Advanced Daylighting Systems: Comparative Study of Prismatic Panels, *Laser-Cut Panels* and *Channel Panels*

Sara Dionísio Palma Santos

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Instituto Superior Técnico – Universidade Técnica de Lisboa

Supervisor: Prof. Doutora Maria Luísa de Oliveira Gama Caldas (FAUTL)
Co-Supervisor: Prof. Doutor Manuel de Arriaga Brito Correia Guedes (IST)

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Introduction

The warning from the international scientific community to the problems of carbon emissions and global warming, have already started in the 1970s, resulted in the creation of new strategies, more integrated, to improve the energy efficiency of buildings, accounting for about 40 % of world energy consumption. The sustainable and bioclimatic architectural design, including the use of daylight in buildings, has been one of the components of this strategy. Besides reducing energy consumption in buildings, daylight is also one of the main ways of achieving good indoor comfort in buildings. In this way, the advanced daylight systems turn out to be a tool to achieve important improvements on the quality of indoor daylight and significant reductions on the energy consumption of buildings.

The main goal of this study is to evaluate comparatively the performance of different advanced daylight systems in order to better understand its contribution to the use of daylight in buildings. With this goal, a first step consisted of understanding the role and importance of daylight in architecture. A second step is then the classification and characterization of advanced daylight systems available on the market as well as some systems still under development or prototype. Finally, a third phase consisted of evaluating and analyzing the performance of some of the advanced daylight systems in study. This analysis was based on a comparison between the performance of different systems and a system created as a reference, and also a comparison with results of studies conducted by other authors.

1. Light and Architecture

To understand the relation between light and architecture, it is necessary to understand the importance of light to human being. Given that about 70% of human perception is visual, we can say that man is dependent on light (Vianna et al., 2001). It is mainly through vision that we experience architecture, and light is the means to it, showing to our eyes the space, shape, texture and color.

1.1 The role of daylight in architecture

Until the introduction of lighting by gas in the beginning of 1800, and electric lighting in 1900, the daylight was the main source of light (Baker et al., 2002). Since the Roman groin vault to the Paxton's Crystal Palace of the nineteenth century that major structural and constructive changes in architecture reflected a continuous interest by increasing daylight in buildings (Lechner, 2001). From the twentieth century, with easy access to electrical power efficient, cheap and abundant electricity, artificial lighting beginning to be used in a continuous and extensive way (e.g. in commercial buildings), not only as a supplement to light natural. The combination of new technologies, from air-conditioning to electric lighting, allow greater flexibility in the design of built space and allow the buildings to be completely independent from the external climate. However, the continuous use of these technologies is a major cost in terms of energy consumption.

It was with the energy crisis of the 70, that the daylight potential was again recognized. More efficient use of natural light can significantly reduce total energy consumption of buildings. In the EU 27, the electricity consumption in lighting in the residential sector represents about 20% of total consumption in this sector. In the services sector, this percentage may reach 60% (DGEG, 2009). Since the latter sector buildings have essentially a daytime occupation, most of the energy requirements for the lighting can be provided with natural light. An effective use of daylight can also reduce the amount of energy needed for heating and cooling of buildings. In addition to the important contribution in reducing energy consumption, daylight in buildings is also a major contribution to the human comfort and well-being.

1.2 The availability of daylight – the climate and the context

The daylight intensity and the illuminance of the sky are not constant or uniform. One of the main reasons for this variation is the apparent movement of the sun in the sky depending on the season and time of day. Atmospheric conditions defined by climate and subject to occasional variations, are also a factor that influences the daylight variation. While the overcast sky is characterized by an atmosphere full of thick dark clouds in which the sun is not visible and a relatively low illuminance (between 5 000 lux and 20 000 lux), the clear sky is characterized by clean atmosphere without clouds, and a very high illuminance (between 60 000 lux and 100 000 lux).

The geographical and urban characteristics also affect the variation in the availability of daylight. The latitude of a place influences directly the period of availability of daylight. The orientation of buildings is also of extreme importance, and the simple design of the building with a correct shape and orientation contribute to a better daylight inside the building, which can have a positive effect on the thermal comfort and energy consumption. The slope of the ground and the morphological configuration of the surroundings may also influence the luminosity inside the built space.

1.3 Physical and subjective aspects of light

The light can be characterized and evaluated in terms of its different objective and subjective aspects. In physical and objective terms, the light is defined as the band of electromagnetic radiant energy located between certain wavelengths to which the human eye is sensitive to (Hopkinson et al., 1966). Our perception of space, natural or built, is mainly the result of reflection of light by the different space surfaces.

There are several factors and parameters for assessing quantity and quality of light obtained in the interior of buildings. The main quantitative parameters regarding the daylight design are the *Illumination Level* and the *Daylight Factor*[1]. Although these parameters are effective in quantitative specification of indoor daylight, they do not assess the degree of visual comfort or discomfort. Thus, it is necessary to use other performance parameters capable of evaluating the quality of daylight inside buildings, such as illuminance distribution and uniformity. However, a uniform illuminance distribution does not guarantee the absence of glare and excessive contrast.

A good daylighting project aims to achieve an adequate visual environment to ensure indoor lighting conditions required for carrying out different tasks in an efficient and precise way, while also providing visual comfort and well-being of its users. The requirements for a good view consist of: adequate lighting levels in the working plan, proper distribution and balance of illuminances, mitigation of glare problems and lack of excessive contrasts.

1.4 Daylighting Basic Strategies

Several basic strategies for use of daylight in buildings should be considered in the early design phase in order to greatly improve the quantity and quality of daylight inside buildings. Besides the concern on providing a comfortable visual environment, these strategies must also take into account two essential aspects such as thermal comfort and energy consumption of buildings. First, the potential gains and heat losses through the glazing should be considered. The second aspect concerns the reduction of energy consumption of the building, reducing or eliminating the use of artificial lighting during the day and reducing the need for mechanical air-conditioning by reducing the building heating and cooling need. In this way, orientation and shape of the building, interior space planning, color, side lighting and zenithal lighting, should be part of the basic strategies of natural lighting.

2. Advanced Daylighting Systems

The introduction of advanced and innovative systems and strategies of daylighting in buildings is a tool to achieve substantial improvements in the quality of indoor daylight in buildings and, thus, contributing to

[1] The Daylight Factor (DF) is the ratio between the illuminance at a given point inside and the illuminance simultaneously available outside in an horizontal unobstructed plan (Hopkinson et al., 1966)

reduce the energy consumption. The advanced daylight systems have as main objectives to improve and optimize the amount and distribution of indoor daylight in buildings that have deep plans and limited access to natural light, mostly peripheral. At the same time, they seek to improve visual comfort of users, avoiding the occurrence of glare, and to obtain solar shading. There are many ways to classify the advanced daylight systems. The classification used in this study is based on the geometric characteristics of the systems, which are grouped into three groups: reflector systems, integrated window elements and light transport systems.

2.1 Reflector systems

Reflector systems, as the name implies, are reflectors positioned externally or internally in relation to the glass. As these systems are large, they have a great impact on the architecture of the building.

Light Shelves

In general, the light shelves are composed of a horizontal, fixed or mobile deflector, positioned inside or outside the glass facade and above the vision of the occupants. This system provides sun protection and redirects the incident daylight on its upper surface to the interior of buildings. There is a wide variety of light shelves resulting from the large number of geometric and constructive parameters that can be adjusted to suit different applications. The anidolic light shelves are advanced systems composed of an anidolic horizontal reflector with curve geometry, which can redirect sunlight towards the plan of the ceiling and in large depth when compared to a conventional light shelf.

Anidolic Zenithal Openings

Anidolic zenithal openings have high angular selectivity and allow the diffuse light from the sky to be captured, without allowing the penetration of direct sunlight (IEA, 2000). These systems are composed of two anidolic elements and a reflective element making the connection between them. These systems are designed to be used on roofs of buildings and facing north (northern hemisphere) and therefore prevent the occurrence of direct glare and overheating inside buildings.

Anidolic Solar Blinds

Anidolic solar blinds consist of a grid of hollow reflective elements, where each element is composed of three-dimensional parabolic concentrators. The elements are designed in order to block most of the sunlight of high altitudes, and transmit the diffuse light of low altitudes, thus providing an angularly selective light transmission. When used on the façade of the buildings, this system can be placed as a fixed panel over the entire length of the glazing unit, or just on top of the glazing unit in order to keep the view to the outside.

Light-Guiding Shades

The light-guiding shades are fixed exterior shading systems used with the main goal of improving the daylighting in buildings in sunny climates while providing necessary exterior shading to reduce solar gains through the glazing unit (Solartran, 2008). This system consists of two anidolic reflective elements, forming an opening through which direct sunlight enters and is reflected to the back part of the room.

2.2 Integrated window elements

The integrated window elements consist of miniature or micro scale devices, positioned in a plan parallel to a simple glass pane or between double glass panes.

Prismatic Panels

The prismatic panels are made of a series of transparent acrylic prisms forming on one side, a flat surface and on the other side, prismatic faces sometimes partially covered with an aluminum film with high specular reflectance. The prismatic panels allow the redirection of daylight to the interior of the room and can act simultaneously as shading devices. The systems can be applied as fixed or mobile systems, positioned in the vertical plane of the facade or on the roof, between the glazing panes (fixed configuration), on the exterior or interior side of the glazing unit. When used in façades and in order to maintain the view to the outside, its use is more appropriate at the top of the windows.

Louvres and blind systems

The louvres and blind systems are conventional devices used as solar shading, protection against glare and daylight redirecting systems. They are usually made of a series of horizontal, vertical or oblique lamellas that can be placed inside, outside or between panes of double glazing windows or zenithal openings. Currently, there is a wide variety of non-conventional blind systems. The Fish and Okasolar systems are advanced and consist of horizontal lamellas, fixed between panes of a double-glazing unit, with the purpose of solar shading or light redirection depending on the solar elevation angle of the incident light.

Laser-Cut Panel (LCP) and Channel Panel

The Laser-Cut Panel system (LCP) is a transparent acrylic panel with a series of thin and parallel cuts made by a laser cutting machine. The cut surfaces become small internal reflectors that allow redirecting a large amount of light deep into the room through a large range of angles, while maintaining a transparent view through the panel (Edmonds, 1993). The Channel Panel system consists of two LCPs together and ensures that most of the light is redirected toward the ceiling plan, preventing the occurrence of glare. These panels can be integrated into windows or skylights, with the task of redirecting the direct and diffuse light, shading, or both.

Sun-Directing Glass

The sun-directing glass consists of a double glazing unit inside which there are acrylic transparent lamellas that capture and redirect sunlight into the room. Its design is optimized to redirect the light with incidence angles between 25º and 50º and to prevent the emission of light below the horizontal plan (Rubert, 1998). Its main application is on façades, in a fixed position at the top of the glazing unit and above the view level of the occupants and in combination with conventional shading in the bottom of the window opening.

Holographic Optical Elements (HOE)

The Holographic Optical Elements (HOEs) applied to daylighting systems are light redirecting elements consisting of a holographic film placed between panes of laminated glass (Bahaj et al. 2008). These systems use the principle of diffraction of light and allow a selective redirection of light. The HOEs may be integrated in different daylight systems such as zenithal light guiding glass, in order to redirect light from areas close to the sky zenith to the back part of the rooms; or directional selective shading systems, allowing selective redirection of light.

Translucent Insulating Materials – Aerogels

Aerogel is a structure of silica particles highly porous which allows the transmission of light, while functioning as a highly effective thermal and acoustic insulation. It consists of about 95% air and 5% solids and is therefore an extremely light material (Cabot Corporation, 2008). The aerogels are chemically stable and resistant to ultraviolet (UV) and its thermal, acoustic and optical properties are constant over time. (Cabot Corporation, 2008). Several daylighting systems have been adapted to integrate the use of aerogels, both in vertical glazing and roofs.

2.3 Light transport systems

The systems for light transport are advanced systems that collect and concentrate the direct sunlight, carrying it over long distances and finally distributing it in the form of diffuse light to the interior of buildings.

Heliostats

The heliostats are systems that follow, capture and concentrate the sunlight, controlled by automatic monitoring mechanisms to follow the path of the sun, redirecting it to a receiver (redirector mirror or a lens), whose main function is to produce a concentrated light beam. The beam is transported through distribution or transmission systems, secondary reflectors properly distributed in the building or pipes with different finishes to the building's interior spaces without direct daylight.

Light Ducts

The light ducts are daylight systems that capture sunlight through skylights located on the roof or façades of buildings carrying it along ducts to rooms where daylight is inadequate or nonexistent. This system comprises three components: i) a transparent skylight who acts as a collector/concentrator of sunlight, ii) a light duct, highly reflective, used as the transport system of the captured light and iii) a luminaire which is the emitter and transmitter of light transmitted to the interior of the building. These systems work better for short light ducts and high outdoor illuminance.

Optical Fibers

Optical fibers aim to transport the daylight over long distances to the building interior where daylighting is not possible or insufficient through the opening of conventional glazing. This system for light transport is composed of three components: i) an outside sunlight collecting panel formed by Fresnel lenses monitored automatically tracking the movement of the sun, ii) optical fiber cables that carry the sunlight captured by the collector and iii) interior luminaires that transmit and diffuse light to the building interior. The outside collector panel shall be exposed to a maximum of direct sunlight and the length of optical fiber cables should not exceed 15 meters (Espacio Solar, 2008).

Anidolic Ceilings

The anidolic ceilings are systems that use the optical properties of combined parabolic concentrators to capture and concentrate the light from areas close to the sky zenith, and transmit it to the building interior. This system consists of a rectangular cross-section duct placed above the suspending ceiling, and two anidolic optical elements placed at both ends of the light duct, on the outside and inside the room.

3. Case Study

The main goal of the case study is to evaluate, through experimental tests, the performance of some of the advanced daylight systems described before in comparison to a simple solution of conventional glass. For this, a physical model was created where samples of advanced daylight systems were incorporated. The performance analysis of the systems was made through measurements and photographic records, for the geographical conditions of Lisbon (latitude 38°4'). Only some of the systems described before were part of the case study. Only systems consisting of elements integrated in glazing units were tested, since their small size and scale make it possible to incorporate them into a physical model experiment. The case study focused on three types of systems integrated in glazing units – prismatic panel, laser-cut panel and channel panel.

3.1 Methodology and design of experimental models

The physical model was built with a scale of 1/10 and has the purpose of simulating a rectangular room, with certain dimensions that allow the study of the distribution of daylight deep into the room. The room has real dimensions of 4.0 m wide, 7.5 m deep and 3.0 m high. In the smallest façade, which is facing south, there is an opening for the glazing unit. The opening starts 0.8 m above the floor and reaches the ceiling. The opening width is the same as the room width. The glazing unit is divided into two parts: a lower part (dimensions 4 m x 1.2 m) that allows the view to the outside and an upper part (dimensions 4 m x 1 m) above the eye level of the occupants, where the advanced systems are placed to enhance the entry of daylight.

The systems used in the model are real scale samples obtained directly from the manufacturers. The prismatic panel model Siemens 48/5 used in the model is manufactured by the company Siteco, while the laser-cut panel (LCP) and the channel panel systems used were developed and patented by the Energy Research and Lighting Group coordinated by Ian Edmond from the Queensland University of Technology, Brisbane, Australia. The prismatic panel and channel panel systems were tested in vertical position. The LCP, besides being tested in vertical position, was also tested for the slopes of 10º and 20º.

3.2 Measurements and photographic records

Several measurements and photographic records were made with the built physical model, under real sky and sun. These measurements and photographic records are the basis for quantitative and qualitative evaluation and analysis of the different advanced daylight systems.

In order to obtain a more complete evaluation of the systems performance, the measurements were taken not only under overcast sky, but also under clear sky. The Daylight Factor (DF) was the parameter used to quantify the indoor daylight level. The measurements were registered for seven points along a line perpendicular to the center of the glazing unit. The measuring points are spaced one meter from each other and located at a horizontal plan 0.80 m above the floor.

The measurements under overcast sky were made for the seven points previously mentioned for each of the daylight systems. For technical reasons, under clear sky the measurements were performed for only six of the seven points. In these measurements, each system was tested for the summer and winter solstices (June 21^{st} and December 22^{nd} respectively) and the equinoxes (March 21^{st} and September 21^{st}) in order to obtain an acceptable simulation of the different daylight conditions along the year. For each of those days, the measurements were made for three periods of the day: at 9:00, 12:00 and 17:00 on summer solstice and equinoxes, and at 9:00, 12:00 and 16:00 in the winter solstice.

Besides the measurements under clear sky, also photographic records were made, for the different systems, under clear sky, on the same days and times. Were also made photographic records in overcast conditions, for each of the systems.

3.3 Quantitative and qualitative analysis of the results

The analysis of results focuses on the qualitative and quantitative aspects of lighting, both important for achieving an appropriate bright interior.

Quantitative analysis

From the results obtained two graphs were prepared for each situation (type of sky, date and time): a graph of Daylight Factor - DF (%) and a graph of Relative Difference (%) between the DF of each system and the DF of the reference system. The most relevant graphs are presented along with the analysis.

In the graphs of Figure 1 and Figure 2, the results of the measurements for the different systems tested under overcast sky are presented. As illustrated in Figure 2, under overcast sky only the systems laser-cut panels (LCP's) with a slope of 10 ° and 20 ° show significant improvements of DF throughout the room when compared to the reference (simple glass). The system with the worst performance is the prismatic panel: throughout the depth of the room the DF levels are lower than with the other systems.

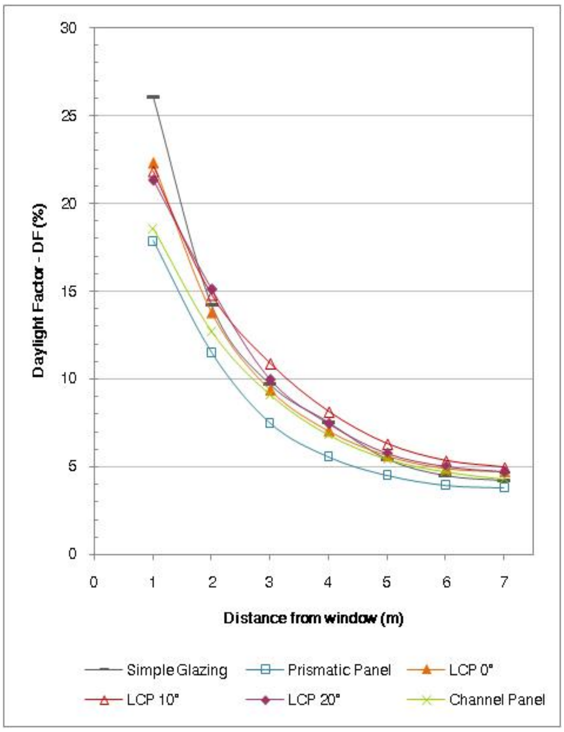

Figure 1 – Measured Daylight Factor (%) under overcast sky conditions, at the working plane.

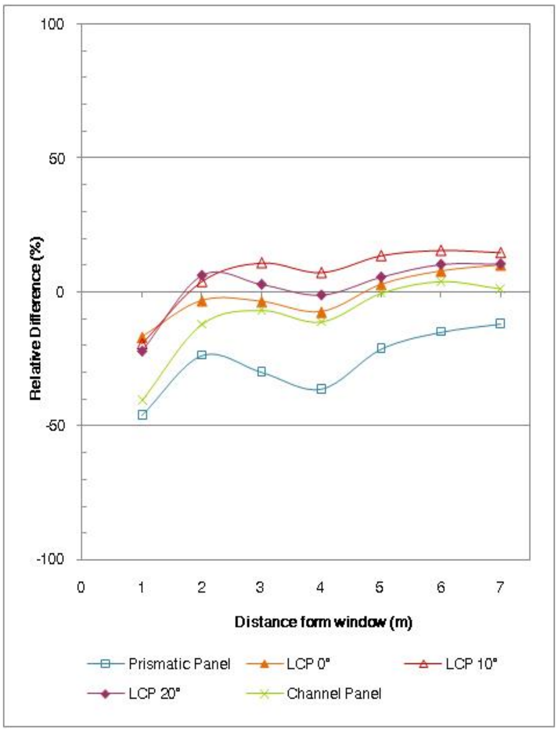

Figure 2 - Relative difference (%) between DF of each system and DF of simple glazing under overcast sky conditions, at the working plane.

The graphs of Figure 3 and Figure 4 refer to the results of the measurements for the different systems under clear sky for June 21st at 12:00 noon. Both charts show for all LCP's (0 °, 10 ° and 20) improvements in almost the entire depth of the room and for the channel panel improvements only at the back part of the room. From these systems, the LCP with a 20° slope is highlighted, with improvements of around 30% in the back part of the room, when compared to the simple glass. The prismatic panel is presented again as the system with the worst performance reducing the DF along the entire the depth of the room, when compared to the simple glass. The results for LCP's have some similarities with the results obtained in a study developed by Edmonds (1993) that concludes that substantial improvements in the working plan lighting can be achieved by tilting the panel.

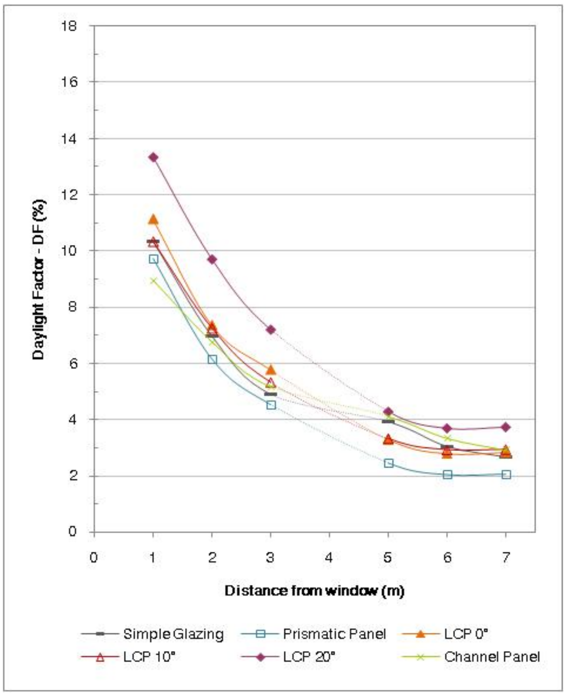

Figure 3 – Measured Daylight Factor (%) under clear sky conditions for June 21st at 12.00 am., at the working plane.

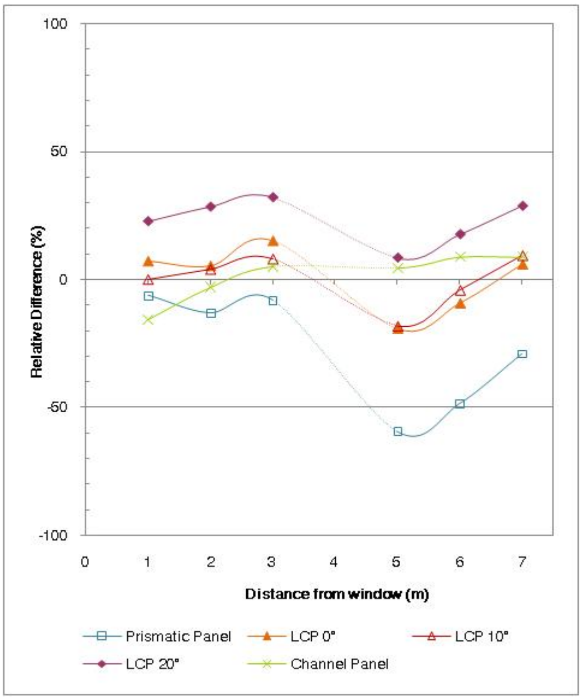

Figure 4 - Relative difference (%) between DF of each system and DF of simple glazing under clear sky conditions for June 21st at 12.00 am., at the working plane.

In the graphs of Figure 5 and Figure 6, the results of the measurements for the different systems under clear sky are presented for December 22nd at 16:00. In contrast to the previous situation characterized by high solar altitudes, in situations of low solar altitudes the LCP positioned vertically (0 °) stands out from the other systems and in particular from the LCP's with 10° and 20° slopes. At 7m room depth, the vertically positioned LCP (0°) registers improvements of 20% when compared to the reference system. The channel panel performance is lower than the other systems, since for low solar altitudes most of the incident sunlight is redirected back to the outside. The prismatic panel is once again among the systems with lower levels of DF.

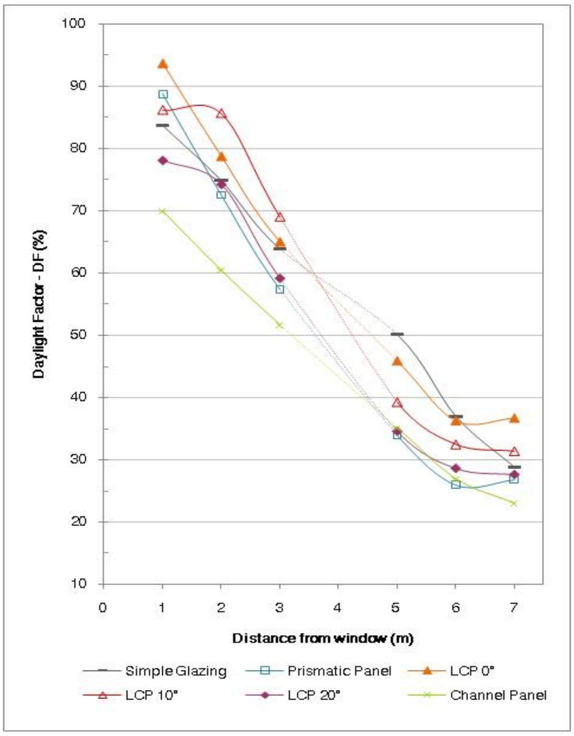

Figure 5 – Measured Daylight Factor (%) under clear sky conditions for December 22st at 4.00 pm., at the working plane.

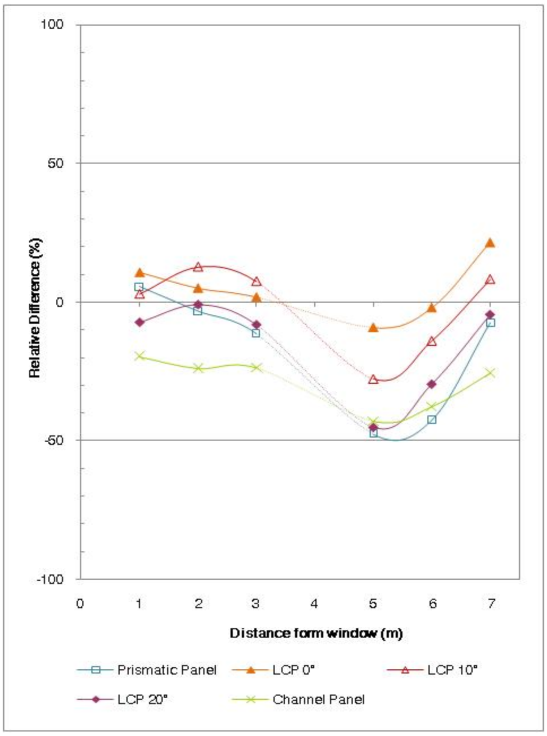

Figure 6 - Relative difference (%) between DF of each system and DF of simple glazing under clear sky conditions for December 22st at 4.00 pm., at the working plane.

Qualitative analysis

A qualitative assessment of the indoor daylight was made by photographic records. The most relevant photographic records are presented together with the analysis.

In Figure 7, pictures of the room interior with the different daylight systems are presented. The pictures were taken under clear sky for March/September 21st at 12.00.

The incidence of light in the ceiling plan is visible in all the images shown in Figure 7 except in the image of the reference system. It is also visible that the greater the tilt angle of the laser-cut panel, the greater the amount of light redirected in depth towards the ceiling. It is also possible to observe that the channel panel leads to a greater redirection of light in depth towards the ceiling plan when compared to the prismatic panel.

The use of the systems under study allows in one hand to redirect the incident sunlight to the interior of the room, increasing levels of daylight at the back part of the room and the on the other hand it allows to have solar shading in the area close to the glazing unit. Although all systems provide some solar shading, the channel panel and prismatic panel systems are the only ones who do it effectively (Figure 7). However, all systems show a need for incorporation of additional shading devices – interior/exterior lamellas or venetian blinds – in order to avoid the penetration of direct sunlight through the glazing area not covered by the daylight system, preventing glare.

The photographic records of Figure 7 show also glare due to LCP's and Channel Panel systems. This happens when sunlight heats the system and is reflected towards the vision of the occupants. The use of these systems can reduce in part the direct view to the outside, which explains why they are ideal at the top part of the glazing. Despite the high brightness of the sky in some of the images in Figure 7, the reflection of light incident on the walls and ceiling close to the glazing unit reduces the contrast between the light from the window and the surrounding area, reducing the glare resulting from the vision of too bright areas of sky.

Figure 7 – Pictures of the room interior with the different daylight systems taken under clear sky for March/September 21st at 12.00 am.

3.4 Final considerations

In general, there is an agreement between the quantitative analysis carried out with the results obtained in the measurements, and qualitative analysis carried out by photographic records. Both analysis, quantitative and qualitative, of indoor daylight showed that the use of the tested systems is most appropriate in climates dominated by clear sky conditions. In general, under both conditions of the sky, the LCP is the most efficient system in terms of redirection of daylight in depth. Comparing the performance of the laser-cut panels for three different slope angles (0 °, 10 °, 20 °), the conclusion is that the LCP 20 ° is the most effective for medium and high solar altitudes, while for the low solar altitudes LCP 0 ° and LCP 10 ° have generally superior performance. Therefore, the LCP system should be incorporated into flexible systems so that they can be continuously adjusted according to the angle of incidence of solar rays in order to achieve maximum penetration of daylight in depth.

Regarding the channel panel, the conclusion is that it is effective under clear sky as it redirects in depth the sunlight from high altitudes, blocking the sunlight from low altitudes, largely eliminating the problem of glare. On the other hand, regarding the prismatic panel, the conclusion is that it is not an effective system in terms of redirecting daylight deep into the room for both conditions of overcast and clear skies, since it rarely presents improvements in the indoor daylight levels.

Finally, the conclusion is also that advanced daylight systems should be combined with movable solar shading devices (e.g. exterior lamellas and/or venetian blinds), positioned in order to shade the glazing area not covered by the daylight system and avoiding glare.

Conclusion

An important goal of this work is to highlight the importance of the advanced daylight systems as part of the strategies for daylighting, as they are an important tool to achieve substantial improvements in the quality of daylighting inside buildings with deep spaces where there is difficulty in access to daylight peripheral and thus contribute to reducing its energy consumption. This study showed that the use of the three systems tested - prismatic panel, laser-cut panel and channel panel - is most appropriate in climates dominated by clear sky conditions and that, in a general way, only the channel panel and laser-cut panel systems contribute to a better use of daylight in comparison with a standard glazing solution.

It is also important that the incorporation of advanced daylight systems in buildings is considered since the early design process and taking into account the various basic strategies of daylighting, in order to achieve a good performance of the buildings at different levels: lighting, thermal and energetic.

The feasibility of implementation of some of these systems is still questioned because of the relation between their performance/efficiency and their costs associated with its acquisition and monitoring. However, the continued rapid advances in materials science and production technologies promises further improvements in performance as well as reducing initial costs and maintenance.

While in the past to reduce the energy consumption of the lighting focused particularly on strategies to increase the efficiency of light bulbs, and other ancillary equipment, future energy savings will certainly result from the adoption of advanced systems and strategies of daylighting, a theme of passive architecture that has often been neglected, and that concerns the conceptual interface of one of the areas that architects usually indicate how fundamental to architectural design: the light.

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