Preliminary results on a novel photo-bio-screen as a shading system in a kindergarten: visible transmittance, visual comfort and energy demand for lighting

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Abstract

A study on a novel photo-bio screen (PBS) used as a shading system in a real building is presented. The green microalgal culture (*Scenedesmus obliquus*) of the PBS allows a screening of the direct sunlight and a production of biomass containing bioactive compounds. The PBS was tested in a kindergarten classroom at Saint Marcel (Aosta Valley, north-west of Italy) and monitored for 3 weeks (June-July 2016). The visible transmittance T_v of PBS was determined through in situ illuminance measurements, while the daylight amount in the room and the energy demand for lighting ED_l were calculated through Diva-for-Rhino simulations (using the median measured T_v as input). The analysis was split in two phases: (*i*) the real room (with south-facing windows and external obstructions); (*ii*) the same room without obstructions, analyzed parametrically by changing the site (Turin, Östersund, Athens, and Abu Dhabi) and the orientation (south, west, north, and east). For both phases, the results for PBSs were compared to what obtained applying a traditional venetian blind VB of comparable light transmission to the window.

From the monitoring campaign, the T_v of the PBS was found to have a quite high variation as a function of the dynamic boundary conditions, so an median value of 0.75 was identified as the reference T_v. From ~~the~~ simulations, it was found that the daylight amount and the ED_l for PBS and the VB were comparable, with slightly better results for the PBS in Turin and Athens and slightly better results for the VB in Östersund and Abu Dhabi.

Keywords: photo-bioreactor; static shading system; visible transmittance; useful daylight illuminance; daylight glare probability; energy demand for lighting; energy savings.

1. Introduction

This paper presents a study on a novel photo-bio screen (PBS) used as a shading system in a real building, which integrates the ability of green microalgae cultures to shield the direct sunlight, i.e., to selectively absorb the red radiation (wavelength = 0.6 - 0.7 µm), and the capability to generate biomass containing bioactive compounds. Several factors provide the PBS with a special appeal from the sustainability point of view: the carbon dioxide bio-sequestration and oxygen supply as result of the photosynthesis performed by the microalgae (which enhances the indoor air quality of a space), the production of biomass in indoor cultivation, the enhancement of indoor environmental quality (IEQ). Indoor comfort increases since indoor air quality (IAQ) improves, the direct sunlight is screened and scattered as greenish light, and the visual appeal of the green surface could improve psychological well-being of the occupants.

The PBS tested in the present work is a low density polyethylene (LDPE) ice cube bag consisting of circular cubicles arranged with square packing. The aqueous culture of microalgae (*Scenedesmus obliquus*) contains nutrient supply and an inorganic carbon source and is embedded inside the circular cubicles. No mixing is provided. PBS can be hung up to the interior glass surface using a curtain system until no longer useful, then biomass can be harvested, dried and processed to extract lipids, proteins and carbohydrates, and the plastic bag can be recycled. PBS is transparent and permeable to CO_2, with a reduced thickness and light-path, and easy to hand and to install. Furthermore, it could have different visible transmission T_v and biomass load, depending on the quantity of window area that is covered and on the nutrients that could be used. It is also cheap, disposable or recyclable and it does not need maintenance, thanks to the sterility of containers, the reduced fouling phenomena and the brief life-cycle of selected microalgae (1-3 months).[1] The only maintenance required is the periodic replacement of PBSs, which are easily removable elements. Finally, PBSs can be produced industrially and, due to their reduced sizes and modularity, they can be combined in different geometries according to any pattern and applied to vast glass surfaces for a large scale production of biomass. Different PBS types were achieved and tested in a previous work.[1] Plastic bags that consist of circular cubicles without mixing arranged with square packing and with an inorganic carbon source showed to be more feasible for *S. obliquus* cultivation. The daylighting in the presence of PBS was found to be higher than in the presence of glazing with venetian blinds, with a decrease in the energy demand for lighting ED_l up to -57%. To maintain the possibility of a view to the outside, the most optimal solution was found to be the subdivision of the window in two horizontal stripes, applying the PBSs to the upper stripe and leaving a double pane glazing without blinds for the lower stripe. This optimization of the 'glazing + algae' layout was tested during the present study in order to effectively match view out and shading purposes.

1.1 Objectives of the study

Within this context, the study presented in this paper had the following objectives:

- to expand the previous work[1], applying the photo-bio screens PBSs as a static shading system in a real indoor environment: a kindergarten classroom
- to measure the visible transmittance T_v of the PBS to assess the daylighting in the classroom and the corresponding ED_l, with regard to: (*i*) the real space; (*ii*) the same space, assumed without obstructions and for which the site and the orientation were changed. This second step was taken to make the results more general for a sample classroom, independently of the mountain setting and of the building layout that characterize the case-study selected. For both steps, the analysis was carried out comparing the performances (in terms of daylighting and ED_l) of each space with PBSs and with a traditional venetian blind VB.

In the previous paper, the possibility of using hanging plastic bags as photo-bio-reactors for microalgae culture was studied. The following research activities were addressed: (i) several prototypes, with different layout, size, shape, surface, and area/volume ratio, were tested and their performances were compared from the viewpoint of microalgae growth; (ii) the best cultural conditions of microalgae were investigated, as the cultural medium and the mixing conditions were varied; (iii) an optimal device configuration and a set of cultural conditions were selected to carry out an experimental measurement of the light transmittance T_v trough the plastic bags, which were used as PBSs applied to a window in a laboratory room; (iv) dynamic simulations were run to calculate the performances of PBSs in terms of visual comfort perceived by the occupants of the target room, and of energy demand for lighting ED_l which may get reduced by using PBSs. Some features of the room were changed to create different cases for which to calculate and to compare the daylight amount and the corresponding energy demand for lighting: site (Turin, L=45.1°N and Palermo, L=38.3°N), orientation (south, real case, west and north), glazing and shading system (real glazing alone, a package glazing + photo-bio screen, a package glazing + venetian blind).

In the present paper, the performances of the of the photo-bio-screens (PBSs) selected in the previous work were assessed when installed in a real room, a kindergarten classroom located in Saint Marcel, Aosta Valley, in the north-west of Italy (L = 45.7°N). The following research activities were taken: (i) the T_v of the PBS installed in the real classroom was experimentally determined through illuminance measurements; (ii) a new set of simulations were run, simulating ~~the~~ PBSs applied to glazing of the kindergarten classroom in its real configuration, with the aim of assessing the visual comfort for the occupants as well as of the correlated supplementary ED_l. The room was simulated in its real configurations. Furthermore, some features of the room were changed: site (Turin, northern Italy, L=45.1°N; Östersund, Sweden, L=63.2°N; Athens, Greece, L=37.9°N; and Abu Dhabi, United Arab Emirates, L=24.4°N), orientation (south, real case; west, north, and east), and glazing and shading systems (real glazing alone, package glazing + PBS, package glazing + Venetian blind, that is the same configurations used in the earlier study). The new set of simulations that was carried out was meant to improve the characterization of PBS so as to cover a larger sample of sites, thus expanding the results from the earlier study.

2. Literature review

Recently, photo-bio-reactors (PBRs) have been used as elements of urban construction[2] and as architectural components. Some examples of real buildings and projects are shown in Fig. 1. In this context, the project of bio-responsive façade, BIQ (Bio Intelligent Quotient) house in Hamburg [3] (Fig. 1a), the Urban Algae Folly District exposed in Milano, at the Food EXPO 2015 by ecoLogicStudio [4] (Fig.1b), The Green Loop, Marina City Algae Retrofitting, Chicago by Influx Studio [5] (Fig. 1c), the GSA retrofitted project in Los Angeles proposed by HOK [6] (Fig. 1d) represent recent applications of microalgae in buildings. Glasses integrating an algae bioreactor within a façade were also studied and prototyped by Kim [7] (Fig. 1e) to increase the indoor air quality in buildings through the photosynthesis of microalgae.

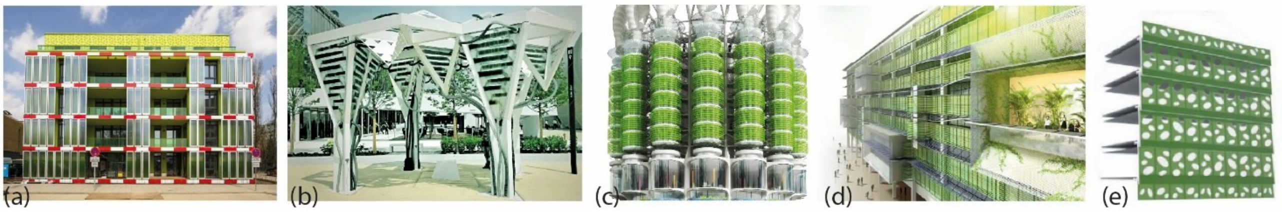

Fig. 1. Examples of algae façades: (a) apartment building BIQ, Hamburg[3]; (b) Urban Algae Folly District Food EXPO 2015, Milan by ecoLogicStudio[4]; (c) the Green Loop, Marina City Algae Retrofitting, Chicago by Influx Studio[5] ; (d) the GSA retrofitting project in Los Angeles by HOK[6]; (e) Glass integrating an algae bioreactor within a façade by Kim[7].

An interesting and thorough review was carried out by Elrayies [8] that mainly focused on exploring the proper types of PBRs for integration with buildings; the overall bioprocess and the design considerations, regarding PBRs and their technical requirements; the environmental and energy performance of PBRs, including their challenges and prospects.

The main criticisms related to the integration of PBRs within a façade are: the complexity of the components; the need for specific micro-organism growth rate conditions; and the necessity of continuous maintenance, because of the fouling of reactor walls by microalgae.

CO_2 bio-sequestration includes processes that use photosynthesis to assimilate and store CO_2 into high energy, long-term biochemical products. Managed forestry is a traditional terrestrial bio-sequestration technology; in this case the carbon uptake rate for land plants (lignocellulosic biomass) is 0.3–0.9 kg m^{-3} yr^{-1} .[9] Without subtracting arable land, the capture and biological fixation of atmospheric CO_2 by microalgae during photosynthesis is a very promising technology. The carbon uptake rate for microalgae was evaluated to be 25.6 kg m^{-3} yr^{-1}.[10] Carbon dioxide may be both extracted from the ambient air or provided from industrial exhaust-gas sources.

Microalgae are grown in aqueous media, at different salinity grade, containing as nutrients: phosphates, nitrates and sulfates and organic or inorganic carbon sources. Residual nutrients present in wastewaters (municipal, industrial and agricultural) could be cheap raw materials for the cultivation of microalgae, in this context, micro-algal biomass represents a by-product of the wastewater treatment.[11] The water requirement for fixing 1 kg of CO_2 by microalgae is 140–200 kg while it is more than 550 kg for trees.[8] Currently, worldwide production of micro-algal biomass is about 9000 ton yr^{-1} and the production cost is 20-200 USD kg^{-1}.[12]

Microalgae can be cultivated in open and raceway pond or in PBRs. The most common types of closed PBRs are tubular, column and flat plate. Each configuration shows benefits and weaknesses and the cost is the most important factor that influences the choice.[13] Recently, a new type of PBRs was assessed: transparent PE or PVC hanging bags.[14,15] These PBRs are mixed up by bubbling air, irradiated under sunlight or by artificial lighting cycles and sealed at the bottom in a conical shape to prevent microalgae settling.[16] The main advantages of this type of PBRs are: low cost, flexibility, transparency, reduced bio-fouling [17] and permeability to CO_2.[18]

Microalgae consist of three main components: lipids, proteins, and carbohydrates. Due to their high lipid productivity, microalgae gained enormous attention worldwide for the production of renewable biodiesel, bioethanol, and bio-hydrogen.[13] Nevertheless, microalgae could also be an important source of valuable products for human and animal nutrition [19], high-added value molecules for nutraceutical [20], pharmaceutical and cosmetics industry.[21]

The green microalgae *Scenedesmus* genera is considered to be one of the main carbon sequester.[22] *Scenedesmus obliquus* species reveals high growth rate and can be cultivated in various environmental systems[23] and in a wide temperature range, 15-35°C, which covers the swinging of the indoor building temperatures. *S. obliquus* is able to biofix CO_2 (0.03–50% v/v) [24] and to form aggregates of two or more cells which reflect, scatter and absorb light. Some studies with *S. obliquus* showed the possibility of carrying out cultures for long periods: one month [25], two months [26], and 6 months.[27] Pagliolico et al.[1] demonstrated that: (*i*) *S. obliquus* can be cultivated in transparent polyethylene flexible hanging bags for at least 21 days, with natural light/dark cycles at controlled indoor environmental temperature; (*ii*) plastic bags with circular cubicles arranged with a square packing perform better than other geometries or packing of the cubicles; (*iii*) mixing is not necessary; (*iv*) the inorganic carbon source is cheaper than an organic one and allows *S. obliquus* growing up with a similar trend.

The effect of real environmental conditions (location, variable sunlight and temperature, and orientation) on practical performances of large scale production units are poorly reflected by laboratory experimental results, obtained controlling light conditions and few variables at a time.[28]

The impact of electric light or of daylight (sunlight and skylight) on algae-systems was addressed in many studies.[28-36] These were mainly focused on aspects such as: biomass (carbohydrate/lipid) productivity; cell growth; efficiency of CO_2 fixation; production rate for different light sources, latitudes, orientations, shading effects (for both indoor and outdoor cultivating systems); increase in the rate of photosynthesis through specifically designed PBRs. As far as the visible transmittance of algae-based systems is concerned, the literature review revealed that very few studies have addressed this topic so far, and through qualitative approaches. For instance Kim[7] describes a system which was designed and prototyped for a real application to an office building in Seoul, with the purpose of replacing the current glazing systems. In this study, Kim paid attention to aesthetical issues and to the possibility of guaranteeing a view to the outside for the occupants, as well as of offering good energy and structural performances. The optical properties of the system, though, were not measured.

The T_v and the consequent IEQ in terms of visual comfort for the occupants has been investigated in quantitative terms only by the Authors of the present work[1] for different types of microalgae cultures and PBR designs, following the simulation methods developed in previous studies on the T_v properties of translucent panels.[37,38]

3. Experimental procedure

3.1 Reactor design and micro-algal culture conditions

The PBS device consists of two low density polyethylene sheets (200x300 mm; 0.05 mm thick) thermally welded so as to create circular cubicles with square packing (Fig. 2b). The interconnection between cubicles allows free circulation of fluid, microalgae and gas bubbles. No mechanical mixing is performed.

The microorganism used in this work is the *Scenedesmus obliquus* CCAP 276/38, a freshwater microalga. Culture conditions were described in a previous work.[1] The culture was settled in a liquid medium containing sodium bicarbonate ($NaHCO_3$) as inorganic carbon source, and was poured into five PBSs which were hung up to the glazing surface (Fig. 2a). The experiments were performed at the kindergarten during three weeks, from June14 to July 4, 2016. The microalgal grow rate in the test room showed a similar trend to that observed by the Authors in the previous study[1]. A monitoring of three weeks was chosen as optimal period for cultivating the microalgae in PBSs in a range of temperature between 20°C and 35°C.[1]

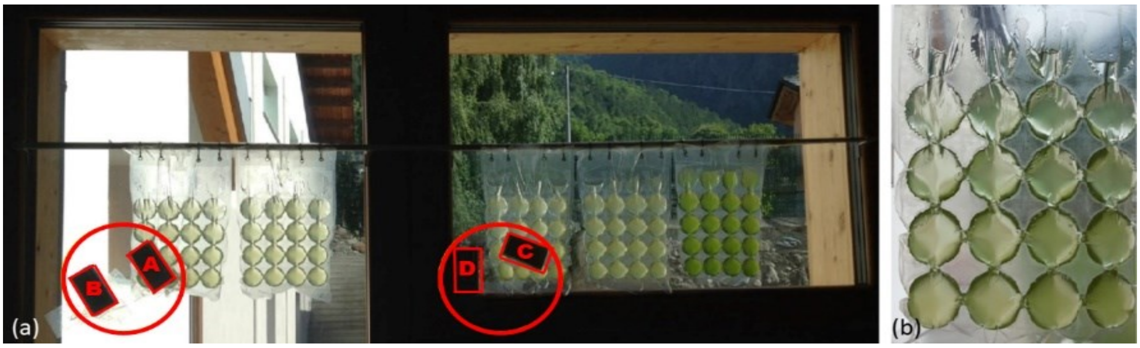

Fig. 2. Images of the PBSs installed in a classroom of a kindergarten in Saint-Marcel, Aosta, Italy.

3.2 Light transmittance T_v

The T_v was derived from in-the-field measurements, using the equipment installed in a real classroom in the kindergarten at Saint Marcel, Aosta. The equipment consisted of four data-loggers (illuminance meters) Gigahertz X-2000 (accuracy with regard to V(λ) curve matching: f1 < 10%; with regard to the incidence direction - cosine low -: f2 < 10%).

The illuminance-meters were positioned in pairs according to the following layout (Fig. 2):

- two illuminance meters were positioned behind the glazing + PBS (sensors A, C)
- two illuminance meters were positioned behind the glazing, without PBS (sensors B, D).

The illuminances were monitored with a time-step of 5 minutes throughout the monitoring period. Per each time-step, the average illuminance of the two loggers after the glazing (sensors B, D) was calculated and the same operation was carried out for the two loggers behind the glazing with PBS (sensors A, C). The T_v was then calculated through the equation (1):

$$T_v = \frac{\text{mean E of loggers behind the glazing+algae system}}{\text{mean E of loggers behind the glazing}} = \frac{\text{mean E of loggers(A,C)}}{\text{mean E of loggers(B,D)}} \quad \text{Eq. (1)}$$

Beside the metrological accuracy class of the instruments, another experimental error may be concerned with the position of the loggers, especially the ones positioned behind the PBSs. Actually, these sensors were meant to be right behind the cubicles containing the microalgae, but some misalignments may have occurred during the installation or the monitoring phase, with the result of a slightly different income of radiation depending on the specific layout and size of the PBS, i.e., through the plastic interstice between cubicles rather than through the cubicle itself.

3.3 Simulations for IEQ (visual comfort) and energy saving

A set of simulations were carried out to assess the performance of PBSs applied to glazing, in terms of IEQ (visual comfort, mainly) for the occupants as well as of the correlated ED_l to supplement daylight. The software Daysim, which uses the validated Radiance algorithm for annual calculations, was used for this purpose. Daysim was managed through DIVA-for-Rhino, which allows a 3D model to be built in Rhinoceros, assigning a set of Radiance compatible materials to the geometries, and then to be exported into Daysim for simulations. The simulation results are eventually re-imported into Rhinoceros for visualization purposes. A series of scripts were specifically written in Phyton to process the huge amount of annual data and to calculate the values of static and dynamic climate-based daylighting metrics.

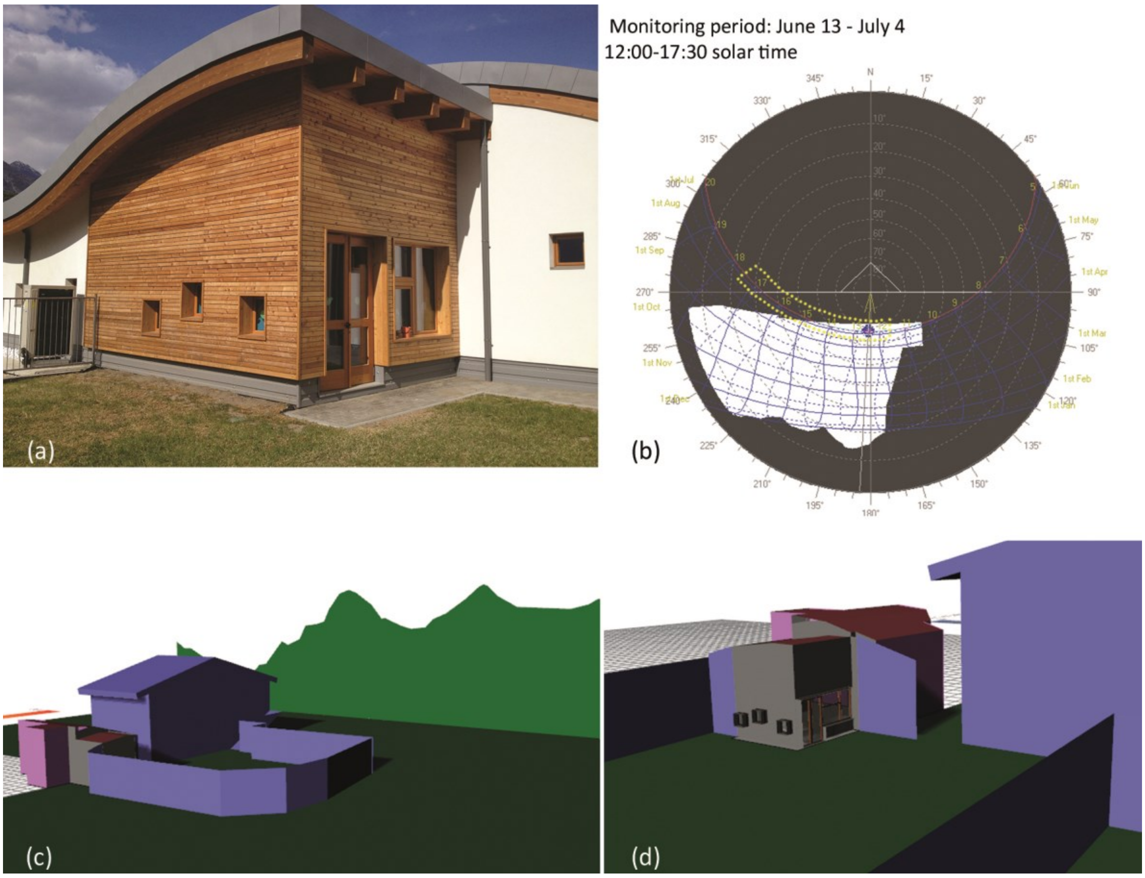

Fig. 3. View of the classroom used as test-case in the study, with shading mask and the simplified 3D model to show the obstructions for the real building.

The analysis was divided in two phases:

1. PHASE 1. A sample kindergarten classroom was selected and simulated in its real configuration (Fig. 3). The space has one window and one French-window, both facing south, and three small windows facing west. The external obstructions, including the gymnasium of the school and the profile of the surrounding mountains, were modeled into the 3D Rhinoceros model for this simulation stage (Figg. 3c-d). Fig. 3b reports the shading mask for the south-facing façade, thus visualizing the amount of obstructions for the windows (gymnasium, roof, mountains).

   The room has the following photometric and lighting system characteristics: a double pane selective glazing (T_v=65%), equipped with PBSs; visible reflectance R_v of walls, floor and ceiling: 60%, 30% and 70%, respectively; room orientation: south; target illuminance over the work plane, E_{wp}: 300 lx; corresponding lighting power density, LPD: 6 W/m^2; control system for electric lighting: a photo-dimming sensor (parasitic power due to stand-by of the sensors = 0.12 W/m^2; luminaires' ballast loss factor = 10% of the luminaire power) with an occupancy sensor that automatically switches off the luminaires when no presence is detected (delay time set to five minutes). For the simulations, as no weather file is available for Aosta on the EnergyPlus weather database, the climate file of Turin (a town close-by) was used. Prior to running the simulations, a verification of the match between the climate file of Turin and the real climate conditions in Aosta Valley was carried out. Irradiance data measured in five weather stations in Aosta Valley (Aosta, Cogne, Etroubles, La Thuile, and Donnas) were collected with a time-step of one hour by VdA - ARPA (Aosta Valley Regional Agency for Environment Protection)[39] and compared to the irradiance data contained in the Turin.epw climate file. The local data relative to the years 2015, 2016, and 2017 were used for the comparison. The five weather stations measured the total irradiance, while the EnergyPlus climate file for Turin contains the single direct and diffuse components. Therefore, the comparison was done using the total irradiance (Figg. 4 and 5). Fig. 4 shows the findings from June 14 to July 4, 2016; for this period, the total irradiance data acquired at the weather station at Politecnico di Torino is also plotted, as a further element of comparison.

   Fig. 5 shows the annual total irradiance measured for 3 years (2015, 2016, and 2017) versus the annual irradiance calculated from the EnergyPlus climate file. Analyzing the datasets for the monitoring period, some differences can be observed between the measured and the statistical irradiances. Some days were clear in Aosta Valley and overcast in the climate file (e.g., June 14 and 15) or vice-versa (e.g., June 16). Nonetheless, if the full monitoring period is considered, the total irradiances are comparable (Fig. 5a): the relative difference between the measured and statistical total irradiance data was in the range -4.0% ÷ +9.2% (La Thuile, Aosta, respectively). The relative difference is even smaller if a whole year is considered (Fig. 5.b), being in the range -7.4% ÷ +4.9% (La Thuile, 2016; Etroubles, 2017, respectively). As a result, the climate file of Turin from EnergyPlus can reasonably represent the climate conditions of Aosta Valley for the period considered.

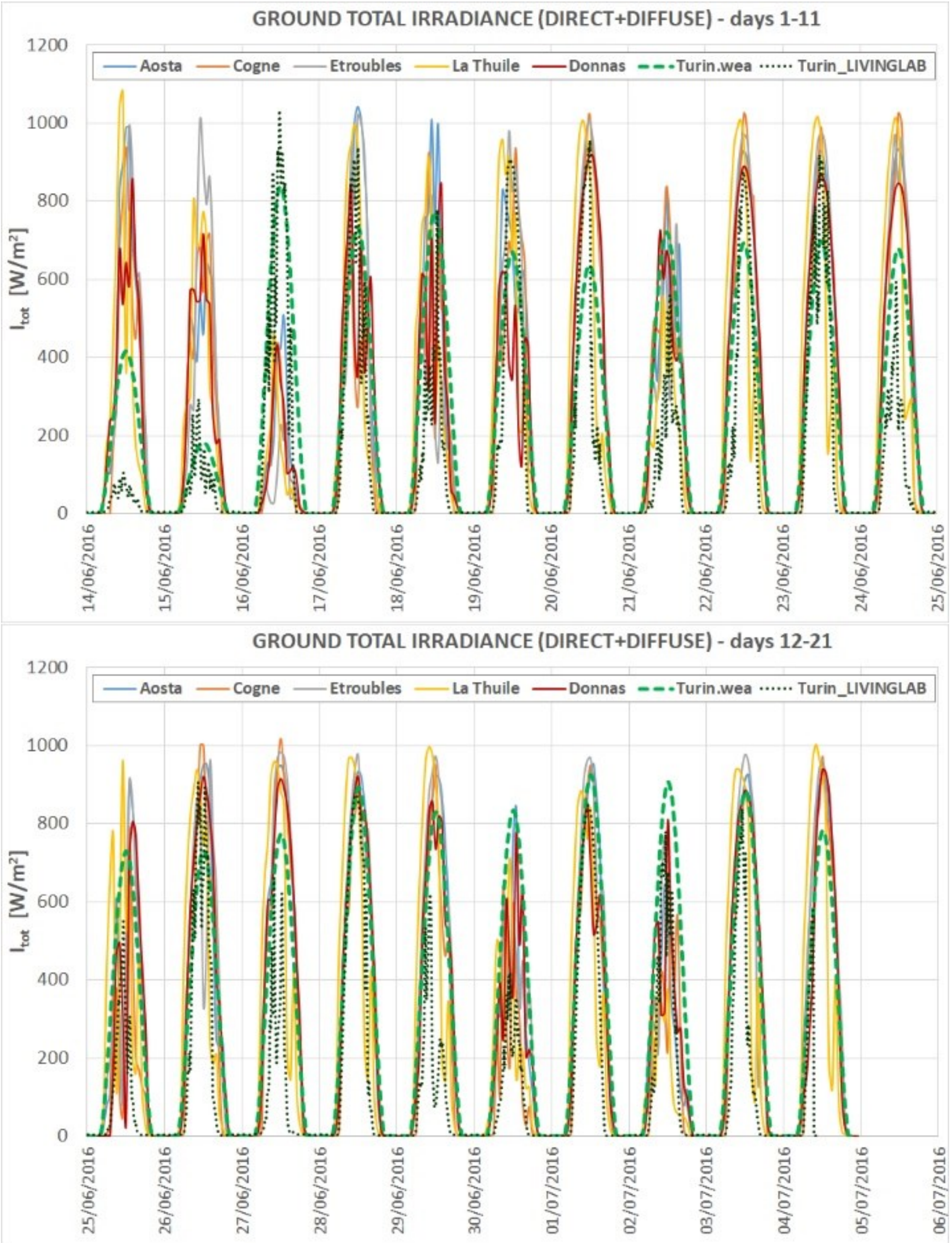

Fig. 4. Total irradiance (direct+diffuse) profiles for 5 locations in Val d'Aosta, one in Turin, plus the climatic file used for simulations. Data for the monitoring period (June 14 – July 4, 2016) are shown.

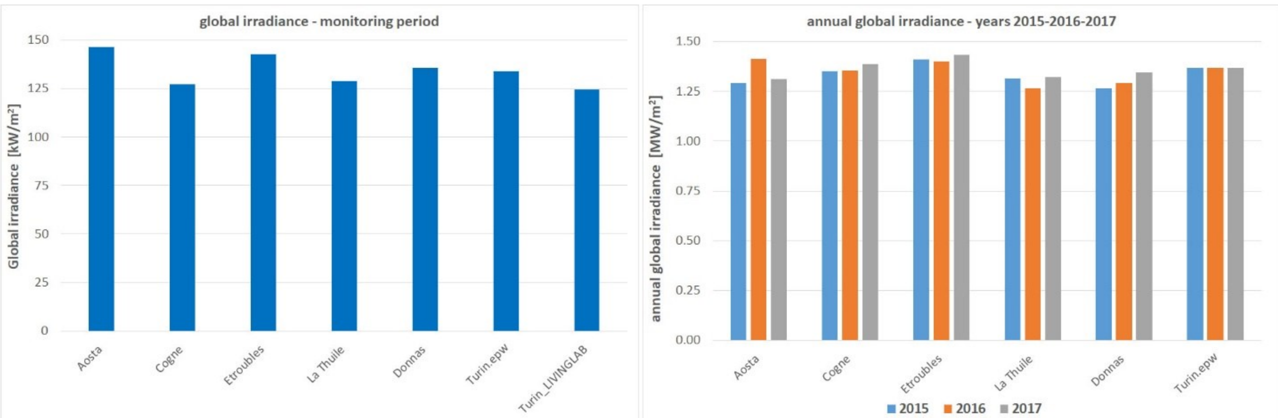

Fig. 5. Total irradiance values for 5 locations in Val d'Aosta, plus the climatic file used for simulations. LEFT: data for the monitoring period (June 14 – July 4, 2016); RIGHT: data for 3 years: 2015-2016-2017.

2. PHASE 2. The real configuration of the classroom was modeled to carry out a parametric study and to analyze the impact of a number of variables, such as the climate and the orientation, on the daylight amount into the room and on the ED_l. The aim was to make the results more general, independently of the characteristics of the site in terms of obstructions (mountains and other parts of the building itself). In more detail, the following features of the room were changed to create different cases for the analyses:
   - *obstruction*: the south-facing windows were assumed as non-obstructed, that is that both the school gymnasium and the profile of the mountains were neglected
   - *site*: beside Turin/Aosta, northern Italy (L=45.1°N), the room was also located in Östersund, Sweden (L=63.2°N), Athens, Greece (L=37.9°), and Abu Dhabi, United Arab Emirates (L=24.4°N). These four sites were selected to represent a wide range of latitudes (from 24.4°N to 63.2°N), with highly different sun paths and consequently different shading requirements. The different sun paths of the four sites are shown in Fig. 6. Besides, the four sites also present a large range of daylight availability and solar exposure, both in absolute terms and in terms of a different ratio of the direct to diffuse components. To quantify this, the *luminous exposure* LE was calculated for the four sites. The LE is a climate parameter, which was introduced in the recent standard EN 15193-1:2017[40] to synthetically represent the daylight availability of a site, based on its climate. It is defined as the ratio of the direct to the total external horizontal illuminance, both measured or calculated daily from 8 am through 5 pm, and then summing up all the daily contributions of the 365 days of a year. The climate files of the four locations were used for this calculation and a script in Python was specifically written to extract the LE. It was found: for Östersund, LE = 0.39; for Turin, LE = 0.45; for Athens, LE = 0.55; for Abu Dhabi, LE = 0.68. Therefore, the locations that were selected represent a large variety of climates, ranging from conditions with yearly-round predominant direct sunlight (Abu Dhabi, LE = 0.68) to conditions with predominant diffuse skylight (Östersund, LE = 0.39).
   - *orientation*: the room was assumed to be facing south (real case), west, north, and east.

For both phases of the study, the following glazing and shading systems were compared:

- the real glazing alone: this was assumed as baseline reference against which to assess the shading capabilities of different shading systems; the glazing has a visible transmittance T_v = 0.65 (specular transmission), assumed from manufacturer's technical datasheet
- venetian blinds (VB) as shading system (forming a *glazing+VB combination*). According to the DIVA-for-Rhino algorithms[41,42], the blinds in the closed condition have a diffuse T_v of 25%, with a complete cut-off of the direct solar radiation. The algorithm that simulates the occupant behavior is based on an irradiance set-point: whenever during the annual simulation an irradiance over 50 W/m^2 is detected on any point of the workplane (a typical

condition which causes thermal discomfort), the blinds are closed down and remain closed for the rest of that day

- PBSs as shading system (*glazing+PBS combination*), with a visible transmittance for the package $T_v = 0.494$, with a scattered transmission (see section 4.1).

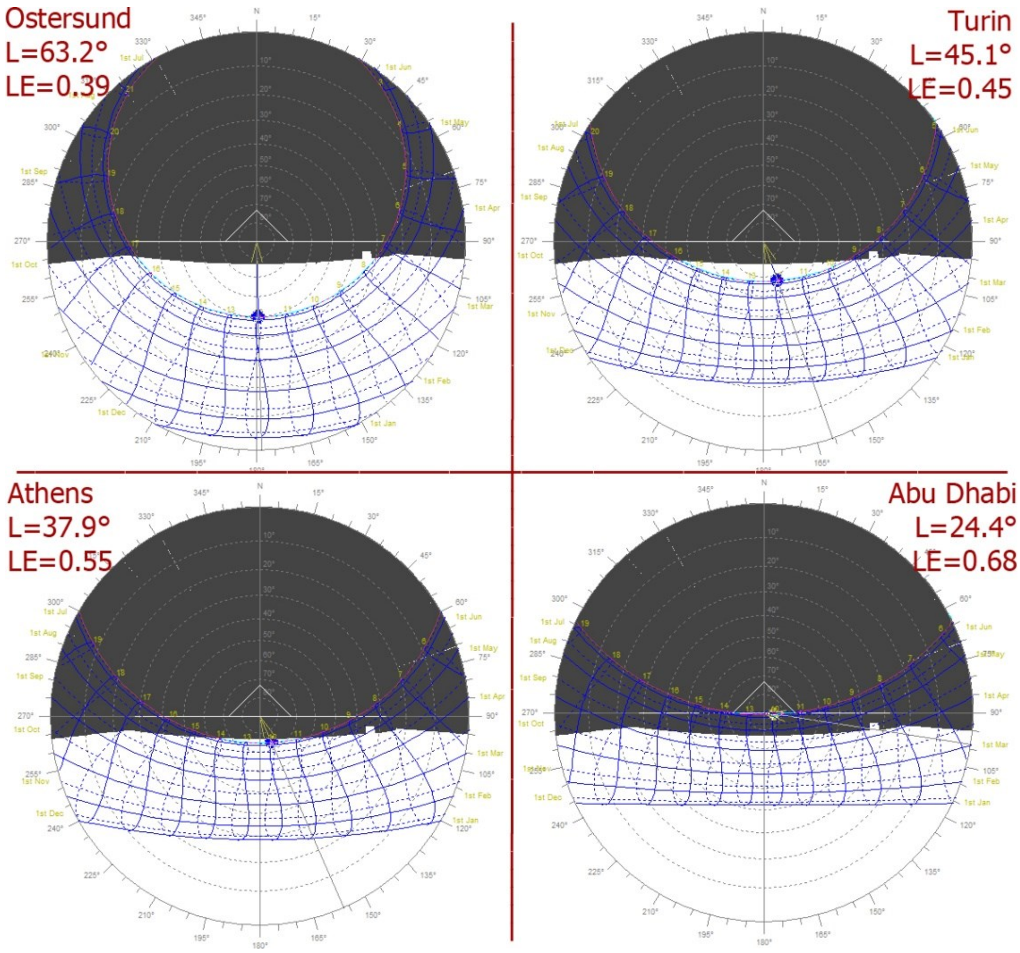

Fig. 6. Sun-paths for the classroom used for the parametric study, without external obstructions.

The amount of daylight in the room was quantified through the average daylight factor (DF_m) over the workplane and through the spatial Daylight Factor [43], that is the percent of workplane exceeding the standard requirement.

Beside the DF analyses, the daylighting was also assessed through some climate-based daylight metrics (CBDM): these account for both sunlight and skylight that dynamically enter an indoor room throughout a year for the considered site.[44,45] The following CBDM were used: spatial Daylight Autonomy ($sDA_{300/50\%}$) [46], Daylight Autonomy DA and Useful Daylight Illuminance (UDI).[47] The $sDA_{300/50\%}$ is defined as the percent of an analyzed area that meets a minimum daylight E of 300 lx for 50% of the operating hours per year, while the UDI metric is the percent of occupied time during the course of a year when the E lies in three ranges: E<100 lx (a too scarce daylight, which pushes the users to switch on electric lights); 100 lx<E<3000 lx (the ideal illuminance level for users); E>3000 lx (potentially excessive daylight, resulting in discomfort for the occupants). Both metrics were included in recent technical recommendations:

$sDA_{300/50\%} \geqslant 55\%$ for a '*nominally accepted* daylight sufficiency' and $sDA_{300/50\%} \geqslant 75\%$ for a '*preferred* daylight sufficiency' [46,48]; average DA>50% and average $UDI_{100\text{-}3000}$ > 80%.[47]

The potential glare in the considered space was investigated by calculating the annual Daylight Glare Probability (DGP).[49] A single user was assumed (with the eyes 0.8 m above the floor level, according to the position of a child sitting at a table), with a direction of view normal to the south-facing windows. This is as a worst-case under which to compare the two technologies (PBSs and VBs). In a more realistic scenario, though, the users would tend to adapt themselves to reduce the discomfort perceived, changing their direction of view in response to the ambient conditions ('adaptive zone', introduced by Jakubiec et al.[50]).

The ED_l was expressed in [kWh/m^{2}yr], similarly to the other energy demands (for cooling, heating).

The DF and the CBDM values were calculated using Radiance, managed through DIVA-for-Rhino, while the annual DGP profile was calculated using Evalglare (also managed through DIVA-for-Rhino). All the analyses were performed using a time-step of an hour within an occupancy profile 8:00 am - 6:00 pm [46,48], for all the days throughout a year and without any lunch breaks (i.e. 3650 hours/year).

Figure 7 visualizes the two phases of the simulation approach described above.

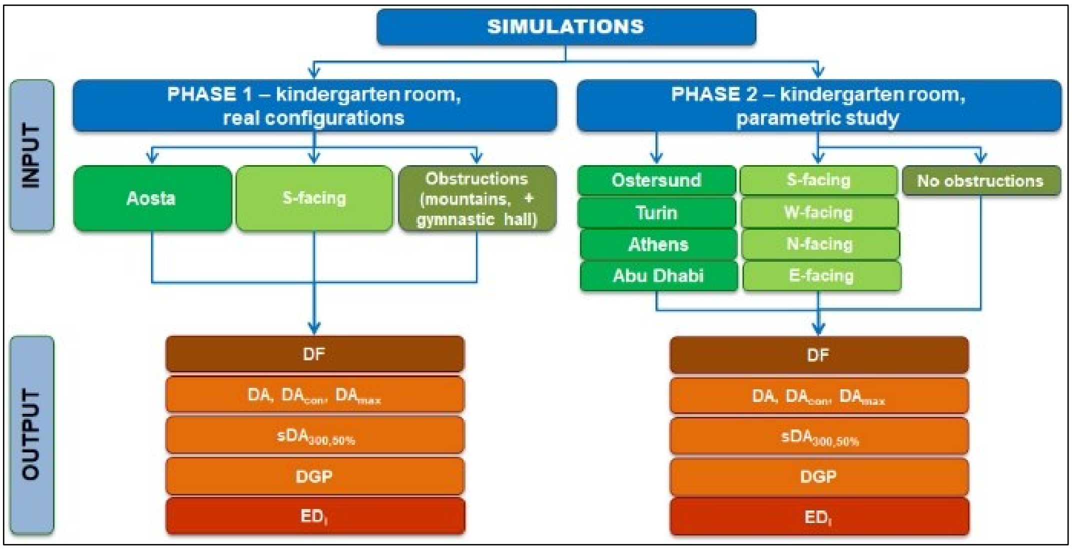

Fig. 7. Schema of the simulation approach consisting of two phases.

4. Results

4.1 Determination of T_v

The T_v values which were calculated from the illuminance data measured throughout the monitoring period are shown in Fig. 8. The following main trends were observed from the analysis of the results:

- the T_v of the PBS is highly changing with the time of the day, in a range 0.5÷2. Some values over 2 were also recorded: these were considered as outliers and therefore excluded from the analysis

- therefore, for a number of time-steps, a T_v value greater than 1 was observed. This may be due to the scattering effect through the plastic cubicles containing the culture, which seem to act as biconvex lenses that produce a refraction effect, especially for the solar rays coming with high incidence angles. Indeed, this finding was in line with what already observed in the previous study from the same Authors[1]
- an analysis of the potential link between the T_v values and the sky conditions was carried out, to explore if the light transmittance changes with different combinations of direct and diffuse solar radiation. Such analysis was carried out on a daily basis: each day was labeled as either 'clear', 'intermediate (with a prevailing clear contribution)', 'partly cloudy (with a prevailing cloud contribution)', or 'overcast', based on the total daily irradiance, and the median T_v value for each day was determined (Fig. 8). The results showed that a clear trend cannot be identified, as the T_v values show similar ranges and median values for the various sky types, as follows: the six clear skies occurred during the monitoring period showed T_v values in the range 0.67-0.88, with a median T_v of 0.78; the six intermediate skies of T_v values in the range 0.67-0.87, with a median T_v of 0.72; the six partly cloudy skies f T_v values in the range 0.67-0.85, with a median T_v of 0.73; the three overcast skies T_v values in the range 0.75-0.86, with a median T_v of 0.76. Such a 'chaotic' behavior of the visible transmittance of PBS was also observed during the earlier study from the Authors[1].

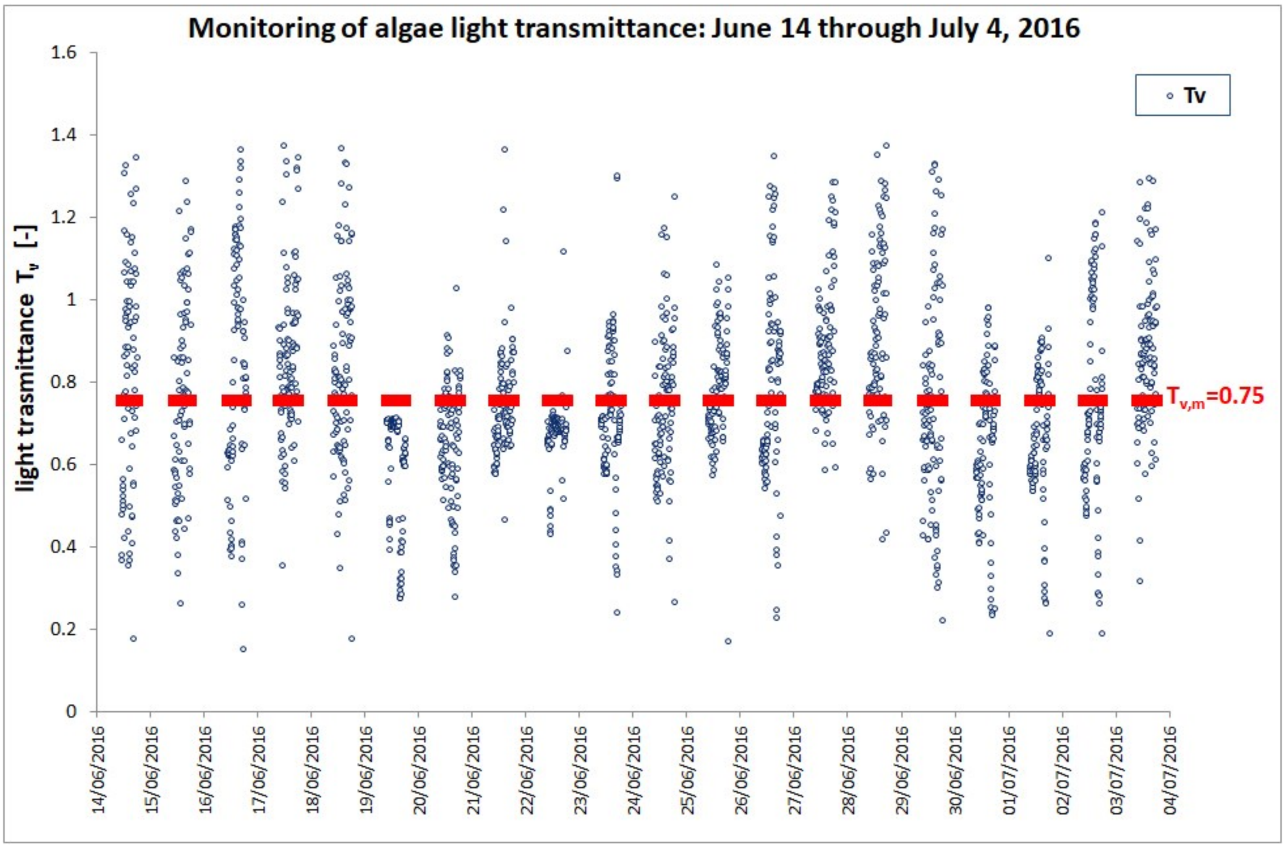

Fig. 8. Variation of the T_v of the PBS system during the monitoring period.

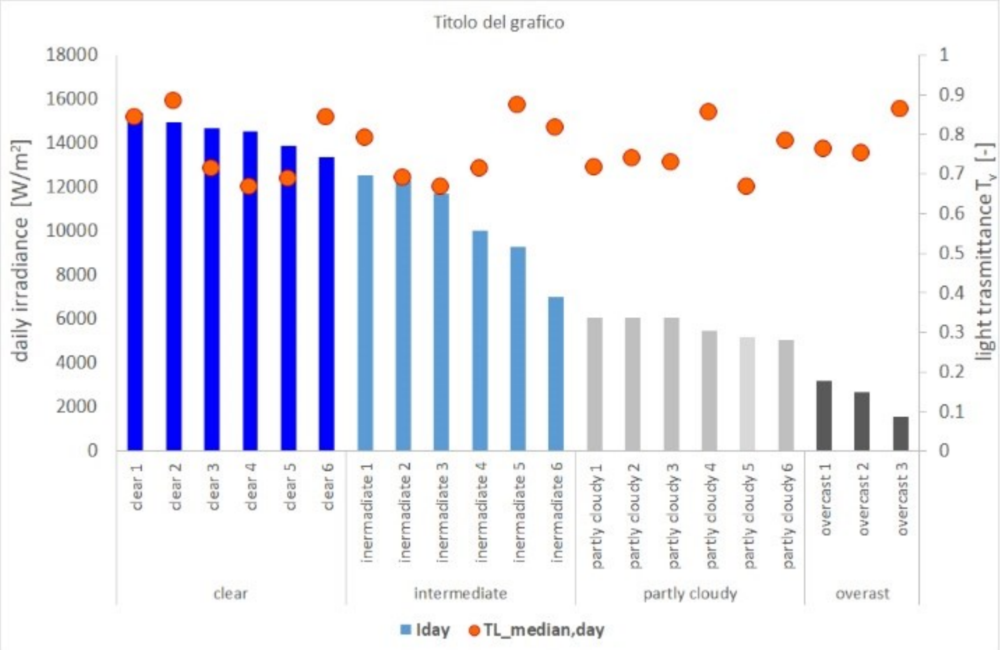

Fig. 9. Analysis of the median light transmittance calculated for each day of the monitoring period versus the sky type.

Considering the variation of T_v with time and boundary conditions, an 'average' T_v value to equivalently represent the visible transmittance was used. The median of T_v values recorded during the monitoring period was therefore calculated for the purpose: the equivalent (median) T_v was 0.75, which is in good accordance with the value found by the Authors[1] in the earlier study ($T_v = 0.76$).

The T_v of the glazing+PBS combination was determined as simple product of the two T_v values of the two elements: the glazing had a T_v value of 65% (from the manufacturer's datasheet), the PBS a median value $T_v = 0.75$. Therefore, the T_v for the package (glazing+PBS) was found through the product 0.65*0.75 = 0.49. As a next step, a new *trans* material, with a total T_v of 0.49, was built and added to the material libraries in DIVA-for-Rhino. This new material was used as input for the simulations to model the transparent component glazing+PBS. In more detail, the following parameters were implemented to model the trans material: diffuse transmittance $T_{v,diff} = 0.49$; specular transmittance $T_{v,spec} = 0.01$; diffuse visible reflectance $R_{v,diff} = 0.16$; specular reflectance $R_{v,spec} = 0.01$. this new purposely-built material was used as input for simulations.

4.2 Calculation of CBDM and ED_l for the real classroom (PHASE 1)

Figures 10-11 show the results that were obtained from the simulations for the real classroom, in the presence of external obstructions (gymnasium and mountains). The annual profile of workplane illuminances and DGP values, as well as of the use (switch on/off and dimming) of the lighting systems and of the blinds, are shown.

The results allow the following considerations to be drawn:

- as far as the daylight factor DF is concerned, the daylighting in the classroom is not compliant with the Italian regulations for both the shading systems considered, neither in terms of DF_m nor of spatial distribution of sDF values over the workplane (required values: DF_m>5% [51]; sDF > 75% [46]); is it worth stressing that the requirements in the Italian standards are particularly strict (DF_m>5%), as the classroom is conceived for young children. A DF_m>3% would be satisfactory for any other type of classroom: in this case, the room with VB would be compliant with such a criterion, unlike the room with PBSs (DF_m = 3.12% and DF_m = 2.23%, respectively)
- differently, according to the CBDM metrics, the daylighting in the classroom is satisfactory: the $sDA_{300/50\%}$ value would allow the credits of the LEED-US [48] to be gained ('*nominally accepted* daylight sufficiency' for the VB and '*preferred* daylight sufficiency' for the PBS. Furthermore, the DA and the $UDI_{100\text{-}3000}$ values are complying with the requirements of the UK Education Funding Agency for both shading systems. Finally, both shading systems are perfectly effective in excluding a glare perception for the reference occupant ($DGP_{>0.40}$ = 0%)
- the energy demand for lighting is comparable for the two shading systems, with a lower ED_l value for the PBS (-7.9%)
- as for the comparison between the PBSs and VBs, the daylighting in the classroom is slightly higher for the PBS according to DA metrics (Δ[DA] = +5.4%; Δ[$sDA_{300,50\%}$] = +37.3%; Δ[DA_{con}] = +1.2%), while the $UDI_{100\text{-}3000}$ results are practically the same. The ED_l obtained for the PBSs is lower, accordingly (Δ [ED_l] = -4.5%).

As a general conclusion, it seems that PBSs perform slightly better than the VBs to control the daylight amount in the considered classroom, with a reduced energy consumption, even though the daylight factor is lower.

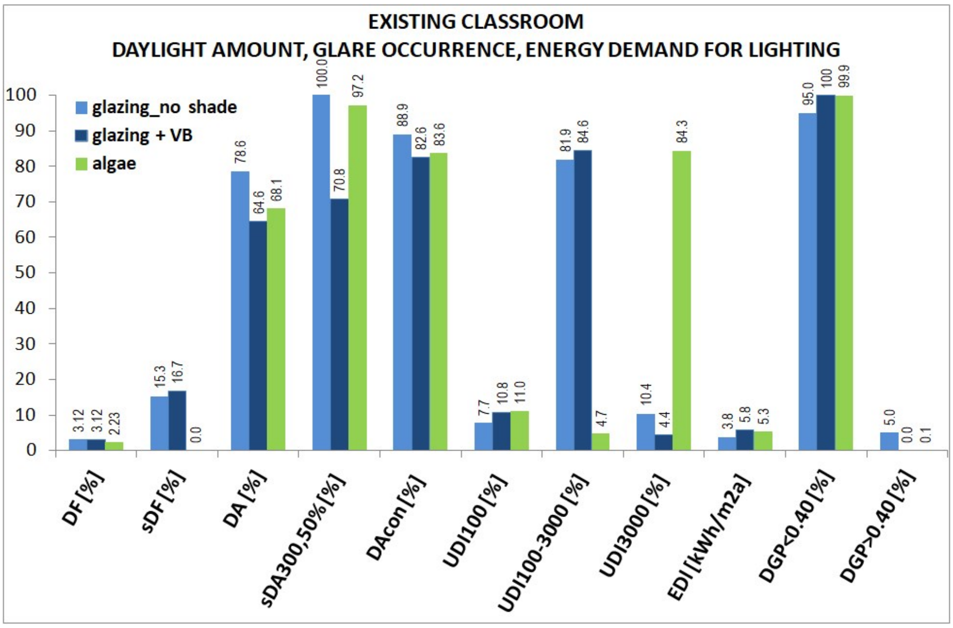

Fig. 10. Real classroom: CBDM and ED_l results (average values).

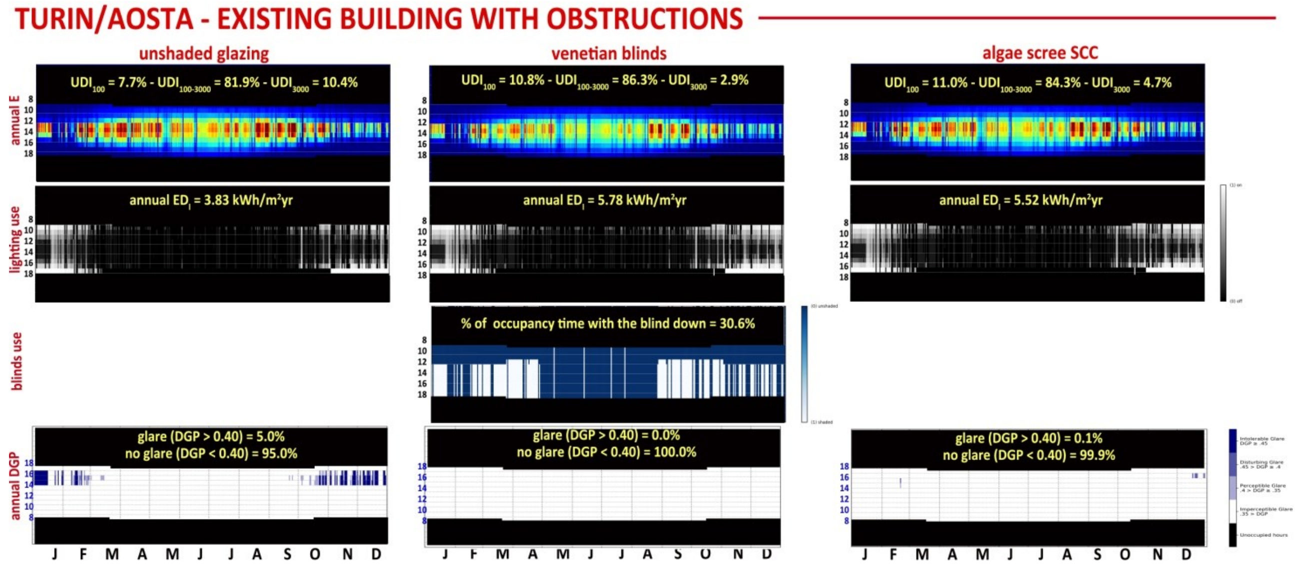

Fig. 11. Real classroom: E, UDI, DGP and ED_l annual values.

4.3 Calculation of the CBDM and of ED_l for the parametric study (PHASE 2)

Figures 12-16 show the simulation results for all the sites and glazing/shading systems considered (for the sake of brevity, the results found for south-facing rooms only are displayed in Fig. 12). At a quick glance, a generally higher daylighting in the presence of the PBS than of VB appears for south-facing rooms (for all the three considered climates), with a lower energy demand for lighting, but the opposite trend was observed for west-facing and north-facing rooms. Nevertheless, some exceptions were also identified. A more in-depth analysis is reported in the following sub-sections.

4.3.1 Mean Daylight Factor DF_m

The results in terms of mean Daylight Factor DF_m are quite simplistic and not particularly meaningful for the parametric approach, as this metric does not account for the site latitude nor for the orientation; furthermore, it refers to an overcast sky condition only. Consequently, the results that were obtained are basically a function of the T_v of the glazing/shading package as well as the transmission mode (specular/diffuse) only and can be summarized as follows:

- for the case of glazing alone (T_v = 0.65, specular): DF_m = 4.05%
- for the case of glazing + VBs (T_v = 0.25, diffuse): DF_m = 4.05%
- for the case of glazing + PBSs (T_v = 0.49, diffuse): DF_m = 3.01%.

The DF_m is the same for the glazing alone and with VBs, since under an overcast sky condition the blind is retracted, so basically the glazing alone determines the daylighting inside the space (and the glazing is the same for the two configurations). The fact that the VB is a mobile shading system explains why the DF_m is higher than what observed for the PBS, which is a static shady that cannot be retracted when the sky is cloudy.

4.3.2 *Climate-Based Daylight Metrics based on work plane illuminance (DA – $sDA_{300,50\%}$ – UDI)*

The results for DA, $sDA_{300,50\%}$, and UDI are shown in Figures 13-15. In detail, the following considerations can be drawn:

- as far as the Daylight Autonomy is concerned, for south-facing rooms the DA values for the glazing+PBS are higher than the corresponding values found for the VB (Δ = +18.9% as average of the four considered sites), resulting comparable to the values found for the glazing alone. This shows that: (a) on an annual basis the PBS allow a slightly higher daylight amount into the room, compared to the VB; (b) the scattering effect of the microalgae acts as a shading system, minimizing the transmission of direct solar rays, but without reducing significantly the amount of diffuse daylight into the room (compared to the glazing alone). Differently, for west-facing and north-facing rooms the opposite trend was observed: daylighting in the room is lower in the presence of PBS than of VB (average Δ = -3.6% for west-facing rooms and average Δ = -9.7% for north-facing rooms), with the exception of west-facing rooms in Abu Dhabi (Δ = +4.1%). East-facing rooms show a peculiar trend: the DA values are higher for the glazing+PBS than for the glazing+VB combination, a trend that is qualitatively comparable to south-facing rooms and opposite to west-facing rooms. Furthermore, comparing the results obtained for east-facing and west-facing rooms, it appears that the DA values for east-facing rooms are considerably lower when in the presence of the glazing+VB combination, while only a minor decrease is observed in the presence of the glazing+PBS combination. This appears to be mainly due to the particular algorithm that is implemented in DIVA-for-Rhino to control the VB: once the VB is closed, it remains in that state for the rest of the day (it is then retracted at the beginning of the next day). This implies longer period of blind activated on an annual basis for east-facing room compared to west-facing rooms, with a reduced daylight amount admitted into the spaces. Fig. 14 shows the frequency of use of the blind in the pulled down position for all the locations and site considered.
- the $sDA_{300/50\%}$ is generally equal to 100% for most cases, but for cases with values lower than 100%, it shows trends with the same meaning as the DA (as one could expect), confirming that the daylighting in the rooms with the PBSs is higher than in the presence of a VB for the south orientation and lower for the other two orientations (with the exception of west-facing rooms in Östersund)
- the UDI values show a different trend compared to the DA-based metrics: the $UDI_{100\text{-}3000}$ values for rooms with glazing+PBS system are constantly slightly lower than the corresponding rooms with VB (Δ = -10.8% for south-facing rooms, Δ = -8.5% for west-facing rooms, Δ = -2.6% for north-facing rooms; Δ = -2.6% for east-facing rooms). Conversely, the UDI_{3000} values are higher, highlighting a potential glare risk, which was not confirmed by the glare analyses through the DGP values (see section 4.3.3). The output found for east-facing room showed an

opposite trend, as the UDI100-3000 values are higher for cases with PBS than for cases with VB. As outlined earlier, this is due to the peculiar algorithm implemented in DIVA-for-Rhino to control the VB.

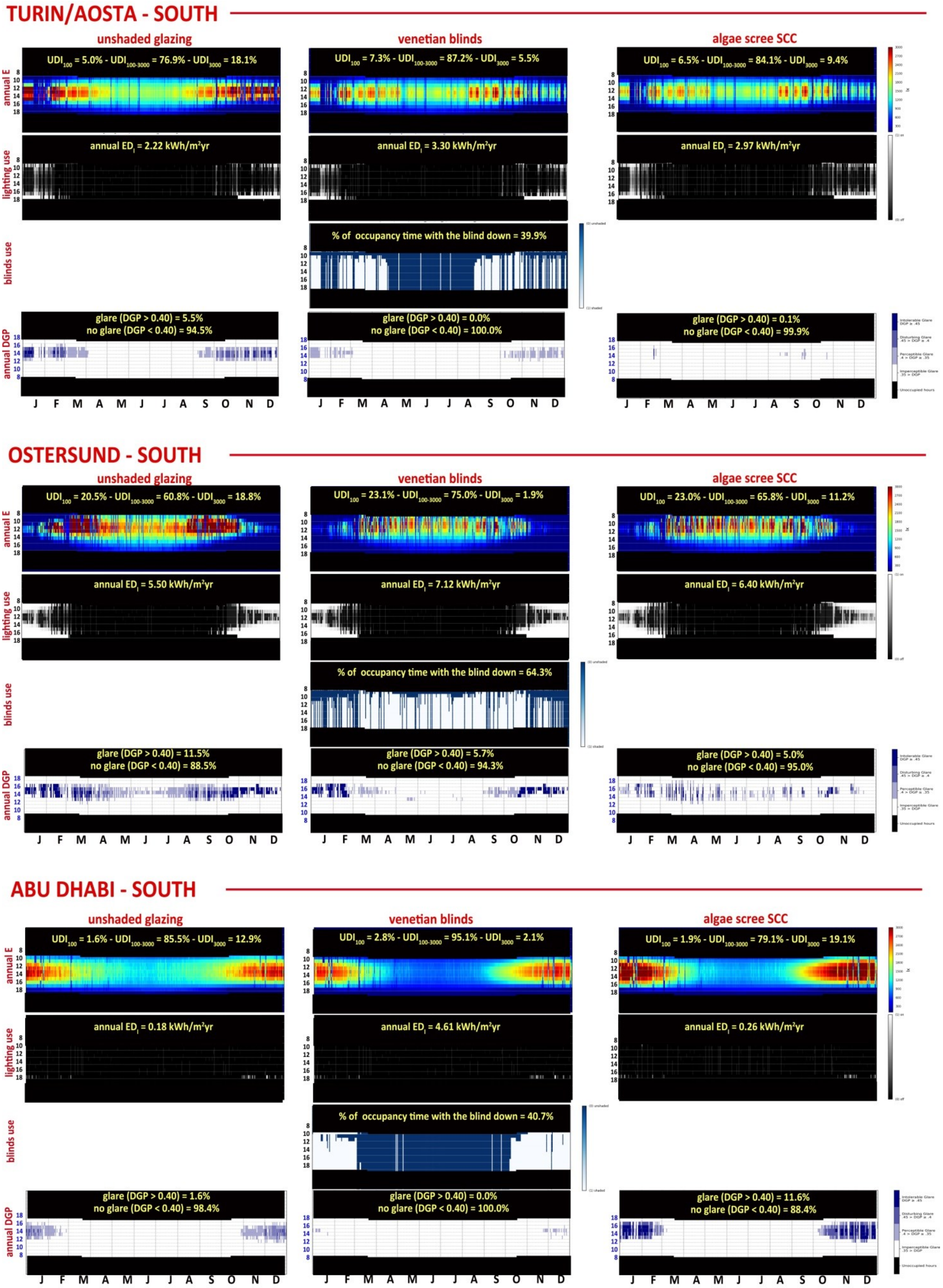

Fig. 12. Parametric study: Daylighting results for south-facing rooms.

Fig. 13. Parametric study: DA, $sDA_{300/50\%}$ and UDI values.

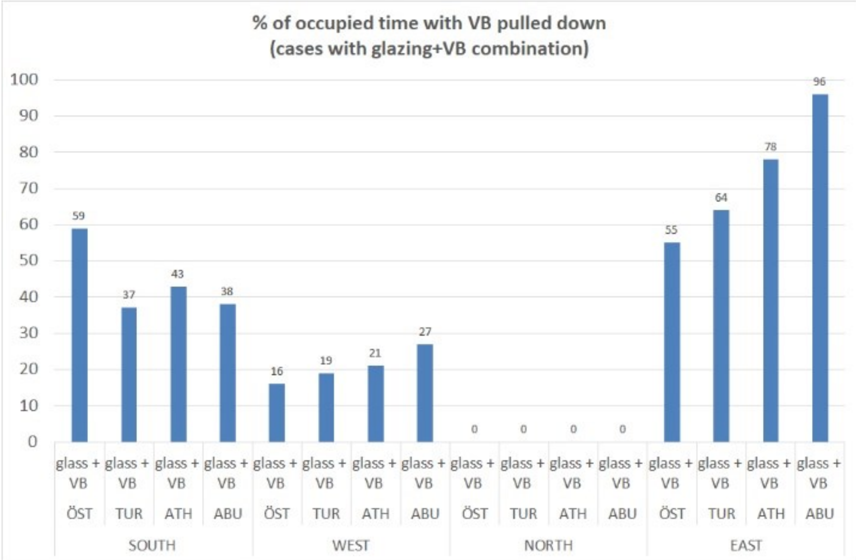

Fig. 14. Frequency of use of VB during the occupied hours for all the cases considered.

4.3.3 Glare issues (DGP)

Figure 15 shows the DGP results that were found for the worst-case scenario of a direction of view perpendicular to the windows. Results that were obtained for south-facing, west-facing and east-facing windows rooms only are shown, as the occurrence of glare for north-facing room is negligible.

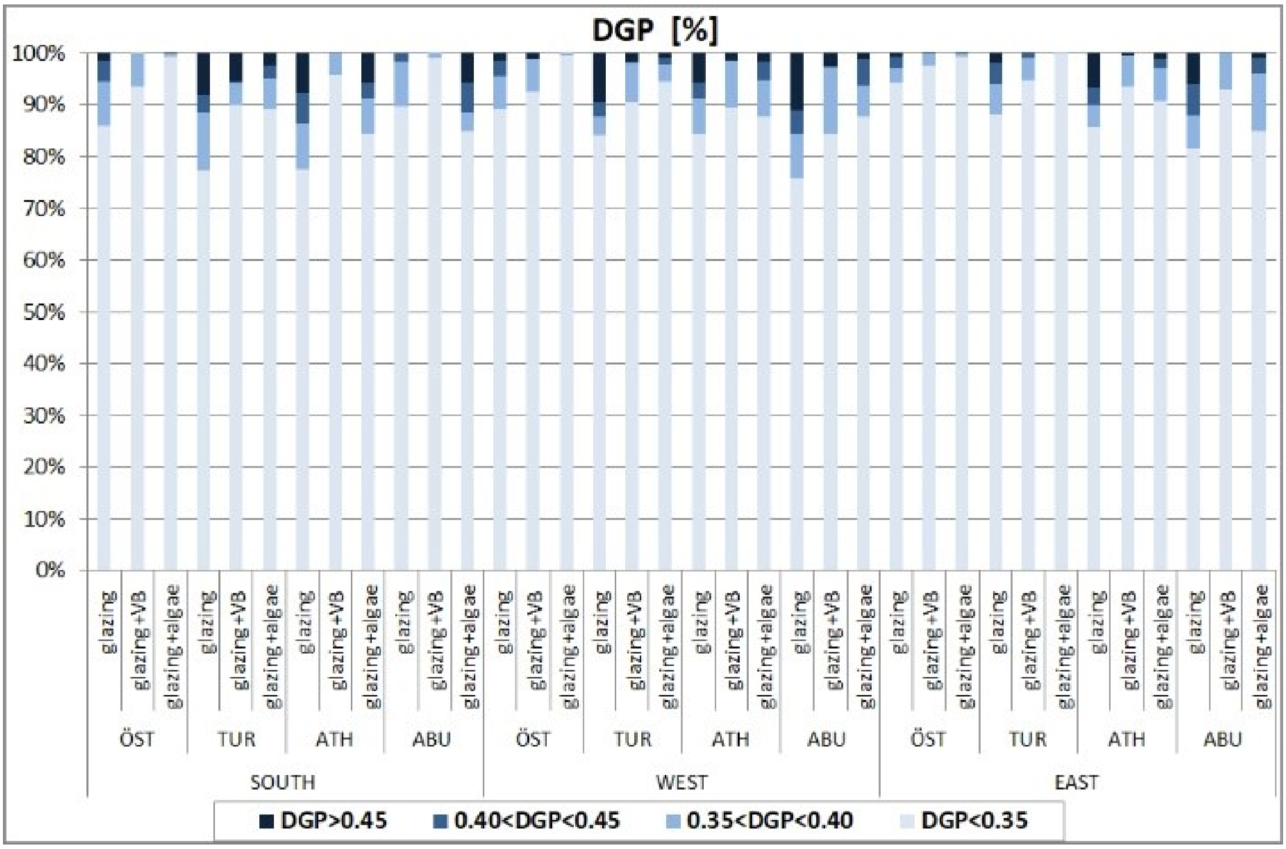

Fig. 15. Parametric study: DGP values.

As for the comparison between different glazing/shading systems, both the VB and the PBS proved to be reliable systems to effectively control glare. In general terms, the performances observed with the two systems were similar: the PBSs were slightly more effective for both south-facing and west-facing rooms located in Östersund and in Turin, but less slightly effective for the same rooms located in Abu Dhabi. The occurrence of time-steps with DGP > 0.40 was found to be: (*i*) for south-facing rooms: 6.4% for PBS, and 1.5% for VB; (*ii*) for west-facing rooms: 3.5% for PBS, and 1.8% for VB; (*iii*) for east-facing rooms: 1.7% for PBS, and 0.5% for VB.

4.3.4 Energy demand for lighting ED_l

Figure 16 summarizes the results that were found in terms of energy consumption due to the lighting systems. For all the considered sites and orientations, the following observations may be stressed:

- for south- and east-facing rooms (averaging the values found for the four sites), the ED_l values for the glazing+PBS are lower than the values found for the VB (Δ = -38.2% and Δ = -53.6%, respectively)
- for west- and north-facing rooms, the opposite trend was found, with the rooms with PBS consuming more electricity for lighting than the rooms with the VB (Δ = 18.6% and Δ = 62.7%, respectively)
- all ED_l values are lower than 8.0 kWh/m^{2}yr, confirming a generally reduced consumption, in accordance with the high daylighting admitted into the rooms through the two considered shading systems.

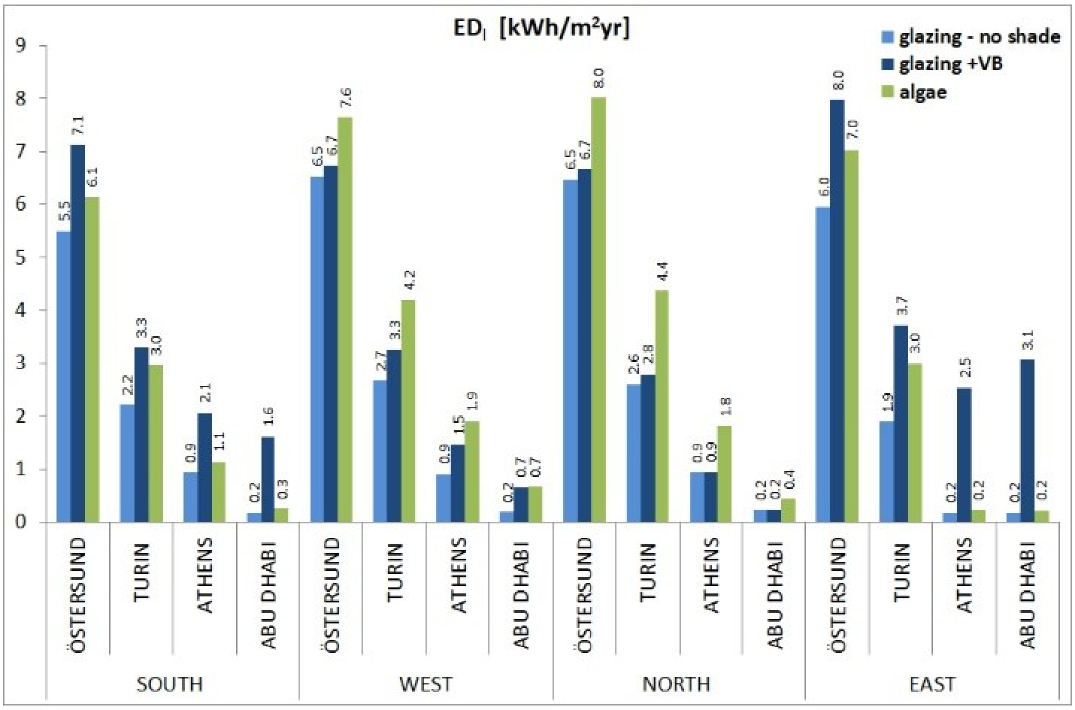

Fig. 16. Parametric study: energy demand for lighting ED_l results.

It can be observed that the above results are consistent with the trends that were observed for the CBDM metrics (more daylighting for rooms facing south in the presence of PBS and the opposite for the other orientations).

4.3.5 View to the outside

Last but not least, the possibility for the occupancy to enjoy a view to the outside was considered. The positive effects of a view out are well documented in the literature. For instance, a review carried out by Farley and Vitch [52] highlights how "*people prefer natural rather than built or urban views from windows. Windows with views of nature enhance work and well-being in a number of ways including increasing job satisfaction, interest value of the job, perceptions of self-productivity, perceptions of physical working conditions, life satisfaction, and decreasing intention to quit and the recovery time of surgical patients. However, the access to a view did not improve the performance of students or actual productivity of office workers*".

Unlike the workplane illuminance, the DF and the DGP, there is no formal requirement concerning the view to the outside (neither in quantitative nor in qualitative terms). Furthermore, as educational buildings for children are concerned, there is a substantial lack of metrics, as illuminance, DF and DGP requirements are typically defined for the grown-ups. Berret et al. [53] carried out a study on how a classroom design can affect the pupils' learning, but when it comes to introduce specific indicators for the view out, they only focus on the window sill, which should be designed below child's eye level and on interesting or green near and far views through the window.

Qualitatively speaking, it is worth stressing that the presence of the PBSs hung to the windows, covering the whole surface of the glazing as assumed in this study, limits the view to the outside, while the VBs allow a view out for all the time-steps when the blind is not pulled down to shade the direct sun. A partial view is still offered when the blind is pulled down with the slats not totally closed. Nonetheless, it is also important to remark that the VBs are closed to guarantee a total shade of the window for long periods throughout the year, up to over 40% of the occupancy time, with a peak of 64.3% for south-facing rooms in Östersund (see Fig. 14). There are days when the blinds remain constantly in the closed position.

For cases with PBSs, it is also true that these represent a natural element in constant visual contact with children (and teachers), with an effect that is potentially similar to a view of natural scenes out of the window. It is probably better to have a view of green microalgae covering a window than a view through that window of a brick wall. PBSs may also be touched and the cubicles, partially infilled with water, may be pressed, thanks to their compression resistance and flexibility. A light pressure over the cubicles may be useful to avoid the microalgae sedimentation and to contribute to the well-being of the occupants: as anti-stress practice during break times for teachers and as educational tool to teach pupils to take care of living organisms. Anyway, to overcome the limited view out, the optimal application of this system should be to position the PBSs in the upper part of the window, to intercept the most problematic sun rays while still allowing a view. The shape, size and layout of the modular PBS containing the microalgae was studied and optimized during the first phase of the research [1]. For this reason, changing the size was not considered at this stage of the research and it was decided to work on reducing the glazing area with PBSs and on the fragmentation of the window in two parts: a '*daylighting window*' (upper part), with a specific shading function, and a '*view window*' (the lower part). Such fragmentation is a strategy well documented in a number of daylighting handbooks, such as IEA. [54]

Figure 17 shows a render of one configurations with a trade-off between shading and view functions, as well as the difference in terms of CBDM and ED_l values between this configuration and the one with the PBSs covering the whole glazing (for the real classroom). With the 'view out configuration' of PBSs, a small increment of the daylighting is observed compared to the case of PBS over the whole glazing, in terms of DF_m (+27.1%), DF_i (from 0% up to 31.9%) and of DA (+9.3%), which results in a slightly lower ED_l (-8.4%). The glare occurrence remains substantially unaffected. As a matter of fact, these differences can be considered as negligible: applying the PBSs to the upper part of the glazing does not compromise the shading, still allowing a good daylighting and a view to the outside.

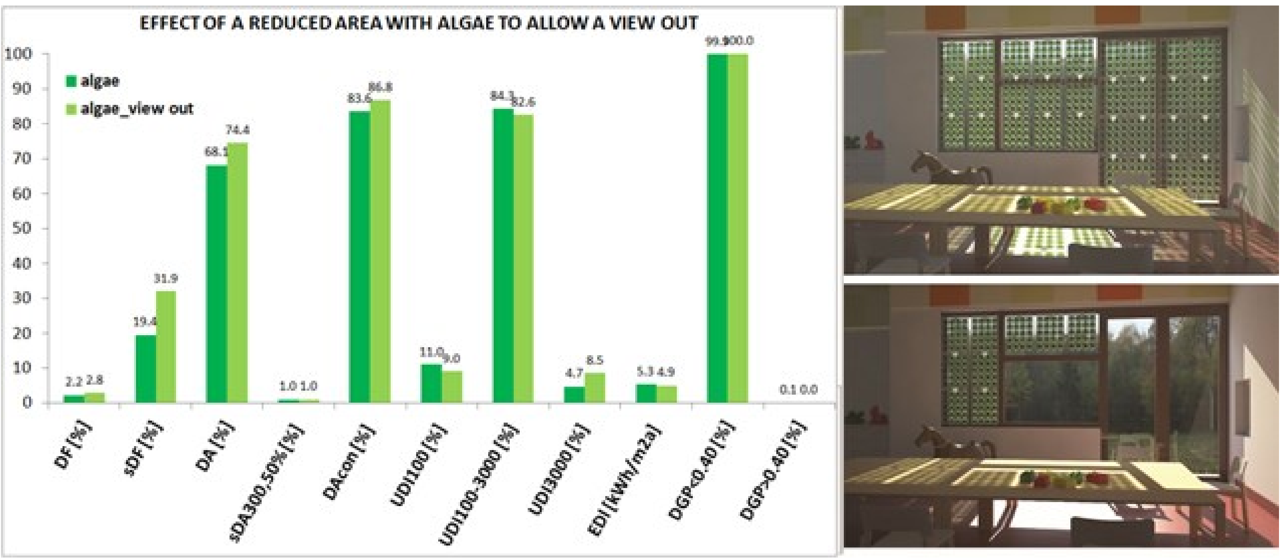

Fig. 17. Renders of a layout of algae partially covering the windows so as to allow a view out (real classroom).

5. Discussion

This study has two innovative aspects: (*i*) to have measured the light transmittance T_v of an innovative micro-algae photo-bio-screen (PBS) used as a static shade; (*ii*) to have determined through simulations the ambient performances in a room where such PBS is installed. The measurement of the T_v of photo-bio-reactors has not been addressed so far in the building literature.[8] In this study, the T_v of the PBS was determined through a long-term monitoring (for a period of 3 weeks), while the ambient performances in a room were determined through an extensive simulation study, starting from a real kindergarten classroom.

The T_v found from measurements was used as input file (light transmittance of a glazing+PBS combination) for the set of simulations. Through simulations, the latest climate-based daylight metrics were assessed, such as the $sDA_{300/50\%}$ [46,48], the DA, the $UDI_{100\text{-}3000}$ [47], and the DGP (not required in any standard yet, but validated in the literature as the most reliable metric for glare analyses). Furthermore, the energy demand for electric lighting was also quantified. Simulations were carried out through a parametric approach, assessing the effect of variables such as site and orientation on the daylighting into the considered room.

The performances of the PBS as a shading system appear promising, as they were found to be comparable to a traditional VB. Especially for south-facing room, the daylighting was higher, with a corresponding lower ED_l. On the other hand, if the same rooms were facing west or north, the daylighting in the presence of PBSs was slightly lower than what observed with the VB, with an increased ED_l. This trend is even enhanced for east-facing spaces, for which the VB is pulled down in the morning and then remains in that state for the rest of the day, thus producing more frequently shaded rooms during the course of a year. Compared to PBS for the same rooms, daylighting is lower and the energy demand is higher.

As far as the effect of the climate is concerned, the four site selected present different sky conditions that statistically occur during the course of a year. As mentioned earlier, the Luminous Exposure LE ranges from 0.30 for Östersund (where overcast skies and the diffuse sky component are prevailing) to 0.68 for Abu Dhabi (where sunny skies and the direct solar component are prevailing). Consequently, the impact of such external conditions on the daylighting inside a space and the corresponding energy demand for lighting is highly different among the different sites. In short, the following trends were observed:

- the number of hours during which the VB is kept in the closed position year-round (see Fig. 14) is higher for Abu Dhabi, followed by Athens, Östersund and Turin. For Abu Dhabi VB remains closed for 53.7% of occupied hours (as average of south-, west- and east-facing rooms) with a peak value of 96% for east-facing rooms.
- the daylight amount in the space considered, described by all CBDM metrics (DA, DA_{con}, $sDA_{300,50\%}$, $UDI_{100\text{-}3000}$) is higher for Athens ($DA_{average}$ = 83.1%, $UDI_{100\text{-}3000,average}$ = 89.8%), followed by Abu Dhabi and Turin ($DA_{average}$ = 75.0%, $UDI_{100\text{-}3000,average}$ = 88.2%) and by Östersund ($DA_{average}$ = 58.3%, $UDI_{100\text{-}3000,average}$ = 72.6%). Therefore, Turin and Abu Dhabi show equal values of DA and UDI, although they have quite different climates, but it happens that the daylighting in the rooms is the same in a sunnier climate where the VB is closed for most time year-round and in more overcast climate where the VB is used far less
- the energy demand for lighting ED_l is lower for Abu Dhabi, followed by Athens, and by Turin, while the highest consumption was observed in Östersund.

As far as the glare issues are concerned, the PBSs proved to be effective in controlling the glare discomfort. The DGP values in the rooms with PBSs were similar to what observed for rooms with the VB: the associated DGP values were slightly better for both south-facing and west-facing rooms located in Östersund and in Turin, but slightly worse for the same rooms located in Athens and in Abu Dhabi.

As for the possibility of a view to the outside, which is limited in the presence of PBSs covering the whole glazing surface of a room, the simulation results showed that limiting the presence of PBSs to the upper part of the glazing (to allow a view out for the occupants) resulted in an increase of the daylight amount (DF_m = +27.1%, DA = +9.3%), with a slightly lower ED_l (-8.4%), without reducing the effectiveness in the glare control ($DGP_{>40}$ = 0.1% of the occupancy time throughout a year).

At the Authors' knowledge, an extensive study as the present one on the light performances of photo-bio-reactors as façade elements is novel and original as there is nothing similar in the literature. In his thorough review, Elrayes [8] points out that "*even though the aforementioned studies strongly support the role of PBR façades in optimizing daylight levels, further studies are required to measure daylight levels and distribution all over task levels*". The present paper is in line with this recommendation, as it contributes to increase the knowledge on the non-trivial connection between the PBRs used as a façade elements and the daylighting admitted into a space.

It is worth stressing that the focus of the research was to assess the feasibility of our innovative PBSs as shading system in order to use the high transparent areas in buildings' façades for a good yield in terms of production of bio-mass and active high-added value molecules for nutraceutical.[20] For this purpose, façades were identified as good elements as they typically represent a large area with high solar exposure levels, that favor the growth of microalgae. The PBS layout was therefore optimized so as to allow a modularity for the most suitable coverage of transparent façades of any area.

Another innovation of our researches is concerned with the main properties of the PBS itself.[1] Actually, the PBS requires no maintenance over the brief life-cycle of selected microalgae (1-3 months), thanks to the sterility of container and the reduced fouling phenomena.[17] Furthermore the PBS is conceived as single-use disposable device. After the end of the life-cycle of the microalgae, they could be used as an important source of high-added value products for human and animal nutrition.[1]

A limit of the study is concerned with the choice to model, for the annual simulations run with Radiance, a complex systems such as the PBS with a *trans* material with a constant T_v. This is a simplification of the real behavior that was observed through the monitoring: on the one hand the T_v changed values with time, both as a function of the sky condition and of the position of the sun in the sky during a day. On the other hand, T_v values often resulted over the theoretical upper limit of 1: this seems to be due to the fact that the clusters of algae scatter light and the cubicles act as biconvex lenses, resulting in a refraction of outside daylighting with an increase of the T_v values. Such a behavior is in line with was observed in the earlier study.[1] Considering the practical difficulty in modeling a dynamic T_v during the course of a year, a constant value was attributed to the *trans* material used in Radiance, determined as the median of the monitored T_v values. Furthermore, the resulting transmission is not perfectly diffusing as assumed in the construction of the *trans* material. These simplifications may have affected the simulation output. For this reason, as an exploratory sensitivity analysis of the results, further simulations were run, limited to the cases of south-facing rooms located in Turin: for these cases, the T_v of PBSs was varied, and new simulations were run to calculate the DF, the CBDM metrics and the ED_l. The following four values were used as input: $T_{v,algae} = 0.65$, $T_{v,algae} = 0.70$, $T_{v,algae} = 0.80$, and $T_{v,algae} = 0.85$. The T_v of the four glazing+PBS combinations were recalculated and new trans materials were specifically created and added to the library of materials in DIVA-for-Rhino. For each metric (DF, CBDM, ED_l), the relative percent difference of the results obtained for the $T_{v,algae}$ modified was calculated with respect to the results obtained for $T_{v,algae} = 75\%$ (the reference value used for the parametric study). The results are summarized in Table 1. The higher differences were observed for the Daylight Factor (20%), which is linearly depending on the light transmittance T_v of the transparent component (range: -12.5% ÷ +19.5%), while for CBDM metrics and the energy demand for lighting ED_l the relative difference is never greater than 10%. This means that changing the T_v of PBS in a quite wide range (0.65 ÷ 0.85) results in a difference lower than 10% for all metrics except for the DF. Such a difference is typically considered acceptable for lighting and daylighting applications. This is only a preliminary exploration, which was carried out for south-facing rooms located in Turin only. The same analysis should be repeated for the other sites and orientations considered in the study. A more thorough sensitivity analysis of the results will be the object of a dedicated study in the next future.

Table 1. Relative percent difference of the values of DF, CBDM metrics, EDl calculated with a varied $T_{v,algae}$ compared to the values calculated using the reference value of the parametric study ($T_{v,algae} = 0.75$). Each relative difference was calculated through the formula: $(metric_{Tv,algae} - metric_{Tv,algae=0.75})/ metric_{Tv,algae=0.75}$.

	DF	DA	$sDA_{300,50\%}$	DA_{con}	$UDI_{100-3000}$	$DGP_{<0.35}$	$DGP_{<0.40}$
$T_{v,algae} = 0.65$	-12.5	-1.9	0.0	-0.9	1.5	9.7	5.2
$T_{v,algae} = 0.70$	-9.3	-1.2	0.0	-0.5	0.6	8.6	5.0
$T_{v,algae} = 0.75$	0.0	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
$T_{v,algae} = 0.80$	15.6	3.1	0.0	1.4	-5.4	-1.8	2.0
$T_{v,algae} = 0.85$	19.5	3.8	0.0	1.8	-7.6	-6.2	-0.1

A more accurate characterization of the visible transmittance of the PBS should be done using a photometric integrating sphere: but this can be done in a laboratory with a discrete light source, thus allowing the light transmitted for a set of incident directions (the so-called Bidirectional Transmittance Distribution Function BTDF). Nevertheless, in a real building, the PBSs installed as a façade system would receive light not only from the sun, but also from the sky dome, thus performing in a way which would be different compared to what measured in a laboratory. As a consequence, some approximations are needed to perform a complex analysis on the daylighting admitted into a space.

Another limit is concerned with how the illuminance were acquired during the monitoring period for the calculation of T_v, especially with regard to the data loggers positioned right behind the PBS: actually, small displacement of the instrument may result in a different acquisition area of the bag containing the algae (consisting of cubicles and inter-spaces) and hence in a different T_v calculated. Anyway, the T_v values obtained in the presented and in the early study, where the same PBSs were applied to a different room, turned out to be practically the same ($T_v = 0.75$ vs. 0.76).

The conclusions obtained in the present study and the earlier study[1] from the same Authors on the comparison between the PBSs and the VBs as shading system are slightly different: the overall light transmittance of the glazing+PBS system was slightly higher in the earlier study, due to the higher T_v of the glazing (0.72 vs. 0.65, the T_v of the PBS being substantially found to be the same in the two studies): this explains why the conclusions found in the earlier study showed a higher daylighting in the presence of the PBS compared to the VB, with higher values of the CBDM metrics and a lower ED_l. On the other hand, more frequent glare problems were also observed (higher $DGP_{>0.40}$).

It is worth also stressing that the optical density of the algae increases with time during their life cycle, and so does the T_v, of PBS accordingly. This aspect is particularly complex to be modeled for each time-step during an annual simulation, so it was taken into consideration through a simplification, by calculating the median value of T_v over time. Anyway, the growth rate of the algae was also measured as part of the analyses of the present study: this was found to be consistent with the growth rate measured in the earlier study.

As a general comment, it should be noted that the perception and the acceptance of a luminous environment for children might be different from what happens for adults. However, a substantial lack of metrics suitably developed for children is to be highlighted, as the metrics commonly accepted and used as reference were developed for adults. The only input which can be introduced to account for the specific characteristics of pupils is their height. This was considered by positioning the calculation point of the DGP 80 cm above the floor, which is the position of the eyes of a pupil sitting. Accordingly, the workplane was positioned 50 cm above the floor (that is the typical height of a table for children). In this regard, it would be interesting to investigate the acceptance shown by children toward the space they spend their activities through specifically developed surveys and metrics.

6. Conclusions and future work

Prototypes of photo-bio screens (PBSs) were installed as static shading devices in a real kindergarten classroom in Saint-Marcel, Aosta, north-west of Italy. The devices consist on an array of circular cubicles containing a culture of the microalgae *Scedenemus obliquus*. In this study, the effect of PBSs on the daylight of the room was analyzed by means of two approaches: (*i*) an in-situ three weeks monitoring of the illuminance values transmitted through the PBS to calculate the visible transmittance T_v, and (*ii*) a series of Daysim/Radiance simulations, using the T_v measured in-the-field as an input, to calculate the daylight amount in the space as well as the corresponding supplementary energy demand for lighting. The performances of the PBS were compared to the ones of a traditional VB, with regard to two configurations: (*a*) the real space, with obstructions due to the gymnasium and to the surrounding mountains; (*b*) the same space, analyzed parametrically changing the site and the orientation.

The main results which were found in the study are:

- the light transmittance of PBS, calculated as median value of the T_v values throughout the monitoring period of 3 weeks, was found to be 0.75, a value in good agreement with the value found in the earlier study by the same Authors (T_v = 0.76). It is worth stressing that T_v values over the theoretical maximum value of 1 were also registered during the monitoring: this seems to be due to the refraction effect caused by the clusters of microalgae and the circular cubicles, that act as biconvex lenses
- for the real classroom (with obstructed windows facing south), the Daylight Factor was found to be not compliant with the requirement set by the Italian legislation ($DF_{average}$ > 5% for kindergarten classrooms[51]). If a less strict requirement was assumed ($DF_{average}$ > 3%, which is the criterion for all the other types of classrooms), the performance in the presence of the PBS would be below the threshold ($DF_{average}$ = 2.23%), while it would be compliant in the presence of a VB ($DF_{average}$ = 3.12%). Nonetheless, if CBDM metrics were used, such as the DA, the $sDA_{300,50\%}$ or the $UDI_{100\text{-}3000}$, the performance would be compliant with the minimum requirements set by recommendations and protocols, such as the UK Priority School Building Programme [48] or the LEED v4 [49]. It appears therefore clear that the obsolete DF criterion should be abandoned in Italian regulations and replaced by a verification approach that is based on CBDM
- the daylighting in the considered classroom equipped with the PBSs showed performances that were strongly similar to what was found for the same rooms equipped with a moveable VB. According to the DA and $sDA_{300,50\%}$ values across the space, daylighting was slightly higher for rooms with the PBSs facing south and east, and slightly lower for rooms facing west and north. However, the magnitude of the difference was less than 15% for most conditions
- the PBSs proved to effectively control the glare perception in the room, in a similar way to what performed by a VB. The associated DGP values were slightly better for both south-facing and west-facing rooms located in Östersund and in Turin, but slightly worse for the same rooms located in Athens and in Abu Dhabi
- the simulation of the real case showed that the DF_m and the are lower than the requirements set by current regulations and standards; on the contrary, the $sDA_{300,50\%}$ DA and the $UDI_{100\text{-}3000}$ values are compliant with the requirements set by the technical recommendation. Therefore, there is a discrepancy depending on which metric and/or standard is used. The Authors encourage the definition of more harmonized and unambiguous analysis protocols
- an issue concerned with the view to the outside needs to be stressed for the PBS, constantly limited for the occupants if the PBSs are applied to the whole window (as assumed in the study). Nevertheless, limiting the application of PBSs to the upper area of the glazing hardly produces an increase in the daylighting into the room,

with a reduced ED_l, without increasing the glare perception (DGP values = 0.1% of the occupancy time). This shows that the shading effect is maintained still allowing a view out.

The use of PBSs showed to be a promising technology as a trade-off between the daylighting inside a space, the shading effect and the ED_l. Furthermore, the method adopted in the study could be applied to other transparent or translucent façade components, such as responsive technologies based on phase change materials, in order to quantify their impact on the daylighting and the energy consumption for a building. A first attempt in this direction was proposed in [55].

The on-going activity is being focused on a more accurate determination of the T_v of the PBSs, through a long-term monitoring and using luminance images and an integrating sphere: the luminance of the whole PBS can be compared to an image of the same glazed area without the-PBS, more accurately than with illuminance meters. Such an analysis will allow a more in-depth investigation of the refraction effect played by the biconvex lenses the cubicles consist of. Afterwards, an attempt to model a 'dynamic' T_v as a function of the transient sky conditions and the different time of the day will be carried out to optimize the input data for the simulation process.

A further step to expand the analysis on photo-bio-screens in buildings is concerned with a study on how the PBSs are accepted and perceived by the occupants in real rooms: a survey to investigate their subjective assessments regarding such systems will be addressed in the future. As a particular research field, how such acceptance is concerned with young students and pupils will be addressed at some point in the future, through specific questionnaires and new dedicated metrics, or using existing metrics to be suitably modified or re-calibrated.

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