Static and Dynamic Strategies for Improving Daylight Use in Side-Lit Classrooms: A Case Study

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Abstract

Daylight plays a very important role in educational buildings, as it allows to create a pleasant environment, to enhance students' performance and to provide better health conditions to the occupants.

For these reasons, and also to save energy in artificial lighting, a great body of literature has dealt with the study of daylight in schools in the past years. Although some quantitative criteria are already in use for assessing daylight effectiveness for several visual tasks – e.g. minimum illuminance values and daylight factors – the distinction between well and badly daylit spaces very often rely on qualitative issues, such as the avoidance of discomfort glare conditions.

Moreover, current design practices rely on standard sky patterns, and neglect the specific climate-related issues, and the time varying appraisal of the indoor space.

The present paper contributes to this research field by exploring the use of different strategies to enhance daylight levels in a school located in Sicily and selected as a case study. The building is mainly made up of side-lit classrooms, exposed to different orientations.

The strategies that are investigated rely both on traditional static devices (e.g. light shelves and reflective glazing) and on more advanced dynamic concepts (e.g. sensor-controlled blinds and electrochromic glazing). All the selected devices are already available on the market.

The daylight performance is assessed in the Radiance-based environment provided by DAYSIM 4.0; the model is calibrated upon a measurement campaign. To this aim several Climate Based Daylight Metrics (CBDM) are used to provide a deeper insight of the potentialities of each solution. Further developments are discussed in the conclusions.

1. Introduction

Daylighting in school buildings has been a subject of interest for many years, since daylight plays a crucial role in educational spaces. Indeed, daylight in schools is able to create a pleasant environment, to enhance academic performance, to promote better health, and to provide significant energy savings. For all of these reasons, the importance of daylight in schools is internationally recognized today (Meresi, 2016). In order to optimize daylighting in school buildings, several strategies are possible, mainly aimed to improve daylight uniformity within the classroom, to reduce glare risk close to the windows, and to avoid insufficient daylight availability in the back of the room (Reinhart and Weissman, 2012).

In this regard light shelves may be an effective solution. Light shelves consist in plane elements (horizontal or slightly inclined) placed in the upper part of a window (internally, externally or both) to control and redistribute incoming daylight. In particular, light shelves are expected to redirect incoming light by reflection towards the ceiling, and from there to the back of the room, while also reducing the high levels of daylight near the window. This obviously improves illuminance uniformity (Claros and Soler, 2002).

One of the main properties of a light shelf as a daylighting device is its reflectance. Light shelves reflectance can be specular or diffuse. Studies showed that specular light shelves are more effective than diffuse ones under low and medium solar altitudes (i.e. in winter), although the latter perform better at high solar altitudes (i.e. in summer). The appropriate height of a light shelf from the floor is around 2.00 m. The optimum width is between 80 cm and 100 cm, while the optimum position (inner or outer) usually depends on the specific boundary conditions (Meresi, 2016).

An alternative strategy to the use of light shelves to improve daylighting in classrooms is the adoption of *dynamic glazing*.

As opposed to static glazing, dynamic "smart" glazing can switch its optical properties when subject to an appropriate input, such as voltage, light or heat. Amongst smart glasses, *electrochromic glazing* (EC) is the most popular typology: when a voltage pulse is applied between two transparent electrodes, ions move between the EC glazing and an ion storage films, and the overall transparency is changed. A voltage pulse with opposite polarity makes the device restore its original properties. However, small voltage is needed for switching (Hee et al., 2015). Electric power is needed only for switching, i.e. no power is needed to maintain the windows in their clear or dark state, but only to change them from one state to the other.

In EC, the glazing transparency may be reduced from around 0.65 in the clear state to less than 0.05 after switching. If controlled according to the indoor illuminance level, EC glazing can create a building shell that is adaptive to the needs, i.e. able to reduce the solar radiation admitted into the room in case of excessive daylight illuminance or when glare occurs.

Tests using scale models showed that EC glazing would eliminate over-illumination in an office, while maintaining quite good daylight autonomy; however, when the sky is overcast, artificial lighting would be extensively used (Ajaji and André, 2015). In principle, EC glazing cannot improve daylight uniformity within the indoor spaces.

In this paper, both these technologies (light shelves and EC glazing) will be tested on a real case study. The case study is a classroom with east-facing windows, where an experimental campaign has highlighted the need to reduce light levels close to the windows, and to provide a better illuminance distribution, especially in the back of the room.

2. Methodology

When studying the exploitation of daylight in enclosed spaces, several metrics are available.

One of the most common metrics is the *Daylight Factor* (DF): it is defined as the ratio of the daylight illuminance at a given point inside a room to the daylight illuminance measured at the same time on an unobstructed horizontal plane. Direct sun light is excluded for both interior and exterior values (Carlucci et al., 2015). However, according to several authors, the daylight factor does not properly account for non-overcast skies; it makes no difference among different window exposures, and it does not describe how the illuminance varies with time. Finally, it is expressed as a percentage, hence no information is provided about absolute illuminance values.

In order to overcome all these shortcomings, other metrics have recently been introduced. Amongst these, the *Useful Daylight Illuminance* (UDI) is defined as the fraction of the time in a year when the indoor horizontal daylight illuminance at a given point falls within a given range (Carlucci et al., 2015). Three bins are usually identified, separated by a lower and an upper illuminance threshold. The upper bin represents the percentage of time when excessive daylight illuminance occurs, which might lead to visual discomfort; the lower bin represents the percentage of time when daylight illuminance is scarce. Finally, the intermediate bin is associated with the time when appropriate daylight illuminance is attained. According to the original UDI definition (Nabil and Mardaljevic, 2002), the lower and upper thresholds are set respectively to 100 lx and 2000 lx. Later studies (Mardaljevic et al., 2009) proposed to further split the intermediate bin, making a distinction between *supplementary UDI* ($E < 500$ lx) and *autonomous UDI* ($E > 500$ lx). When this latter condition occurs, the second case supplementary artificial lighting is most likely not needed.

In this paper, the UDI is calculated according to three bins: $E < 300$ lx (*fell-short* UDI), $300 \text{ lx} < E < 2000$ lx (*suitable* UDI), $E > 2000$ lx (*exceeded* UDI). Indeed, 300 lx seems to be a more suitable value than 100 lx to set a lower threshold for classrooms, and it is consistent with the actual binding prescriptions set by (UNI EN 12464-1:2011).

Finally, the *Spatial Daylight Autonomy* (sDA) is the percentage of the indoor space that meets a minimum daylight illuminance level for at least 50 % of the time of occupancy in a year (Carlucci et al., 2015). Again, the minimum threshold is set to 300 lx. The advantage of the sDA is that it returns a single value representing the whole area. However, it does not account for the amount by which the illuminance threshold is exceeded.

In any case, in order to calculate all these parameters, it is necessary to evaluate the time-varying illuminance distribution within the indoor space. In this paper, the calculation will be performed by simulating the classroom with DAYSIM. DAYSIM is a daylighting simulation software based on the RADIANCE algorithm, able to compute time-varying daylighting illuminance on a sensor grid for any building geometry (Gibson and Krarti, 2015). Real sky conditions, available as TMY weather files, may be used for simulations. DAYSIM was validated against experimental data in Reinhart and Walkenhorst (2001), and Reinhart and Breton (2009), and is nowadays regarded as a reliable tool for daylight simulations.

3. Case Study

3.1 Experimental Campaign

The building selected as a case study is a school built in the 1960s in a town located in Sicily (Southern Italy, LAT. 37°21’N, LON. 13°51’E). The classrooms are mainly oriented to the east and south, while offices and recreational rooms are oriented to the north and west (see Fig. 1).

In this paper, only one classroom representative of the whole set of spaces facing east is investigated. The classroom measures 5.4 x 6 m² and 3.5 m in height, and has two clear double-glazed windows with a fixed clerestory at the top and three panes of glass at the bottom (see Fig. 2 for the details), resulting in a total glazed area of 5.26 m². It hosts 25 students from 8:00 a.m. to 3:00 p.m., from Monday to Saturday. The installed lighting power density is 8 W/m², and no dimming control systems or shading devices are in place except for plastic rolling shutters operated manually from inside.

Fig. 1 – View of the school selected as a case study

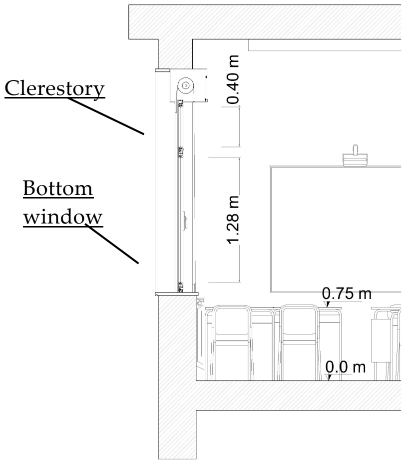

Fig. 2 – Vertical section of the classroom

The first step of the study involved a detailed field survey of the geometrical and optical features of the rooms. To this aim, a Leica X 310 laser distance meter was used to set up the geometrical model, while a Minolta T-10 lux meter and a Minolta LS-100 luminance meter were used to define the optical properties of the different surfaces. The main features of the instruments are shown in Table 1.

The values of luminance (L) and illuminance (E) measured on the opaque surfaces allowed to define their visible reflectance. Indeed, under diffuse reflection, the following relation holds:

$$\rho = (\pi \cdot L)/E \tag{1}$$

The results are reported in Table 2.

Table 1 – Main characteristics of the instruments

Solution	Range	Accuracy
Leica X 310 (laser meter)	0-150 m	±0.001m
Minolta T-10 (lux meter)	0.01-300 klx	± 3 %
Minolta LS-100 (luminance meter)	0.01-50 kcd/m²	± 0.2 % (±1 digit of measured value)

Table 2 – Optical properties of the surfaces

Solution	Reflectance or Transmittance
Courtyard tiles (outside)	$\varrho = 0.20$
Outer plaster (dark-yellow colour)	$\varrho = 0.41$
Inner plaster – walls (pale-yellow)	$\varrho = 0.75$
Inner plaster – ceiling (white)	$\varrho = 0.85$
Marble tiles – floor	$\varrho = 0.32$
Desks and seats (wooden)	$\varrho = 0.55$
Blackboard	$\varrho = 0.08$
Windows frames (aluminium)	$\varrho = 0.78$
Glazing: clear double pane	$\tau = 0.70$

Another series of measurements allowed to quantify the illuminance levels on a horizontal grid of 72 points equally spaced within the classroom (70 cm grid resolution) at the height of 80 cm above the floor (UNI EN 12464-1:2011). The illuminance levels were measured on December 22 at 10:30 a.m. without the use of any artificial light sources, to appreciate the contribution of daylight only to the brightness of the environment.

The measured illuminance values are shown in Fig. 3 as isolux curves filled with a false colour gradient depicting different daylight intensities. Based on these results, as well as after surveying teachers and students on their perception of brightness levels throughout the year, it emerges that the main issue is represented by discomfort glare for the students seated close to the windows. Indeed, values close to 4000 lx were measured for these positions while in all the other points the illuminance is always above the minimum threshold of 300 lx (UNI EN 12464-1:2011). The peak values close to the window on the north side of the room are due to a direct spot of sunlight hitting the wall through the windows, what is clearly observable in the same Fig. 3 (upper picture) that provides an interior view of the room at that time.

3.2 Proposed Solutions

A series of different strategies employing several technological solutions are proposed to improve daylight distribution within the room, ranging from the most traditional ones like blinds or reflective windows to the most advanced concepts such as light shelves and electrochromic windows.

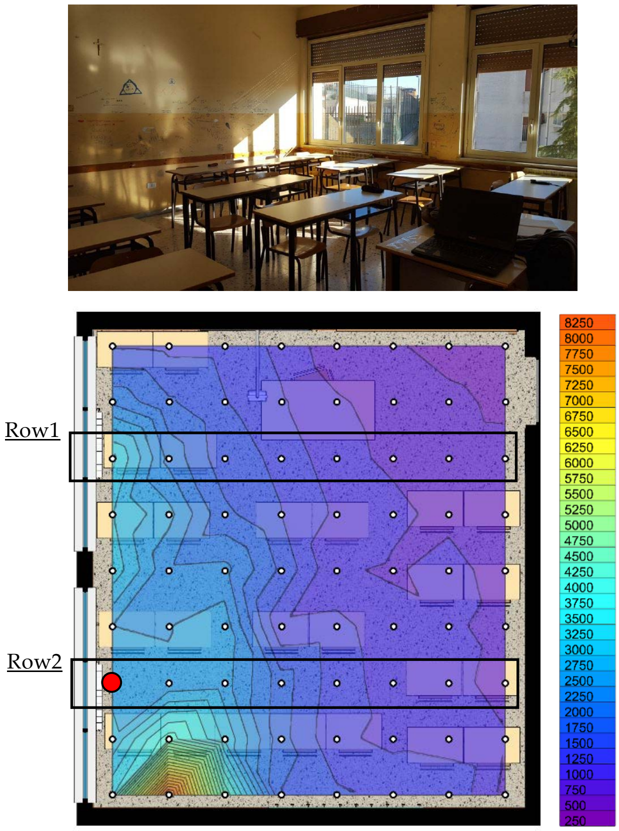

Fig. 3 – Interior view of the room (top) and measured illuminance distribution (bottom) on December 22 at 10:30 am

In particular, the following cases are investigated:

- *Case B*: base case (as previously discussed);
- *Case BL*: as in case B, but with the addition of an internal light shelf placed at the bottom of the clerestory (2.20 m above the floor);
- *Case BLB*: as in case BL, but with the additional use of light-colored internal blinds for the bottom glasses, triggered by an automatic control system;
- *Case EC*: electrochromic panes triggered by an automatic control system instead of clear ones for the bottom windows, while the clerestory retains clear glazing;
- *Case ECL*: as in case EC, but with the additional use of an internal light shelf placed at the bottom of the clerestory;
- *Case R*: reflective panes instead of clear ones for the openable parts, while the clerestory retains clear glazing.

The reasons for studying these technologies to improve daylight distribution are manifold: first, they are able to reduce light levels close to the windows without affecting the daylight availability in the back of the room, thanks to the clerestory and to the light shelves, when used. Secondly, they allow a comparison between static (reflective windows and light shelves) and dynamic devices (automated blinds and EC windows). Finally, all the products chosen for simulation purposes are already available on the market and thus represent practical refurbishing solutions. Their main optical characteristics, as gathered from the manufacturer data sheets, are summarized in Table 3.

The proposed internal light shelf is 0.8 m in width; Preliminary simulations showed that this size optimizes illuminance values at the back of the classroom, while an external light shelf would not produce any improvements due to low sun angles. The visible reflectance of the light shelf is $\rho = 0.9$ (see Table 3); diffuse reflectance with a 10 % specular component is considered in the simulations.

As far as electrochromic (EC) glazing is concerned, the technical data sheets provided by the manufacturer report a switching time of less than 3 seconds when a voltage of 120 V is applied; the power needed for switching is 5 W/m^2. The values of visible transmittance in the clear and the tinted states are reported in Table 3.

The logic of activation of these devices, as well as the one to trigger the internal blinds, is to prevent high illuminance values and glare occurrence for the desks close to the windows. More specifically, whenever the illuminance in the control point (highlighted in red in Fig. 3) exceeds 2000 lx, the dynamic devices are automatically triggered in the respective scenarios. This threshold value is consistent with the one adopted by Mardaljevic and Nabil (2008) when studying the energy benefits of different daylighting solutions for sidelit office rooms.

Table 3 – Optical properties for the selected technologies

Solution	Reflectance or Transmittance
Internal light shelf (0.8 m width)	$\rho = 0.90$
Vertical light-coloured blinds	$\rho = 0.80$
Electrochromic (double glazing)	$\tau = 0.05 – 0.65$
Reflective (double glazing)	$\tau = 0.47$

Although a thermal analysis lies outside the scope of this paper, it is worth highlighting that all the proposed window solutions have an U-value close to that of the base case scenario (U = 2.7 W/m^{2}K), in order to not affect the amount of heat exchanged by temperature difference between the indoor and the outdoor environment. However, further studies on these aspects are needed since different optical properties lead to different g-values and thus affect the room energy balance as well.

4. Results and Discussion

In this section, the fine-tuning of the Radiance parameters is first discussed, and the model built in DAYSIM for simulation purposes is validated by comparison with the measured illuminance values. Then the results of the simulations for the solutions described in Section 3 are presented. The discussion of the results is based on the use of the metrics introduced in Section 2.

4.1 Model Validation

In order to validate the model and to fine-tune the Radiance parameters, various simulations were run by adjusting the parameters until a mean error below 20 % was achieved between measured and simulated mean illuminance profiles. Since DAYSIM is a climate-based software, it needs to know the site location (to evaluate the sun's position in the sky vault) and the time profile of direct and diffuse horizontal irradiance to estimate illuminance and luminance levels on a user-defined grid of points. These data are available on TMY weather files; in this work, the file referring to Catania Fontanarossa weather station was used.

However, it must be remarked that during the measurement campaign – launched on December 22 at 10:30 a.m. – the presence of some clouds was registered. This affected the value of the global illuminance on an unobstructed horizontal plane, which amounted to 11 klx. This value does not correspond to what reported on the weather file (60 klx on December 22 at 10:30 a.m., measured in clear sky conditions). For this reason, the simulations were run by using the data available in the weather file for December 20 at 10:00 a.m., when a global illuminance of around 12 klx is reported on the horizontal plane.

The values of the Radiance parameter retained after tuning and validation are reported in Table 4. With these parameters, the simulated illuminance profiles for the rows of points depicted in Fig. 3 are reported in Fig. 4 (dashed lines), and show a good agreement with the measured values (solid lines). A certain underestimation of the daylight illuminance close to the windows (at a distance below 1.70 m) is registered, which may be due to some inaccuracy in the exact tracing of direct sun rays, such as the one that produces the above-mentioned spot of direct sunlight. On the other hand, the contribution of the diffuse sunlight is simulated with much more accuracy. Overall, the model is considered accurate enough to compare the different proposed solutions for improving daylight exploitation.

It may be interesting to underline that the duration of the simulations was about 30 minutes, except in those cases with light shelf (around 50 minutes).

Table 4 – Radiance parameters used for the simulations

Parameter	Value
Ambient bounces (ab)	5 - 7*
Ambient divisions (ad)	2048
Ambient super-samples (as)	512
Ambient resolution (ar)	512
Ambient accuracy (aa)	0.075
Limit reflection (lr)	8
Specular threshold (st)	0.15
Specular jitter (sj)	0.70
Limit weight (lw)	0.004
Direct jitter (dj)	0.7
Direct sampling (ds)	0.15
Direct pretest density (dp)	512

(* the second value is used in the simulations with light shelves)

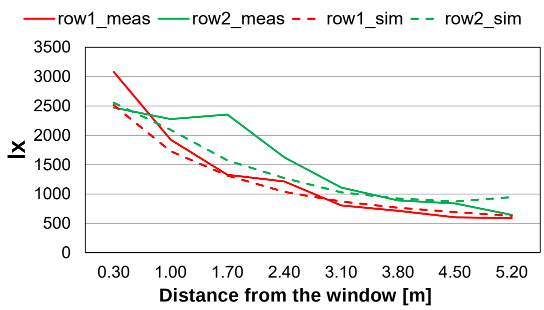

Fig. 4 – Illuminance profiles for two sections of the room

4.2 Simulation Results

The results of the simulations show a good daylight availability within the room in the base configuration (B), as observed from the values of the *spatial Daylight Autonomy* in Fig. 5. Indeed, sDA = 91 %: this means that more than 90 % of the floor area is sufficiently daylit (i.e. the illuminance is above 300 lx) for more than 50 % of the occupancy period. However, very similar figures are expected also when using reflective windows (case R).

As far as the introduction of an internal light shelf to the existing configuration is concerned (case BL), this solution on the one hand reduces the daylight availability in proximity of the windows but, on the other hand, it increases the daylight availability at the back of the classroom. These two contrasting effects seem to balance, hence sDA is around 91 %.

The use of EC windows would reduce the sDA to 70 %, since the back of the classroom would be severely penalized. However, coupling them with an internal light shelf (case ECL) allows the distribution of daylight and the same performance as in the base-case (sDA = 91 %). The worst scenario is given by the combined use of internal blinds and light shelves (case BLB), since for this configuration the illuminance values are the lowest everywhere within the room, and sDA amounts to around 50 %.

To sum up, according to the recommendations by IES (IES, 2012), the existing configuration (with or without internal light shelf), as well as the use of reflective windows and EC windows with a light shelf, all provide good spatial Daylight Autonomy (sDA > 75 %). The other solutions (BLB and EC) are only rated as *nominally acceptable* (sDA > 55 %).

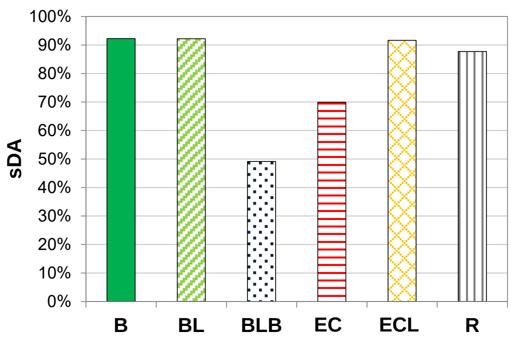

Fig. 5 – Spatial Daylight Autonomy for the proposed solutions

However, one should also take into account the magnitude and duration of the daylight levels achieved throughout the year. To this aim, one can assess the mean value of the *Useful Daylight Illuminance*, according to the three bins previously defined. This allows to evaluate for how long the amount of daylight within the classroom is not satisfactory (UDI < 300 lx), acceptable (300 < UDI < 2000 lx) or too high (UDI > 2000 lx) for normal visual tasks (see Fig. 6), thus complementing the spatial analysis provided by the sDA.

As expected, the worst performance pertains to the BLB scenario, where for almost 60 % of the time the mean illuminance is too low (UDI < 300).

However, even the use of electrochromic windows – coupled (ECL) or not coupled (EC) with a light shelf – significantly worsen the availability of daylight in the classroom, as demonstrated by UDI values very close to those of the BLB scenario.

On the other hand, the best performing solution is the adoption of reflective windows (R): in this case, acceptable mean daylight levels are achieved for more than 80 % of the occupancy period, while potential discomfort glare occurs only 10 % of the time. In fact, reflective windows reduce the excessive illuminance measured close to the windows, and establish a more pleasant visual environment if compared with the base case (B): here, acceptable daylight levels are predicted for around 70 % of the year, but potential discomfort glare could occur for more than 20 % of the time.

Finally, the results are interpreted in terms of *mean annual illuminance uniformity*, in order to appreciate the capability of the different strategies to evenly distribute daylight. The *illuminance uniformity* is the ratio of the mean to the maximum illuminance measured within the space.

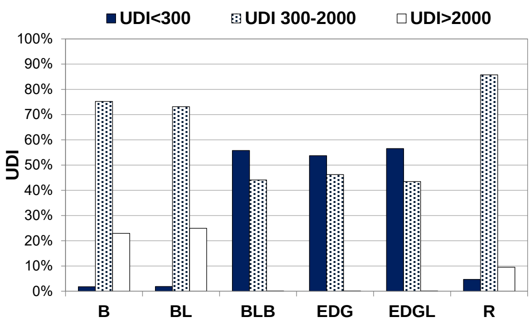

Fig. 6 – UDI values for the proposed solutions (spatial mean)

The results, reported in Fig. 7, show that none of these configurations can reach the minimum illuminance uniformity prescribed by UNI EN 12464 for classrooms in educational buildings (60 %), although the norm does not explicitly state the duration of the period of analysis.

The reader should not be misled by the fact that EC windows – especially if coupled to a light shelf – get the highest illuminance uniformity. In fact, the previous analyses suggest that the illuminance values are just 'uniformly low' within the room for these configurations. Better results are expected with reflective windows (R), since the illuminance uniformity rises to 50 %, while the base case (B) has a value of 46 %. Slightly worse results are given with the internal blinds, with or without light shelves.

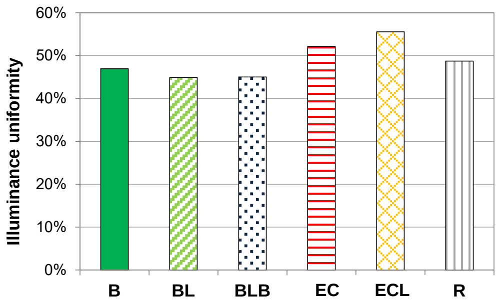

Fig. 7 – Mean illuminance uniformity for the proposed solutions

5. Conclusions

A daylight analysis of an existing classroom facing east has been carried out by means of both measurements and numerical simulations. The main issues of the classroom were found to be the too high illuminance values close to the windows and the uneven distribution throughout the space. To overcome these problems, the paper considered the adoption of different solutions already available on the market, and compared their performance by climate-based daylight metrics.

The outcomes of this analysis show that for this temperate climate, room exposure and geometrical configuration, reflective windows outperform electrochromic windows (with or without internal light shelves) and internal blinds in improving daylight distribution throughout the year. However, the exposure of the windows (south) is expected to have a great influence on the results.

The authors are conducting further analyses to study how other exposures, configurations, and logics or threshold values of activation for the dynamic devices could affect the results here presented. The energy needs for artificial lighting systems, as well as those for triggering the electrochromic windows and activating the internal blinds, will be considered as well.

Nomenclature

Symbols

A	Area (m^2)
DF	Daylight Factor (%)
E	Illuminance (lx)
I	Solar irradiance (W m^{-2})
L	Luminance (cd m^{-2})
sDA	Spatial daylight autonomy (%)
U	Thermal transmittance (W m^{-2} K^{-1})
UDI	Useful daylight illuminance (%)

Greek letters

ρ	Reflectance (-)
τ	Transmittance (-)

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