Daylighting performance of three-dimensional textiles

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ABSTRACT

The pattern and permeability characteristics that compose three-dimensional (3D) textiles are important as a textile shading component to the architecture, engineering and construction (AEC) industry. Moreover, due to their complex geometry, 3D fabrics require a detailed modeling for correct evaluation of performance.

This paper aims to present and investigate the optical properties of six 3D fabrics proposed as an alternative to traditional roller blind shading systems, which could guarantee high daylight availability and visual comfort.

The light transmission distribution for the different samples has been characterized by carrying out angular visual transmittance measurements, using integrating sphere optical benches, and virtual modeling using Radiance's genBSDF tool. The Bidirectional Scattering Distribution Function (BSDF) calculated with Radiance shows a good fit with the optical angular measurements, which were used as a benchmark and to calibrate models. The performance of the 3D textiles, in terms of illuminance, daylight availability, and glare, was assessed considering two of the set of 3D textiles as alternative materials for a movable internal roller shade system in an open office. The innovative system was compared with a traditional single layer fabric roller blind under different shading control strategies, 3D fabrics demonstrate the potential of increasing Daylight Autonomy while providing better uniformity and better connection with the outdoors due to a higher openness factor. The shading effect created by the 3D geometry of the textile can increase the openness factor while restricting glare.

1. Introduction

1.1. Daylighting in office space

Designing an office environment, especially an open space, requires special attention from the designer. There are many factors that determine the spatial representation of an indoor space including management, usability, visual and thermal comfort. These variables depend on measurable and simulated conditions as well as the subjective perception of individual users, and building characteristics.

In the case of buildings that have a high window to wall ratio (WWR), it is necessary to guarantee the control of incident solar radiation on transparent surfaces because as it has been shown, an excess of radiation itself can significantly modify the perceived thermal sensation of the users near the glazed surface [1]. Similarly, it is essential to modulate and control the luminous flux to protect workers from direct glare and undesired reflections on computer's monitor surfaces.

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It is possible to entrust the performance control solely to the glass, but in some cases, it is critical to choose the proper ratio that allows for an optimal balance between the solar factor, which controls solar gains, and light transmission, which affects daylighting and glare aspects, due to the dynamic nature of the problem and variation of outdoor conditions.

It is important to ensure that this control strategy does not affect the availability of natural light, which is essential to reduce energy requirements from lighting equipment and to allow the right level of illuminance in the work plane. At the same time, an effective system for controlling the natural luminous flux, which is able to provide the user with a perception of high comfort, must allow the user to maintain visual contact with the external environment. For example, in cooling dominated locations it is necessary to reduce the solar factor value, indirectly affecting the luminous performance if an appropriate selectivity index is not guaranteed. On the other hand, the low light transmission values required to guarantee control of glare phenomena are not compatible with the transparency usually required for daylighting.

The way to overcome this problem is to give the glass the possibility to adapt its solar or lighting properties in accordance with requested energy or lighting performance. In this way, electrochromic glazing represents a valid alternative because they allow control of the glass transparency based on daylight, on solar radiation or internal gains [2]. Another alternative is to maintain high DA values while reducing WWR by increasing the daylight efficiency of glazed surfaces by the use of redirecting shading systems [3].

The simplest and cheapest solutions are manually operated and consist of standard shading systems (roller blinds, louvers, Venetian blinds). However, the effectiveness of manual systems is not adequate, because they rely on users' intervention to adapt to shading positions over time. Under manual control, the activation (closing) of a shading system is generally triggered by glare phenomena under sunny sky conditions, which is not balanced by equally effective stimuli for the opening. In the worst case scenario, the device is set to a permanent (closed) position that results in a static solution [4], [5] because the system could remain active even when the discomfort conditions are non-existent [6] which penalizing the outdoor view.

Consequently, the angular response of a system, considered static, influences the optical performance during the day, due to the variation of the incidence angle of solar radiation over the surfaces.

The most common control alternative for office buildings are shading devices automatically controlled with the use of sensors and actuators controlled by scheduled parameters. This is not necessarily the best or most effective solution. Often users tend to override shading systems controls, due to a lack of correspondence between the level of illuminance foreseen by the embedded daylight strategies and the real user's need, determining a continuous control to ensure illuminance levels on the working plane, avoiding glare phenomena [7]. Furthermore, users often accept uncomfortable conditions if outdoor views are maintained [8].

Past studies were limited to specific case studies or addressing conventional solutions. 3D textile systems could be suitable and smart solutions for shading devices and in particular, for roller shades, due to their enhanced angular properties and their capability to provide different optical performance under different sky conditions in different days of the year even if they remain constantly closed as an alternative to operated shades. Considering this option, their performance is highly dependent to site location, position, geometry, and texture.

1.2. Computer simulation of complex fenestration

Complex fenestration systems (CFS) by definition [9][10] are systems that block, filter or redirect direct, diffuse or reflected sunlight depending on incidence light angles. 3D textiles due to their complex material characteristics and geometries belong to this group. Their light scatter distribution cannot be easily described by mathematical models, or by parametric models, defined from experimental measurements or simulations. Their optical behavior is strictly related to the material, geometry, and field of application. The only reliable approach to is to characterize the optical properties of these materials by means of the Bidirectional Scattering Distribution Function (BSDF) [9], [11]. This continuous function determines the light-surface interaction for every incoming incidence direction or given angles, returning the portion of scattered light in the outgoing direction. Discretization of the directions is based on a representation in accordance with Klems definition [9] or in a scenario with higher resolution such as Tensor Tree definition. The BSDF for a fenestration system can be determined from physical measurements using a goniophotometer [12] video-goniophotometer [13], or computer simulation [14], [15]. GenBSDF is a program

distributed with the Radiance simulation software [16] which generates an XML file that can be used in daylight and energy simulations.

Unlike clear glass or diffusing materials with regular scatter distributions, assessing the annual daylight performances of CFS requires specific simulation methods. The traditional approach used in many daylight research [17] based on Daysim cannot be applied if CFS is to be modeled by the BSDF model, which is not supported by Daysim and especially not in annual simulations. In order to assess the annual daylight performance of CFS, the Radiance matrix methods can be used: three-phase [18], five-phase [19] and daylight coefficient [20]. The choice between these methods is based on different factors such as type of analysis, shading system and accuracy required. In the proposed paper, we selected the daylight coefficient method because is the most suitable approach when using different models (e.g. BSDF and trans) to simulate the shading devices.

Another fundamental aspect of the simulation of the dynamic complex fenestration system is the control strategy. Control strategies can be based on radiation level, working plane illuminance, vertical illuminance, glare index or sun position and external illuminance. As shown in several studies, they can influence the daylight performance and visual comfort [21], [22] significantly, with differences reaching up to 60% for mean daylight autonomy [23].

2. Materials

2.1. A general explanation of 3D textiles

Textiles usually consist of two-dimensional geometry, the weft, and the warp. They have a wide range of applications from clothes and fashion to reinforcement for composite materials. On the other hand, in the last twenty years, a new type of textile was developed to introduce new functions into the textile world: 3D fabrics [24].

3D textiles can be defined as fabrics that are able to control the third dimension based on the thickness of the spacer layer. "In 3D-fabric structures, the thickness or Z-direction dimension is relevant with respect to X and Y dimensions. Fibers or yarns are intertwined, interlaced or intermeshed in the X (longitudinal), Y (cross), and Z (vertical) directions"[25]. Nowadays several typologies of 3D textiles are produced from weaving processes, geometries, configurations and shedding mechanisms.

Spacer fabrics are resistant to rips, abrasions, and their structure allows them to stretch and recover their original shape after compression or tension. External layers can be customized as regular textiles in terms of texture, thickness, and color. For the current study, different 3D fabrics were selected. They were considered as a representative selection of particular textiles because of their different patterns, openness factors, and thicknesses. The main goal of the optical measurements was to understand how these characteristics influence their angular optical behaviors.

2.2. Samples description

Textiles, presented in Fig. 1, are typically used in the fashion sector, as mattress covers, car interiors, backpacks, and shoes to guarantee perspiration. They typically consist of two layers connected and separated by polymeric filaments (PES, PP); defining the length of these interlayer filaments allows the control of the thickness of the 3D textiles. In particular, 6 types of textiles are considered (T1 to T6), as an example of a technological transfer approach from other industry sectors:

- T1 is a 3D textile made of polyester. The thickness of the textile is different from the other samples (20 mm, but can reach 50mm) because it is used as the exterior padding and ventilation layers for mattresses. The front and back surfaces are characterized by a partially shifted rhomboidal weave.. The rhomboidal weave is manufactured by twisting several thinner yarns that lead to thicker and opaque main yarns. Spacer yarns made of polyester connect the two layers, creating a typical 3D warp textile. The upper and lower layer are not perfectly aligned. A misalignment of 1/20 of the tissue thickness could be noticed considering the crossing section of the fabric.
- T2 a 3D textiles made in polyester used in the clothing sector as padding for jackets shoulders. The two layers (front and back) present the same geometry and weave, but they are transposed. The translucency of the fabric

layers is obtained due to the weaving technique and yarn structure. As with the previous textile, the two-layers are interconnected by a series of polyester yarns.

- T3 is a 3D textile made of run proof polyester used in the clothing sector as a padding material for shoes and backpacks.
- T4 is a 3D textiles made of polyester used in the clothing sector.
- T5 is a particular 3D textile made of polyester. It differs from other alternatives because of the geometry of the textile itself. Traditional 3D textiles are constituted by a double layer of plain textiles parallel to one another using an orthogonal yarn that maintains the spacing between the two exterior textile faces. In this case, the yarn of the textile is arranged to create single spaced element orthogonal to the single face plain textile.
- T6 is a 3D textile made in polyester used in the clothing sector as padding for sofas and furniture.

Fig. 1 Different samples of 3D textiles. The presented images are representative of the arrangement of the samples over the sample port when the sample is oriented with $\theta=0^\circ$.

Further images of T1 and T2 samples are reported below in Fig. 2 and will be analysed and simulated in detail. These images were taken for different angles of view with respect to the angle of incidence. In this way it is possible to appreciate the complex geometry of the samples, having the possibility to understand the current section of the fabric itself

Fig. 2 Representative images of T1 and T2 samples. The samples are shown in both orientations ($\theta=0^\circ$ and $\theta=90^\circ$) while the photographs were taken at the same viewing angle (ϕ).

3. Methods

The main goal of this work is the characterization and modeling of 3D textiles to evaluate their behavior as shading products.

The measurements of the optical properties of 3D textile materials were done to have input data and a benchmark for the following simulation results.

The simulation process was conducted in four main steps:

- i. Digital reconstruction of the geometry of selected fabric samples (T1 and T2).

- ii. Modeling of the bi-directional optical properties of the 3D textile reconstructed in a digital environment.
- iii. Investigation and definition of different daylight shading control strategies for a representative office model.
- iv. Glare simulations and evaluation of daylight availability for different roller shades, comparing traditional and 3D textiles, under different control strategies.

3.1. Measurements of the optical properties

The optical characterization of the selected 3D fabric was done using two different instruments:

- A spectrophotometer Perkin Elmer LAMBDA 950, to characterize homogeneous portions of the fabric that represented properties of the material constituting the fabric itself.
- A large integrating sphere optical apparatus, to evaluate optical performance representative of large textured 3D fabric samples.

The spectrophotometer produces a maximum 1.2 x 0.7 cm light beam (measured on the transmittance sample port) and is suitable for homogeneous materials or those with a dense discontinuous texture, like common textiles with a low openness factor, for which the geometry characteristics of the instruments ensure accurate measurements. The solar properties measured for the entire representative solar radiant power spectrum are between 250-2500 nm.

The facility is necessary to perform accurate measurements of complex samples. A meaningful optical performance measure of sample requires an incident light beam large enough to irradiate a representative portion of the sample [17]. The large integrating sphere optical apparatus presents a collimated light beam with a maximum diameter of 9 cm measured over the sample surface, adjustable by the use of a diaphragm. The sphere is 75 cm in diameter and is internally coated in Spectralon®, a non-selective coating between 300 and 2500 nm, with a solar reflectance higher than 90%. A 300-Watt tungsten free halogen lamp is mounted on a rotating arm that permits change of incidence angle of the light source over the sample surface, reaching angular dependent measurements in accordance with the arrangement of samples over the sample port. The optical transmittance is measured as the ratio of the energy transmitted by the sample mounted on the sample port on the energy directly entering the sphere, corrected with the auxiliary port correction method [26].

The initial position equal to $\theta=0^\circ$, which is the one presented in Fig. 1 for every sample. The angular properties are measured with a light beam incidence angle (ϕ) between 0° and 60° . The measurement step is 15° . The procedure is then repeated two times, for every sample, starting from the initial position (Fig. 1) and subsequently for a clockwise rotation of the sample over the sample port ($\theta=90^\circ$).

The solar properties are evaluated between 250-1750 nm, by the use of an array of two spectrometers equipped with the following detectors: NMOS for the 250-900nm range and InGaAs for the 900-1700nm range. The measurement covers 95.6% of the solar radiant power spectrum, measured between 250-2500 nm and the solar quantities were calculated from the spectral data using the reference solar spectrum presented in [27].

3.2. Complex fenestration system model

For the samples collected and measured in the experimental campaign, two are selected for digitalizing the geometry and subsequent computation of the BSDF. In particular, T1 and T2 (3D-warped knitted fabrics present large optical angular variation. 3D textiles, compared to traditional roller shade fabric, allow an overall openness factor increment while limiting conditions of glare due to self-shading created by the 3D geometry and the overlap between the two fabric layers (front-back). The 3D textiles were modeled using the software Rhinoceros and Grasshopper for the parameterization of the model based on manufacturer specification and geometrical reconstruction. As shown in Fig. 3, the front and back of the textile were modeled recreating highly defined meshes, whereas the interlayer yarns were generated randomly between the two layers maintaining fixed the density for cm^2 , as in the manufacturing process. Nevertheless, the result could be affected by the accuracy of the model in terms of geometry, materials, and simulation parameters used. Given the complexity of 3D-warped textiles, regarding the scale of the components and flexible-stretchable feature of textiles, the definition of a precise geometrical model represents the biggest challenge in the simulation workflow. In order to guarantee high accuracy of the digital models, first, the samples were stretched and fastened on a rigid frame and then measured with a gauge and digitalized with the aid of scan to mesh technology.

In addition, several model iterations were carried out to reduce the openness factor in order to take into account the thickness of the two textile layers (front and back). In order to define Radiance material parameters, each fabric of T1 and T2 was measured separately in a two-dimensional homogenous configuration, provided by the manufacturer, using a spectrophotometer Perkin Elmer LAMBDA 950. For the textile T1, Fig. 3 on the left, a Radiance *plastic* model with a ρ_v equal to 0.70 was assigned to all the textile components (front, back, and interlayer). Whereas for the sample T2, Fig. 3 on the right, the front, and the back surfaces are characterized by a Radiance *trans* model [28] with ρ_v equal to 0.70 and τ_v equal to 0.32, as shown in Table 1. The interlayer yarns have the same properties used for T1. Material properties, as well as the geometric model of the fabrics, were used to develop Radiance models. BSDF with Klems resolution of the models were determined via simulation using *genBSDF* exploiting the ray-tracing method implemented in the program [15].

Fig. 3 Digital model and schematic section of T1 and T2.

Table 1 Radiance materials parameters, for fabric T1 and T2, in accordance with the primitive format (A1-A7 selected parameters for trans material) []

	Material	A1	A2	A3	A4	A5	A6	A7
T1 and spacer yarns	Plastic	0.85	0.85	0.85	0	0.5	-	-
T2	Trans	0.7	0.7	0.7	0.01	0	0.56	0

3.3. Open office model for daylight analysis

A traditional open space office located in Milan (45° 28' N, 9° 10' E), Italy, was chosen as a case study. The office space, as shown in Fig. 4, is 8 m wide, more than 15 m long, with a total height of 3 m, and it can host up to 24 working spaces. The room receives natural light from only one side due to a south facing curtain-wall, with a 90% Window to Wall Ratio (WWR). The percentage of glazing surface and orientation defines a working space where an effective shading system and control strategy are required to ensure an adequate visual comfort. As shown in Table 2, standard reflectance [29] values were applied on the surfaces modeled in Rhinoceros. To the fully glazed solution, three different typologies of roller shades were added to the model, on the inner side of the glazing façade. In particular, a traditional white roller shade with a visual transmittance equal to 0.2 and two different 3D textiles (T1 and T2) were modeled, the latter two systems are presented in the last paragraph. To assess the horizontal illuminance and annual metrics such as Daylight Autonomy (>300 Lux), Useful Daylight Illuminance (300 lux < Eh < 3000 lux), and spatial Daylight Autonomy (300 lux < Eh) [30] throughout the year between 8 am to 6 pm, a grid with 130 points (0.45 x 0.45 m) was created at desk level (0.85 m), that characterizes a typical section of the space. In addition to the illuminance sensor grid, two points of views placed 1.8 m from the façade, with opposite orientation (West and East) were placed in order to estimate the Daylight Glare Probability (DGP) in realistic critical working positions.

Fig. 4 Open office configuration.

Table 2 Reflectance and visual transmittance properties of the opaque and transparent surfaces used in the model.

Surface	Material	A1	A2	A3	A4	A5	A6	A7
Wall	Plastic	0.5	0.5	0.5	0	0	-	-
Floor	Plastic	0.2	0.2	0.2	0	0	-	-
Ceiling	Plastic	0.8	0.8	0.8	0	0	-	-
Furniture	Plastic	0.5	0.5	0.5	0	0	-	-
Frame	Plastic	0.5	0.5	0.5	0	0	-	-
Ground	Plastic	0.3	0.3	0.3	0	0	-	-
Glass	Glass	0.71	0.71	0.71	-	-	-	-
Roller shade	Trans	0.87	0.87	0.87	0	0	0.25	0.05
3D textile – T1	BSDF	-	-	-	-	-	-	-
3D textile – T2	BSDF	-	-	-	-	-	-	-

3.4. Daylighting simulation settings and Shading control strategies

The daylight performance is strictly related to the materials optical properties of the façade, such as glazing visual transmittance and shading device color and translucency. However, for internal movable systems, the control strategy is crucial to the overall performance. For this reason, in order to evaluate the performance of the shading systems on an annual basis in different configurations, three shading control strategies were applied:

3.4.1. Horizontal Illuminance - E_h Control

The first control aims to keep the horizontal illuminance (E_h) level over a specific task area within the threshold of 3000 lux [31]. The task area is placed 1.8 meters from the façade, where the user is located. If the illuminance level exceeds the threshold, the shading device is deployed covering the window area completely. The annual activation profile, in Fig. 5a was defined considering the E_h results from the annual simulation in the case of shading always up. Horizontal illuminance was selected over vertical eye illuminance (E_v) as control variable because, in preliminary simulations, both strategies lead to similar operation predictions and potential real E_h sensor are easier to place. Similar activation schedules are likely due to the high WWR and position of the sensor.

3.4.2. Control by sun geometry

The second strategy aims to avoid disturbing glare by controlling the sun penetration inside the space. In this case, the control is based on the calculation of the sun angles in combination with two statements:

- i. The direct sun reaches the table surface, 0.9 m from the façade and 0.8 m from the floor
- ii. The ratio between direct and diffuse horizontal external radiation exceeds 1.5 m

The latter condition is defined considering the solar radiation from the weather file. If the two statements are true, the shading systems are activated to fully cover the glazed area.

Initially, other typologies of glare control were taken into account, based on vertical eye illuminance (E_v) and enhanced simplified DGP (eDGPs) [32]. However, using the E_v through simplified DGP (DGPs) is only reliable when no direct radiation hits the observer [33]. While using the eDGPs requires an additional time-consuming preliminary simulation. For these reasons, sun penetration was considered. In fact, the presence of direct sun over the task area is strongly connected to the risk of glare and overheating. Furthermore, the proposed approach does not require preliminary simulations. The annual activation profile is shown in Fig. 5b.

Fig. 5b shows the activation profiles of the shading devices for the E_h illuminance and Sun-penetration control. The main difference is visible in the summer months, from May to August, when the sun has higher elevation and its penetration into the space is short so that the shading is rarely activated or not activated at all. Instead, given the high WWR and the high visual transmittance of the glass, the first part of the open office, where the illuminance sensors are placed, turns out to be over lit (higher than 3000 Lux) for most of the time.

3.4.3. “Always deployed” control

For reason of comparison, the previous control strategies are compared with a worst-case scenario where the shading systems are always deployed. This scenario describes a user who rarely operates the blinds [34].

Fig. 5 Annual profile shading activation for the two different strategies named Horizontal Illuminance (a) and control by sun geometry (b). Blue deployed, white not deployed solar shading system.

3.5. Daylight simulation workflow

The daylighting analyses were performed using Radiance [16]. In order to assess the overall performance of the new shading system, two different analyses were performed: daylight availability and glare probability.

3.5.1. Annual daylight availability

The Daylight Coefficient method was employed to perform fast annual simulation. The algorithm is based on the matrix equation $\mathbf{E} = \mathbf{C}_{dc} \cdot \mathbf{S}$ where $\mathbf{E}$ is the annual computed illuminance and $\mathbf{C}_{dc}$ is the daylighting coefficient matrix that relates the sensors points to the skydome. Finally, $\mathbf{S}$ is the sky matrix that describes the sky condition at each hour of the year using the Perez model [35]. The simulation parameters are reported in Table 3.

An annual simulation was performed for each shading system (i.e. roller Shade, T1, and T2) as a result of relative illuminance values over the year. In the phase of post-processing, the illuminance values with shadings deployed were combined with illuminance values with only a glazing system (no shading system) according to the control strategy schedule. Different daylighting indexes were calculated considering the combined illuminance file.

Table 3 Radiance simulation parameters for Annual Daylight availability

ab	ad	lw
10	50000	1e-5

3.5.2. Point-in-time glare

The glare analysis was performed generating point-in-time renderings for the three days, 21st of March (equinox), 21st of Jun (summer solstice) and 21st of December (winter solstice) for each hour during working hours, from 9:00 to 17:00. For these simulations, the *rad* function of Radiance was used. The simulations were set on medium quality changing some of the rendering parameters as shown in Table 4. The sky condition was defined using the Perez model and feeding the *gendaylit* [36] function, deriving the radiation values from the same weather file used in the annual simulation. According to LEED v4 [37], the radiation input for a point in time is the average of the hourly value of two days within 15 days of the equinoxes and solstices.

Table 4 Radiance simulation parameters for point-in-time glare evaluation.

ab	ad	aa	as	lw
5	1024	0.15	512	1e-5

In this case, four steps composed the analysis procedure:

- v. A point in time simulation was run for the hours and days defined. For this first run, no shading devices were used into the scene and 24 HDR images were generated.
- vi. The HDR images were analyzed with *evalglare* in order to identify the sky conditions that cause glare problems. Evalglare task area detection method was used to detect luminance values higher than the mean luminance in the predefined specific task area (i.e. computer screen). A standard multiplication factor equal to 5 was used. For example, if DGP [38] was higher than 0.4, the sky was selected for the next step.
- vii. The second round of simulations has been performed using the glare skies and the scene with the different shading devices.
- viii. The HDR images generated from the three steps were analyzed again with *evalglare* and the results were combined with the results from step ii in order to define the daily glare analysis.

The figure (Fig. 6) below shows the flowchart of the process.

Fig. 6 Flow chart of the simulation process

4. Results

4.1. Experimental results

The following are the spectral solar transmittance measurements of the 6 samples analyzed and shown in Fig. 1. The values given refer to a light source with an incidence angle normal to the surface, a condition that is expressed by $\phi=0^\circ$. All samples were measured with the same arrangement as presented in Fig. 1

The distribution of the curve is characteristic of the translucent material with which all fabrics are made, that is, on average, low-density polyethylene.

The shifting of curves is instead due to the openness factor of the different fabrics analyzed. This parameter is closely related to the geometry of the fabric itself. The presence of holes with large, small or medium size strongly influences the whole transmittance value itself, independently from the warp density.

Sample T3 presents low values of spectral visual transmittance because unlike the other fabrics analyzed, it does not have the same openness factor value for the upper and lower layers of the 3D fabric. In this case, the lower layer consists of black fabric with a very low openness factor compared to the upper layer. The spectral response curves were then integrated in accordance with ISO 9050 to derive solar transmittance properties for every sample measured. The integrated values were then obtained for the two main wavelengths representative of solar radiation: visible (VIS) and near-infrared (NIR). The results are reported comparatively in Table 5 for each of the fabrics.

Fig. 7 Spectral transmittance curve of the samples (T1 to T6).

Table 5 Integrated visual properties of the samples (ISO 9050) for Normal incidence of the light beam ($b=0^\circ$) and in accordance with the standard solar spectrum [27].

	τ [-]
T1	0.48
T2	0.37
T3	0.03
T4	0.65
T5	0.54
T6	0.36

The following images present the solar properties of the 3D fabric by modifying both the angle of incidence of the light source on the surface of the fabric itself and by changing the position of the sample on the sample port by rotating it with a clockwise rotation of $\phi=90^\circ$, in accordance with section 3.1 description. The measured values at $\theta=60^\circ$ incidence angle for sample T2 are not reported because the particular geometry didn't permit significative measurement for that particular incidence angle, as a result of the self-shading effect due to the geometry of the textile. The measurements were influenced by the orientation of the sample on the sample port not only in accordance with geometry but also in accordance with the different arrangement of the fabric fibers, every time the sample was rotated. Another possible reason could be the non-uniformity of the fabric and the beam because the area could be not uniformly illuminated, and at the same time, the density of the fibers is probably not exactly constant over the area.

T1

T2

Fig. 8. Angular visible transmittance (τ_v) of all the samples. Samples are measured with $\phi=0^\circ$ and then again were rotated clockwise of 90° ($\phi=90^\circ$). θ represents the Incident angle of the light beam over the sample (θ from 0° to 60°)

All the curves show a flat behavior because of two reasons:

- there is a relevant, yet variable, radiation component directly going through the holes of the shades, in this case, the void to material ratio affects the magnitude of the transmittance;
- the color and the nature of the materials do not present a significant selectivity behavior.

If the average dimension (diameter) of the light beam is comparable to a homogeneous portion of the representative texture of the sample, this deviation should not occur, because of the positioning, for normal incidence of the light beam, it should be invariant.

However, in this situation, independent from orientation, position or stresses derived from its own weight, a rigid sample able to keep its geometry constant is not being evaluated.

In this case, there is a material that is subjected to relaxation phenomena depending on whether the resultant surface forces are parallel or orthogonal to the fabric fibers.

The material presents a strong biaxial behavior, which is closely linked to the geometry of the fabric.

To overcome this problem, a weak pre-tension was applied to the sample by means of a support frame. The textile was not perfectly stretched, because that situation would not represent a real installation condition of the material when used as a shading device system. Tensioning could also affect the average spacing of the fabric warp and waft, increasing, or in some cases decreasing, the transmittance of the textile material.

4.2. Comparison between measured and simulated angular transmittance values

As previously stated, for the two 3D fabrics T1 and T2, two BSDF matrices were defined, which describe direct and hemispheric angular transmittance of the samples in accordance with the radiation incidence angle. All the possible ingoing and outgoing directions of the incident radiation are described by means of a discretization which consists in a hemispheric space subdivided into 145 patches, according to the standard defined by Klems [11] and as shown in Fig. 9.

The simulated comparative curve was reconstructed by points by taking the values of hemispherical angular transmittance from the BSDF matrix, selecting the values corresponding to the hemispheric patches that can reproduce an incidence angle that is comparable to the ones used during the measurement campaign. The central position of the hemisphere represents the direction between 0 and 5°, increasing up to 90° moving towards the concentric patches located at the periphery of the system. In order to compare the behavior of the samples that were measured with the ones generated through simulations, only patches of the BSDF data along the directions highlighted by the letters A, B, C and D were selected, Fig. 9.

Fig. 9 Klems Sky Subdivision in 145 Patches [11] (left) and identification of patches for hemispheric angular transmittance calculation directions applied to T1 (middle) and T2 (right) samples. The selected directions were A, C for $\phi=90^\circ$ samples, and D, B for $\phi=0^\circ$ ones.

Given the complexity of the geometry, to define the most appropriate *genBSDF* parameters, a convergence test was performed varying the main settings. The most significant variations were observed in the number of light bounces in the ray tracing. Fig. 10 shows that the results converge with a number of ambient bounces (-ab) around 8-10. Due to the variation in the geometry in the three dimensions, the number of samples per patch (-c) increased compared to the

default value. The final *genBSDF* parameters are +f +b -n 4 -c 4000 -dim [0.4213 0.4591 0.4394 0.4846 -0.018] -r [-ab 8 -ad 700 -lr 10], with the definition of different parameters described in [39].

Visible BSDF matrixes contained in XML files were attributed to internal shading system surfaces as inputs for Radiance software in order to calculate the daylight levels and the visual comfort.

Fig. 10 BSRF convergence test of $T1_{\theta=0^\circ}$ (left) and $T2_{\theta=90^\circ}$ (right). Variation angular visual transmittance based on ambient bounce parameter (-ab) in *genBSDF*.

The hemispheric angular behavior measured for the two T1 and T2 samples was used as a benchmark for the accuracy of the processed BSDF model. The graphs in Fig. 11 compare the angular performance curve measured for T1 and T2 fabrics, both in $\phi=0^\circ$ and $\phi=90^\circ$ position, with an angular transmittance curve derived directly from the simulated BSDF matrix.

Fig. 11 3D textile directional scatter distribution function for 3D textile T1 and T2 and comparison with the measured values.

There is considerable overlap of results for all samples measured with $\phi=90^\circ$ arrangement [reference to Fig. 11 bottom images]. This behavior mainly depends on the lack of angular behavior of the T1 and T2 samples analyzed for the orientation considered. For this orientation ($\phi=90^\circ$) more light passes through without scattering and therefore no strong angular selectivity occurs. For the T2 sample, the alignment of the holes is not clearly present, but for the set of incidence angles considered, the light source affects single portions of fabric belonging to one of the two layers of the 3D fabric, resulting in a strictly diffused behavior of the fabric.

A different situation occurs when the sample is considered with $\phi=0^\circ$. In this case, the variability of the angle of incidence of radiation has a significant influence on both the measured and simulated performance. In addition, in this case, it is possible to observe [reference to Fig. 11 upper images] how the simulation can be considered representative of the sample even if there are some differences that will be presented later.

A symmetric behavior could be expected for sample T1 $\phi=0^\circ$ while the model itself was evaluated according to the two directions B and D. An asymmetry was intentionally inserted in the 3D fabric model and in particular, a misalignment between the two lower and upper layers of the 3D fabric as precedent described in cap 2.2.

4.3. Daylight Analysis: Working plane illuminance

Box plots in Fig. 12 represent the Daylight Autonomy (DA) values for each point of the calculation grid, showing the results of selected internal roller shades for three different shading control strategies.

Horizontal illuminance and control by sun geometry strategies have similar elevated high median value daylight autonomy compared to the always-deployed strategy that shows more variability. More specifically, the DA in the worst case scenario (roller shades always deployed), ranged between 20% to 85%, with a median value equal to 48% for a traditional fabric roller shade. Whereas the proposed 3D textiles have a higher median value around 65 for T1 and 70% for T2 with a total range between 35% and 85%. Implementing the control strategies, the median DA value is similar for the different textile solutions, with a slight increase of around 5% for 3D fabric roller shades. Nevertheless, the range between minimum-maximum and between the second-third quartile values are compressed. In particular, traditional textile values ranged between 40-50% to 90%; T1 varied between 55% to 90%, and T2 ranged between 60% to 90%. In addition, independent from the control strategy, the box plot ranges show that 3D textile roller shades provide more uniform illuminance than traditional roller shades. A more compact DA box plot implies a higher spatial Daylight Autonomy (sDA), then a better light distribution for the entire depth of office space.

Fig. 12 Daylight Autonomy box plots for the shading systems (e.g. Roller Shade, T1, and T2) considering different control strategies

The curve distribution plots in Fig. 13 confirm the results shown in the box plots. The spatial distribution of Daylight Autonomy, with shading system always deployed, for the 3D textile (T2) is more evenly distributed all over the floor area compared to a traditional roller shade. The daylight distribution for the roller shade configuration shows a drastic drop in DA percentage from the first third of the floor area near the window, with DA values around 40-50%, while T2 does not show any value below 50%. Due to the increment in the DA values, there is also an increment in the number of hours over the threshold of 3000 lux. However, the UDI curve in

Fig. 13 Fig. 13 displays that the increase is significant only in the first meter close to the façade (over 30% of the time), a portion of the floor without desks, therefore with a marginal effect on user's comfort.

Given the lack of interaction between users and manual shading systems, which are frequently deployed, installing a textile roller shade with higher visual transmittance and openness factor, such as T1 and T2, could improve the daylight level over the year and at the same time can reduce the lighting energy consumptions. Nevertheless, shading fabrics have to control the visual comfort principally, guaranteeing an adequate reduction of glare.

Fig. 13 Curve distributions of Daylight Autonomy and Exceed Useful Daylight Illuminance on the working plane with always-deployed control strategy for a traditional roller shade blind and 3D textile roller shade (T2). Glazing surface highlighted in cyan.

4.4. Daylight Analysis: Glare Probability

Fig. 14 shows the glare analysis for the two selected views when no shadings are applied. Since the façade is oriented Ssouth, the East view suffers from glare during the morning hours and the West view during the afternoon. Moreover, March and December are the periods when the glare problem is more intense, while in June when the sun is higher in the sky, the glare is just perceptible.

EAST	WEST
No Shading (March, June, and December)	No Shading (March, June, and December)

Fig. 14 Comparison of the daily glare distribution for two different orientations (EAST, WEST) and during three days over the year (21th March, 21th June, 21th December)

Fig. 15 shows the glare analysis when shadings are deployed during the hours when DGP was higher than 0.4. The graphs show also the comparison in terms of DGP of the three shading systems applied: Roller shade, T1 and T2. The traditional roller shade provides better glare control for both the views; the DGP values are always in the imperceptible DGP area (green area). Since T1 is the most permeable system, it has the highest DGP values. In particular, for some hours on the West view, the DGP reaches intolerable values. Finally, the T2 system has higher DGP values than the standard roller shade while providing a comfortable view to the user, DGP increases to perceptible values (i.e. DGP range 0.35 – 0.4).

Fig. 16 presents the comparison of the interior luminance values for the three shading systems tested on March 21st at 15:00. In this comparison, it can be appreciated a difference in the functionality and visual transmission of the different systems. While the traditional roller shade is independent of the angle of incidence and has a very low transmission, the T1 and T2 systems' transmission is higher. In particular, the façade is too bright adopting the T1 system and more light hits the desk area, luminance values are approximately 1500 cd/m² against 800 cd/m² of the T2; this light condition causes a discomfort glare situation. Instead, using the T2 system, the scene is bright as the T1 solution, despite the different geometry and light scattered, it presents an acceptable DGP value, equal to 0.39.

EAST	WEST
Roller Shade, T1, and T2 – December	Roller Shade, T1, and T2 – December

Roller Shade, T1 and T2 – March

Roller Shade, T1 and T2 – March

Fig. 15 Comparison of the daily glare distribution in Milan for two different orientations (EAST, WEST) and during two days over the year (21th March, 21th December) evaluating the effectiveness of three different shading device materials: traditional roller blind, T1 and T2

Fig. 16 Comparison of the Glare distribution by the use of false colors plots for 21th of March, h 15:00, Window facing South, Milan. Comparison of three different shading materials: Standard roller blind, T1 and T2

5. Conclusions

The analysis presented has made it possible to understand the potential of solar protection systems made by 3D fabrics, which are currently used in production sectors.

The technology transfer process envisaged here would allow the creation of a new type of system that could be used alongside, or in some cases, replace traditional roller blind systems made with single layer fabric.

The main difference between single layer fabrics and 3D alternatives with multiple layers is the possibility to have a strong and pre-determined directional behavior related to the incident radiation, allowing alternative strategies for light modulation and redirection.

The high manufacturing flexibility of 3D fabrics permits highly transparent materials, as in the case of T4, T5 and T6 fabrics, and materials with optical performances comparable to blackout curtains, with solar and/or luminous transmittance values between 0 and 5%. An example of this possibility is shown by the measured values for sample T3. Unlike traditional single layer fabric, 3D systems allow varying the performance locally, modifying the geometry of the system only on isolated portions of the textile surface. It is also possible to combine textile layers with different geometries, thicknesses, and weft and warp relationships on different parallel planes. In this way 3D fabrics can reduce the perceived dimension and luminance of the solar crown, which cause visual disturbance to the users if perceived in the field of view [40].

In this paper, the potential of 3D fabrics employed as shading systems were analyzed.

- The BSDF model of two 3D systems were generated using computer simulation and calibrated against angular measured data.

- Three different control strategies were applied to the case study: 1) interior illuminance below a threshold value, 2) preventing glare, and 3) always deployed to simulate a worst-case scenario.
- The three controls were used to compare the novel 3D system to a standard roller shade.
- The investigation was carried out analyzing the annual daylight availability and potential glare for specific days, presenting the 3D textiles as a good alternative for shading devices material.

The simulations carried out for T1 and T2 fabrics demonstrate the potential of these systems in increasing Daylight autonomy, while at the same time ensuring a better uniformity and a better indoor illuminance level. This increase is coupled with good control of glare phenomena due to direct solar radiation. Some caution must be used for systems similar to T2 under conditions that provide high angles of incidence of solar radiation even if the manufacturing flexibility of the system may provide adjustments able to resolve high transparency problems for high incidence solar angles.

Currently, a technological project is needed to integrate the material as a substitute for traditional single layer fabrics in solar protection systems for buildings. A simple material substitution is not possible in every system since it is not to be overlooked, for example, that the thickness of a 3D fabric, greater than that of traditional fabric, could create problems during the deploying or packaging phase of dynamic systems. On the other hand, these materials would be easy to apply in the case of shading systems consisting of movable panels. In this case, it would become essential to define a main mounting direction and orientation, in order to guarantee the positive exploitation of the material directional behavior.

Future developments of the analysis foresee the application of the material to a real case scenario, as well as its monitoring to assess the effectiveness of sun protection. HDR images of the system and context will be collected as a benchmark for the results obtained during the simulation path carried out, and in particular to analyze the presence of unexpected glare phenomena.

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