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Design to Thrive

Toward new design of laser cut panels for scattering of sunlight at high latitudes

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Abstract: Probably the most profound daylighting paradox is connected to utilization of sunlight as the light source. Its enormous luminous intensity creates huge but not utilized potential. The scattering of sunlight proved to be a successful method in the new design of skylights at NTNU, Norway; high latitude and climate plied an important role in its design as well.

Roof-lighting provides greater potential for illumination than side-lighting. However, its application is limited to top-floors; new side-lighting solutions are needed. One of existing daylighting systems, laser cut panels (LCP), can be applied on the window to redirect daylight toward the ceiling; IEA Task21 studies proved that LCPs might significantly increase daylight level at high latitudes (Norway or Chile). However, patches of intense sunlight appear in the room creating risk of glare.

The aim is to develop an alternative design of window LCPs to simultaneously scatter and redirect sunlight upwards. Their performance was studied in a scale model; LCPs were positioned in the upper part of a vertical “window”. The model was tested (HDR photos) in artificial sun. Results are promising; the passage of direct sunlight is decreased and the distribution of light significantly increased minimizing the risk of glare.

Keywords: daylighting, laser cut panels, scattering, window, high latitudes.

Introduction

Probably the most profound paradox in the field of daylighting is connected to utilization of sunlight as the light source. Its enormous luminous intensity creates huge potential but in practice sunlight is most often reflected out by different forms of sun shading devices. There are mainly two reasons why: overheating and/or glare. The overheating risk depends very much on the size of the window and its thermal properties, g-value, while the glare depends on the distribution pattern of light in the room.

As the illumination due to sunlight is typically one magnitude higher than the illumination due to the sky, it is reasonable to expect that the glazing area needed for using sunlight for illumination should correspond to a small fraction of a typical window that delivers enough daylight in all conditions, including overcast sky. Allowing transmittance of sunlight through a small part of window reduces the danger of overheating significantly. The glare is even a more pronounced issue. There are several daylighting systems utilizing sunlight, which also aim at reducing glare. Most of them redirect light rays falling at the window toward the ceiling, e.g. laser cut panels (LCP), known also as Edmonds' panels (from Australian inventor Ian Edmonds). The original design of LCPs involved cutting acrylic panels with laser making linear-parallel cutting lines. Previous studies (Reppel, 1998) (Edmonds, 1999), (Labib, (2012) and (Ruck, 2000) proved that LCPs covering the upper part of the window increases daylight level in the room significantly. However, patches of intense sunlight appear in the room creating strong luminance contrasts and periodically glare as a consequence of the transmitted, redirected and scattered sunlight.

As the illuminance due to sunlight falling orthogonally on a surface (e.g. 50.000 lx) is typically two magnitudes higher than the illuminance level in interiors (e.g. 500 lx), a simple planar reflection of sunlight, e.g. up to the ceiling turns out not to be sufficient for glare protection. Could scattering solve the glare problem? The scattering of sunlight by circularly perforated acrylic plates proved to be very successful in the new design of skylights developed for students' studios (Knoop, 2016), (Matusiak, 2017). The project has been developed for Trondheim 63° 25' N (Norway) where the mean noon solar latitude is about 30°. By fine adjustment of the relation between the thicknesses of the plate, the size of the holes and the distance between them it is possible to ensure sunlight scattering also for other similar locations.

Obviously, roof-lighting provides greater potential for illumination than side-lighting. However, application of roof-lighting is limited to top-floors. The aim of the present study was to develop a new design of LCPs for side-lighting; more specifically for upper part of windows; the passing sunlight was supposed to be simultaneously scattered and redirected upwards. The hypothesis was that closely distributed cutting forms like half-circles or fish are the most rational ones for the purpose. Through luminance map pictures, panel's light behaviour will be analysed to estimate which design is best when it comes to the reduction of light transmittance; estimation of glare will be done in a further real scale study with people involved.

Laser cut panel (LCP)

The laser cut panel was invented by Ian Edmonds in 1989. It is a thin transparent acrylic panel having parallel laser cuts that are perpendicular to the panel surface. The idea behind the invention is to create reflection of light internally in the material. The surface of each laser cut works as an internal mirror that deflects light passing through the panel. The cuts are described by cut spacing D to panel width W.

When positioned on the window surface a LCP deflects high elevation sunlight, while transmitting low elevation skylight, or sunlight during early mornings, late afternoons and winter. A very high fraction of light is deflected upward reducing glare (Labib, 2012). The researchers from Norwegian University of Science and Technology (NTNU), Heidi Arnesen and Øyvind Aschehoug, studied daylighting fluctuations in a test room in Sandvika, Norway, where LCPs were fixed in the upper part of windows. Under overcast skies, the test room showed minimal changes in light level and distribution; however, under clear skies, the LCP increased the light level and improved the light distribution across the floor during most days of the year (Ruck, 2000) (Labib, 2012). LCPs can be also used as a louver within a window system. Opened louvers act as a shading system (summer) and when closed they redirect daylight upward (winter)(Reppel and Edmonds, 1998). LCPs can be tilted, usually by fixing them with clips to cover around one-third of the window, as secondary glazing inside tilted windows. These windows are manually tilted outwards to an angle at which all incident sunlight is redirected by the LCPs, providing good penetration of natural light into the building. The Technical University of Berlin (TUB), Germany, studied tilted LCPs and showed that when the tilt angle was 20°, under overcast skies, the panels did not change light levels dramatically, whereas under clear skies, the daylighting performance was improved by adjusting the position of the panel depending on the time of day and year (Ruck, 2000). LCPs can also be used in skylights to admit low-elevation light and block high-elevation light.

A new design of LCP was developed at NTNU in 2016, the design of cuts was changed from liner to circular and LCP were positioned horizontally beneath skylights developed for students' studios. The scattering of sunlight by circularly perforated acrylic plates proved to be very successful (Matusiak, 2017).

Some of the main advantages of a LCP are: It maintains the view through the panel, a very high proportion of light is deflected toward the ceiling, flexible manufacturing process, relatively economical and they require little maintenance (Ruck, 2000).

Procedures and Methodology

Panel Design

Three geometries configurations were analysed: Edmond's (Figure 1b) and two new proposed forms; half-circle (concave) and double-convex (Figure 1a). From these, six typologies of panels were defined. Half circle shape was presented in four (A, B, C and H) while double-convex was proposed in two panels (D and E)(Figure 1b). The variation between same panel's geometry is the spacing distance between cuts and the proportions of shapes. The intention was to verify possible and considerable changes in the way light is scattered. The dimensions of the panels were defined according to the proportions of the model's reference window (10x17cm) of the office room utilized as a case of study. Panel's height and location correspond to one-third of the reference window's height. They were made in an 85x10x52mm acrylic sheet. Edmond's cuts were designed according to Edmond's D/W ratio (Edmonds and Pearce, 1999), new proposed panel's cuts were defined following Edmond's panel cut spacing and the minimum laser machine acrylic cut capacity.

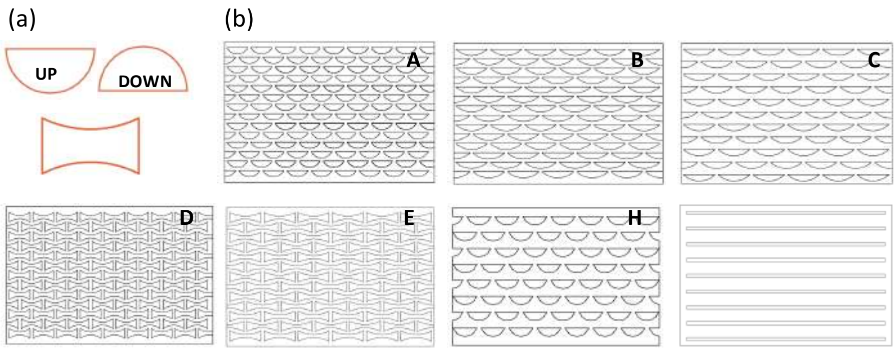


Figure 1. (a) Half circle and double-convex geometry (b) Laser cut Panels: A – B – C – D –E – H and Edmonds

Experiment set up and equipment

An existing office room (6.7x5.0x2.76mt) located at NTNU campus (Trondheim, Norway) was selected as a reference case for testing of scattering capability of proposed panels. A 1:10 scale model (50x32x29cm) was built (Figures 2a) where each panel was tested under clear sky condition simulated in an artificial sun located at the NTNU Daylight lab (Figures 2b). The size of this model was chosen to be large enough for a comfortable observation, covering two windows for testing two situations simultaneously and enabling good conditions for taking photos of the interior. Walls, ceiling and floor, were constructed using 3mm MDF boards. For the interior, it was decided to use standard values of light reflectance values (LRV). Used LRV for walls, floor and ceiling were 50 (Pale grey), 20 (dark grey) and 70 (pale yellow) respectively. LRV of the used coloured papers was reviewed with a NCS colour scan 2.0 and atlas. One of side walls had circular openings (Figure 2a) in order to put a reflex digital camera (Nikon D600) with a AF-DX fisheye-Nikkor 10.5mm f/2.8G ED. These openings were covered with a black fabric during measurements (figure 3b). From the outside, the model was kept with MDF natural colour. The material of the windows was a sheet of 3mm acrylic. From inside and outside, frames were covered with an opaque black tape in order to avoid light reflexion from them (Figure 3c).

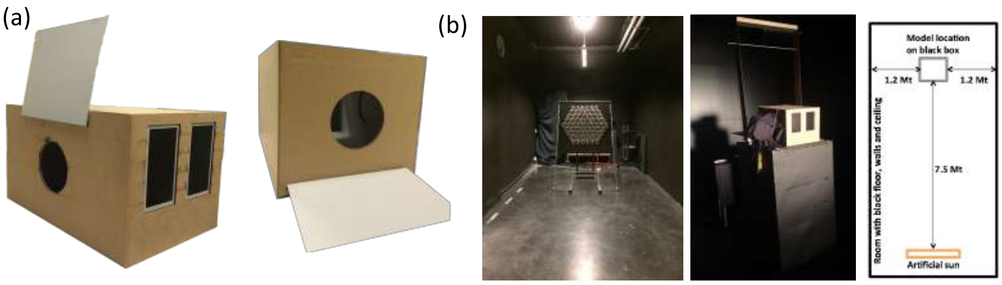


Figure 2. (a) 1:10 scale model (b) Artificial sun, work area and a plant distribution.

A sun angle positioner was designed (Figure 3a). The model was positioned on top of a wood sheet (Figure 3b), which could be sloped precisely at chosen sun angles. The camera was also stuck with wood strips and placed on a wood surface fixed on the wood sheet (Figure 3b). The sun angle positioner was fixed to a one-meter height wood box.

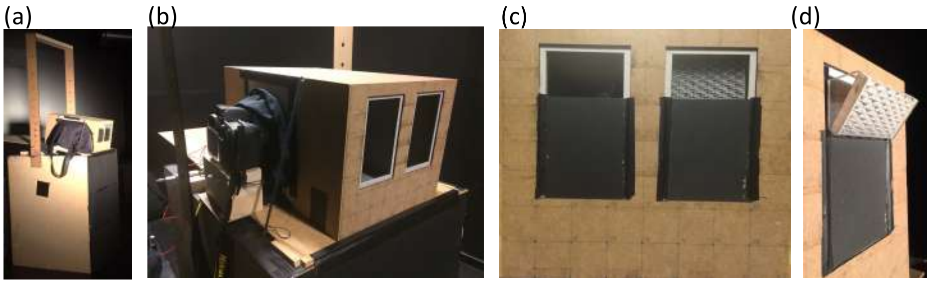


Figure 3. (a) Sun angle positioner with camera installation (b) Digital camera mounting (c) Windows settings (d) Acrylic tilt angle positioner with panel from outside.

Each panel was tested and located in the one-third upper part of the model's reference window in order to redirect light upwards, leaving the lower part for view. Contrary to traditional textile curtains, screens or diffusing glass, which distribute light in the rotationally symmetrical way (in all directions including downwards), the proposed LCP scatter the transmitted light only in the upwards directions, clearly reducing the probability of glare.

Base case (without panel) with Edmond's panel and Edmond's with each proposed panel light performance was compared. In the artificial sun, they were analysed under different sun angles degrees from 5° to 60° and in different positions: vertical-up, vertical-down and tilted inwards and outwards by 5° (from 5° to 40°)(Figure 4c). In order to test and tilt each panel, it was created a tilt angle positioner (Figure 3d), which was made in acrylic for avoiding extra reflected light or obstruction towards the interior of the model. These were adhered in panel's lateral sides (Figure 3d). Two-third lower part of the window was covered with an opaque black paper; this allowed evaluating the light coming from panel only (Figure 3c). All panels were tested assuming 0° azimuth angle only (South façade in the north hemisphere and north façade in the south hemisphere) and under sun angle from 5° (winter) to 60° (summer). In Trondheim (63°25′47″N**,** Norway) during summer the highest sun angle is around 50° and in Punta Arenas (53°10'S, Chile) around 60°. A hanger E4-X lux meter was used for evaluating artificial sun light uniformity over model's facade. A Kodak grey card and hand held Minolta LS-100 Luminance meter have been used for references physical measurements for further calibration in HDR software, Photosphere.

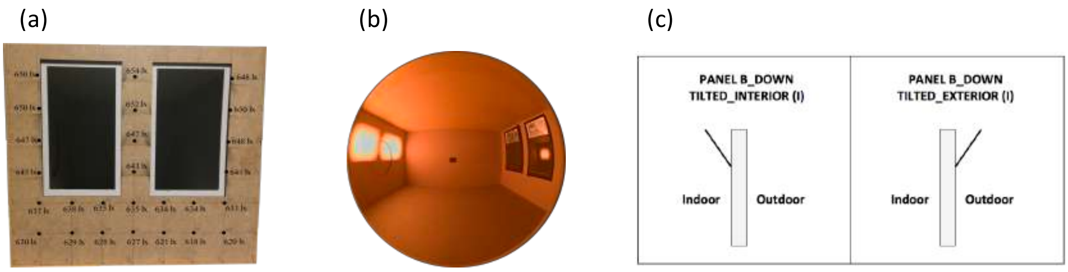


Figure 4. (a) Façade grid for taking vertical illuminance uniformity. (b) Rectangular black paper on a wall for taking Luminance measurement for further camera calibration (c) Tilted positions analysis

Lighting monitoring and measurements

Before starting panel's light monitoring (pictures), the uniformity of the light from the artificial sun over the selected façade was checked. For this purpose, it was generated a 4x4cm grid and vertical Illuminance measurements were taken over the façade (Figure 4a). All measured illuminance were around 600 to 650lx. For each tested panel, High Dynamic Range (HDR) photos of the interior of the model were generated in order to develop a Luminance map picture. HDR images were done for every sun angle and positions (vertical up, down and tilted). The camera was situated in the middle plane of the total height of the model, in order to cover all light falling on each interior surface. A Nikon D600 digital reflex camera with a Nikon fisheye lens was utilized for this purpose. The following camera settings were used (Reinhart and Stein, n.d.): white balance – daylight, ISO 100, auto bracketing, off sensitivity, auto focus, off aperture – fixed f/5.6. Exposure variations were achieved by varying the shutter speed in manual exposure mode with step 1 EV. Series 10+ pictures were taken according to interior light conditions. In addition to photos, references of physical measurements were taken with a calibrated hand held Luminance meter. The readings were used for further calibration of the HDR images. All images were processed and combined into HDR images using Photosphere software, which was calibrated according to the measured Luminance readings over the rectangular black spot inside the model (18.16cd/m2) (Figure 4b).

Results

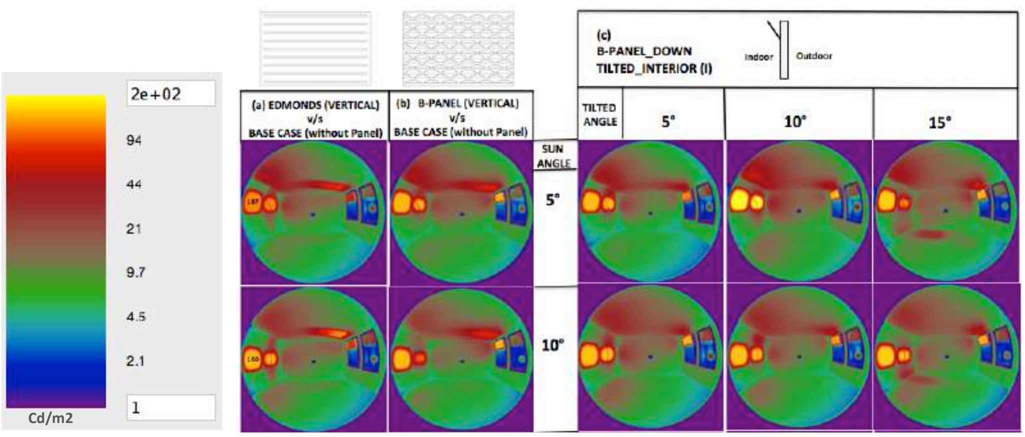
Base case (without panel): Between 5 to 15 degrees, there is soft sun patch on the floor and strong ones on the wall (a maximum of 187 cd/m2). From 20 to 60 degrees, intense sun patch on the floor can be seen (a maximum of 210 cd/m2). From the window's material (LCP) the light is basically transmitted to the wall. Redirected or scattered light to the ceiling cannot be seen (Figure 5a or b). Therefore, there is no deep light penetration into the room.

Edmond’s reference panel (vertical): From 5 to 20 sun angle degrees, no sun patch can be seen on the floor, this appears from 25° to 60°. There is deep light penetration into the room at 5° and 10° mainly. From 5° to 15°, the redirected-scattered light covers the total width of the room. At higher angles from 35° to 55°, there is still soft scattered sunlight to the ceiling. Sun patches on walls and floor can be seen at most angles (Figure 5a).

Panels with double-convex and half-circle geometry were evaluated vertically. Half-circle geometry panels were evaluated in vertical-up and down orientation. Under these positions, the panel with the most favourable sun patch performance was selected for doing tilted position analysis. Analysis through HDR images did not show clear and significant evidence that the same geometry, but different shape’s proportions and cuts distance could alter the manner and intensity of scattered light from panels. However, up, down and tilted orientation showed clear changes on the form light is redirected and scattered. After analysing half-circle versus double-convex vertically, it could be observed that the half-circle shape presents better performance than double-convex. All the up-alternatives allow sunlight falling down on the floor in many pictures showing 20°- 45°sun angles. From down-alternatives, B-panel functions best. Sun patch on the wall/floor is weakest, meaning that the scattering of light is best for 20 and 25 degrees, for 30° - 45° it is difficult to see a clear difference between all panels. In concequence, B-Panel was analysed in tilted position. Tilted inwards untill 15° degree showed better light behaviour than outwards. There are several HDR pictures, it has been decided to show pictures of B-panel down inwards which had a better sun patch performance.

B-Panel down and vertical behaves quite similar to Edmond’s panel. They redirect light to the ceiling at most angles, covering almost half of ceiling from 5° to 20°. The main difference is the light falling to the floor. B-Panel brings weaker sun patch on it. From 5° to 25° there is no sun patch on the floor. From 30° to 45°soft sun patch can be perceived on the floor and from 50 to 60 degrees small one can be seen (Figure 5b).

B-Panel down and tilted (5° to 15°), from 5 to 15 sun angle degree, there is soft sun patch on the floor (maximum around 50cd/m2), but intense ones on the wall (around 150cd/m2). With respect to light penetration into the ceiling of the room, better performance can be seen at angles lower than 10°. At higher tilted angles there is the possibility of having stronger sun patch on the floor. From 20 to 30 sun angle degree, stronger sun patch can be seen at 15° tilted angle, being the weakest at 10° (10 cd/m2). From 35° to 45° sun angle and at every tilted angle, sun patch of approximately 30 cd/m2 can be detected. Light is redirected and scattered to the ceiling reaching one-third of the ceiling. Finally, from 50 to 60 sun angle degree, there is small, but intense sun patch (80cd/m2) on the floor. Light is redirected and scattered to the ceiling, this light affects half of the ceiling surface (Figure 5c).



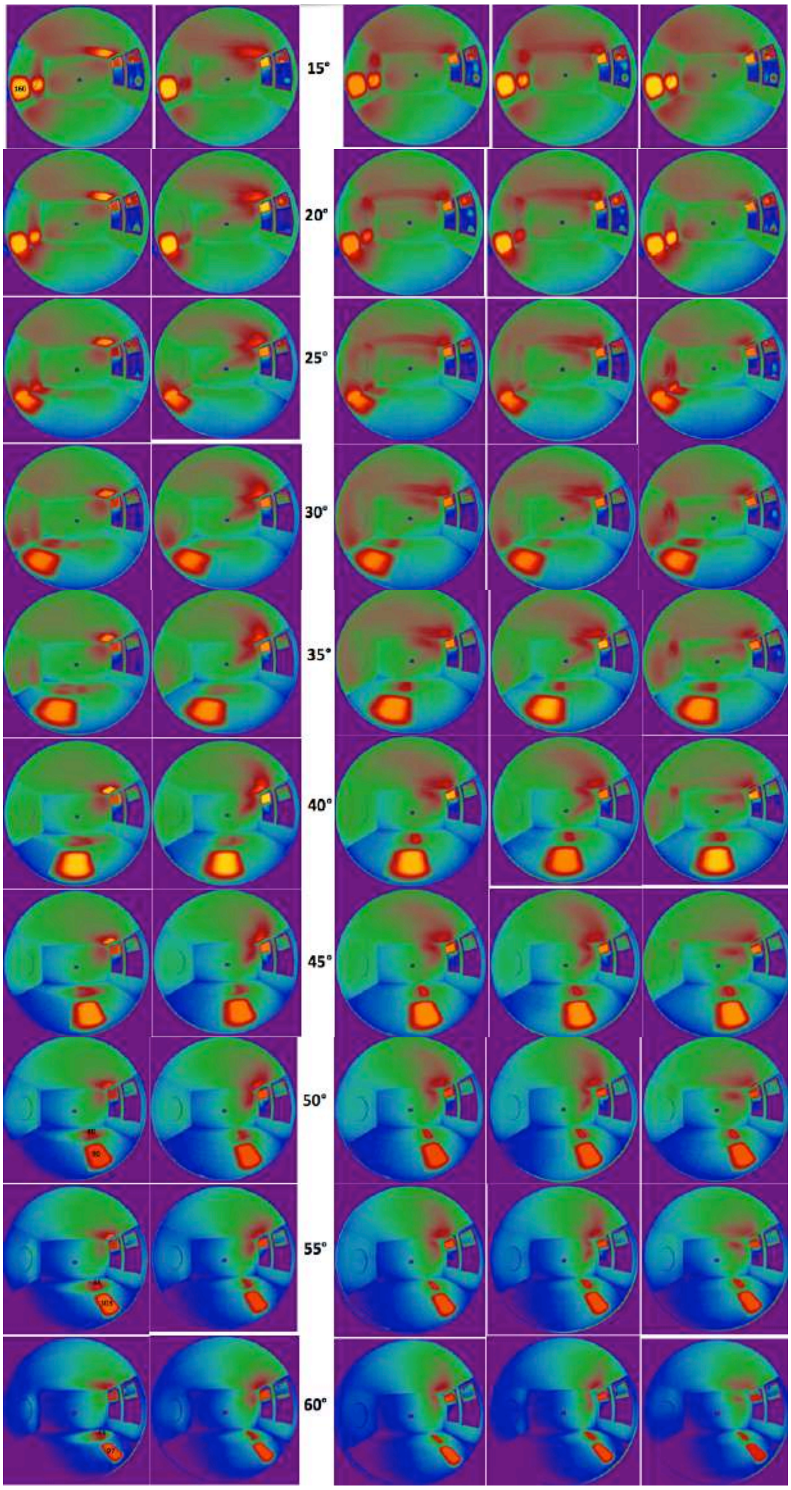


Figure 5. HDR images (a) Edmond's v/s Base case (b) B-Panel vertical v/s Base case (c) B-Panel tilted inwards

Discussion

According to previous studies, in a high latitude scenario, the most important sun angles are 20°- 45°. At angles lower than 20 the sunlight will pass through the material and in order to avoid this, the material has to be sloped; for angles higher than 45 the material has to be sloped also. Furthermore, studies done by NTNU and TUB university showed that LCPs encrease light levels under clear sky conditions, this improve when the panel is tilted 20°.

There is no light levels improvement under overcast scenario (IEA Task 21). Compared with this study, in vertical position, Edmond's panel allows sun patch on the floor and intense ones on the wall (from 20° to 45° sun angle). Light penetration into the room is weak. At angles lower than 20 degrees, sun patch on the floor are reduced, but there is some very intense on the wall. There is deep light penetration into the room. At angles higher than 45°, light penetration is very weak, strong sun patch are visible on the floor. B-panel in a vertical position and from 20° to 45°, there is absence and weaker sun patch on the floor. Deep light penetration through the ceiling improve between 5° and 20°; from 25° to 45° this is powerless. At 50° to 60° this is even weaker, intense sun patch can be seen on the floor. B-Panel works more desirable at 10° tilted inwards, there is very deep light penetration into the room and sun patch reduction from 5° to 25°sun angles. At higher angles, from 30°to 45°, there is less light penetration into the room. Finally, at very high angles, from 50° to 60°, light penetration is very weak and intense sun patch are visible on the floor. Further analysis is required at different azimuth angles (e.g 45°) and under overcast scenario. As a reference in previous studies (student studios at NTNU) diffuse transmittance of acrylic LCP measured in an artificial sky (overcast sky simulator), oscillated around 90-95% depending on the form of cuts.

Conclusion

Edmond's reference panel works better (sun patch and light penetration) under lower sun angles (5° to 15°). Therefore, in a high latitude context, this would be suitable during winter where main sun angle in Trondheim and Punta Arenas are 5° and 10° respectively. This will be possible as long as there is sun light availability. At higher angles (20° to 60° - Summer) this panel allows sun patch on the floor and walls. Edmond's and B-Panel perform quite similarly; the main difference is that the second one scatters light better allowing weaker sun patch on the floor and wall, reducing the probability of glare. Finally, B-Panel tilted position's results are promising; the passage of direct sunlight is minimized and the distribution of light is much more even minimizing the risk of glare from the floor. Light penetration into the room is improved at most sun angles. The slope should not be more than 10° because at higher tilted angle there is the possibility of having stronger sun patches on the wall and floor. At very high sun angle from 50° to 60°, higher tilted angle may be required in order to get deeper scattered light into the ceiling, but not necessarily softer sun patches on the floor.

References

Edmonds, I. and Pearce, D. (1999). Enhancement of crop illuminance in high latitude greenhouses with laser-cut panel glazing. *Solar Energy*, 66(4), pp.255-265.

Knoop M. editor (2016) Daylighting and Electric Lighting Retrofit Solutions DOI: 10.14279/depositonce-5162 · License: CC BY 4.0

Labib, R. (2012). Improving daylighting in existing classrooms using laser cut panels. *Lighting Research and Technology*, 45(5), pp.585-598.

Matusiak B. (2017) Daylight is more than an energy saving issue, DOI: 10.5772/65866, chapter in the book *Energy Efficient Buildings*,

Reinhart, C. and Stein, R. (2014). *Daylighting handbook*. 1st ed. USA

Reppel, J. and Edmonds, I. (1998). Angle-selective glazing for radiant heat control in buildings: theory. *Solar Energy*, 62(3), pp.245-253.

Ruck, N. (2000). *Daylight in buildings*. 1st ed. Berkeley, CA.: Lawrence Berkeley National Laboratory.