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In-situ evaluation of high-performance glazing based on illuminance and glare

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Abstract. High-technology glazing panes are designed to meet the need for natural light, while optimizing key functions such as reducing solar heat gain in spaces and/or redirecting daylight to the rear of the spaces. However, the actual performance in terms of both illumination and glare protection of these glazing systems is often unknown. This study aims to compare the visual comfort performance of four complex fenestration systems by means of point-in-time measurements under real sky conditions and for different seasons. The tested systems included: two glazing types with embedded seasonal solar protection, namely, MicroShade™ and Coolshade™, one prototype of daylight redirecting glazing with embedded micro-mirrors (GEMM), and one clear glazing. We conducted our tests in side-by-side nearly identical spaces in the NEST building in Dübendorf, Switzerland. Results showed a higher daylight provision for clear and daylight redirecting glazing. Discomfort glare assessment from daylight showed that MicroShade™ was substantially more efficient at addressing glare due to sunlight for high sun angles when compared to Coolshade™. The performance of the GEMM prototype was highly dependent on the glazing pane used and one pane provided a promising performance when it comes to mitigating glare risks for high sun positions. However, none of the systems were able to provide an adequate glare protection for lower sun positions. The performed measurements provide a basis for the calibration of simulation models.

1. Background

The extensive use of glazing as a building façade has become a common feature in commercial buildings. These building types require careful design decision-making that accounts for user's needs. Among these, access to daylight appears to be of primary importance, both in terms of the appreciation of occupants for natural light – approximately 80% of occupants claim to prefer daylight to electric lighting [1–3] – as well as in terms of the non-image forming effects of light, with notably the crucial role of (day)light for synchronizing circadian rhythms [4,5] and its effects on other bodily processes necessary for our well-being and health [6–8]. In parallel, the access to views out through windows has shown its positive impacts on human workplace satisfaction, increasing productivity, focus, life satisfaction, stress modulation, and patient recovery time [9–15], while views also satisfies fundamental human needs for visual information about location, time, weather and activities outside the building [16,17]. Thus, the extensive use of glazing in commercial buildings seems to be a sound approach, and high-performance glazing can offer promising combinations of properties when it comes to ensuring protection against excessive solar gains and/or glare, or bringing natural light deeper into the space.

The International Commission on Illumination (CIE) defines glare as the "condition of vision in which there is discomfort or a reduction in the ability to see significant objects, or both, due to an unsuitable distribution or range of luminances or to extreme contrasts in space or time" [18]. Glare is common in workspaces and is a source of disturbance to building occupants [9] that can affect their productivity [19]. Multiple metrics have been established to characterize discomfort glare from daylight from objective measurements. Of these, hybrid metrics are based on both saturation and contrast effects, amongst which the Daylight Glare Probability (DGP) [20] – adopted for daylight glare prediction in the European standard EN 17037 [21] – was shown to be one of the most robust and reliable metrics [22,23].

High-technology glazing systems are designed to meet the need for natural light, while optimizing certain key functions like managing solar heat gains. However, this usually requires a trade-off. Reducing heat loads generated by solar gains for instance can also indirectly affect indoor illumination. Similarly, light-redirecting glazings, which aim at increasing daylight penetration through embedded reflective or refractive components, can cause discomfort due to glare from daylight and do not prevent per se from overheating. In general, it is therefore difficult to optimize glazing for multiple objectives and complex fenestrations systems are often only tested for the objective for which they have been optimized.

2. Objectives

This study aims to compare the visual comfort performance of four complex fenestration systems by means of measurements under real sky conditions, with a focus on the depth of penetration of daylight in the space (illuminance distribution) and the effectiveness of the offered protection against glare from the sun. Evaluations were conducted for both low (winter) and high (summer) sun positions and all the systems allowed to maintain at least a partial view to the outside. This study does not cover the topics of daylight spectral power distribution and outdoor view clarity.

3. Methods

3.1. Experimental protocol

We conducted our tests in nearly identical side-by-side spaces located within the SolAce unit in the NEST building in Dübendorf (CH) [24]. In these spaces, the upper part of the façade was designed to test complex fenestration systems. We tested a total of four systems including two glazing types with embedded seasonal solar protection, namely, MicroShade™ [25] and Coolshade™ [26], one daylight redirecting glazing prototype with embedded micro-mirrors (GEMM) [27,28] and one clear glazing. The glazings were mounted successively in the upper part of each space (see Figure 1(a) and 2). We carried out the on-site monitoring during the summer and winter seasons on sunny days. We focused on point-in-time measurements and conducted seven pairwise comparisons spread over the two seasons (see Table 1).

3.2. Experimental space

SolAce is living lab that can be used for a variety of in-situ experiments, including energy performance and carbon neutral living assessments [29]. Our side-by-side testing spaces are South-West oriented and can be separated from the rest of the module by means of curtains, as represented in Figure 1(a). The facade was designed with operable windows and external shading fabric in the lower part, and with fixed shading panes in the upper part. We performed our tests with the curtain of the lower part down and without artifical lighting to better focus on the upper part. Prior to testing, we measured the reflectance of the indoor surfaces, and conducted measurements of indoor lighting conditions with the upper windows blacked out to ensure enough similarity between the side-by-side spaces.

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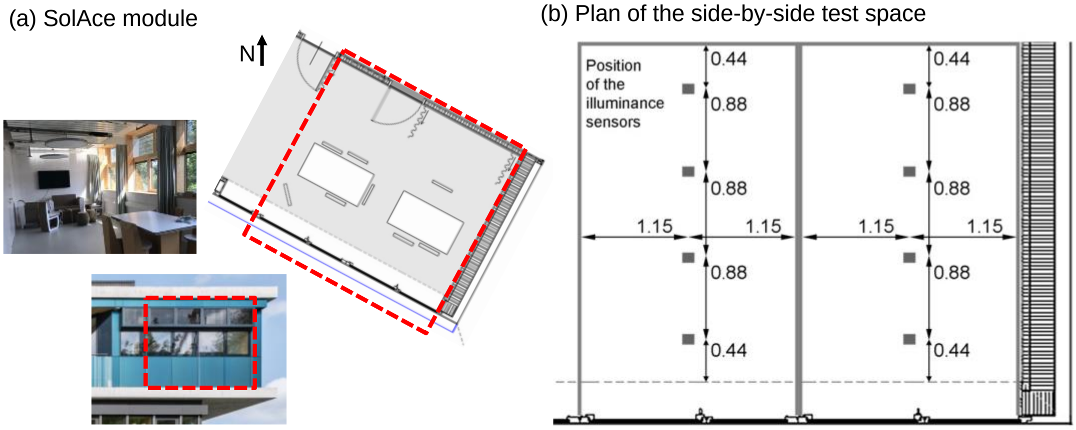

Figure 1. (a) Layout and views of the indoor space in the SolAce unit with in red the side-by-side test space; (b) Plan of the side-by-side test space (numbers are reported in meters) with the location of the illuminance sensors

Figure 2. Views of the two rooms with the GEMM (left), MicroShade™ (center) and Coolshade™ (right) glazings fitted on the upper part of the façade. The textile blinds of the lower windows were kept down during the testing

Table 1. List of glazing comparisons and test dates for each season

Comparisons	Upper part of the left space	Upper part of the right space	Summer[(a)]	Winter
1	Coolshade™	GEMM[(b)] (Summer: C+E) GEMM[(b)] (Winter: D+E)	Jun. 03, 2020	Feb. 23, 2021
2	Coolshade™	MicroShade™	Jul. 13, 2020	Feb. 22, 2021
3	GEMM[(b)] (Summer: B+C)	MicroShade™	Jul. 14, 2020	-
4	Clear glazing	GEMM[(b)] (Winter: D+E)	-	Feb. 23, 2021
5	Clear glazing	MicroShade™	-	Feb. 24, 2021

[(a)] The clear glazing was not available in Summer

[(b)] GEMM is a prototype and different glazing panes were used. The panes used involved: prototypes “C&E” for the comparison to Coolshade™ in Summer, prototypes “B&C” for the comparison to MicroShade™ in Summer, prototypes “D&E” for the comparison to Coolshade™ and to the clear glazing in Winter in Summer. This alternation of glazing pane was the result of glazing damage and incompatibility of window pane size between the left and right spaces, and not an experimental design choice.

3.3. Fenestration systems

Four fenestration systems were compared to one another in different pairwise configurations:

- Coolshade™ (aka., Swisslamex Coolshade™) is a laminated safety glass with a mesh of solar protection lamellae (1.27 mm wide, spaced 1.27 mm apart and inclined at 30°) inserted by

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lamination. The mesh can be customized and integrated into different types of glazing. Coolshade^{TM} was a prototype from Glaströsch and was mounted within the original NEST SolAce unit.

- MicroShade^{TM} is a micro-structured perforated foil that can be integrated into double or triple insulating glazing units. The perforations are slanted through the thickness of the sheet to provide additional shading from the sun.
- GEMM includes a polymer film which contains small reflective parabolic micro-mirrors comparable to the horizontal slats of venetian blinds with micrometer dimensions (50-150 micrometer). The concept behind this glazing is to redirect the incoming solar radiation to the rear of a room in winter. For the summer, the original design included an additional layer of horizontal micromirrors aimed at blocking the sun, but this extra layer was not integrated in the prototype.
- Finally, and in order to have a baseline, we added a clear glass to our selection of fenestration systems. In order to remain consistent with the performance of current systems, we have chosen a triple insulated glazing with a high solar heat gain coefficient. This glazing however was not delivered on time for the summer studies and could only be included in the winter comparisons.

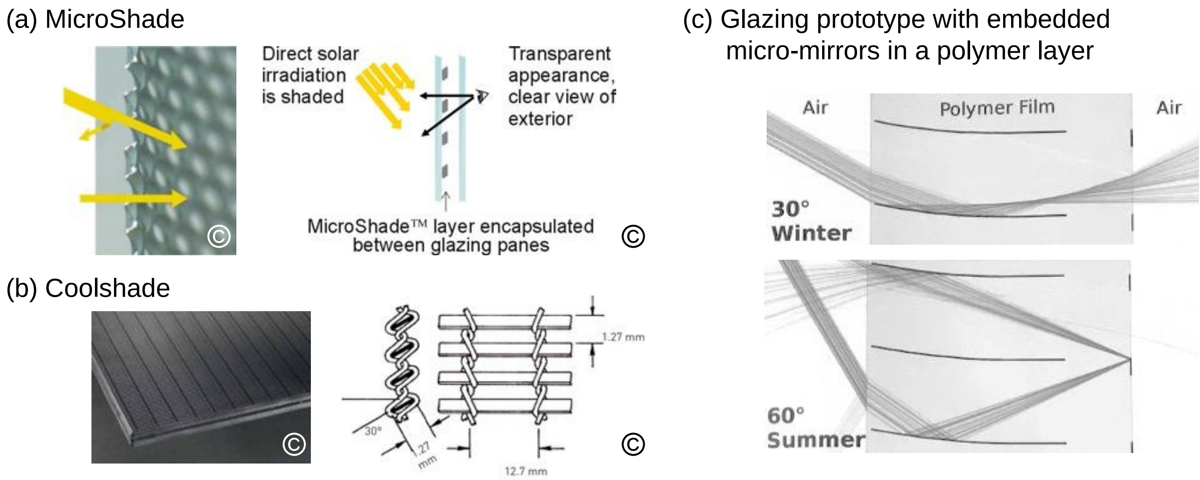

Figure 3. Conceptual diagrams and drawings from the fenestrations systems: (a) MicroShade^{TM} (image source: [30]) ; (b) Coolshade^{TM} (image source: [26]); (c) GEMM (adapted from Gong et al., 2016 [31]).
Note that the GEMM prototype used in this study **only** included to horizontal redirecting micro-mirrors.

Table 2. Glazing properties

Glazing	Nr. of panes	U-value	SHGC	t_{vis}
Coolshade™	3	0.9	0.47	NA
MicroShade™ (MS-A)	3	NA	0.1-0.33[(a)]	0.49
GEMM (prototype)	2	NA	NA	NA
Clear glazing (Silverstar EN2plus 3-fach)	3	0.8	0.53	0.74

[(a)] The Solar Heat Gains Coefficient (SHGC) of MicroShade™ depends on the angle of incidence (0.1 for high sun position and 0.33 for low sun position)

3.4. Testing equipment and analysis methods

We performed a series of point-in-time measurements simultaneously in both spaces. For the illuminance measurements, we relied on eight horizontally mounted Delta Ohm HD2021 TBA photodiode sensors (accuracy: ±10% of reading (lux)) connected to an Onset HOBO data logger. Four sensors were distributed in the center of the room as presented in Figure 1(b). For glare assessment, we used two digital single-lens reflex cameras Canon EOS D70 equipped with a fish eye lens and Kodak neutral density (ND) filters, which were calibrated using the procedure described in Pierson et al (2020)

[32]. As the images were taken with the sun in the field of view, we relied on aperture sizes (f) of 18 or 22. While capturing the images, we also measured the vertical illuminance right next to the camera with the illuminance meter LMT Pocketlux 2 (accuracy: ±7% of reading (lux)), and the luminance of a reference sample in the space using the luminance meter Minolta LS100 (accuracy: ±2% ±1 digit of reading (cd/m^2)). The measurements enabled us to calibrate the images according to the luminance ranges measured in the space. We derived the DGP by running Evalglare version 3.02 [33,34] on the calibrated HDR images. For some images we encountered pixel-overflow for the sun-disk even using the ND filters. Those images were corrected by adjusting the sun-pixels while matching the vertical illuminance for the full image using a correction procedure in Evalglare. We relied on DGP glare thresholds and their corresponding predictions (which were established based on the feedback from study participants) for the interpretation of the glare results (see Table 3).

Table 3. DGP thresholds and their corresponding predictions

DGP thresholds	Prediction
<0.35	Imperceptible
0.35-0.40	Noticeable
0.40-0.45	Disturbing
>0.45	Intolerable

We report the results in terms of absolute values – for both illuminance and glare – and compare the glazings in pairs according to the experimental design shown in Table 1. The results are grouped into (1) comparisons involving daylight redirecting glazing (GEMM), and (2) comparisons between the solar control glazing.

4. Results

4.1. Discomfort glare from daylight with sun in the field of view

The glare measurements were taken under clear sky conditions with the sun in the field of view while the viewing direction was horizontal and perpendicular to the façade (directly facing outside). These represent critical scenarios, which has the advantage of informing us about the possible protection by the different complex fenestration systems. The results are reported in Table 4. Winter solar elevation was in the range of 30-33° and summer solar elevation in the range of 50-53°.

The performance of each system remains steady during each season for both Coolshade™ and MicroShade™. For GEMM, the performance depends strongly on the window pane prototype in place. Although the choice of the glazing pane studied was not part of the objectives of this research (but a question of availability of panes), we realized while analyzing the results that fabrication quality could significantly affect their properties for incident angles in the range 45-55°, in particular in regard to the direct-direct transmittance of the pane and therefore to the induced glare.

Table 4. List of glazing comparisons and test dates for each season

Season	Date	Time	Solar azimuth(a)	Solar elevation(b)	Left	Right	DGP left	DGP right
Summer	2020-06-03	15:40	239°	53°	Coolshade™	GEMM (pane E)	0.68	0.91
	2020-07-13	15:49	239°	52°	Coolshade™	MicroShade™	0.72	0.36
	2020-07-14	16:03	243°	50°	GEMM (pane C)	MicroShade™	0.29	0.41
Winter	2021-02-22	14:38	197°	31°	Coolshade™	MicroShade™	0.93	0.79
	2021-02-23	14:15	190°	32°	Coolshade™	GEMM (pane E)	0.87	1
	2021-02-23	15:07	205°	30°	Clear glass	GEMM (pane E)	1	0.97
	2021-02-24	14:00	186°	33°	Clear glass	MicroShade™	1	0.86

(a) Azimuth is measured in degrees clockwise from north
(b) Elevation is measured in degrees up from the horizon

4.1.1. *Daylight redirecting glazing*

The GEMM prototypes are in part 'hand-made' from different fabrication batches and we observed fairly large variations between the different prototypes made available. In the winter, we used the GEMM pane E in comparison to the clear glazing and to Coolshade™ (measurements performed at different moments so with slightly different conditions). DGP values for the GEMM pane E reached 0.97 and 1 while it reached 1 for the clear glazing and 0.87 for Coolshade™ (see **Figure 5**). All these values are associated with an intolerable glare perception. For the summer measurements, the GEMM pane E led to a similarly high DGP value of 0.91 while Coolshade™ showed a DGP of 0.68 (still intolerable glare). We used the GEMM glazing pane C for the comparison to MicroShade™ (see **Figure 4**), which led to a DGP of 0.29 for the GEMM pane C (imperceptible glare), and 0.41 for MicroShade™ (disturbing glare). Given that not all systems could be measured for all conditions (cf. Table 1), these results show us that, beyond the volatility in glare mitigation for the GEMM panels due to their still prototype-level production process, all systems generally tend to have a poor glare protection performance for the low sun angles found in the winter months.

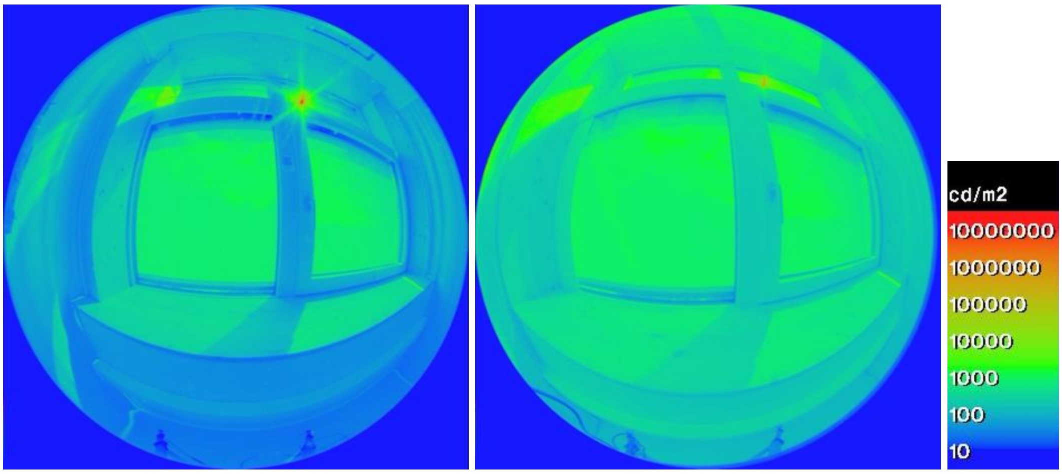

Figure 4. High Dynamic Range (HDR) images of GEMM (left) and MicroShade™ (MS-A) (right) glazings with sun in the field of view taken on July 14th 2020 at 16:03

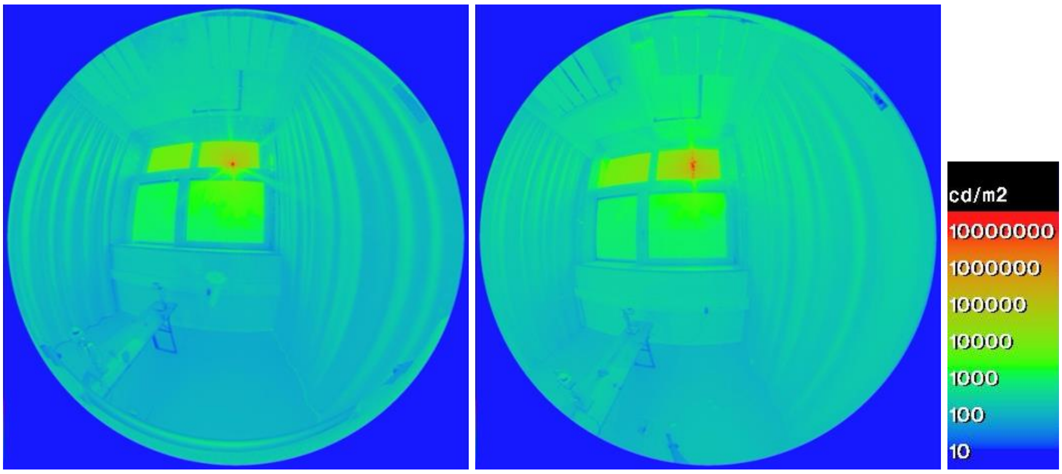

Figure 5. High Dynamic Range (HDR) images of Coolshade™ (left) and GEMM (right) glazings with sun in the field of view taken on February 23rd 2021 at 14:15

4.1.2. Seasonal solar control glazing

Concerning the seasonal solar control glazing, predictions showed that MicroShade™ was able to provide higher glare protection compared to Coolshade™ given the summer sun angles, with a DGP of 0.36 (which corresponds to a 'noticeable glare' rating), while Coolshade™ reached 0.72, rated as 'intolerable' (see Figure 6). However, both fenestration systems performed very poorly for winter sun angles and all measurements were consistent with an intolerable glare (see **Figure 7**). We note that these glazings are designed to offer a seasonal solar control and are in this sense permissible to the winter sun for the solar heat gains. The unprotective behavior towards glare in winter is therefore expected.

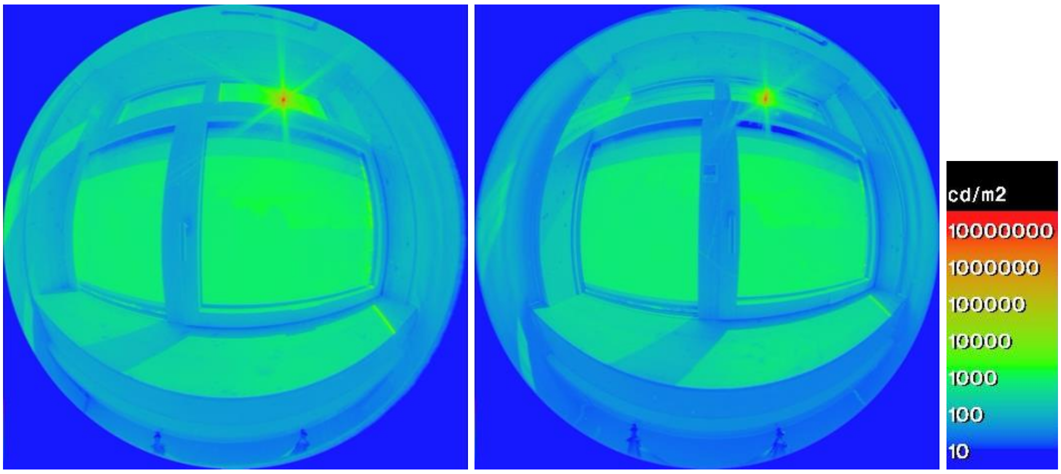

Figure 6. High Dynamic Range (HDR) images of Coolshade™ (left) and MicroShade™ (MS-A) (right) glazings with sun in the field of view taken on July 13th 2020 at 15:49

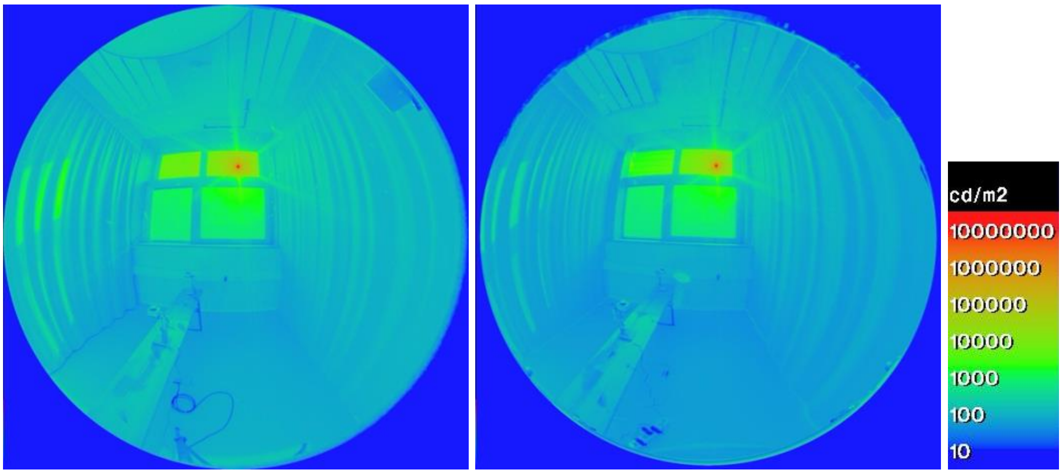

Figure 7. High Dynamic Range (HDR) images of Coolshade™ (left) and MicroShade™ (MS-A) (right) glazings with sun in the field of view taken on February 22nd 2021 at 14:38

4.2. Illuminance

4.2.1. Daylight redirecting glazing

Illuminance measurements focused on the daylight redirecting glazing (**Figure 8**) showed that GEMM consistently provided higher illuminance levels in the space than the glazing with seasonal solar control. This difference is larger for MicroShade™ (75% reduction) than for Coolshade™ (63% reduction) under summer sunny conditions. We also found that clear glazing provides higher daylight illuminance than GEMM in winter, both under direct (35% increase) and indirect sunlight (that is, when the direct sun is not facing the façade) (55% increase).

4.2.2. *Seasonal solar control glazing*

Illuminance measurements were focused on glazing with seasonal solar control (see **Figure 9**) and confirmed the advantage of light provision for Coolshade™ compared to MicroShade™ (14% higher illuminance level for a sunny summer day, and 77% for a sunny winter day). Coolshade™ being worse for glare than MicroShade™, it was therefore expected that the former would be better at letting in daylight.

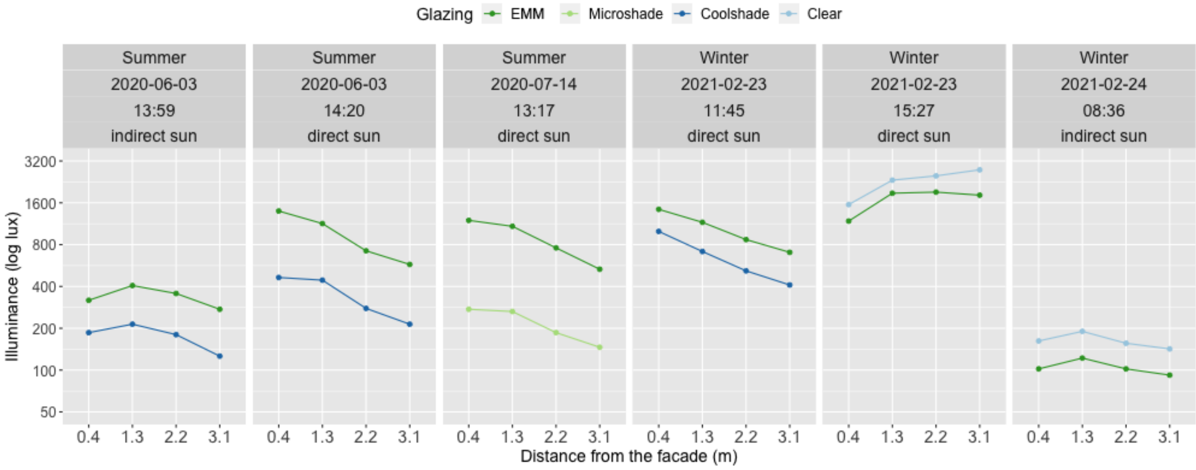

Figure 8. Sample of illuminance measurements (log scale) as a function of room depth (in meters) for the daylight redirecting glazing. Reference glazing: GEMM

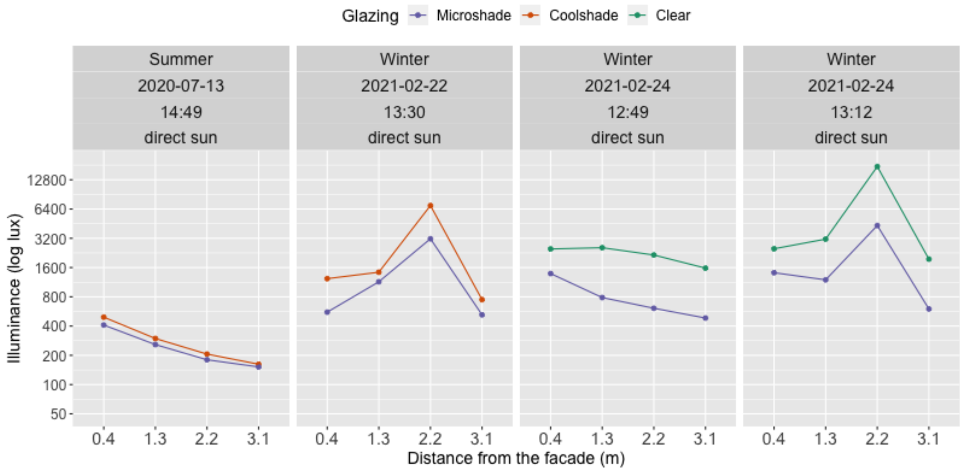

Figure 9. Sample of illuminance measurements (log scale) as a function of room depth (in meters) for the glazing with seasonal solar protection. Reference glazing: MicroShade™

5. Discussion

In this experimental study, we tested the first prototypes of the GEMM micro-structured glazing, which are still far from being optimized. Variations in the manufacturing processes induced a variation in the actual geometries which impacted the visible transmittance and its angular dependence. In the original and theoretical design of GEMM, the direct transmittance was supposed to be less than 1% for a solar elevation of 48° and above. The fabricated prototypes did not reach this target. Further, only the first set of nearly horizontal micromirrors are implemented, while the second set of vertical ones for backwards redirection are still missing. Therefore, the effect of the blocking angle for overheating protection (and glare) is not yet achieved. However, for the prototype pane C, the glare protection seemed promising for the summer sun position. Glare protection provided by this pane outperformed the solar control glazing while allowing more daylight into the back of the space. But given the extremely large differences between the windows tested, it would be necessary to finalize the prototypes and conduct further studies to make a conclusive statement about the performance of this new fenestration system.

We conducted this study to compare four glazings using a side-by-side configuration but the specifics of the set up, issues with system delivery / quality and capricious weather made it impossible to ensure a complete and clean dataset for the two seasons. The resulting point-in-time measurements thus only represent a snapshot of the actual performance of the systems and only for critical sun positions (i.e., when the sun is in the field of view and viewing direction is perpendicular to the façade) in both summer and winter. We should note that in real office settings, an occupant's desk would more typically be positioned perpandicularly to the façade and the viewing direction would thus be parallel to the window instead. In that case, the sun is typically in the peripheral field of view and situations as critical as those investigated should thus only occur for a limited time. In addition, clear skies are not necessarily representative of all conditions encountered throughout the year. Under these circumstances, continuous measurements would have been more representative of the systems' performance but would also have required continuous access to additional testing facilities. Simulation-based analyses could nicely complement this gap by providing annual evaluations, which could also be run for different desk positions.

6. Conclusion

Complex fenestration systems are becoming increasingly popular and it is necessary to adequately characterize their performance in terms of daylight provision and glare protection from direct sunlight in order to anticipate the visual comfort conditions provided to occupants. In this study, we compared the illuminance distribution and discomfort glare risks associated to four complex fenestration systems by means of measurements under real conditions for both winter and summer sun positions. The results showed, as expected, a higher daylight provision for clear and daylight redirecting systems. Daylight glare assessment showed that MicroShade™ was substantially more efficient at addressing glare from sunlight for summer sun angle compared to Coolshade™ (glare prediction of 'noticeable' to 'disturbing' compared to 'intolerable'). However, the two systems equally failed at providing a glare protection from sunlight in winter, which confirms a strong impact of the sun position on the effectiveness of these fenestrations systems. The performance of the GEMM prototype was highly dependent on the glazing pane used but one pane provided a promising performance for the summer sun position with a 'imperceptible' glare prediction. All the systems allowed to maintain the view to the outside, which is a very laudable benefit in comparison to the more traditionally used opaque shading systems.

7. Acknowledgments

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