 and 8.6% in S3 making EC2 more transparent to daylight in three of its states.

3. Evaluation criteria

3.1. *Operational energy*

To simulate the operational energy of the office room TRNSYS software was used [18] (for the simulation framework, refer to Ref. [19]). The office room has four computers and two groups of LED light fixtures (5 W/m^2) that contribute to the internal gains in the room. LED lighting supplements daylight by switching on only when illuminance falls below 300 lx and switches off once it exceeds 500 lx.

The basic air change (ventilation + infiltration) is 1.21 h^{-1} during the occupied hours and 0.24 h^{-1} during unoccupied hours [20]. 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 (see table A.4). For unoccupied hours and night ventilation, 5 air changes per hour were 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

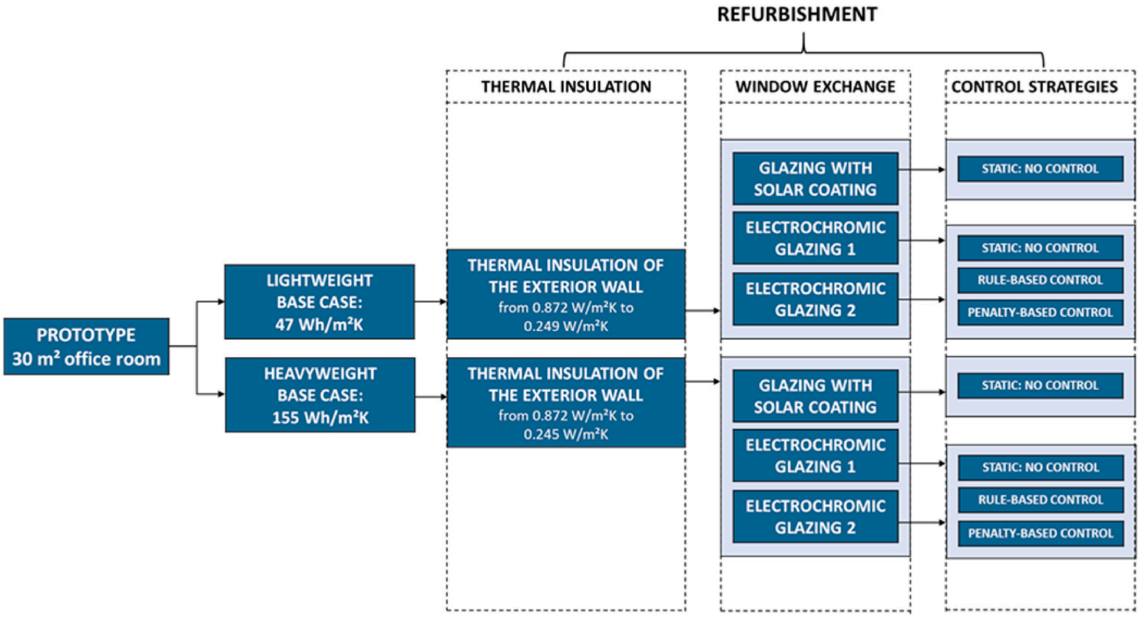

Fig. 3. Base cases and methodology for refurbishment.

Table 1
Properties of the glazing types. (* CRI of transmitted daylight according to DIN EN 410 [17].)

Glazing type	U_g W/m^{2}K	SHGC	T_{sol}	T_{vis}	CRI*	Shading state
Old (to be replaced): double-glazed insulating window with 12% air 22% argon and 66% krypton	2.8	0.77	0.70	0.81	98.2	–
Glazing unit with solar, double silver coating (SC) and krypton gas filling	1.1	0.31	0.23	0.38	93.7	–
Electrochromic glazing 1 (EC1): insulated glass unit with low-E coating, 90% argon and 10% air filling						
Clear state	1.3	0.43	0.29	0.44	90.5	S0
Low tinted		0.21	0.07	0.12	83.4	S1
Middle tinted		0.16	0.02	0.04	77.4	S2
Fully tinted		0.14	0.004	0.007	73.6	S3
Electrochromic glazing 2 (EC2): insulated glass unit with low-E coating, 90% argon and 10% air filling						
Clear state	1.3	0.48	0.31	0.43	95.4	S0
Low tinted		0.33	0.17	0.25	91.3	S1
Middle tinted		0.28	0.12	0.19	88.3	S2
Fully tinted		0.21	0.057	0.093	80.6	S3

respectively with a setback of 3 K during unoccupied hours. Although the standard prescribes an upper threshold of 27 °C for the considered region [20], our model includes a highly-glazed façade that is more likely to contribute to overheating, therefore we lowered the upper threshold to 25 °C based on the comfort results obtained from the preliminary simulations.

Since the use of heat-pump-based systems in buildings is becoming more popular, a heat pump and a chiller system were assumed for heating and cooling in this study. The annual average of seasonal performance factor was considered $\eta = 4.2$ for heating and $COP = 4.0$ for cooling to convert energy consumption of occupants to end-use energy [21], see section 4.1. Lastly, the end-use energy was converted to the primary energy using the primary energy factor of 1.8 [6], the results are reported in section 4.3.

3.1.1. Control strategies for EC-glazing

Two control strategies and a static clear state were defined to operate both EC-windows (refer to Table 2):

1. Static clear state (NoCtrl) is used as the baseline condition. EC-windows are never tinted in this state.
2. Rule-based control (Rad): classical control that is dependent on the incident global radiation on the facade. The windows tint to an "S3, S3, S0" configuration when the sensors register global radiation equal to or beyond 200 W/m^2. This threshold is prescribed for the installation of devices for sun protection by DIN EN 4108–2 for south-oriented windows in non-residential buildings [20].
3. 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 [19]. To do so, 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

Table 2
Controls for EC-glazing.

Control strategies	Condition	EC tinting state ░░▒▓ [Top, Middle, Bottom zone]
Clear state (NoCtrl)	Fixed not-shaded	[S0,S0,S0] Clear
Control by radiation (Rad)	Radiation $_{global}$ < 200 W/m^2 Radiation $_{global}$ ≥ 200 W/m^2	[S0,S0,S0] Clear [S3,S3,S0] Fully tinted except for the bottom zone
Optimal/Penalty based control (Pen)	Penalty-based algorithm [19]	[var., var., var.] S0, S1, S2 or S3 Thermal, visual and energy aspects with the same weighting fraction

in the total penalty function. Meaning, that the priority is the same among energy savings, thermal and visual comfort provision.

$$Penalty_{total} = \left(\omega 1 \times P_{dgp} + \omega 2 \times P_{daylight} + \omega 3 \times P_{art.light} + \omega 4 \times P_{pmv} + \omega 5 \times P_{energy}\right) \tag{1}$$

3.2. Embodied energy

Initial embodied energy refers to the indirect energy that is consumed in the production of the materials and direct energy that is required to construct buildings [25,26]. 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, we focused on the analysis of indirect embodied energy only. This data is available in the environmental product declaration (EPD) since it is the minimum requirement that is needed for the declaration [27]. Although transport and assembly also contribute to the total life cycle of any building, Ylmen et al. have reported that these phases have a low environmental impact in comparison to the production and operation of buildings [28].

For data collection, the German standardized database Ökobaudat was used that reports various types of datasets for construction materials for determining their resource use and global ecological impacts [29]. Since Ökobaudat does not contain datasets for glazing with solar coating or EC-glazing, we have relied on the EPDs that were released by the glazing manufacturers [22,23]. As of today, only a few EC-glass companies released EPDs for their products [23,24,30]. Therefore, we selected the most recent EPD and used the same data for the embodied energy of both EC-glazing units discussed in this contribution. Nevertheless, these values may differ based on the production processes of the respective manufacturers of EC-glazing. The data in our analysis is presented as the yearly average, where the total embodied energy derived from the EPDs or Ökobaudat (see Table 3) is divided over the net floor area and the building life span of 60 years.

3.3. Occupants‘ comfort

This section presents the parameters through which the achievement of visual and thermal comfort could be ensured. Additionally, Table 4 summarizes the performance categories of each criterion that is

Table 4
Evaluation criteria and the performance categories used in this study.

Evaluation criteria	Sub-criterion	Parameters	Performance Categories
Primary energy	Operational energy	Primary energy calculated from sensible cooling, heating, and electric lighting demand from TRNSYS considering: COP heating = 4.2, COP cooling = 4.0, COP lighting = 1; electricity primary energy factor = 1.8	
	Embodied energy	Total renewable and non-renewable energy (MJ) based on the EPDs and Ökobaudat for the 60-year life span	
Occupants comfort	Predicted mean vote (PMV)	Clothing factor: Clo = 0.5 clo: $T_{out\text{-}avg24h} > 18$ °C Clo = 1 clo: $T_{out\text{-}avg24h} \leq 18$ °C Metabolic rate: 1.2 met Air velocity: 0.1 m/s Internally calculated by TRNSYS	Cold: PMV < -0.5 Neutral: $0.5 \leq$PMV$\leq +0.5$ Warm: $+0.5<$PMV
	Useful Daylight Illuminance (UDI)	Horizontal illuminance (Eh) calculated using Radiance 3-phase method	Dark: Eh $<$ 300 lux Useful: 300 lux $\leq$ Eh $\leq$ 3000 lux Bright: Eh $>$ 3000 lux
	Simplified Daylight glare probability (DGPs)	DGPs is calculated based on vertical illuminance (Ev) using Radiance 3-phase method	Acceptable: $0.35<$DGP Perceptible: $0.35\leq$DGP<0.4 Disturbing: $0.4\leq$DGP<0.45 Intolerable: $0.45\leq$DGP

Table 3
Quantities of the materials before and after refurbishment. Primary energy: Ökobaudat [29] and EPDs [22,23].

Material	Quantity				Unit	Total renewable and non -renewable energy per unit (MJ)	Service life
	Base case (lightweight)	Base case (heavyweight)	Refurbished (lightweight)	Refurbished (heavyweight)			
Plaster	1.172		1.172		m^3	1141.9	As building
Insulation	6.669		8.899		m^3	533.4	As building
Concrete masonry (Wall)	7.364	13.224	7.364	13.224	m^3	1494.5	As building
Gypsum	132.600		132.600		m^2	68.2	As building
Ceramic	60.000		60.000		m^2	121.3	As building
Precast concrete (Ceiling/Floor)	60.000 (20 cm thickness)	60.000 (26 cm thickness)	60.000 (20 cm thickness)	60.000 (26 cm thickness)	m^2	622.200 (20 cm) 808.86 (26 cm)	As building
Glazing	14.000 (no exchange)		14.000 (+ exchange after 30 years)		m^2	Old: 482,7 Solar: 1318.7 [22] EC: 9413.1 [23,24]	30 years
Frame	15.200 (no exchange)		15.200 (+ exchange after 30 years)		M	636.7	30 years

presented and discussed in section 4.

3.3.1. *Thermal comfort*

For the assessment of thermal comfort via Predicted Mean Vote (PMV), clothing factor, metabolic rate and air velocity are necessary. Clothing insulation is defined by the factors 0.5 or 1 clo, respective of the exterior temperature in summertime and wintertime. The selected metabolic rate is 1.2 met, which corresponds to the occupants' activity level at the office [31]. Air velocity indoors is 0.1 m/s. Thermal comfort can be achieved when PMV is between +0.5 and −0.5 and PPD is kept below 10% (ISO 7730, Class B) [32].

3.3.2. *Visual comfort*

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 experience of glare, the simplified method was used in this paper by simulating vertical eye illuminance (Ev) at 120 cm height. This was done for every glazing and EC-combination in Radiance lighting simulation tool [33]. Glare experience was rated according to the following scale: acceptable glare (DGP <0.35), perceptible glare ($0.4 > \text{DGP} \geq 0.35$), disturbing glare ($0.45 > \text{DGP} \geq 0.4$), intolerable glare ($\text{DGP} \geq 0.45$). According to DIN EN 17037:2019, "good-class" glare protection is achieved when the values that exceed 0.4 are kept below 5% of the annually occupied time [34].

4. Results

4.1. *Operational energy*

Despite the same level of insulation and identical windows in the base cases, the operational energy of the lightweight office room is approximately 7 kWh/m^{2}a or 26% higher than in the heavyweight construction primarily due to the increased heating and cooling (see Fig. 4).

This difference is attributed solely to the thermal mass. Additional thermal mass delays the peak loads for both cooling and heating. By using sufficient night flushing on a summer night, inner surfaces can keep the room cool for the next day. On a winter day, thermal mass absorbs and keeps the solar radiation and then releases the heat gradually into the room. Since solar absorptivity and reflectivity of the surfaces were assumed the same in both lightweight and heavyweight base cases, no significant difference in electric lighting was expected.

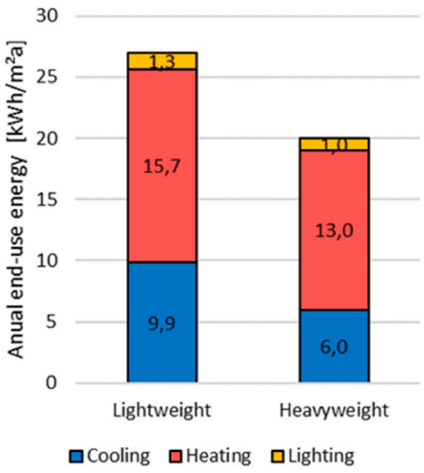

Fig. 4. Annual end-use operational energy of lightweight and heavyweight base cases before the refurbishment.

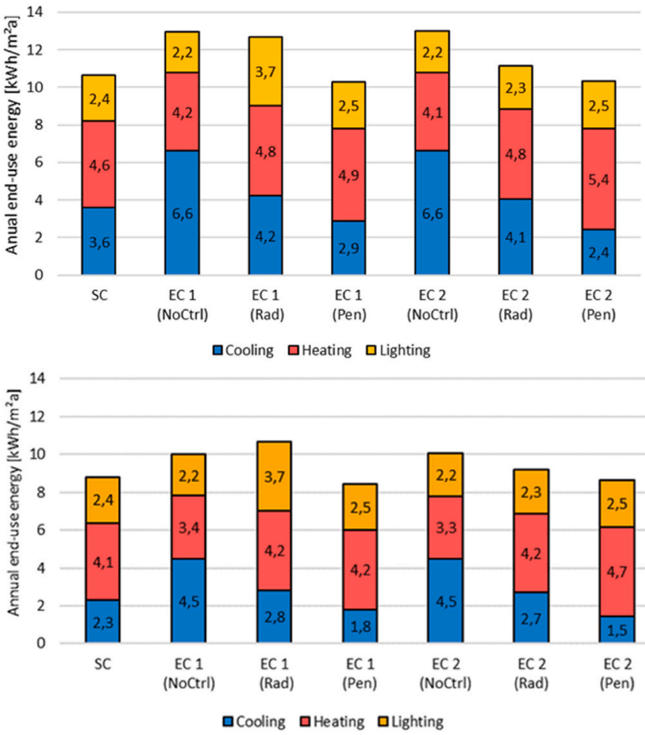

Fig. 5. Annual end-use operational energy of lightweight and heavyweight construction after the refurbishment.

The increase of thermal insulation in the exterior wall and the exchange of windows in the lightweight variant have substantially reduced heating and cooling energy in all cases (see Fig. 5). The highest reduction by approximately 17 kWh/m^{2}a or 63% (in comparison to the lightweight base case) is seen in configurations with EC1 and EC2 when they are controlled by penalty-based control.

In the case with heavyweight construction, the reduction is similar for the variants with the increased thermal insulation and solar-coated glazing (SC), EC1 and EC2 when controlled through the penalty-based approach. Here the reduction is 11 kWh/m^{2}a or 55% in comparison to the heavyweight base case.

Notably, the lighting electricity for EC1 with rule-based control is higher than the EC2 under the same control condition. This increase in lighting demand is due to the lower visible transmittance of EC1 (Tvis = 0.007) compared to EC2 (Tvis = 0.093). Therefore, when the shading is active (IT $\geq$ 200 W/m^2) the top and middle zones of EC1 become fully tinted leading to a higher energy demand for lighting in this control.

In both lightweight and heavyweight cases, the penalty-based control outperforms the rule-based control. However, the improvement is of bigger magnitude for EC1 when compared to EC2. This behavior can be explained by the lower Tsol for EC1 in the dark state (Tsol = 0.004) in comparison to the darkest state of EC2 (Tsol = 0.057). The lower the solar transmittance, the better is the shading protection which results in a lower cooling demand in both lightweight and heavyweight cases.

It is noteworthy, that the impact of thermal conductance is less prevalent than the radiative transmittance in cases with large WWR. Tsol in SC (0.23) is lower than in EC1 (0.29) and EC2 (0.31). Therefore, the solar heat gain during daytime reduces the heating demand in EC variant more than in SC variant. The delta in U-value (+0.2 W/(m^{2}K) for EC) is not significant enough to influence the total heating demand that may occur during unoccupied hours with the setback temperature of 3 K.

4.2. *Embodied energy*

The embodied energy of the lightweight prototype is lower than of

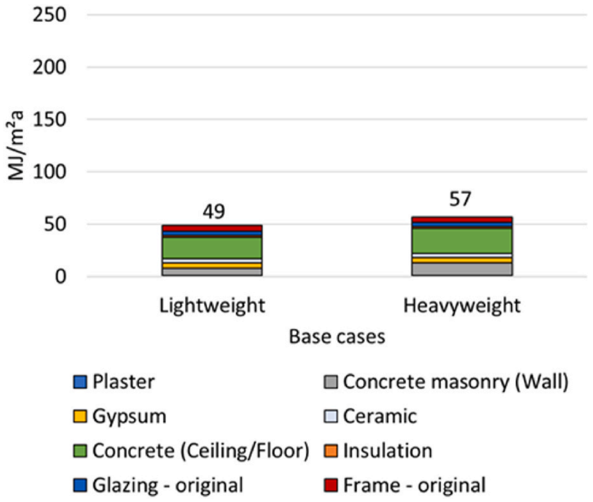

Fig. 6. Embodied energy of the lightweight and heavyweight constructions before the refurbishment.

the heavyweight prototype due to the additional concrete in the heavyweight construction. However, this difference is only 8 MJ/m^{2}a (refer to Fig. 6).

The increase of thermal insulation and the replacement of the original windows with solar-coated glazing and a frame result in an increase by 26 MJ/m^{2}a in both construction types (Fig. 7). In the scenario with EC-glazing, the increase in embodied energy is extreme in comparison to the base cases with the original windows: 152 MJ/m^{2}a (and 126 MJ/m^{2}a in comparison to the scenario with glazing with solar coating). The embodied energy of EC-glazing alone (146 MJ/m^{2}a) exceeds the embodied energy of the rest of the materials in the office room. This trend is opposite to what was observed with the operational energy, where the lowest values of annual end-use energy were reached with the variants with EC-glazing.

4.3. *Total primary energy*

In this section, primary operational and embodied energy was combined. The primary energy factor of 1.8 was applied to convert end-use energy to primary energy [6]. In base cases, the operational energy makes up 78% and 70% of the total primary energy (Fig. 8). The operational energy comes close to the percentages (80 %–90%) reported in Ref. [3]. Although, the slightly higher embodied energy (22% in the lightweight base case and 30% in the heavyweight base case) can be explained by the extensive framing and glazing that was necessary for the 14 m^2 windows.

After replacing the original window with the window with solar coating and adding thermal insulation, the total primary energy was decreased from 224 MJ/m^{2}a to 144 MJ/m^{2}a in the lightweight prototype and from 188 MJ/m^{2}a to 140 MJ/m^{2}a in the heavyweight prototype.

In the variants with EC1 and penalty-based control, the operational energy makes up only 25% percent in the lightweight and 21% in the heavyweight prototype (Fig. 9). Although EC-glazing slightly reduced the operational energy, this reduction does 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 in both construction types.

4.4. *Occupants' comfort*

4.4.1. *Thermal comfort*

Hourly results of the individual local predicted mean vote (PMV) based on the users' position (G1: near the window, refer to Fig. 2) were

Fig. 8. Embodied and operational energy of lightweight and heavyweight base cases before the refurbishment.

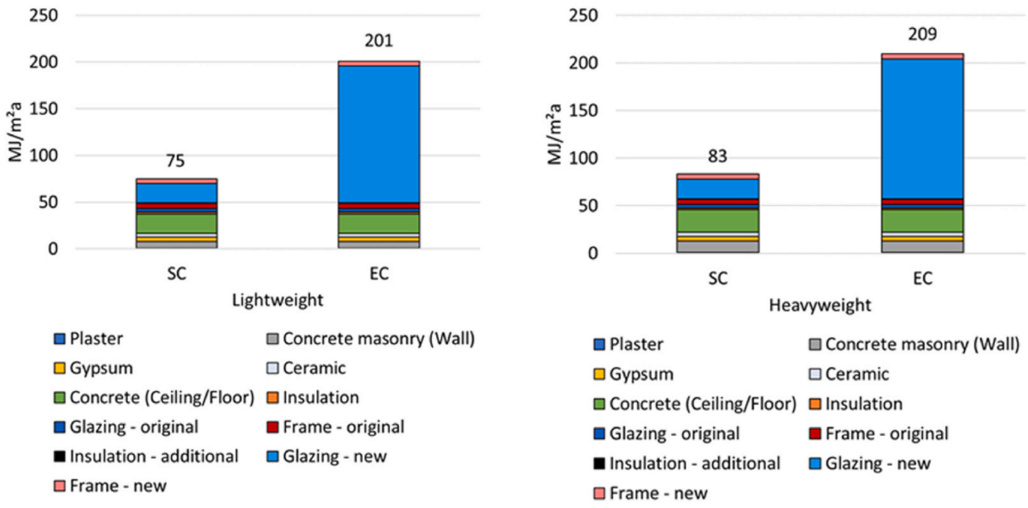

Fig. 7. Embodied energy of lightweight and heavyweight constructions after the refurbishment.

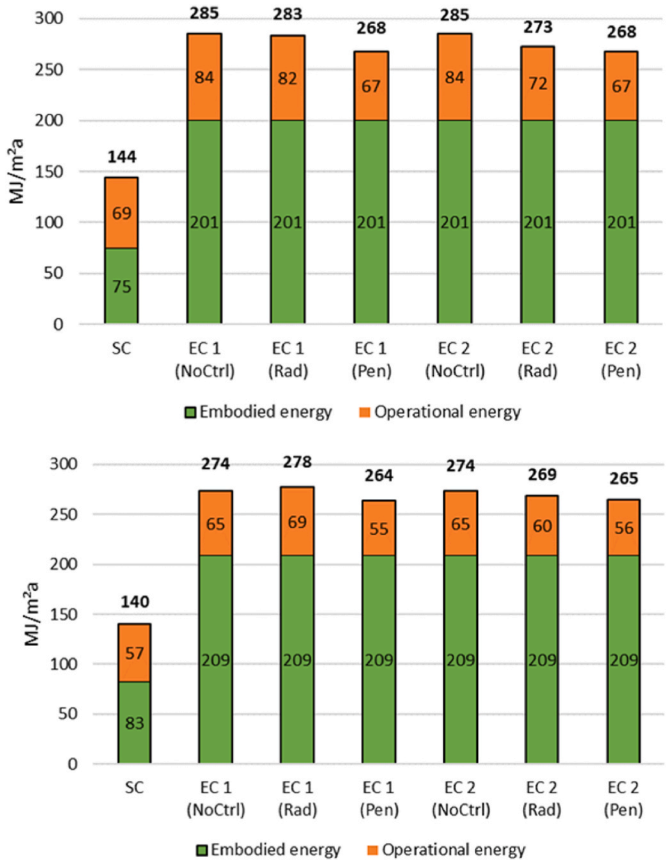

Fig. 9. Embodied and operational energy of lightweight and heavyweight construction after the refurbishment.

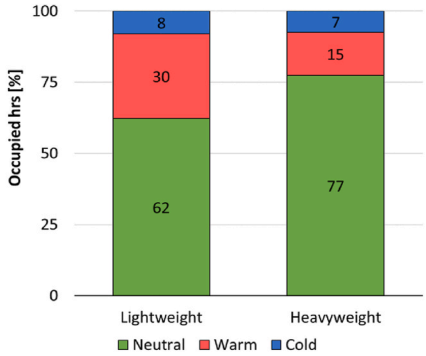

Fig. 10. The overall thermal comfort in lightweight and heavyweight base cases before refurbishment.

processed over the complete year. Based on the analysis, occupants will feel comfortably only 62% of the occupied time in the lightweight base case and 77% in the heavyweight base case (see Fig. 10).

In the refurbished variants with solar-coated glazing, the users are comfortable 88% (lightweight) and 93% (heavyweight) of the occupied hours. Only EC-glazing with penalty-based control outperforms variants with solar-coated glazing, especially in the lightweight construction. This highlights the importance of the control strategy. Fig. 11 shows that the EC2 with penalty-based control has the least amount of hours of thermal discomfort, outperforming rule-based control in both construction types.

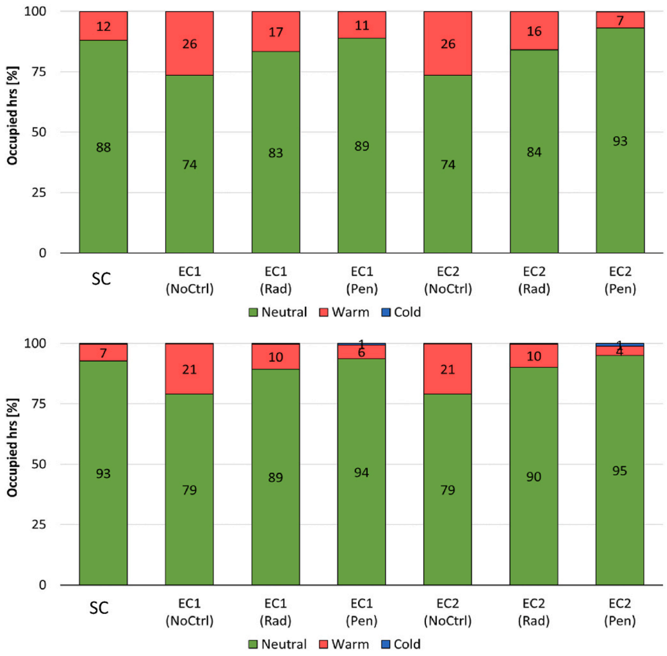

Fig. 11. The overall thermal comfort in the lightweight and heavyweight construction after the refurbishment.

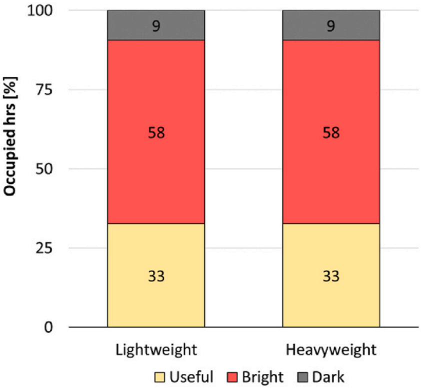

Fig. 12. Useful daylight illuminance in the base cases before the refurbishment.

4.4.2. Visual comfort

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 (Fig. 12) and solar-coated (Fig. 13) windows. On the other hand, “dark” hours (illuminance <300 lux) show the need for supplementary electric lighting. EC1 with penalty-based control provides the highest amount (86%) of the occupied hours within the useful range of illuminance.

Since the reflectivity of the surfaces is the same in both lightweight and heavyweight variants, the UDI values are similar except for EC1 (Pen) and EC2 (Pen) with penalty-based control (see Fig. 13). Considering that the penalty-based control obtains the most favorable state of the window for a specific point in time by optimizing energy, thermal comfort, and visual comfort, the algorithm may find different tinting solutions.

In the case of glare probability, only 53% of the occupied hours are within the acceptable range in the lightweight and heavyweight base cases (Fig. 14).

Exchanging the original window with the solar-coated window increased the percentage of acceptable hours to 90% (Fig. 15). However, EC2 with penalty-based control outperformed all other variants, eliminating the possibility of glare.

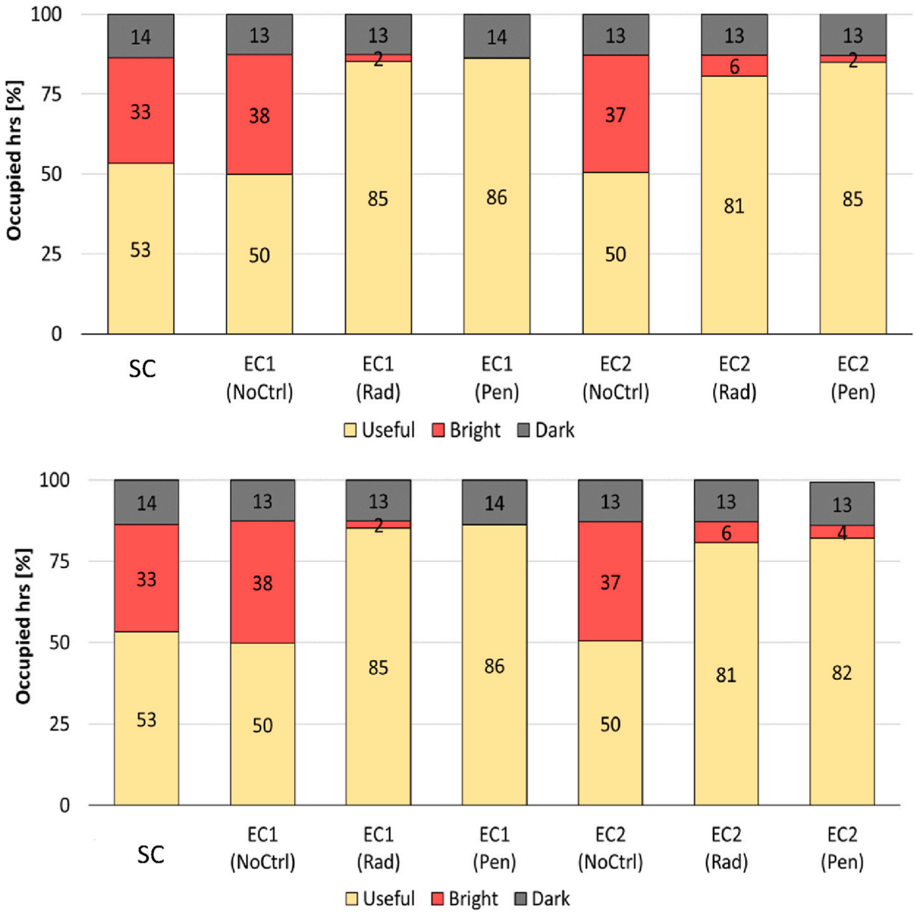

Fig. 13. Useful daylight illuminance in the lightweight and heavyweight constructions after the refurbishment.

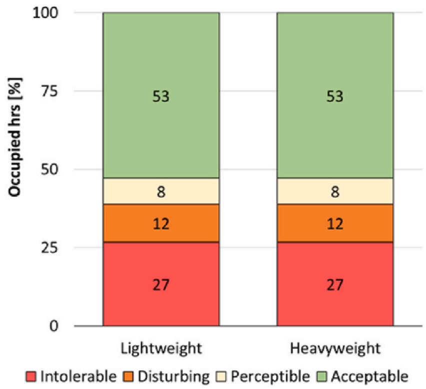

Fig. 14. Glare probability in base cases before the refurbishment.

5. Discussion

In this paper, we have used a multi-objective evaluation approach to assess operational energy, embodied energy and occupants' comfort in a refurbished prototypical office room in Mannheim, Germany. The room prototype was assumed as two variants, a lightweight and heavyweight construction. The refurbishment consisted of the addition of thermal insulation and the exchange of the original window to a solar-coated or EC-window. Two types of EC-windows that are available on the market were investigated with 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. In the lightweight prototype with EC1 or EC2 and penalty-based control, operational energy decreased the most: from approximately 27 kWh/m^{2}a to just 10 kWh/m^{2}a. The solar-coated window also led to significant savings by reducing operational energy to 11 kWh/m^{2}a. In the heavyweight variant, the reduction of operational energy from approximately 20 kWh/m^{2}a to 9 kWh/m^{2}a took place in the rooms with solar-coated and both EC-windows, when the latter were automated via penalty-based control. While the penalty-based control considers the impact of thermal inertia in each timestep and activates the shading system accordingly [35], it can be concluded that the solar-coated and both EC-windows were equally successful in reducing operational energy in both construction types. Regarding the impact of different control strategies on the performance of the two EC-glazings, there was a minor difference in (operational) energy when the penalty-based control was used, as it tailors separate optimal solutions for each window.

The embodied energy of the refurbished variants with EC-glazing was significantly higher in comparison to the variants with solar-coated glazing. Despite that the variants with EC-glazing demonstrated a decrease in the operational energy, it could not compensate for the significant increase of embodied energy. In consequence, the total primary energy of these variants was considerably higher than of those with the solar-coated glazing.

It is noteworthy that the embodied energy of EC-glazing exceeded the embodied energy of all other materials in the room (Fig. 7). In this contribution, we have used the data from the Environmental Product Declaration (EPD) of one of the EC-glazing products that is currently available on the market. The primary energy needed to manufacture EC-glazing was significantly higher in the EPD than what was reported previously in the literature [11,12]. Since literature findings were based on the laboratory production processes (and were scaled up to an

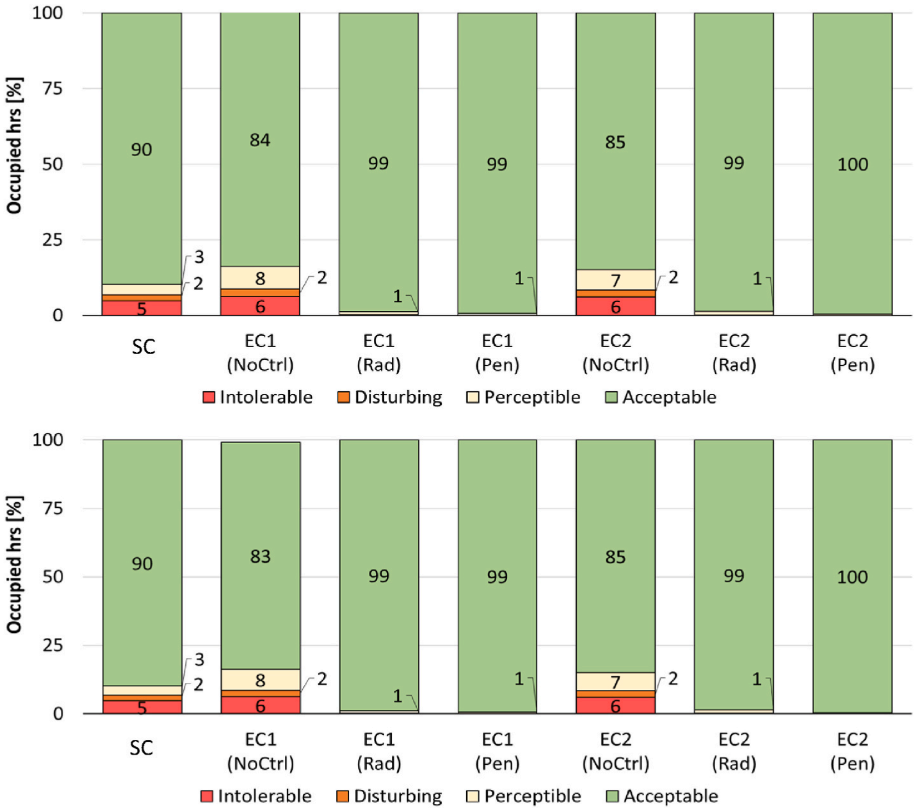

Fig. 15. Glare probability in lightweight and heavyweight construction after the refurbishment.

industrial level [11]), we considered the EPD of the real EC-glazing to be a more reliable source for this analysis. The representatives of the EC-glazing company have explained that the high resource use and the carbon footprint reported in the EPD are mainly related to the saturation level of the manufacturing plant that is currently not operated at the full capacity [36]. The resource use and the carbon footprint that are reported in the EPD will continue to decrease with the increased penetration of EC-glazing in the market. A future switch to the increased use of renewables would contribute to a decrease of the environmental footprint. Based on this projection, it is expected that embodied energy will keep on decreasing over the next years and will potentially come closer to values reported in Ref. [11].

As for other criteria, both EC-windows could ensure a higher level of thermal comfort when controlled via penalty-based control. The same is true for visual comfort, the variants with EC-glazing performed better than the solar-coated glazing when useful daylight illuminance and glare probability were considered. As this control is based on the ranking procedure, it sought an optimal combination for the top, middle and bottom window zones based on the properties of glazing. Therefore, the tint activation was not identical in two EC-windows when penalty-based control is used. However, one has to remember that the penalty-based control is a theoretical control that shows the potential of EC-windows and as of now, it has not been fully applied in practice [37].

The tinting frequency of EC-glazing systems on different window zones automated by penalty-based and rule-based controls for the lightweight office room can be seen in figure A.5. The rule-based controller had fully tinted the upper zones for 41% of the occupied hours of both, EC1 and EC2. This refers to the percentage of hours when the global radiation received on the window surface exceeded the threshold (radiation $_{global} \geq 200$ W/m^2). On the other hand, the behavior of the penalty-based controller is different for the two EC-glazing systems. The middle zone for the EC1 was kept fully tinted for 32% of occupied hours while for EC2 this percentage was 54%.

It is noteworthy that indicators such as view and color rendering index (CRI) were not taken into consideration for the assessment of visual comfort in this study, although they can be investigated by referring to the tinting frequency of EC-glazing systems over total occupied hours. Figure A.5 shows that the penalty-based control provides an unobstructed outside view when the middle zone is in the clear state for 37% (EC1) and 30% (EC2) of occupied hours. The percentage of time with the top zone in the clear state providing additional daylight from the sky is 70% (EC1) and 42% (EC2) of occupied hours.

It is well known that tinted EC-glazing can oftentimes alter the appearance of color indoors. The configurations that result in CRI <80 took place only for 2% of the occupied hours in the rooms with EC1 and penalty-based control in our results (see figure A.5), meaning that acceptable indoor color quality was likely achieved with the rest of the tinting combinations in our model [38]. EC2(Pen) happened to be in a fully-tinted state for 16% of occupied hours, although the CRI of the EC2 in a fully-tinted state is within the acceptable range: CRI = 80.6 (see Table 1). Further multi-channel spectral climate-based daylight simulations are necessary to evaluate the color quality of light in the space.

6. Conclusion

In this contribution, we have investigated different aspects of electrochromic windows for the refurbishment of largely glazed office rooms. Although electrochromic windows were found to effectively reduce operational energy, the variants with electrochromic glazing resulted in higher annual primary energy than those 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 based on the available Environmental Product Declaration. However, the resource use and the carbon footprint are expected to decline as electrochromic windows penetrate the market.

In terms of thermal comfort, both of the two investigated electrochromic glazing types performed slightly better when a penalty-based control, which represents an optimized theoretical solution, was applied. Electrochromic windows significantly improved occupants' visual comfort in both construction types compared to the static glazing with solar coating. However, the difference between a rule-based and the penalty-based control was rather minor.

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

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

Table A.1
Construction properties of base case and refurbished prototypes.

Member	Area (m^2)	Thickness (m)	U - value (W/m^2K)	Thermal Category	Solar Absorptance
Base case: lightweight room prototype					
Floor	30	0.32	0.35	Adiabatic	0.8
Ceiling	30	0.32	0.35	Adiabatic	0.1
Int. Wall (N + E)	36.3	0.12	3.01	Adiabatic	0.1
Ext. Wall (S + W)	**22.3**	**0.25**	**0.87**	**External**	**Inside:0.1** **Outside:0.7**
Base case: heavyweight room prototype					
Floor	30	0.38	0.35	Adiabatic	0.8
Ceiling	30	0.32	0.35	Adiabatic	0.1
Int. Wall (N + E)	36.3	0.22	2.53	Adiabatic	0.1
Ext. Wall (S + W)	**22.3**	**0.35**	**0.83**	**External**	**Inside:0.1** **Outside:0.7**
Post-refurbishment: lightweight room prototype					
Floor	30	0.32	0.35	Adiabatic	0.8
Ceiling	30	0.32	0.35	Adiabatic	0.1
Int. Wall (N + E)	36.3	0.12	3.01	Adiabatic	0.1
Ext. Wall (S + W)	**22.3**	**0.35**	**0.25**	**External**	**Inside:0.1** **Outside:0.7**
Post-refurbishment: heavyweight room prototype					
Floor	30	0.38	0.35	Adiabatic	0.8
Ceiling	30	0.32	0.35	Adiabatic	0.1
Int. Wall	36.3	0.22	2.53	Adiabatic	0.1
Ext. Wall (S + W)	**22.3**	**0.45**	**0.25**	**External**	**Inside:0.1** **Outside:0.7**

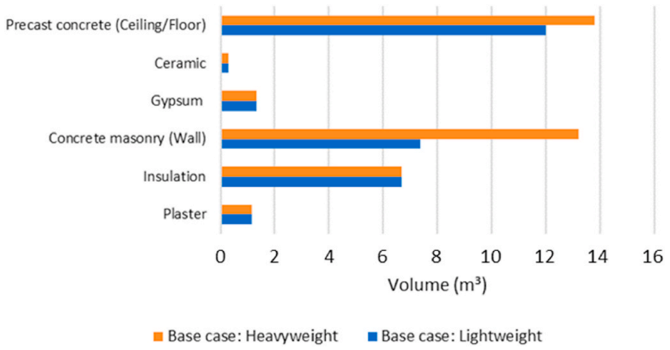

Fig. A.2. Material volume before refurbishment excluding frame and glazing.

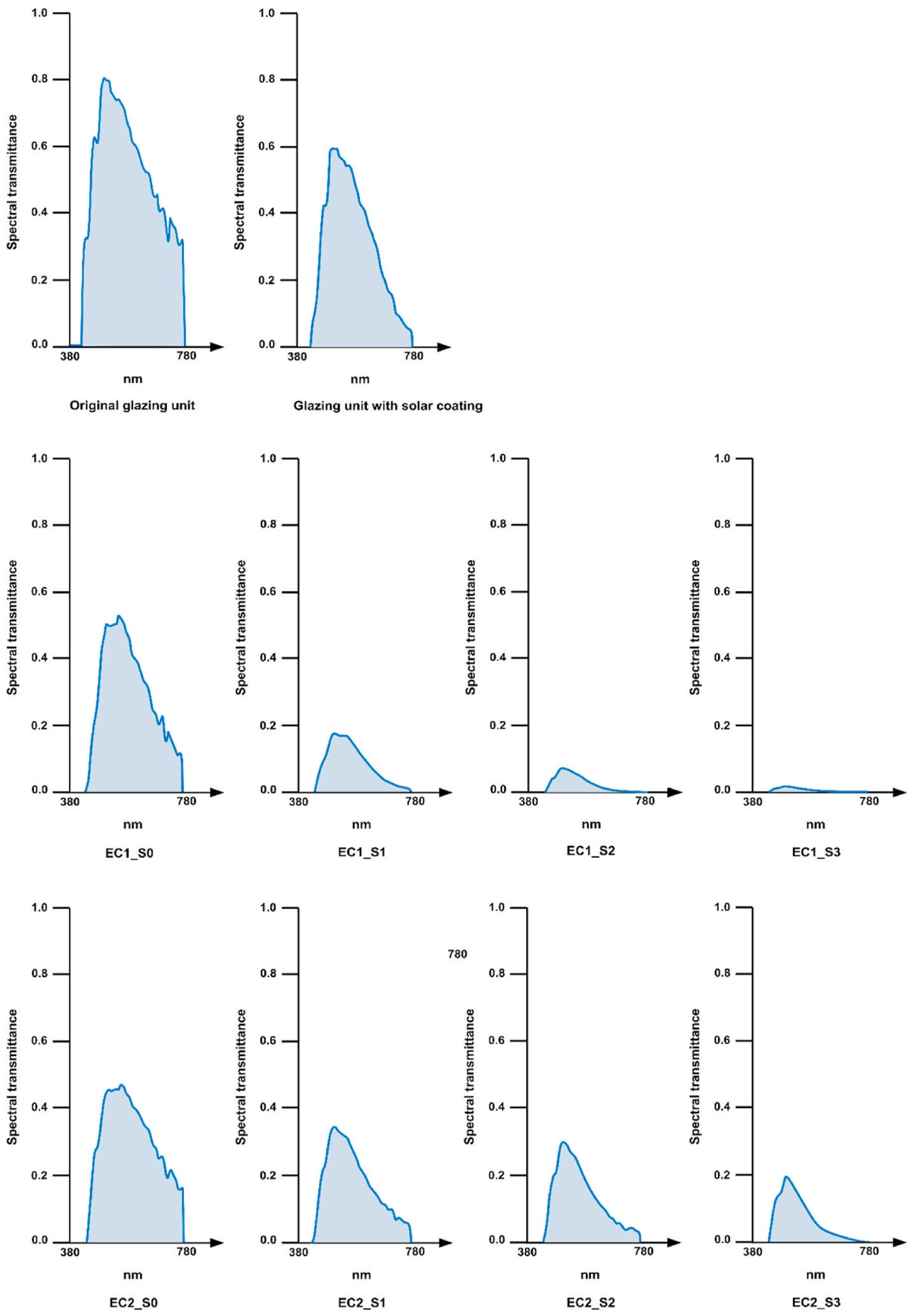

Fig. A.3. Spectral transmittance of glazing configurations with D65 illuminant.

Table A.4
Boundary conditions in the office rooms.

Item	Description	Additional details
Room geometry	Length = 6 m Width = 5 m Height = 3.3 m Window area = 14 m^2 WWR = 85%	Open-plan office 3D geometry in Rhino
Weather data	Mannheim, Germany 49.48° N, 8.46° E	Temperate climate (Cfb) IWEC.epw weather file format
Internal gains	4 people, light work (4 × 145 W)*">* 4 computers (4 × 140 W) LED lighting in 2 groups (5 W/m^2)	Daylight based control for artificial lighting in TRNSYS set-points: 300 lx–500 lx
Ventilation/infiltration	Occupied: n = 1.21 h^{-1} Unoccupied: n = 0.24 h^{-1}	

(*continued on next page*)

Table A.4 (*continued*)

Item	Description	Additional details
Increased ventilation	Occupied: $n = 3\ h^{-1}$ Unoccupied: $n = 5\ h^{-1}$	$T_{in} > T_{out}$ &; T_{in}>23 °C $T_{out\text{-}avg24h} > 18$ °C &; $T_{in} > T_{out}$ &; T_{in}>21 °C
Heating/Cooling* set-point temp	Heating set-point = 21 °C Cooling set-point = 25 °C	Unoccupied: 18 °C Unoccupied: 28 °C

*A reversible heat pump with the efficiency of $\eta = 4.2$ for heating and $\eta = 4.0$ for cooling.
*Gain ASHRAE: 145 W person AVI 24 °C. Sensible: 52% (convective = 22%, radiative = 30%), latent: 48%

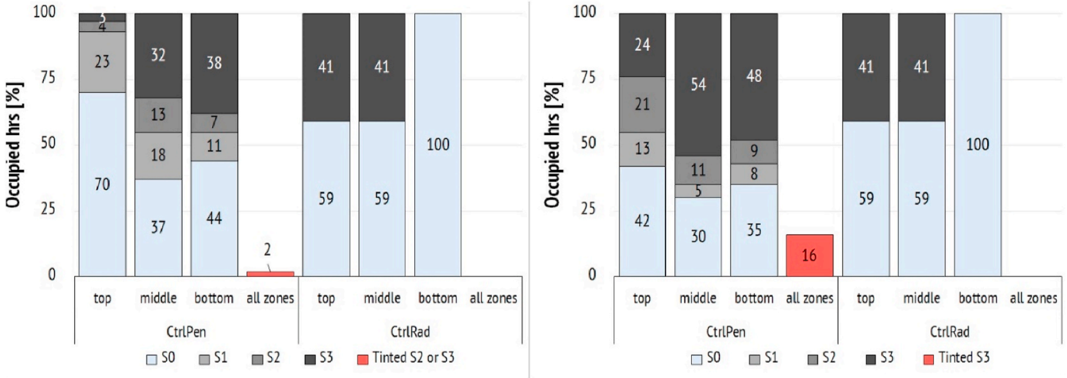

Fig. A.5. Tinting frequency of EC-glazing systems on different zones (top, middle and bottom) automated by penalty-based and rule-based controls for the light-weight case.

References

[1] European Commission, Energy Performance of Buildings Directive, 2019.
[2] European Commission, In Focus: Energy Efficiency in Buildings, 2020.
[3] T. Ramesh, R. Prakash, K.K. Shukla, Life cycle energy analysis of buildings: an overview, Energy Build. 42 (10) (2010) 1592–1600.
[4] A. Stephan, R.H. Crawford, K. de Myttenaere, A comprehensive assessment of the life cycle energy demand of passive houses, Appl. Energy 112 (2013) 23–34.
[5] S.O. Ajayi, L.O. Oyedele, O.M. Ilori, Changing significance of embodied energy: a comparative study of material specifications and building energy sources, J. Build. Eng. 23 (1) (2019) 324–333, https://doi.org/10.1016/j.jobe.2019.02.008.
[6] GEG 2020, Gesetz zur Einsparung von Energie und zur Nutzung Erneuerbarer Energien zur Wärme- und Kälteerzeugung in Gebäuden, 2020.
[7] European Commission, Harvesting Solar Energy with Multifunctional Glass-Polymer Windows, 2015.
[8] H.R. Wilson, High-Performance Windows, 2004.
[9] E.S. Lee, E.S. Claybaugh, M. LaFrance, End user impacts of automated electrochromic windows in a pilot retrofit application, Energy Build. 47 (Suppl. 3) (2012) 267–284, https://doi.org/10.1016/j.enbuild.2011.12.003.
[10] D.B. Belzer, An Exploratory Energy Analysis of Electrochromic Windows in Small and Medium Office Buildings – Simulated Results Using EnergyPlus",” *PNNL-19637*, Pacific Northwest Natl. Lab, Richland, WA., 2010.
[11] C. Baldassarri, A. Shehabi, F. Asdrubali, E. Masanet, Energy and emissions analysis of next generation electrochromic devices, Sol. Energy Mater. Sol. Cell. 156 (2016) 170–181.
[12] S. Papaefthimiou, E. Syrrakou, P. Yianoulis, Energy performance assessment of an electrochromic window, Thin Solid Films 502 (1–2) (2006) 257–264.
[13] dena-Studie, Büroimmobilien, Energetischer Zustand und Anreize zur Steigerung der Energieeffizienz, 2017.
[14] Ecofys Germany GmbH, Klimaschutz durch Reduzierung des Energiebedarfs für Gebäudekühlung, 2011.
[15] Bundesministerium für Verkehr, Bau und Stadtentwicklung, “Typologie und Bestand beheizter Nichtwohngebäude in Deutschland, 2011.
[16] Fraunhofer-Informationszentrum Raum und Bau, Typisierte Bauteilaufbauten – Präzisierung der Pauschalwerte für Wärmedurchgangskoeffizienten aus der Bekanntmachung der Regeln der Datenaufnahme im Nichtwohngebäudebestand, 2011.
[17] Glass in building – determination of luminous and solar characteristics of glazing, German version EN 410:2011, DIN EN 410, DIN EN 410 (2011).
[18] Trnsys, Transient system simulation tool, Accessed: Nov. 16 2021. [Online]. Available: http://www.trnsys.com/.
[19] A. Ganji Kheybari, T. Steiner, S. Liu, S. Hoffmann, Controlling switchable electrochromic glazing for energy savings, visual comfort and thermal comfort: a model predictive control, CivilEng 2 (4) (2021) 1019–1053, https://doi.org/10.3390/civileng2040055.
[20] Thermal Protection and Energy Economy in Buildings: Part 2: Minimum Requirements to Thermal Insulation, 2013. DIN 4108-2, DIN 4108-2.
[21] M. Miara, Bewertung der Effizienz von Wärmepumpen basierend auf Untersuchungen im realen Betrieb, Freiburg, Germany, 2016.
[22] AGC Glass Europe, Environmental Product Declaration: Low-E/solar Control Double Glazing Units.
[23] I.-S. G. SAGE Electrochromics, Environmental Product Declaration. Double Pane Electrochromic Insulating Glass Unit.
[24] I.-S. G. SAGE Electrochromics, Environmental Product Declaration: Triple Pane Electrochromic Insulating Glass Unit.
[25] A. Stephan, R.H. Crawford, K. de Myttenaere, Towards a more holistic approach to reducing the energy demand of dwellings, Procedia Eng. 21 (2) (2011) 1033–1041, https://doi.org/10.1016/j.proeng.2011.11.2109.
[26] R. Zeng, A. Chini, A review of research on embodied energy of buildings using bibliometric analysis, Energy Build. 155 (6) (2017) 172–184, https://doi.org/10.1016/j.enbuild.2017.09.025.
[27] Sustainability of Construction Works – Environmental Product Declarations – Core Rules for the Product Category of Construction Products, 2014. DIN EN 15804 + A1, DIN EN 15804 + A1.
[28] P. Ylmén, D. Peñaloza, K. Mjörnell, Life cycle assessment of an office building based on site-specific data, Energies 12 (13) (2019) 2588, https://doi.org/10.3390/en12132588.
[29] Ökobaudat [Online]. Available, https://www.oekobaudat.de/.
[30] View Dynamic Glass, Environmental Product Declaration: Processed Glass.
[31] The American Society of Heating, Refrigerating and air-conditioning engineers (ASHRAE), “thermal environmental conditions for human occupancy, ANSI/ASHRAE Standard 55 (2013), 2013.
[32] Ergonomics of the Thermal Environment — Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria, 2005. ISO 7730.
[33] G. Ward, Radiance: a validated lighting simulation tool, Accessed: Nov. 16 2021. [Online]. Available: https://www.radiance-online.org/.
[34] Daylight in Buildings, 2019. DIN EN 17037, DIN EN 17037.
[35] A.G. Kheybari, S. Hoffmann, Exploring the potential of dynamic façade systems: an exterior shading system versus a switchable window, Bauphysik 42 (6) (2020) 277–288, https://doi.org/10.1002/bapi.202000034.
[36] Eloise Sok, Saint-Gobain, Personal Communication, 2021.
[37] LiSA, Drittmittelprojekt, Licht- und Solarmanagement mit aktiven Und Modellprädiktiv geregelten Komponenten [Online]. Available: https://www.bauing.uni-kl.de/gst/forschung/drittmittelprojekte/lisa/.
[38] Light and lighting, *Lighting Of Work Places - Part 1: Indoor Work Places*, DIN EN 12464-1, 2019. DIN EN 12464-1.