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Window view clarity evaluation in electrochromic glazings☆

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ABSTRACT

The Quality of View (QV) through windows significantly impacts human well-being, with view clarity representing a crucial aspect within QV assessments. Electrochromic (EC) windows, capable of dynamically adjusting tint levels to manage light and heat penetration, offer varying degrees of view clarity. Evaluating this clarity is vital for comprehensively understanding how EC windows influence human comfort in architectural settings and also complements the related subjective assessments.

This study introduces a unique approach to assess the clarity of views facilitated by EC windows. Employing advanced image processing techniques, a novel methodology was developed for this purpose, generating 3456 images through the Radiance engine. These images considered multiple factors such as viewpoint, tint level, separate window zones, and time of day for different building orientations. Using the Landolt-C chart as a simulated view target under diverse EC window configurations, the study compared simulated images with a reference image, applying the Saliency Guided Enhanced Structural Similarity algorithm (SG-ESSIM) —an image quality assessment algorithm.

The study's outcomes underscore the method's ability to identify optimal EC window configurations, effectively maximising QV. Furthermore, this methodology offers opportunities for integration with subjective clarity assessments and EC window control strategies, supporting a more comprehensive understanding of QV trade-offs in dynamic façade design.

1. Introduction

Windows serve multiple purposes in architectural spaces, including providing natural daylight and establishing a visual connection with the outdoors. This interaction is fundamental to human-centric design, as daylight and access to outdoor views enhance occupant productivity, mood, and overall well-being [1–3]. Exposure to natural and unobstructed views may alleviate eye strain, reduce stress levels [4,5], and create a calming indoor environment. While "interesting" views may increase occupants' tolerance for glare [6], achieving a consistently clear view throughout the day, as well as a balanced performance [7], remains challenging in environments prone to excessive sunlight and glare. Electrochromic (EC) glazing has emerged as a promising solution to address these issues [8].

EC glazing represents advanced dynamic window technologies. Its multilayer coatings enable tint adjustment through electrical voltage, allowing precise control over visible light and solar heat [9]. By dynamically adapting to varying daylight conditions, EC glazing not only reduces the need for artificial lighting but also minimises glare and regulates solar heat gain, contributing to energy efficiency in buildings [10,11]. These features are particularly valuable in regions with intense sunlight, where maintaining visual and thermal comfort can be challenging [12].

The unique functionality of EC glazing lies in its ability to enhance indoor environment qualities by independently controlling sections of the window. For instance, tri-zone or split-pane EC systems divide a window into three separately adjustable zones—typically dedicated to light management, view clarity, and shading for privacy or balustrade purposes [10], which offers improved visual comfort and energy efficiency compared to whole-window EC systems [11,13]. However, EC glazing is not without its drawbacks. In addition to challenges like switching time issues, electrolyte leakage, and high production costs [14], a significant limitation is the occurrence of colour shifts and optical irregularities, which can negatively impact indoor aesthetics and

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user perception. Existing studies have explored the extent of this shift and its impact on occupant experience [15,16], but there remains a lack of strategies to mitigate its effects.

Besides, among the key metrics influencing occupant satisfaction is the quality of view (QV), which encompasses factors such as view content, view clarity—the ability to discern external scenes without distortion or obstruction—and unobstructed access to natural scenes [17]. High QV has been linked to psychological and physical benefits, including stress reduction, enhanced mood, and increased cognitive function [18,19]. Participants exposed to window views exhibited lower stress indicators, including decreased skin conductance and heart rate, compared to participants without access to window views [18]. Window access has been associated with improved working memory, concentration, and overall cognitive performance [19,20]. Additionally, windows providing daylight and views have been linked to increased job satisfaction, enhanced perceptions of self-productivity, and reduced eyestrain [20,21]. However, while EC glazing technologies offer dynamic daylight management, their use at higher tint levels can compromise view clarity, underscoring the need to carefully evaluate these trade-offs in the design of occupant-centred spaces.

Recent research has begun to operationalise view clarity in empirical terms. For example, Konstantzos et al. [22] introduced the View Clarity Index based on subjective ratings across different shading configurations. Kent et al. [23] described clarity as the ability to "see and discern view content," emphasising its sensitivity to shading design and environmental conditions. Ko et al. [24] similarly identified glazing distortions and light reflections as important moderators of perceived clarity.

1.1. Research gap and problem statement

Despite the growing body of research on EC glazing, most studies focus on its energy-saving potential and its impacts on thermal and daylight performance [25–27]. Limited attention has been given to its influence on view clarity—a key component of occupant experience. Given that clarity is a subjective concept, existing assessments often rely on subjective surveys [28,29]. While insightful, they are prone to biases stemming from individual perceptions, viewing angles, and specific environmental conditions [30].

There remains a need for more quantitative and replicable methods that can evaluate view clarity under controlled conditions. Objective, image-based metrics offer the potential to complement subjective evaluations by providing consistent, scalable assessments of visual quality. By applying computational analysis across systematically varied environmental and glazing parameters, such approaches can help reduce observational biases and support early-stage design decisions.

This study addresses this gap by proposing a simulation-based framework for evaluating view clarity using computer vision techniques. The methodology enables systematic analysis across different tint levels, times of day, seasons, viewing positions, and window orientations, offering new insights into how EC glazing configurations correlate with changes in perceived visual quality.

1.2. Computer vision techniques for human visual simulation

Advances in computer vision have introduced powerful tools for simulating human visual perception [31], offering novel approaches to evaluating visual quality in architectural contexts. By analysing visual features such as edge sharpness [32], saliency [33], and structural similarity [34], these methods provide a bridge between objective performance metrics and subjective human comfort, fostering the design of occupant-centred spaces.

Edge detection algorithms, which emphasise contours and sharp transitions in images [35], are foundational to computer vision techniques simulating human perception. The human visual system relies heavily on edge information to interpret clarity and spatial structure. Metrics such as Edge-Based Structural Similarity (ESSIM) focus on comparing edge strength and alignment between reference and distorted images, indicating perceived clarity [36,37].

Saliency mapping identifies regions of an image that naturally attract human attention based on features like brightness, contrast, and spatial arrangement. This approach aligns closely with the human visual system's focus patterns, enhancing the ability to quantify visual prominence [38]. Saliency-driven methods have demonstrated strong correlations with subjective judgments of visual quality, as evidenced in works like Visual Saliency-Induced Index [39] and saliency-based gradient metrics [40].

The Structural Similarity Index (SSIM) and its extensions, such as Multi-Scale SSIM (MS-SSIM), have been widely adopted for evaluating image quality. These methods simulate human perception by comparing luminance, contrast, and structure between images. More recent developments incorporate saliency weighting into these metrics, such as the Saliency-Guided Enhanced Structural Similarity (SG-ESSIM) algorithm, which assigns greater importance to visually prominent areas, improving alignment with human perception [41].

The SG-ESSIM algorithm combines edge-based clarity and saliency mapping, providing a comprehensive metric for human-centric image evaluation. Unlike traditional approaches that treat saliency as a post-processing weight, SG-ESSIM integrates saliency into the computation of local image quality. This method has shown significant improvements in correlating with subjective scores, offering low computational complexity and high accuracy across benchmark datasets [41]. The integration of saliency directly into the ESSIM framework exemplifies a significant step forward in image quality assessment.

1.3. Objectives and research questions

This study aims to develop a quantitative framework for examining the relationship between EC glazing and view clarity, contributing to the broader understanding of QV in building interiors. By leveraging the SG-ESSIM algorithm, the research investigates how changes in EC glazing configurations, environmental conditions, building orientations, and viewing positions are correlated to view clarity.

The study also seeks to bridge the gap between subjective assessments and computational analysis by providing a replicable methodology for quantifying visual quality. Rather than replacing human-centred evaluations, the proposed approach is intended to complement perceptual research and support the development of hybrid evaluation frameworks that combine simulation and occupant feedback.

The following research questions guide this exploration in different building orientations:

- Q1: What is the relationship between electrochromic glazing and window view clarity at different tint levels?
- Q2: How are temporal variations associated with changes in perceived clarity?
- Q3: How do different viewing positions within a room correlate with clarity through EC glazing?

Through this investigation, the study offers a systematic method for early-stage design assessment and simulation-driven analysis, enabling a deeper understanding of how EC glazing settings may influence perceived visual quality under diverse daylighting conditions.

2. Methodology

In this section, the methodological framework used to evaluate view clarity through EC glazing is outlined. A combination of 3D modelling, simulation, and image processing techniques was applied to explore the relationship between tint levels, viewing angles, and seasonal lighting conditions (Fig. 1).

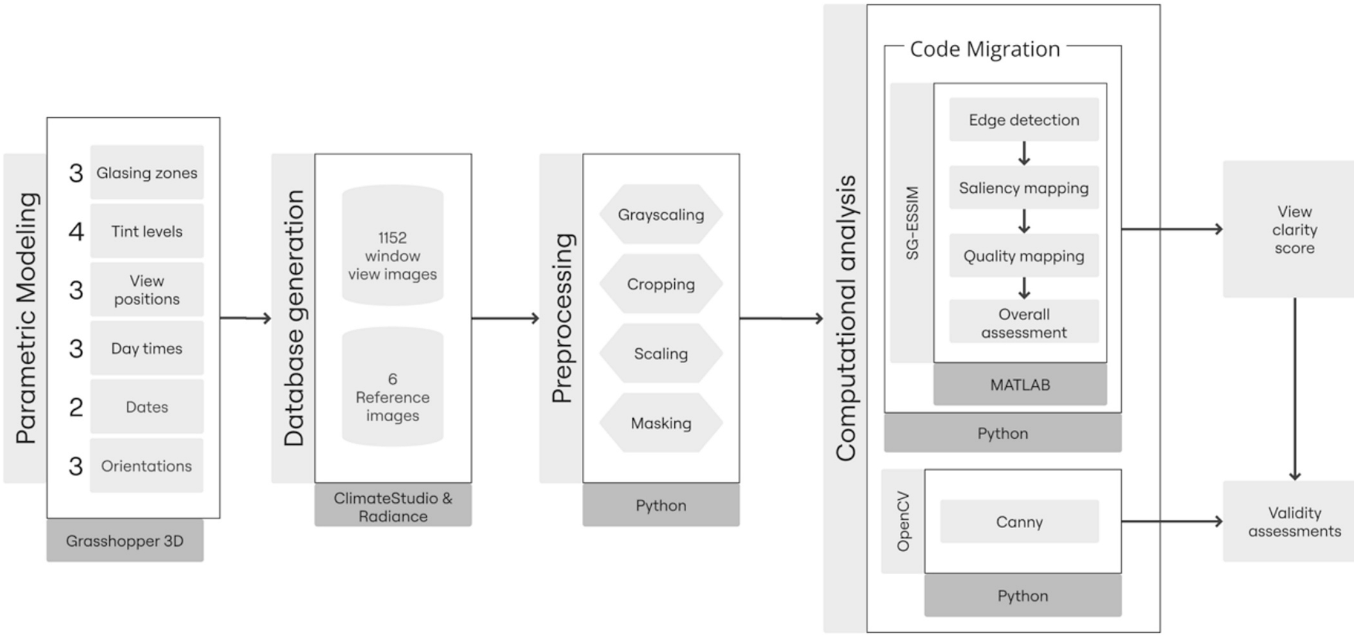

Fig. 1. The view clarity assessment framework.

2.1. 3D modelling and simulation setup

A 3D model of an office room equipped with electrochromic glazing was developed using the Grasshopper environment in Rhinoceros 3d. The room, located in Isfahan, Iran—a region characterised by clear, sunny skies and significant seasonal variations in daylight and temperature—has dimensions of 6 m in length, 5 m in width, and 3 m in height. The model was positioned on the sixth floor, 15 m above ground level, to mitigate the effects of ground light reflections.

The electrochromic window spans 70 % of the south-facing wall (Fig. 2). To model the 3-zone electrochromic glazing, the glazing was divided into three equal horizontal zones (top, middle, bottom), and each zone's tint level could be independently adjusted across four states, ranging from clear to fully tinted (Table 1). A similar configuration was applied to the east- and west-facing windows to enable consistent comparative analysis across orientations.

Three distinct viewpoints —Left (L), Middle (M), and Right (R)— were selected to assess the clarity of the view through the electrochromic window (Fig. 2, Top left and Bottom). These positions correspond to observer locations from left to right as seen from within the room facing the window. These viewpoints were located 3 m away from the window, aligned along the room's central axis, with eye-level positions at 1.17 m above the floor. The gaze direction was set to the centre of the window for all viewpoints, ensuring consistent viewing angles

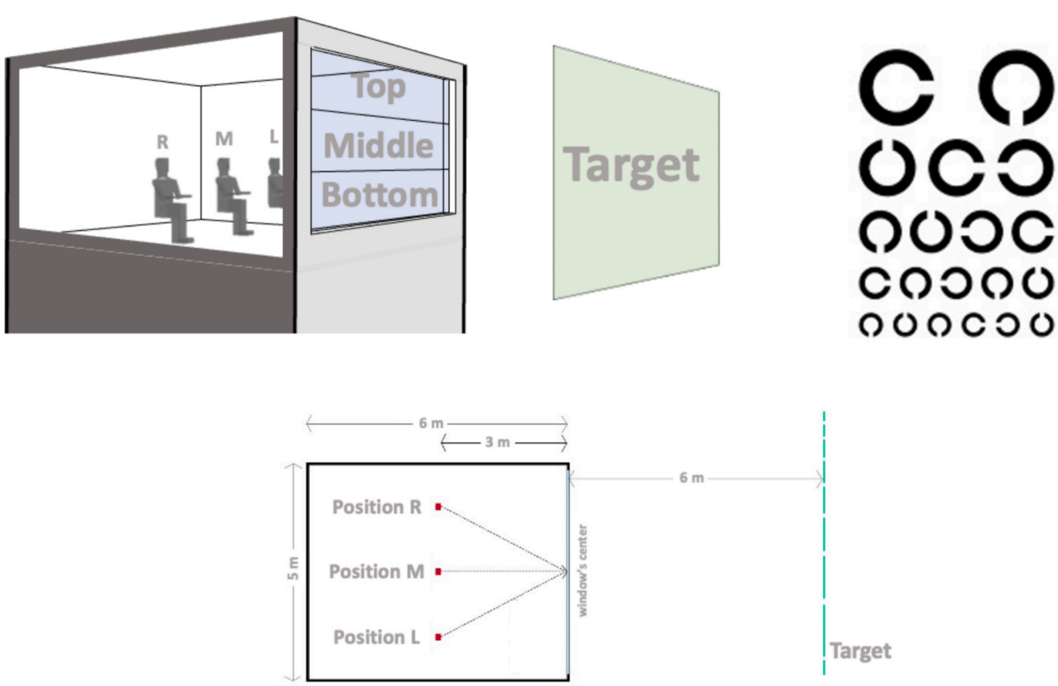

Fig. 2. Top left: 3D model of the study room, Top middle: view target plane as building in front of the study room and a base for placing the view target, Top right: Landolt-C chart as a displayed window view target, Bottom: floor plan of the study environment.

Table 1
The model materials' features and the EC glazing tint levels. TL: The glazing's Tint level ranges from 0, the clearest level, to 3.

Glazing	Visible transmittance (%)
TL 0	59.7
TL 1	17.3
TL 2	5.5
TL 3	0.9

Material	Reflectance (%)			Roughness	Specularity (%)
	R	G	B		
Ceiling	86	85	78	0.2	35
Walls	73	66	54	0.2	21
Floor	36	37	36	0.2	7

across all tests (Fig. 4).

To assess the clarity of the view through the electrochromic glazing, a Landolt-C vision testing chart was selected as the target (Fig. 2, Top right). The Landolt-C optotype, widely used in ophthalmology for vision clarity tests [42], consists of a ring with a gap in varying orientations (top, bottom, left, right, and diagonal positions). The stroke width is 1.5 of the diameter, and the gap width is the same [43]. The standardised design of the chart ensures consistency in the visual edges and gaps, making it suitable for machine-learning algorithms to detect and assess visual clarity effectively.

In previous studies, the Landolt-C chart has been employed for evaluating image clarity through different media [44], and its geometric simplicity and regularity make it an ideal choice for reproducibility in research. For this study, the chart was placed at a fixed distance of 6 m from the window, without any background obstructions, ensuring that the only variable affecting the clarity of the view was the tint level of the electrochromic glazing.

To ensure uniformity across different windowpanes and viewpoints, the Landolt-C chart was rotated by 90 degrees, resulting in equal-sized Landolt-C characters appearing in each window section (Fig. 4). This approach ensures that all panes are assessed consistently, regardless of the glazing's tint level. The material properties of the Landolt-C target were set to a high-contrast black, enhancing the visibility of the gap edges for accurate clarity analysis.

2.2. Database development

The database of window views was generated through simulations conducted at three distinct times (09:00, 12:00, and 15:00) on the 21st of March and June for all 3 orientations, using the Radiance engine in ClimateStudio v2.0.8978.19909. The 21st of March (spring equinox) and the 21st of June (summer solstice) were chosen to capture distinct seasonal lighting conditions in Isfahan. March 21st represents balanced daylight, with the sun at a moderate angle, offering insight into typical spring lighting. June 21st, with the longest daylight hours and highest sun altitude, simulates the most intense sunlight conditions, critical for testing the performance of electrochromic glazing under peak solar exposure.

To capture the impact of different optical states on view clarity, we modelled all available tint levels of the electrochromic glazing as individual scenarios for each orientation and viewing position. This scenario-based approach allowed for a systematic comparison of clarity across all possible glazing conditions, independent of a specific control logic.

3456 renders were generated to support the analysis (Fig. 3). Additionally, six reference renders were created without window glazing to serve as control images representing the clearest possible view. These renders allowed for the evaluation of the relative clarity of the electrochromic glazing under various tint levels. Renderings were generated using 90 samples per pixel to ensure high image quality with reduced noise. The simulation employed six ambient bounces to accurately capture complex interreflections within the scene. A weight limit of 0.01 was set to optimise rendering time by disregarding negligible light contributions.

2.3. Computational analysis and image preprocessing

To quantitatively assess the clarity of window views, we used the Saliency-Guided Enhanced Structural Similarity (SG-ESSIM) algorithm [41]. The SG-ESSIM method operates in four steps. First, edge detection is performed using ESSIM, an image quality metric [37], to compute the edge strength of images, a critical visual feature given the human eye's sensitivity to edges when interpreting visual scenes [41]. Next, a saliency map is generated to identify the areas of the image most likely to attract attention based on edge strength and other visual features. In the third step, a quality map is calculated by combining edge strength and saliency, creating a local similarity map that emphasises visually important regions while downplaying less significant areas. Finally, an overall quality score is derived by averaging the local similarity values across all pixels, yielding a score between 0 (no similarity) and 1 (perfect similarity), which quantitatively measures the view clarity through electrochromic glazing. In this study, the score was multiplied by 100 to facilitate easier comparisons. This research's developed framework was then evaluated by comparing the renders with reference images (control group) (Fig. 5).

The following steps were applied to prepare the images for analysis:

- Grayscale conversion. The window views and reference images were first converted to grayscale as the edge detection algorithms in this study operate on single-channel images.
- Cropping Images. After grayscale conversion, the window area was cropped by identifying the corner points of the window. This process reduces image noise and ensures that only relevant sections of the image are retained for further analysis.
- Image Scaling and Drawing Quadrilateral. The cropped images were scaled to a consistent size of 600 pixels to maintain consistency across the dataset. A quadrilateral representing the window frame

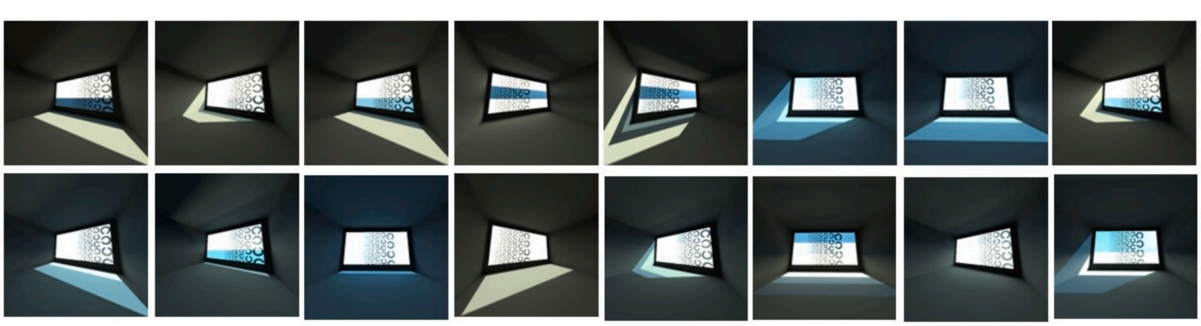

Fig. 3. Samples of generated renders for view clarity assessment.

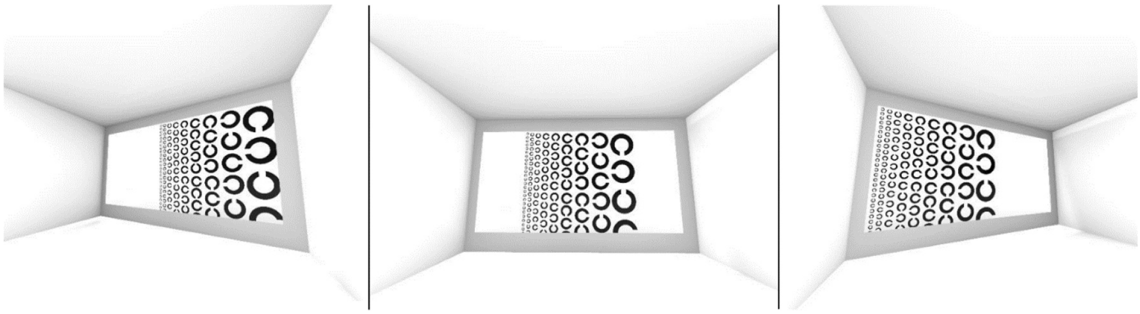

Fig. 4. Samples of the reference window views. left: position R, middle: position M, and right: position L. These view images were simulated without any glazing.

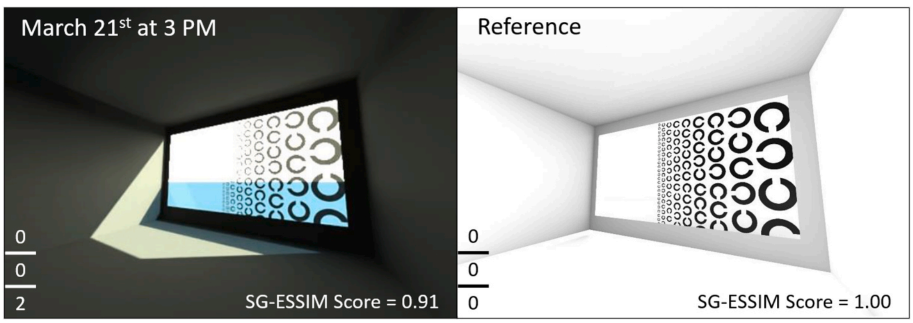

Fig. 5. Comparing the clarity score of a render with the control group image. the tint level of each glazing section is presented on the left below each render.

was drawn on each image, aligning the window areas for accurate comparison.

- Masking Non-Window Regions. Following scaling, a mask was applied to isolate the window regions from non-relevant areas in the images. The masked areas were replaced with a neutral value to ensure that only the window content contributed to the subsequent similarity analysis.
- SG-ESSIM Score Calculation. The SG-ESSIM algorithm was applied to compute similarity scores for both the full images and the masked images. These scores were based on structural similarity, edge strength, and visual saliency. The score for the full window view evaluates overall similarity, while the score for the masked view focuses exclusively on the clarity of the window region, excluding external elements.

SG-ESSIM was chosen for this study due to its ability to model human perception. Traditional metrics like Mean Squared Error and Peak Signal-to-Noise Ratio fail to account for human attention, treating all parts of an image equally [45]. Metrics like the Structural Similarity Index [34] and Multiscale SSIM [46] improve on this by considering structural content, but they still lack integration of saliency [41]. SG-ESSIM overcomes these limitations by focusing on visually salient regions, making it more effective for evaluating the clarity of window views where edge sharpness and contrast are critical. Additionally, SG-ESSIM provides a high correlation with human quality judgments while maintaining low computational costs, making it an ideal choice for this study[41].

2.4. Validation

To validate the accuracy of the SG-ESSIM algorithm, we applied Canny, an edge detection algorithm, on window view renders to be able to visually comparison of edges with numerical SG-ESSIM scores. The Canny edge detection algorithm is a robust method for identifying edges in images by following a structured, multi-step process. First, it smooths the image using a Gaussian filter to reduce noise, then calculates gradient magnitudes and directions to detect edge intensity and orientation. Non-maximum suppression is applied to refine edges by keeping only local maxima along the gradient direction, ensuring sharpness and accuracy. A double thresholding technique then categorises pixels into strong, weak, or non-edges based on gradient intensity, followed by edge tracking by hysteresis to connect weak edges to strong ones, preserving continuity and eliminating noise [47]. This approach ensures optimal edge detection with high accuracy and noise resilience. To this aim, the OpenCV library [48] in Python was employed. After computing the SG-ESSIM clarity scores and validating the visual consistency of edge detection, statistical analyses were conducted to systematically evaluate differences.

2.5. Statistical analysis

To examine how view clarity varied across different electrochromic tint levels, times of day, viewing positions, and orientations, a series of statistical analyses was conducted. One-way Analysis of Variance (ANOVA) was applied separately for each independent variable to determine whether differences in SG-ESSIM scores were statistically significant. When significant main effects were detected ($p < 0.05$), post-hoc comparisons were performed using Tukey's Honest Significant Difference (HSD) test to identify specific group differences.

All statistical analyses were conducted using R version 4.4.2. Statistical significance was interpreted at the 95 % confidence level unless otherwise specified.

3. Result and discussion

In this section, the correlation between changes in factors such as time of day, tint levels, viewing positions, building orientations and seasonal lighting variations on changes in the clarity of views provided by EC windows is explored.

3.1. Tint level and view clarity across orientations

Fig. 6 illustrates how the Total Tint Level (TTL) influences view clarity, as measured by SG-ESSIM scores, across east-, south-, and west-

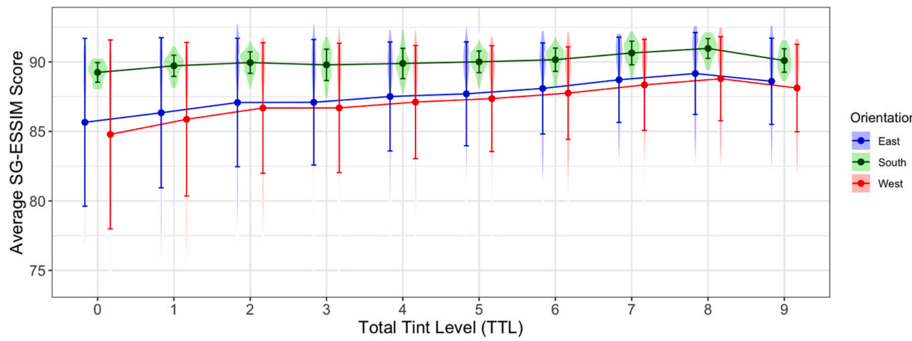

Fig. 6. SG-ESSIM scores for view clarity across total tint levels for different orientations.

oriented windows. Across all orientations, clarity scores improve as tint levels increase from TTL 0 to TTL 8 before a slight decline at TTL 9. This trend demonstrates the capacity of EC glazing to enhance perceived clarity by modulating daylight intensity and contrast.

On average, south-facing windows exhibited the highest clarity (peak at TTL 8 = 91.0), followed by east-facing (TTL 8 = 89.2) and west-facing (TTL 8 = 88.8) windows (Table 2), with the superior clarity of south-facing orientations attributed to higher sun angles and a more consistent luminance distribution across the façade during daytime hours. In contrast, east- and west-facing windows, which receive more oblique, uneven, and fast-changing light, especially in the morning and afternoon, experience greater potential for glare and luminance variability, leading to reduced perceived edge clarity in SG-ESSIM assessments and higher standard deviations compared to the south.

The slight decline in view clarity at TTL 9 (all zones were set to TL 3) compared to TTL 8 is likely attributed to excessive darkening at the highest tint state. At TL 3, visual transmittance is approximately 6 times lower than at TL 2, leading to substantially reduced luminance and contrast. This extreme reduction in visible transmittance can impair edge detection and the perception of structural details, thereby diminishing overall clarity. Under very low luminance conditions, structural information becomes less discernible, which may contribute to lower SSIM values [34]. This result is also consistent with previous findings indicating that at low transmission levels, electrochromic glazing can diminish the perceived connection to the external environment [23,49].

Statistical analysis supports these trends. A one-way ANOVA confirmed that TTL significantly affects SG-ESSIM scores for all three orientations ($p < 0.001$). However, the strength of significance and the clarity gains vary by orientation (Table 3):

South: A highly significant and consistent improvement in clarity scores was found as TTL increased. Post-hoc comparisons show TTL 7 and TTL 8 provide significantly higher clarity than lower levels (e.g., TTL 0 to 4), with p-values <0.001. This suggests that moderate-to-high tinting (TTL 7–8) is optimal for south-facing windows, where direct sunlight is strong but evenly distributed.

East and West: Although ANOVA results were significant ($p < 0.001$), post-hoc tests reveal fewer statistically significant differences between tint levels. This reflects the greater variability in lighting conditions for east- and west-facing windows, caused by rapid solar movement and uneven exposure during morning and afternoon, respectively. Despite the lower statistical resolution, the peak clarity for both orientations still occurs at TTL 8, suggesting consistent behavioural patterns across façades.

Table 2
Summary of SG-ESSIM scores for view clarity across different Total Tint Levels (TTL).

TTL	East	South	West
0	85.7 ± 6.0	89.2 ± 0.7	84.8 ± 6.8
1	86.3 ± 5.4	89.7 ± 0.8	85.9 ± 5.5
2	87.1 ± 4.6	90.0 ± 0.8	86.7 ± 4.7
3	87.1 ± 4.5	89.8 ± 1.1	86.7 ± 4.7
4	87.5 ± 3.9	89.9 ± 1.1	87.1 ± 4.1
5	87.7 ± 3.7	90.0 ± 0.8	87.4 ± 3.8
6	88.1 ± 3.3	90.2 ± 0.8	87.8 ± 3.3
7	88.7 ± 3.1	90.6 ± 0.9	88.3 ± 3.3
8	89.2 ± 3.0	91.0 ± 0.7	88.8 ± 3.0
9	88.6 ± 3.1	90.1 ± 0.8	88.1 ± 3.2

Table 3
Statistical summary for ANOVA on TTL by Orientation.

Orientation	F (df_1, df_2)	p-value	Significant TTL Differences (Tukey HSD)
South	F(9, 1142) = 16.2	<0.001	TTL 5 vs 0, TTL 6–8 vs 0–4 (especially TTL 8 > all lower levels)
East	F(9, 1142) = 3.95	<0.001	TTL 7–8 > TTL 0–3 (weak pairwise significance; TTL 8 vs 0p ≈ 0.039)
West	F(9, 1142) = 4.16	<0.001	TTL 7–8 > TTL 0–3 (e.g., TTL 8 vs 0p ≈ 0.012)

Full Tukey HSD test results for all three orientations are presented in Supplementary Table S1.

These findings indicate that dynamic EC control strategies should be tailored to orientation, confirming previous research, primarily focused on thermal comfort and energy performance, that supports this approach [12]. For south-facing façades, maintaining TTL 7–8 throughout the day may enhance clarity without compromising glare control. However, east and west façades may benefit from more responsive, real-time tinting schedules to adapt to fluctuating solar angles and luminance contrasts, particularly during early morning and late afternoon periods.

Moreover, the lower baseline clarity in east and west windows, especially at TTL 0 (east: 85.7, west: 84.8 with the highest possible visual transmitance), reinforces the need for façade-specific EC calibration and possibly architectural shading enhancements (e.g., vertical fins for west-facing windows) to mitigate directional glare and edge blur.

3.2. Temporal variations and view clarity across orientations

Fig. 7 and Table 4 represent the time change trend in view clarity across east, south, and west orientations. Overall, the time of day significantly influenced objectively measured perceived clarity, but the nature and magnitude of this effect varied considerably by orientation.

South: For the south-facing façade, SG-ESSIM scores remained relatively stable throughout the day, with a slight increase from morning to noon (Fig. 8). ANOVA revealed a statistically significant effect of time ($p = 0.03$), and post-hoc tests (Table 5) indicated a marginal difference between 9:00 and 12:00 ($p = 0.05$). However, no significant difference was found between 12:00 and 15:00 ($p = 0.99$). While these results suggest a minor temporal effect, the observed changes are small and do not reach the higher threshold of significance ($p < 0.001$) applied elsewhere in this study. Therefore, they are not further interpreted. This supports the overall observation that south-facing windows provide

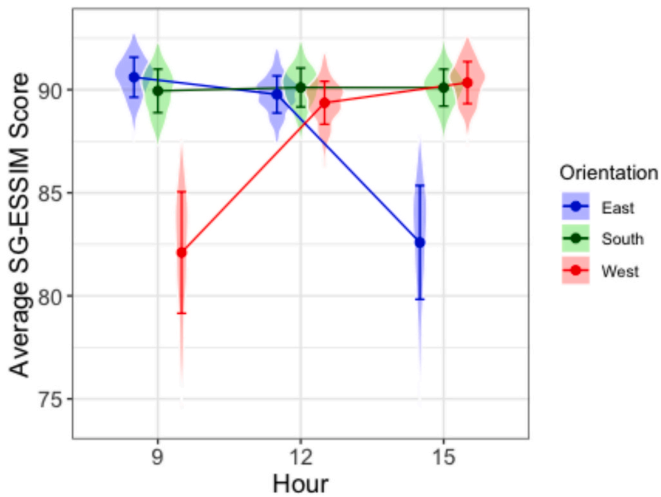

Fig. 7. SG-ESSIM scores for view clarity across time of day for different orientations.

Table 4
Summary of SG-ESSIM scores for view clarity across different times of day.

Hour	East	South	West
09:00	90.6 ± 1.0	89.9 ± 1.1	82.1 ± 3.0
12:00	89.8 ± 0.9	90.1 ± 1.0	89.4 ± 1.0
15:00	82.6 ± 2.8	90.1 ± 0.9	90.3 ± 1.0

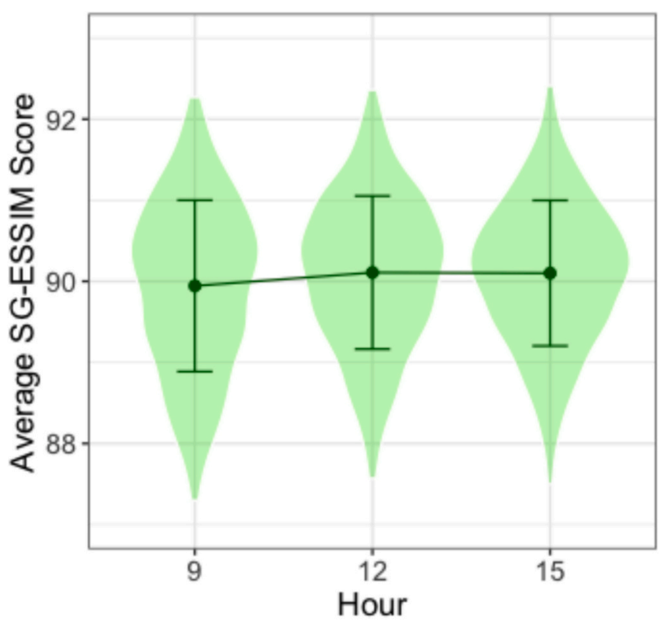

Fig. 8. SG-ESSIM scores for view clarity across time of day for south orientations.

consistent clarity throughout the day, likely due to more balanced solar angles and even daylight distribution.

It is also possible that occupants' tolerance to daylight glare increases as the day progresses [50], potentially contributing to the slight temporal variation observed. These findings are consistent with prior works by Lee [2] and Tuaycharoen [6], who emphasised the importance of solar geometry and light intensity in shaping occupants' visual experiences. The stability of clarity between noon and afternoon also highlights a design opportunity for simplifying dynamic glazing control

Table 5
Statistical summary for ANOVA on time of day by orientation.

Orientation	F (df_1, df_2)	p-value	Significant Pairwise Differences (Tukey HSD)
South	F(2, 1149) = 3.54	0.029	12:00 > 9:00 (p = 0.049)
West	F(2, 1149) = 2160	<0.001	15:00 > 12:00 > 9:00 (all p < 0.001)
East	F(2, 1149) = 2388	<0.001	9:00 > 12:00 > 15:00 (all p < 0.001)

profiles in south-facing zones—an idea less explored in earlier literature.

West: For west-facing windows, view clarity increased dramatically over the day, with scores rising from the lowest point at 9:00 to the highest at 15:00 (Fig. 7). ANOVA revealed a highly significant effect of hour ($p < 0.001$). Tukey's test showed significant clarity improvements from morning to noon and from noon to afternoon (both $p < 0.001$). These results can be attributed to the oblique and low solar angles in the early morning, which create excessive contrast and reduce visibility. As the sun shifts westward in the afternoon, daylight penetrates more directly, improving luminance uniformity and enhancing edge sharpness. This finding supports the use of time-adaptive EC control in west-facing windows, with lower tint levels in the morning and darker states in the afternoon to mitigate potential overexposure.

East: In contrast, the east-facing windows showed a marked decline in clarity over the day (Fig. 7). ANOVA again indicated a significant time effect ($p < 0.001$), with clarity scores dropping from their peak at 9:00 to the lowest point at 15:00. Post-hoc results confirmed significant differences across all pairwise comparisons, especially between 9:00 and 15:00 ($p < 0.001$). This trend reflects how early morning light provides optimal viewing conditions due to low glare and balanced contrast via EC galazings. However, by the afternoon, low solar angle creates low light and high contrast, which likely reduces perceived clarity. These results suggest the need for higher tint levels earlier in the day. Designing dynamic EC profiles that increase tint levels before noon could preemptively manage this shift and maintain optimal clarity.

To explore whether view clarity varies across months, SG-ESSIM scores were compared between March (3) and June (6) for each orientation. Fig. 9 illustrates the distribution of average scores and variability across the two time points. South-facing orientation shows narrow and symmetric distributions, indicating consistently high clarity with minimal variability. In contrast, East and West orientations exhibit broader and more dispersed violin shapes, reflecting greater variability in view clarity across both months.

A one-way ANOVA was conducted separately for each orientation to test for differences in SG-ESSIM scores across months and is presented in Table 6.

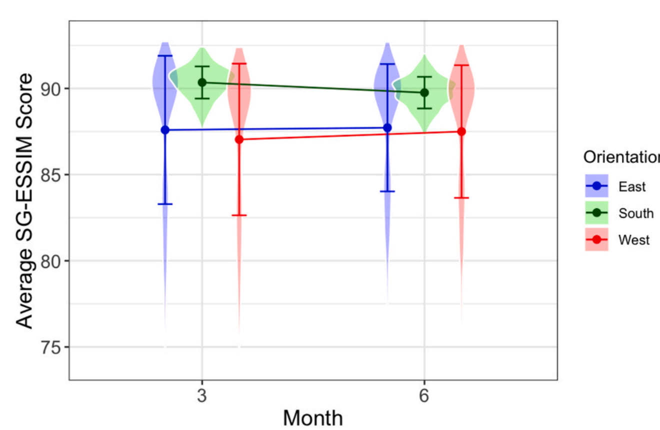

Fig. 9. SG-ESSIM scores for view clarity across months, 3: March and 6: June, across all orientations.

Table 6
Statistical Summary for ANOVA on month by orientation.

Orientation	F (df_1, df_2)	p-value	Significant Pairwise Differences (Tukey HSD)
South	F(1, 1150) = 117.8	<0.001	March > June ($p < 0.001$)
West	F(1, 1150) = 3.56	0.06	No significant difference
East	F(1, 1150) = 0.30	0.58	No significant difference

For South-facing windows, SG-ESSIM scores were significantly higher in March (90.3 ± 0.9) compared to June (89.8 ± 0.9). For West-facing windows, a small increase was observed from March (87) to June (87.5), though this difference was not statistically significant. For East-facing windows, average scores remained nearly unchanged across months (March: 87.6, June: 87.7).

The significant difference in SG-ESSIM scores between March and June, observed only in the South orientation, suggests a correlation that may relate to the unique solar geometry and light distribution associated with south-facing exposures. Unlike East and West orientations, where sunlight enters primarily during limited morning or late afternoon hours, South-facing windows receive more consistent and direct sunlight throughout the day, especially as the sun climbs higher in the sky between spring and early summer. This shift may influence luminance balance, contrast, or glare potential in the view field, all of which are factors that affect the SG-ESSIM metric. In contrast, East-facing views are predominantly affected during the morning, and West-facing views receive more light later in the day, but both are subject to more transient and directional light, which may not change as consistently between March and June. As a result, the stability in SG-ESSIM scores across months in East and West orientations might reflect the lower sensitivity of these views to seasonal shifts in daylight patterns. It is also worth noting that the variation observed in the South is small in absolute terms, though statistically significant, which highlights the importance of using robust visual quality metrics when evaluating subtle temporal trends in view clarity.

3.3. Viewing positions and view clarity across orientations

As shown in Fig. 10, the average scores for south-facing windows remained relatively stable across all positions, while scores for east and west orientations declined at the R position (Table 7).

Statistical analyses supported these observations. For all three orientations, one-way ANOVA, in Table 8, revealed a significant effect of viewing position on SG-ESSIM scores (all $p < 0.001$). Post-hoc Tukey tests further indicated that for all orientations, view clarity at the R position was significantly lower than both L and M positions ($p < 0.001$), with no significant difference between L and M.

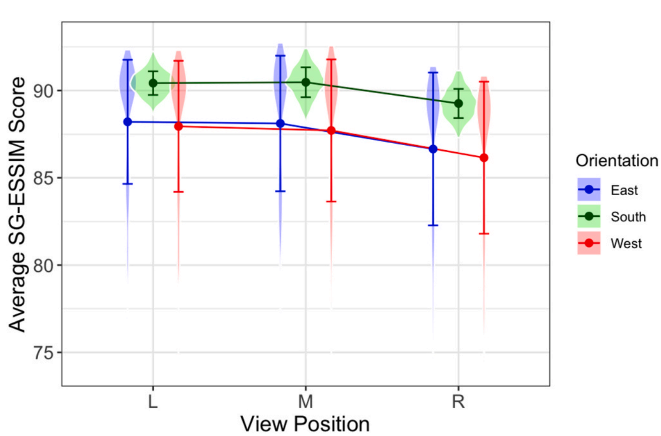

Fig. 10. SG-ESSIM scores for view clarity across viewing positions, L: left, M: middle and R: right, across all orientations.

Table 7
Summary of SG-ESSIM scores for view clarity across different viewing locations.

Viewing location	East	South	West
L	88.2 ± 3.6	90.4 ± 0.7	87.9 ± 3.8
M	88.1 ± 3.9	90.5 ± 0.9	87.7 ± 4.1
R	86.6 ± 4.4	89.3 ± 0.8	86.2 ± 4.4

Table 8
Statistical summary for ANOVA on viewing positions by orientation.

Orientation	F (df_1, df_2)	p-value	Significant pairwise differences (Tukey HSD)
South	F(2, 1149) = 288.6	<0.001	R < M = L (R significantly lower than both, $p < 0.001$)
West	F(2, 1149) = 22.13	<0.001	R < M = L (R significantly lower than both, $p < 0.001$)
East	F(2, 1149) = 18.77	<0.001	R < M = L (R significantly lower than both, $p < 0.001$)

Given the symmetrical setup of environmental variables between the L and R viewing positions, similar patterns in clarity scores would be expected. One potential explanation for the consistently lower clarity observed at the R position is the spatial distribution of the Landolt-C optotypes. From the R viewpoint, smaller and more distant C-shaped characters occupy a larger portion of the visible field compared to the L and M positions. Because smaller optotypes result in less pronounced edge features in the rendered images, the SG-ESSIM algorithm may detect lower structural similarity scores, independently of the actual optical performance of the glazing. Future studies could test this hypothesis by rotating or randomising the Landolt-C chart layout to isolate spatial bias effects. Understanding this effect can also inform architectural design strategies by emphasising central, direct views.

3.4. Validation of SG-ESSIM scores with edge detection

The edge detection process applied to the rendered window views, as described in the methodology, was used to validate the SG-ESSIM results. For this purpose, several pairs of renders belonging to the south-facing window were compared visually to assess the algorithm's accuracy in representing clarity differences. An example is presented in Fig. 11, which shows results for March 21st at 9:00 AM from view position 2.

The visual comparison confirmed that SG-ESSIM scores align closely with the clarity of the detected edges. Renders with higher SG-ESSIM scores displayed sharper and more well-defined edges, while lower scores corresponded to diminished edge clarity. By randomly selecting additional render pairs for comparison, the consistency of this relationship was reaffirmed, demonstrating the robustness of the SG-ESSIM algorithm in quantifying view clarity.

3.5. Limitations and future integration with perceptual research

While the objective approach to evaluating window view clarity offers advantages in scalability, repeatability, and control over environmental parameters, we acknowledge several important limitations that must be considered when interpreting the results.

First, clarity is inherently a subjective and perceptual construct, closely tied to human vision, cognitive interpretation, and context. The experience of clarity may vary significantly between individuals depending on factors such as age, visual acuity, task, mood, and even cultural associations[17,51]. As such, the SG-ESSIM metric employed in this study should be considered a quantitative proxy—useful for pattern identification and relative comparisons—but not a substitute for fully

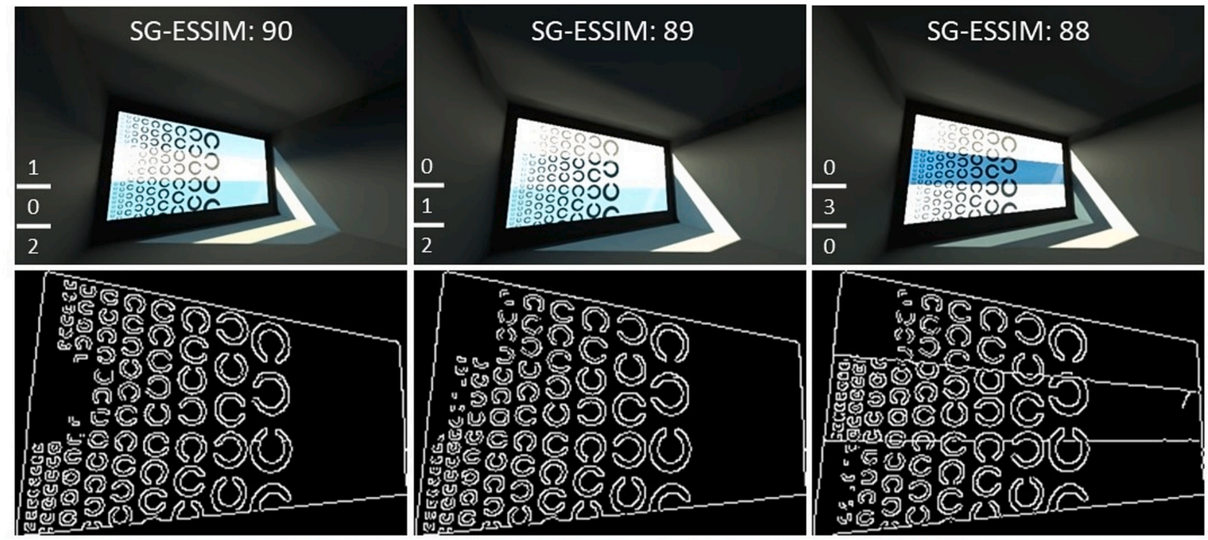

Fig. 11. Comparison of SG-ESSIM scores with the result of edge detection for different electrochromic glazing configurations. The top row shows rendered window views with varying tint levels, each annotated with its respective SG-ESSIM score. The bottom row illustrates edge detection results used to validate the result.

human-based evaluation.

Second, the simulation-based workflow involves multiple assumptions and simplifications that introduce abstraction from real-world complexity. These include the use of a specific climate and sky model, idealised material and optical modelling of electrochromic glazing, omission of inter-reflection effects between adjacent glass panels, and lack of dynamic adaptation to internal lighting conditions or occupant behaviour. These assumptions enable controlled comparisons but limit generalisability to real-life spaces, where variability and multimodal interaction (e.g., between light, materials, and human activity) can significantly affect perceived clarity. Besides, the SG-ESSIM algorithm, though robust, is inherently dependent on image features such as edge sharpness and saliency. Furthermore, while it aligns closely with human perception, it does not account for other subjective aspects of view quality, such as emotional or aesthetic responses to the view.

Rather than aiming to fully resolve these challenges, the goal of this study is to offer a complementary approach—a structured, reproducible methodology that can be integrated with perceptual studies. By systematically varying orientation, viewing position, and time of day, and applying a consistent image-based clarity metric, we provide a framework for early-stage design analysis, simulation testing, and potential benchmarking. Importantly, this work serves as a foundation for hybrid methods that combine computational models with empirical validation through human-subject-based research. For instance, SG-ESSIM-based predictions could be correlated with user responses to evaluate the accuracy or used to guide the design of perceptual experiments that vary conditions in a targeted, data-informed manner. Furthermore, while this study primarily focused on view clarity as a performance metric, future research could benefit from a broader, multidimensional approach. Integrating additional aspects, such as colour perception, thermal comfort, glare protection, and as well as different control strategies, would enhance the practical applicability of the findings, supporting more holistic occupant-centric design strategies.

4. Conclusion

This study developed a scalable, simulation-based framework to assess the view clarity in electrochromic glazing systems, an essential component of occupant comfort and visual satisfaction in building interiors. By developing a quantitative framework using the Saliency-Guided Enhanced Structural Similarity algorithm, the research sought to objectively evaluate how various electrochromic glazing configurations, environmental conditions, and viewing positions influence view clarity.

The findings reveal that in tri-zone electrochromic glazings, moderate to high total tint levels, specifically TTL 7 and 8, maximise view clarity, particularly for south-facing facades, while east- and west-facing facades require medium adaptive tinting strategies to accommodate rapidly changing solar exposure.

The study also aimed to bridge the gap between subjective assessments and computational analysis, providing a replicable methodology for quantifying visual quality. Rather than replacing human-subjective evaluations, the proposed approach is positioned as a complementary tool to support further research with enhanced quantifiable data on view clarity. This hybrid perspective seeks to strengthen early-stage design decision-making processes while laying a foundation for integrating objective metrics with perceptual validation.

Addressing limitations (section 3.5) in future research will yield a more comprehensive understanding of how electrochromic glazing systems perform under real-world conditions, thereby enhancing human comfort, well-being, and connection to the outdoors.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT to polish and improve the readability and language of the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and took full responsibility for the content of the published article.

CRediT authorship contribution statement

Peiman Pilehchi Ha: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Nasim Goli Baghmahyari:** Writing – original draft, Validation, Software, Methodology, Formal analysis, Conceptualization. **Farhad Barahimi:** Writing – original draft, Visualization, Methodology, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Peiman Pilehchi Ha reports financial support was provided by VILLUM FONDEN. Peiman Pilehchi Ha reports a relationship with VILLUM FONDEN that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2025.116040.

Data availability

Data will be made available on request.

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