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The Natural Light and the Daylight Factor in a Non-Residential Building

Case Study of the Classroom of an Educational Center

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Possiamo perdonare un bambino quando ha paura del buio.
La vera tragedia della vita è quando un uomo ha paura della luce.

— Platone

Ai miei genitori

Abstract

Light, or its absence, represents a substantial issue in architecture. Its presence is essential to define the space; natural light in particular, "soft" and continuous, has this task. Natural light design aims to minimize the energy consumption of buildings and maximize well-being in confined spaces. It is an element of improvement of comfort conditions. The variability of natural light during the day is a positive stimulus both from the biological and psychological point of view for the human being and work environments lit by natural light are considered much less stressful for the eyes. In addition to that, when a workplace is exposed to natural light it makes it more productive, more efficient, healthier and more creative. Furthermore, a proper design of the building should guarantee, at least during the hot seasons, the correct implementation of natural light, in such a way to reduce the energy intake of artificial lighting.

The present study is designed to analyze natural lighting in a classroom of the Environmental Education Building of Pozuelo de Alarcón (CREAS). This building was chosen due to the commitment that the Municipality of Pozuelo has with the environment and the leading design in terms of sustainability and energy efficiency. After an overview of the current state of art and the theoretical principles, the experimental work began with the precedent monitoring campaign included between February 24 and March 6, 2017. Ten luxmeters, connected to OPUS 200 and 08, were first strategically located inside the classroom, in accordance with standard EN ISO / IEC 17025: 2017 and EN 12464-1: 2012; they were set up to do a continuous data recording.

The results is classified according to three scenarios: 1) days with clear skies;

2) days with intermediate skies; 3) days with overcast skies. For these three possible situations, the Daylight Factor (DF) was calculated, for each luxmeters, for 3 different hours, 9 AM, 12 AM and 16 PM. This new database with the use of Surfer, an interpolation software, has allowed us to know the lighting horizontal distribution on the working plane of the classroom. I do the same with the experimental data obtained from the Velux Light Simulation program, with the same conditions of experimental modeling. In fact, thanks the simulation of the environment, we obtain the distribution of lighting in the classroom work plane.

The next step was the main one, the modeling of the workshop room on DesignBuilder, software that is capable of developing the analysis of natural lighting based on the Radiance software. From here, we have exported and studied the values of Daylight Factor (DF).
With the collected data, a validation of the DesignBuilder program was possible with the comparison with the data of the site and those obtained with Velux. The results show a consistency between experimental and simulation values.

This work shows that areas with wide windows, such as the classroom under study, present heterogeneous lighting and the great deal of light can cause both thermal and light discomfort.

At this point, it was necessary to check the performance of the incorporation of different passive systems to obtain a more homogeneous DF, by guaranteeing lighting comfort for users. So the redesigned classroom's behavior was analyzed: thanks to the insertion of two skylights and window blinds in the side openings, the situation improved substantially.

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Chapter 1

Introduction

This thesis concerns the study of natural lighting in a classroom, more precisely of the workshop room of an environmental education center, the CREAS building, located in the north-west Madrid hinterland, in Pozuelo de Alarcón.

The reasons that led me to investigate this issue go back to the energetic nature of the project, in fact the subject has always aroused great interest in me and I took the opportunity to examine it more closely.

The aim of this Master Degree's thesis is therefore to provide an accurate lighting analysis of the data collected, both measured directly on site and simulated through software modeling.

The on-site investigation was carried out in advance and, having access to the data, it was decided to analyze them using a digital model to study the features in detail, one of which is the daylight factor, DF, center of my study. The analysis will be immediately categorized by choosing 3 types of sky (Clear, Intermediate, Overcast) according to which to divide the data and then conduct the search.

The thesis can be divided into the following chapters: after the first one which contains this brief introduction, the second chapter deals with investigating the state of the art, through a historical excursus, proceeding with of past research on natural lighting and control systems for the latter.
In the third chapter, then, the theoretical arguments regarding the study of light and natural lighting are dealt with, with the description of the effects that this has on man and with the various factors that can evaluate it.
In the fourth one, after having dealt with the most theoretical part, the ultimate

goals of the thesis are explained.
In the fifth chapter we proceed to describe the object of study and here is provided the methodology of study of the phenomenon.
The sixth chapter is reserved for the description of the survey and its results, describing the data obtained in situ, and those collected from the simulations, the ones previously made on Velux and the ones I carried out on DesignBuilder. The purpose of this chapter is to validate this software with the help of data already present, interpreted in a dimensionless manner, and process them, exposing the most relevant elements of the survey carried out. Thanks to this research work it is possible to analyze some important factors related to natural lighting, results that are detailed in the final conclusions of this thesis.

I worked up to this point at the Polytechnic of Madrid and the survey was further developed at my home university, the Polytechnic of Turin, making improvements to the current state of the workshop room by inserting passive systems as control light system, window blinds and skylight, with the aim of controlling the light flows of the studied environment.

Chapter 2

State of the Art

As it will be explained, the natural light coming from the sky consists of three components [59]:

1. Direct light from the sun;
2. Natural light diffused in the atmosphere (including clouds), which is the diffuse component of the sky;
3. Light coming from reflections in the ground and objects in the outdoor environment.

Not deepening into the theoretical aspects for now, analyzed in the Chapter 3, in these sections we will talk about how man has used the sun as a light source to illuminate interior spaces through history. This will allow us to understand more deeply the solutions that have been used over time to illuminate the living spaces by using sunlight.

2.1 Brief Historical References

Regarding daylight issues, several daylight strategies have been described and assessed by literature. The commonly used systems seek to generate shade and protect spaces from solar radiation, what we seek for light conditioning is the redirection of light inwards without generating glare.
The control of solar radiation and the possibility of adapting facade elements to the interception of solar rays is a practice of all time. Construction and technical devices to control the amount of sunlight that can penetrate the environment can be found both in warm and temperate regions and in more extreme latitudes with harsher weather. On one side they are useful to prevent the overheating of the

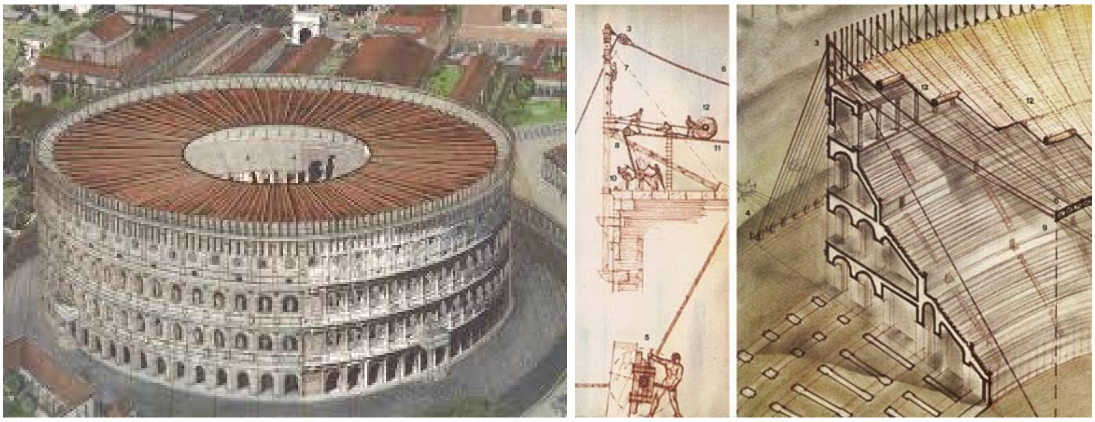
Figure 2.1: Urban complex of Ait Ben Haddou, Ouarzazate, Maroc

Source: C. Bin, Ait Ben Haddou, Ouarzazate, Maroc, February 2019

rooms and the consequent discomfort in their use, on the other side to ensure the entry and heat of daylight even in the severe winter conditions.
In this sense, the constructive culture of Morocco, cited as example, to this day demonstrates the link to the protection from sunlight: note the small size of the openings and the overhang in order to protect them from light (Figure 2.1). [23]
Also the Roman tradition has left unique examples in which attention was given to the problem of the sun: an blatant case, the *Velarium*, a complex system of curtains used to protect bystanders during the events in the Flavian Amphitheater, known as Colosseum, in Rome (see Figure 2.2). The engineer René Chambon, thanks to calculations and the modeling of the immense awning system, elaborated also by Dassault systèmes, explained how in the Colosseum, fans of gladiator fights could shelter from the sunlight. Thanks to 240 large wooden poles, 240 linen sheets measuring 2x50m, 50 km of hemp ropes from 8 to 10 mm in diameter and 150 to 200 metre of 80 mm hemp ropes with a similar breaking load to that of elevator cables.
According to Pliny the Elder, the surprising way in which about 25,000 m^2 of canvas (about 3 or 4 regular football fields) were opened and closed, was «a more admirable spectacle than the gladiators fights themselves».[1]

Even the Medieval times left their mark in terms of protection from sunlight. Not in Europe, characterized by simple and rational constructions, but in other civilizations such as Islamic and Japanese ones, they have devoted considerable care in designing comfortable buildings which contrast atmospheric agents and solar

Figure 2.2: Reconstrucion of *Velarium*, the awning system at the Roman Colosseum



Source: [1]

radiation. The use of wooden structures (like shutters) to protect environments in the first case or walls of heavy rice paper framed to diffuse light avoiding its direct impact in the second one, can be considered the precursors of screening elements used today.
The Middle East heritage then reached Europe, following the traffic that flourished around the Late-Medieval periods. In this period the use of double fixtures with Venetian blinds became more widespread, facade elements for solar control that entered in the everyday Italian construction practice.
During the Renaissance, in Europe, the use of panels supported by supports in imitation of military tents spread. Also in this case were generated the prototypes of those that would later become the current outdoor curtains.
But then, for most of the Modern era, the external curtains were the only facade elements used to counter solar radiation, with an almost ornamental use.
A renewed attention to the problem and its control in civil construction started at the beginning of the 20th century. The evolution of knowledge and new technologies in the building sector contributed to this and new models were defined. The problem of radiation became a fundamental component in the conception of the architectural organism.
Just think of Le Corbusier, one of the pioneers of the modern architecture, that in the 1923 said that «architecture is the masterly, correct and magnificent play of masses brought together in light». This is to highlight how architecture and natural light are inextricably linked to one another so that the former could not exist without the latter. Le Corbusier, in fact, revolutionized the relationship with the light of architecture of the Twenties and Thirties, introducing ribbon windows - *le fenêtre en longuer*, one of the five principles of architecture theorized in 1923 in

Towards an Architecture, together with the *pilotis*, the *toit terasse*, the *plan libre* and the *facade libre* - and *brisesoleil*, the shielding of solar radiation.

After a few decades of general stagnation, during which solar shading took on a secondary role in the formal definition of the envelope, also due to the growing availability of low-cost electricity, a renewed interest in the optimization and modulation of sunlight in architectural works, the recovery of executive practices and design approaches that have reinstated solar shading in the repertoire of technological elements indispensable in good architectural design. In the last few years the concept of shielding has been formalized and in some way standardized following, among other things, ever greater attention to the problems of energy saving and sustainable building.

In 1980 Edward Mazria, in the volume *"The Passive Solar Energy Book: A Complete Guide to Passive Solar Home, Greenhouse and Building Design"*, one of the first exhaustive studies on bioclimatic design, indicated a series of rules of thumb - called *patterns* - aimed at the correct design of a passive solar system. *"Each pattern tells us how to perform and combine specific acts of building."* [2]
There are First-Level patterns, which give the building its general shape and fix its orientation, the location on the site, the indoor space distribution, the position of the windows, etc..
They are followed by Second-Level patterns, which provide criteria for choosing a passive system and provide details for its design, such as the choice of the passive solar system, materials, etc..
Finally those of the Third Level, which include specific instructions to make the building a more efficient passive system; among these, in addition to the external insulation and summer cooling systems, Mazria also indicated the use of solar shading.
Solar shielding is now an integral part of every architectural work, without distinction of intended use.
This intensive return to the use of solar protection in design has also been determined by an enhancement in IT equipment for sustainable architecture. Today, therefore, we are witnessing a wide variety of technological proposals with functionally and technically valid compositional proposals (see an example of lighting design of the Terminal 4 at Madrid Barajas airport, Figure 2.3). [23]

Figure 2.3: sunblind of the Terminal 4 at Madrid Barajas airport

Source: https://www.rsh-p.com/projects/t4-madrid-barajas-airport

2.2 Light Project

Firstly, for the consideration of a correct lighting design of a building, it should be recalled that there are a series of premises, among which it is possible to highlight the following [59]:

- Lighting should facilitate the definition of a person's situation in space and time;
- Lighting should be integrated into the architecture and interior design since the beginning of the project and it should not included in a subsequent design step;
- The various options of shape, color and lighting materials should reinforce the objectives of the architectural and interior design instead of acting independently;
- Lighting should create a feeling and an atmosphere adapted to people's needs and expectations;
- Lighting should facilitate and promote communication between people;
- Lighting should define principles and transmit messages that go beyond simple clarity, it's about expressing something;
- Lighting must be original in its basic forms of expression; it should not be a mass product that simply reproduces what already exists;
- Lighting should facilitate the perception and recognition of the environment.

To sum up, lighting an environment is often a complex task mainly taken into consideration during the design phase of the building. [3] However, lighting should be designed for the tasks that individuals perform within that environment.
As indicated in the European standard EN 12464-1:2011, different activities require different levels of light: the more detailed the occupation, the greater the light requirement. In the case of the schools, the high school classes should be lit at an illuminance of 300 lx, a corridor may only require 100 lx, whilst studying an engineering drawing room may require 750 lx. [53] [4]
So, the use of natural light in buildings has two main objectives: the first is to reduce energy consumption; the second is to improve the quality of light in internal spaces. Daylight not only has the properties of illuminating a space but giving it better quality. We must not forget that light must be designed in detail to reach high levels of visual performance, bearing in mind that it can cause glare, distraction and it can reduce the stimuli linked to the activity carried out by producing, in an underhand way, reflections or shadows in the visual system.

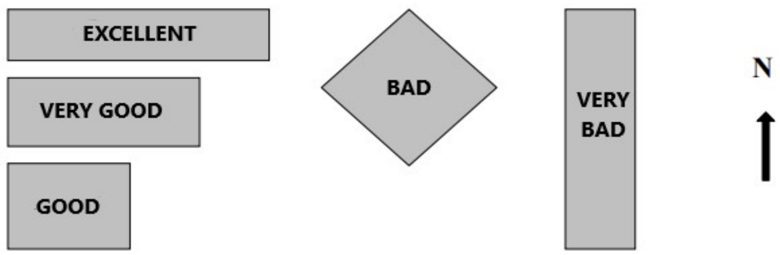
2.2.1 Shape and Orientation of the Building

The orientation and shape of the building is essential to obtain a high-quality natural lighting. This not only affects the lighting but also the energetic gains of it. This is the first approach that must be made at the time of design and although it is conditioned by the size, shape and conditions of the plot.
There are two important aspects:

- The adjustment of the building in its location and its relationship with the sun's path;
- Allow people to know where they are inside a building.

This sense of orientation comes from contact with the outside world, and can be obtained from the perception of natural light, even if there is no outward vision.
The effects of obstructions and orientation in the availability of sunlight can be found using a *sun Path Diagram* or *Stereographic Diagram*. This diagram is a projection of the whole sky; the horizon is represented by the outer circle and the zenith by the point in the center. The concentric circles represent constant elevation lines above the horizon. The perimeter scale provides the azimuth, the support in degrees from the north. In the diagram, the horizontal edges are drawn as circular arcs and the vertical edges as radial lines.
A sun path diagram can be used to read solar elevation and azimuth at a given time. These angles can then be used to draw shadows on the plane of the place.

Figure 2.4: Favorable and unfavorable orientations of buildings to ensure that most of the spaces have access to natural light



Source: [4]

The Figure 2.4 shows buildings with different shapes and orientations and indicates in which cases the situation is more favorable.

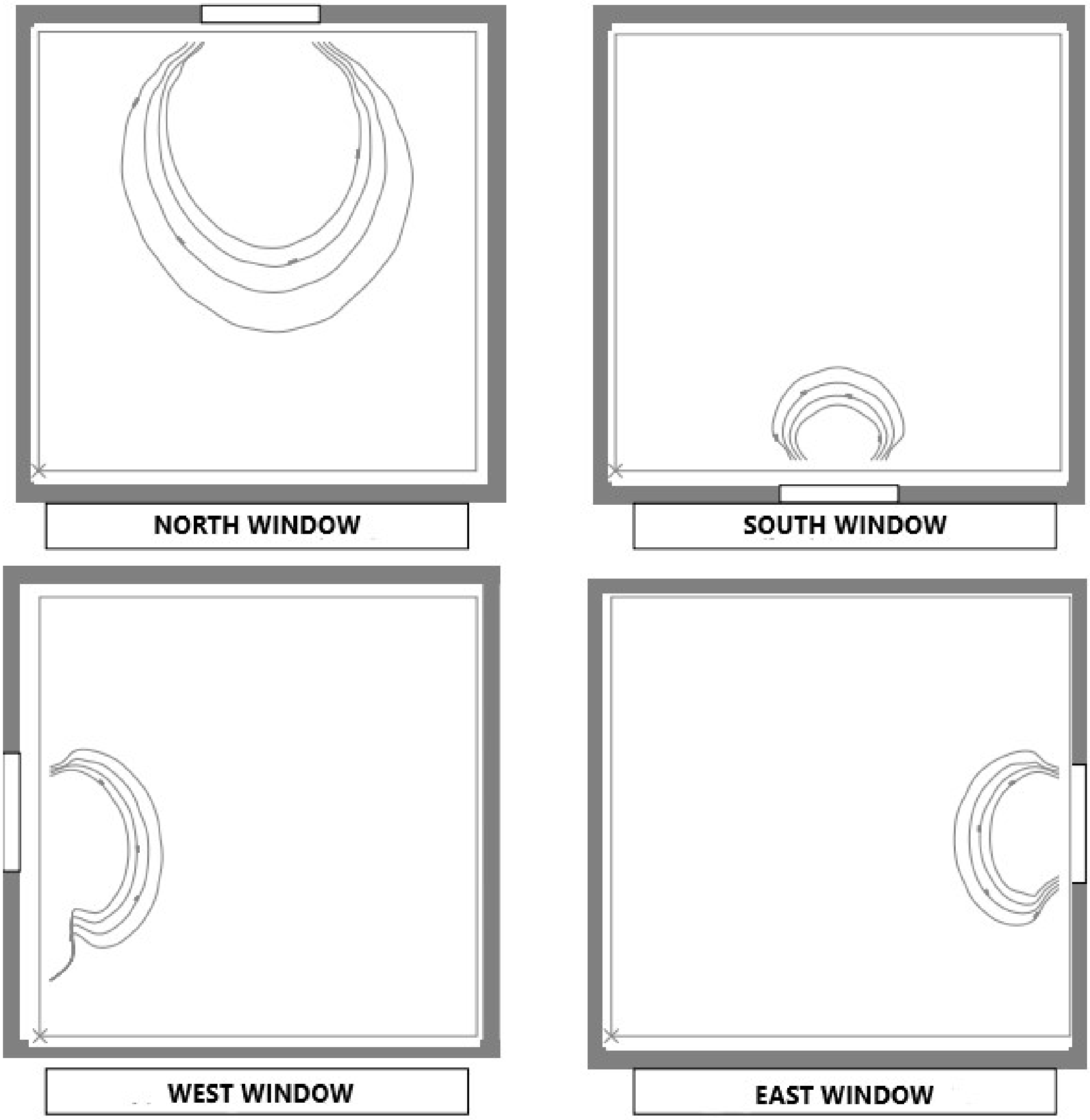
2.2.2 Natural Lighting System

We call natural lighting system the components that in a building or construction are used to illuminate with daylight. The quantity, quality and distribution of the interior light depends on the joint operation of the lighting systems, the location of the openings and the surface of the enclosures.[46] [4] There are basically three natural lighting systems used:

1. Side lighting;
2. Zenithal lighting;
3. Combined lighting.

1. Side Lighting The light comes from an opening located in a side wall, and so the illuminance of the work plane near these openings is significant and contributes considerably to the general lighting. If we move away from the window, the value of direct lighting decreases rapidly and the relative proportion of the indirect component (reflected and diffuse) increases. However, as shown in Figure 2.5, the amount and distribution of the lateral through an opening in a wall depends fundamentally on the orientation of the wall where it is located. In general, the windows oriented to the North receive sun (direct lighting) from dawn to dusk, those facing East only allow the entry of direct radiation from dawn to noon, those located to the West from noon to dusk and those located towards the South does not receive direct lighting, they only receive diffuse and reflected lighting.

Figure 2.5: Differences between the resulting isolux curves in the same interior space modifying only the location of the window in the North, South, West or East wall



Source: [4]

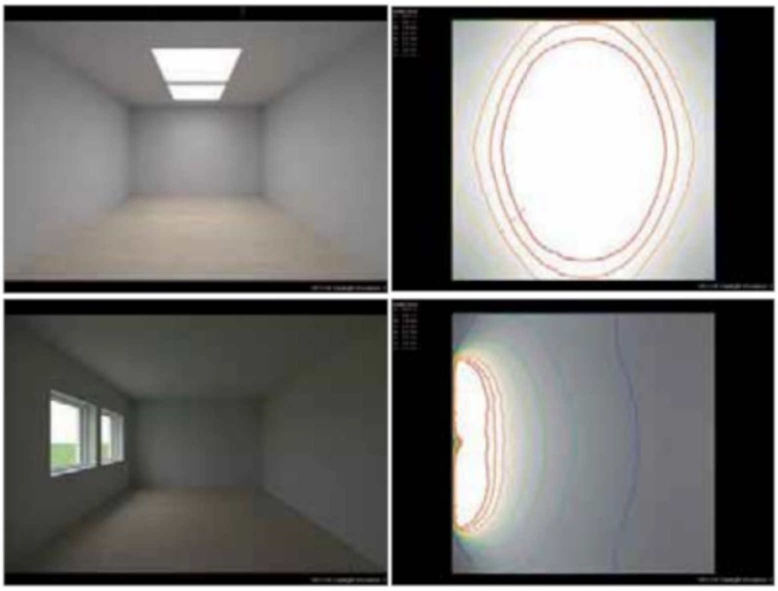


Figure 2.6: Zenithal and Lateral Openings

Source: [49]

2. Zenithal lighting It is generally used in locations with a predominance of cloudy skies. The work plane is illuminated directly from the brightest part of these types of heavens, the zenith. The proportion of indirect lighting generally does not exceed 25%. The Figure 2.6 shows the difference between a lateral lighting distribution and a zenithal one placed in the same local.

3. Combined Lighting In combined lighting there are openings in walls and ceilings. In a space where the building's exterior is not clearly divided into walls and ceilings, for example in vaulted enclosures, it is considered as lateral illumination if the opening is lower than 2.5 m. Above this height, overhead or upper lighting is considered. In a combined lighting, the ratio of the direct and indirect component of the lighting can be located between the two extremes mentioned above.

For reasons of easy constructions and costs, most of the windows for natural lighting are made through the side walls. The most important factor to keep in mind when illuminating laterally is orientation.
Designs with unilateral lighting have three problems to solve:

- The poor distribution of side lighting;
- Direct sunlight, which can cause glare;
- The fact that only the premises with a wall to the outside or to the ceiling

(sky) can be illuminated with natural light.

To solve these problems you need to know the possible systems you can use. These will be explained in the following paragraphs.

2.2.3 Capturing Light Systems

To use the components and elements of capturing natural light in architecture with minimal effectiveness, it is necessary to know their behavior. Most of the time a component produces very different consequences in terms of lighting or thermal conditions depending on the circumstances, so it is necessary to select which of the effects is more important. [59]

Gallery A gallery can be described as a covered light space attached to a building. It can be opened to the outside or it can be closed by means of crystals. It allows natural light to enter the interior parts of a building connected to the gallery by passing elements. It provides a reduced level of illumination and lower contrast in the interior areas adjacent to the gallery.

Patio A patio is a space enclosed by the walls of one or more buildings and is open to the outside at the top and sometimes in one direction. The patios have similar light properties to the outer space but through them the illumination is reduced with natural light and ventilation. The finishes of the walls that enclose it influence the lighting performance of the patio: with luminous colors or specular surfaces, for example, the lighting levels are increased.

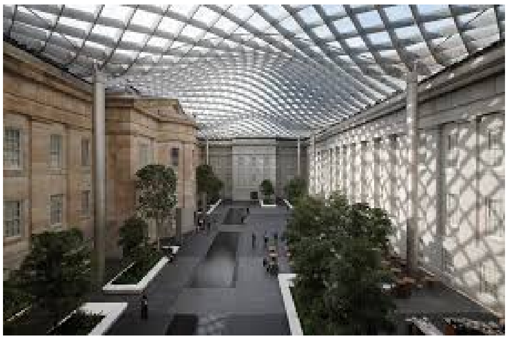
Porch A porch is a covered light space attached to a building at ground level, open to the outside environment. It is an intermediate space that allows the entrance of natural light to the parts of the building directly connected to the porch and protects them from direct sunlight and rain.

Atrium An atrium is a space enclosed laterally by the walls of a building and covered with transparent or translucent material. It is an interior space of a building that allows light to enter other interior spaces joined to it by passing elements. It provides a reduced level of lighting and lower contrast in relation to the spaces connected to the atrium, so it has a small impact on the use of lighting with natural light. Its dimensions may vary depending on the size of the building. Normally it occupies the total height of the building. The roof may consist of a metal structure that supports the glazing. The interior finishes must have a high reflectance to ensure good penetration of natural light.

(a) The *Galleria Subalpina*, the liberty style arcade/gallery in Turin

(b) The interior patio's school of the Ponzano Veneto (TV) - C+S project

(c) A section of the 18km of porches in Turin



(d) The Atrium of the National Gallery in London

Figure 2.7: Example of Lighting Collection System

Other examples of systems that help to let the sunlight enter deep into the space and to create a better light quality are as follows:

Solar Tube It is a space designed to reflect solar beams to dark interior spaces; it can also provide ventilation. These systems are used when a room is not able to receive natural light because it has no wall exposed to the outside or because it is considered insufficient natural light entering.
It is made up of three parts:

1. an external collector of light;
2. a conductor of lights whose surfaces are coated with highly reflective finishes, such as mirrors, aluminum, highly polished surfaces or paint, in order to reflect the solar radiation;
3. an internal emitter of light (outlex tube).

Translucent Roof It is defined as a horizontal opening partially constructed with translucent materials, which separates the interior space from the exterior or two interior spaces superimposed.

(a) Solar Tube or sun Tunnel - VELUX

(b) The Gridshell Translucent Roof at the British Museum in London

(c) An example of Curtain Wall - The Fondation Cartier in Paris

(d) An example of Translucent Wall - The market, sport center and library *Barceló* in Madrid

(e) The Bundestag Dome in Berlin

(f) The house of Zaha Hadid in London

Figure 2.8: Other example of Lighting Collection System

Curtain Wall A curtain wall implies a continuous translucent or transparent vertical surface without structural function, which separates the interior from the exterior of a building. It generally consists of a metal frame that supports said transparent or translucent surface. It allows the lateral penetration of natural light and the gain of direct sunlight and exchanges of views, but not always ventilation. Increase the light level in areas near the wall.

Translucent Wall This type of vertical enclosure is constructed with translucent materials. The surface separates two luminous environments, allowing the lateral penetration of light and diffusing it through the translucent material.

Dome It allows the overhead lighting of the space located under it. It can be made of glass, acrylic material or polycarbonate. When perforated, it is made of opaque building materials and perforations may be covered by the above translucent materials.

Skylight A skylight is defined as a horizontal or inclined opening built into the roof. It allows the aerial penetration of natural light in the space below, sometimes protecting against direct radiation or directing it towards lower environment. The opening is usually covered with glass or transparent or translucent plastic, and said closure can be fixed or collapsible.

2.2.4 Materials and Irradiance

In order to respecting psychophysical conditions, the proper design of openings is of great importance. In fact, they are the lighting source inside a building and they, as a transparent building materials, play a critical role in terms of both natural lighting and the overall thermal load of the building: allowing the entry of solar radiation, or reflected from the sky, from the ground and from buildings surrounding, these materials allow the lighting of the rooms and contribute to their heating. For that reason, it is fundamental to perfect the quantity and location of the openings in the building envelope in order to control natural light intensity.
It is clear that the study of correct daylighting forces us to tackle the problem from the earliest stages of design, with an appropriate choice of the orientation of the building, of the size and shape of the transparent surfaces, of the materials used. [27] The objective of guaranteeing the well-being of those who live and work within the buildings involves the examination of different and sometimes conflicting aspects. Large windows allow the individual to work in adequately and naturally illuminated environments on the one hand, on the other they oblige to protect those in the rooms from the considerable thermal load that solar radiation produces and from

Figure 2.9: The importance of daylight with system of windows

Source: https://www.velux.com/deic/daylight/daylight-with-roof-windows-flat-roof-windows-and-modular-skylights

the phenomena of dazzling and local discomfort. It is therefore an optimization problem which must take into account these contrasting aspects, but which cannot ignore the indispensable need for light and air felt by man in his activities (Figure 2.9). In addition, aspects relating the effect of solar radiation on the materials used in interiors must be considered. It must be taken into due consideration when particular value assets (books, paintings, fabrics, furniture, etc.) are kept in the rooms, which are very sensitive to prolonged exposure to light radiation. This is not all; as stated in an article recently published by the weblog *ArchDaily* "the absence of discomfort at the time of seeing is not enough to measure the visual success of a space. Things like the rate of blinking, level of glare, or light blindness help to determine the environmental quality of a room. Other things that are vital to consider include representations of color, low reflection, and uniform distribution of light." [5]
The variety of themes makes the lighting project so complex.

2.2.5 Window

The windows is the typical opening of the building used for the exploitation of natural light in interior lighting. The window design objectives are to:

- Maximize the transmission of light per unit of glazed area (frames and slender window blades);

- Control the penetration of direct sunlight on the work plane;
- Control the contrast of clarity within the visual field of the occupants, especially between the windows and the surrounding surfaces of the premises;
- Minimize the effect of reducing radiation income due to the angle of incidence of the light -reduction effect by cosine This means that windows located in the upper part of the walls produce more illuminance than a lower window of the same area;
- Minimize the glare of the veil on the work planes, resulting from the direct vision of the light source in the upper windows;
- Minimize diurnal heat gains during the summer period;
- Maximize the daytime thermal gains in winter to allow natural space heating;
- Provide shade over glazed areas to avoid seasonal overheating or glare according to the orientation of the facade where the window is located.

Glazing

After considering the shape and general orientation of the building in the paragraph 2.2.1 and the openings position in the paragraph 2.2.2, it is necessary to elaborate on the glazing shape.
As a general rule, high or very high glazing can cause problems of thermal control and glare. Low or very low glazing can produce excessively low levels of illumination, especially where overcast skies, atmospheric pollution or where adjacent buildings reduce the availability of natural light. The shapes of the windows may differ. A first approach is to define the relationship between height and width. In this way the windows can be classified as [59]:

- Horizontal Windows with shape coefficient $1/2$
- Vertical Windows with shape coefficient 2
- Intermediate Windows with shape coefficient from $1/2$ to 2

It mainly influences the distribution of light in the illuminated space, the quality of vision and the potential for natural ventilation.

With horizontal windows the indoor illumination is a band parallel to the wall of the window, which produces very little difference in the distribution of light throughout the day, with little glare. The relatively large horizontal dimension allows a panoramic view.

With vertical windows the interior lighting is a band perpendicular to the wall of the window, thus producing a very variable light distribution throughout the day. This window form offers better lighting in the areas furthest away from it; however, there is more glare. The external views are limited horizontally but may contain a greater depth of field, combining the background and the views at medium and great distance.

The number of openings clearly affects the brightness and temperature control.
If there is more than one window in the same room, the sum of the surfaces of all the windows must be considered from a luminous point of view. If there is, hence, a large window or several small windows with the same total area, the amount of light admitted in the room will be the same, since the relation between the glazing and the average lighting with natural light in a room is approximately linear; but we must bear in mind that the distribution of light, vision and natural ventilation are affected.

Window Size

With a growing formalism for daylighting as well as other architectural science areas, a number of rules developed usually based on [6]:

1. Window to floor area ratio;
2. Window head height (or ceiling height) to room depth ratio;
3. Window to window wall area ratio.

1. Window-to-Floor Area Ratio Aero-lighting is one of the aspects inherent to the hygiene and healthiness of the environments in which living beings must dwell, and is part of the factors that contribute to obtaining habitability. Specifically it is a set of mathematical relationships between the volumes of the environment and the "lights" that allow ventilation and lighting, such as doors and windows.
In Italy, it is guaranteed by law: all living spaces must have an adequate windowed and opening area, so as to guarantee minimum natural lighting and ventilation. The article we are referring to is the the art. 5, paragraph 2 from the Ministerial Decree of 5 July 1975: *For each dwelling, the width of the window must be proportionate so as to ensure an average daylight factor value of not less than 2%, and in any case*

the open window area must not be less than 1/8 of the floor surface area (regarding the daylight factor, see the paragraph 3.4.1).

This rule is one of the most known in the world: in London, in terms of health, comfort and effective teaching of children, 20% window area to floor area are recommended in school, for the residential building 10% is enough. A similar rule existed at the turn of the 20th century in Germany for industrial spaces and for buildings in New York (schools 17% to 25%, offices 17% and residences from 10% to 13%).

2. Window head height to room depth ratio This is a rule of thumb, popular in various textbook: in general the maximum room depth shall be from 2 to 2.5 times window head height for continuous fenestration and curtain wall construction. Given the variety of values available, this data has a restricted validity.

3. Window to window wall area ratio For the sake of argument, it is reported this rule of thumb related to limiting glazed area more for thermal reasons (heat loss and gain control) that for lighting ones. Rules associated with the latter are of more direct interest such as those drawn from studies carried out in the 1970s and 1980s: if the window to window wall area ratio was between 20 and 30% users were satisfied but if it fell below 20% satisfaction declined steeply. It was noted, however, that a 20% ratio will probably result in inadequate daylighting at the rear of the room.

2.3 Systems for Lighting Control

As explained in the 2.1 section, the use of solutions to protect internal environments from solar radiation is part of the building culture itself, at all latitudes and in any age. The techniques that are related to the control of sunlight, mainly are used to avoid overheating in interior spaces and improve thermal conditions, few of these strategies are to improve natural light conditions. [7]
The commonly used systems seek to generate shade and protect spaces from solar radiation, what we seek for light conditioning is the redirection of light inwards without generating glare.
So a series of passive systems, mainly for sun protection, used for the conditioning and improvement of lighting comfort in buildings, will be here presented.

2.3.1 Solar Shading Device: definition

In more recent times, regulations (at every level: community, national and local) has been added to best design practice. The standards, in some cases, oblige the use of solar shading to contain energy consumption. At EU level, a first indication is found in the European Energy Performance of Building Directive 2002/91/CE. The solar shading devices were defined by the Italian UNI 8369-4:1988 as *"technical element with the function of controlling in a specific way the radiant energy, the lighting, the heat flow and the visibility between the internal spaces and the external spaces"*. [7]
The Italian Decree Law 192 of 2005 define the external shading device as *"systems that, applied to the outside of a transparent glass surface, allow a variable and controlled modulation of the luminous energy and optical parameters in response to solar stresses.*[7]

The decision to install a screen and the type of system designated may be influenced by considerations of a different nature than simple solar control as guaranteeing privacy and preventing glare. The use of shielding on windows will affect its shading coefficient.
It will depend on:

- The solar properties of glass and screen material;
- The heat transfer coefficients on the window surfaces;
- The geometry of the screen;
- The incidence angle of solar radiation.

The important properties of the screen material are the material's reflectance and the transmittance to solar radiation. For example, screens of different colors have different solar performances. A white screen tends to give high performance, while dark screens give less brilliant results. [28]

Regardless of the type of product used, the categories that characterize a shield can be traced back to four:

- The morphology, which indicates the shape assumed by the devices (lamellar, horizontal or vertical, with panels or grid);
- The position with respect to the closure (internal, external or intermediate);

- The movement (fixed or mobile). The movement can be rotating or sliding, both horizontal and vertical. To the latter category belong the already mentioned Venetian blinds, while the horizontal sliding systems have recently become very widespread. For example, in residential building that uses external walkway systems as a horizontal connection element, or through the use of guides in near the openings;

- The placement plane with respect to the closure (horizontal, vertical parallel to the facade, vertical orthogonal to the facade, inclined). The horizontal or vertical position depends fundamentally on the angle of the solar radiation that comes in the facade. In the south facing areas, horizontal screens should be preferred, while in the east and west vertical screens are advisable.

Basically all types of solar shading can be traced back to these four categories, the choice of which can obviously vary considerably from project to project.

2.3.2 Regulation

The operation of the solar shading is delineated with respect to the devices, according to the methods of operation against radiation and the need for brightness in the interior spaces [8]:

- Active devices, which allow to vary the ratio between the incident solar radiation and the solar radiation transmitted according to the mutation of the solar angle α, producing the increase or decrease of the shielding surface or the relationship between the opaque and the open surface. This supporting the use of the “active” typology especially in the case of discrete variations of the solar angle α or of the need for a precise control of the windowed surfaces;

- Passive devices, which concern the situations of stability of the solar radiation during the different seasonal periods or the necessity of shielding for a specific period;

- Dynamics devices, which allow the portions of the shielding surface to be varied automatically or programmed according to the windowed surfaces.They can perform other functions than the basic sun protection that they interact with the context, modifying not only their position, as already happens with mobile screens, but also their own characteristics.

Active or *dynamic* shields involve the use of automation devices to manage the drive and regulation. They work through the use of a motor, supported by the equipment

of the control systems capable of activating the shielding elements according to the set environmental conditions, or the use of the function controls aimed both at the automatic positioning of the shielding elements according to determined climatic, environmental conditions and temporal, both to the established orientation of the elements (for example, of lamellar typology).
In particular, the control function includes the procedures for automatically activating the opening and closing of the elements with respect to certain times. The lighting control procedures are aimed at activating the elements according to the sensors calibrated with respect to the photometric levels set.

They can also perform other functions or interact with the context, modifying not only their position, as already happens with mobile screens, but also their own characteristics.
An example of the first case are the photovoltaic shields, which perform the dual function of protection and electricity generation, favored in this by the inclined position which increases the amount of intercepted radiation. By definition, the shielding is constantly exposed to the sun, and an inclined position would be optimal, at least in our latitudes, to capture the greatest possible amount of radiation. Furthermore, the presence of air currents allows the temperature of the panel to be lowered, contributing to an increase in performance.
A significant example of the second case is instead the solar shading developed by the Nikken Sekkei studio for the new Sony headquarters in Tokyo, which uses a porous ceramic system capable of absorbing part of the rainwater; when it is hit by solar radiation, the water contained in it evaporates and removes heat from the same shielding elements, consequently lowering the temperature on the facade by an amount, according to experimental tests, of about 2 °C.

2.3.3 Type of Shading System

From the energetic point of view, a fundamental classification divides the screens, according to their position with respect to the closure [7]:

a. **External position** is the best performing as protection from overheating because it intercepts solar radiation before it passes the glass and converts it, into heat.

b. **Internal position** is not recommended because it intercepts solar radiation when it has already entered.

c. **Intermediate position** represents a sort of ideal solution, since it does not expose the device to atmospheric agents and at the same time prevents the propagation of heat inside of the room.

Two other solutions which cannot be classified according to the position of the shielding, but of the technology will be examined:

d. **Combined with photovoltaic cells**

e. **Electrochromic Glazing** (a.k.a. smart glass or dynamic glass)

In the following paragraphs we explore the application and the geometrical, physical and performance of the solar shading.

a. External installation

The external installation ensure the implementation of the front barrier with respect to the glass surface and the thermal energy dissipation. It guarantees efficacy against direct and diffused solar radiation but it is possible that it involves critical conditions due to construction and management, with particular relevance in the case of buildings in height development. [8]
The typological articulation develops as follows:

- Passive zenithal (i.e. fixed) shading devices, which produce the shadow sections towards the spaces below. They are composed of slatted elements (of different materials like concrete, wood, metal and glass) inclined according to the established angle: this is aimed at intercepting the incident solar radiation during periods of high temperature, allowing instead, the transmission to solar radiation during periods at reduced temperature;

- Passive (i.e. fixed) vertical and horizontal shading devices, which produce the shadow sections towards the parallel internal spaces (in an inclined position with respect to the solar angle α prevalent of the context). They are composed of elements with slats or pre-oriented blades (of different material composition, for example, in wood, metal and glass) applied vertically and at a reciprocal distance less than the size of the elements themselves;

- Active orientable azimuthal devices, which produce the shadow sections according to the rotation directed to control the solar radiation with respect to the azimuthal path, producing reflection or refraction towards the interior spaces. They consist of shovel elements of ogival section (for example, in extruded aluminum) applied vertically and operated in mechanical (manual or motorized) mode;

- Active shielding blade devices, which produce the shadow sections according to the rotation directed to control the solar radiation through the horizontally execution and parallel to the windowed surfaces, producing reflection or refraction towards the interior spaces. They are composed of elements with ogival or wing section blades of different materials, for example, metal sheets, aluminum, wood and glass;

- Active shading devices with adjustable louvers, which produce the shadow sections according to the rotation directed to control the solar radiation with respect to any solar angle α. They are composed of lamellar elements (this is the "Venetian" type) of different materials as aluminum, metal or wood) applied horizontally and operated in mechanical mode (manual or motorized), with the possibility of packing in the upper position;

- Active Packable or Folding shutters, according to the execution of contiguous segments connected by hinges. They are composed of opaque or perforated panel, frames supporting a filtering fabric, with different opening factors and with the possibility of packing for lifting or lateral dragging by means of the guide profiles;

- Active Sliding shutters, composed of sliding panels and frames supporting a filtering fabric of different compositions, for example, in aluminum, sheet metal perforated or wood), with different opening factors, with the possibility of sliding (in motorized mechanical mode) inside the guide profiles;

- Active roll-up screens, which produce the shadow sections towards the internal parallel spaces through planar positioning (where the consistency determines the opaque, darkening or filtering formulation) and adjustable. They are composed of sheets (of different composition, for example, in textile, plastic or metal form), which can be operated by means of guides or upright profiles, with or without dumpster;

- Active solar blinds composed of:

  - the drop-down curtains, characterized by the arrangement of the roll-up curtain with gravity actuation (with the lower fixing) or with lateral guides;

  - the arm awnings, with simple supports or with box type;

  - the canopies, in a fixed or retractable form;

  - the veranda awnings, placed above the inclined or vertical pitches) or attic awnings, for the zenithal shielding of open spaces.

b. Internal installation

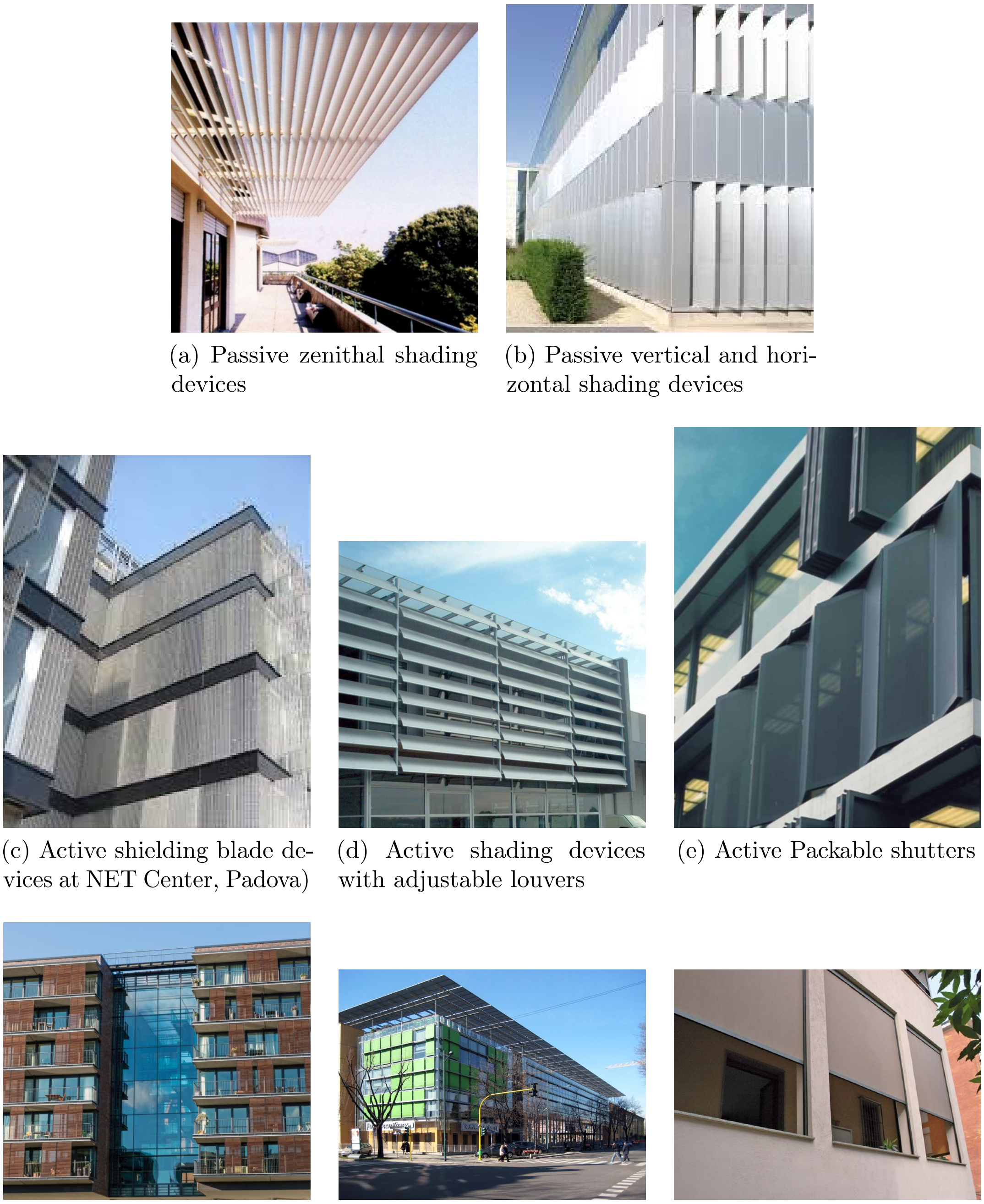
The internal installation provides for the achievement of a reduced solar performance compared to the glass surface, resulting in an easy construction and management and efficacy against diffuse solar radiation, even in the case of perspective exposure to the north. [8] The typological articulation develops as follows:

- Active roller blinds that produce the shadow sections towards the parallel spaces by adjusting the fabric unwinding, made up of sheets (in general, of fabric or plastic) operated by the guides, with or without box;
- Active curtains in the "Venetian" type that produce the sections of shade according to the rotation directed to control the solar radiation with respect to any solar angle α, made up of lamellar elements (in aluminum or other metal, wood, for the general width between $15 \div 50$ mm) applied horizontally and operated in mechanical mode (manual or motorized), with the possibility of packing in the upper box;
- Active drop curtains that produce shadow sections together with the reduction of the phenomena of luminous glare, composed of sheets (of different physical composition, for example, transparent, opaque, metalized and darkening) characterized by the “pleated" configuration (that is, made from fabric panels in regular and constant folds of amplitude equal to about 20 mm);
- Active vertical band curtains that produce shadow sections in the ways performed by the type of vertical azimuth shields, composed of sheets (of different composition, for example, in fabric, metal, wood or PVC) subjected to angular adjustment on the axis vertical, according to the suspension defined by the upper current track.

c. Intermediate installation

The integrated installation is located inside the cavity of the double-glazing closures and ensures the implementation of an intermediate solar performance with respect to the external and internal installation 2.11. It involves:

- conditions of easy construction and management. In fact the application is combined with the double-glazing closure and the products currently offer high performance;



(a) Passive zenithal shading devices

(b) Passive vertical and horizontal shading devices

(c) Active shielding blade devices at NET Center, Padova)

(d) Active shading devices with adjustable louvers

(e) Active Packable shutters

(f) Active Sliding shutters

(g) Active green roll-up screens by Renzo Piano

(h) Active solar blinds drop down curtains

Figure 2.10: Example of External Shading Devices

- efficacy against direct and reflected solar radiation;
- the functional decrease in relation to diffuse solar radiation (due to the double reflection);
- determination of the variable solar factor g (in general, between $0.30 \div 0.45$), depending on the material of the shield and the glass surface.

The typological articulation observes:

- the establishment of adjustable lamellae (in “active” form), which produce the shadow sections by means of rotation aimed at controlling the sunlight and participate in increasing the thermal transmittance (attenuating the thermal dispersion of the windowed surfaces, composed of:
  - the laminated elements (in general, of aluminum, for the general width between $12.5 \div 16$ mm), applied horizontally and operated in mechanical mode (motorized);
- the creation of fabric or grid screens (in “active" or “passive" form), composed of textile sheets operated in mechanical mode (drop-shaped or motorized);
- the constitution of preoriented micro-lamellae screens (in “passive" form), aimed at the reflection or diffusion of solar radiation in the indoor spaces with respect to the specific solar angle α
- the constitution of the filtering films applied to the glass surfaces (in “passive" form), aimed at the reflection or diffusion of solar radiation in the internal spaces, composed of:
  - polyester films with a layer of metal oxide is deposited.

The facade installation integrated between the buffer closure and the external closure (‘double wall” type) provides for the realization of a solar performance similar to the external installation. It involves:

- the conditions of easy construction and management (for example, for high-rise buildings). The devices are manufactured in such a way as to avoid the risk involved with wind solicitation and outdoor atmospheric conditions;
- determination of the solar factor g, variable (in general, between $0.10 \div 0.25$), depending on the material of the shield and the glass surface.

Figure 2.11: Example of integrated installation with grid screens and micro-lamellae

Source: [8]

The solar shading devices are placed inside the cavity where are protected from atmospheric agents and external contaminants. Moreover, these devices reduce the heat supply depending on the outside temperature and solar radiation conditions. [8]

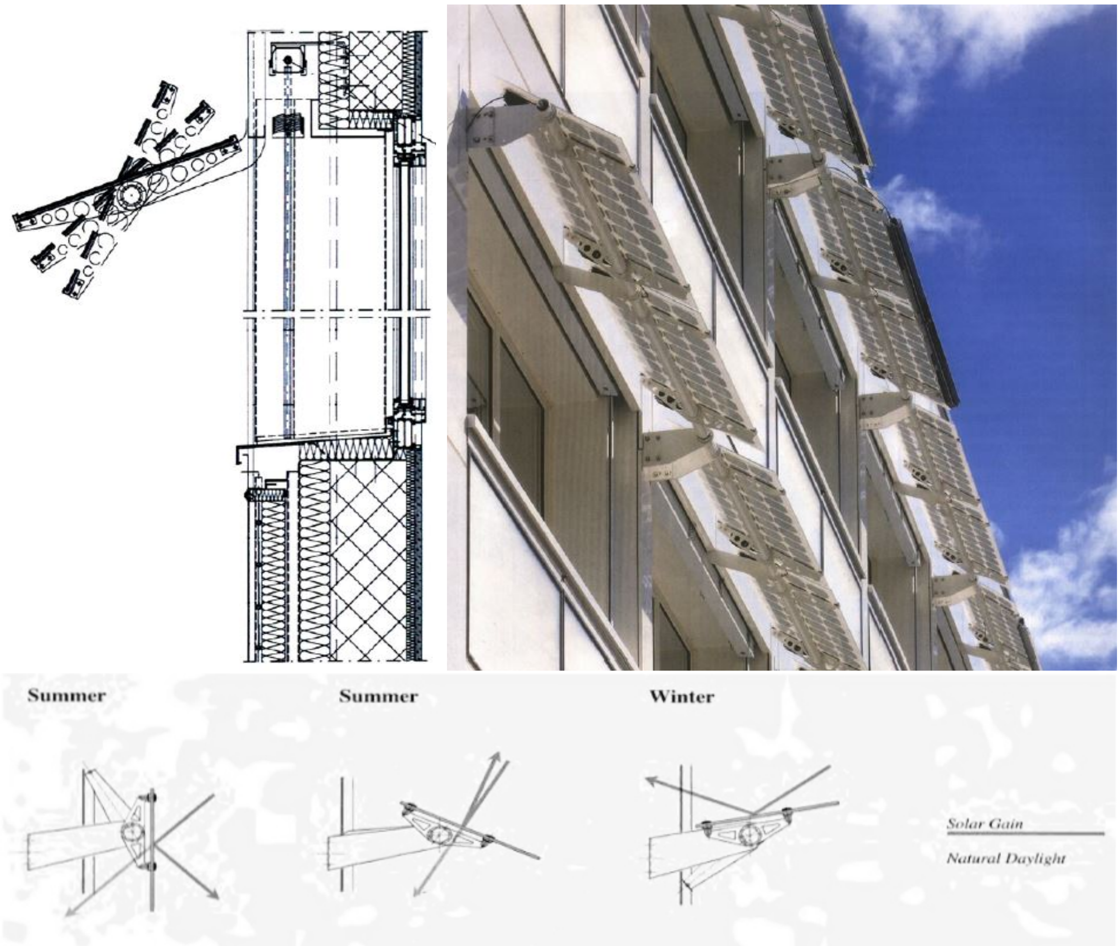
d. Installation combined with photovoltaic cells

The shielding application is proposed as a possible field of use of active solar devices: for the contribution to the energy conditions; and for the contribution towards the use of alternative and sustainable sources. In this regard, we note the execution of the photovoltaic modules aimed at converting solar radiation into electrical energy, simultaneously guaranteeing shielding from natural light (Fig. 2.12). Luminous calibration devices affirm themselves as mediation tools between the variable outdoor climatic conditions and those relatively constant in the internal spaces.

They are useful for filtering and intervening on energy flows, until they are accumulated to obtain electricity. The operation involves the direct conversion of solar radiation into electrical energy through the use of photovoltaic cells (generally in silicium). The photovoltaic cells are composed according to:

- The monocrystalline type. The resulting cells are opaque and the color varies from blue and gray to black (this derives from the anti-reflective coating in titanium oxide, aimed at optimizing the collection of solar radiation);

Figure 2.12: Combination with photovoltaic modules and scheme of behavior in the different seasons of the shielding system (with qualitative patterns of reflected and transmitted radiation inside).



Source: [9]

- The polycrystalline type. The resulting cells are defined by an opaque blue color.

The crystalline photovoltaic cells are produced in small disks (generally square shaped of thickness = 0.4 mm), mounted in modules arranged on laminated glass plates (through the interposition of transparent resinous layers) and connected by conductors designed to absorb and to transfer the electricity produced. The modules are transparent, translucent or opaque, according to the connective configuration (which involves a variable light transmission with respect to the distance between the cells).

The execution of photovoltaic modules (aggregated in sandwich compounds) takes place in a frameless form or with a frame in aluminum profiles.

This last solution allows you to work on larger lights and the glasses can also cover the support elements, creating the image of the curtain wall.

They are used individually or connected (in series and/or in parallel) to create “strings" (such as sets of modules connected in series) and “photovoltaic fields” (established by the modules and by the connections referred to a single system).

Their application with respect to the enclosure follows assembly criteria:

- indipendent, if the arrangement has no closing function and is not conditioned by the morphological constitution;

- by overlapping, with the use of structures adjacent to the vertical closures.

The construction assumes the compatibility both with the building envelope (and, therefore, with the relative fixing structures of the panels), and with the orientation conditions (for which the southern view is preferred, providing limited losses in the east facing and west), by the inclination specified by the geographical location.

The use of photovoltaic *brise-soleil* makes possible to calibrate (using cell patterns) and absorb light radiation: the distance between the cells of a string is variable (between $2 \div 10$ mm), as is the distance between the strings themselves, which can thicken or distance depending on the needs. [8]
The advantages of combining transparent shielding systems with photovoltaic systems are the following:

Natural Cooling: the photovoltaic cells are installed on an open structure on both sides to facilitate ventilation and air circulation and cooling.

Angle Optimization: the cells can be tilted so as to expose their surface to the sun’s rays, offering 15% more efficiency than fixed-cell systems. The same angle guarantees the maximum shielding effect;

Light Shelf: in certain situations (for example, with gray skies in winter) the screens can be tilted to reflect light inside the building. For this purpose, special structures can be made in which the rear part of the screens has a reflective surface. Further energy savings can be achieved by reducing artificial light consumption, especially if the natural light and shielding control system is integrated into a computerized system.

Figure 2.13: Electrochromic Windows: Flexible Solution for a Solar Control

Source: [10]

The large and widespread construction of buildings in which photovoltaic systems integrated in solar shading systems are applied will result in significant global energy savings in the future.[9]

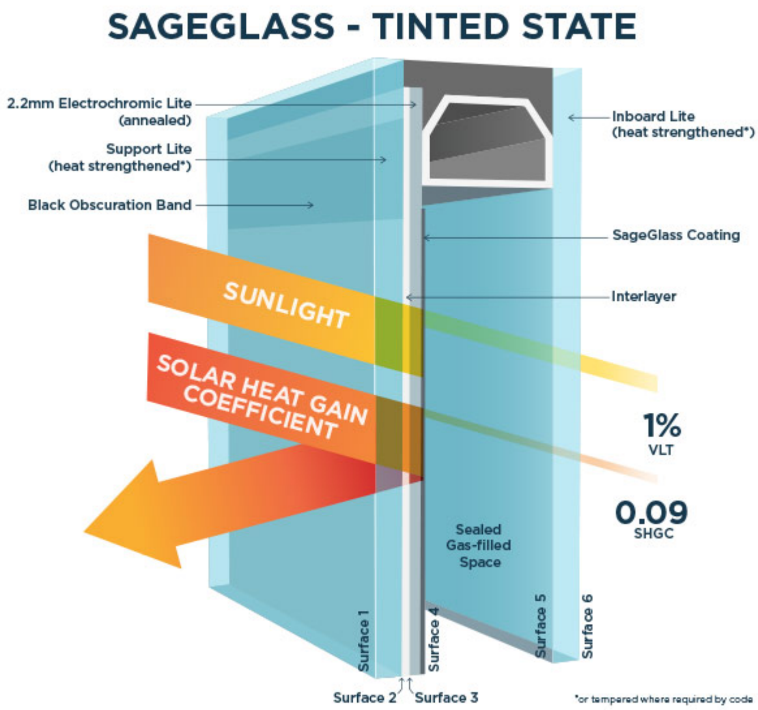
e. Electrochromic Glazing

The normal windows are equipped with common glass. These maintain their transparency regardless of whether there is a downpour outside or the summer sun. They also take all the outside heat and light inside the room. On their own, therefore, the classic glasses are not able to improve well-being within the home.

Electrochromic glass, on the other hand, is able to change its level of darkness depending on the amount of light that hits it. This process can take place automatically, a bit like the photochromic lenses of eyeglasses, but can also be set based on your needs with the help of a smartphone. So electrochromic glass, which can be directly controlled by building occupants, is popular for its ability to improve occupant comfort, maximize access to daylight and outdoor views, reduce energy costs and provide architects with more design freedom. Electrochromic glass is a smart solution for buildings in which solar control is a challenge, including classroom settings, health-care facilities, commercial offices, retail spaces, museums and cultural institutions. (Fig. 2.13)

Companies as Saint-Gobain believed in high-performance glazing solutions for

Figure 2.14: Layers of the Electrochromic Glass Sageglass



Source: [10]

excellent living spaces. This is how Sageglass, their product, is born which offers a variety of control options: users can operate automatic control settings to manage light, glare, energy use and color rendering (blue, gray or green). The controls can also be integrated into an existing building automation system. Users can also change the tint level via the SageGlass mobile app.

In addition, SageGlass can help building owners achieve their sustainability goals through energy conservation by maximizing solar energy and minimizing heat and glare. The company declares that their product allows building owners to achieve cost savings over the building's life cycle by reducing overall energy loads by an average of 20 % and peak energy demand by up to 26 %. The widespread use of smart glasses is also facilitated by the ease of installation and maintenance.

Electrochromic windows change from transparent to tinted by applying an electrical current. A voltage Low-voltage, in fact, causes a chemical reaction that gives rise to the gray color until it is completely darkened. In any case, electricity is only used in the transition phases. It is therefore used in the transition from the transparent to the darkened state and vice versa.

The five layers of electrochromic coating (Fig. 2.14) include two transparent

conductor (TC) layers: one electrochromic (EC) layer, sandwiched between the two TC layers; the ion conductor (IC); and the counter electrode (CE). Applying a positive voltage to the transparent conductor in contact with the counter electrode causes lithium ions to be driven across the ion conductor and inserted into the electrochromic layer. Simultaneously, a charge-compensating electron is extracted from the counter electrode, flows around the external circuit and is inserted into the electrochromic layer.
Taking as an example the large floor-to-sky window, it takes less than three minutes to go from complete darkness to a transparent state. However, as already mentioned above, it is possible to vary the coloring of the glasses according to your needs, they are also programmable. Their activity can be set based on the season, the position of the sun or weather conditions. [11]

2.4 A Summary

In this chapter we understood the importance of natural light design in order to develop sustainable buildings.

Over the past 30 - 40 years, numerous innovative technologies have been created to take advantage of natural light. The modular and parametric design and the technological approach have been studied. Basically, there are two types of systems to take advantage of daylight: side-lighting and top-lighting, both analyzed so far.
The first is the most classic, i.e. the conventional vertical opening towards the outside which, however, rapidly decreases the incoming light as you move away from the window. The deeper a room, the less natural lighting will be inside it.
Lighting systems from above are represented by roof openings. These must be examined very carefully due to possible overheating due to incorrect design.

As a summary, in fact, a study conducted by Ing Liang Wong highlights how these systems can be divided into two categories:

1. LGS or Light Guidance Systems, which are the simplest ways to illuminate by reflecting and directing light right down the room;

2. LTS or Light Transport Systems, able to accumulate and distribute sunlight in the most internal areas of a building.

1) The most conventional shading systems, such as sunscreens or Venetian blinds, are the most commonly used as they are simple and inexpensive. However, they

Table 2.1: Strengths and weaknesses of light guiding systems

Light guiding system	Tilt-able	Solar shading	Ease of application	Ease of maintenance	Thermal reduction	Allow view
Light guiding shade	No	Yes	Window	Easy	Yes	Yes
Reflective blinds	Yes	Yes	Window	Easy	Yes	Limited
Venetian blinds	Yes	Yes	Window	Easy	Yes	Limited
Movable blinds	Yes	Yes	Window	Easy	Yes	Limited
Light shelves	No	Yes	Window	Easy	Yes	Yes
Prismatic louvers	Yes	Potential	Window	Easy	Yes	Limited
Mirror systems	No	Yes	Fixed Louvre	Difficult	Yes	Limited
Prismatic glazing	No	Potential	Window & Roof	Difficult	Yes	Limited
Translucent louvers	Yes	Yes	Window	Difficult	Yes	Limited
Transparent insulated glazing	No	Potential	Inside Double Glazing	Easy	Potential	Limited
Toplight on roof	No	No	Roof	Difficult	Potential	Limited
Solar screens	No	Yes	Window	Difficult	Yes	Limited
Skylight on roof	No	No	Roof	Difficult	Potential	Limited
Lightscoop skylight	No	No	Roof	Difficult	Potential	Limited
Shed-type rooflight	No	No	Roof	Difficult	Potential	Yes
Holographic films	No	Yes	Inside Double Glazing	Easy	Potential	Yes
Active modular glazing panel	No	Yes	Window	Easy	Yes	Yes
Three-layered rooflight	No	No	Roof	Difficult	Potential	Limited
Façade panels with PCM	No	Potential	Inside Double Glazing	Easy	Potential	Limited

can be integrated into existing openings, improving light distribution and reducing glare and overheating in close proximity to the windows. Other examples of LGS can therefore be light shelves, fixed louvers, light directing louvers or glass.
They can be installed at the top of a typical window, however allowing light into the room and can be found both on the inside and outside the window, as well as in the central part of a double-layer glass.
There are innovative types of skylights defined as active or passive; the former may even have components to track the position and path of the sun.
"A higher level of useful daylight illuminance could be achieved when a rooflight to floor area ratio is between 0.15 and 0.20. A rooflight area of up to 20% of the total building floor area could contribute to more than 1000 lx of illuminance in horizontal plane"[13]
A table is shown with the strengths and weaknesses of each of the LGS studied. (Tab. 2.1)

2) The LTS, more complicated but also more effective, are used in rooms larger than 10 m. Their job is to collect, redirect, transport and distribute sunlight within the rooms. Examples of LTS are the light pipes, vertical between the floors or horizontal through walls, which bring the light at a distance of even 30 m inside the buildings. Their application is however limited by the diameter of the tubes which cannot be less than 20 times their length.
There are also Anidolic daylighting systems, which are a small type of light pipe. They contain curved light collectors that increase their performance and can illuminate a room of around 40 m^2, improving light flow inside the buildings.

Table 2.2: A summary of strengths and weaknesses of both light guiding and transporting systems.

Daylighting system	**Strengths**	**Weaknesses**
Light guiding system	Easier to implement and apply to window opening Easier to maintain Cheaper compared to LTS Higher efficiency with longer hour of workplane illuminance	Lower efficiency compared to LTG Practicality depends on tiltable angle of system Subject to external obstruction Potential view obstruction Some LGS may require high demand of user participation Expensive and require modification to building interior
Light transporting system	Minimum external obstruction Applicable to buildings with complicated design	Higher maintenance rate Performance constrained by overcast sky conditions and changeable solar altitudes Light leakage from roof penetration

In general, *"despite a wide range of developed and commercially available daylighting systems that have been reported, their applications have been limited by a lack of studies on their utilizations and high initial costs."* [13]
For this reason, a table is presented summarizing the strength and weakness characteristics of the two LGS and LTS systems. (Tab. 2.2)

Chapter 3

Theoretical Fundamentals

After seeing how far the research has progressed in terms of exploiting the benefits of natural lighting, a theoretical introduction has been drew up in order to illustrate what are the dominant factors within this field, what they represent and the effect on occupants of the room under examination.

3.1 Photometry

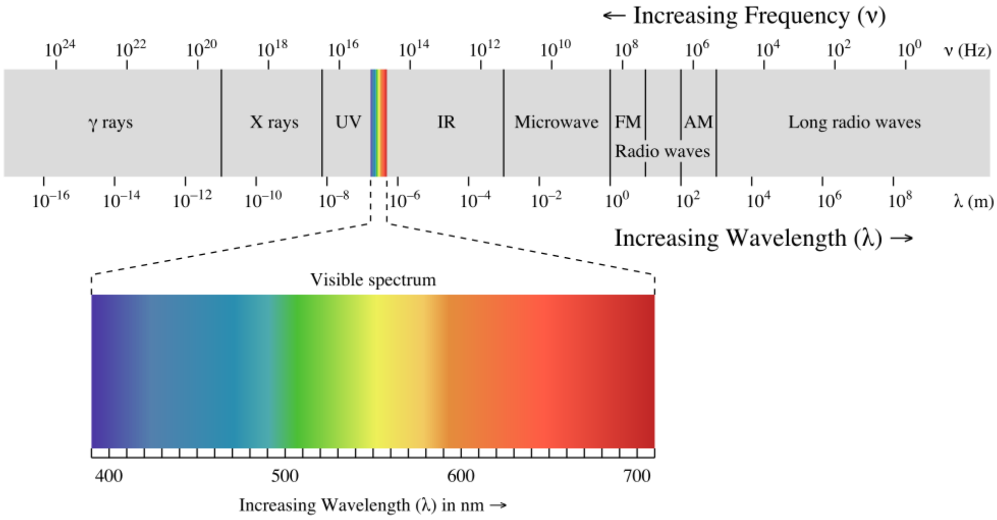
3.1.1 Light and Electromagnetic Radiation

The light is conventionally the part of the electromagnetic radiation that is received by the human eye. The Illuminating Engineering Society of North America (IESNA) defines light as *"radiant energy that is capable of exciting the retina and producing a visual sensation"*. [14] The visible region is only a portion of the radiant energy spectrum emitted by the sun; in fact the wavelength means a frequency range of roughly 380-780 nm (Figure 3.1) instead the sun, which can be assimilated to a black body characterized by an apparent surface temperature of about 5780 K, emits in the surrounding space a very high amount of radiant energy (equal to $3.88 \cdot 10^{26}$ W) in a range of wavelengths between 0.2 and 3 µm.

3.1.2 Basic Photometric Principles

The sun is therefore a light source, whose emission can be characterized through physical quantities which describe its chromatic quantity and quality: luminous flux, in terms of quantity and emission spectrum, in terms of quality. The luminous flux is the effect the total emission of the source - or also the entity of the luminous impression produced by the radiation emitted by the source - has on the eye. The emission spectrum represents the distribution of the luminous flux for the

Figure 3.1: The electromagnetic spectrum, with the visible portion highlighted



Source: https://www.engineeringtoolbox.com/electromagnetic-spectrum-d_1929.html

wavelengths responsible of the different chromatic sensations. Quantitative and qualitative characteristics of light are in any case perceived by the human eye, which weighs differently the different monochromatic radiations depending on its wavelength. [14] We write:

$$\Phi_e(\lambda) = \frac{d\Phi_e}{d\lambda} \tag{3.1}$$

to indicate spectral radiant flux, in other words the power associated with a monochromatic radiation (W/μm) with λ that is the wavelength, while the radiant flux (W) will be:

$$\Phi_e = \int_0^\infty \Phi_e(\lambda) d\lambda \tag{3.2}$$

is the flow rate of radiant energy and so we can define $\Phi(\lambda)$, spectral radiant flux, measured in lumen per micron (lm/μm):

$$\Phi(\lambda) = K(\lambda)\Phi_e(\lambda) \tag{3.3}$$

Where $K(\lambda)$ is the spectral luminous efficacy (lm/W), the ratio of luminous flux to radiant flux. In other words, spectral luminous efficacy describes the absolute eye response of the normalized efficiency function. [15]

The luminous flux (lm) will be:

$$\Phi = \int_0^\infty K(\lambda)\Phi_e(\lambda) d\lambda \tag{3.4}$$

The eye tends to adapt to the average lighting conditions of the surrounding environment: for example, during the day the photo-receptors that show us the light in three bands of color are the cones (photopic vision), at night instead the rods are activated and we see only gray tones (scotopic vision). [15]

The CIE defines $K(\lambda)$ for photopic vision as 683 lm/W at 555 nm. For other wavelengths, $K(\lambda)$ for photopic vision can be calculated using the following equation:

$$K(\lambda) = K_{max} V(\lambda) \tag{3.5}$$

Where:
K_{max} = 683 lm/W;
$V(\lambda)$=the value of the photopic spectral luminous efficiency function for that wavelength (Figure 3.2).

For scotopic vision, spectral luminous efficacy is denoted by $K'(\lambda)$, and can be calculated using the following equation:

$$K'(\lambda) = K'_{max} V'(\lambda) \tag{3.6}$$

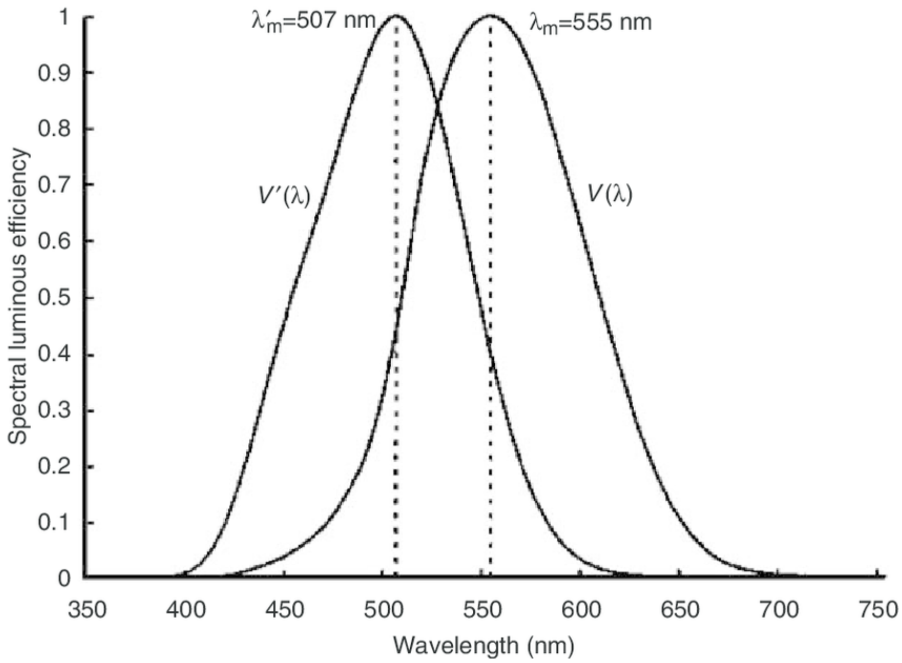
Where:
K'_{max} = 1700 lm/W;
$V'(\lambda)$=the value of the scotopic spectral luminous efficiency function for that wavelength (Figure 3.2). By definition, all other wavelengths are scaled according to either the photopic or the scotopic luminous efficiency functions. This luminosity functions are standard functions established by the Commission Internationale de l'Éclairage (CIE) and may be used to convert radiant energy into luminous (i.e. visible) energy. [16]

3.1.3 Photometric Quantities

Luminous Intensity I is the measure of visible power per unit solid angle of light, measured in candela, the amount emitted, in a given direction, by a monochromatic radiation of frequency $=540 \times 10^{12}$ Hz that has radiant intensity = 1/683 W/sr^2 in that direction. It depends on the elements that guide the light, such as the reflectors. The photometric curve (LVK) is the graph that represents it on the photometric polar diagram. The luminous intensity I is measured in candela (cd)[15][14].
It is also related to luminous flux via the relation:

$$I = \frac{d\Phi}{d\omega} \tag{3.7}$$

Figure 3.2: Photopic $V(\lambda)$ and Scotopic $V'(\lambda)$ luminosity functions.



Source: https://www.researchgate.net/figure/The-CIE-photopic-and-scotopic-spectral-luminous-efficiency-functions-V-and-V-0_fig1_258169165

And so the luminous flux is:

$$\Phi = \int_{4\pi} I d\omega \tag{3.8}$$

Illuminance E is the measure of luminous flux incident on a surface per unit area. The SI unit for illuminance is lux (lx) i.e. $1\mathrm{lm/m^2}$ and it is defined as:

$$I = \frac{d\Phi}{dS_{ric}} \tag{3.9}$$

with S_{ric} represents the incident surface.

Luminance L is the only photometric measure perceived by the human eyes. Describes the impression of brightness that both light sources and surfaces give and depends on their reflectance index (color and surface); in other words, luminance is the density of visible radiation in a given direction. The SI unit for luminance is candela per square metre ($\mathrm{cd/m^2}$). A non-SI term for the same unit is the nit. Indeed, we define it:

$$L = \frac{d^2\Phi}{d\omega dS_{em}\cos\epsilon} = \frac{dI}{dS_{em}\cos\epsilon} \tag{3.10}$$

Where:
S_{em} is the emitter surface;
ϵ is the emittance angle. [15][14]

3.1.4 Basic Concepts in Optics

Optics deals with the study of light ray paths and phenomena related to the propagation of light in general. Light, in a vacuum and in transparent materials, travels in a straight line. There are situations in which the straight path of a ray of light can be deviated, these are the following physical phenomena:

a. reflection, whenever the light meets a material on which it bounces;

b. refraction, whenever the light passes from a transparent medium to another transparent medium (for example a ray of light that first passes through air and then water, or glass, or plastic, etc ...);

c. transmission, whenever the light passes through an object;

d. absorption, whenever the object absorb part or all of the incident light.

These properties are discussed in this section. Note that these properties are applicable to light but also to other forms of electromagnetic radiation. However, to simplify, the study will be limited to light. [14]

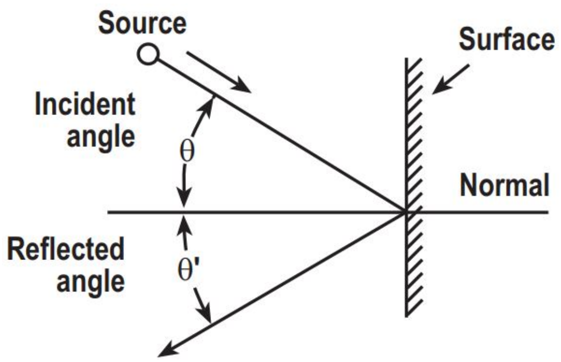
3.1.4.1 Reflection

Reflection is the optical phenomenon whereby a light ray that hits a mirror (or, in general, a reflecting surface) is reflected away from the surface to the half-space where the light source is located. There are different types of reflection: specular, in the case of highly glossy surfaces such as a mirror, spread, with rough surfaces, and diffuse, also called Lambertian dispersion, in the case of opaque surfaces. Specular reflections demonstrate the law of reflection.

The ray that hits the reflecting surface is called the *incident ray*, while the one that comes back is called the *reflected ray*. At the point where the incident ray strikes the surface, we can trace the perpendicular to the surface itself and define two angles: the angle of incidence θ, between the normal and the incident ray, and the angle of reflection θ', between the normal and the reflected ray (Figure 3.3). Experimentally we observe that:

- the angle of incidence θ is always equal to the angle of reflection θ';

Figure 3.3: Law of reflection



Source: [14]

- the incident ray, the reflected ray and the normal to the reflecting surface at the point of incidence they all lie on the same level.

3.1.4.2 Refraction

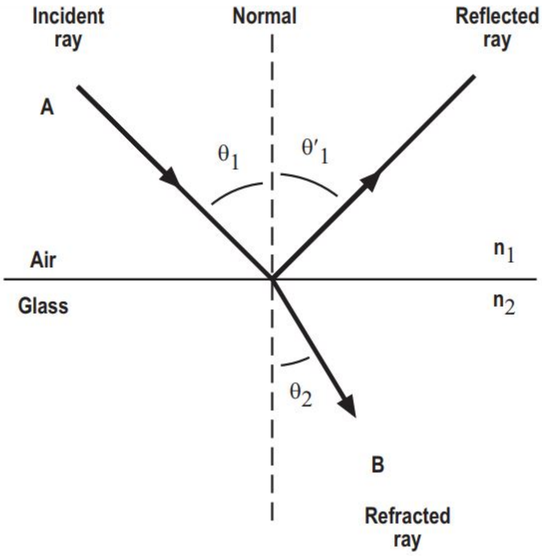
Up to this point, we considered cases in which light passes through a single medium: air. The next step will be to observe what happens in cases where light passes through different media and passes, for example, from air to water. it is called refraction the optical phenomenon that occurs whenever a light ray passes through the surface that separates two transparent media of different densities (for example, air and glass, air and plexiglas, plexiglas and water, air and water, etc.).
The following concepts can therefore be introduced:

- it is called the incident ray that reaches the separation surface of the two media;
- it is called refracted ray what passes in the second medium;
- the angle of incidence (as already seen for the reflection) is that formed by the perpendicular to the separation surface and the incident ray;
- the refraction angle is the one formed by the refracted ray and the perpendicular to the separation surface.

So refraction depends on the angle θ but also on the refractive index of material n, defined as the ratio of light speed in vacuum and light speed in the material:

$$n = \frac{c}{v} > 1 \tag{3.11}$$

Figure 3.4: The refraction phenomenon and the Snell's law



Source: [14]

On the basis of equation (3.11) we can deduce that n is always greater than 1, since the speed v in any material is always less than the speed of light in a vacuum $c \cong 300 \text{km/s}$.

There is a physical law, shown in the figure 3.4, known as *Snell's law*, that allows us to calculate the relationship between the refraction angle and the incidence one knowing the index of refraction:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \tag{3.12}$$

Where:
n_1 = the refractive index of medium 1;
n_1 = the refractive index of medium 1;
θ_1 = the incident angle;
θ_1' = the reflected angle;
θ_1 = the refracted angle.

Actually, after having separately examined the two phenomena of refraction and reflection, It should be pointed out that the two phenomena take place simultaneously: when a light ray affects a flat surface separating two homogeneous and transparent media, a part of the incident light is reflected and a part is refracted, as can be seen in the figure 3.4.

It is important to observe these phenomena also from the energetic point of view, considering that if part of the incident ray is reflected, part of the energy that the ray transports (light energy) will be reflected with it and that therefore the refracted ray will carry a reduced energy load .

3.1.4.3 Transmission

When light passes through an object, it is called transmission. The transmission is defined as:

- direct: when the material (glass, plastic, etc.) lets much of the light in;
- diffuse: when the light coming out of the vehicle spreads in all directions (translucent material);
- mixed: when the light spreads according to a privileged direction.

3.1.4.4 Absorption

Absorption is the ability of a material to absorb the energy associated with electromagnetic radiation, more specifically with the incident ray of light, which propagates inside it. Many materials select which wavelength to absorb and which to transmit; this capability is called *selective absorption*. The absorption *law of Lambert* correlates the amount of light absorbed by a substance with its concentration, its chemical nature and the thickness of the medium crossed. In practical terms, light that hits a material loses some of its energy in a way that is directly proportional to the type of material and the thickness of material. This law is defined as:

$$I = I_0 e^{-\alpha x} \tag{3.13}$$

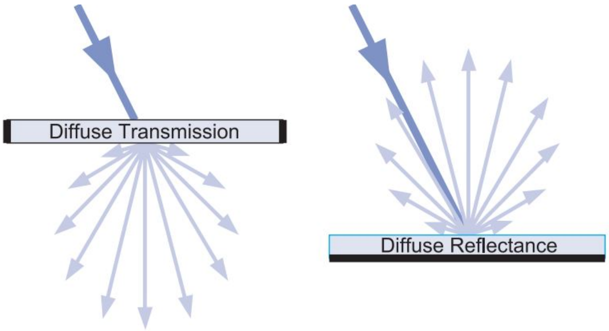
Where:
I = luminous transmitted intensity;
I_0 = luminous intensity entering the material;
α = the absorption coefficient;
x = the thickness of the object

3.1.4.5 Diffusion (Scattering)

When light hits a rough surface, the light is reflected or transmitted in many different directions at once, which is called diffusion or scattering (Figure 3.5). The amount of diffuse transmission or reflection that occurs depends on two factors:

- the difference between the two materials' refractive index;

Figure 3.5: The reflected and trasmitted Diffusion



Source: [14]

- the size and the shape of the particles in the diffusing material compared to the wavelength of the light.

The phenomenon refers to the dispersion of light by more or less microscopic objects: an example of light diffusion is given by the blue color of the sky (*Rayleigh scattering*): the (white) light of the sun affects the earth's atmosphere, whose molecules, during the day, diffuse more easily the higher frequencies (i.e. the colors close to blue and violet); consequently, while the light comes to the earth directly from the sun, the diffused blue light comes to us from all directions.

3.2 Basics Concept in Colorimetry

Hints of colorimetry are still needed. Colorimetry is the measurement science used to quantify and describe physically the human color perception. The colors of the objects derive from the spectral characteristics of the light that affects them and from the monochromatic properties of absorption, reflection and transmission of the objects themselves. The spectral composition of the radiation, coming from the object, stimulates the three types of cones present on the human retina producing the sensation of color. In fact, the color of an object is identified by the spectral composition of the visible radiation coming from it. The three types of cones present on the retina have a different sensitivity when the wavelength varies: the vision of a particular color is given by the combination of the three stimuli, of different intensity, coming from the three receptors.[17]

The trichromatic theory predicts that by appropriate mixing of three "primaries", a stimulus equivalent to the corresponding monochromatic radiation can be obtained for each wavelength. The triplet corresponding to the "white energy", is the one that corresponds to a radiation having a constant energy distribution for each wavelength.

Three primary stimuli often used correspond to the following wavelengths:

- R: $\lambda = 700$ nm;
- G: $\lambda = 546.1$ nm;
- B: $\lambda = 435.8$ nm.

The additive synthesis of three primaries does not allow to generate all the colorimetric space. Therefore, three functions have been constructed based on which all possible chromatic stimuli can be generated additively. So, it is possible to pass from the coordinates RGB to XYZ by means of linear transformations.The RGB color space and XYZ color space were created by the International Commission on Illumination (CIE) in 1931. The CIE defined a two-dimensional space called the Chromaticity Diagram (Figure 3.6) which included all the colors visible to the human eye, regardless of luminance. Any color within this two-dimensional space can have a luminance that varies from white to black: if the luminance component is also taken into account, the space thus defined becomes three-dimensional and can be represented using an XYZ coordinate system.

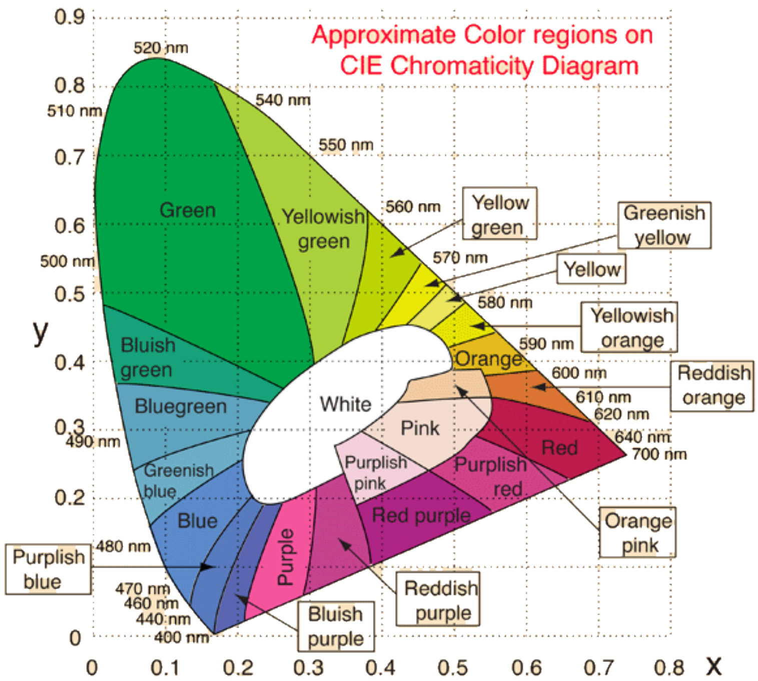
- At the center of the CIE diagram there is a point (indicated with a small circle), of strategic importance. It is the so-called "CIE Illuminant", taken as a reference and corresponding to the radiation emitted by a white surface illuminated by average daylight;
- Along the bell curve perimeter there are all the spectral hues with their maximum saturation;
- At the top of the diagram there are the families of the greens; in the lower left the blues, in the lower right the reds.

The diagram is based on the concept of Standard Observer, which is based on systematic analysis carried out on a large sample starting from the properties of the human visual system. [18]

3.3 Natural Lighting

After analyzing the light, deepening photometric principles and optics and photometric concepts, it is fundamental to analyze natural lighting to know what are its characteristics and its effects on human beings. Natural lighting is an essential

Figure 3.6: Illustration of the CIE 1931 xy Chromaticity Diagram



Source: http://www.gianlucatramontana.it/blog/2017/07/teoria-del-colore-spazi-di-colore-e-modelli/

element in lighting design. The contribution of natural light must be privileged, as in addition to energy-type benefits it brings psychological benefits to people.
Natural light comes from natural light sources, the sun and the sky, which contrast with the artificial light sources, the bulbs. [15]
Luminous efficiency is the fundamental characteristic of a light source. It is equal to the ratio between the luminous flux emitted and the energy flow emitted:

$$\eta = \frac{\Phi}{\Phi_e} \tag{3.14}$$

Where Φ_e is the flux product by radiation, so, recalling the (3.4) and the (3.2) equations, we can write:

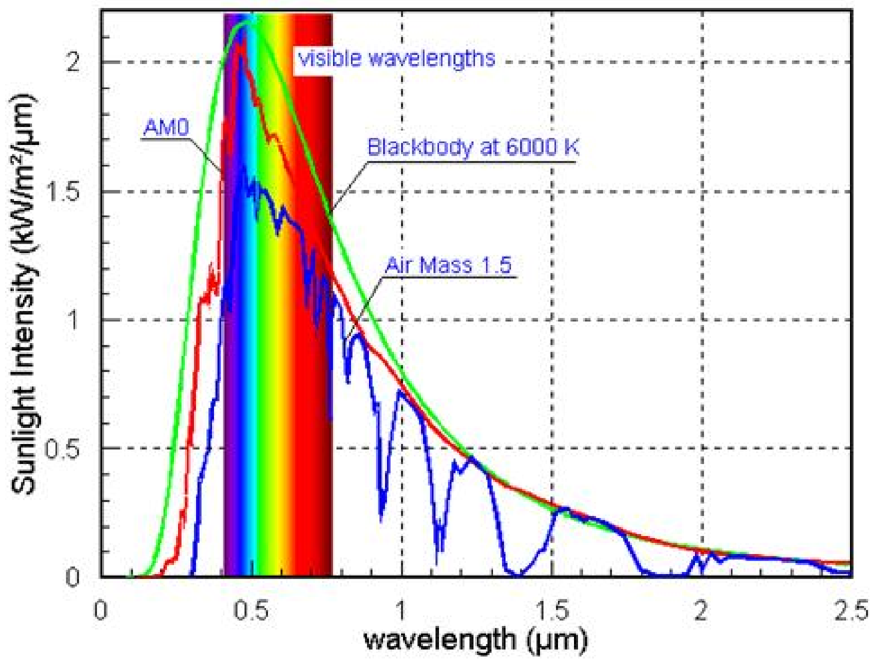
$$\eta = \frac{\Phi}{\Phi_e} = K_{max} \frac{\int_0^\infty V(\lambda)\Phi_e(\lambda)\,d(\lambda)}{\int_0^\infty \Phi_e(\lambda)\,d(\lambda)} \tag{3.15}$$

3.3.1 Natural Light Sources and Solar Radiation Spectrum

The main natural light features are that it covers the entire visible spectrum, from violet to red, and dynamic, as opposed to artificial light source. From the energy point of view, the amount of power emitted by the sun per unit area is called *Solar*

Irradiance SI. As indicated in section 3.1.1, solar radiation has a continuous spectrum outside the atmosphere, very similar to that of a black body. The magnitude of direct extra-atmospheric solar irradiance on a surface normal to solar rays is called *Solar Constant* G_{sc} and is worth about 1361 W/m^2. Outside the atmosphere the sky appears black.
The figure 3.7 shows the typical curve of a black body and the emission curve referred to the earth's surface: the two deviate a lot, especially in the $300-600<$ nm. [14] [15]

Figure 3.7: Solar radiation spectrum



Source: [19]

The extraterrestrial radiation above the atmosphere is partly:

- reflected by clouds;
- absorbed by atmospheric gases;
- scattered by nitrogen and oxygen molecules.

These losses depend on the time of day, cloud cover, moisture content and other contents and can attenuate direct solar irradiance and determine diffuse solar irradiance. The Diffuse component of the flux deviated for the first time by atmospheric gases, then encounters other molecules and suspended particles that divert it all around. From all this a diffused light field is generated, identified with the term light of the sky.

3.3.1.1 Direct and Diffuse Radiation

The light that reaches the surface of the Earth is therefore the sum of the diffuse sky's radiation, which comes from every point of the sky, and of the direct sunlight that has not been diverted and that preserves the original spectrum and direction. On the purposes of the quantity and quality of the natural lighting in architecture, it is necessary to emphasize how the direct and diffuse radiation are both of great importance.

Direct Component sunlight is a warmer white and concentrated light whose high luminance produces very marked contrasts and causes disturbances in vision (glare and visual discomfort). Because of the reduced visual area occupied by this type of light and his marked directionality, this object's spatial perception is not optimal. Since these are perceived with an excessive asymmetrical luminosity, this may prevent us from fully reaping its three-dimensionality. [20]

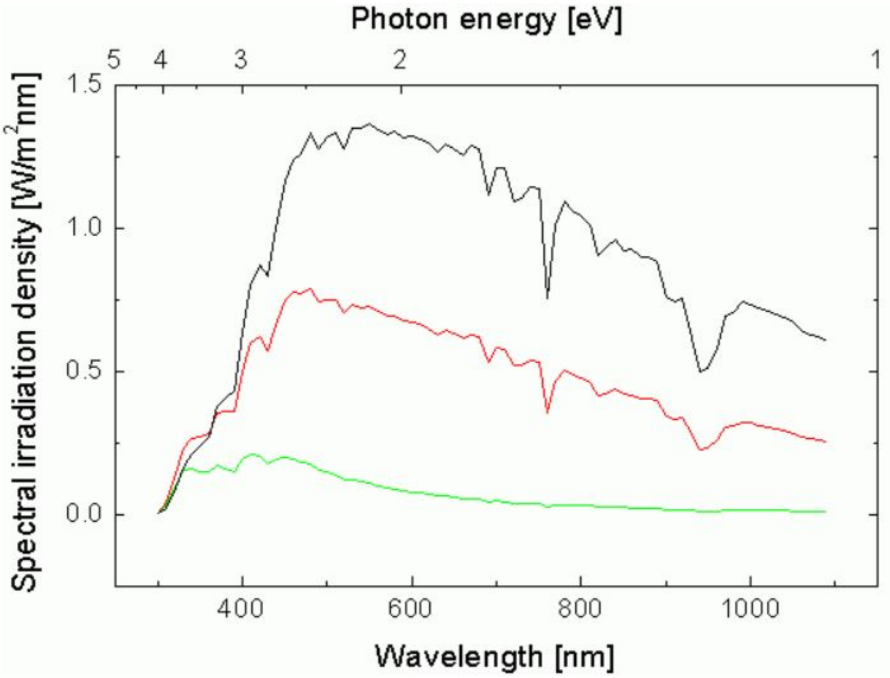
Diffuse Component The light coming from the sky is a cooler white light whose luminance, distributed over the entire sky, is contained. Being a diffused light, it is uniform and therefore produces little marked contrasts between the different parts of a room, as well as between the inside and the outside. Here again, the perception of the resulting objects is a bit flat due to the lack of effects that highlight the different parts. The best effect is obtained, therefore, ensuring the coexistence of both components. [20]

3.3.2 Natural Light Impact

First of all, to know the amount of natural light that penetrates into an indoor environment, the quantity of light that, for every moment, reaches the Earth should be known: the direct and diffused components depend very much on atmospheric and meteorological conditions.

When the sky is clear and the sun is very high in the sky, direct radiation is around 85% of the total insolation striking the ground and diffuse radiation is about 15%. Conversely, in very turbid atmospheres, the amount of radiation that reaches the Earth directly from the sun is reduced, while that from the sky prevails. Atmospheric conditions like clouds and pollution also increase the percentage of diffuse radiation. On an extremely overcast day, pretty much 100% of the solar

Figure 3.8: Comparison of typical irradiation spectra (recorded at 12 am on March the 28th 1987 in Golden, Colorado USA)



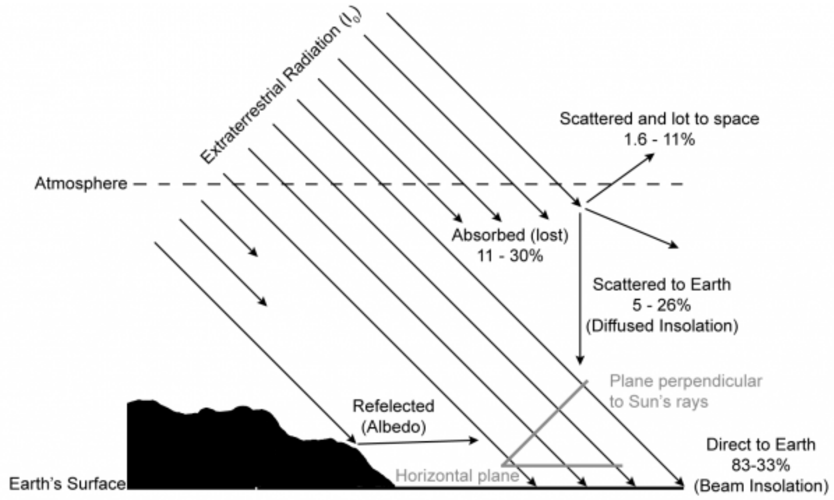
Source: https://www.tfp.ethz.ch/Lectures/pv/spectrum.html

radiation is diffuse radiation.
The percentage of the sky's radiation that is diffuse is much greater in higher latitude, cloudier places than in lower latitude, sunnier places. Also, the percentage of the total radiation that is diffuse radiation tends to be higher in the winter than the summer in these higher latitude, cloudier places. The sunniest places, by contrast, tend to have less seasonal variation in the ratio between diffuse and direct radiation. [21]

The attenuation of the light in the atmosphere depends also on temperature, pressure, pollution, moisture and many more. The figure 3.8 shows an example of spectra of direct normal (black), global horizontal (red), and diffuse (green) radiation registered in Colorado USA. The red curve is composed of the direct irradiance (black curve corrected for the incident angle) and the diffuse background (green curve).[22]

In order to assess what the actual amount of solar radiation incident on the Earth's surface is, the thickness of the atmosphere that the radiation must be able to cross must also be taken into account. The more the sun is perpendicular to the earth's surface (daylight hours), the radiation passes through a smaller layer

Figure 3.9: The effect of the atmosphere on the solar radiation reaching the Earth's Surface



Source: https://www.itacanet.org/the-sun-as-a-source-of-energy/part-2-solar-energy-reaching-the-earths-surface/

than during the pre-evening hours, when the thickness crossed by the radiation is greater.[23]

In other words, the greater the layer to be crossed, the greater the energy content retained by the atmosphere before the solar radiation can reach the Earth's surface (Figure 3.9).

3.3.3 Solar Geometry and Sun as a Source of Light

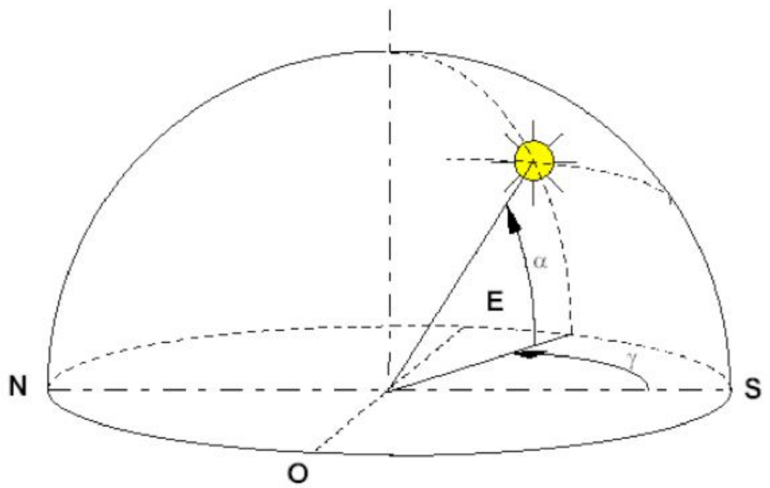
To be able to calculate the solar radiation on a plane on the earth's surface, you need to know the relative position of the sun on the sky and the plane's coordinates. The sun position is defined if the reference system is specified, in fact it is function of both the geographic localization and the time.
For an observer who is on the Earth the sun seems to move about 1° every day from West to East along the Ecliptic (the solar apparent path on the celestial sphere which it makes in a year). This is because of the Earth's *Revolution movement* around the sun done in a year. The inclination of the Earth Axis in comparison to the Axis of the Ecliptic is 23°27′, so also the respective plans of the celestial Equator and of the Ecliptic, perpendicular to them, intersect each other maintaining the same angle. [20]

Suppose an observer on Earth and the celestial sphere concentric to the Earth. At a given instant, the observer will be identified, in the sky, by his zenith, corresponding to the intersection of the sky with the normal of the earth's surface where the observer is placed. On the celestial sphere, opposite to the zenith, there is the nadir.

The *Solar zenith angle* (θ_z) is the angle formed by the vertical zenith direction to centre of the sun's disc. This angle can vary at most between 0° and 90°.

The position of the sun in relation to a point on the Earth is determined by the solar altitude angle, α, and by the azimuth angle, γ (Figure 3.10).

Figure 3.10: Solar altitude angle (α) and Solar azimuth angle (γ)



Source: https://www.tfp.ethz.ch/Lectures/pv/spectrum.html

The *Solar altitude angle* (α) is the angle formed by the direction of the solar rays, those directed towards the Earth, with the Earth's horizon.

The *Solar azimuth angle* (γ) is the angle formed between the projection on the horizontal plane of the sun rays and the south direction. It is positive if the projection falls towards the east (before solar noon) and is negative if the projection falls towards the west (after noon) and can vary between 0° and ±180°.

Knowing the Solar geometric properties, in addition to the phenomena of the sky, is the way to assess the amount of solar radiation that reaches the Earth's surface at a given time.
In general, in a north latitude, the sun paths are the ones represented in the figure

3.11. It is reported specifically the sun path diagram of Madrid: the highest curve refers to the summer solstice (on June th 21^{st}); the lower curve at the winter solstice (December the 21^{st}); the yellow colored area is the annual variation of the sun path. [24]

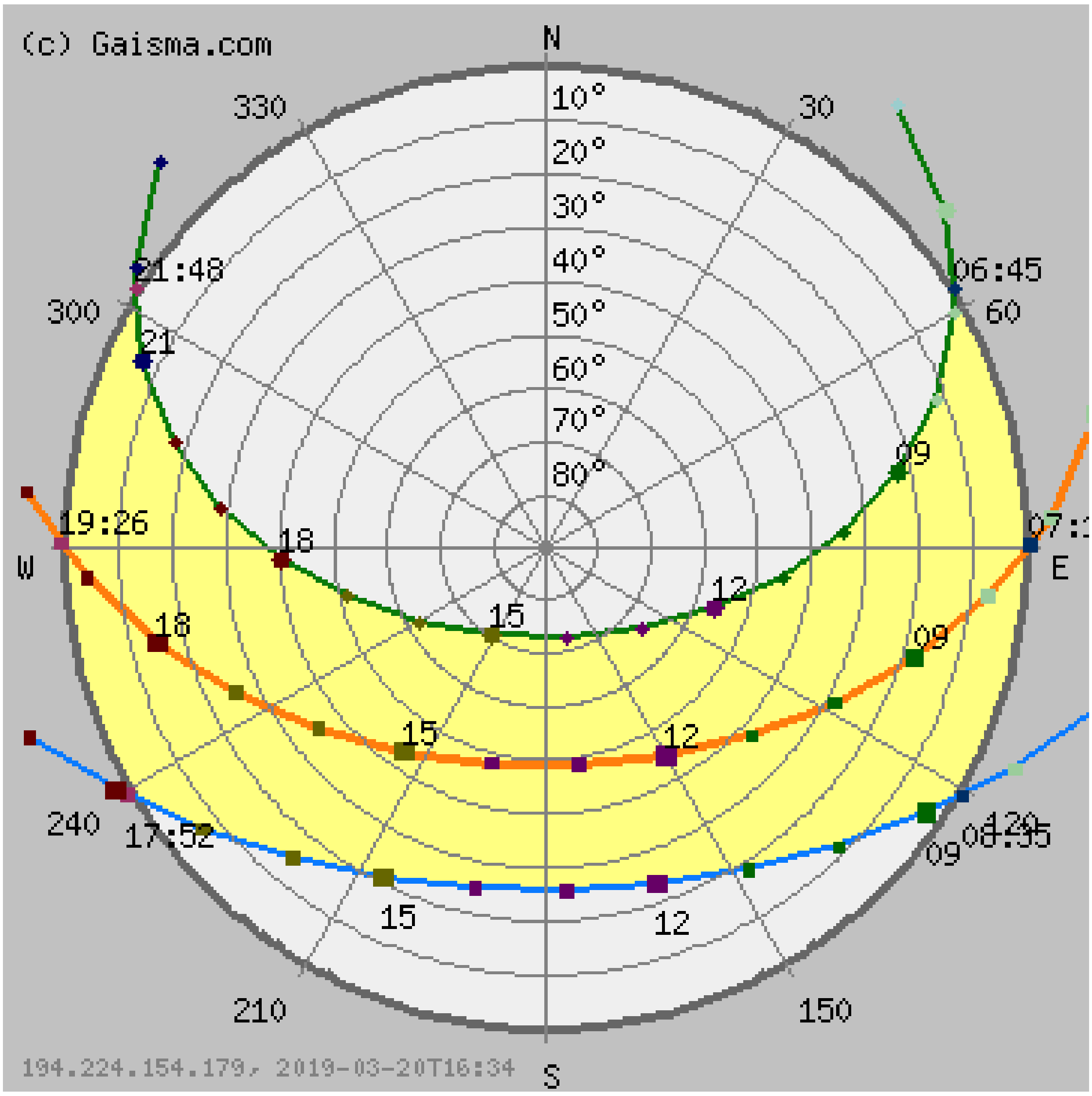
In our hemisphere, as it follows from the sun path reported (Figure 3.11) the north facade of a building will rarely be hit by direct solar radiation; on the contrary, the facade facing south will always be sunny. Obviously, the inclination of the rays with respect to the normal to the facade will be smaller in winter (sun lower on the horizon) and greater in summer. The facade facing East and West will receive, respectively, solar radiation before and after noon. Ideal alignment for most buildings is East to West in its longest side or main facade (or at least within 30° of South), with most glazing on the north facade for indirect daylight and south facade for passive solar gain; this general rule, however, can be modified according to the case studies. [24]

The cosine effect With regard to the inclination of the solar rays that impact on the Earth's surface, it should be remembered that, in accordance with Lambert's law, the amount of energy that the surface itself receives depends on this angle. The irradiance on such a surface is smaller than the total irradiance I_0 because of the cosine effect and is the maximum amount of solar energy that could be collected on a horizontal plane at the Earth's surface if the atmosphere did not scatter and absorb any radiation. Considering I_0 is the irradiance intensity on the normal plane and the irradiance intensity on the horizontal plane I_{0h} can be calculated from:

$$I_{0h} = \cos\theta_z \tag{3.16}$$

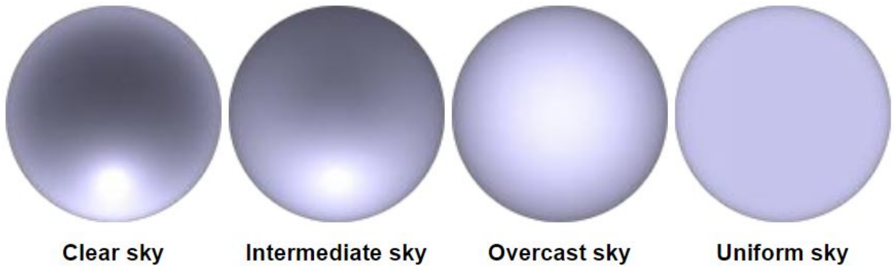
Where θ_z is the solar zenith angle.
Note that since cosine values fall between 1 and –1, I_{0h} will never be greater than I_0, and $I_{0h} = I_0$ at point where $\cos\theta_z = 1$ ($\theta_z = 0$ °C).
In fact, considering that solar radiation affects the earth's surface with parallel rays, it can be seen that a surface orthogonal to the direction of the sun's rays will receive an energy share greater than a surface that will result more and variously inclined. Furthermore, the total amount of energy intercepted by a surface not only includes the radiation directly intercepted, but also the diffused or reflected one. [25]
Therefore, in order to prevent (or dispose of) a certain amount of solar energy, it will be necessary to take advantage of an adequate intercepting shield, which is the

Figure 3.11: sun Path diagram - Madrid, Spain



Source: https://www.gaisma.com/en/location/madrid.html

Figure 3.12: Model of Sky Distributions by CIE



Source:
https://www.new-learn.info/packages/clear/visual/daylight/sun_sky/sky_types.html

basis for solar collection systems (these will be discussed later).

3.3.4 Sky as a Light Source

The illumination produced by the sky on a surface varies depending on the level of luminance characterizing the different parts of the sky. The luminance distribution depends on the weather conditions which refer to different sky models.

3.3.4.1 CIE Sky Types

The CIE has made successful attempts to create such sky models (Figure 3.12) that are a very valuable tool for everybody dealing with daylight. In fact, the use of sky models makes it possible to refer to standardized conditions and to compare different design solutions.[26]

The first models of the sky made reference to extreme weather conditions, completely clear or covered sky. In this perspective, the CIE normalized the "Clear Standard Sky" in 1965 and the "Overcast Standard Sky" in 1955. More recently, the equation proposed by Nakamura, based on a series of measurements of natural lighting conditions carried out in Japan, has standardized the "CIE Intermediate Sky". The objective is to describe the real conditions of natural lighting with a better approximation, introducing into the calculation algorithms quantities taking into account:

- the turbidity of the atmosphere;
- The level of pollution of the atmosphere, specific to the various geographical areas.

The various models of the sky will then be presented:

Clear Sky The luminance of the standard CIE clear sky varies over both, altitude and azimuth. It is brightest around the sun and dimmest opposite it. The brightness of the horizon lies in between those two extremes. Kittler's model was chosen as a representative, which in 1965 defined the luminance of the generic point P of the celestial vault as a function of the angular distance of P from the sun and from the zenith and the height of the sun on the horizon.

Intermediate Sky The standard CIE intermediate sky is a somewhat hazy variant of the clear sky. The sun is not as bright as with the clear sky and the brightness changes are not as drastic. We can refer to the analytical model of Pierpoint which uses a formula similar to that of Kittler with the coefficients appropriately modified to take into account a greater diffusion.

Overcast Sky The luminance of the standard CIE overcast sky changes with altitude according to the Moon and Spencer's sinusoidal formula. Here are take in consideration typical meteorological conditions typical of a clear and dry atmosphere, with overcast skies that prevent the direct perception of the sun, such as those that occur for example in mountain locations in winter conditions. It is three times as bright in the zenith as it is near the horizon.

Uniform Sky The standard uniform sky is characterized by a uniform luminance at each point. Given its simplicity, it was so used when analysis were done by hand or with tables. The sky acts like an extended source that emits according to the law of Lambert.

3.3.4.2 CSTB Sky Types

Based on the data collected during an extensive luminance, illuminance and radiation measurement campaign, the Building Scientific and Technology Centre (CSTB for his French acronym) in Nantes proposed to classify the skies into five categories [27]:

1. Cloudy
2. Intermediate overcast sky
3. Average sky
4. Clear intermediate sky
5. Clear sky

Table 3.1: Luminosity Index depending on the Sky Types

CSTB Sky Type	Luminosity Index
Cloudy C	0,00<In<0,05
Intermediate overcast IC	0,05<In<0,20
Average M	0,20<In<0,70
Clear Intermediate IS	0,70<In<0,90
Clear S	0,90<In<1,05

Source: [27]

The classification criterion, shown in the table 3.1, is based on the value assumed by the *Luminosity Index* I_n defined as:

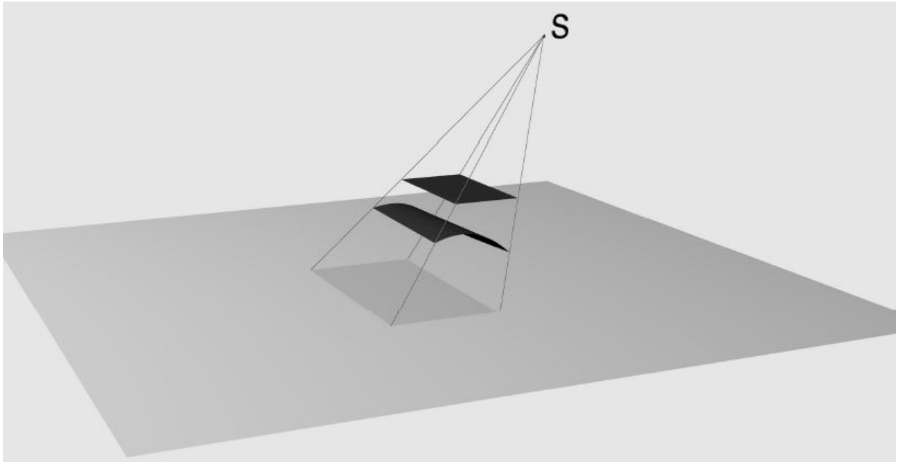
$$I_n = \frac{1 - K_{dM}}{1 - K_{dT}} \tag{3.17}$$

Where:
K_{dM} = measured value of the ratio of diffuse/direct irradiance;
K_{dT} = theoretical value of clear sky.

3.3.5 Shadows from the Movement of the Sun

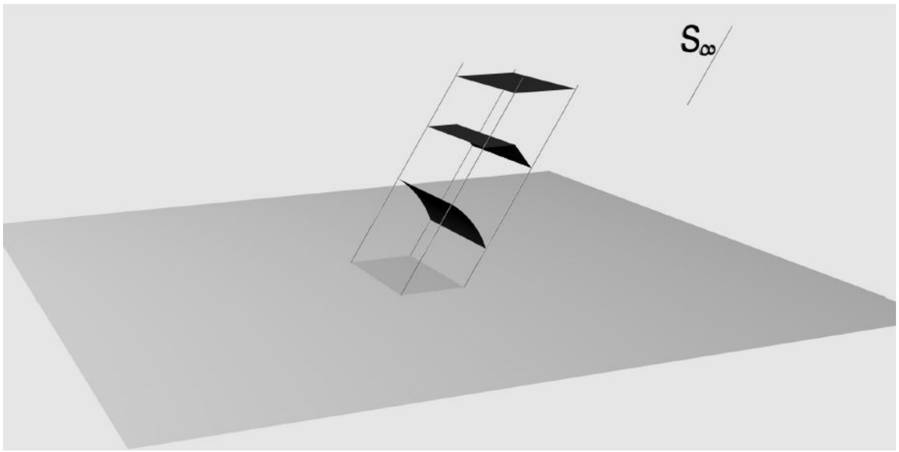
Since the solar movement is understood as the relative movement of the sun with respect to the Earth, considered as a reference of the solar trajectories in the sky, it is necessary to identify which are the ways in which the solar rays impact on the earth's surface and on the objects placed on it. We consider the vectorial characteristic of the solar rays, divorced from their energy content. In these conditions, therefore, we can take advantage of the rules established in the field of projective geometry and the related shadow theory.
Therefore, consider a point source of light that projects its rays to impact on a plane figure placed horizontally and parallel to the position of the frame of reference, coincident with the earth's surface. In these conditions the shadow of the figure will be shown on the reference framework and with a ratio of similarity between the objects of the projection.
So, there is a correspondence between an object in space and its projection on the plane of reference. However, this is not a one-to-one correlation.
In fact, the shadow, produced by the projective cone of the rays drawn between the light source and the shadow carried on the frame, is the result from the intersection of planes (also inclined with respect to the horizontal and the projective cone itself) (Fig. 3.13).

Figure 3.13: Point light source and different intercepting surfaces



Source: [23]

Figure 3.14: Infinitely distant light source and different intercepting surfaces

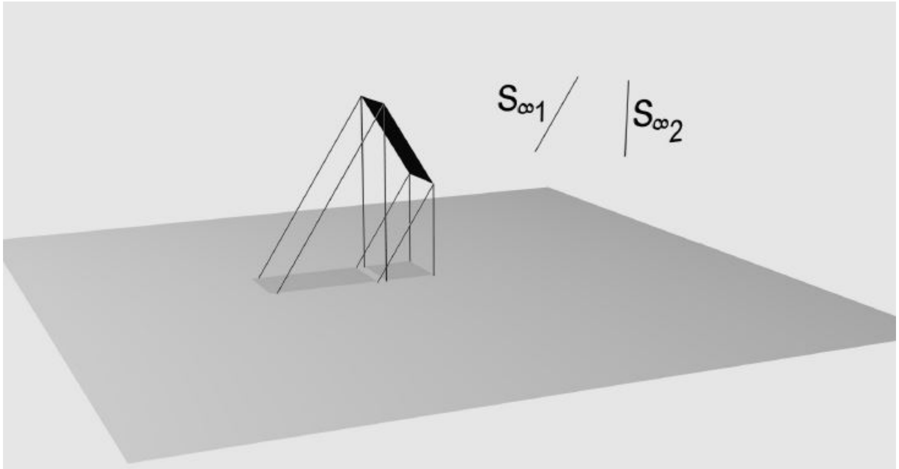


Source: [23]

On a practical level, this simple observation helps to usefully understand that, when it may be required a precise areal portion in the shade, the result can be achieved according to multiple arrangements and alternatives of the shadow plane.

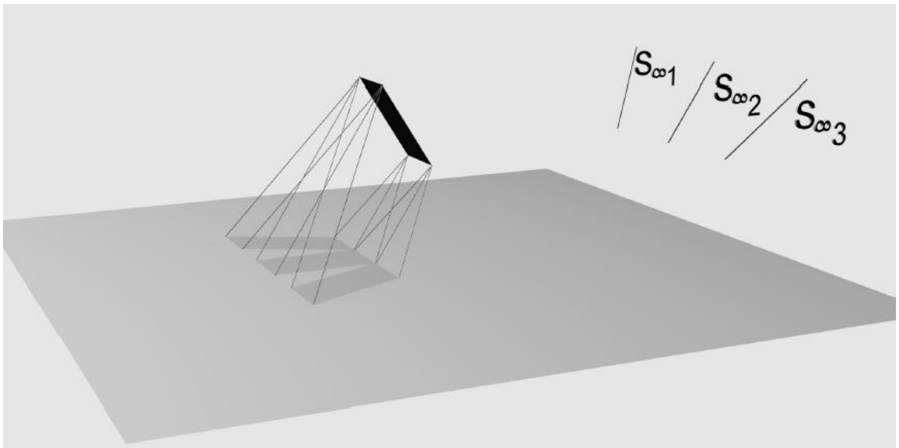
It should also be emphasized that the same result is not only obtained by the interposition between the framework and the source of light of plane surface.
Similar results can in fact also be obtained with complex surfaces (with a simple or double curvature, etc.), with plane composed surfaces.
If the light source were an approximate point placed at infinity, as in the case of the sun, the rays of the light beam have such characteristics that they are all parallel to each other (also known in projective geometry as improper beam lines, Fig. 3.14). Compared to the cases just introduced, this means that a geometric surface belong-

Figure 3.15: Influence of the different inclination of the solar rays



Source: [23]

Figure 3.16: Influence of the direction taken by the rays with respect to the intercepting surface



Source: [23]

ing to a plane parallel to the frame is projected onto the latter in an equal and congruent figure.
As in the case of a point source of light, also in this case there is no biuniqueness between the plane object in the space and the corresponding shade on the plane of the reference: the latter is the result of a projection of any object - however oriented plane or curve surface, set of plane elements etc. - that is contained within the beam of rays incident on the frontier (also called shadow separator).

Consider again, for simplicity, a flat surface however oriented in space and a direction of the solar rays.
The shadow changes according to two degrees of freedom.

On the one hand, in fact, the *inclination* of the solar direction can vary with respect to the position of the plane (Fig. 3.15). This inclination can theoretically assume values between 0° and 180°, both at 0° and at 180° the rays are parallel to the plane of reference and there is not shade to the plane. Indeed, the inclinations that practically find confirmation in reality must be assumed in the interval between 0° and 90° and are dependent on the latitude of the site object of the analysis. It is assumed that the maximum value of 90° is the inclination of the rays of the vertical limit position of the sun in areas close to the equator.

In these conditions values between 0° and 360° can be assumed.
However, practically, the angle is assumed to coincide with the direction of the South. This specification helps to understand that the angles that can be used for solar study purposes are 45° in the clockwise direction starting from the direction taken as reference and 45° in the opposite direction. This is because, with reference to the movement of the sun with respect to the Earth, the solar trajectory is deviates from the direction of the South for maximum angles representative of the angle of sunrise and the angle of sunset of the sun. [23]

3.3.6 Glass and Solar Radiation

Surely, concerning the natural illumination of buildings, the material of first importance is glass; in fact, the light transmission concerns the behavior of a glass panel with respect to light. Here its main characteristics are briefly reported. [28]

The glass transmits the thermal radiation coming from the sun through three mechanisms, *reflection*, *transmission* and *absorption* (Figure 3.17), which for what concerns the solar control, are defined by the following parameters:

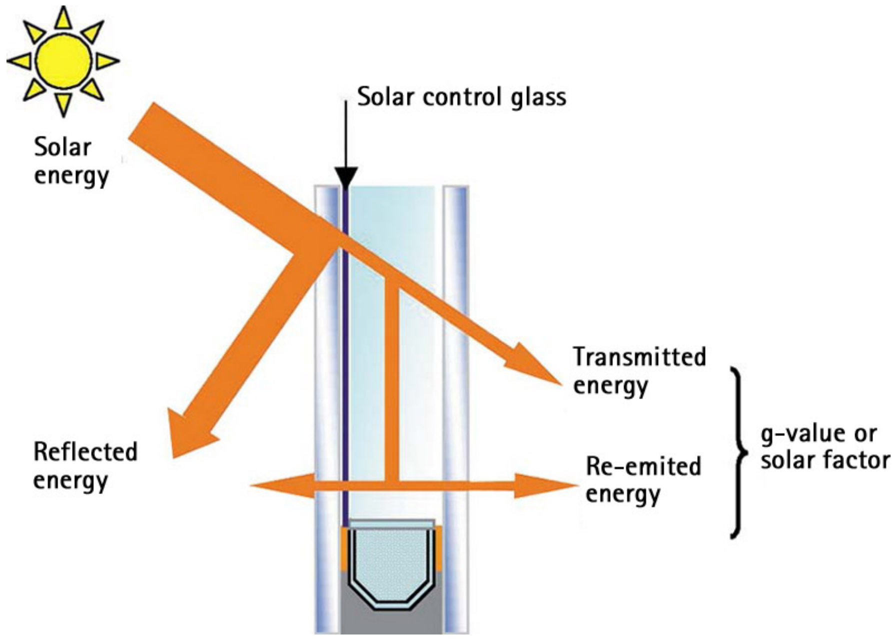
Reflection: it is the percentage quantity of solar radiation in conditions of normal incidence reflected by the glass towards the atmosphere (ρ_e reflection coefficient).

$$\rho_e = \frac{\Phi_{e,r}}{\Phi_{e,i}} \tag{3.18}$$

Absorption: it is the percentage of solar radiation in conditions of normal incidence absorbed by the glass (α_e absorption coefficient).

$$\alpha_e = \frac{\Phi_{e,a}}{\Phi_{e,i}} \tag{3.19}$$

Figure 3.17: Illustration of Solar Transmission loss



Source: https://www.saflex.com/es/saflex-guide/general/solar

Direct transmission: it is the percentage of solar radiation in conditions of normal incidence transmitted directly by the glass (θ_e transmission coefficient).

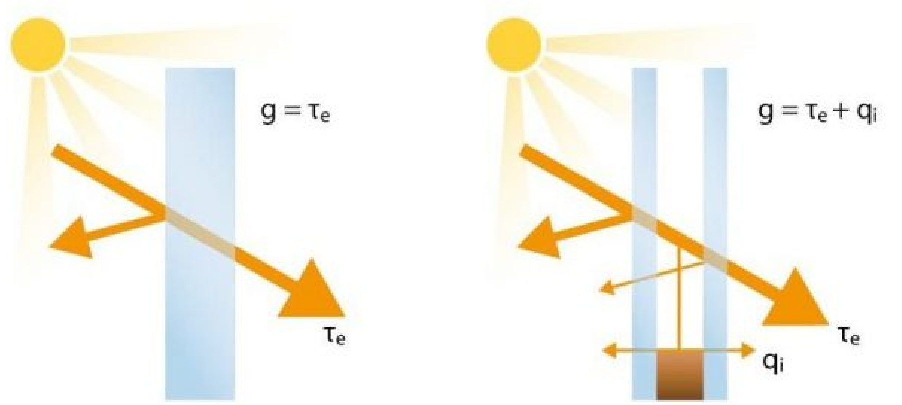
$$\theta_e = \frac{\Phi_{e,t}}{\Phi_{e,i}} \tag{3.20}$$

$$\rho_e + \alpha_e + \theta_e = 1 \tag{3.21}$$

Total transmission: it is the total solar radiation in conditions of normal incidence transmitted through the glass through all the mechanisms of thermal transmission. It is composed of the direct transmission, also known as a short wave component, and the part of the absorption that is dissipated towards the inside by high wavelength and convection radiation, also known as the long wave component (with q_i is the internal heat transfer factor). The proportion of absorbed energy dissipated both inwards and outwards depends on the configuration of the window and on the external exposure conditions.

All the properties of glass against solar radiation depend on the angle of incidence.

Figure 3.18: The Solar Factor g for single-layer and 2-layer glazing



Source:
http://biblus.acca.it/guida-al-vetro-in-edilizia-caratteristiche-termiche-ed-energetiche

Shading coefficient (SC) The heat transfer properties of solar radiation from the glasses can be compared through their shading coefficients.
These coefficients are calculated by comparing the properties of the glass with those of a clear float having a total transmission of 0.87 (a value corresponding to a thickness between 3 and 4 mm). It includes a long-wave and a short-wave shading coefficient. The latter represents the solar thermal transmittance divided by 0.87. The shading coefficient with long waves is instead the fraction of the absorbed energy released towards the inside, divided by 0.87. In other words, the shading coefficient is a dimensioned coefficient equal to the ratio between the solar transmission factor of a glass and that of a clear transparent glass 3 mm thick.
The lower the shading coefficient of a glass, the less solar radiation it will transmit, and the better its shielding capacity will be.

Solar Factor (g) The solar factor g of a glazed surface indicates the percentage of thermal energy that flows through it, compared to the total energy incident on the surface itself.
The value of this parameter can vary greatly, ranging from a minimum of 0.1 to a maximum of 0.9 (10% - 90%).
In the case of a single glass g coincides with θ_e. On the contrary, in the case of an insulating glass unit, the solar factor is enriched by a further contribution: it is, in fact, represented not only by the energy that passes through it directly, but also by the secondary heat flow q_i held back by the double-glazing unit and transmitted towards indoor (see Figure 3.18).

$$g = \theta_e + q_i \tag{3.22}$$

Given the directive 2010/31/EU of the European Parliament on the energy performance of buildings, on 26 June 2015 the inter-ministerial decree on the "Application of energy performance calculation methods and definition of the requirements and minimum requirements of buildings" acknowledges the need to establish the *Global Transmission Factor of Solar Energy* $g_{(gl+sh)}$ where:

- g is the solar factor
- gl is contribution from the glass
- sh is the contribution from the fixed solar protections (the ones mobile or that can be dismantled are not included in the calculation)

The contribution of the only glass solar factor g_{gl} is obtained with:

$$g_{gl} = g_{gl,n} \cdot F_w \tag{3.23}$$

Where:
g_{gl} is the g solar factor measured with normal incidence;
F_w is the exposure function of:

- month;
- exposition;
- type of glass (single glass, insulating double or triple glass)

The information about the contribution of the solar protection, instead, is supplied by the producer.

The value of the total solar transmission factor g_{gl} for windowed components with orientation from East to West passing through South, in the presence of a mobile shield is 0.35 for all the buildings.[29][30]
It is possible to apply this factor also to the mobile solar protections adding a reduction factor
For the calculation of the solar factor we consider the wavelengths between 0.3 and 2.5 mm, therefore, in addition to visible radiation, a part of the ultraviolet (<0.380 mm) and a part of infrared (> 0.78 mm). To ensure good protection from solar radiation, a glass must have a g value of between 15 and 20%, however this leads to a strong reduction in light transmission, with consequent deterioration of natural lighting.

The solar factor is increasingly preferred to the shading coefficient, which is approximately equal to the shading coefficient divided by about 1.15. The shading coefficients are calculated for normal incidence radiation. For other angles of incidence, the glass is compared with clear glass in the same situation. As a result, the shading coefficients are substantially constant for all angles of solar incidence. [31]

The limitation of energy and light: reflective and selective glasses To reduce the emissivity, but also to control the solar and luminous contribution, it can be done a treatment to the glass. It may be a chemical or physical type: in the first case the high temperature of the glass is used at the exit of the casting furnace (about 600 °C) to fix the treatment layer (pyrolytic coatings); in the second case separate installations are used, among which the most advanced is called *Magnetron Sputtering* which allows the deposition of metals under vacuum ionization in different layers of films, allowing a wide chromatic range and a high variability of the luminous and energetic parameters; these deposits are the basis of the production of special glasses with multiple properties called sunscreen, low E and selective.
In the case of pyrolytic deposit, emissivity values of up to about 0.2 to 0.3 are reached, while lower values are obtained with the magnetrons deposit.
Depending on the performance, special glass can therefore be classified as [32]:

Anti-solar glasses or *Reflectors* The anti-solar and reflective glasses have been designed to limit the energy and light supply of external solar radiation, incident on the glass surface. This behavior is due to the property of the coating to reflect outwards and to absorb the incident solar energy making it pass only partly. A similar behavior is obtained for the light radiation which is partly reflected, partly absorbed and partly transmitted. Reflective glasses find their natural use in current hi-tech architectures with structural glass facades in which the control of solar radiation for comfort reasons is a priority, making an essential contribution to reducing the installations' expenses.

Glass for thermal insulation - *Low-emissive* The low-emissivity glasses are designed to optimize the thermal insulation and, at the same time, without excessively penalizing the supply of light and solar energy coming from the outside. The emissivity of the coating is lower also compared to a reflective glass. Low-emissivity glasses are used above all in countries with a cold climate.

Low-emissivity-reflecting anti-solar - *Selective* The anti-solar and low-emissivity glasses enclose the characteristics of the two glasses described above in the same coating. Unlike anti-solar glasses, they allow a greater passage of daylight in return for a limited energy supply of solar radiation: therefore they are called *selective glasses*. Compared to low-emissivity glasses, they have equal or lower emissivities and, consequently, have excellent thermal insulation values. Their use is optimal in regions with a temperate climate where cold and warm seasons alternate. A similar behavior can be obtained by assembling an anti-solar reflective glass with a low-emissivity glass in insulating glass: in this case, however, the luminous flux is reduced as in reflective glass.

3.4 Visual Comfort

As noted above, visual comfort is the goal of the lighting project. In terms of well-being, visual performance can be defined as the relationship between the work performed with a given illuminance and the work carried out under the condition of ideal illuminance. The lighting requirements of a visual task increase difficult visual tasks in the presence of tasks (close and prolonged observation, frequent changes of vision, objects placed at different distances, reduced observation time). This section attempts to study the human visual system and to know the effects of light in order to know the human being's requirements.[33]

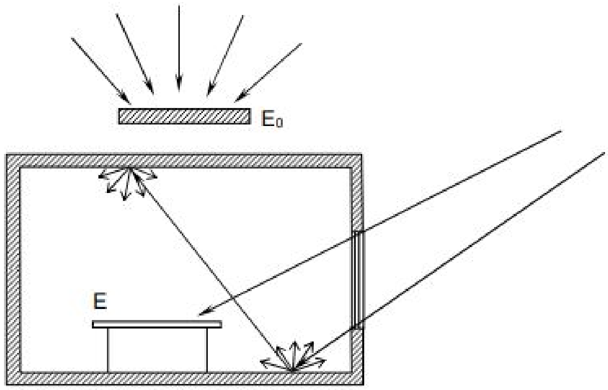
At least 50% of the human brain is devoted to the processing of images. A human vision system is our most efficient and hence primary channel for receiving information used for learning and reasoning. [34]

3.4.1 Daylight Factor

One of the characteristics of fundamental importance in the analysis of the lighting of a room is the Daylight Factor (abbreviated as DF).

The concept of the DF was first introduced in 1895 by Trotter as one of the indicators for assessing the daylighting performance of a building. *"The DF is a daylight availability metric that expresses as a percentage the amount of daylight available inside a room (on a work plane) compared to the amount of unobstructed daylight available outside under overcast sky conditions"* (Hopkins, 1963) (Fig. 3.19). [35] [36]

Figure 3.19: Definition of Daylight Factor



Source: [37]

Based on this definition, the daylight factor can be calculated with the following relation:

$$DF = \frac{E}{E_0} \tag{3.24}$$

From a simple examination of the different phenomena involved, it is shown that it is a function of the following quantities:

- Area of openings;
- Transmission coefficient in the visible of the transparent material that constitutes the windows;
- Area of the different elements that make up the casing and that are present inside the room (walls, floors, ceilings, furnishings, etc.);
- Reflection coefficient in the visible surfaces of the various elements present inside the room;
- Presence of obstructions of any kind, external or internal, which limit the view of the sky;
- Maintenance status of glass surfaces and internal surfaces.

It should also be remembered that the value of the daylight factor varies from point to point within an environment. The average factor of daylight is then introduced, DF_m, where the value is mediated on several measurement points.
This parameter allows to evaluate the capacity of the transparent openings and the enclosure of an enclosed space to guarantee comfortable natural lighting conditions and an acceptable exploitation of natural light.

In the DF the direct sunlight is excluded from both interior and exterior values of illumination. The higher the DF, the more daylight is available in the room. The legislation requires a minimum factor to consider the location suitable for the destination. The minimum values vary according to the intended use. For residential premises it is 2%, but with this value it will probably still be necessary to use artificial light.
In the design it is recommended to consider the illuminance in the worst conditions, coming from an overcast sky. Also the Italian legislation uses the average factor of daylight that refers to overcast sky as a normative parameter; for it sets a minimum value.

There are different methods of calculating the daylight factor, which differ in terms of simplicity of use and above all in terms of reliability in dealing with geometrically complex situations. A basic distinction can be made between methods that globally evaluate the three components and methods that instead individually evaluate each of them.
In general the first type of application is usually sufficient in those cases in which the dimensions of the rooms are reduced and the use of space is not highly specialized (residential building). The second type of application is necessary in large environments in which the use of space is well determined (as classrooms, laboratories, showrooms, etc.) or in geometrically complex situations.
In the following, a first method suitable for non-complex situations from the geometric point of view is presented which directly evaluates the daylight factor globally and a second one to be applied in the case of more complicated geometries that involves the calculation of the different components.[37]
For the sake of completeness and comparison, I believe it is important to illustrate both concepts.

A. Simple Analytical Method This is suitable for checking the lighting performance in regular interior spaces, without external obstructions close to the windows (balconies, loggias, porches, balconies). Although approximate, this method still guarantees reliable and congruent results with the level of precision proper to the building design. This method allows to calculate the value of the average daylight factor, DF_m, considering the internal environment as a perfectly diffused light field, i.e. equal in all points.

The relation to use is:

$$DF = \frac{\sum_i A_i \tau_i \epsilon_i \psi_i}{S(1 - r_m)} \tag{3.25}$$

Where:
A_i = area of the windows;
τ_i = light transmission coefficient of the glass;
ϵ_i = window factor;
ψ_i = reduction coefficient;
S = area of the room;
r_m = reflective coefficient of visible light of the interior surfaces.

The average reflection factor r_m is obtained from the weighted average of the reflection factors of the various surfaces of the environment.

The calculation is simply only apparent as the accuracy of the answer depends on the exact determination of the window factor ϵ_i. This evaluation is simple if the window faces a landscape without obstructions; a little more complex if the obstructions are parallel to the window plane, continuous and of constant height; very complex if the obstructions have varied shape and position. In any case the values of the two parameters ψ_i and ϵ_i can be obtained from diagrams (Fig. 3.20).[37]

B. Complex Analytical Method When considering internal spaces of non-regular shape and in the presence of balconies, loggias, porches, balconies, the different components of the daylight factor must be considered.

Often to simplify the calculation there is a tendency to neglect the component relating to light coming from external obstructions given their low luminance and only the sky component and that due to internal reflections are considered.

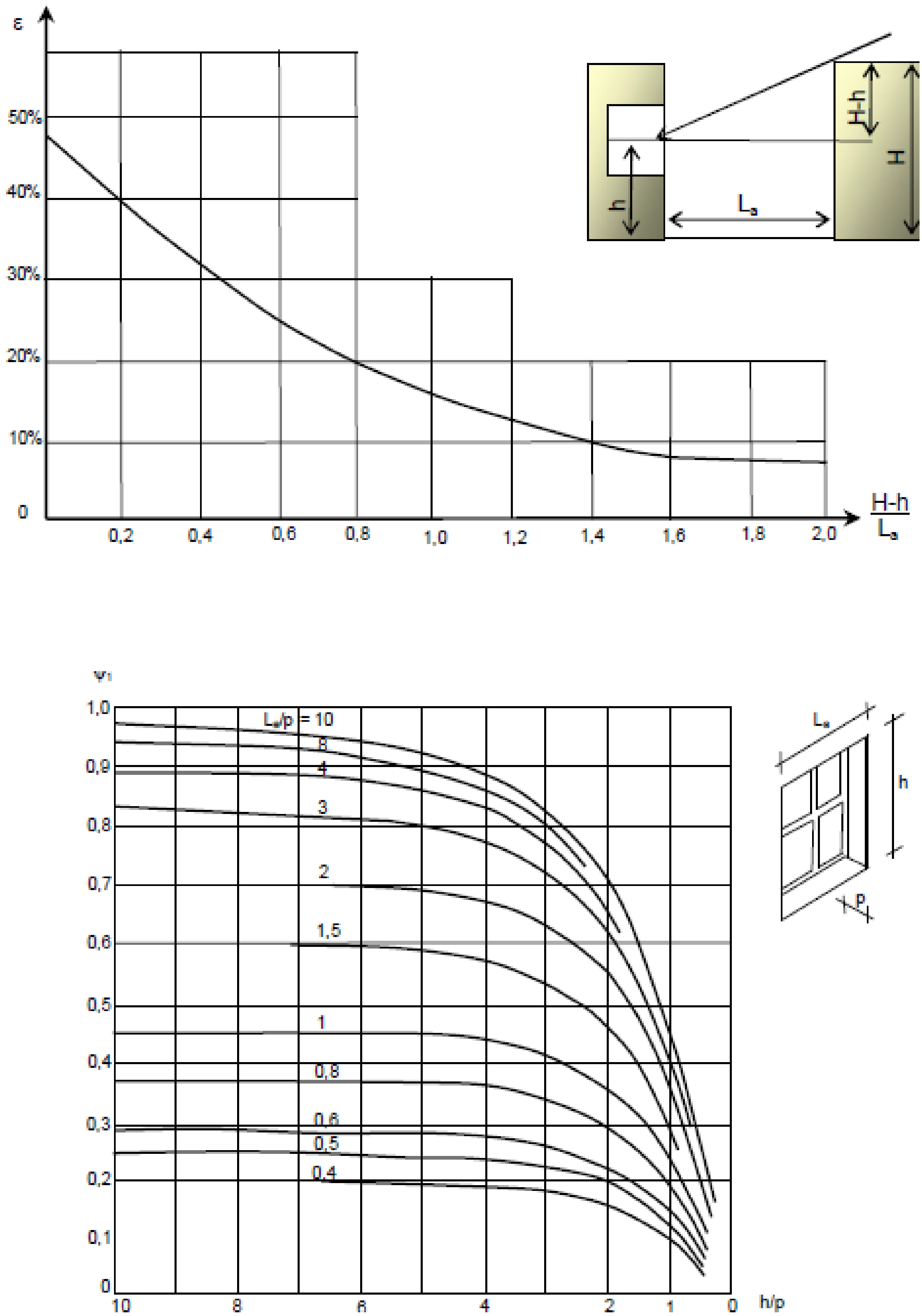
So the relation is:

$$DF = DF_C + DF_{RI} \tag{3.26}$$

Where:
DF_C = *direct factor* or component of the daylight factor due to light coming from the sky;
DF_{RI} = *diffuse factor* or component due to multiple internal reflections.

One of the most widely used methods of calculating the sky component is the French “Centre Scientific Technique du Batiment” (CSTB). The starting point is the determination of the azimuth opening angle, β, and the vertical

Figure 3.20: Determination of ϵ_i, the Window Factor, and ψ_i, the Reduction Coefficient (A Method to determinate DF)



Source: [37]

opening angle, γ, which describe the portion of the sky seen, through the window, from the point P considered.

The azimuth angle β is measured on the horizontal plane passing through P on which the illuminance is to be evaluated. It can be determined using the layout of the room under review as shown in figure 3.21a: tracing the lines which join the P point to the points that represent the projections in plan of the vertical edges of the window. Note that this angle decreases considerably as soon as the P point moves away from the outer wall or from the median axis of the window itself.

The vertical opening angle γ can be determined in a similar way, using a vertical section of the environment, perpendicular to the window plane. Two cases can be presented:

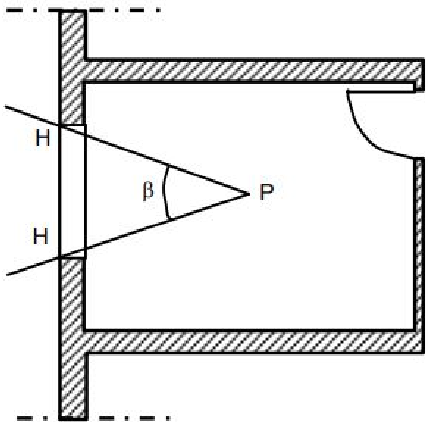
1. there are no obstructions in front of the window and the point P is at the same or greater height than the windowsill;
2. the view of the sky is limited by external obstructions or the point P is located at a lower level than the windowsill.

In the first case, the angle γ can be determined on the vertical plane passing through the P point and the plane containing the bisector of β. Its sides are determined by the intersection of this plane with the work plane and with the outer edge of the window (see Fig. 3.21b).
If the work surface were higher than the window sill, the procedure would not change but, obviously, the angle γ would be reduced.

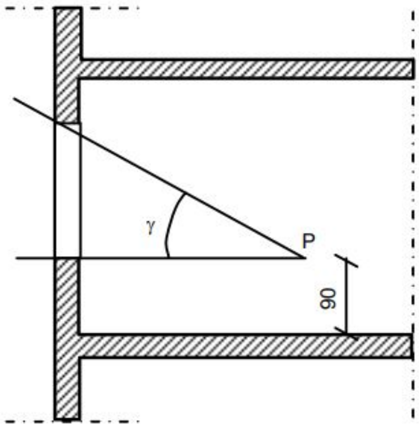
On the other hand, when the view of the sky is limited by external obstructions, two vertical angles must be determined: the first, γ_1, is identified as in the previous case (see again Fig. 3.21b); the second, γ_2, is the vertical opening angle determined by the obstruction (Fig. 3.21c).

In the case where the windowsill is at the same level as the work plane but there is a building that limits the view of the sky, as in Fig. 3.21d, the upper side of the angle γ_2 is determined by the joining segment of P point with the trace aligned with the top of the building in question.

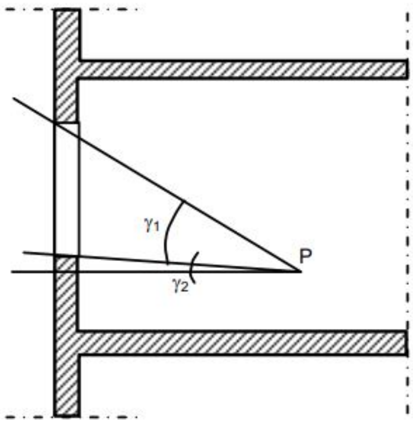
Finally, if both conditions occur (windowsill higher than the work surface and a building in front), the angle γ_2 that must be considered is the greater of



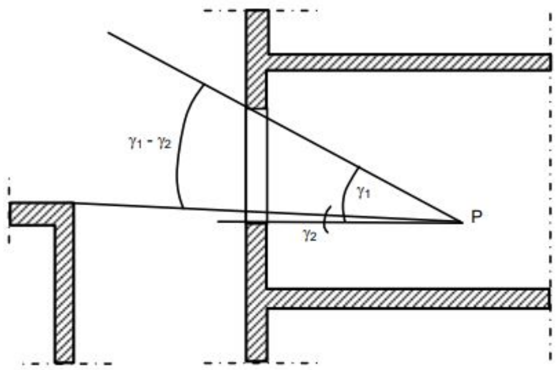
(a) Determination of β, the Azimuth Angle (B Method)



(b) Determination of γ, the Vertical Opening Angle (B Method)



(c) Determination of γ_1 and γ_1 (B Method)



(d) Determination of γ_1 and γ_1 in Presence of a Building as Obstruction (B Method)

Source: [37]

Table 3.2: Frame factor f_t for the main types of frame.

Type of Frame	f_t
Metal Windows and Frame	$0,80 \div 0.85$
Metal Windows and Wooden Frames	0.75
Wooden Windows and Frames	$0,65 \div 0.70$

Source: [37]

the two.

Once the angles β and γ have been determined, it must calculate the *sky factor* generated on P point by the portion of the sky. For this operation, we refer to the specific diagram prepared by CSTB.

At the end, it must be taken into account that the values of the direct factor obtained from the CSTB diagram do not take into account the reduction due to the windows and doors. So, to obtain more credible results, it is advisable to multiply the factor obtained by a correction coefficient, f_t, between 0.7 and 0.85 and equal to the ratio between the surface of the glass and total area of the window. The table 3.2 shows approximate values for different types of windows and doors.

As regards the calculation of the diffuse field, it is assumed that the light is perfectly diffused in the environment. So the diffuse factor, DF_{RI}, is constant in every point of the environment. The proposed calculation is as follows:

$$DF_{RI} = \frac{A_w \cdot t_\epsilon \cdot r_m}{S(1 - r_m)} \tag{3.27}$$

Where:
A_w = window area;
t_ϵ = glass lighting transmission;
r_m = average reflection coefficient of the interior surfaces;
ϵ = window factor, i.e. the ratio of the window illuminance and the illuminance of the horizontal surface exposed to the sky.[37]

3.4.2 Uniformity

The first aspect to be taken into consideration in order not to affect visual performance is uniformity.

The illuminance of immediate surrounding areas will be related to the illuminance of the task area and should provide a well-balanced luminance distribution in the field of view. The distribution of luminances in the field of vision also affects visual comfort. Therefore, the following circumstances should be avoided:

- too high luminances, which can lead to glare;
- too high luminance contrasts, which will cause fatigue due to the constant re-adaptation of the eyes;
- too low luminances and too low luminance contrasts, which can result in a dull and non-stimulating visual environment.

The lighting of the environment must not only be correlated to that of the visual task and the communicating environments, but also not present excessive unevenness. Minimum illuminance uniformity values in the visual task area are defined separately, e.g. for work places according to EN 12464-1, and can be gathered from the respective tables.
The uniformity U_0 is calculated as the ratio between the minimum illumination E_{min} and the average $\bar{E}$ on the examined surface, equation 3.28, keeping in mind that this minimum value must not be undercut at any time.

$$U_0 = \frac{E_{min}}{\bar{E}} \tag{3.28}$$

The determination of uniformity requires a sufficiently close sequence of calculated or measured localized illuminance values to be able to determine minimum illuminance.

3.4.3 Glare G

In general, the eye tends to adapt to the average lighting conditions of the surrounding environment. The human visual system is unable to adapt to excessively different levels of luminance, and therefore to high contrasts, within the visual field. When this happens, the brighter area causes *glare*, reducing visual performance and causing disturbance. Depending on whether the first or second effect prevails, glare is called debilitating (disability glare) or harassing (discomfort glare). The debilitating, which consists in an instantaneous, temporary worsening and it is reversible of the visual functions; in fact the nocturnal one derives from the fact that the rodopsina, photosensitive protein of the rods, responsible for the mechanism of vision, once inactivated by light, takes time to be reactivated). The harassment, which causes a sense of discomfort that does not result in visual disability, but some

disorders and difficulty in concentration, reduction in the ability to pay attention, increase in the probability of error, reduction in performance.[39]
It is difficult to measure this phenomenon: indices have developed to predict the degree of perceived discomfort glare are the *Daylight Glare Index (DGI)* or the *Daylight Glare Probability (DGP).* [40] They are based on four physical quantities:

- the luminance of the glare source, which is the intensity of the luminous flux emitted par unit area of the source;
- the adaptation level, which is the luminous flux reaching the eyes and setting the adaptation of the eyes;
- the solid angle of the glare source, which expresses the size of the glare source as seen by the observer;
- the position index, which is a correction factor considering the different perceptions of glare sources for the horizontal and vertical displacements from the line of vision of the observer.

The equation, by referring to the DGI, shall be verified [41]:

$$DGI = 10log\sum_{i=1}^{n} G_i \tag{3.29}$$

$$G_i = 0.48\frac{L_s^{1.6}\Omega^{0.8}}{L_b + 0.07\omega^{0.5}L_w} \tag{3.30}$$

Where:
n (-) is the number of glaring sources
G_i is the glare constant calculated for each source;
L_s is the source luminance, such as the luminance of the visible sky patch, the obstructions and the ground perceived through the window measured in (cdm^2);
Ω is the solid angle subtended by a glaring source expressed in (sr);
L_b is surrounding luminance, i.e. the average of the surfaces' luminance in the environment, included in the visual field of the occupant's eye in (cdm^2);
ω is the solid luminance, i.e. total solid angle subtended by a window expressed in (sr;
L_w is the average of the window's luminance weighted according to the relative areas of the sky obstructions and the ground in (cdm^2).

Tables with the values of DGI for each area and with assessment criteria of glare in DGI scale is given below (Table 3.3 and Table 3.4):

Table 3.3: Daylight Glare Index

Activity	**DGI**
Laboratory	21
Lecture Room	21
Classroom	21
Computer Lab	21
Drawing Room	21
Music Room	23
Library	21
Gym	23

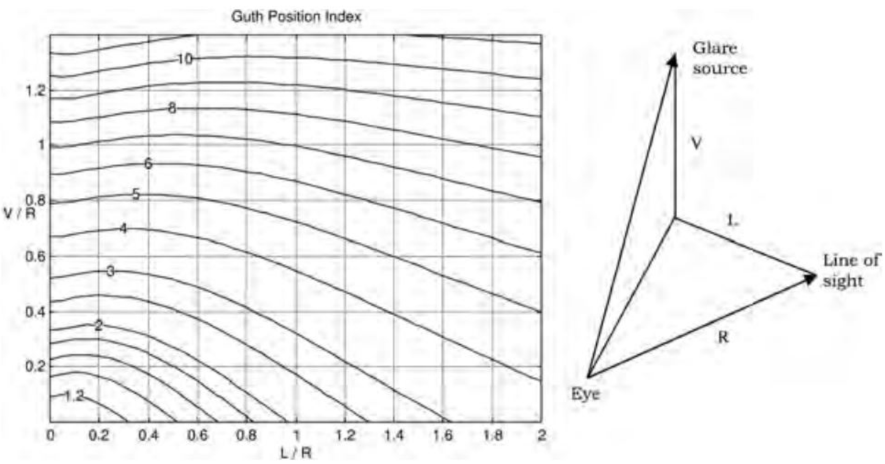
Source: European standard EN 12464-1

Table 3.4: Assessment Criteria of Glare

Assessment Criteria of Glare	**DGI**
Barely perceptible	16 18
Acceptable	20 22
Annoying	24 26
Intollerable	28

Source: European standard EN 12464-1

Figure 3.21: Determination of the *position index*



Source: [42]

Some authors do not always find reliable measurements the ones made with the DGI factor and, for this, they have created an index based on a CCD (charge-coupled device) digital camera, the Daylighting Glare Probability (DGP). It combines the vertical eye illuminance pupilar illuminance, with a modified glare index given by:

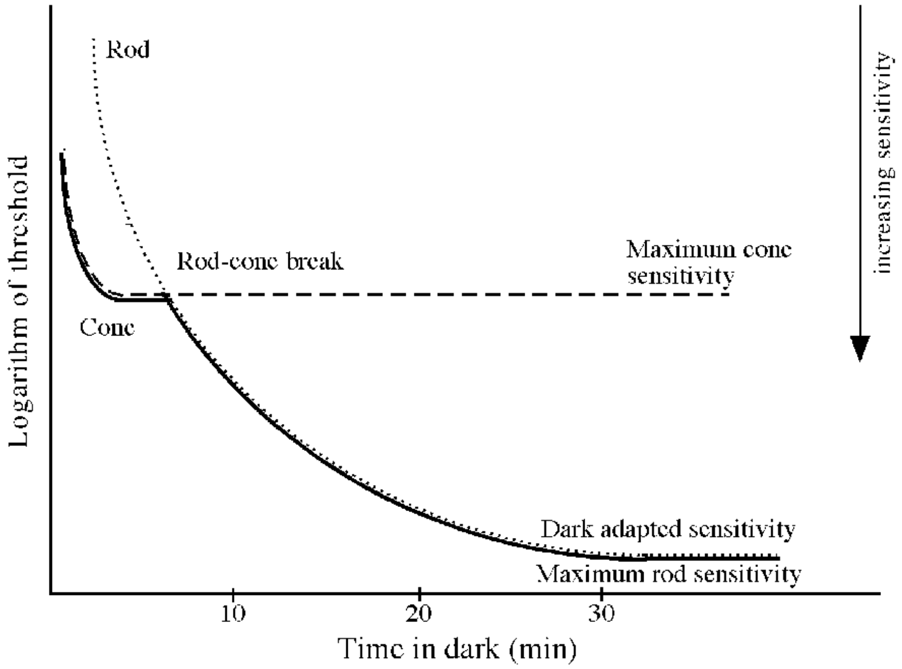
$$DPG = c_1 E_v + c_2 log\left(1 + \sum_i \frac{L_{s,i}^2 \omega_{s,i}}{E_v^{C_4} P_i^2}\right) + c_3 \tag{3.31}$$

Where:
E_v is the pupilar illuminance in (lx);
c_1=5.87×10^{-5};
c_2=9.18×10^{-2};
$L_{s,i}$ is the source luminance;
ω_{si} is the solid angle sustained by source i;
c_3=0.16;
P_i is the Guth position index of source i (empirically determined with figure 3.21).
Both the indexes DGI and DGP are nowadays utilized. [44]

3.4.4 Adaptation Curve

The adaptation to a specific lighting condition, when possible, is not immediate, but requires a certain amount of time: is lower from a condition of darkness to a more enlightened one; greater in the opposite case. The complete adaptation time is of the order of one minute when switching from a dark environment to a

Figure 3.22: Dark adaptation curve. It can be seen the activation of cones or rods, depending on the luminous intensity (I shown in a logarithmic scale)



Source: https://www.semanticscholar.org/paper/Dark-Adaptation-1.-the-Basic-Curve/0eb60716ffc2e42a5a1208ca9f1e7b7e53fcd2c5/figure/1

more enlightened one, and about one hour when switching from brighter to dark environments. The adaptation curve varies in relation to the difference in brightness according to a logarithmic pattern with a very rapid adaptation in the first seconds or minutes and therefore slower (Figure 3.22). The solid line shows the two-stage dark adaptation curve for a normal subject, with a cone branch at the beginning and a rod branch at the end. It can be seen how the illuminance influences the individual's ability to perceive small details at a given distance (visual acuity) but also the speed of perception, that is the time required to perform a visual task. [43]

Visual performance is the ability to react that a person manifests when the details of the object of vision (visual task) enter the observation space. Visual performance is mainly conditioned by three aspects:

a. Visual ability of the subject in terms of visual acuity (i.e. the measure of the ability to resolve fine detail);

b. Characteristics of the visual task;

c. Environmental characteristics.

Visual comfort is also guaranteed by an adequate gradation of contrasts in the visual field (intended as a central field of vision, background and environment). The perception of an object is a function of the luminance contrast of the object and the background. The point c. is what we need to focus on, guaranteeing a correct appearance of the surfaces of the main objects present in the room and of the light sources.

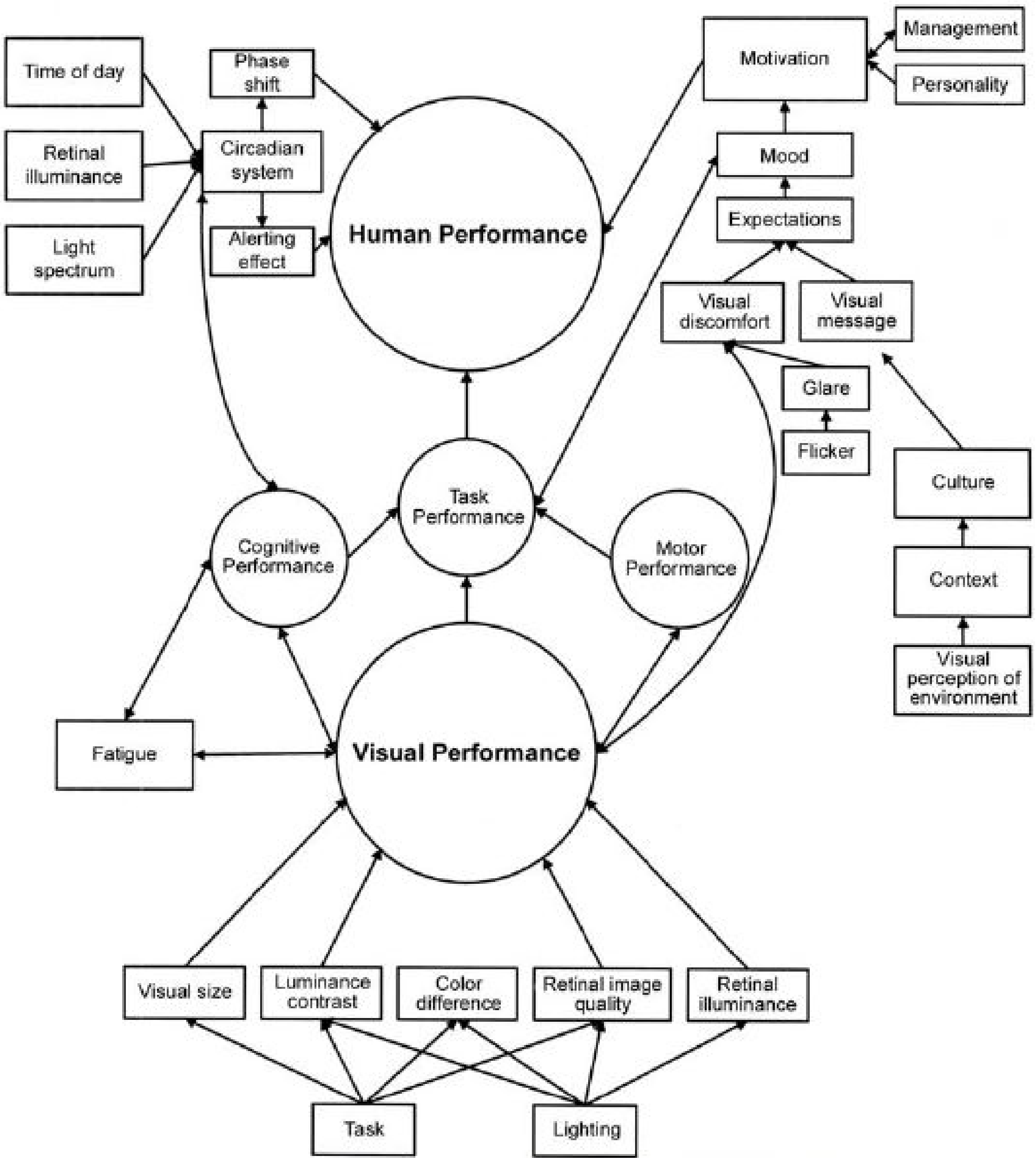
3.4.5 Human Visual System and Performance

The effect of light on humans is one of several factors to be taken into consideration. In the past, lighting design was a process aimed at ensuring visual perception in a specific activity, but currently the project has an integrated approach where many aspects far from the lighting field converge.[45]
"Humans are diurnal animals, heavily dependent on the sense of sight. Light is essential for humans to function efficienty. With light we can see, without it, we cannot."[46]
But light not only influences vision, but also determines cycles for daily and seasonal bodily functioning and influences levels of psycho-physiological activity and mood (Figure 3.23). The capabilities of the visual system are determined by lighting conditions; the state of the circadian cycle is influenced basically by the light-dark cycle; the "message" delivered by the perceptual system is influenced by many factor, lighting being just one of them. [47]

If we think about how we spend our days and how long a person stays indoors instead of in direct contact with natural lighting, it is clear why, in the last years, the awareness of these aspects has considerably grown, also plunging the scientific research into the importance of lighting, including the effects it may have on humans.
In modern societies, according to recent surveys, people spend over 90% of their time indoors. Students spending more time at school than any other building, except at home, highlights the importance of providing comfortable indoor thermal conditions in these buildings. [48]

There is evidence that, in schools illuminated with abundant natural light (DF $>$ 8%), students learn between 20% and 26% faster and get ratings between 7% and 18% higher than schools with standard lighting. A constant and regular exposure to natural light leads to a regularization of the circadian rhythms (sleep-wake cycle) and a reduction of depressive illnesses and, on this line, recent analysis have shown that a reduced exposure to natural light helps to create tiredness, depression

Figure 3.23: How lighting can influence human performance



Source: [47]

but also aggression, decreases immune function and acts on melancholy as well as loss of tone and muscle strength. Lighting levels affect the occupant's physiology and psychology, for this reason designing natural light does not mean respecting legislation, but creating conditions of living comfort. [49]
As laid out in an interesting study by Phillips Lighting and the University Medical Center Hamburg-Eppendorf in Germany, in which two classroom from different institutes were chosen and studied over a school year, the students who work under a standard amount of light commit more errors than those who study with a greater amount of it. Clearly the level of intelligence can not be proved, but is not the same for concentration, in fact also the reading speed tests, like the comprehension exam, improve a lot with a light greater than the "standard". This is why light is considered *"is a conditional factor in learning at school"*. [50]

In the analyzed studies we saw the importance of having both objective and subjective references. The first surveys are based on measurement of parameters including environmental factors such as air temperature, mean radiant temperature, air velocity and relative humidity and human factors (metabolic rate and thermal resistance) of clothing), useful for the calculation of comfort indices. Subjective surveys are possible thanks to the dissemination of questionnaires: at the beginning the requested data were very limited (thermal sensations and preferences), but now they also include questions related to the speed and the dryness of the air.

At the end, lighting is not just about quantity and then illuminance but also about quality related to color temperature - the relative warmth or coolness of lighting- which can influence people [51]: brightness increases cognitive alertness and improves self-control, while darkness reduces the latter and causes cognitive obtuseness. Some researchers disagree with this division, indeed they argue that darkness increases cognitive attention precisely because dark environments are those perceived as dangerous and to be on the lookout. In general, studies have suggested that in learning environments, light levels should be modified when students are executing different types of tasks (writing, reading, reflecting, or engaging in discussion) and fluent lighting is fundamental to encourage students to better attend to teaching, to study harder or to pursue more difficult coursework. [52]

For all these discrepancies and these wide areas still unknown, we can see how fundamental it is to continue the study of illumination.

3.5 Lighting Standards

European and national-level standards regulate lighting levels and how to guarantee comfort giving also general prescriptions on artificial lighting.

The European standard EN 12464-1

The European standard EN 12464-1 [53] is designed for interior spaces and outdoor environments and it highlights the required degree of visibility and comfort in a wide range of working environments. The values stated in the collection of tables, refer to the lowest illuminances in the workspace of a visual object, that can be either horizontal, vertical or placed at an angle. This rule provides that lighting requirements must meet three basic requirements:

- visual comfort, that is the sensation of perceived well-being;
- visual performance, that is the possibility on the part of the students / workers to carry out their activities even in difficult conditions and over time;
- safety, that is the guarantee that lighting does not adversely affect students' safety conditions.

This standard does not offer a specific solution nor does it limit the use of innovative tools; therefore, designers are not limited to developing new techniques.

The Italian Standard UNI 10840

The Italian Standard UNI 10840 [54] deals with specifying general criteria for lighting and natural classrooms and other school premises, to ensure conditions that meet the well-being and safety of students and other users of the school. School premises are mainly used during daylight hours, therefore the UNI 10840:2007 are the general requirements for artificial lighting for natural lighting. According to the standard, natural lighting must be used to the greatest extent possible in order to promote the psycho-physical well-being of the occupants and reduce energy consumption. Glass surfaces have the dual function of allowing visual contact with the external environment and of achieving a satisfactory distribution of the illuminances in the internal environment. The glazed surfaces must be equipped with complete darkening systems to consider the educational needs with the aid of audio-visual media.

The UNI 10840 presents - in a special table - the average illuminances maintained for various types of interiors, tasks or activities that are carried out within the premises. By *average maintained illumination*, it means the value below which the average illuminance, on a specific surface, can never fall. The table shows these values according to the premises considered: classrooms, reading rooms, art education classrooms, language laboratories, entrances, corridors, teachers' rooms, canteen, bathrooms, etc. The luminances shown in this table refer in general to the horizontal work surface at a height of 85 cm from the floor. The average illuminance maintained must refer to specific situations for other positions of the working surface (for example at different heights in the case of nursery or nursery classrooms, or vertical for the blackboard, etc). Among the main parameters that characterize the lighting environment - and that must be considered during the design phase - we find, for example:

- **illuminance distribution:** a well-balanced luminance is needed to increase the sharpness of the vision, the sensitivity to contrast and the efficiency of the ocular functions;
- **illumination**: its distribution greatly influences the perception of the task and its execution quickly and safely;
- **glare:** can cause errors, fatigue and accidents; this phenomenon can be avoided, for example, by adequate shielding of the lamps or by covering the windows with suitable curtains and screens;
- **aspects of color:** the two attributes of appearance of color and color rendering must always be considered separately;
- **flickering and stroboscopic effects:** the flicker causes distraction and can give rise, for example, to headaches; the stroboscopic effects can lead to dangerous situations;
- **energy saving:** the system should respond to the lighting requirements of a specific space without causing energy waste; this requires a careful evaluation of the lighting systems, the devices of the control devices and the available natural light;
- **daylight:** it can provide all or part of the necessary lighting. However, natural light changes throughout the day producing different perceptions of the surrounding environment. On the other hand - due to the horizontal luminous flux that comes from the side windows - natural light can be useful for creating a particular illuminance distribution in the school environment.

For the artificial lighting, the standard prescribes the values of the average daylight factor for the same types of interiors, tasks or activities of artificial lighting. The average daylight factor is calculated using a formula (equivalent to that contained in the Circular of the Minister of Public Works No. 3151 of 22 May 1967) which refers to a simplified model of the environment. The final part of the UNI 10840:2007 defines the criteria to be adopted for lighting inspections.
Finally, an informative appendix, provides the criteria and formulas for the verification of the DGI daylight glare index with, in the bibliography, some texts or documents that can be consulted to deepen themes related to natural lighting.
In the table 3.5) we can see different types of underlined activities that are considered to be the most related to those carried out within the workshop classroom of the CREAS building.

The values of the different columns are the following:

1. Spaces, areas, tasks or activities for which the specific requirements are given. If the space is not collected, it should be adopted the values given for a similar comparable situation;
2. E_m maintained illuminance on the reference surface for the interior, task or activity of column 2;
3. Maximum UGR (Unified Glare Rating) index is the limit for the degree of glare;
4. The minimum illuminance uniformity U_0 on the reference surface for the maintained illuminance given in column 2;
5. The chromatic reproduction index Ra (or color rendering index CRI) for the situations collected in column 2;
6. The last column provides the specific requirements for the situations listed in column 2.

According to the standard, a grid systems must be created to indicate the points where illuminance values are calculated and verified for areas of activity, immediate surrounding areas and background areas. (Table 3.6)

The European standard EN 410:1998

The EN 410 standard [55] specifies the methods for the determination of the luminous and solar characteristics of the windows for building. These features can

Table 3.5: Examples of lighting requirements for spaces, areas, tasks, and activities

Space	Illuminance (lx)	UGR index	Uniformity U_0 (E_{min}/E_m)	R_a index	Notes
Areas with traffic and corridors	100	28	0.4	40	150 lx off ground level if there are vehicles on the route
Stairways, escalators, and travelators	100	25	0.4	40	
Lifts	100	25	0.4	40	In front of a lift, no less than 200 lx
Loading bays	150	25	0.4	40	
Coffee-break rooms	200	22	0.4	80	
Technical facilities	200	25	0.4	60	
Storage spaces	100	25	0.4	60	200 lx if work is continuous
Electronics workshops, testing, and adjustments	1500	16	0.7	80	
Ball-mill areas and pulp plants	200	25	0.4	80	
Offices and writing	500	19	0.6	80	
Check-out areas	500	19	0.6	80	
Waiting rooms	200	22	0.4	80	
Kitchens	500	22	0.6	80	A restaurant's kitchen and dining area should be separated by an adjustment zone
Parking areas	75	-	0.4	40	Illuminance from floor level
Classrooms	300	19	0.6	80	Lighting should be adjustable
Auditoriums	500	19	0.6	80	Lighting should be adjustable to different audiovisual situations

Source: European standard EN 12464-1

Table 3.6: Calculation Grids

Length of the area (m)	Max distance between grid points (m)	Min number of grid points
0,4	0,15	3
0,6	0,2	3
1	0,2	5
2	0,3	6
5	0,6	8
10	1	10
25	2	12
50	3	17
100	5	20

Source: European standard EN 12464-1

serve as the basis for calculating the lighting, heating and cooling of the rooms and allow a comparison between the different types of glazing.

The standard ISO/IEC 17025:2017

The ISO 17025 [56] was also analyzed in the research area; it specifies the general requirements for the competence, impartiality and consistent operation of laboratories and it is used as a guide to carry out the calibration of the termopars.

The CIE Standard (International Commission on Illumination)

The CIE [57] is the best authority on the subject and as such is recognized by ISO, the International Organization for Standardization. The CIE determines the requirements for a daylighting system for interior spaces and outdoor environments giving some specific recommendations and specifying the required equipment for interior working space that offer visual comfort and high efficiency to the users. Their standards target the security and health of the users and determines the amount of standard light. In addition, it proposes some specific solutions for restricting the design and innovation in the design. Daylight, visual comfort, energy consumption in interior and exterior spaces as well as all the required information regarding natural and artificial lighting are precisely defined in the CIE Standards. [58]
Some of the most important are:

- CIE 108, 1994a. *Guide to Recommended Practice of Daylight Measurement*;
- CIE 110, 1994b. *Spatial Distribution of Daylight Luminance Distributions of Various Reference Skies*;
- CIE Standard S 011/E, 2003. *Spatial Distribution of Daylight - CIE Standard General Sky*;
- CIE 171, 2006. *Test Cases to Assess the Accuracy of Lighting Computer Programs.*

The "Guía Técnica de Eficiencia Energética en Iluminación. Centros docentes, IDAE"

This is a technical guidance recommended by the IDAE (Institute for Diversification and Energy Saving) for the design of teaching centers. [59] Spain does not have specific legislation related to school lighting, but it refers to EN 12464-1 and to this guide. The said document expresses techniques and parameters to improve comfort conditions in schools.

The purpose of this guide is to establish a series of guidelines and recommendations to help technicians responsible for projecting or writing technical specifications of lighting installations of teaching centers. This applied to all spaces that are part of an educational institution, classrooms of theoretical education, gymnasiums or common spaces. In this guide, the criteria of quality and design of an educational space are classified as follows: Illuminance and uniformity, control of glare, color rendering index. The values are the same of the EN 12464-1.

Chapter 4

Purpose

In the chapter 2 we analyzed the point at which the research arrived, precisely the state of the art in studying natural lighting inside buildings and in how to defend themselves from it and exploit it.

The starting point was to describe the current state of what could be improved.
The theoretical foundations described in chapter 3 were therefore based on the objective of improving the luminous quality and therefore the environmental comfort for the users of an educational building. In particular, the behavior of natural light was analyzed in the Workshop Room (called in spanish *"Aula Taller"*) of the CREAS building, designed with bioclimatic principles.

The general objective therefore is to measure the Daylight Factor DF through:

- data collected from measurements in situ;
- data obtained from the simulation with the Velux software;
- data exported from the simulation with the DesignBuilder software.

These data were used to verify the conditions of the workshop room and to validate through measurements, the values simulated in the programs compared to those measured with luxmeters in the environment.

The validation of the data and the entire study was carried out by dividing the sky into three categories according to the CIE and European standards on which the programs used work.
The data were then further subdivided into 3 specific times during the period of use of the classroom.

The final aim of the thesis was to find a solution through the use of a passive system to be implemented in the existing building. This was designed to allow more comfort for the users.

Chapter 5

Methodology

This study in the laboratory building of the CREAS building consists mainly of three phases.

The first one consists in reordering the data collected in situ with the use of a grid of luxmeters, thermocouples and a continuous data collection system. This monitoring was carried out for a period of 10 days, between February the 24^{th} and March the 6^{th} , 2017 by a student of the Physics Department of the Polytechnic University of Madrid UPM. Other data has been recovered from the VELUX Daylight Visualizer 3 software.

For the second phase a virtual model of the classroom was designed using the DesignBuilder software. Once the model was completed, I simulated the behavior of the building comparing it with the previously collected data. In order to better interpret the data, they has been converted into maps thanks to the use of the Surfer software.

The third phase consists of a simulation, using different passive construction techniques, with the aim of improving natural lighting in the internal spaces of the CREAS building. These were analyzed in the same way as the original proposal using the DesignBuilder software.

5.1 CREAS Building

The resource center for environmental education CREAS (acronym from the Spanish "Centro de Recursos de Educación Ambiental para la Sostenibilidad") is a center aimed at raising awareness about the environmental problems we live today (Fig.

Figure 5.1: The CREAS Building

Source: https://www.enpozuelo.es/noticia/5860/politica/el-creas-de-pozuelo-recibe-un-premio-en-la-cumbre-del-clima-de-paris.html

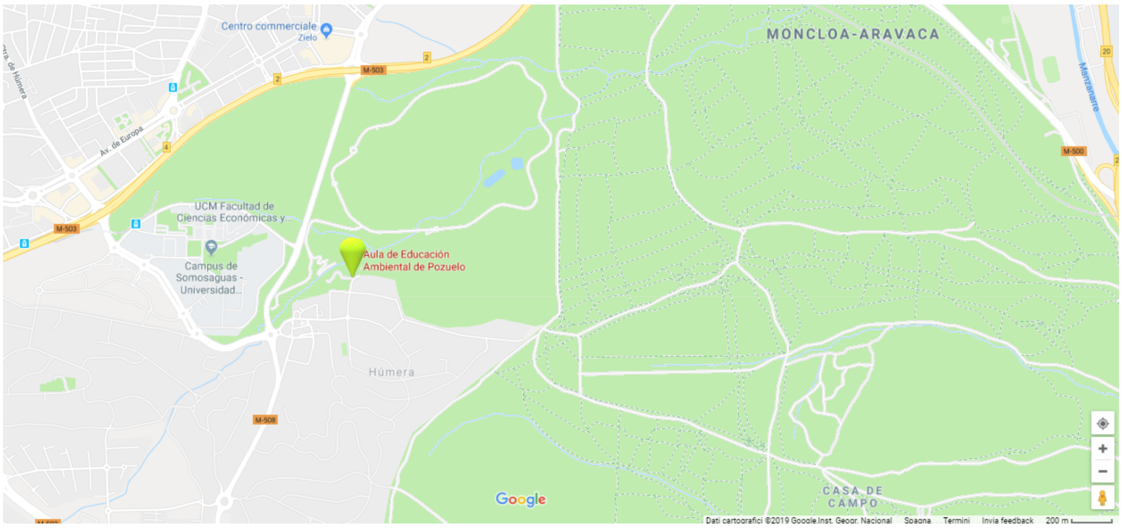
5.1).

The building was born with the need to create a meeting space to expand all those initiatives of the educational community regarding environmental issues. This center inspires both young people and adults to learn and generate innovative solutions for environmental conservation.

The environmental education room, dependent on the Department of Education, has an integrated space with the environment, respected by institutions and organizations. Also thanks to the strong commitment of the municipality to build a building that meets the characteristics of sustainable building that this result has been reached. [60]. This building was designed by architect Antonio Baño Nieva, who has written both articles and books on sustainable architecture and concepts of vernacular architecture. His work is characterized by the use of local building materials to achieve sustainable structures. He is currently a professor at the University of Alcalá.

Even before opening its doors, it was awarded in important national competitions: for example, it received an award for the use of construction techniques aimed at optimally managing resources from Endesa, the largest Spanish electricity company, in the 2009 (Barcelona Meeting-Point-Casa Bioclimática). CREAS was awarded also with the “Green Building Solutions Awards” in occasion of the climate summit

Figure 5.2: Map of the CREAS Building and the area



Source: https://www.google.com/maps/@40.4319983,-3.777097,14z

in Paris in the 2015. [62]

The CREAS educational classroom was chosen to carry out this study thanks to its cutting-edge design in bioclimatic characteristics and energy efficiency. Firstly, a series of systems make this building a jewel of modern architecture. On the other hand, the study of school classrooms is considered very important; present and the future generations spend much of their time in these and their conditions affect the productivity and performance of students. (par. 3.4.5)

In the following sections we will discuss the characteristics of the project and the characteristics of its environment to have a better understanding of what the factors that influence this building would be.

5.1.1 Location

CREAS building is located in the municipality of Pozuelo de Alarcón, in the community of Madrid, Spain. Pozuelo is a municipality where most of its inhabitants live in an urban peripheral system. It has about 85000 inhabitants and is located about ten kilometers from Madrid's Moncloa district.
The CREAS center is near the Somosaguas campus of the Complutense University of Madrid UCM. The center is in a privileged place because besides being adjacent to the forest park of Adolfo Suarez, it has the characteristic that its vegetation is of the area. In the figure 5.2 we see the exact location of the CREAS building, the

pin indicates the exact position of the main building and the surroundings. The geographical position is: latitude 40°25′50″, longitude 3°47′1″, the altitude is 690 m above sea level.

In this position we find some specific climatic characteristics. The temperature during the winter months has a minimum of 4.9°C while in the summer it reaches 36.5°C. This is why it is important to take advantage of solar and geothermal energy to increase the temperature during the winter and protect the various facades , in particular the southern facade, from the excess of radiation with external elements.

According to the image 5.3 (a), we observe that the months with the highest temperature are July and August, remaining more than 20 days of the month above 30°C. Contrary to this, December and January are the coldest months, when frost is almost 10 days a month. According to the coordinates mentioned, the project is located in the northern hemisphere where the sun at the winter solstice reaches 27° from the horizon. On the other hand, in summer it reaches 69°, keeping itself, the sun, always on the south side of the building.

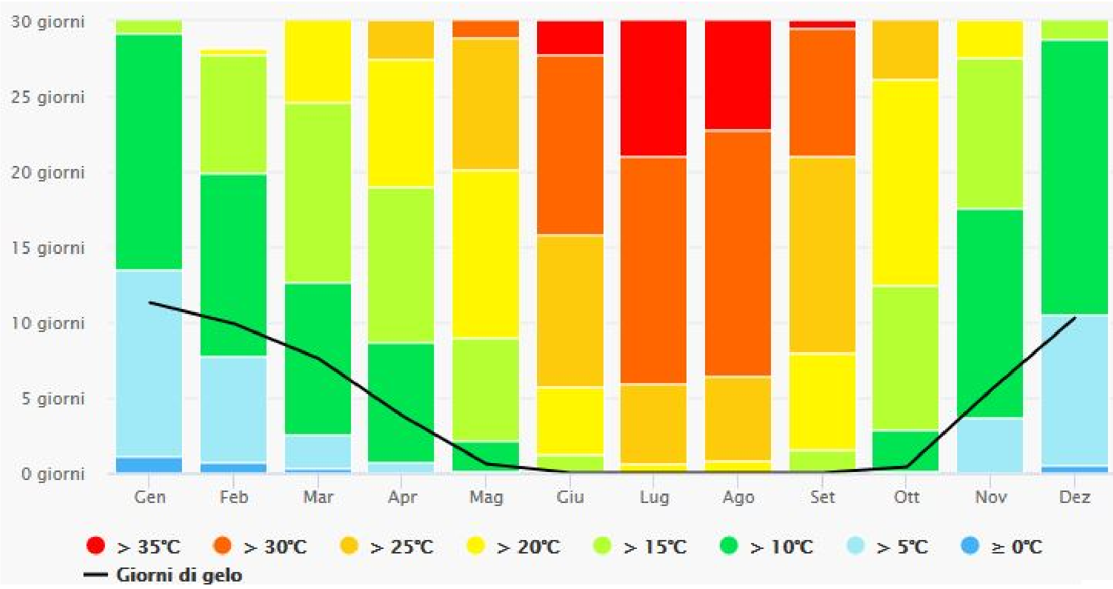
In figure 5.3 (b), we can see that for most of the year the sky is clear. We observe that the intense yellow, representing the sunny days, predominates over the other colors. We also see that the days with greater rainfall coincide with the days with the highest cloudiness. The clearest days match to the summer days that also match to the days with the highest temperature of the year. For this reason it is very important to protect from excess solar radiation in order to preserve a lower temperature than the external and avoid the glare.

In figure 5.4 we observe the sun path diagram with which we can know the angles of solar incidence, depending on the time of day and the period of the year. Let's see how, during the summer solstice, the sun reaches about 70° as an incidence angle with respect to the horizon, this during the summer solstice. During the winter solstice it reaches 25°.

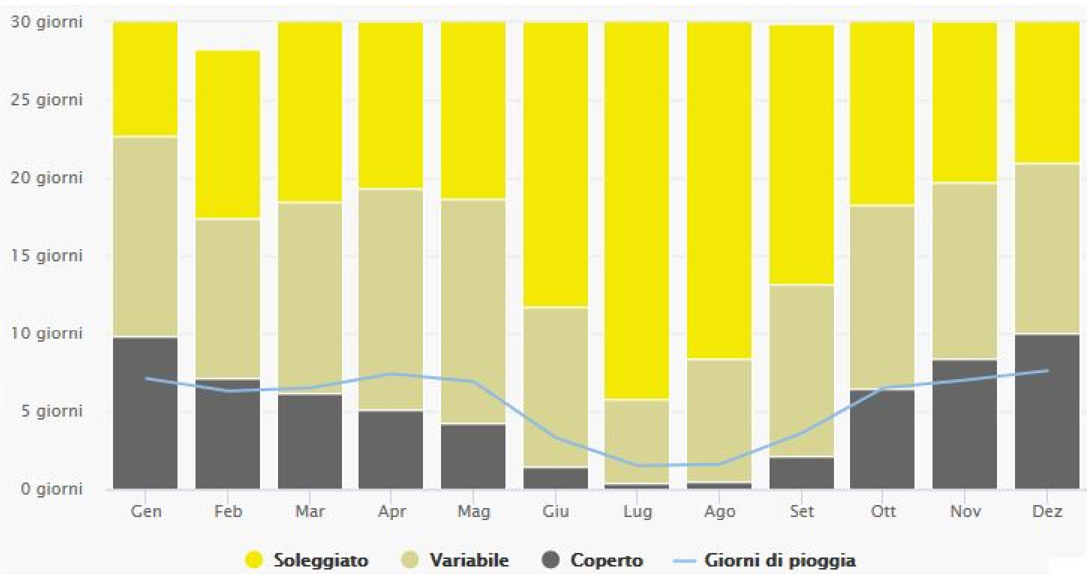
The fact that winter sun is so low compared to the horizon can generate glare inside buildings and, on the contrary, in summer is more perpendicular to the ground. It means that light probably does not penetrate deep enough the structure.
Passive strategies can conflict among the seasons: during the winter, when the sun is low, in order to maintain an adequate temperature inside, we try to put the greatest amount of light to increase the temperature of the environment indoor.

Figure 5.3: Example of External Shading Devices

(a) Maximum Temperatures of Pozuelo de Alarcón

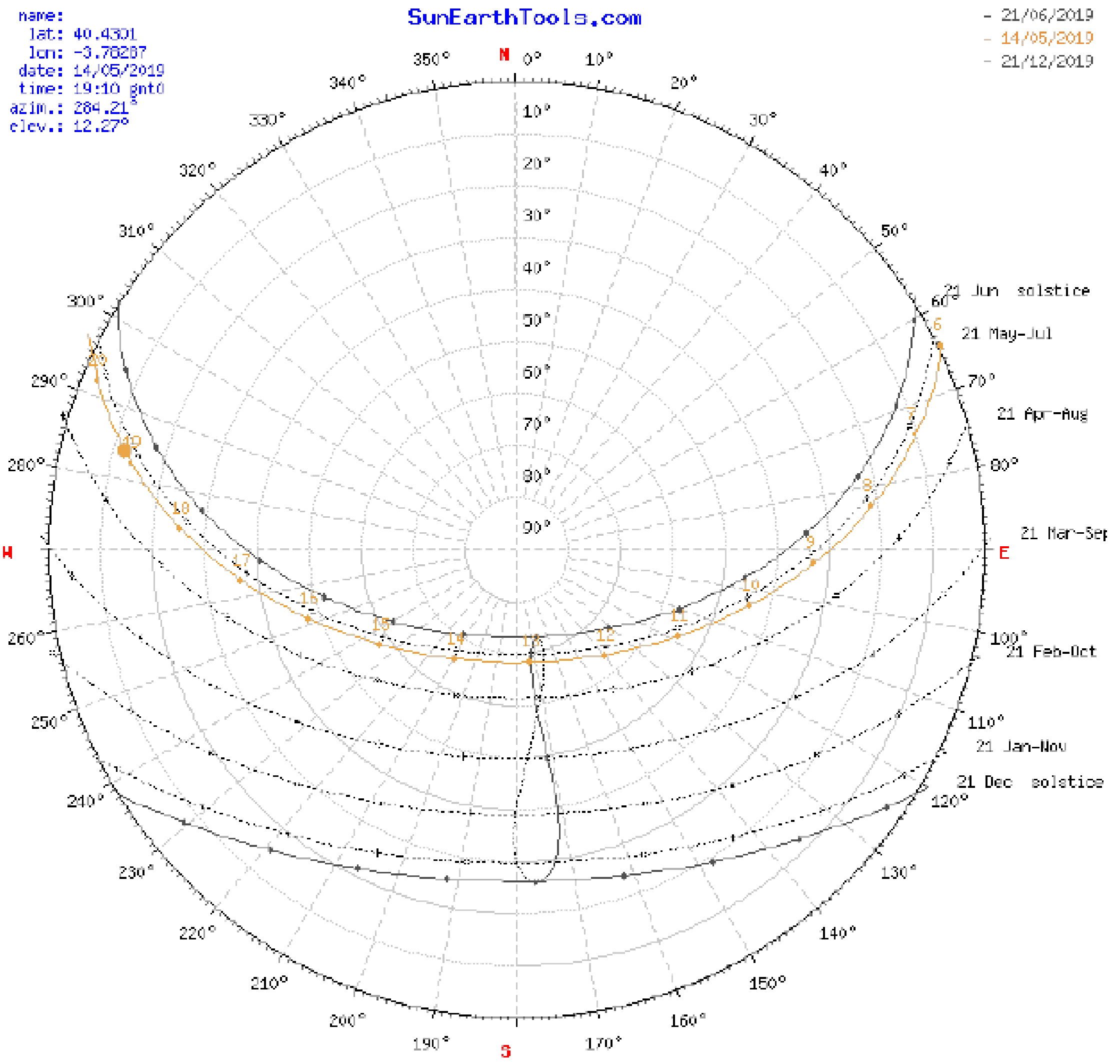


(b) Monthly number of sunny, Partly Cloudy, Cloudy Days and of with Rainfall



Source: https://www.meteoblue.com/it/tempo/previsioni/modelclimate/pozuelo-de-alarcón_spagna_3112989

Figure 5.4: sun Path Diagram of Pozuelo de Alarcón



Source: https://www.sunearthtools.com

The winter strategy in terms of natural lighting would be to redistribute sunlight in such a way that it does not hit surfaces which can generate annoying reflections. On the other hand, during the summer, when the temperature is higher, we try to protect the inner spaces of direct radiation, because it can generate overheating. On the contrary, in terms of natural lighting, it is important to brought to the back of the room the natural light to improve light distribution.

5.1.2 Characteristics of the Building

CREAS building is designed to host activities of knowledge and for spreading environmental values. The building itself intends to educate in this regard.[61]

It is the first public building that has obtained the A certification of the regional administration's Energy Label. [62] The building was built in 2006 and it occupies an area of 397 m^2, of which the workshop classroom, the object of the main analysis, is located in module 1 and it covers and area of 30.9 m^2. The building consists of four main modules that host the various activities and services.
For more information on the building, see the annex A where there are plan, elevation and section of the same.

The building has a modern and, at the same time, welcoming appearance thanks to the use of:

a. simple shapes in the structure (with slight changes in orientation);

b. light colors for the facade;

c. materials such as wood and glass.

As shown in the Fig. 5.5 the building has light colors that allow it to dissipate solar radiation and maintain a good appearance (point b.).
The construction of this building in the ground is in searching for a harmony with the environment, using natural resources such as sun, water, soil and local vegetation, in order to achieve self-sustainability.

In figure 5.6 we observe the distribution of the building, since the four modules are connected by a central corridor. Note that the module 4 where there are the warehouses and the garage is disconnected from internal corridors; this is because this module serves the entire center, so it needs quick access to it. In the plan we can find the exact location of the Workshop Room in the building, which is

Figure 5.5: Facade of the CREAS Building - Workshop Room

Source: C. Bin, Pozuelo de Alarcón, Madrid, Spain, May 2019

located in module 1: this class acts as an independent work space or can be opened by folding a series of sliding panels in the main classroom. This, to carry out activities for a greater number of people. Let's see how the window positioned towards the south facade is completely in glass that gives a great lighting to the room. This study will focus exclusively on analyzing the Workshop Room took it as an independent class.

In the section (Fig. 5.7) are represented some of the passive strategies of the CREAS building. This section corresponds to a cross-section of the main classroom.

The building is positioned by turning the shoulders to the North, using the inclination of the ground to reduce the solar impact of this side and exploiting geothermal energy to reduce heat losses. On the other hand, the southern facade which has greater exposure to the sun uses this explosion to obtain energy gains in temperature.
The greenhouse is also a passive strategy to improve internal temperature. The greenhouse (Fig. 5.8), composed of two glass surfaces, has the function of heating the air: when the air increases its temperature enters through an upper window and, at the same time cold air is absorbed from the inside towards through a lower window. This generates a circular movement, by convection, of the air that heats the interior during the moments when the sun shines. The purpose of the vegetation cover is

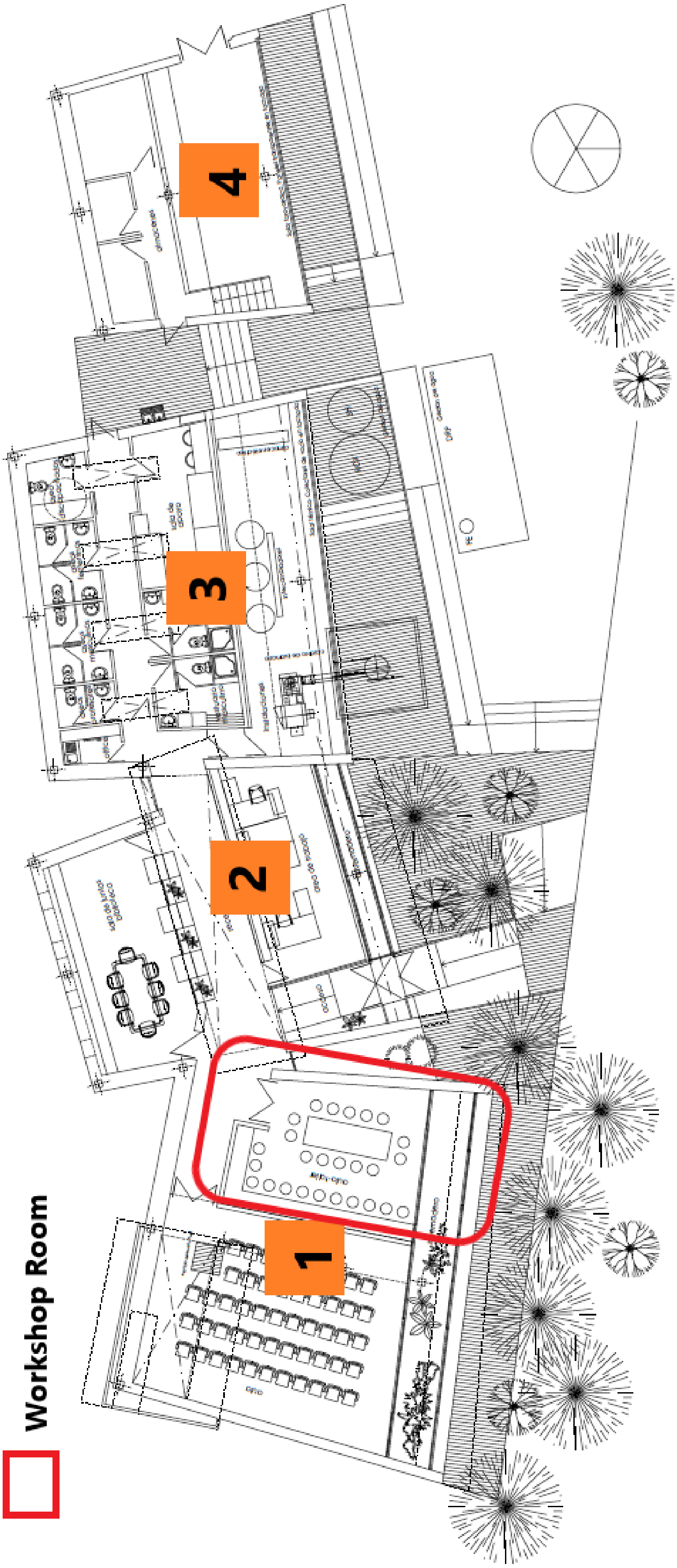
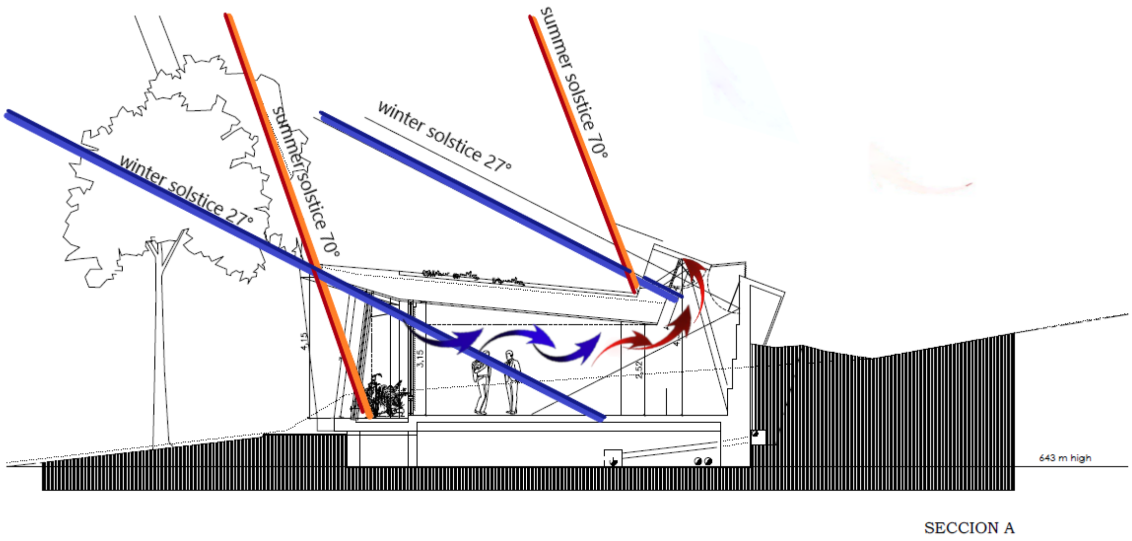


Figure 5.6: CREAS Building and the Workshop Classroom - Ground floor

Source: C. Bin

Figure 5.7: CREAS Building Classroom - Section

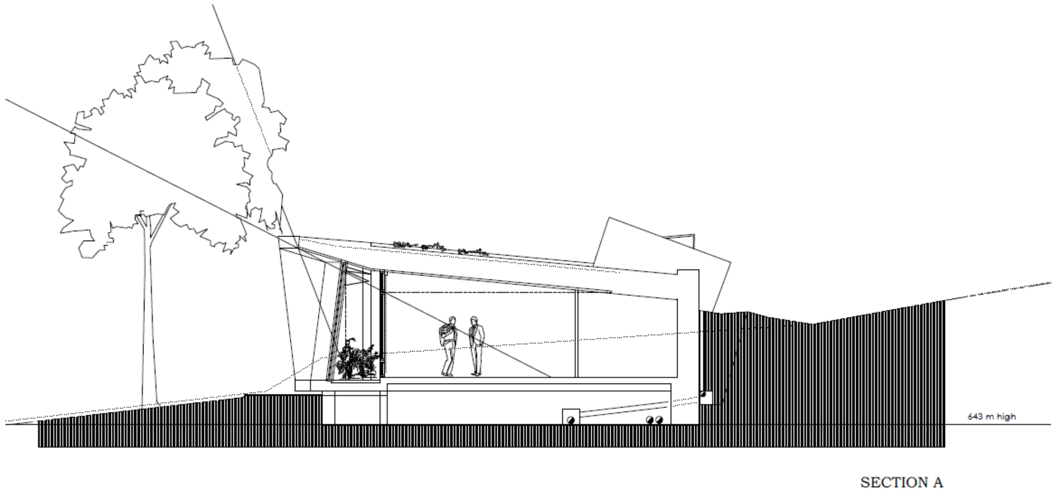


Source: C. Bin

Figure 5.8: The Greenhouse of the Workshop Classroom

Source: C. Bin, Pozuelo de Alarcón, Madrid, Spain, May 2019

Figure 5.9: The section of the Workshop Classroom



Source: C. Bin, Pozuelo de Alarcón, Madrid, Spain, May 2019

to restore a large part of the land planting area to the fauna and flora of the area. It also helps to significantly reduce the roof temperature during the summer months.

In the Fig. 5.7, we also see the strategy of natural ventilation, in the days of the year when the external temperature is comfortable, the windows are open and natural cross-ventilation is generated. Air enters through the main window of the classroom and is expelled through an elevated window located at the rear of the room.
This aerial window also serves as an entrance for natural light to improve its distribution within the class. In this strategy we see how during the summer months, the eaves and reflective surfaces are used to send natural light inwards and therefore to prevent direct influence of the sun and to avoid overheating of the indoor air.
A eave in the front of the building has a similar function: it allows the sunlight to penetrate the building during the winter months, but avoids the direct influence of the sun during the summer months.

We also observed that some deciduous trees were planted in front of the building. This strategy consists of planting high trees and close enough to the building to generate shade during the months of intense heat. In this way the temperature of the building is kept lower than the outside one. During the winter months these trees lose their foliage and the light penetrates the building by heating it.

Another strategy to improve natural lighting is a textile curtain located inside the

Figure 5.10: The Windows' Particular of the Workshop Classroom

Source: C. Bin, Pozuelo de Alarcón, Madrid, Spain, May 2019

greenhouse. These translucent shades have the function of reducing the glare for the users especially during the winter months: as shown in Fig. 5.7 are the months in which greater incidence of the sun is inside the building.
These strategies above mainly concern module 1, which is where the Workshop Room is located. Unlike the main class, the Workshop Room does not have a raised window at the rear of the room, as we can see in Fig. 5.9. The windows (Fig. 5.10) have a wooden structure, the first layer is a simple 8 mm thick glass, this is the window that is completely external. Then there is the greenhouse and the new level of windows. Each of the glass surfaces is composed of a double layer It has the specifications shown in the 5.1 table.
This building was designed using an extensive list of strategies for each element that influences its comfort, functioning, environment and energy consumption. Subsequently, a list of strategies that have been developed to reduce the impact of the building in their environments will be presented. [61]

- Environmental impact strategies;
- Construction strategies;
- Security strategies;
- Strategies in the use of materials;

Table 5.1: Characteristics of the Interior Window of the Workshop Classroom

Construction characteristics of the exterior glasses of the greenhouses			
Material	Thickness(cm)	Conductivity (W/mK)	Emissivity
SGG STADIP CLEAR 44-1	0.8	1	0.84
Construction characteristics of the interior glass of the greenhouses (V2)			
Material	Thickness (cm)	Conductivity (W/mK)	Emissivity
SGG PLANICLEAR 6mm	0.6	1	0.84
Argon	1.2		
SGG COOL-LITE ST 408 4+4mm	0.8	1	0.14

Source: [63]

- Strategies for achieving energy efficiency;
- Strategies to reduce energy consumption;
- Solar energy collection;
- Distribution of solar energy;
- Shading strategy;
- Air movement strategy;
- Passive underground strategies;
- Lighting contribution strategy;
- Consumption strategy for non-renewable resources (water);
- Strategy against noise;
- Maintenance strategy;
- Recycling strategy;
- Strategies with the flora;
- Strategies with the fauna.

This previous list comes from the book CREAS sustainable construction. [61]
Each of these strategies is adequately studied. This demonstrates the complexity of the building and teaches from its own testimony how it is possible to reach a completely self-sufficient building. Among the strategies that influence the natural

lighting of Workshop Room it is worth saving them; the use of eaves, textile curtains, the use of light colors on the walls, the planting of trees to create shade.

5.2 Data Collection

Data collection was the first part of my research work.
First, the data collected in situ were retrieved from the analyzes conducted by the research team of the Physics Department of ETSEM during a period between February and March 2017.
Then these data were compared with the data taken from the Velux Daylight Visualizer 3 software.
At the end a digital modeling was carried out on the DesignBuilder software, thanks to which we obtained other lighting values.
Here the passages are qualitatively examined and only subsequently an analysis of the collected data will take place.

5.2.1 In Situ Data

After a check on the equipment at the university. One by one, the sensors and data loggers were checked and synchronized with the computer program for continuous data collection. After making sure that all the equipment was working properly, we went to the CREAS building to install the equipment.
The Workshop Room was occupied for 13 days in total, between February the 23rd and March the 7th. During this period it was possible to collect complete information for ten days. The first and last days were not taken into consideration as these were the days when the equipment was installed and removed. Similarly, the 1st of March failed, perhaps electricity was cut and there was some change in the system, this prevents them from continuing to record data until 00:00 on March the 2nd. Therefore, the data of these days have not been taken into consideration.

Measurement Tools

For these experiments, materials from the Physics Department of the ESTEM (UPM) were used. With the assistance of the laboratory technician, the luxmeters and thermocouples were manipulated and installed in the classroom to measure the illuminance and the temperature of the class.

The photos and features of the tools used, even if not directly by me, are reported to better understand what the future analysis is based on (Table 5.2).

Equipment Installation

When they were arrived at CREAS, they had arranged the furniture of the workshop classroom in such a way that it simulated the arrangement of a conventional theoretical class. Three rows of desks of five seats each were accommodated.
After arranging the desks, the sensors were installed and was searched the center of the room to place the computer, which runs the data collection program and the data logger.
Then the sensors, luxmeters and thermocouples, were installed strategically to create a grid; they were placed in the manner in which the largest area could be monitored.
In figure 5.11 we observe the order in which the sensors were installed.
One of the sensors was placed inside the greenhouse, the sensor 10. This was initially thought to be located out of the building, but all the sensors had a maximum measuring capacity of 20,000 lux, which makes them useful for taking measurements of internal spaces (during a sunny day in Spain this amount of lux is easily surpassed).

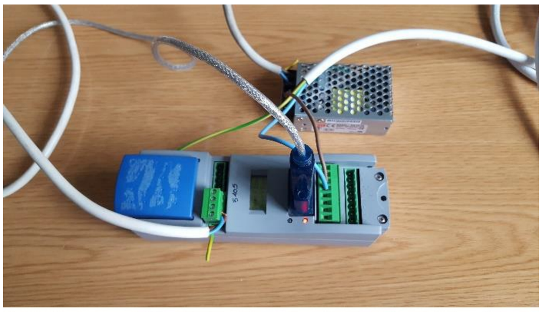
Tape was used to fix the sensors to the table which worked quite well, no sensor moved during the data collection time. The luxmeters were installed together with the thermocouples because if there is a drastic change in the temperature the luxmeters can have alteration in their measurements. The figure 5.6 illustrates how these were positioned.

The data was collected every two minutes during the 24 hours a day. From these, the data between 9 am and 7 pm was taken into account: this is, in fact, the hours during which normally a classroom is used.

5.2.2 Velux Data

An important part of the methodology for carrying out this study is to set up a virtual model to simulate the conditions of the building. This will be used to evaluate the accuracy of simulated data with software compared to those collected in situ. Also, to evaluate how this same space would react if changes were made to the facade of the building.
The thesis developed in the ETSEM Physics Department of UPM with the same data obtained so far, was based on a 3D model initially created on Sketchup and

Table 5.2: Measuring Instruments

Instrument	Description
	• **Opus 200 and 208 Data Logger:** Two types of data loggers of eight inputs and two of two inputs each were used, in order to reach a total of twenty input ports. 10 luxmeters and 10 thermocouples.
	• **Luxmeters Delta OHM HD 2021T:** Ten calibrated luxmeters were used. This instrument have a maximum limit of 20,000 lux.
	• **Continuous Power Bridge Mean Well RS-24-24 24V:** It was used one of these bridges for each of the data loggers, so a total of 4 were used.
	• **Thermocouples type k 10** The type K is the most common type of thermocouple. Accuracy: Standard +/- 2.2C or +/- 0.75%

Source: [63]

	• **Computer:** The computer was connected to the data loggers and, with a specific program, the data was recorded from each sensor.
	• **Tape Measure:** With the tape measure, they located the exact points that were located a priori to cover the entire classroom.
	• **Extension:** The extension was used to locate the computer and the data logger in the center of the classroom. In this way the sensor cables reached all the points of the classroom.

Source: [63]

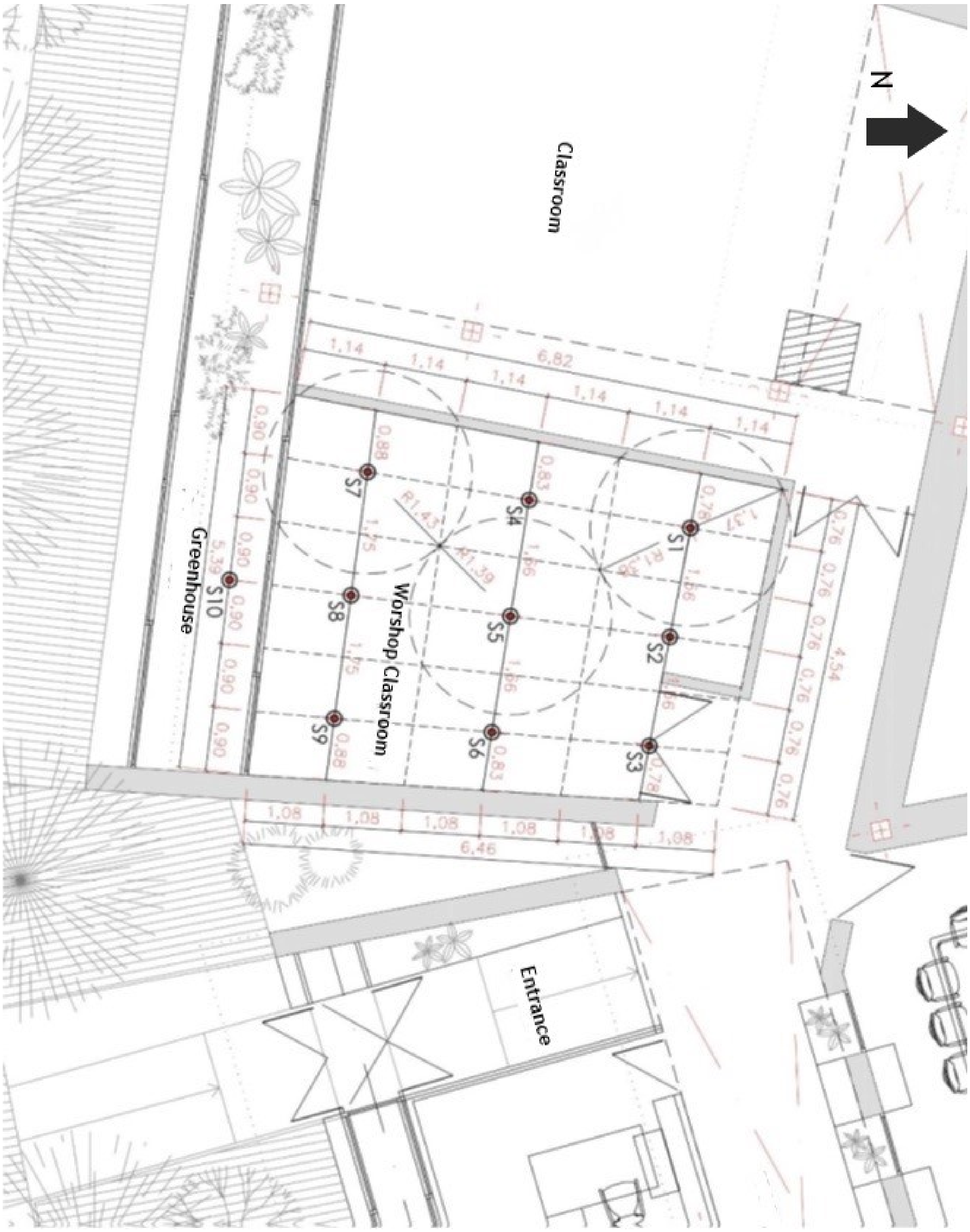
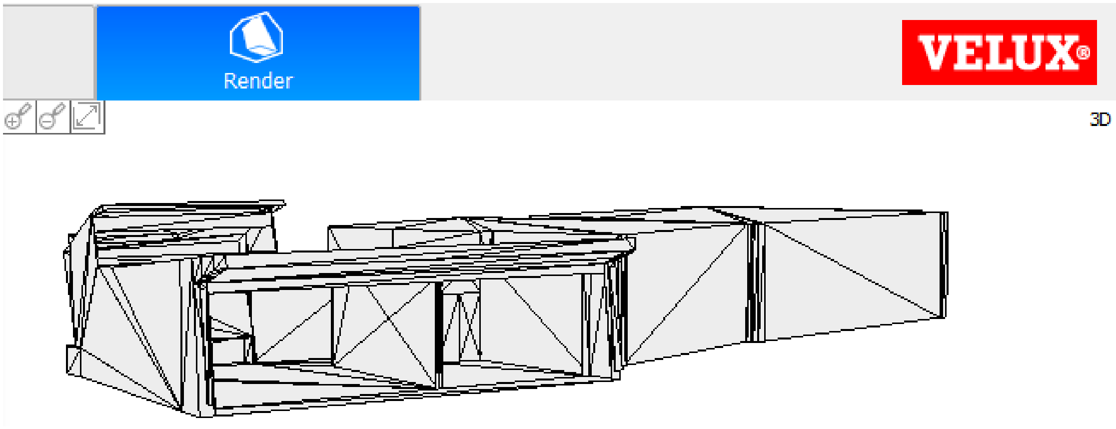


Figure 5.11: The Equipment Installation in the Workshop Room

Source: C. Bin

Figure 5.12: CREAS Building imported in the Velux software



Source: C. Bin

then imported into the VELUX natural lighting analysis software. The data obtained were manipulated to be compared with the data collected in situ.
The VELUX software was chosen thanks to its specialization in the evaluation of natural light in building, it is also a big advantage that has a good compatibility with the Sketchup modeling program since this allows a great flexibility when modeling. Likewise, it has been validated with CIE 171:2006 (standard about "Test cases to assess the accuracy of lighting computer programs) that gives it credibility and, finally, the fact that it is free software is important.
For the fabrication of the Sketchup model, the original building plans that were awarded by CREAS were used. Importing documents in DWG format (AutoCad) began the construction of the original model.
The model was then imported into Velux where the building materials and its exact location were initially specified. By giving the appropriate conditions and the chosen unit of measurement, the values were then obtained at a height of 75 cm corresponding to the height of the work surface. The values were expressed in lux, the same as those collected in situ.

I also have imported my project in Velux Daylight Visualizer at a later stage in order to study the daylight factor with this program 5.12. Here I see the software's limit soon: for the daylight factor simulation, in Velux the user can't specify the sky model and the specific day under study 5.13. The only possible choices are the sunny, Intermediate or Overcast sky conditions. We considered this kind of analysis too general, so I chase to continue my study with the help of DesignBuilder.

Figure 5.13: Daylight Factor Simulation Specification of Velux

Source: C. Bin

5.2.3 DesignBuilder's Data

The application part of the thesis was developed thanks to the use of the DesignBuilder software. I had already used the software before and, for this case study, I downloaded the Version 5.0.1.024. I started by modeling the 3D room examined according to the measurements shown on the DWG files granted by CREAS. Particular attention was paid to the development of the correct openings, necessary for the subsequent analysis. In fact, for this study I based myself on the box related to natural lighting. Radiance daylighting calculations were controlled using a set of options on the Daylighting calculation options dialog which was displayed before the calculations were started. It was important to make a selection here that is appropriate to the building you are analyzing. [64]

For the Report type that I required after the calculations, I selected the type 1 - Map, I saved all of these maps and I exported all the data in a CSV spreadsheet format. For more details about the investigation modes, see the par. 6.2.1.

This methodology seeks to find an effective and free strategy to perform an analysis of the lighting of an interior space, a rapid and easily understandable process is sought for users working in the building sector, giving an alternative to the software previously used, Velux, in the cases of the illuminance simulation and a more complete analysis of the daylight factor values.

Chapter 6

Analysis and Results

This section will be divided mainly into three parts:

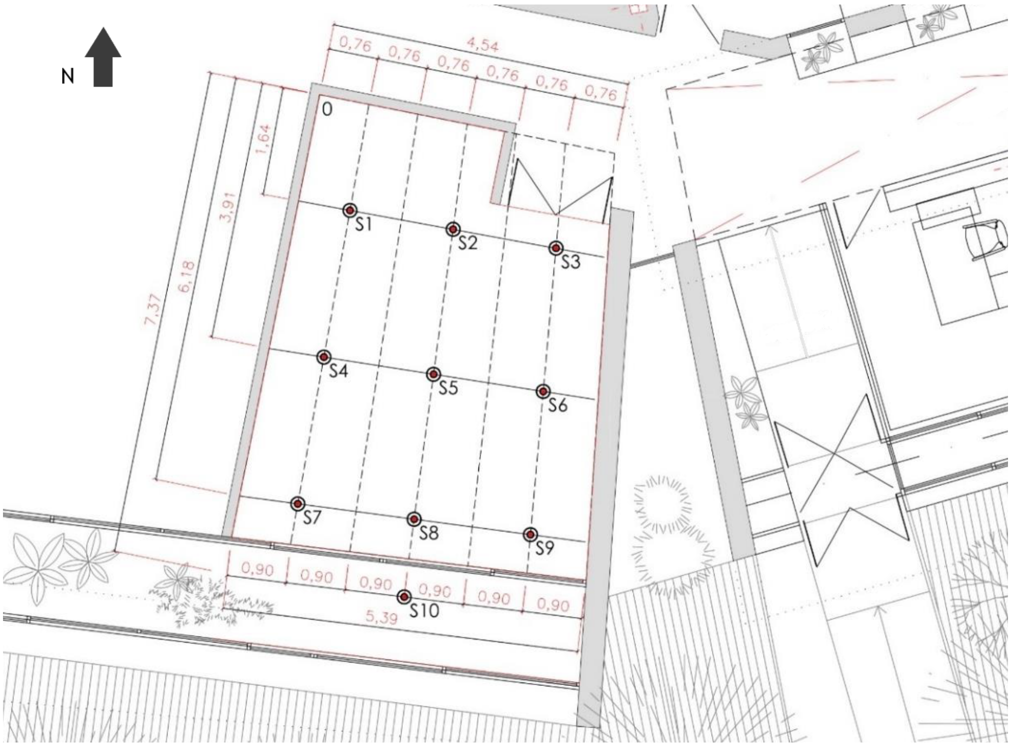
- the first part is composed of the results found in situ and the comparison of these with the data obtained with the VELUX software;
- the second part consists of the validation of the DesignBuilder software, using the information obtained from in situ data and the information obtained using digital methods. The results will be compared each other, also thanks to the map drawn with Surfer (see Att. B and Att. D) and I pull data off a dedicated software, Statgraphics. Similarly to the previous step, the results of this validation will be analyzed before moving on to the next step;
- in the third and last part proposals will be presented in which changes in the windows and in the facade have been made to understand how the building behaves in each of these scenarios. As in the previous cases, the results will be analyzed after being exposed.

In th Attachments section you can find all the tables and graphs made for the analysis of the workshop room, both for the results in situ, for those simulated with Velux and with DesignBuilder and the subsequent study of the different scenario.

6.1 Data collected in situ and compared with the Velux's Data

This section deals with reporting and analyzing the data recovered from the investigations conducted in situ and the data obtained with the software Velux. As explained in the methodology (cap. 5), this study consisted in the continuous collection of data between February the 24^{th} of 2017 and March the 6^{th} of 2017. Of

Figure 6.1: Positioning of the Sensors over the Workshop Room



Source: C. Bin

these eleven (11) days only nine (9) were taken into account, since of three of those days the complete informations was not obtained. The layout of each sensor inside the room is shown in the figure 6.1 (luxmeter and combined thermocouple).
For a subsequent study of the data, the coordinates of the points where the illuminance and temperature sensors (lux meters and thermocouples) were positioned are shown in the table 6.1.

6.1.1 Analysis of the Illuminance [lux] Data

The first thing that was done was to take the average daily for each sensor to understand which were the sensors that received more natural light during the day (Fig. 6.2).
It is worth remembering that for this analysis only the portion of the day was taken into account, between 8 AM and 20 PM. This is because this is the time when the classroom is used, CREAS does not carry out night activities.

In the successive diagram (Fig. 6.2), the first thing that becomes clear is that the the luxmeters positioned far from the window measure lighting values much lower than those next to it or to the sensor 10, placed in the greenhouse, taken as an

Table 6.1: Coordinates of the Luxmeters and Termocouples in the Workshop Room

Nº SENSOR	COORDINATES	
	x [m]	**y** [m]
1	1,65	0,83
2	1,65	2,49
3	1,65	4,15
4	3,9	0,83
5	3,9	2,49
6	3,9	4,15
7	6,2	0,83
8	6,2	2,49
9	6,2	4,15
10	7,37	2,49

Figure 6.2: Graphic with the Daily Average Illuminance per Sensor

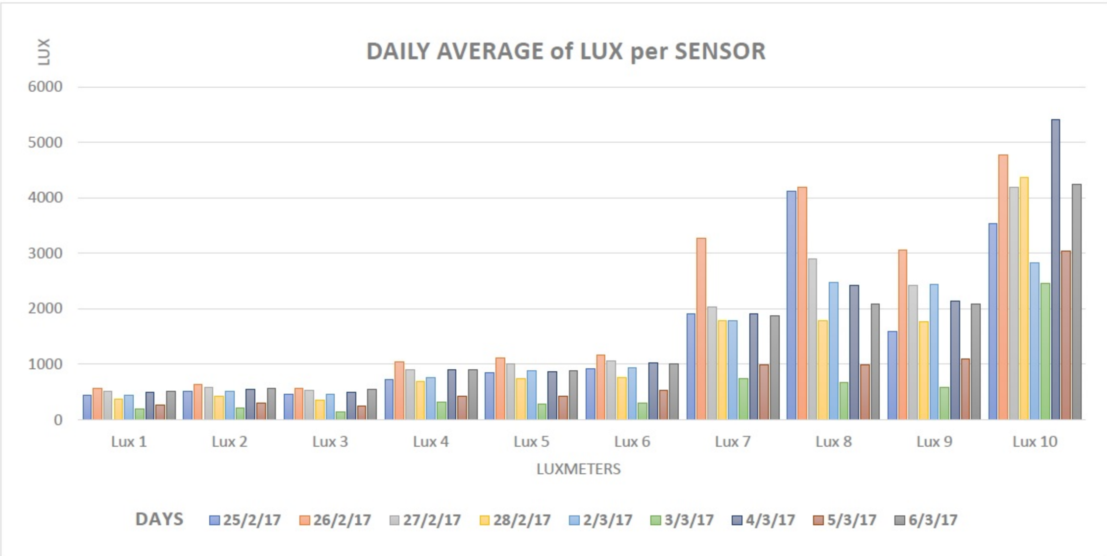


Figure 6.3: Graphic with the Overall Average of Each Sensor

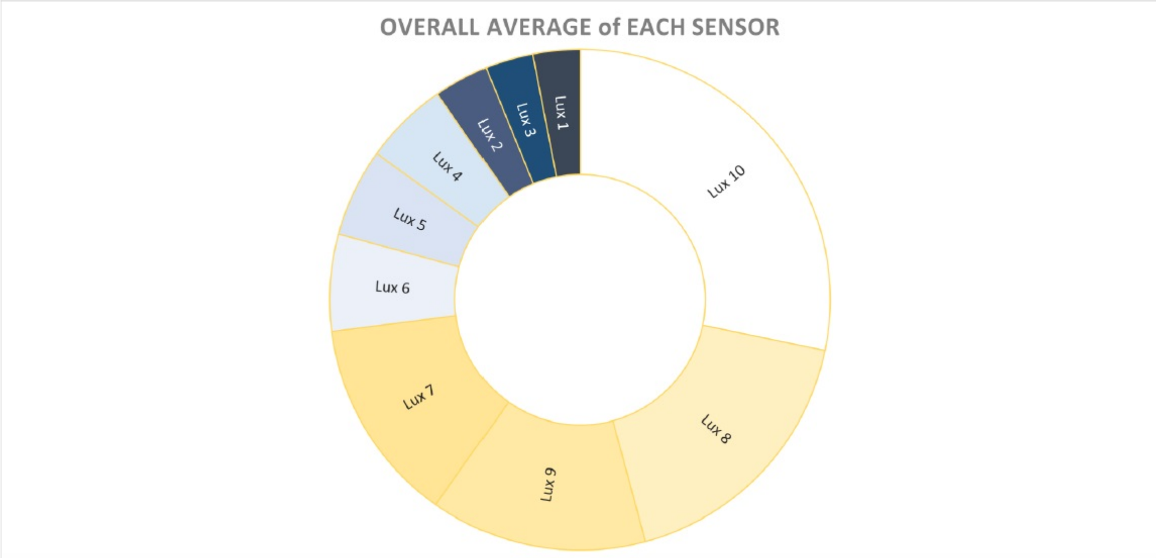


Table 6.2: Overall Average of Each Sensor

Sensor	*Lux 1*	*Lux 2*	*Lux 3*	*Lux 4*	*Lux 5*	*Lux 6*	*Lux 7*	*Lux 8*	*Lux 9*	*Lux 10*
Average [lux]	420,76	479,19	422,89	743,55	780,84	856,47	1809,04	2404,57	1910,74	3871,87

external reference sensor. More to the point the luxmeter 10, in most days it far exceeds the other luxmeters. This fact not only happens to the luxmeter 10 but also to the luxmeters 7, 8 and 9 that form the first row of sensor near to the openings. These four luxmeters exceed the measurement limit of 20,000 lux on February 25th, 26th and 27th, the first three days of analysis. On February 28th, and on March 2nd, 4th and 6th, the luxmeter 10 exceeds the limits equally. And the only days that the limit is not exceeded are March 5th and 3rd. We can also observe which were the sunniest days and such as February 26th, 27th and March 2nd, 4th, 6th. The March 3rd is the day with the highest cloudiness.

This analysis may be supplemented also with the data reported more specifically in the table 6.2, the same represented in the graph in the figure 6.3. These represent the overall average for each sensor and, also with the total values, we can see how the luxmeters 10 exceeds the rest of the sensors by more than 2000 lux.
We can also note that the luxmeters 7, 8, 9 are characterized by having a very high value, so a similar behavior of the luxmeter in the greenhouse. This is because they can receive directly the sunlight during the day; so the daily contribution of lighting depends more by the sun's condition.
On the contrary, the other sensors have a similar behavior throughout the days

Table 6.3: Chosen Dates for Comparing Measured and Simulated Data

Date	**SUNNY**	**PARTLY CLOUDY**	**CLOUDY**
09:00	04/03/2017	25/02/2017	05/03/2017
12:00	04/03/2017	03/03/2017	05/03/2017
16:00	05/03/2017	06/03/2017	03/03/2017

and, depending on the depth in which they are, they behave in a similar way. The luxmeters 4, 5 and 6 are in the middle of the classroom and the luxmeters 1, 2 and 3 are on the back side (North).

We note that, on average, the luxometers 7, 8 and 9 exceed the luminance limits, being between 1800 and 2400 lux. In fact, the recommended value for a classroom according to the standard EN 12464-1: 2012 that between 300 and 750 lux for educational classrooms, depending on the type of activity. [53]

As we can see in table 6.2 the luxmeters 1, 2 and 3 have an average between 420 and 480 which is quite positive, this means that the back of the classroom receives enough natural light. On the other hand, if we go to moments of cloudiness where natural light is very low, it may be insufficient.

6.1.2 Values of Illuminance Studied in Accordance with the Sky's Conditions

To put it into perspective, after having established that the amount of light depends on the sky conditions, it was useful to resort to a division of values according to the external meteorological conditions of the respective days of measurement.

For a clearer study and then being able to compare the data collected with the sensors with the simulated data with the Velux software and subsequently with DesignBuilder, it was necessary to choose three times of the day in which to carry out the checks divided according to three types of sky conditions.
A table (Tab. 6.3) is shown with the days chosen and the division carried out for sunny, partially cloudy and cloudy days. This division was carried out by comparing the standards with the meteorological data available on the days of analysis.

This division has produced the data shown in the table 6.4.

Table 6.4: In Situ Illuminance Data [lux] According to Sky's Conditions

TIME	**Nº SENSOR**	**SUNNY** [lux]	**PARTLY CLOUDY** [lux]	**CLOUDY** [lux]
	1	326	276	167
	2	347	310	189
	3	278	250	123
	4	575	460	254
09:00	5	492	464	234
	6	547	477	280
	7	1289	2962	610
	8	1036	817	568
	9	892	711	563
	10	3747	4002	1893
	1	822	374	315
	2	892	397	351
	3	804	318	283
	4	1678	709	575
	5	1505	601	535
12:00	6	1682	669	623
	7	3571	1714	1360
	8	3403	1548	1247
	9	3259	1337	1318
	10	17220	6414	4525
	1	435	706	104
	2	531	838	121
	3	488	858	56
	4	780	1291	113
	5	811	1350	109
16:00	6	994	1617	140
	7	1710	2873	278
	8	1849	3324	274
	9	1892	3380	282
	10	5872	17922	899

Table 6.5: In Situ Daylight Factor DF Data According to Sky's Conditions

TIME	Nº SENSOR	SUNNY	PARTLY CLOUDY	CLOUDY
09:00	1	8,7%	6,9%	8,8%
	2	9,3%	7,7%	10,0%
	3	7,4%	6,3%	6,5%
	4	15,3%	11,5%	13,4%
	5	13,1%	11,6%	12,4%
	6	14,6%	11,9%	14,8%
	7	34,4%	74,0%	32,2%
	8	27,6%	20,4%	30,0%
	9	23,8%	17,8%	29,7%
	10	100%	100%	100%
12:00	1	4,8%	5,8%	7,0%
	2	5,2%	6,2%	7,8%
	3	4,7%	5,0%	6,3%
	4	9,7%	11,0%	12,7%
	5	8,7%	9,4%	11,8%
	6	9,8%	10,4%	13,8%
	7	20,7%	26,7%	30,1%
	8	19,8%	24,1%	27,6%
	9	18,9%	20,8%	29,1%
	10	100%	100%	100%
16:00	1	7,4%	3,9%	11,6%
	2	9,0%	4,7%	13,4%
	3	8,3%	4,8%	6,2%
	4	13,3%	7,2%	12,5%
	5	13,8%	7,5%	12,2%
	6	16,9%	9,0%	15,6%
	7	29,1%	16,0%	30,9%
	8	31,5%	18,5%	30,5%
	9	32,2%	18,9%	31,3%
	10	100%	100%	100%

6.1.3 In Situ DF Values Depending on the Sky's Types

The focus of the investigations is concentrated here on the daylight factor DF. In fact, this ratio is frequently used in architecture and in the building design to assess the natural light perceived on the work surface within the spaces and to determine whether this is sufficient to complete the activities to which the spaces are provided. A broad explanation of this ratio was given in the paragraph 3.4.1.

Here we limit ourselves to reporting the data obtained by applying the given definition. The values are given considering the reference value as the amount of daylight available in the greenhouse. That because we can not have a sensor on the outside the building; the cable did not allow the building to be completely closed, which, as a public building, was not allowed.
Taking account of this simplification, the table with the DF values found in percentage is inserted below (Tab. 6.5).
According to the standard, the recommended average daylight factor for classrooms and laboratories is 3%, while according to other sources the optimal value must be greater than 4%. [37]
In fact, if it is too low, artificial light sources must always be required. The CISBE Lighting Guide 10 of the year 1999, however, emphasizes that a value greater than 5% may cause less dazzle and an excess of solar heat gain. [65]

In this case are almost always over the 5% limit. The workshop room, having the south face completely open to the outside, captures more natural light than desired, so we observed that results.

For a better understanding of the data, studying the Daylight Factor in the known conditions, we have presented in tabular form:

- the Average values (Tab. 6.6);
- the Maximum values (Tab. 6.7);
- the Minimum values (Tab. 6.8);
- the Standard Deviation (Tab. 6.9).

Let's see how the average values are too high even according to the standards, while those on which we should refer as ideal values are the minimum ones. This data are always found in the sensors 1, 2 or 3.

Table 6.6: Average DF Measured in Situ

Average	**SUNNY**	**PARTLY CLOUDY**	**CLOUDY**
9:00	25%	27%	26%
12:00	20%	22%	25%
16:00	26%	19%	26%

Table 6.7: Maximum DF Measured in Situ

Maximum	**SUNNY**	**PARTLY CLOUDY**	**CLOUDY**
9:00	34%	74%	32%
12:00	21%	27%	30%
16:00	32%	19%	31%

If you report the standard deviation in the table, you can see how the data are dispersed around to the average found. The value is very high in the case of sunny days, while the variability of the data population is much lower in the case of cloudy skies. This is because, in this case, the DF depends only on the diffused component of sunlight, less variable compared to the direct one.
It is usually difficult to reach a value of more than 2% and it is for this reason that this is the value imposed, for example, Italy by the 1975 health decree. In our case, however, the aero-lighting surface (the opening) is about 16 m^2 instead the surface the classroom is 32 m^2. The 1/8 rule (the opening surface must not be less than 1/8 of the floor surface) has been largely overcome, to the point of causing severe glare problems in the environment.

6.1.4 Uniformity in Situ

The uniformity is a factor that is important to take into account. It is a percentage value that is defined by the average illuminance over the minimum illuminance, as you can see in the specific paragraph, the 3.4.2. Lighting uniformity affects our perception of environment and our ability to navigate it. Using the general values measured in situ, we can obtain the uniformity factor in the workshop room.

Table 6.8: Minimum DF Measured in Situ

Minimum	**SUNNY**	**PARTLY CLOUDY**	**CLOUDY**
9:00	7%	6%	6%
12:00	5%	5%	6%
16:00	7%	4%	6%

Table 6.9: Standard Deviation DF Measured in Situ

Standard Deviation	**SUNNY**	**PARTLY CLOUDY**	**CLOUDY**
9:00	27%	33%	3%
12:00	27%	29%	14%
16:00	28%	29%	4%

Table 6.10: Lighting Uniformity for Each Sensor

TIME	**Nº SENSOR**	**SUNNY**	**PARTLY CLOUDY**	**CLOUDY**
09:00	1	0,85	0,91	0,74
	2	0,80	0,90	0,65
	3	1,00	1,11	1,00
	4	0,48	0,60	0,48
	5	0,57	0,60	0,52
	6	0,51	0,58	0,44
	7	0,22	0,09	0,20
	8	0,27	0,34	0,22
	9	0,31	0,39	0,22
	10	0,07	0,07	0,06
12:00	1	0,98	0,85	0,90
	2	0,90	0,80	0,81
	3	1,00	1,00	1,00
	4	0,48	0,45	0,49
	5	0,53	0,53	0,53
	6	0,48	0,48	0,45
	7	0,23	0,19	0,21
	8	0,24	0,21	0,23
	9	0,25	0,24	0,21
	10	0,05	0,05	0,06
16:00	1	1,00	1,00	0,53
	2	0,82	0,84	0,46
	3	0,89	0,82	1,00
	4	0,56	0,55	0,49
	5	0,54	0,52	0,51
	6	0,44	0,44	0,40
	7	0,25	0,25	0,20
	8	0,24	0,21	0,20
	9	0,23	0,21	0,20
	10	0,07	0,04	0,06

Table 6.11: Lighting Average Uniformity

Uniformity	**SUNNY**	**PARTLY CLOUDY**	**CLOUDY**
9:00	0,29	0,29	0,35
12:00	0,23	0,23	0,25
16:00	0,28	0,21	0,23

It was considered useful to calculate the uniformity in all the points where the sensors are placed to highlight how different the values are from each other (Tab. 6.10). On the contrary, the E_{med} at the same time and at the same type of sky, with respect to the minimum value in the same conditions, remains approximately constant throughout the room. In fact the uniformity with, using the E_{med} varies between 0.21 and 0.35. (Tab. 6.11)

Clearly this is not a positive value, in fact the general focus-intensive tasks demand pretend a ratio of 0.6.

The reasons for this negative value are the same as those mentioned in the previous paragraph regarding the study of DF. The large opening in the external side of the classroom dazzles the students next to it and it is less than efficient for those in the north area of the room.

6.1.5 Temperature in Situ

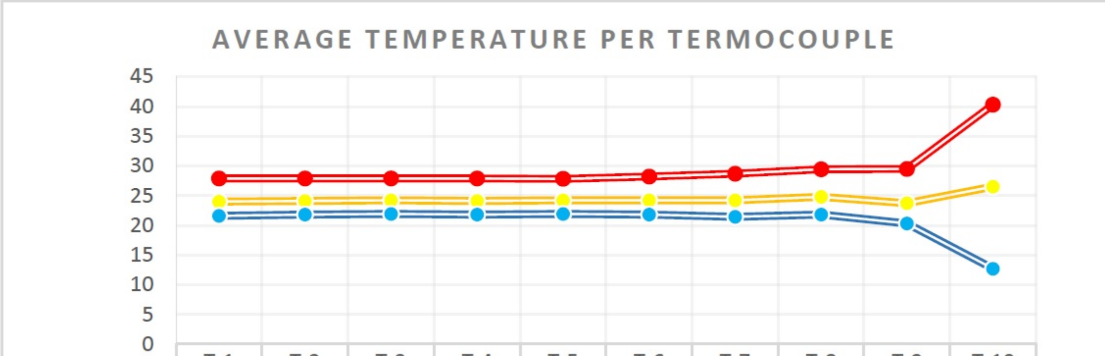
The temperature inside the workshop room was measured in order to know if the values given by the thermocouples were affected by the temperature of the environment. The values obtained for the now known conditions are shown in the table 6.12.
It is observed, also thanks to figure 6.4, how the temperature inside the room remains stable in most of the environment. The thermocouples close to the window (7, 8 and 9) oscillate depending on the day. These have the greatest variations without taking into account the thermocouple 10, the one inside the greenhouse. This luxmeter is quite susceptible to the outside temperature, but also to changes in cloudiness. Although the greenhouse is not properly isolated from the external environment. It has a simple window and simple glass, and there the sun hits this space, the air inside is heated and a greenhouse effect is produced.

In general terms, we observe that the temperature remains supremely stable,

Table 6.12: Temperatures Measured in Situ

TIME	**Nº SENSOR**	**SUNNY** [°C]	**PARTLY CLOUDY** [°C]	**CLOUDY** [°C]
09:00	1	20,7	21,4	21,8
	2	20,5	21,0	21,6
	3	20,9	21,7	22,0
	4	20,3	20,9	21,5
	5	20,1	21,2	21,4
	6	20,8	20,9	21,9
	7	19,8	20,5	21,1
	8	20,3	20,8	21,5
	9	18,3	19,0	19,7
	10	7,9	9,5	11,4
12:00	1	23,1	23,5	22,7
	2	22,6	24,4	22,4
	3	23,5	23,7	22,7
	4	22,8	24,1	22,4
	5	23,3	23,9	22,2
	6	22,9	24,4	22,9
	7	23,7	24,0	21,6
	8	23,3	24,3	22,6
	9	21,6	22,6	20,6
	10	24,2	18,8	14,3
16:00	1	23,9	26,1	23,6
	2	24,8	26,7	24,6
	3	24,4	26,2	23,8
	4	24,4	26,9	23,9
	5	24,2	26,7	24,1
	6	24,9	27,1	24,1
	7	23,9	27,2	24,0
	8	24,6	27,8	23,8
	9	22,9	26,8	22,4
	10	18,6	36,9	15,4

Figure 6.4: Graphic with the Average Temperature of Each Thermocouple



	T-1	T-2	T-3	T-4	T-5	T-6	T-7	T-8	T-9	T-10
T - Av	24	24,1	24,2	24,1	24,2	24,2	24,2	24,8	23,7	26,5
T - Max	27,9	27,9	27,9	27,9	27,8	28,2	28,7	29,4	29,5	40,3
T - Min	21,6	21,8	21,9	21,8	21,9	21,8	21,4	21,8	20,3	12,7

never lower than 21°C in any of the interior points. So we are overall in the comfort temperature, in some cases of temperatures up to 18°C are accepted. On the other hand, we see that all the sensors exceed 26°C which is the comfort temperature. For this reason, measures should be taken to reduce not only the influence of the sunlight, but also the temperature in the moments of greatest radiation.

In the Annex B you can find the temperature distribution maps obtained with the Surfer software, these were useful in the analysis of this quantity.

6.1.6 Velux DF Values Depending on the Sky's Types

In this section we present the results obtained through a computer simulation. In order to compare the results of the VELUX program with real measurement and subsequently with the results of DesignBuilder, after considering the illuminance data, have been transformed into dimensionless values (DF).

The Daylight Factor DF data collected from a previous simulation are shown in the table 6.13. [63]

It is necessary to highlight how the Velux data was obtained by choosing the specific month in analysis and certain hours in which to carry out the simulations. Before simulating, it was possible to locate the sensors in the exact points to obtain more precise results.
The month of March and, according to the subdivision already reported, the hours

9.00, 12.00 and 16.00, with sunny, partly cloudy and cloudy conditions were chosen (see Tab. 6.3). In total nine simulations were carried out for this validation.

The graphs with the comparison of data will be presented in the following section, with the addition of data obtained from DesignBuilder.

Table 6.13: DF obtained with Velux

TIME	**Nº SENSOR**	**SUNNY** [%]	**PARTLY CLOUDY** [%]	**CLOUDY** [%]
09:00	1	10	7,9	7,3
	2	10	9,2	9,1
	3	10	9,3	9,4
	4	18	16,5	14,4
	5	18	17,8	17,4
	6	17	17,3	18
	7	40	35,6	31,1
	8	35	34,8	34,9
	9	29	30,5	32,6
	10	100	100	100
12:00	1	8,8	6,8	7,1
	2	10,6	8,9	9,1
	3	10,8	9,1	9,5
	4	16,4	14,3	14,9
	5	19,2	17,2	18,2
	6	19,3	16,8	18,5
	7	36,1	31,6	32,7
	8	36,9	35,1	35,2
	9	34,7	31,9	32,9
	10	100	100	100
16:00	1	7,7	6,9	7
	2	11,1	9,5	9
	3	13,8	10,8	9,2
	4	14,2	13,4	14,6
	5	22	18,8	17,7
	6	24,6	21,2	17,6
	7	31,6	32,1	33,2
	8	40,2	37,2	35,4
	9	42,4	37,8	32,4
	10	100	100	100

6.2 Validation and Analysis of the DesignBuilder's Data

The values on table 6.13 indicates the starting point of my research work. To these data, we added those which the DesignBuilder software allowed me to extrapolate from the model drawn there.

6.2.1 The DesignBuilder Model

To perform a simulation of natural light using DesignBuilder, we need to work on a model of the building.
There are two options to make the model, the first is to import a model of some of the programs compatible with. The second option is to draw the model within the same program. I opted for the second option to make sure that every detail of the model under consideration was correct and also if the design phase on the software was not quite simple.

The creation of the model (Fig. 6.6) followed the following steps:

1. Fill in the box peculiar to the location with the geomorphological details of the site;
2. Define geometry by:
   - Drawing the entire CREAS building;
   - Editing the workshop room block;
   - Inserting the openings and the features related to it.
3. Rotate the building according to the actual exposure.

At this point, after the obstacle represented by the unconventional geometry of the building's roof and the correct execution of the space dedicated to the greenhouse (see Fig. 6.5, Fig. 6.6 and Fig. 6.7), I did not have to deal with model options regarding stratigraphy, if not the definition of thickness, or regarding the plant and energy system. In fact between all the sheets, the natural lighting has its own as shown in the figure 6.8.
In general, the natural lighting module is an excellent tool to evaluate and optimize the use of the lighting in the building. It works thanks to the *Radiance* calculation engine that offers the optimal solution in terms of lighting performance by calculating the illuminance levels and the daylight factors. It is also able to generate

Figure 6.5: CREAS Building designed on DesignBuilder

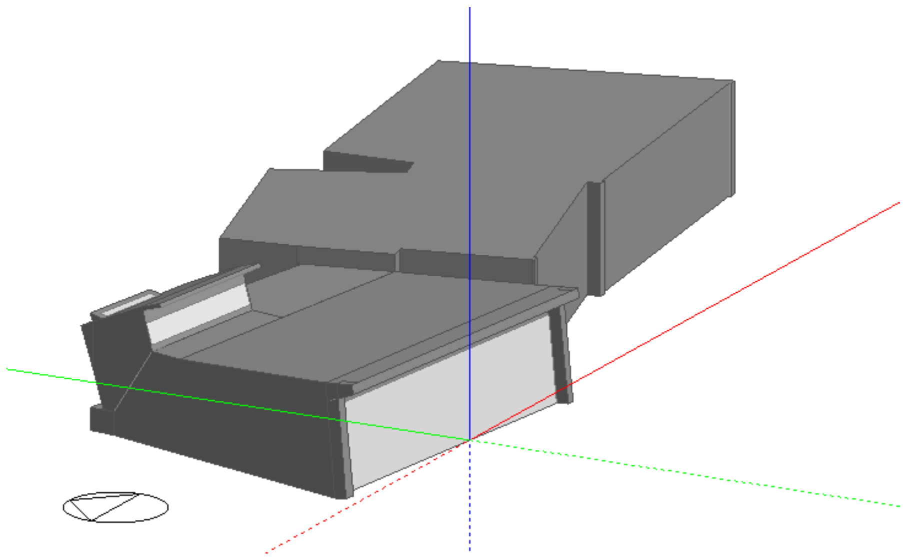


Figure 6.6: Workshop Room designed on DesignBuilder

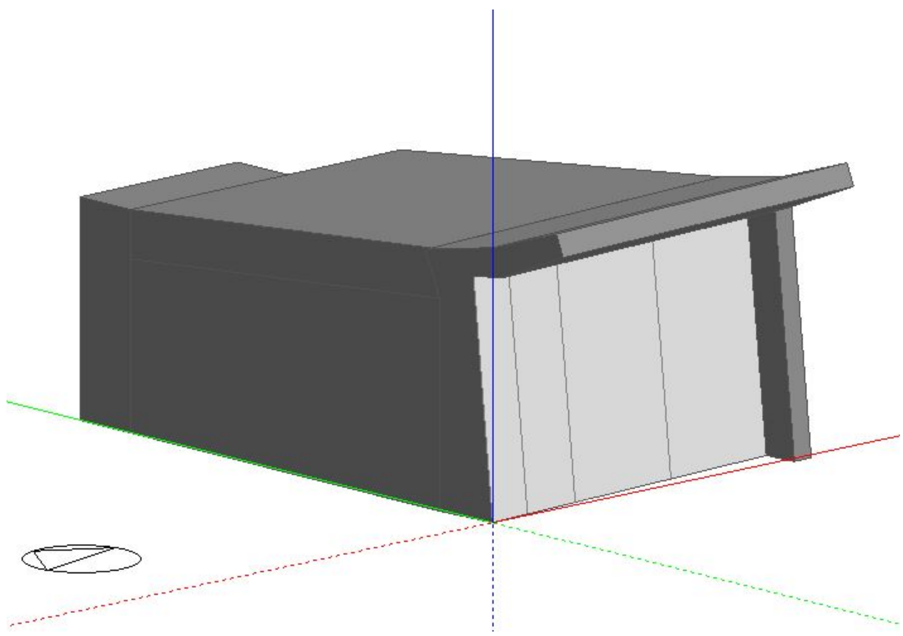


Figure 6.7: Workshop Room's Greenhouse designed on DesignBuilder

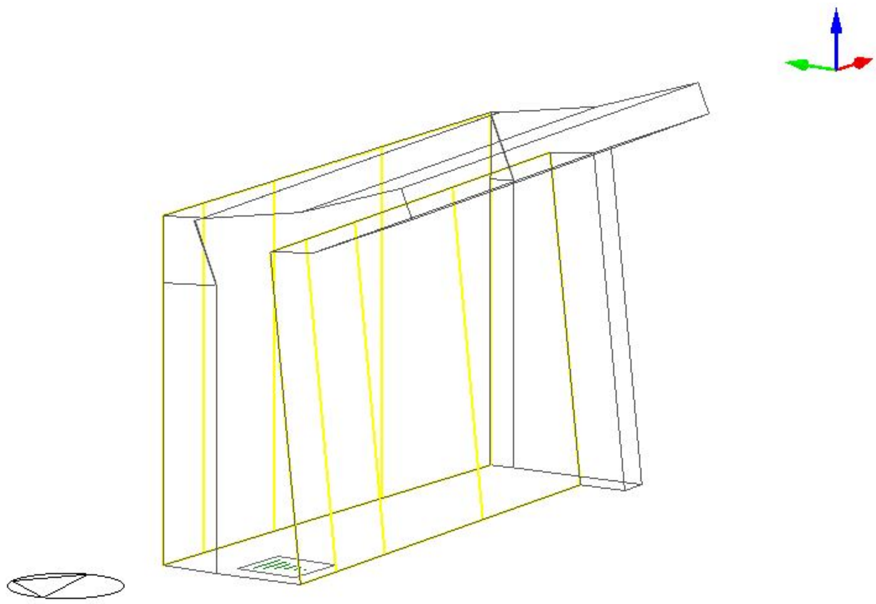


Figure 6.8: DesignBuilder Sheets and Tools

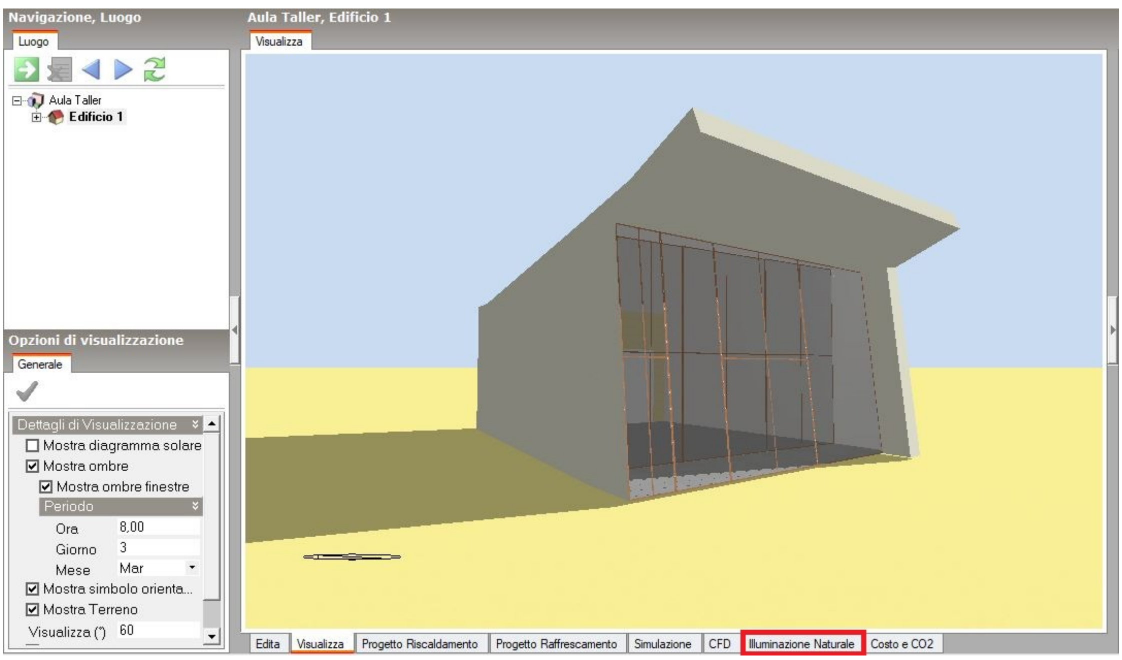
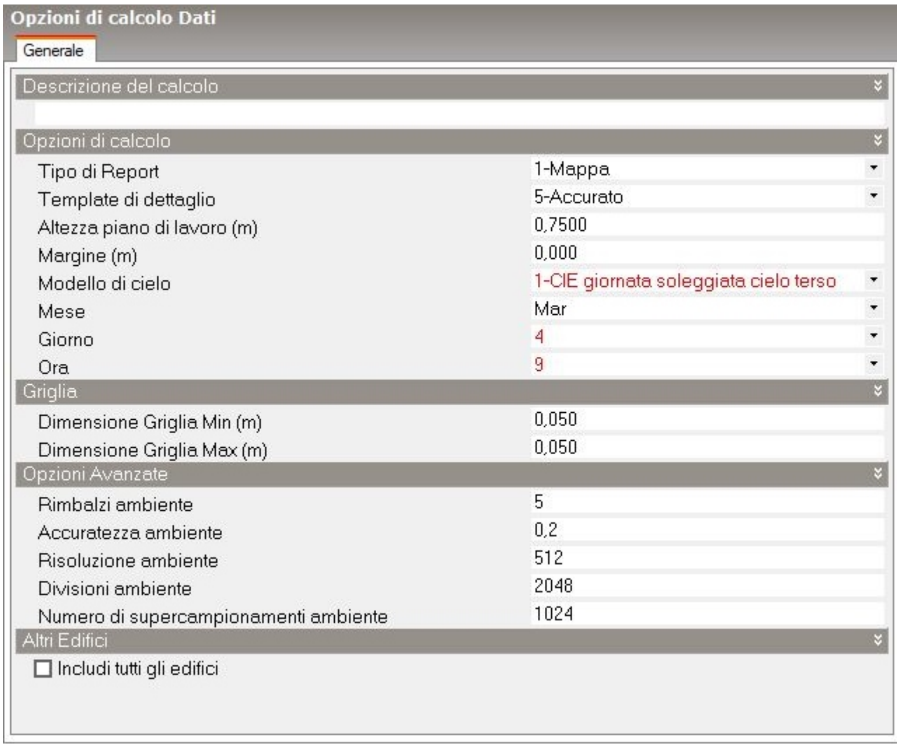


Figure 6.9: Natural Lighting Calculation Options



LEED, BREEAM AND Green Star reports.

To measure all these factors, DesignBuilder is capable of determine the height of the work surface under which the program will do the calculations. I have choose the same of the real data collection, i.e. 0.75 m.

When making the simulation of natural lighting, certain starting calculation options will be required (Fig. 6.9). The first are related to the type of report to be obtained: in fact, data can be obtained on the map, in a table or in preset reports for LEED, BREEAM or Green Star certifications.

After this first specification, a detail template must be selected from the available list: from this option, the advanced options (below in the box of the Fig. 6.10) depend. They are related to bounces, accuracy, resolution, divisions and the number of super-samples of the environment.I choose an accurate detail template.

It is not essential to understand each of these parameters to get to the simulation with the program, but to understand how the calculations are performed and how these parameters affect the simulation, it helps to better understand the

Figure 6.10: Natural Lighting Report Options

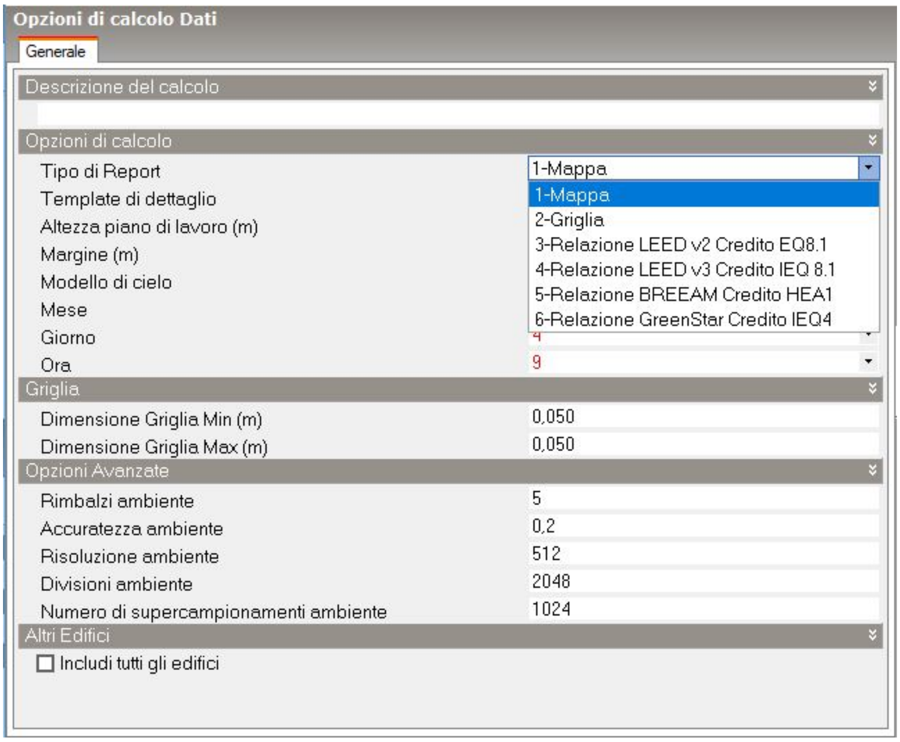
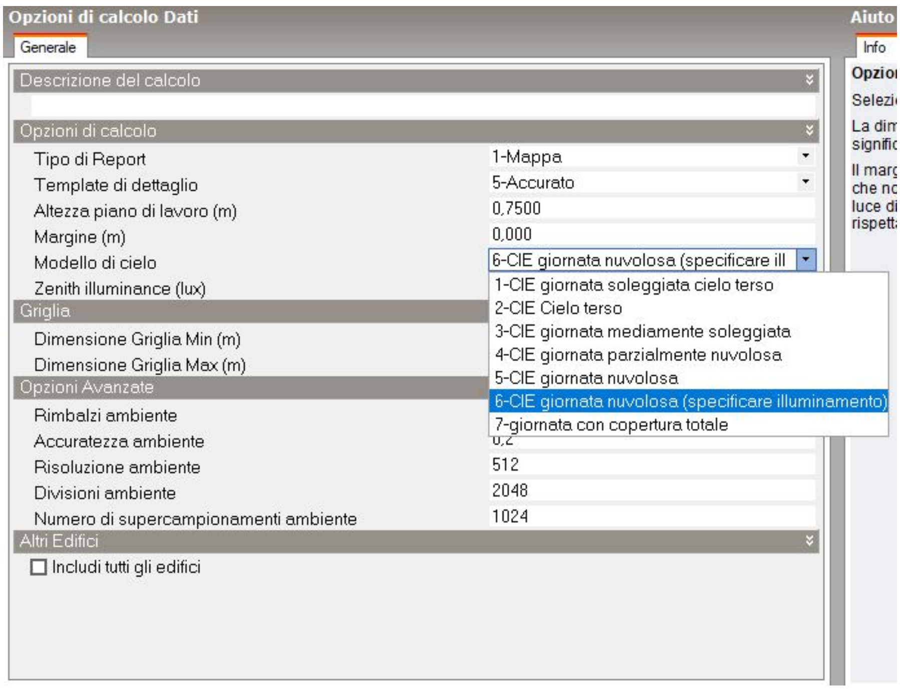


Figure 6.11: Natural Lighting Sky Models Options



results. It is important to keep in mind that Radiance uses a calculation method based on the Monte Carlo statistical model, i.e. it means that you will not get exactly the same values if you repeat the simulation on the same model and with the same calculation options. The more detailed the parameters are defined, the more it is possible to minimize this difference. Not being the extreme accuracy of the statistic model the ultimate goal of the thesis, here the analyzes were carried out accurately, without however changing any of the advanced options.

While the height of the work surface has already been defined here, the margin has been set equal to 0.00 m because, considering the position of the pupils in the classroom as variable, it is important to ensure the luminous quality at each point.

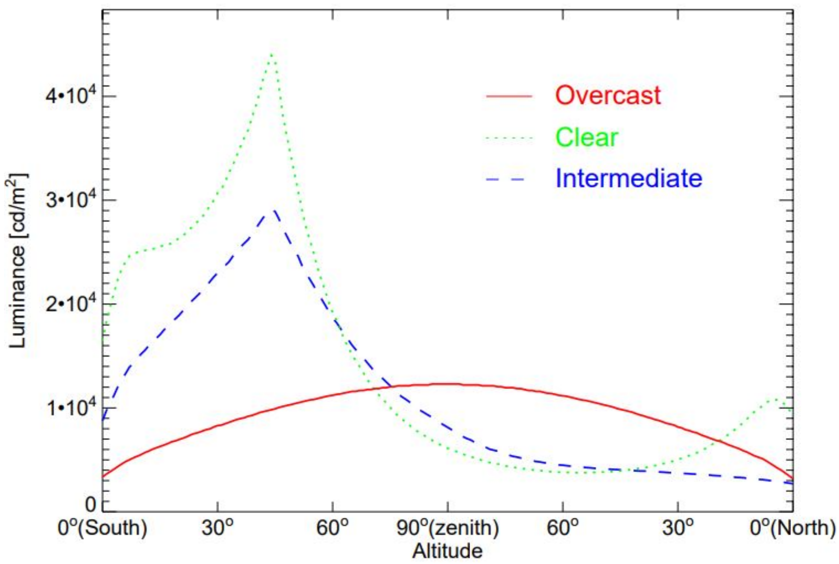
Another option to define is the sky model based on CIE standard (Fig. 6.11). For the choice of this reference was made to the theory analyzed in this regard (see par. 3.5) and to the subdivision in the three conditions of sunny day, partly cloudy day and cloudy day.

- The first one corresponds to the standard distribution of *Clear Sky* with additional direct lighting. It involves very bright portions due to direct sunlight, but also relatively dark areas where this does not affect;
- The second one, the *Partly Cloudy Sky* corresponds to the intermediate distribution between clear sky and cloudy sky, without including direct sunlight;
- The last one corresponds to the standard *Cloudy Sky*, originally called Moon and Spencer Sky. This is the model that is used most frequently for calculating illuminance. In this the brightness of the sky gradually increases with altitude, from the horizon to the zenith, but does not vary with the azimuth.

In the graphic (Fig. 6.12) the basic characteristics of these sky models are presented. Here, the sky point luminance along an arc from the horizon due South, across the zenith to the horizon due North, is plotted for the overcast, intermediate and clear sky models.
Each sky model was generated to provide the same diffuse horizontal illuminance (30,000 lux). The sun altitude and azimuth was set to 45° and 180° respectively. What this example demonstrates is how very different the sky luminance distribution can be, depending on the sky model type. [67]

Finally, to calculate the illuminance distribution, the work plan is divided into cells

Figure 6.12: Sky Luminance Profiles for the Sky Models



Source: [67]

via a network. it is necessary to correctly specify the maximum and minimum dimension of the mesh to obtain the adequate results without extending the simulation time too much.

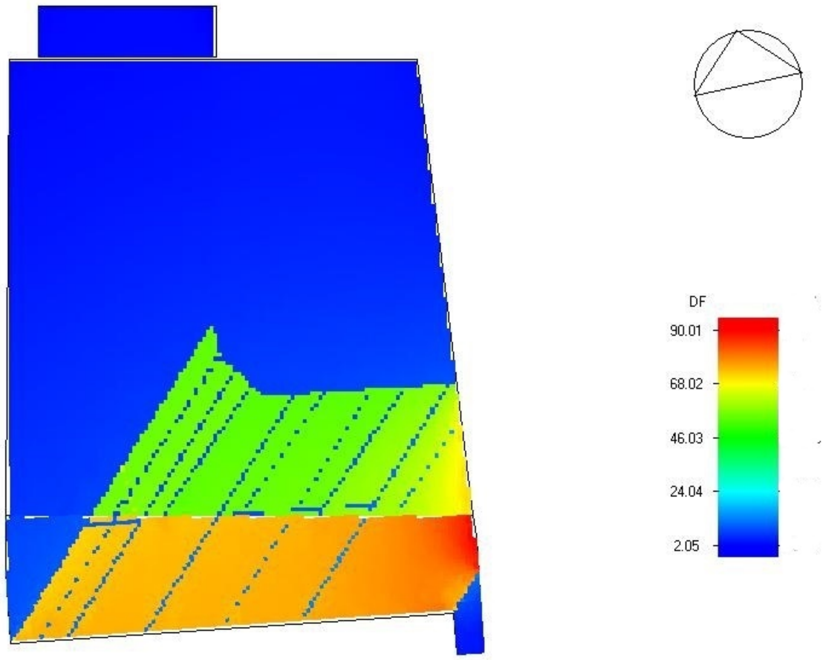
The maximum size of the network is the maximum that can be used to divide the work plan. The smaller the value, the higher the resolution of the results, but it will take time. The minimum size that can be used to fill up the work space in the event that the maximum size is too large. This can be used mainly for the edges of the top.

The smaller the values, the more precise the results will be. In general the minimum size is between 1 and 0.2 times the maximum. An equal value is chosen to maintain a uniform network.

In our case a very small maximum size (equal to 0.05 m) was chosen because we looked for the value of a specific point, given by the coordinates of the luxmeters. A equal value for the minimum size was chosen.

After all these choices, establishing a type *1-Map* report, a map will be generated that shows the distribution of natural light on the work surface, including daylight factor values. The image 6.13 shows an example of a natural light map for the workshop room calculated with Overcast Sky at 16 PM of 2017, March the 5th. It

Figure 6.13: Exemple of Map result from DesignBuilder Analysis



Source: [67]

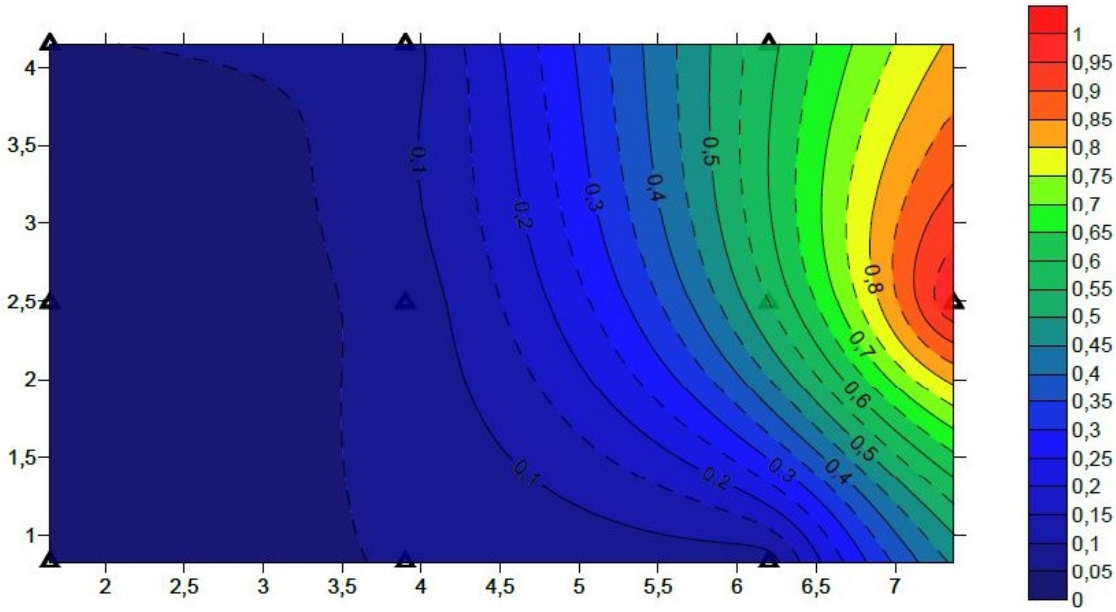
was then possible to export the data in excel format, from which those corresponding to the coordinates where the sensors were positioned were selected.

6.2.2 The Use of the Surfer Software

To visually compare the Daylight Factor DF (the measured and the simulated with Velux and DesignBuilder) data, they were included in the Surfer program. Already cited with regard to the study of temperature measured in situ (par. 6.12), Surfer is a software capable of converting data into contour maps and with surface textures. Scattered data is easily transformed into graphs and surface maps.

The software has an interface that is not able to read data obtained directly from Excel to obtain mappings. It will need to create a *grid* from which to derive the X, Y and Z values. To do it, we need to understand a little about how the program works. The program will ask you to select an Excel file (.xls) and this will try to select rows or columns that will have the purpose of assigning a value to the X, Y and Z axes. The first two are represented by the coordinates of the sensors positioned in the the classroom and the third will be given the value that we are going to study, in our case the daylight factor.
Pressing the OK button the program will create the grid that will be fundamental

Figure 6.14: Exemple of Map created on Surfer



for the realization of our maps. Only later with the command New Contour Layer will it be possible to create a map with contour lines in a 2D plane. A window will open asking you to select a .grd file, generated with the procedure seen above. Once this is done, the program will create a map with various contour lines.
The map, as it is, turns out to be a bit poor in data, so it is necessary to color the contour lines according to a graduated scale and modify the properties of the map (lines, dimensions, opacity, etc.).

The final result of the comparison of the obtained data is reported in the annex D where I report the results of the measured in situ DF (DF_m), the simulated DF with Velux (DF_s) and, at the end, the simulated DF with DesignBuilder (DF_{db}). Here you can see an example of the workshop room's map calculated on DesignBuilder with Clear Sky at 16 PM of 2017, March the 5^{th} (Fig. 6.14). These maps give a qualitative idea of the results, for quantitative analysis see the following section 6.2.3.

6.2.3 Comparison of Data

In the previous paragraphs of this chapter we talked about how we obtained the data and the description of these in a qualitative way. The ultimate goal is to achieve not only qualitative, but also quantitative results and to validate the use of the DesignBuilder program, a program mainly for energy simulation, but also for natural lighting analysis.

After you have fit a linear model using regression analysis, ANOVA (i.e. analysis of variance), is it possible to generate the Linear Trendline or Regression Line to test how well sample data fit a distribution from a certain population. [68] In general, a model fits the data well if the differences between the observed values and the model's predicted values are small and unbiased. To calculate it and so assess the Goodness-of-Fit, we calculated the R-squared, denoted R^2 or r^2. In statistics, it is the coefficient of determination that *"is the proportion of the variance in the dependent variable that is predictable from the independent variable(s)."*[69]
The coefficient of determination normally ranges from 0 to 1:

- 0 indicates that the model explains none of the variability of the response data around its mean;
- 1 indicates that the model explains all the variability of the response data around its mean.

In general, the higher the R-squared, the better the model fits your data.

With this brief introduction on the analyzed data the graphs are reported with a differentiated study for each sky category: clear, intermediate, overcast.
The results obtained with the two different software are compared with the measurements carried out in situ. In general, as a first observation, R^2 is relatively high, since the regression line does not miss any of the points by very much. This happens comparing the DF of the situ with those of Velux, while, as regards DesignBuilder, the value is lowered, settling at $R^2 = 0.765$.
All the regression lines arrive at the value 1, taken as a reference the point outside the classroom, in the greenhouse, and set equal to $DF = 100\%$.

It can be argued that both methods are valid for the study of natural lighting. However, it is important to underline the different functioning of the two programs compared. While in Velux you can place the sensors inside the project area, in DesignBuilder you have to find the coordinates where the luxmeters were located through the export file with the map data. It is certainly less immediate, but in any case, by choosing a small maximum size of the grid, the data will be reliable and true.

Figure 6.15: R-squared and the Trendline for Clear Sky

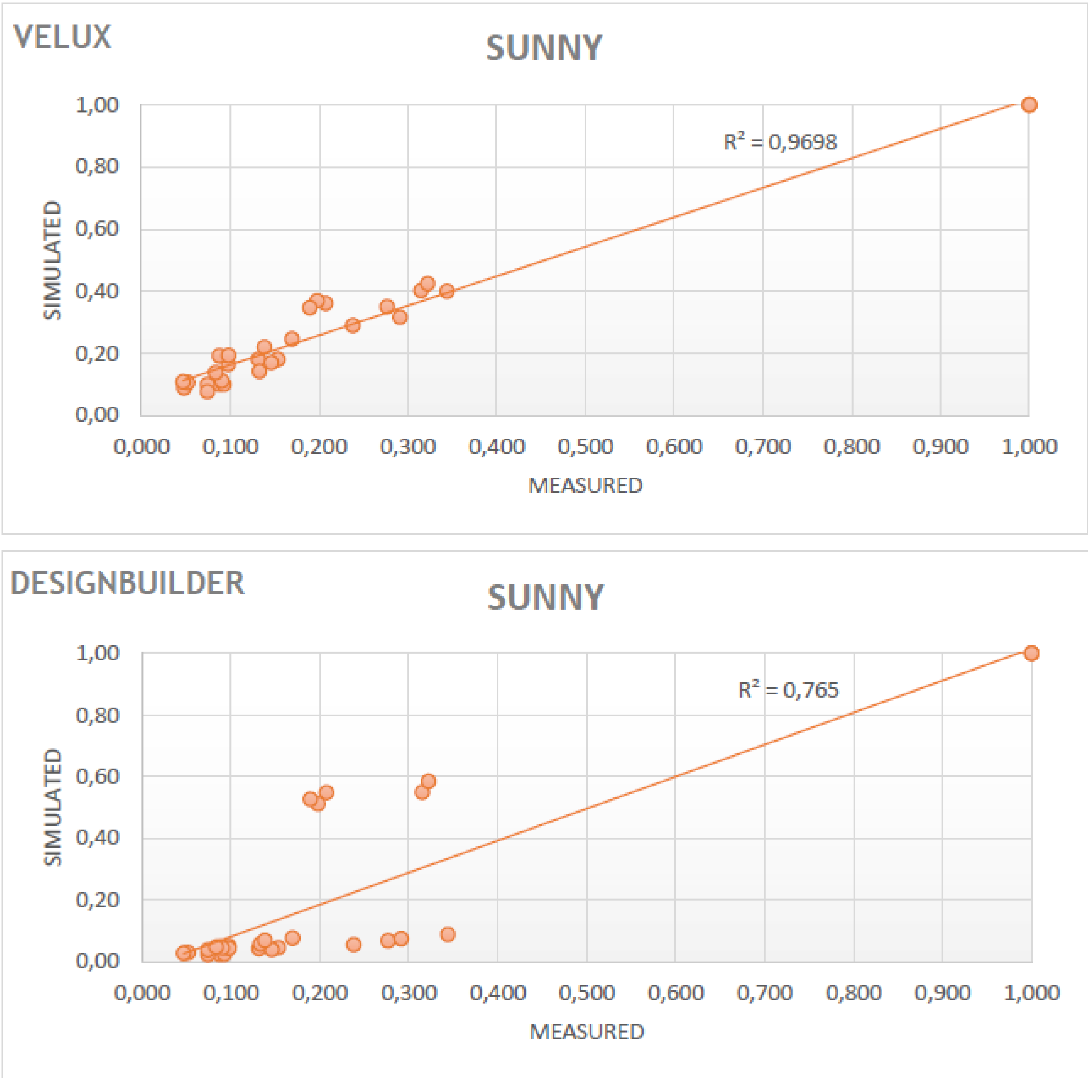


Figure 6.16: R-squared and the Trendline for Intermediate Sky

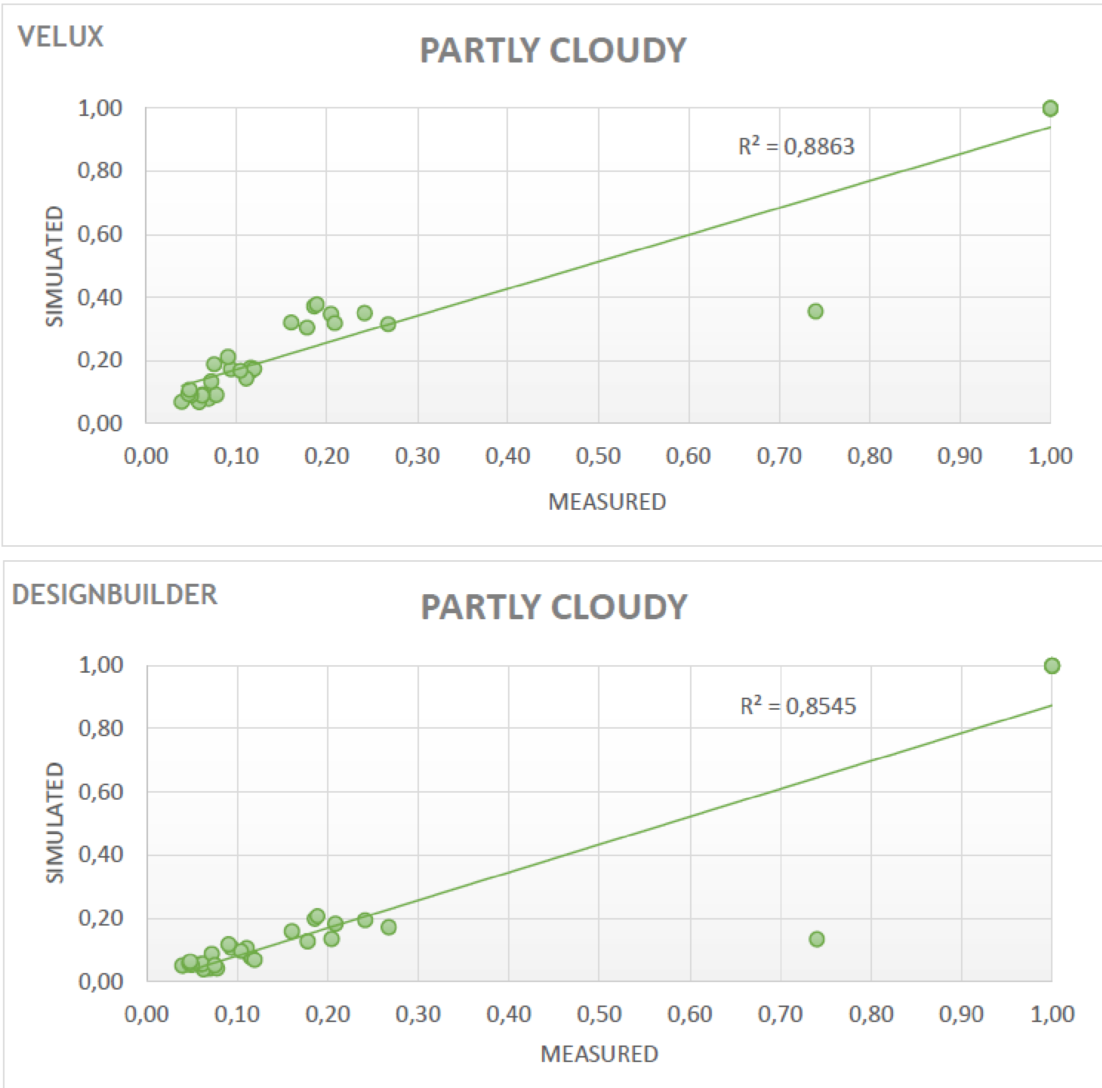
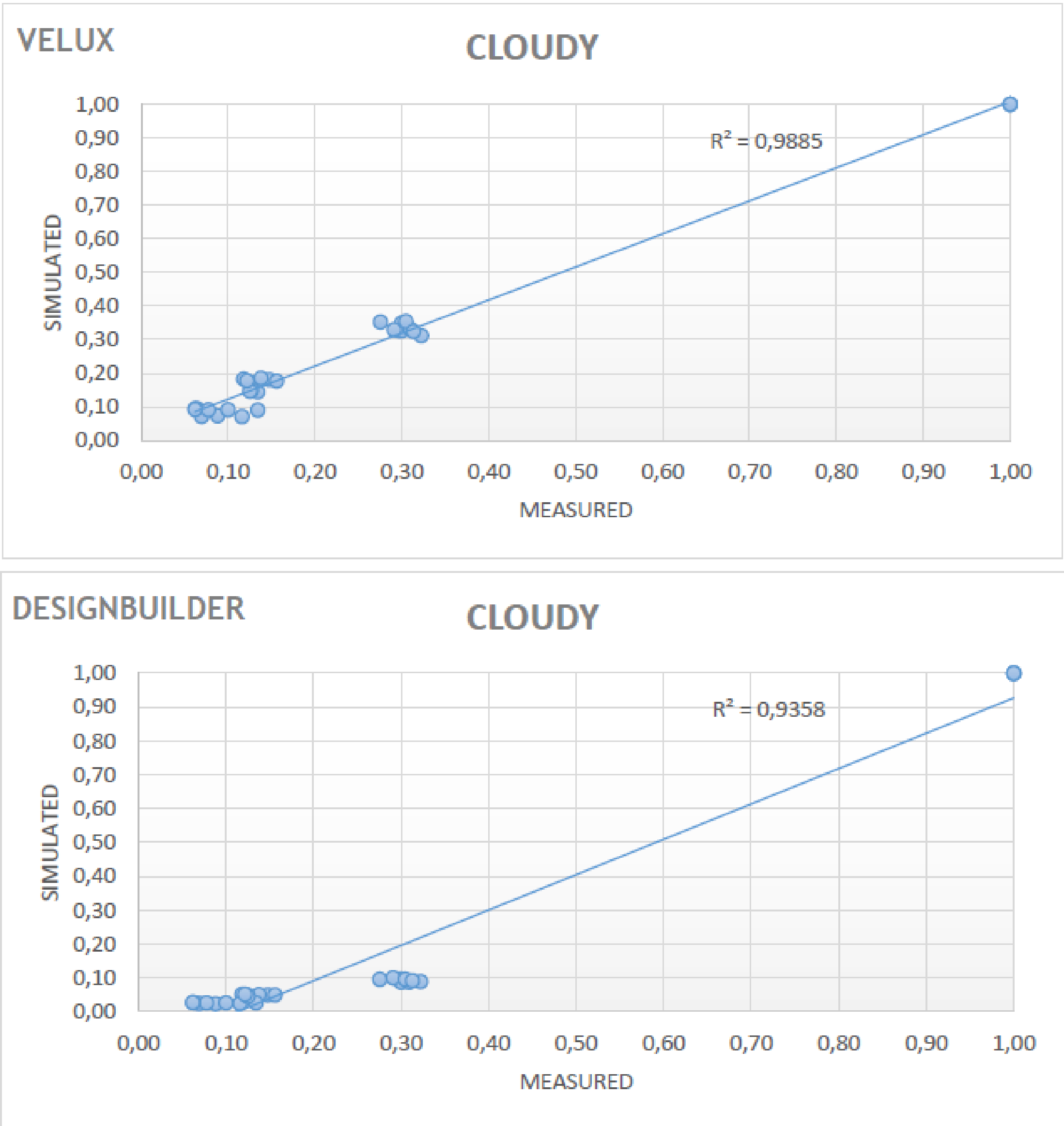


Figure 6.17: R-squared and the Trendline for Overcast Sky



6.3 Environment Optimization

Thanks to the research developed so far, I can continue with the last part of my thesis. In fact the next step is the addition of passive systems in order to change and improve the current conditions examined in situ and through computer simulations. Trying to focus on the analysis of the daylight factor and applying what the norm says, after the complete study of the classroom's behavior, I considered appropriate to continue the analysis only in cases of overcast sky model as required by definition (see 3.4.1).
Through the bibliographic research presented here in the Chapter 2 (State of the Art), we have understood the importance of these systems and the beneficial effects can have on the environment and therefore on the human beings.

So, I will talk about the implementation of passive systems to the building through the use of the DesignBuilder software, more specifically window blind components.

The aim will be to see how, through the implementation of passive techniques to the building, the values calculated improve the classroom's conditions.

6.3.1 Selection and Description of the Scenarios Explored

In the first part of the work, I have to select which passive system can be the right one for the classroom under analysis. The various interventions that have been made on the original construction will be presented.

Addition of Two Windows on the North Side of the Classroom

In this scenario the luminous behavior of the classroom in question with the addition of two windows on the North side of the classroom of (1.6 x 0.6)m is analyzed. Considering the room's height of 3.3 m, I decided to place the two windows 40 cm from the ceiling and, for the one located above the door, 15 cm from it. (Fig. 6.18)

Given the great height of the premises and the skylight reduced compared to the size of the whole block in which the classroom in question is included, it has been noted that the values did not change so they are not reported here.

Figure 6.18: Plan of the Skylights' Project

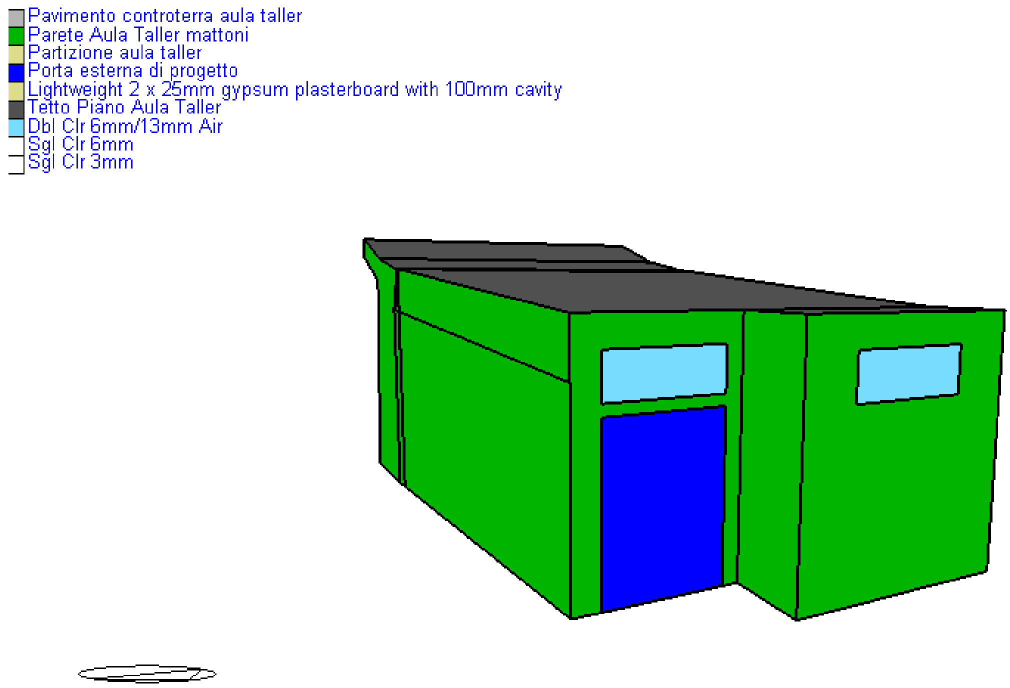


Figure 6.19: Plan of the Roof with Skylights (in lightblue)

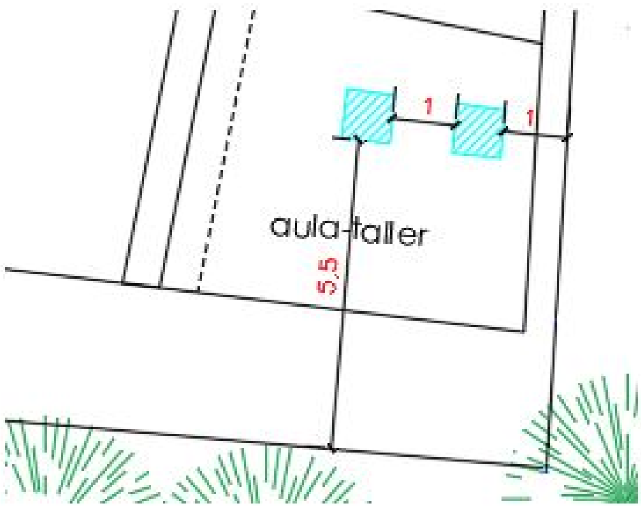
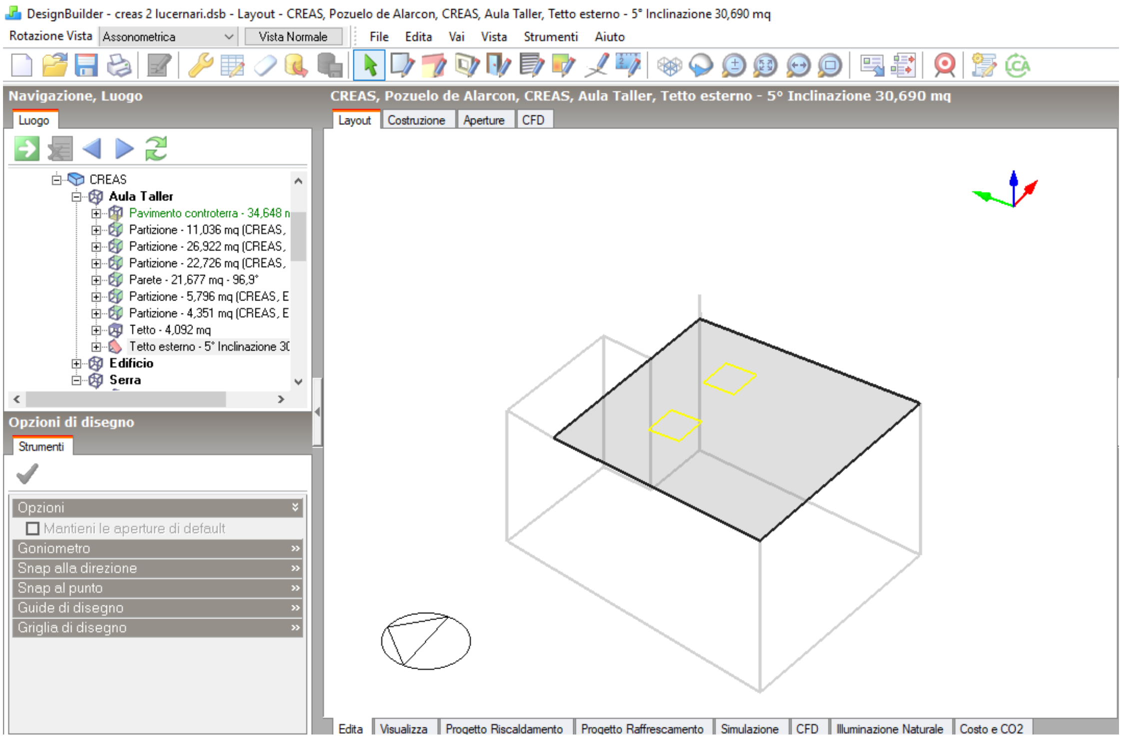


Figure 6.20: Model of the Building with Skylights (in yellow)



Addition of Two Skylights on the Roof of the Classroom

A successive improvement was the project of two skylight in the less illuminated area of the room. In order to select the best type of skylight, I consulted data sheet from well known producer of window as VELUX (see Annex E). After several efforts, I found the better combination of placement, quantity and dimension for the skylights necessary to improve the classroom's condition (Fig. 6.19 and Fig. 6.20).

Addition of Window Blinds

To avoid the thermal and light discomfort risk for who are sitting next to the window, the next step was to consider to reduce the incoming light (and therefore also heat) throughout the building. DesignBuilder offers many options when choosing a window blind system, precisely five blinds (all of these system were examined in detail in the par. 2.3.3):

1. Slat - slatted blinds which have different transmission properties with solar position;
2. Shade - assumed perfectly diffusing, they can be used for diffusing materials such as drapery and translucent roller shades.;

3. Transparent insulation - transparent insulation material to be positioned on the outer surface of an external wall;

4. Electrochromic switching - switchable visible and solar properties based on solar gain;

5. SageGlass electrochromic - multi-state electrochromic glazing systems (see Fig. 2.14).

In the analysis we must taking into account that the data applies only to external and roof glazing, internal windows cannot have window blinds. So I had to think of shielding the windows between the outside and the greenhouse environment which is next to the classroom. By choosing system 1, there are three possible logics or fixed configurations of the physical system:

1. stats always aligned with the sun's rays or with negligible shading (specifically in the winter season);

2. fixed and 45 ° inclined slats;

3. movable slats with a control logic consisting in tilting the minimum angle necessary to completely intercept the direct solar radiation, (specifically in the winter season).

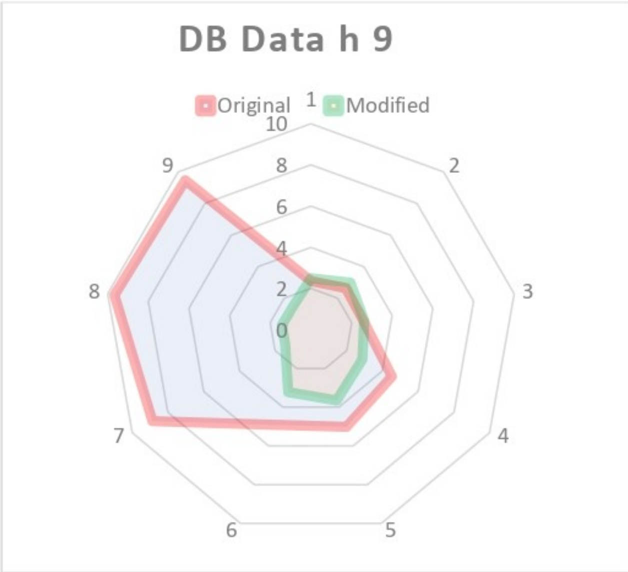
On the basis of studies (see in general Cap. 2 and more to the point see [12]), it has been found that the seasonal logic is all the more convenient the more the winter heating loads and the summer cooling loads are comparable. When instead there is a dominant need throughout the year, how to maximize solar gains or minimize them, it is more convenient to use a simple logic, for example: "never intercept solar radiation" or "always intercept it". This is what happens in places as Madrid, or in our case, Pozuelo de Alarcón, where the need to limit solar gains throughout most of the year is predominant. In this climate the configuration with the fixed 45 ° slats is even more convenient; in fact, although it mostly limits the luminous intakes, it has the advantage of intercepting, in addition to direct radiation, a greater share of the diffused, thus being more effective in containing the thermal gains that would produce overheating. This largely compensates for the greater heating costs induced in short cold periods.

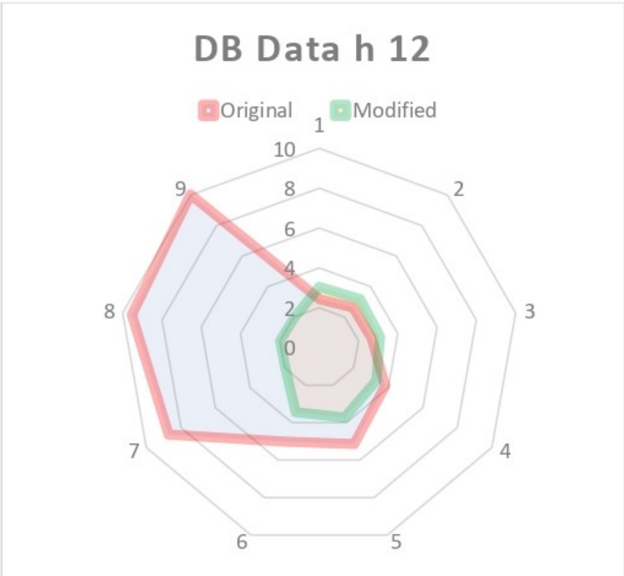
So I decided to conduct simulations thinking about adding external blinds with a fixed slats angle. The simulations were therefore conducted for the three times set

in the paragraph 6.2, for the 9 AM, 12 AM, 16 PM only in case of overcast sky conditions.
I report the data map in the Annex C where it is possible to appreciate how the ratio between internal and external luminance is due to remain constant and to not depend on the time of day, nor on the period of the year (data were calculated on the basis of exterior illuminance, not through the indication of day of the year), nor on the orientation of the space (we can appreciate the improvement over the original).
The values obtained in the original case and in the case improved thanks to the passive system insertion are shown in the graphs 6.21 and in the table 6.14.
As we could see in the previous analyzes, the original data showed that the values of the daylight factor were extremely high on the sensors 7, 8 and 9, the ones closest to the wide external windows. This causes glare and general discomfort to the occupants. Modifications are evaluated in the radar charts represent in the figure 6.21 which place numeric values, increasing in value, from the center of the radar to the perimeter. This type of graph provides a very clear comparison, especially within different partial loads.

Let's see how the DF's values remain approximately constant in the various points of the classroom, even if with lower values by adding the two skylights and the external shields. The aim was in fact to reduce the light coming from the side openings and increase the brightness in the interior of the classroom. The broadly constant values of daylight factor in the workshop room make possible to evenly adjust the light; see in the Tab. 6.15 that the uniformity is always about equal to or greater than 0.6. The values improve in all the points where the sensors are placed.

Figure 6.21: Graphs of the Different Data Exported from Desigbuilder in the original case and the modified one





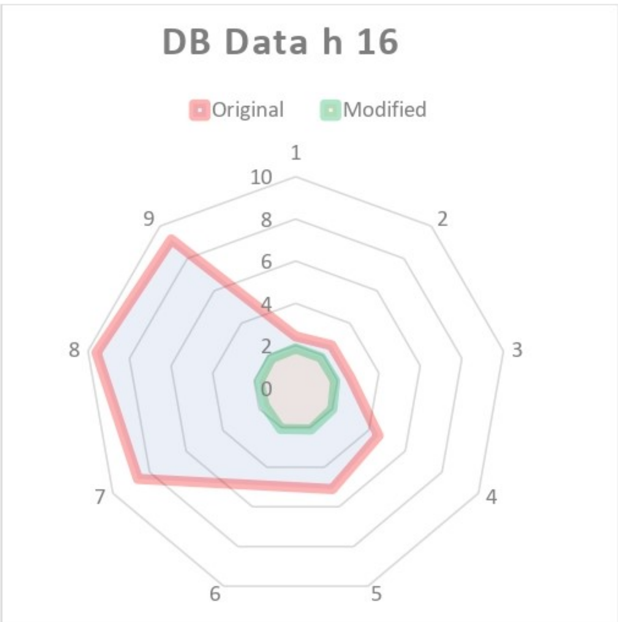


Table 6.14: Comparison Between Original Data and Improved Situation's Data

TIME	Nº SENSOR	COORDINATES		CLOUDY	
		X [m]	Y [m]	DF_{db} [%]	DF_{db_mod} [%]
09:00	1	1,65	0,83	2,36	2,50
	2	1,65	2,49	2,63	2,98
	3	1,65	4,15	2,58	2,62
	4	3,9	0,83	4,53	2,87
	5	3,9	2,49	5,01	3,65
	6	3,9	4,15	4,91	3,22
	7	6,2	0,83	8,86	1,44
	8	6,2	2,49	9,67	1,42
	9	6,2	4,15	9,47	1,40
	10	7,37	2,49	100	100
12:00	1	1,65	0,83	2,44	3,05
	2	1,65	2,49	2,65	3,18
	3	1,65	4,15	2,68	3,10
	4	3,9	0,83	3,83	3,31
	5	3,9	2,49	5,14	3,73
	6	3,9	4,15	5,02	3,45
	7	6,2	0,83	8,70	1,97
	8	6,2	2,49	9,53	1,99
	9	6,2	4,15	10,03	1,96
	10	7,37	2,49	100	100
16:00	1	1,65	0,83	2,44	1,87
	2	1,65	2,49	2,63	1,88
	3	1,65	4,15	2,65	1,90
	4	3,9	0,83	4,53	2,01
	5	3,9	2,49	5,10	2,10
	6	3,9	4,15	4,92	2,07
	7	6,2	0,83	8,63	1,70
	8	6,2	2,49	9,59	1,75
	9	6,2	4,15	9,17	1,82
	10	7,37	2,49	100	100

Table 6.15: Comparison Between Original Uniformity Data and Improved Situation's Uniformity Data

Uniformity	CLOUDY	
	DF_{db}	DF_{db_mod}
9:00	0,35	0,57
12:00	0,25	0,69
16:00	0,23	0,89

Chapter 7

Conclusions

This work was carried out in order to contribute to the methodology and way of evaluating internal spaces to improve the lighting comfort using natural light as the main source of light.

In general, we are able to draw conclusions regarding the lighting of the workshop room and the validation of the DesignBuilder software. We looked at the research by dividing the data by time and sky models.

With regard to the situ data, we can delineate the behavior of the illumination in the workshop room depending on the sun path. In the morning hours, the western side of the classroom has a higher solar incidence. It is here that the values are higher: here the outer walls and the eaves block the sun allowing to touch only one corner of the interior of the classroom.

We see how, as the hours pass and the sun changes position, it heads towards the other side of the classroom, the east side. We observe how between 11 AM and 17 PM the sun is quite strong in the front of the room. This is because at that time of year the sun hits the interior of the building directly through the window.

We also note that the first row of luxmeters near the windows, i.e. the luxmeters 7, 8 and 9, report high levels of direct solar incidence. This means that the classroom users who are sitting next to the window will have direct light and that will generate both thermal and light discomfort.
About that fact, we see that the temperature of the classroom reached a maximum of 33°C on February the 25^{th} around 17 PM, which corresponds to the maximum temperature inside the environment. At the same time, inside of the room, an

average temperature of 30°C was measured. This day was one of the sunniest which means that the influence of sunlight affects the interior temperature of the workshop room. This generates discomforts and we clearly see that some type of protection must be implemented. Due the absence of them, the DF values are between 19% and 27%: these are excessively high values, seeing the standards that refer to 2% minimum and values $\geq 4\%$ are excellent. It is clear that, even if a limit is not set, the more this value grows, the more the aspects of lighting are amplified.

In this part, we also try to look for correlation between the illuminance and the temperature inside of the workshop room, but it would be better to keep studying in this sense, for example, transforming the lighting data into heat values, in order to compare them with the temperatures.

Also the uniformity was studied and, about this, we have found a bad, but predictable value of 0.35 maximum (in case of Overcast Sky) instead of the 0.6 recommended. The reasons for the negative values it can be traced back to the absence of protective systems against sunlight and to the simultaneous presence of large external openings.

So at this point, I designed improvement on DesignBuilder based on what I found in the overview on the state of the art, until I get to significant enhancements.

Among the range of possibilities offered by the software, I chose to develop an immediate solution, most applicable in design and economics terms. The insertion of skylights is viable, the architect has already realized them in other rooms of the building, but he not designed ones for this room, even if it is a place of central importance.

Since it was not enough to take natural lighting at the back of the workshop room, but it also served to limit the entry of light and the sun from the side windows, an external protection system was inserted. Solar gains were limited by micro-louvers with fixed slats angle, considering the sun path during the year in the Pozuelo de Alarcón area.

As it turns out, the results show a decrease in the daylight factor in the sensors placed near the openings and an increase in the values in the sensors placed at the bottom of the room. I found a correct value of uniformity during the day, equal to or greater than the 0.6 minimum.

Similar results could also be obtained with the other systems' installation, such as the replacement of simple glazing by electrochromic glazing, which also do not limit the view of the environment and of easy installation, but this is certainly a more expensive technology.

As a conclusion, we must consider how easy it was to study and interpret values with the use of the daylight factor DF, a dimensionless term, unlike the previous research carried out on the same subject with the use of values expressed in lux (illuminance values). In fact it is important to work with absolute values because this allows not only to know the distribution of natural light, but also to know the increase and the global decrease of the lighting. This method we use give us a wide range of possibilities to study not only the uniformity of light inside the classroom, but also to know if the levels of illuminance are adequate according to the standard used.

We did the comparison of the data with other programs and the validation of the program DesignBuilder. Addressing research with data divided by clear, intermediate and overcast skies according to the standards, has made that this validation intuitive and close to the true as possible.

The geometry modeling on DesignBuilder was not so easy and the possible simulation options are numerous, so initially it is necessary to study the program thoroughly in order to obtain the correct data. To use tools such as Velux and DesignBuilder, despite this, is so useful to try to better understand the behavior of a future building or in the case of an existing building renovation: both software are valid in the study of natural lighting.

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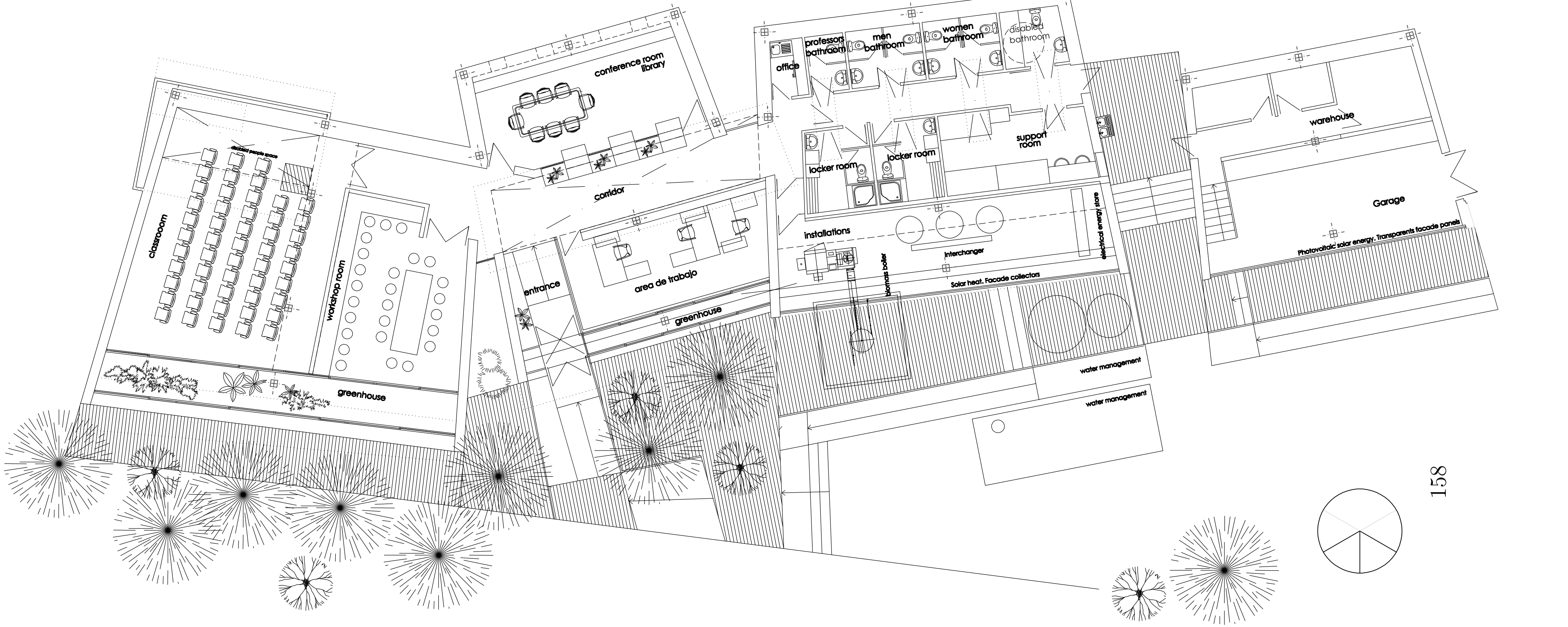
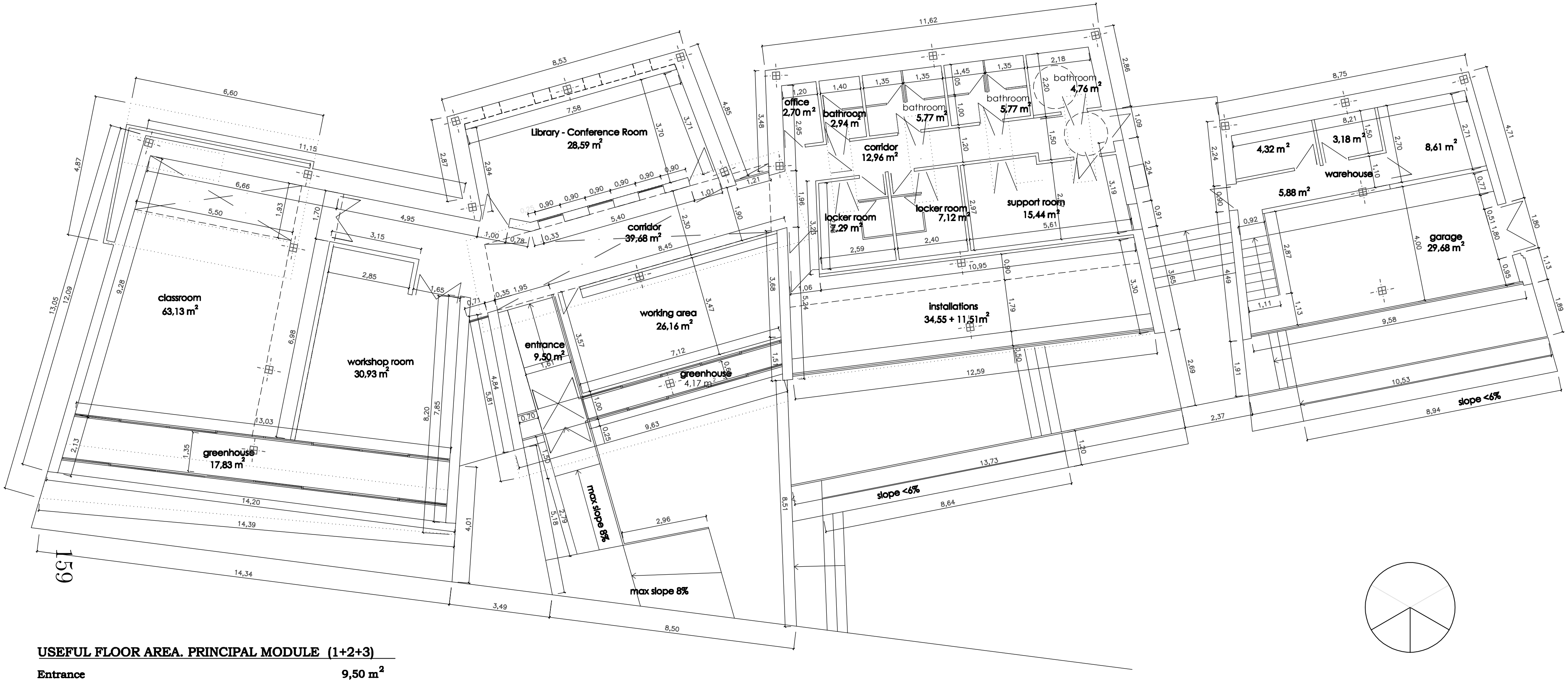
Attachments

Attachment A

The Creas Building



Project:	CREAS - "AULA DE EDUCACIÓN AMBIENTAL" POZUELO DE ALARCÓN (MADRID)
Developer:	MUNICIPALITY OF POZUELO DE ALARCÓN
Designer:	Architect: Antonio Baño Nieva
June 2007	
Plan: LAYOUT OF THE BUILDING	Scale: 1/200 · nº 1



USEFUL FLOOR AREA. PRINCIPAL MODULE (1+2+3)

Entrance	9,50 m^2
Corridors	39,68 m^2
Workshop Room	30,93 m^2
Classroom	63,13 m^2
Classroom and Workshop Room's Greenhouse	17,83 m^2
Working area	26,16 m^2
Working Area's Greenhouse	4,17 m^2
Library - Conference Room	28,59 m^2
Corridors	12,96 m^2
Office	2,70 m^2
Professors Bathroom	2,94 m^2
Men Bathroom	5,77 m^2
Women Bathroom	5,77 m^2
Bathroom for disabled people	4,76 m^2
Men Locker Room	7,29 m^2
Women Locker Room	7,12 m^2
Support Room	15,44 m^2
Utility Room	34,55 + 11,51 m^2
TOTAL USEFUL FLOOR AREA	330,86 m^2
TOTAL SITE SURFACE	397,76 m^2

USEFUL FLOOR AREA. GARAGE MODULE

Corridor	5,88 m^2
Warehouse 1	4,32 m^2
Warehouse 2	3,18 m^2
Warehouse 3	8,61 m^2
Garage	29,68 m^2
TOTAL USEFUL FLOOR AREA	51,67 m^2
TOTAL SITE SURFACE	71,96 m^2

Project: CREAS - "AULA DE EDUCACIÓN AMBIENTAL" POZUELO DE ALARCÓN (MADRID)

Developer: MUNICIPALITY OF POZUELO DE ALARCÓN

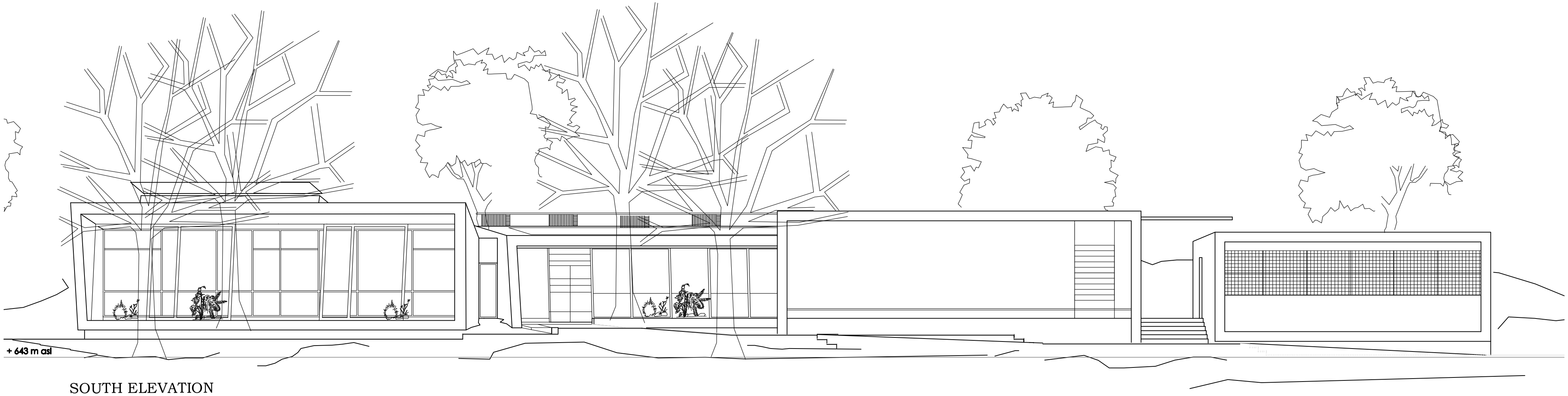
Designer: Architect: Antonio Baño Nieva

June 2007

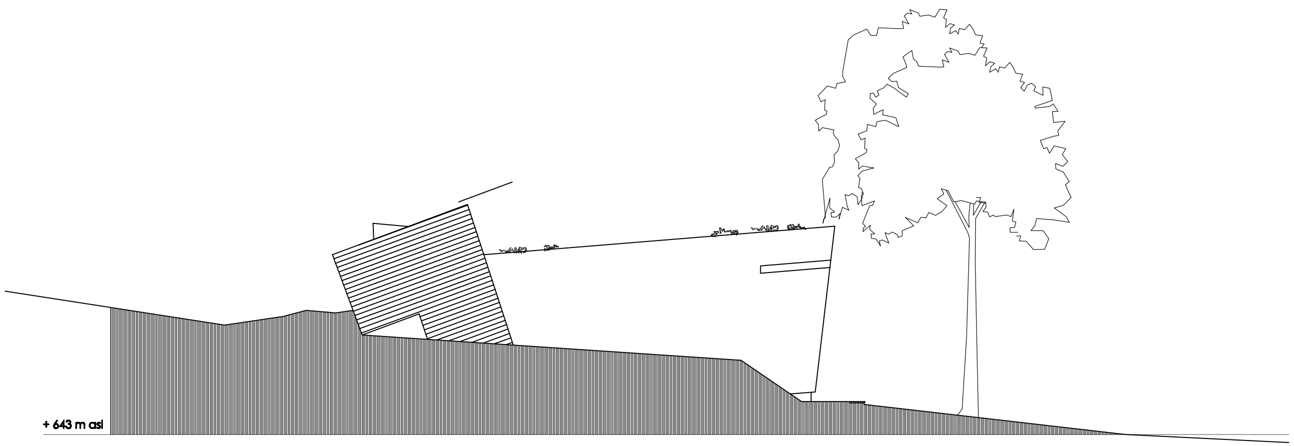
Plan: LAYOUT OF THE BUILDING

Scale: 1/200

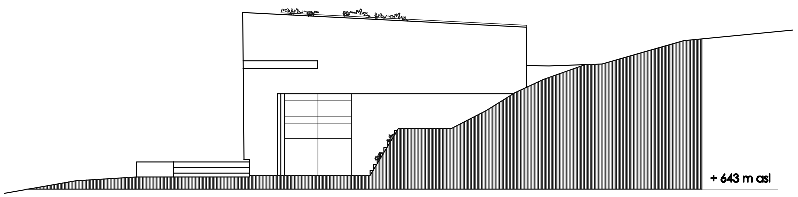
nº 2



SOUTH ELEVATION

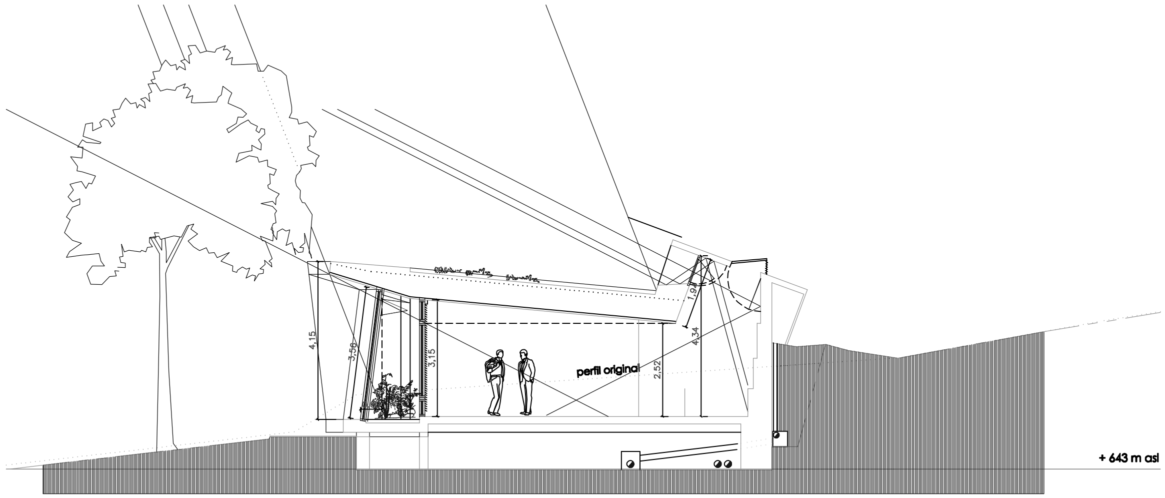


WEST ELEVATIONS

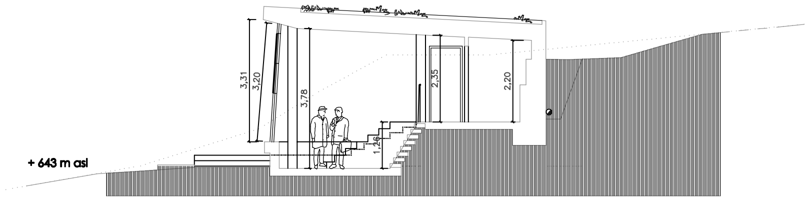


EAST ELEVATION

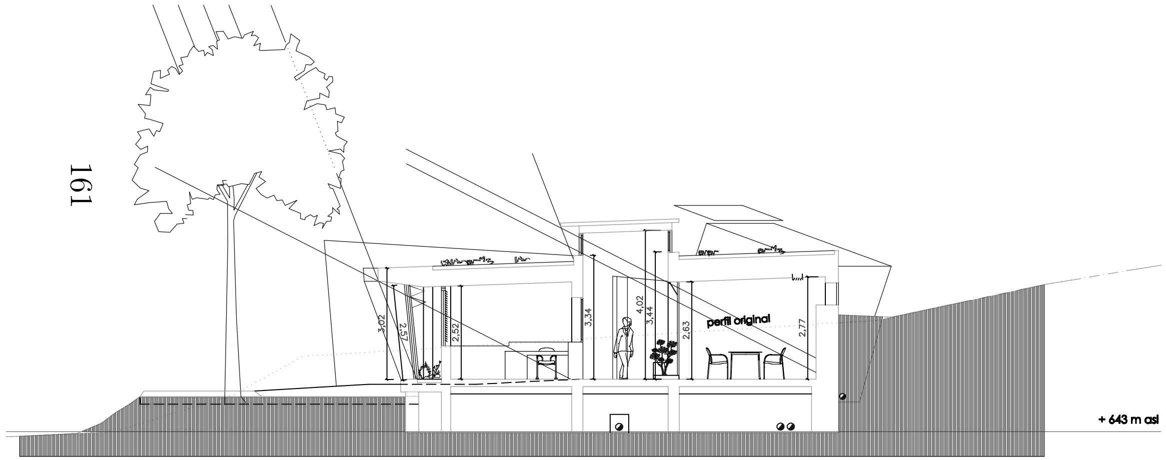
Project:	CREAS - "AULA DE EDUCACIÓN AMBIENTAL" POZUELO DE ALARCÓN (MADRID)
Developer:	MUNICIPALITY OF POZUELO DE ALARCÓN
Designer: June 2007	Architect: Antonio Baño Nieva
Plan: ELEVATIONS OF THE BUILDING	Scale: 1/200 nº 3



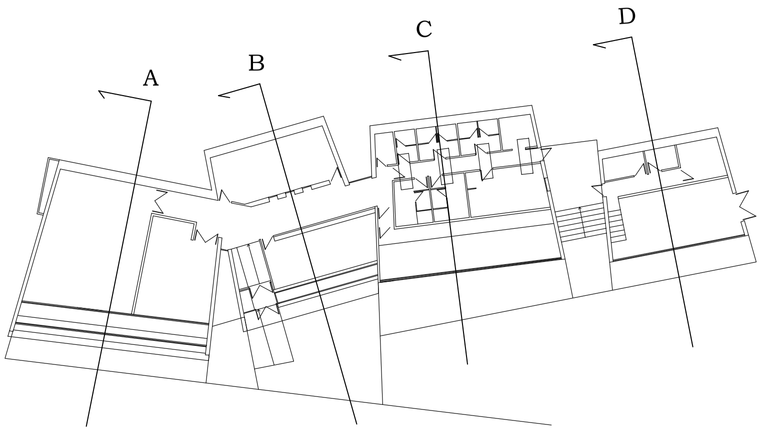
A SECTION

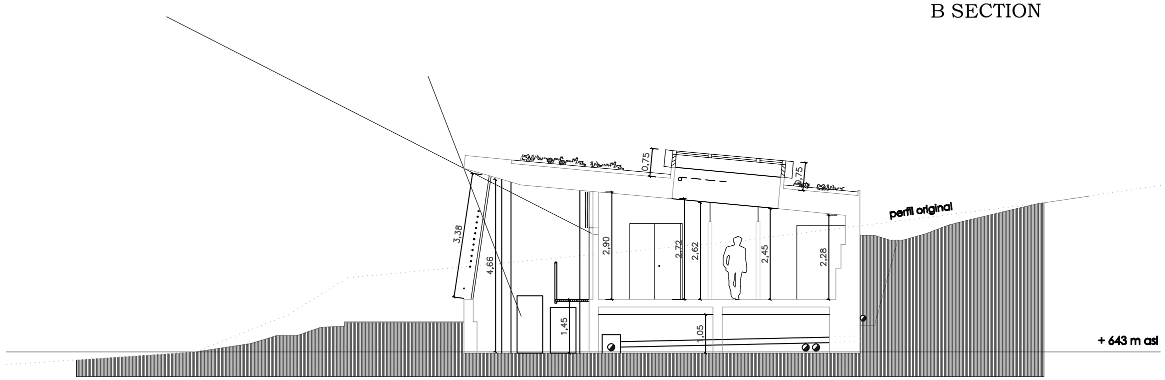


D SECTION



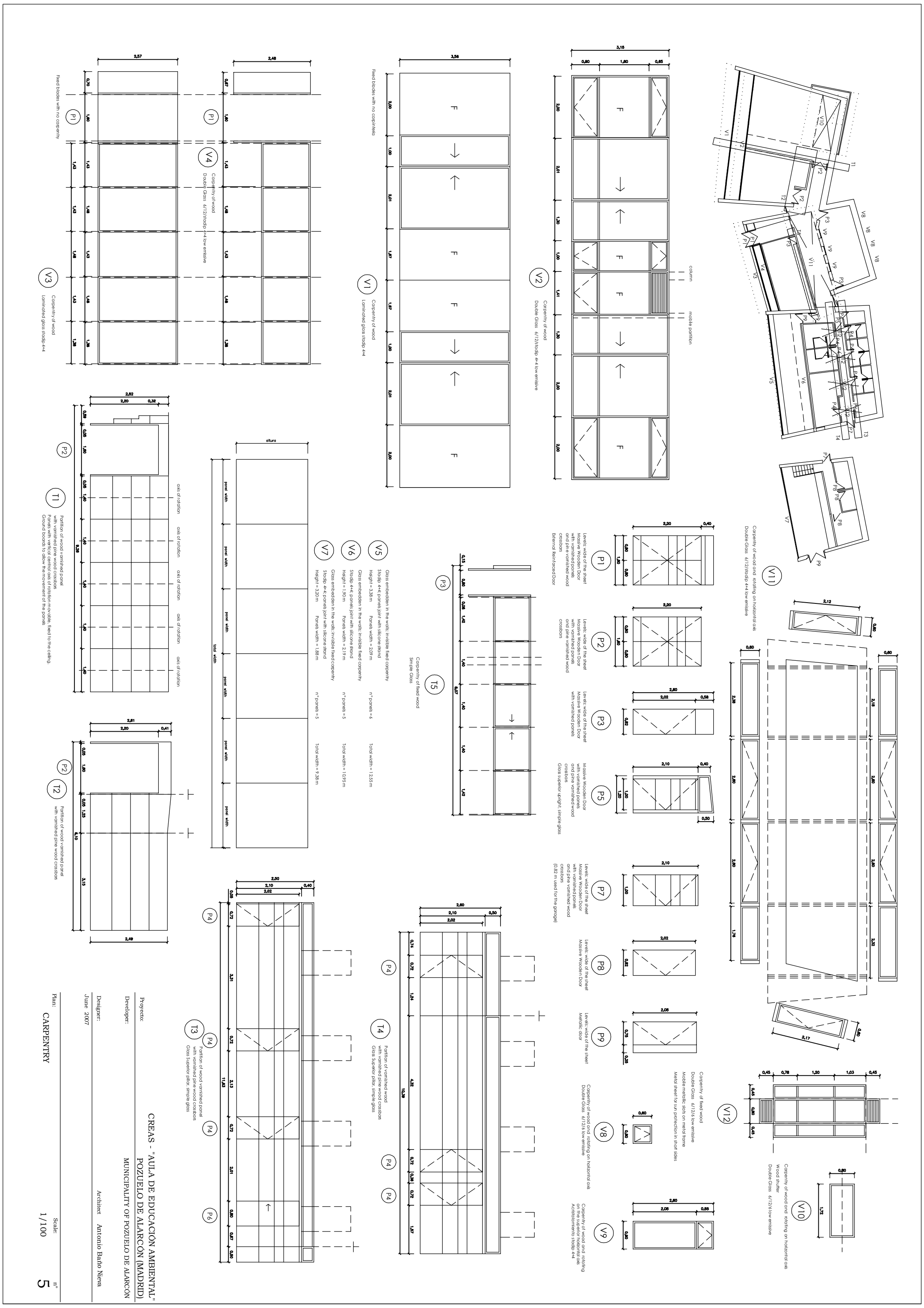
B SECTION





C SECTION

Project:	CREAS - "AULA DE EDUCACIÓN AMBIENTAL" POZUELO DE ALARCÓN (MADRID)
Developer:	MUNICIPALITY OF POZUELO DE ALARCÓN
Designer:	Architect: Antonio Baño Nieva
June 2007	
Plan: SECTIONS OF THE BUILDING	Scale: 1/200 — nº 4

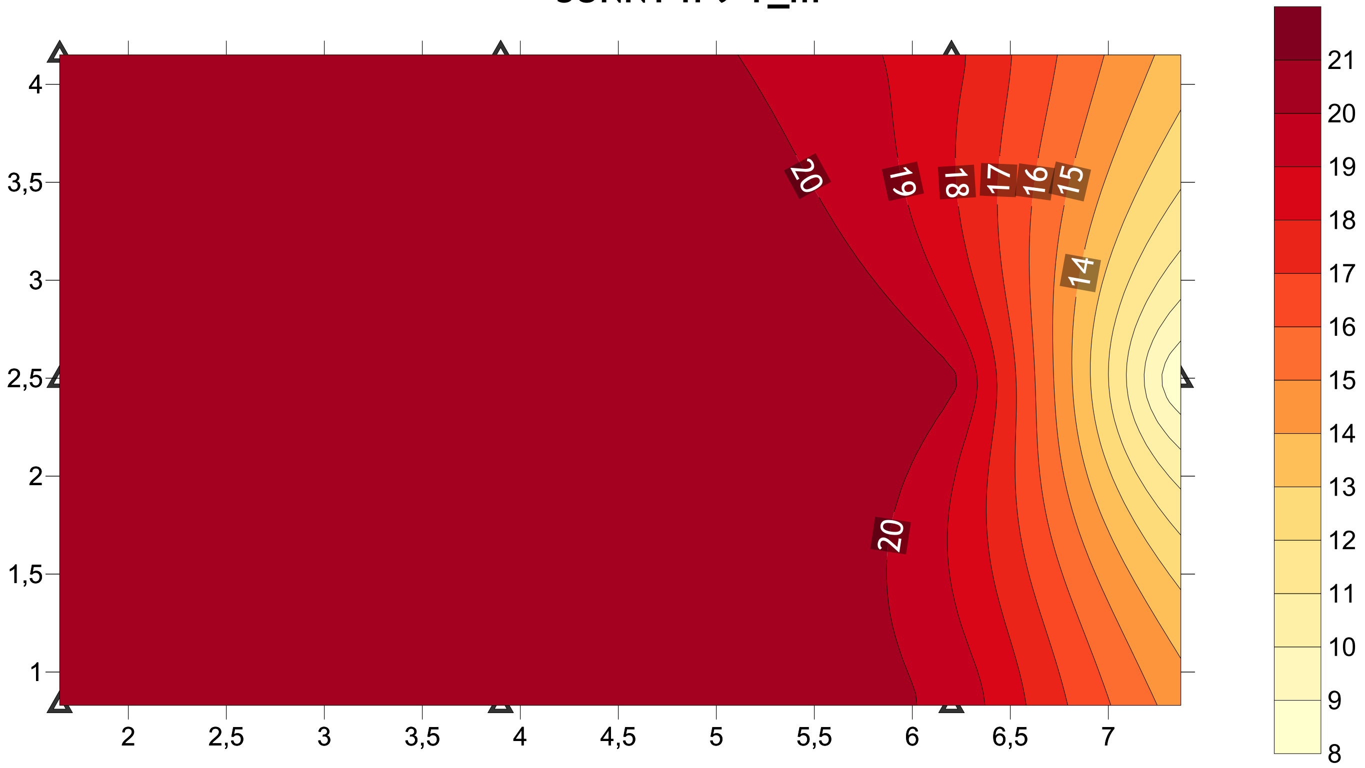


Proyecto:
CREAS - "AULA DE EDUCACIÓN AMBIENTAL"
POZUELO DE ALARCÓN (MADRID)
Developer:
MUNICIPALITY OF POZUELO DE ALARCON
Designer:
Architect: Antonio Baño Nieva
June 2007
Plan:
CARPENTRY
Scale:
1/100
n°
5

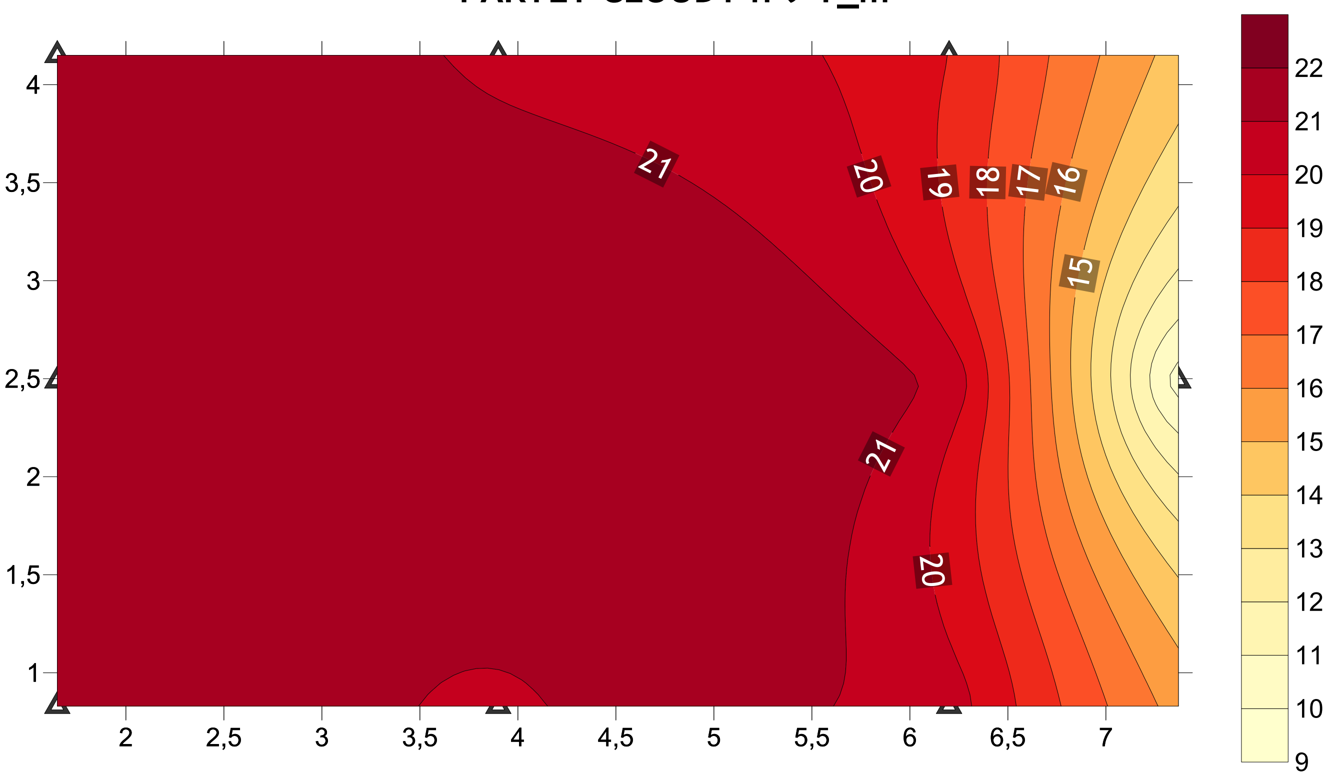
Attachment B

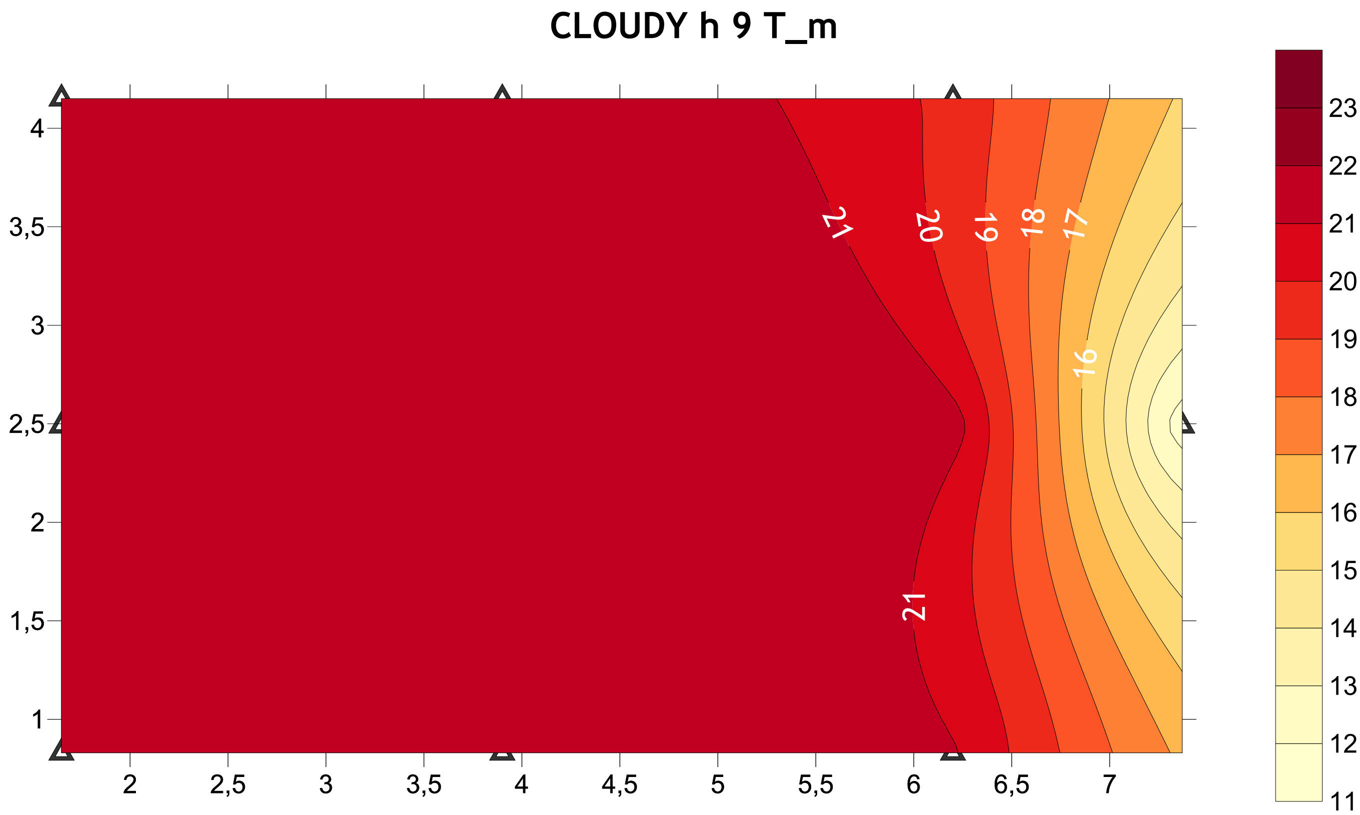
Surfer T

SUNNY h 9 T_m



PARTLY CLOUDY h 9 T_m




CLOUDY h 9 T_m
4
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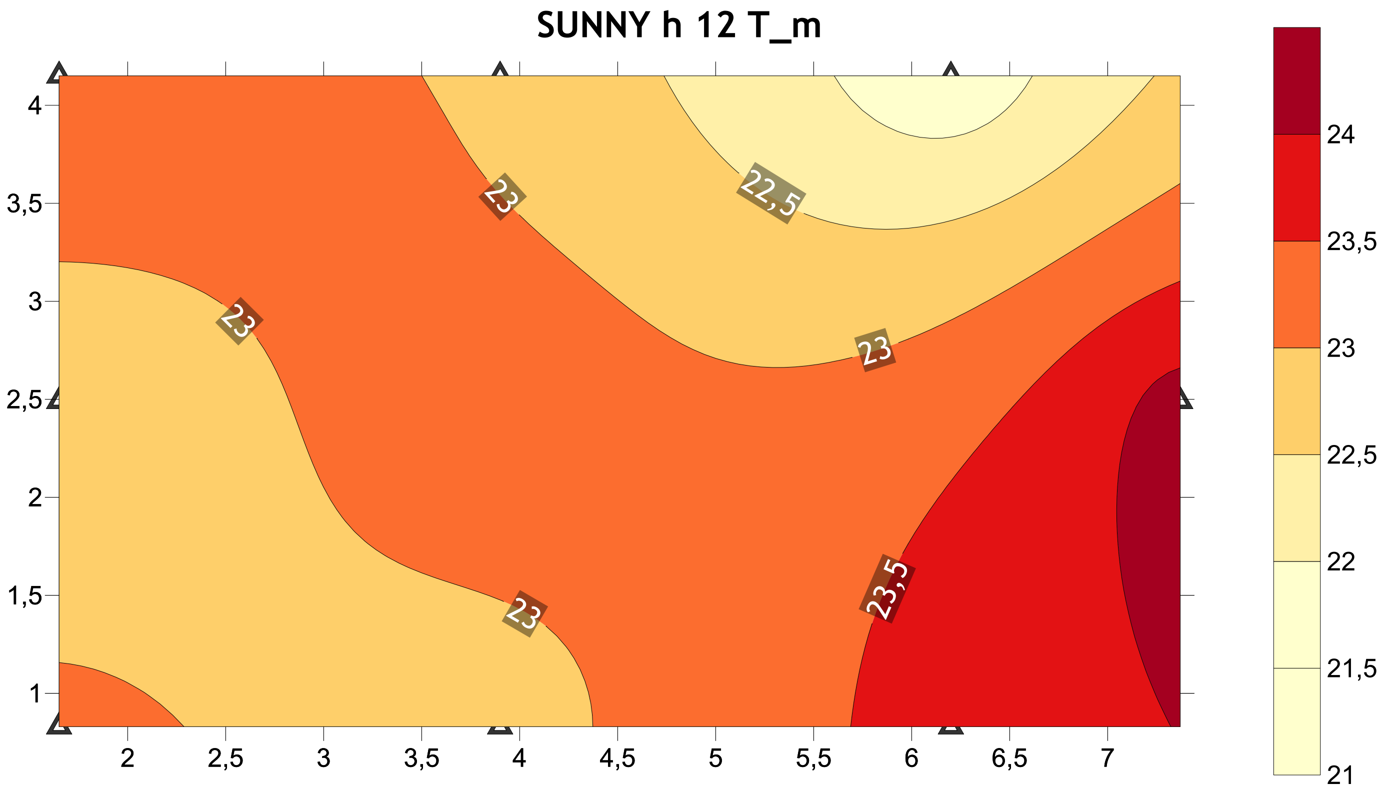
SUNNY h 12 T_m
4
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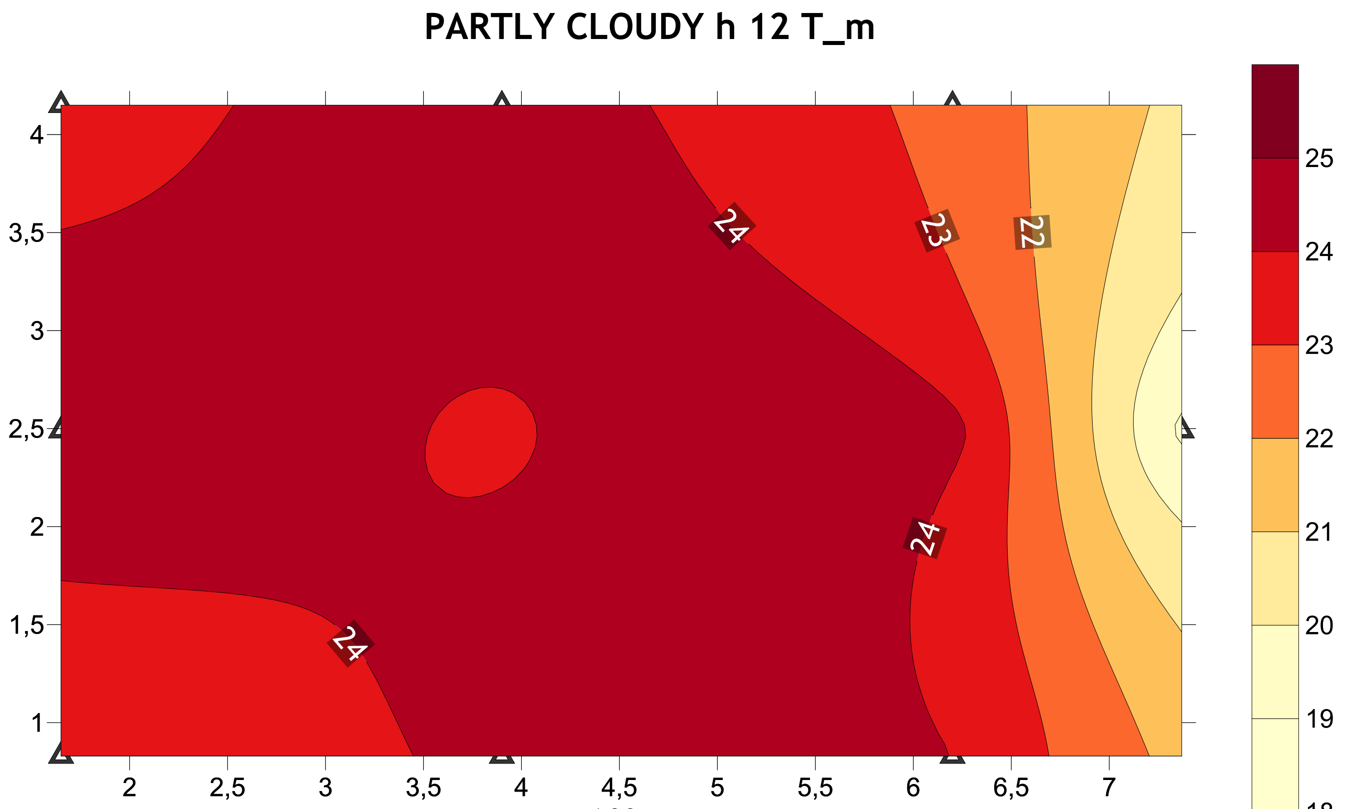
PARTLY CLOUDY h 12 T_m
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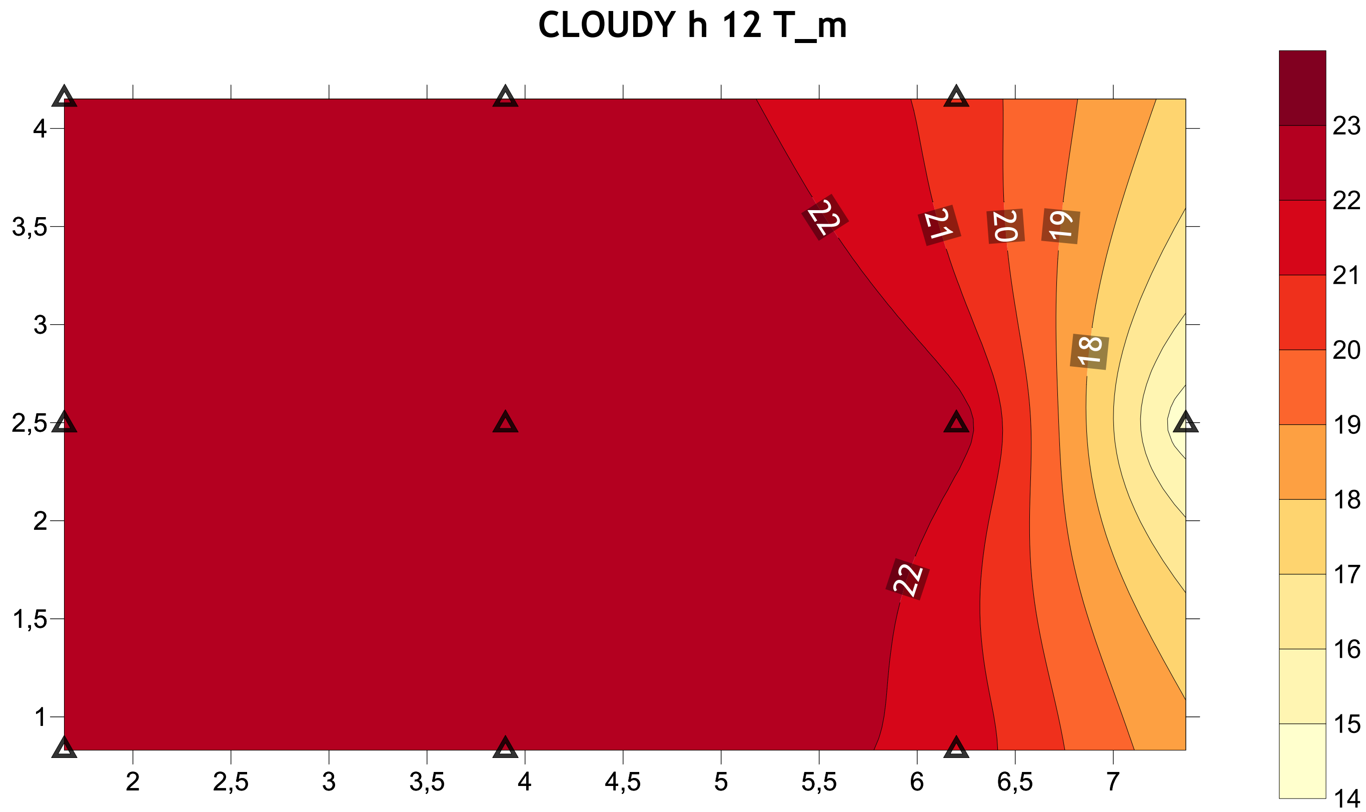

CLOUDY h 12 T_m
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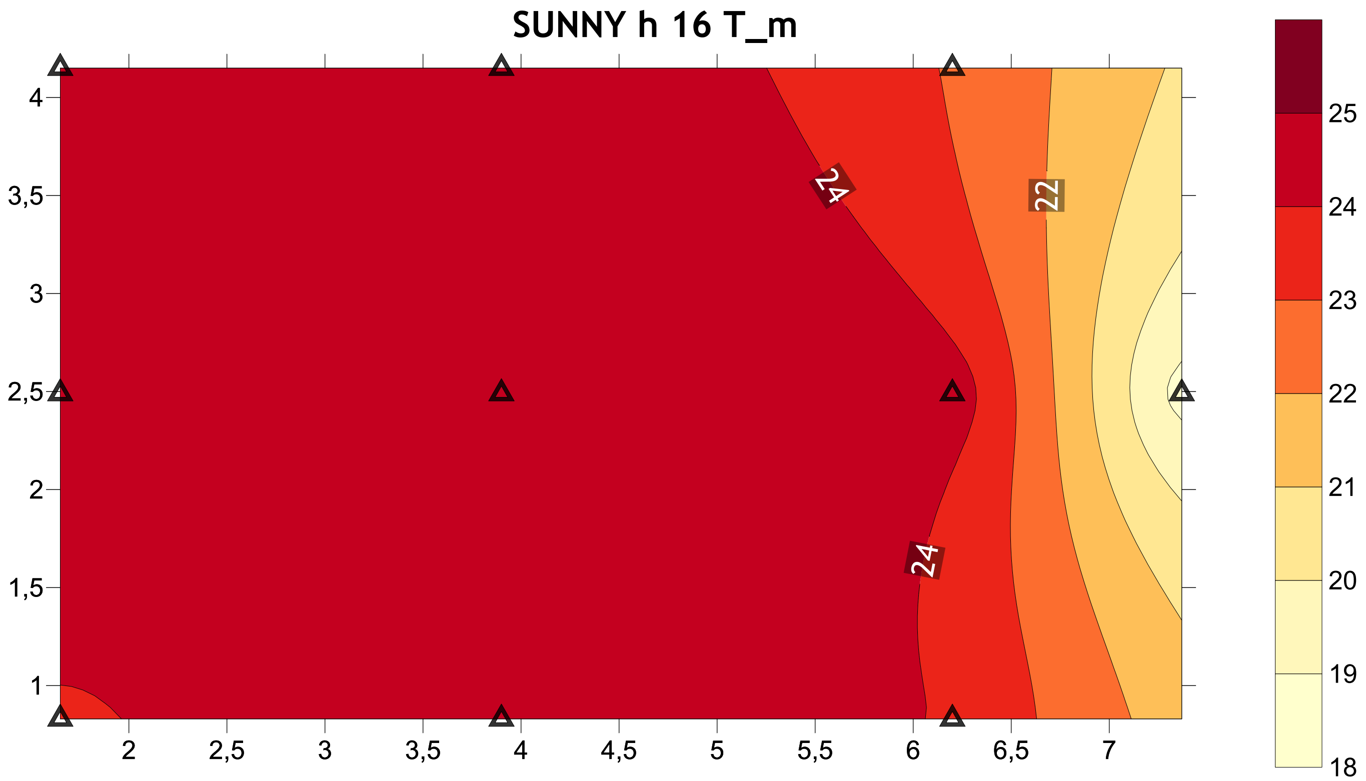
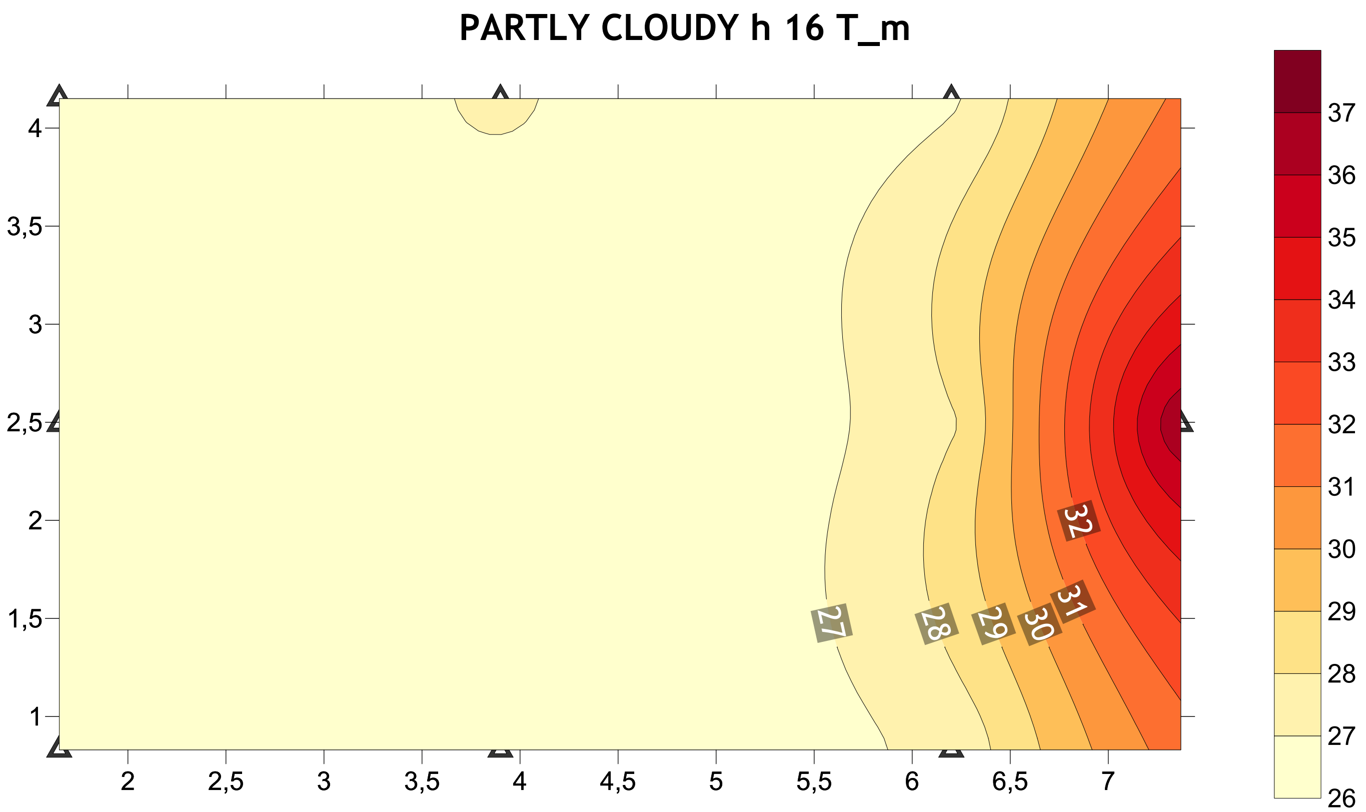
6,5
7
22
21
20
19
18
22
23
22
21
20
19
18
17
16
15
14


SUNNY h 16 T_m
24
22
24
4
3,5
3
2,5
2
1,5
1
2
2,5
3
3,5
4
4,5
5
5,5
6
6,5
7
25
24
23
22
21
20
19
18


PARTLY CLOUDY h 16 T_m
27
28
29
30
31
32
4
3,5
3
2,5
2
1,5
1
2
2,5
3
3,5
4
4,5
5
5,5
6
6,5
7
37
36
35
34
33
32
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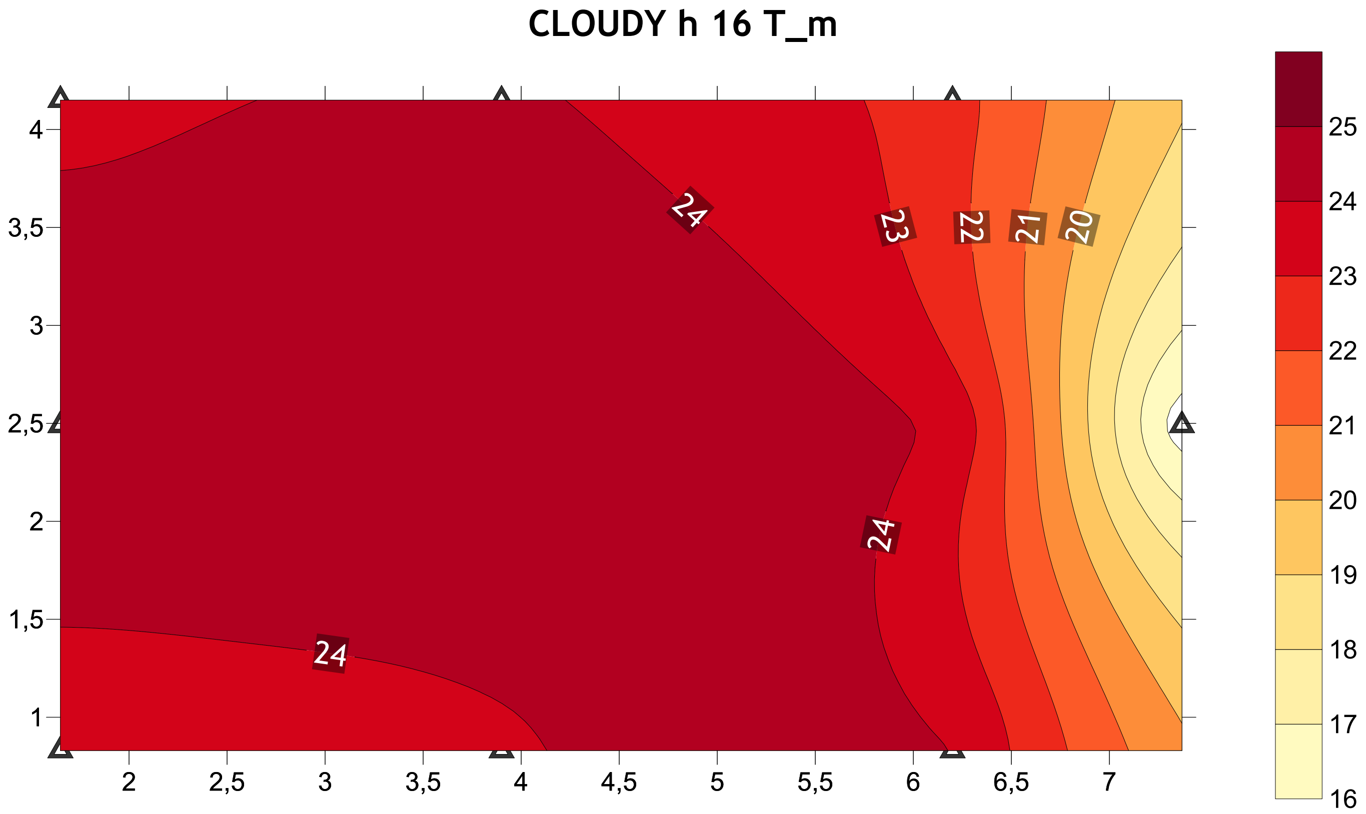
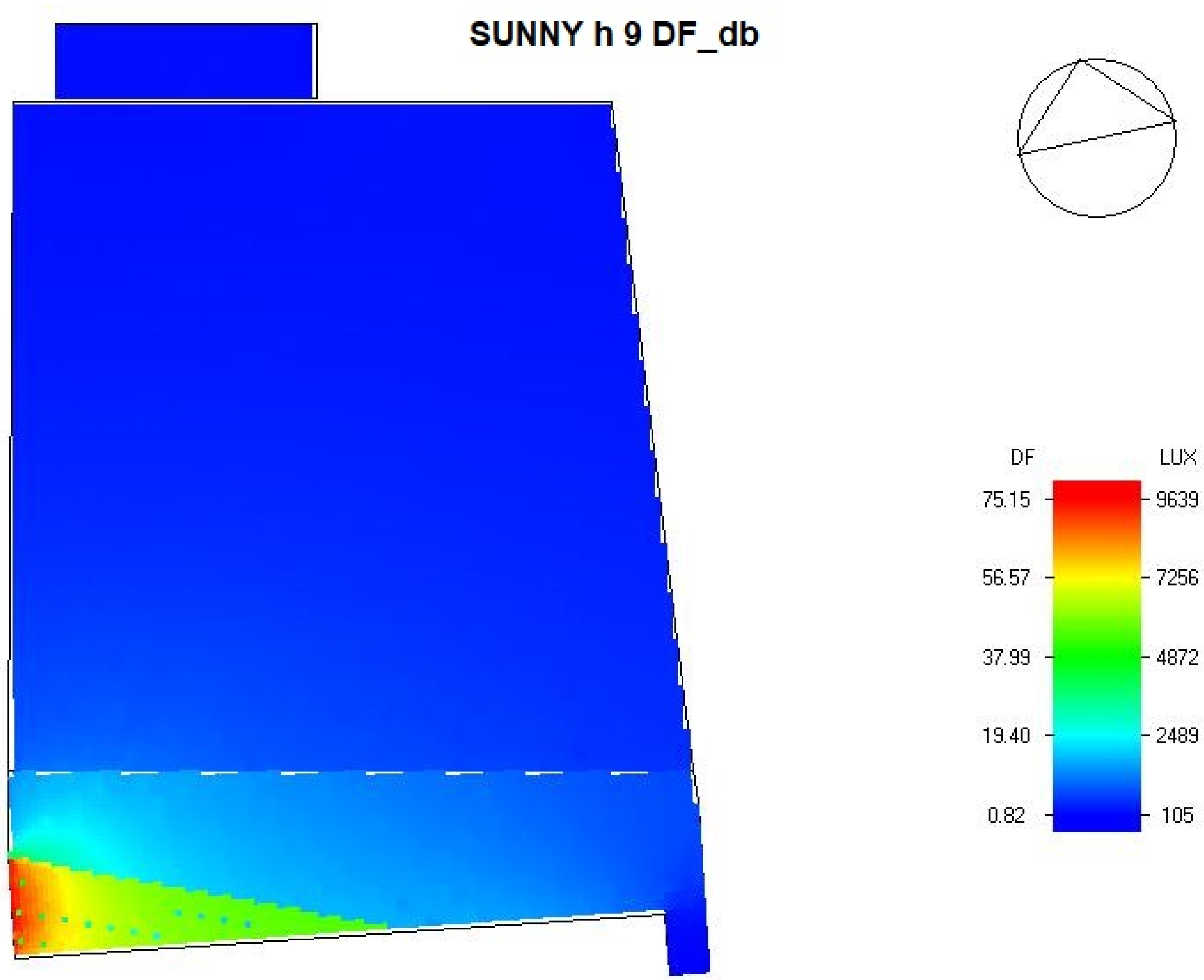
29
28
27
26


CLOUDY h 16 T_m
24
23
22
21
20
24
24
4
3,5
3
2,5
2
1,5
1
2
2,5
3
3,5
4
4,5
5
5,5
6
6,5
7
25
24
23
22
21
20
19
18
17
16

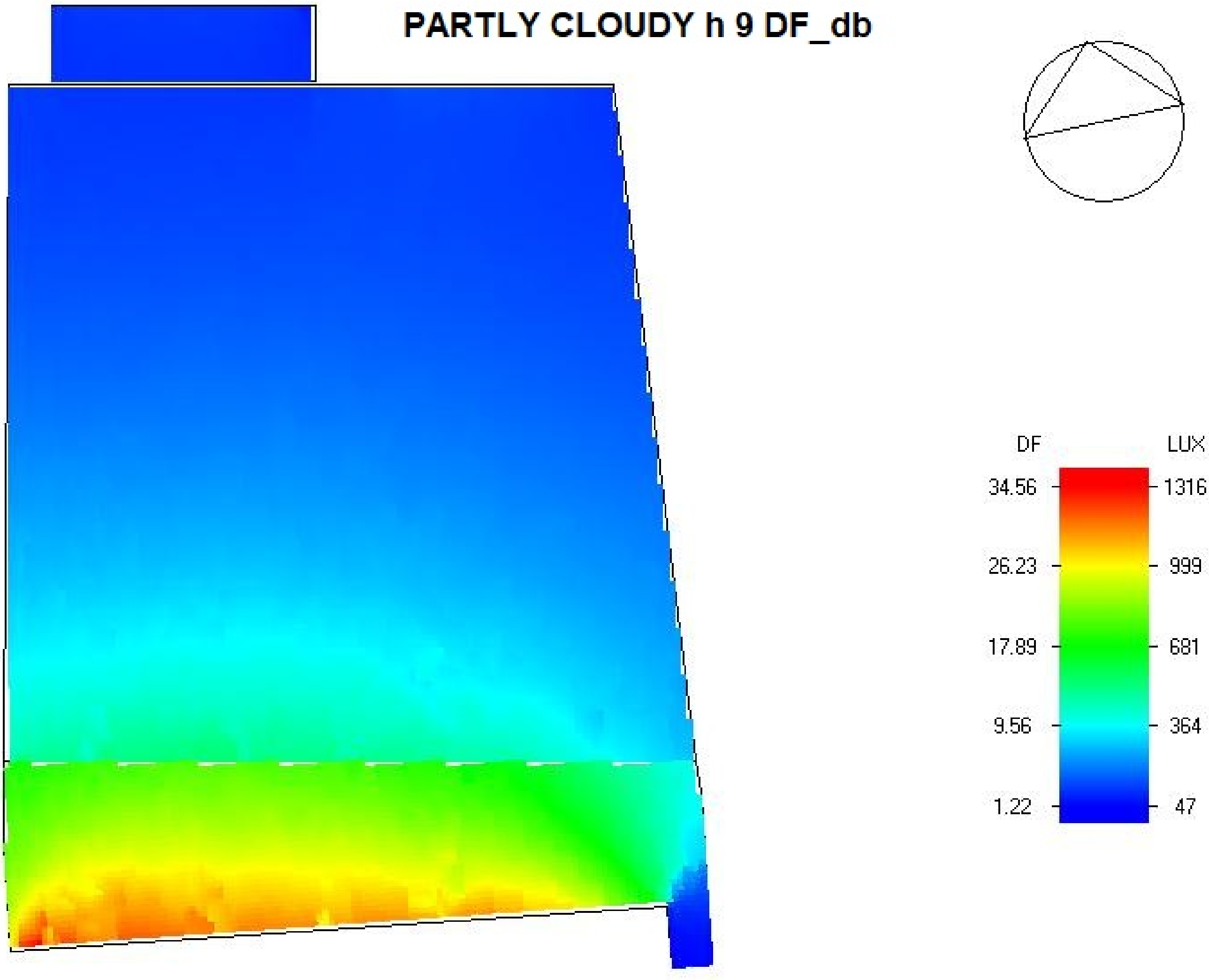
Attachment C

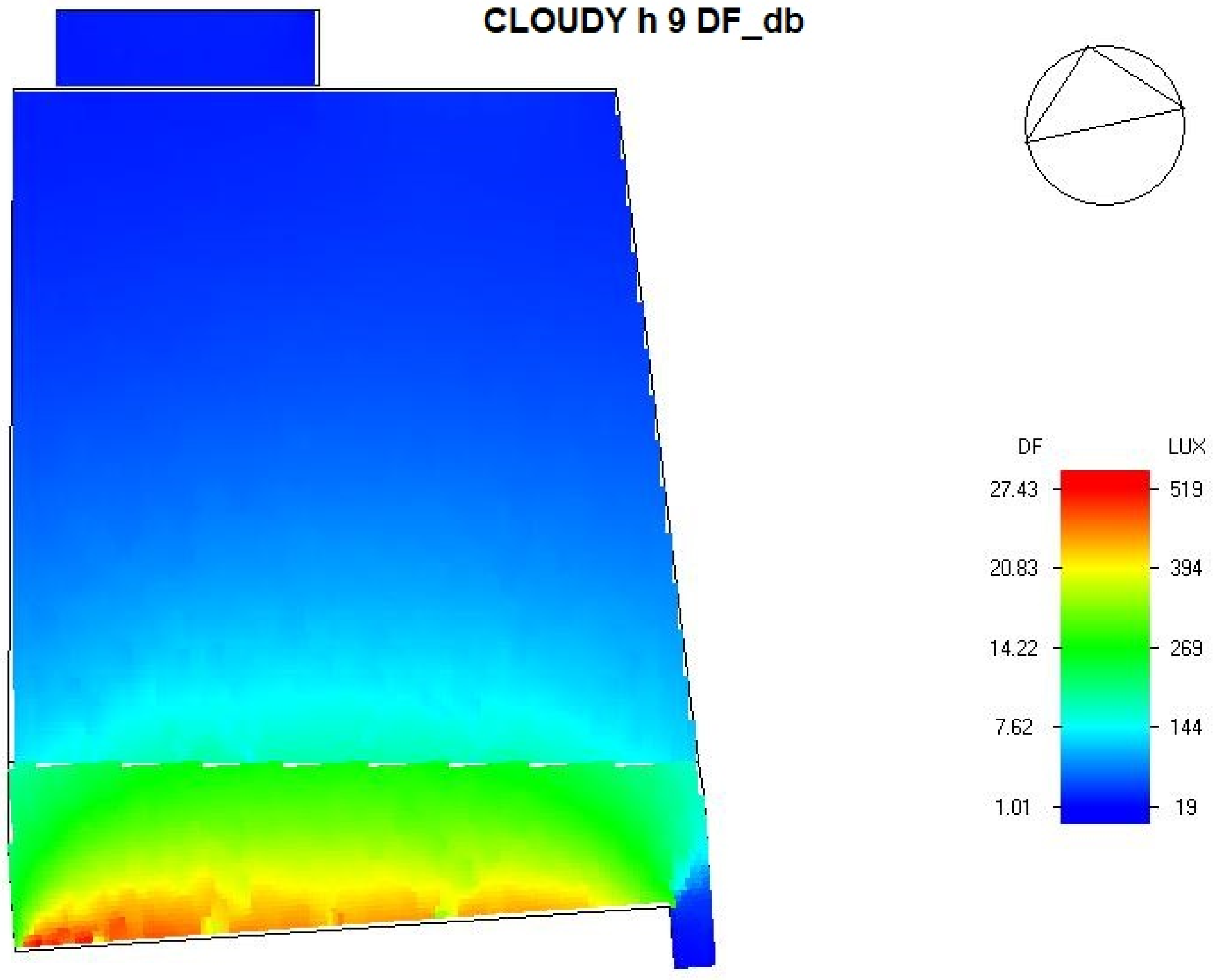
DesignBuilder DF

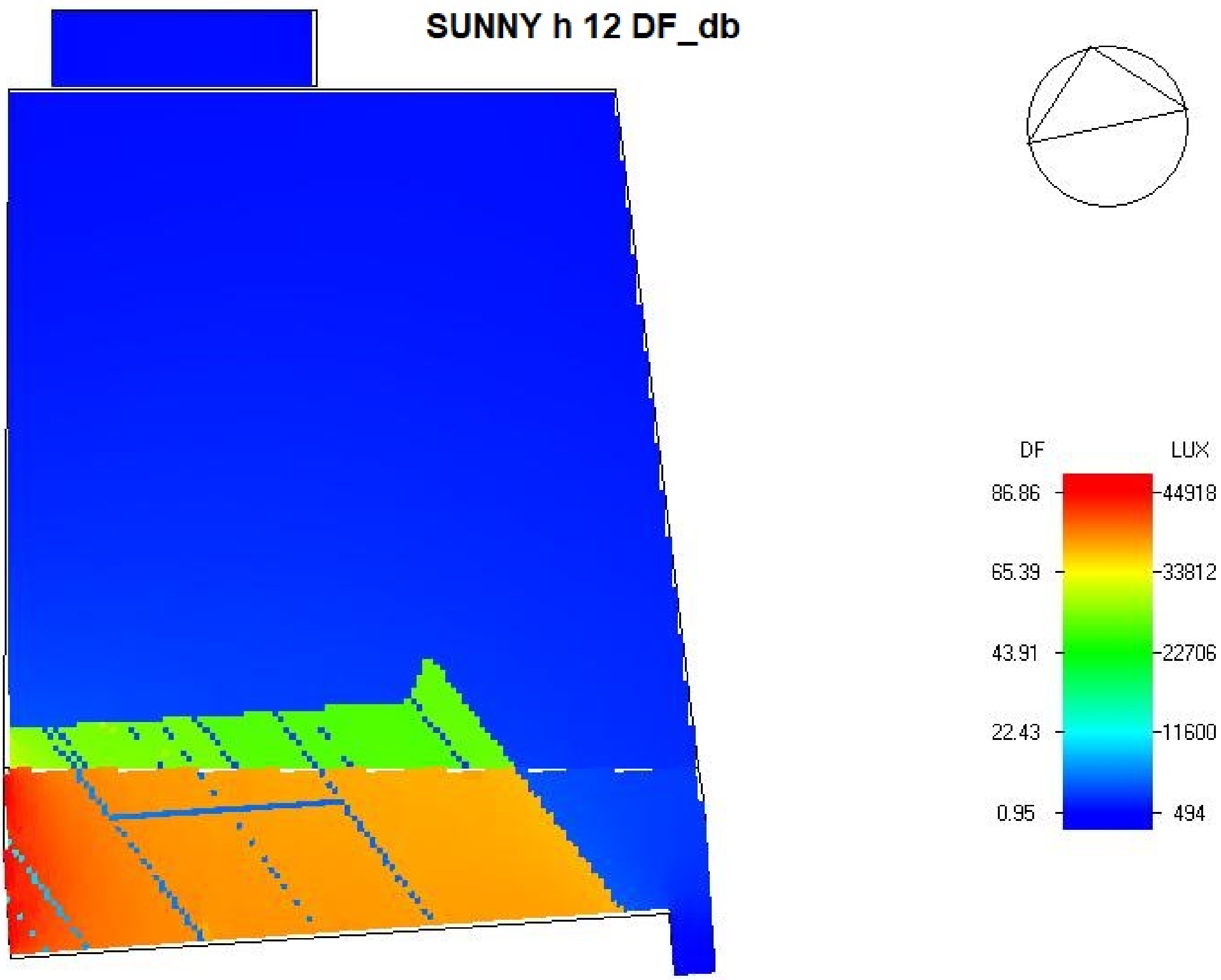
Original Case

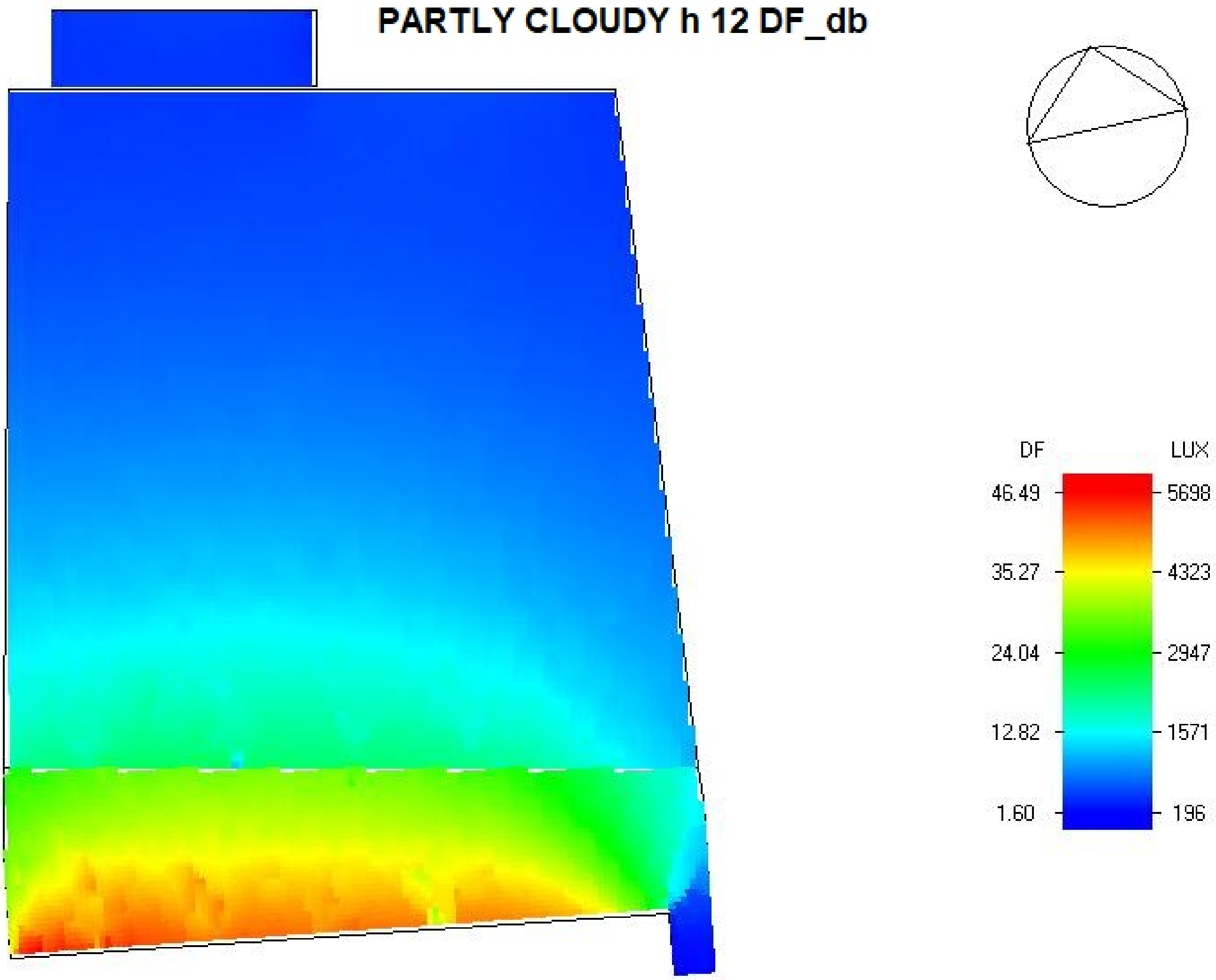


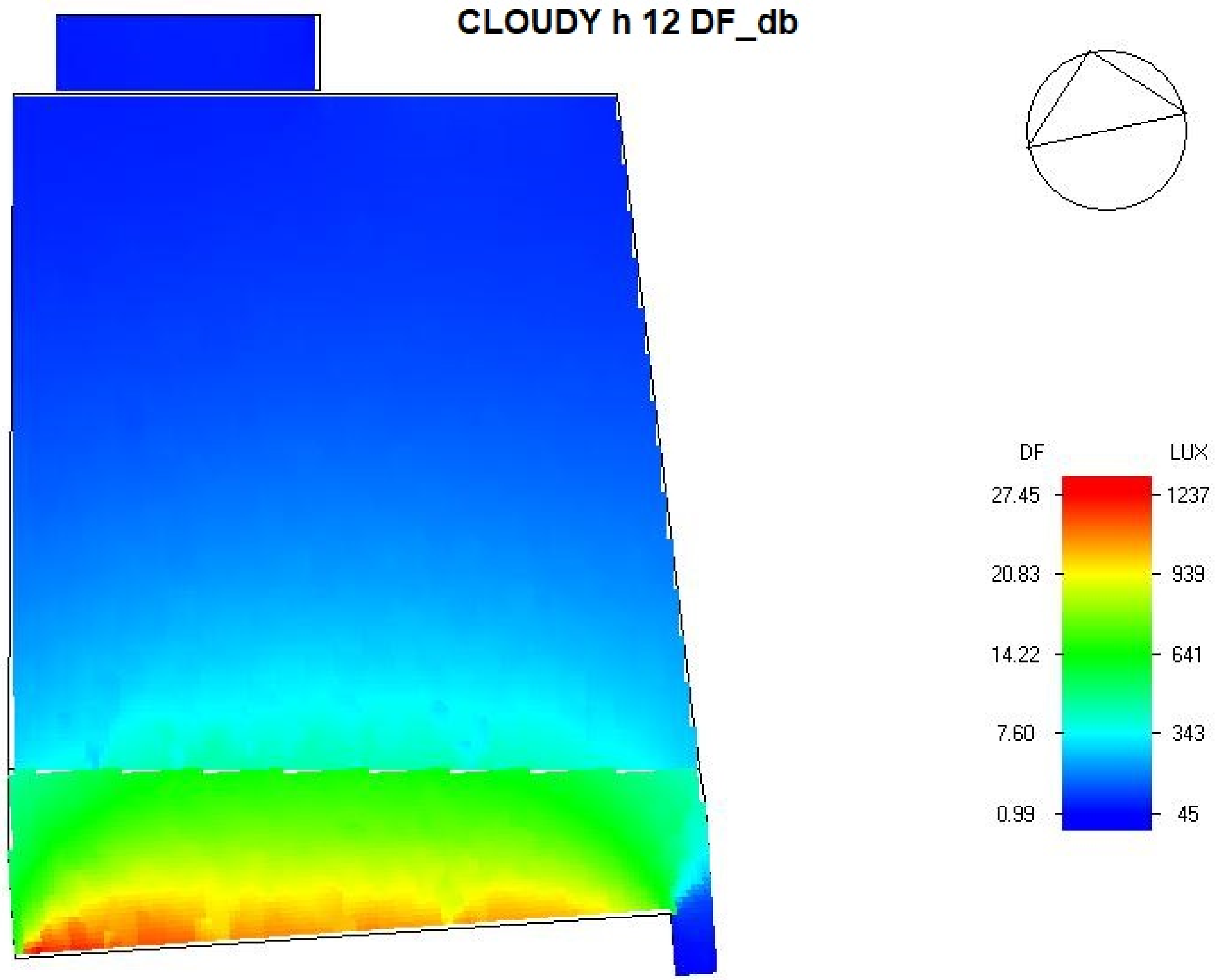
SUNNY h 9 DF_db
DF
LUX
75.15
9639
56.57
7256
37.99
4872
19.40
2489
0.82
105

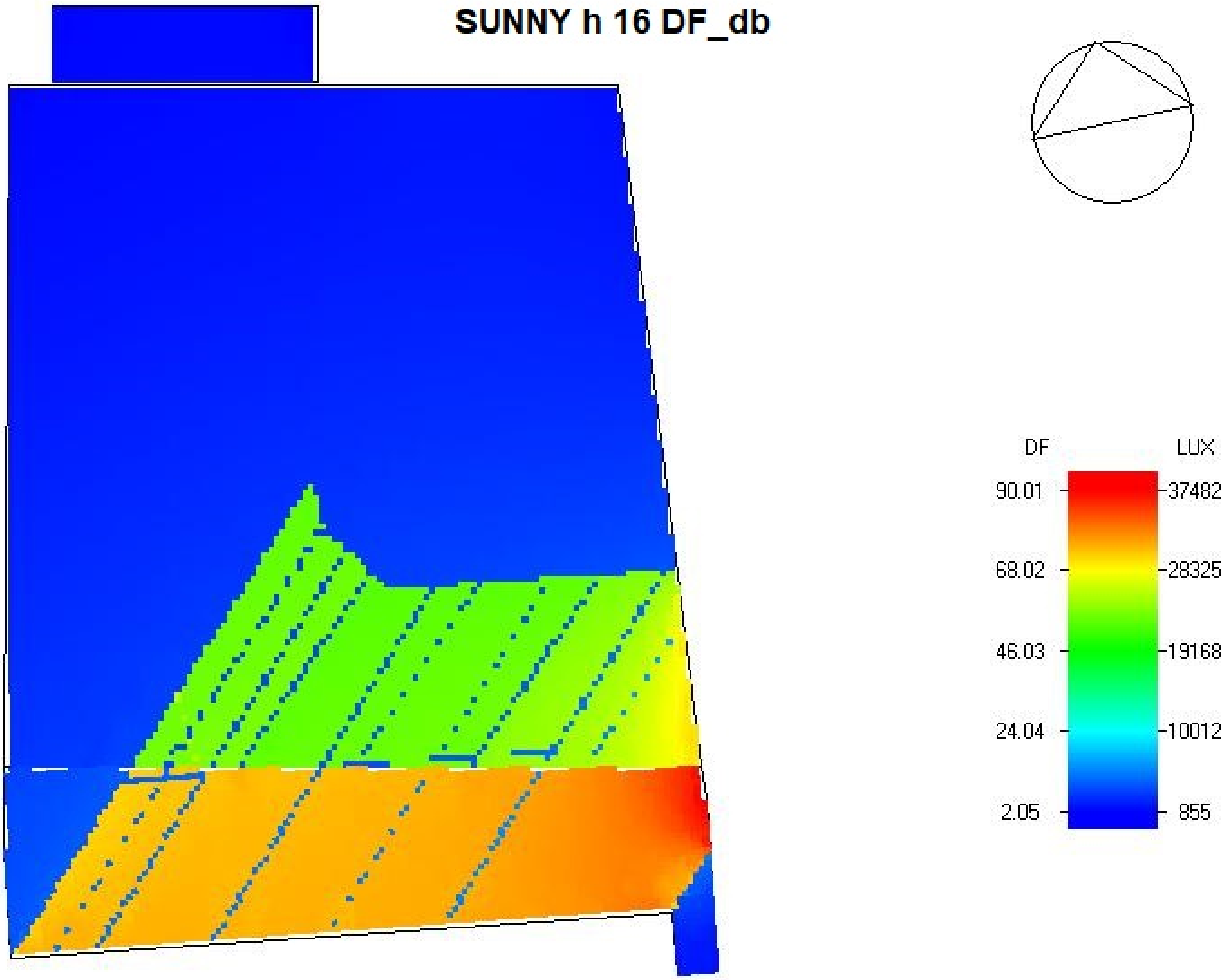

PARTLY CLOUDY h 9 DF_db
DF
LUX
34.56
1316
26.23
999
17.89
681
9.56
364
1.22
47


CLOUDY h 9 DF_db
DF
LUX
27.43
519
20.83
394
14.22
269
7.62
144
1.01
19

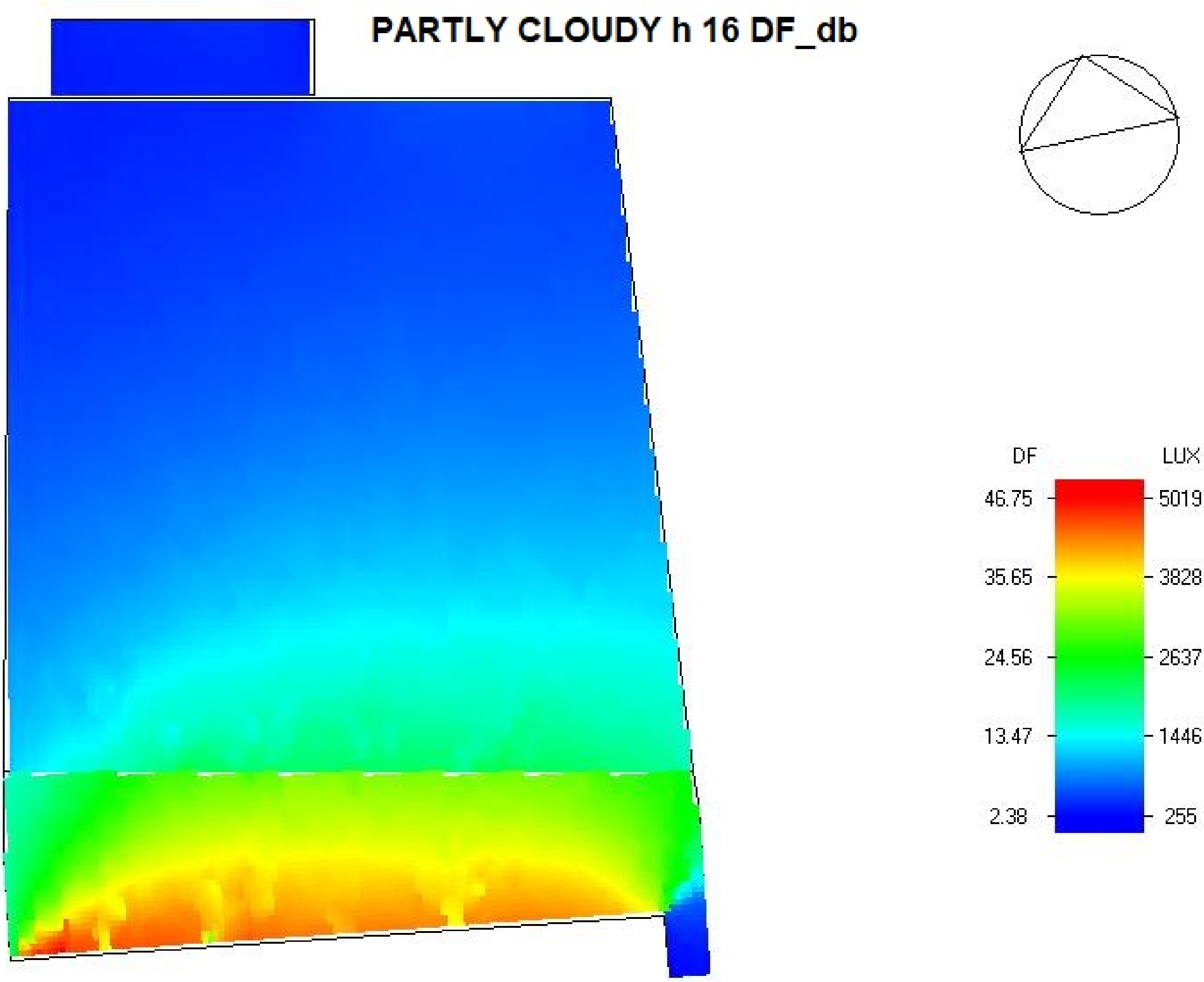

SUNNY h 12 DF_db
DF
LUX
86.86
65.39
43.91
22.43
0.95
44918
33812
22706
11600
494

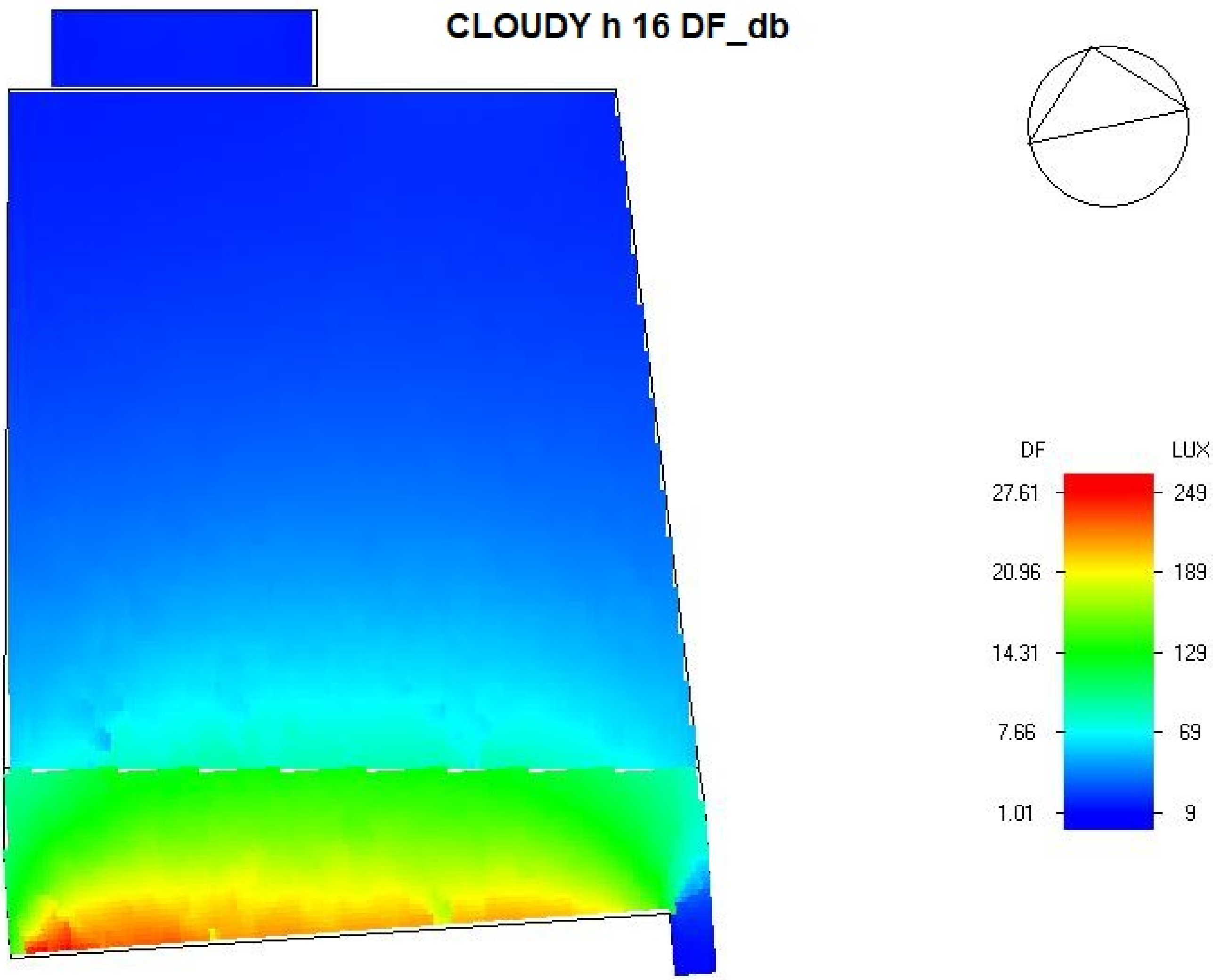

PARTLY CLOUDY h 12 DF_db
DF
LUX
46.49
5698
35.27
4323
24.04
2947
12.82
1571
1.60
196


CLOUDY h 12 DF_db
DF
LUX
27.45
1237
20.83
939
14.22
641
7.60
343
0.99
45



SUNNY h 16 DF_db
DF
LUX
90.01
68.02
46.03
24.04
2.05
37482
28325
19168
10012
855

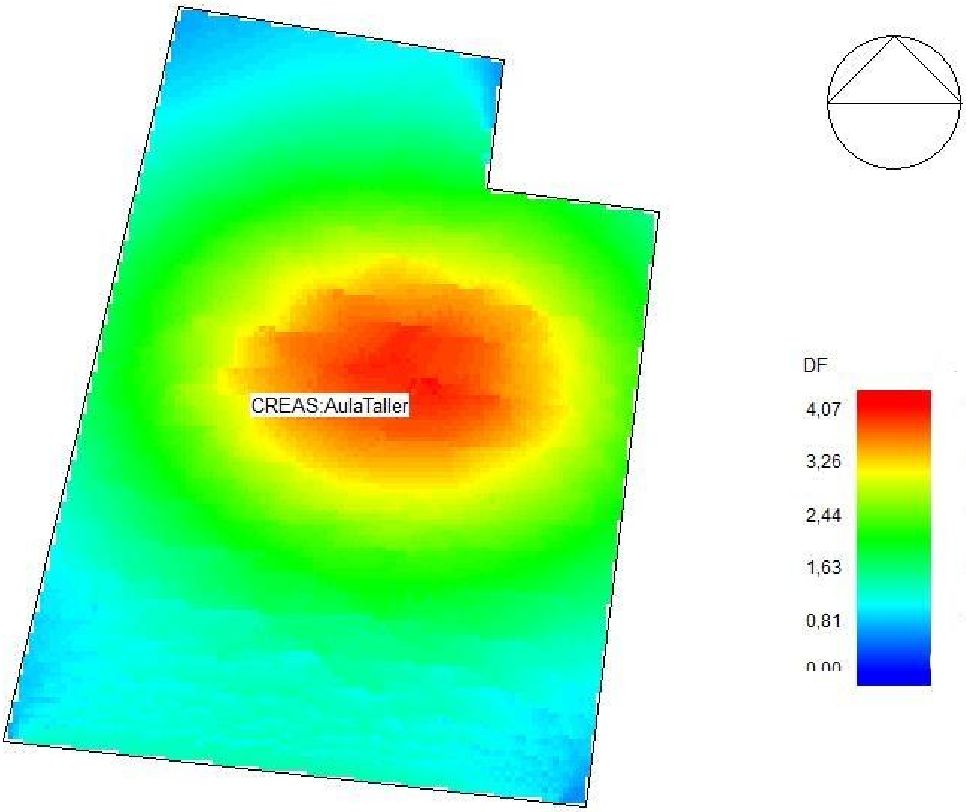

PARTLY CLOUDY h 16 DF_db
DF
LUX
46.75
5019
35.65
3828
24.56
2637
13.47
1446
2.38
255



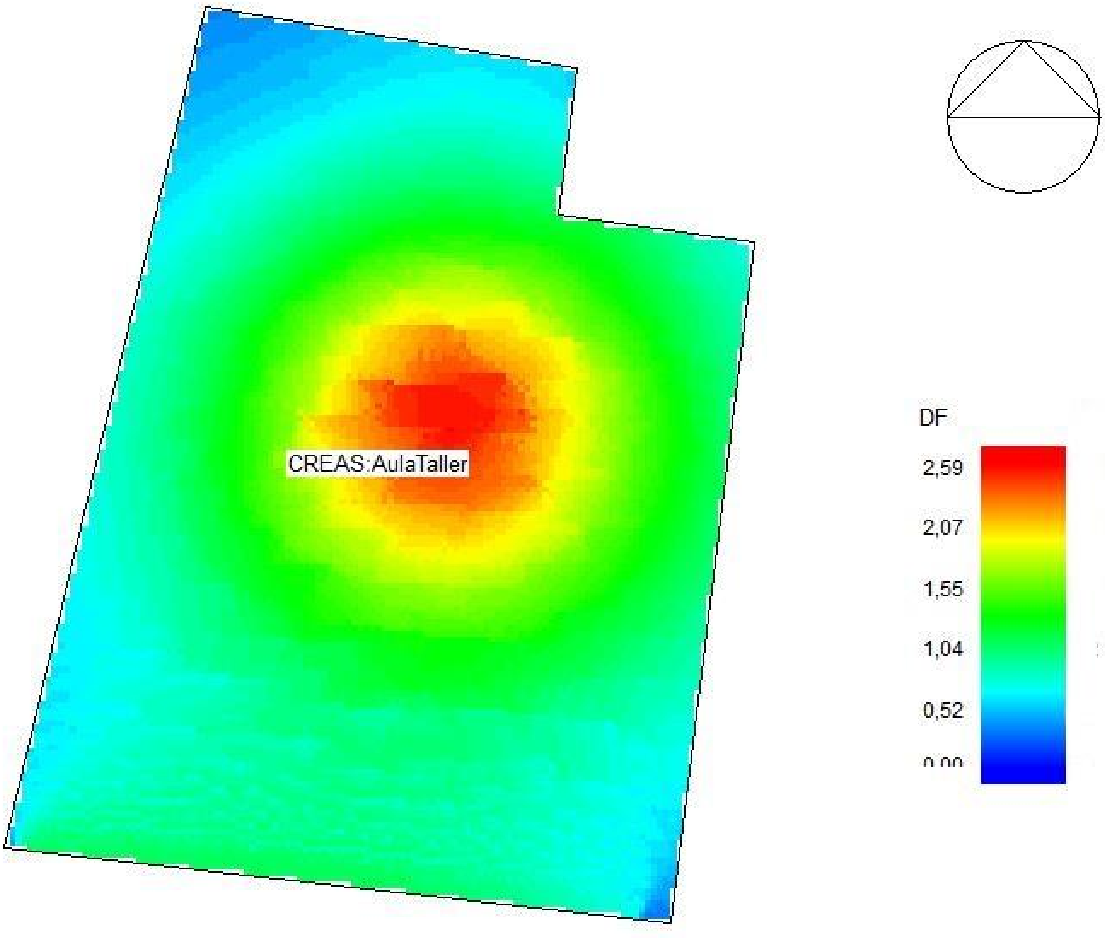
CLOUDY h 16 DF_db
DF
LUX
27.61
249
20.96
189
14.31
129
7.66
69
1.01
9

Improvement

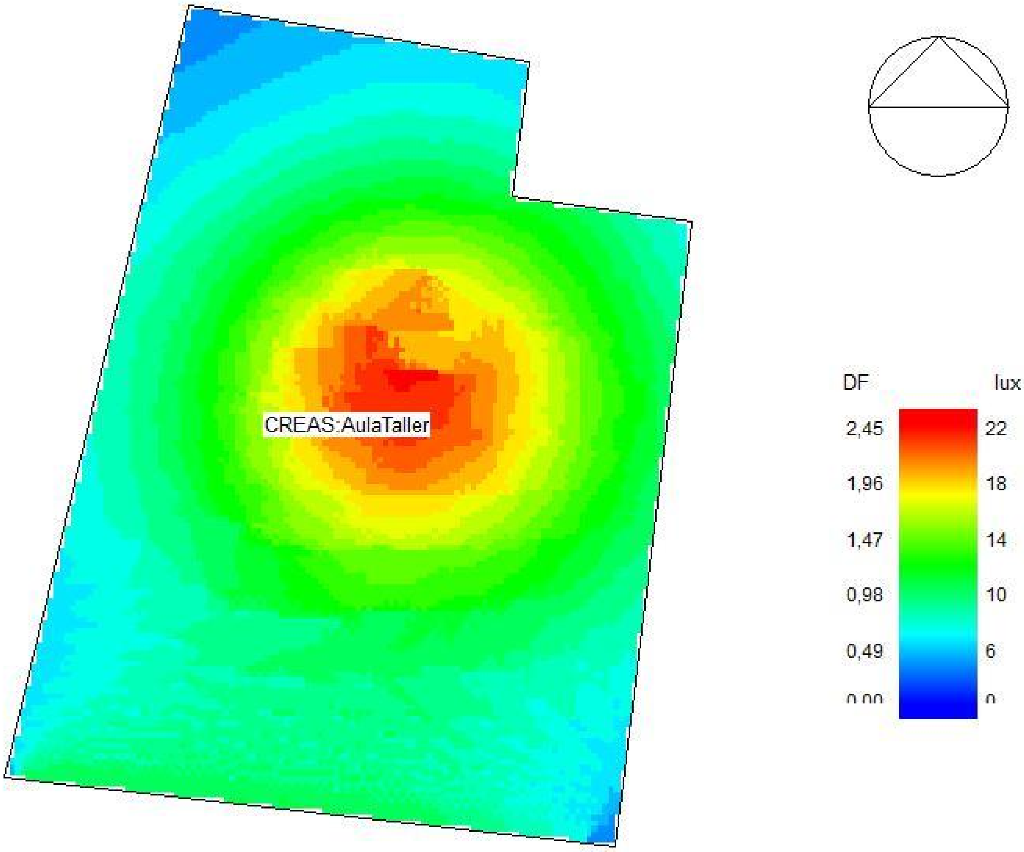
CLOUDY H 9 DF_db with skylights and without window blinds



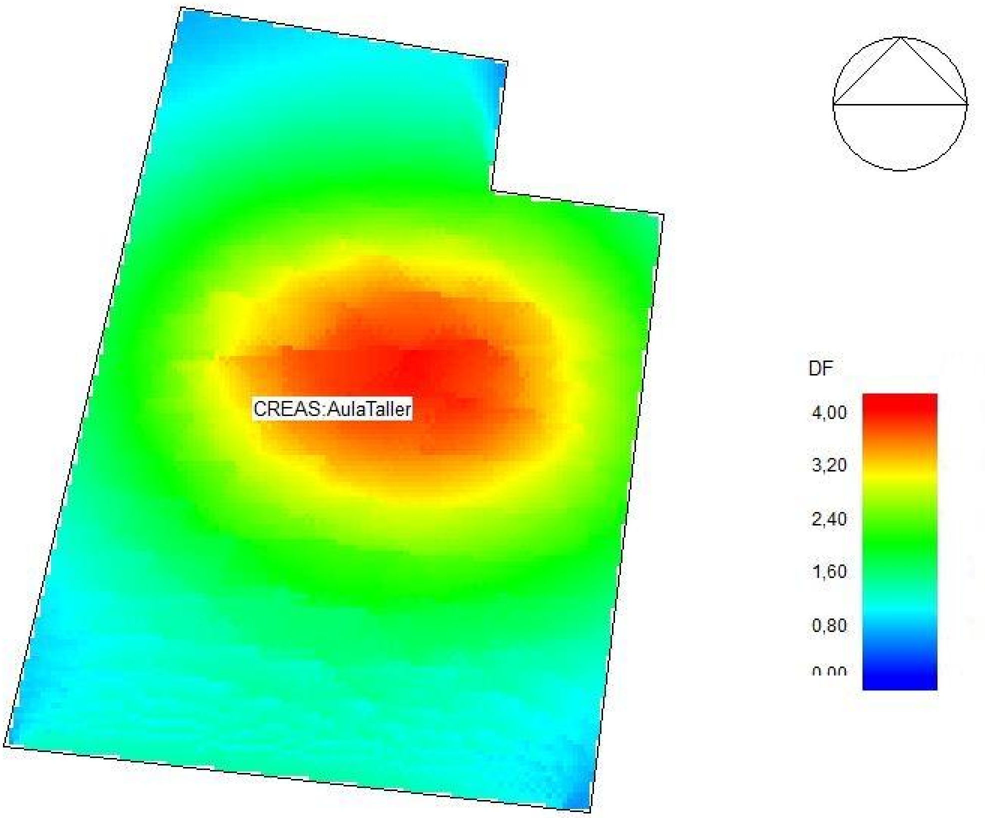
CLOUDY H 9 DF_db with skylights and with window blinds



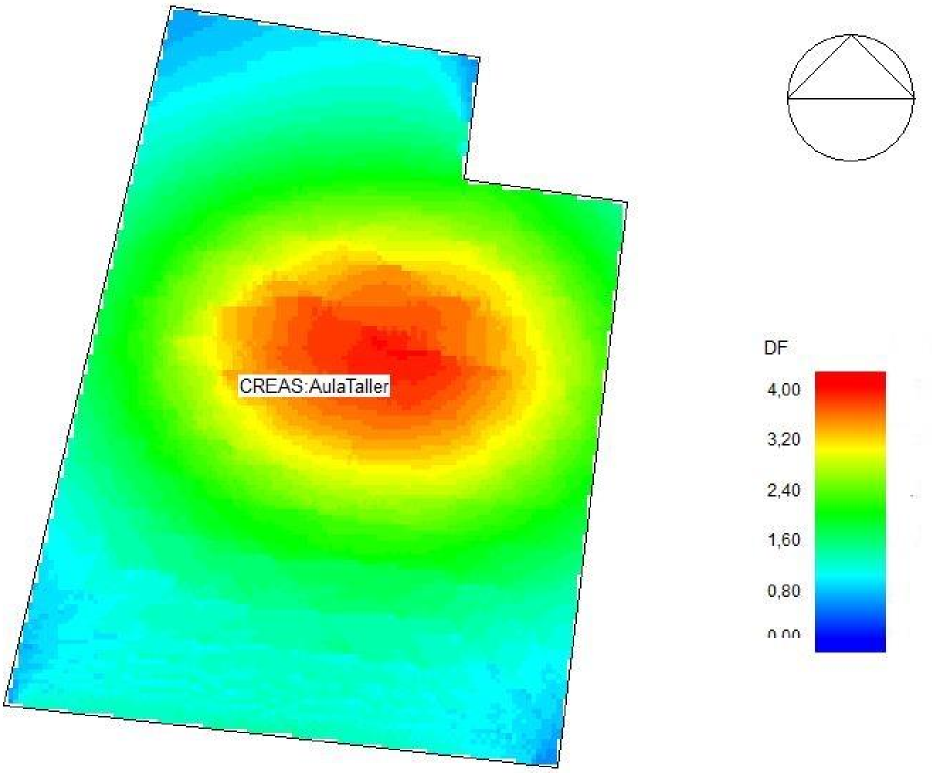
CLOUDY H 12 DF_db with skylights and without window blinds



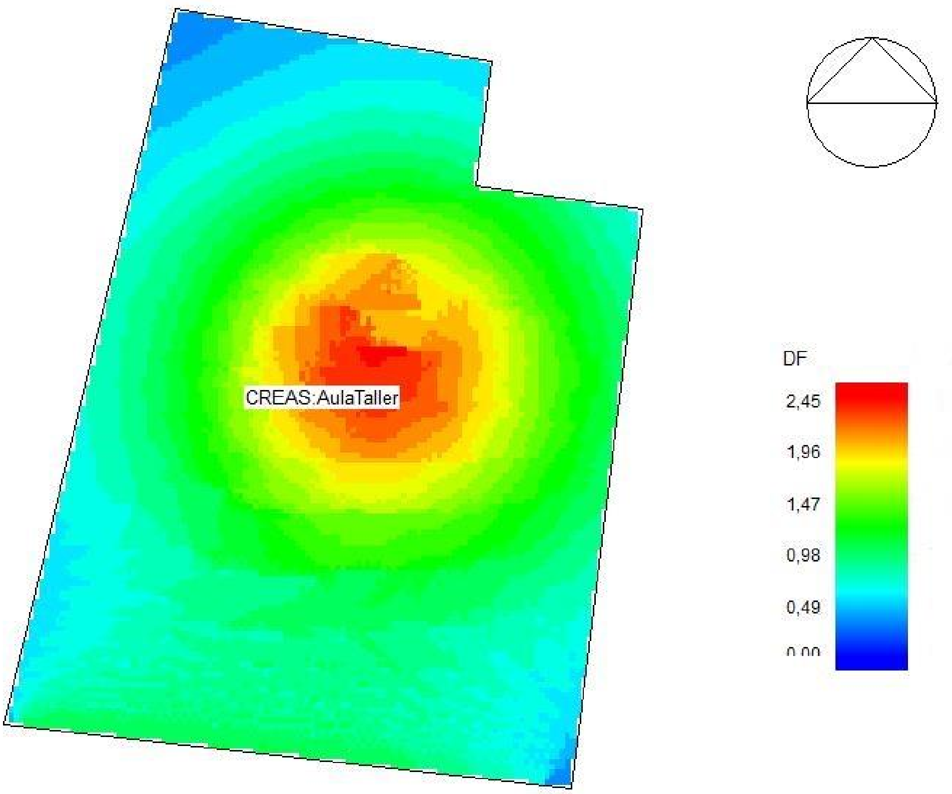
CLOUDY H 12 DF_db with skylights and with window blinds



CLOUDY H 16 DF_db with skylights and without window blinds

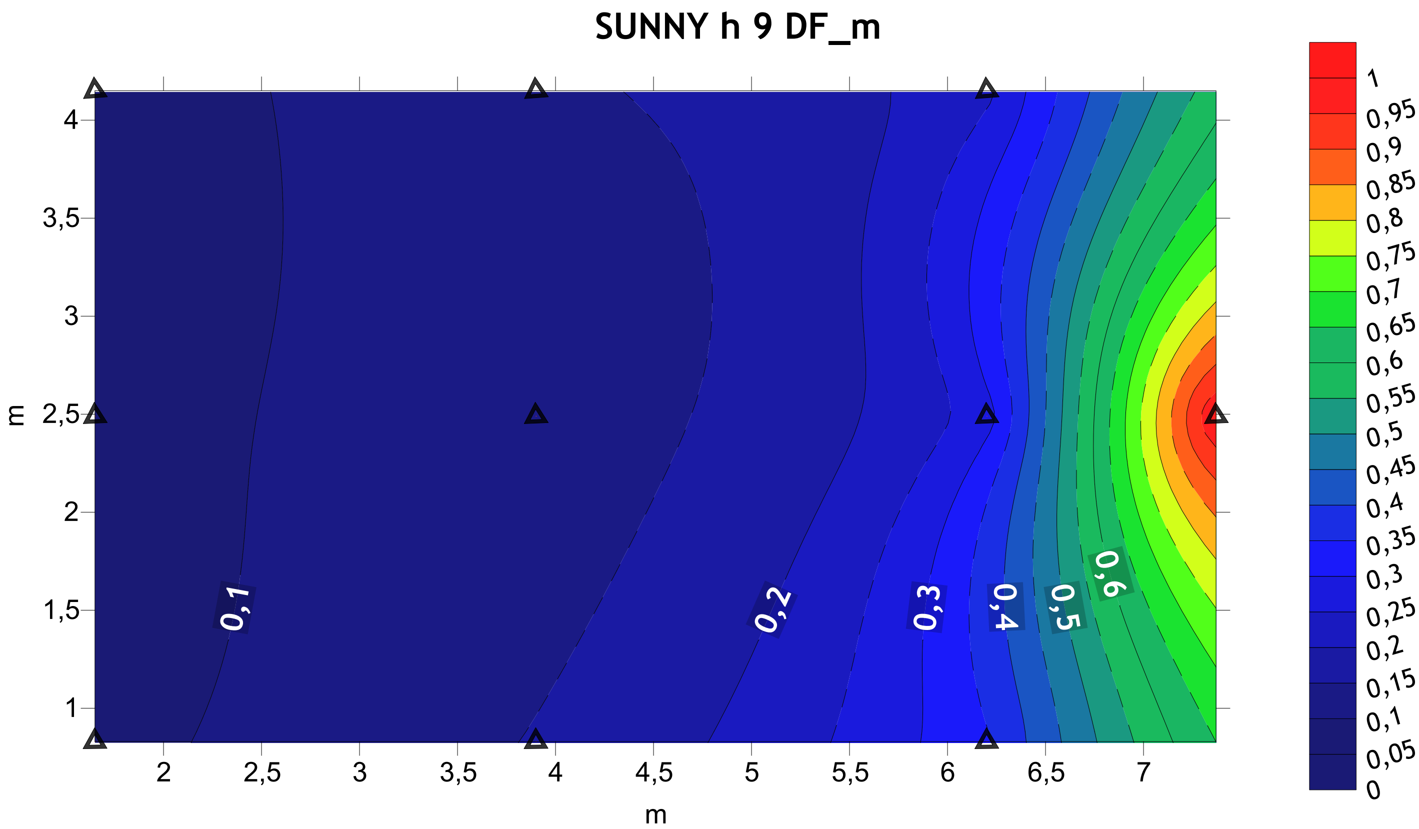


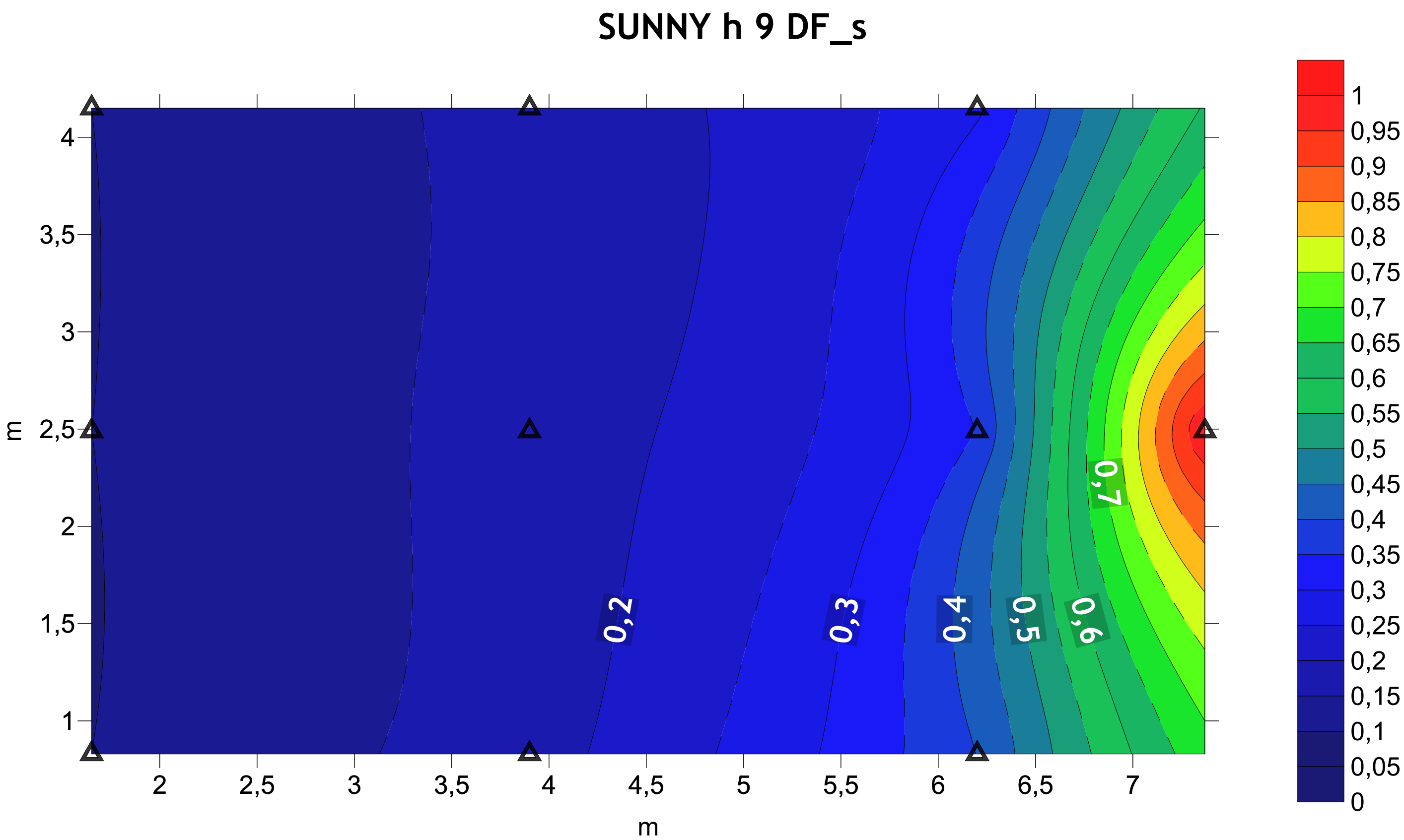
CLOUDY H 16 DF_db with skylights and with window blinds

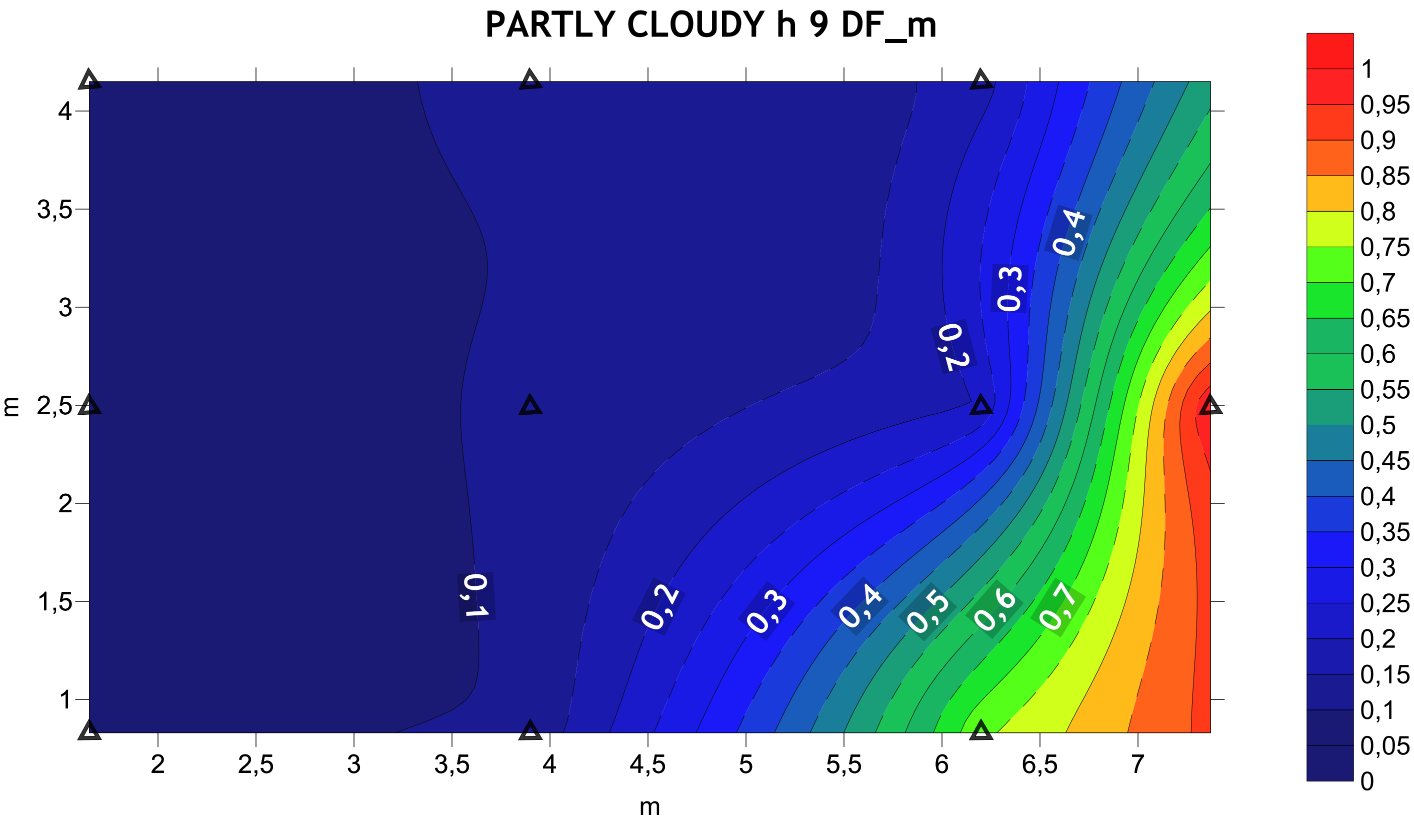


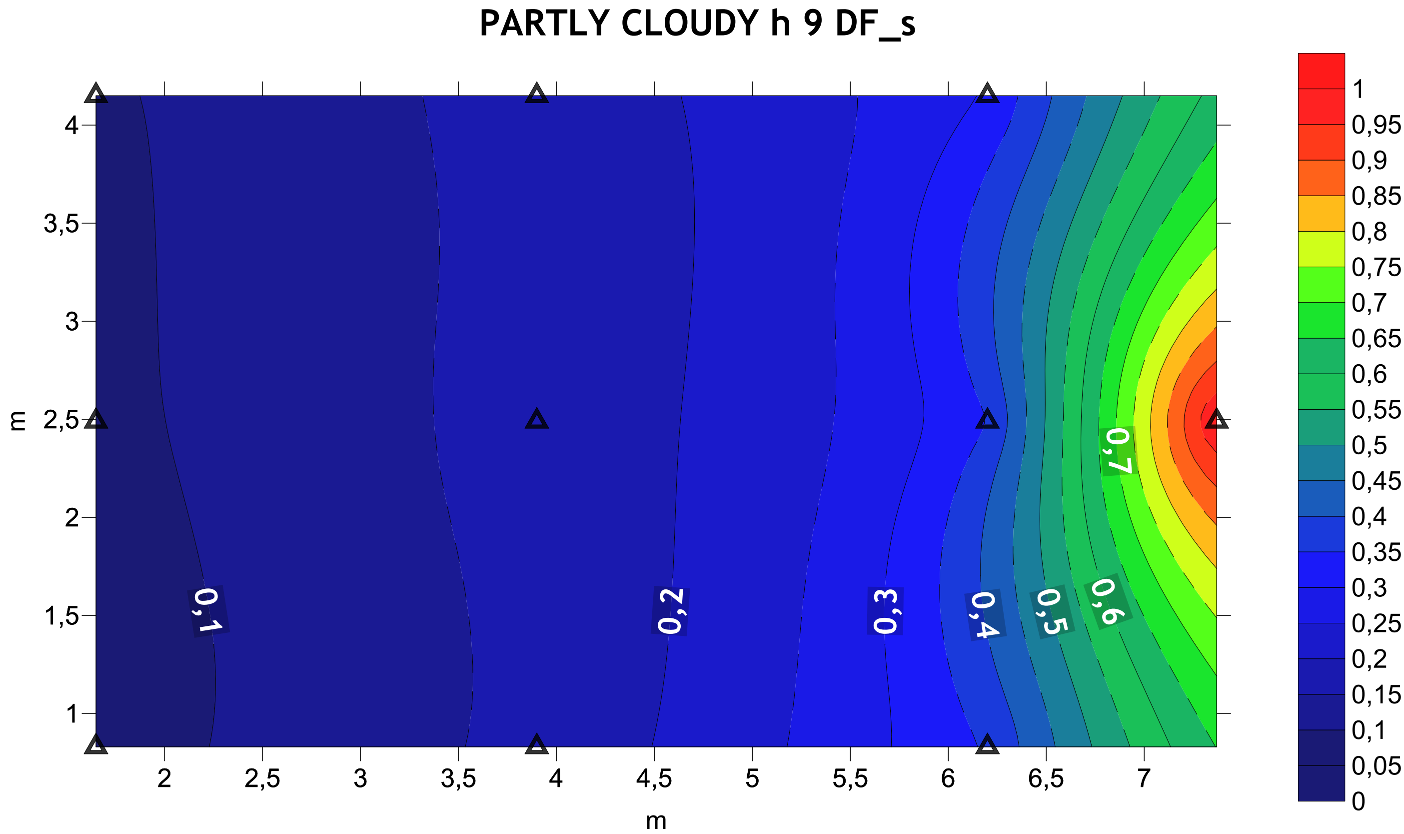
Attachment D

Surfer DF

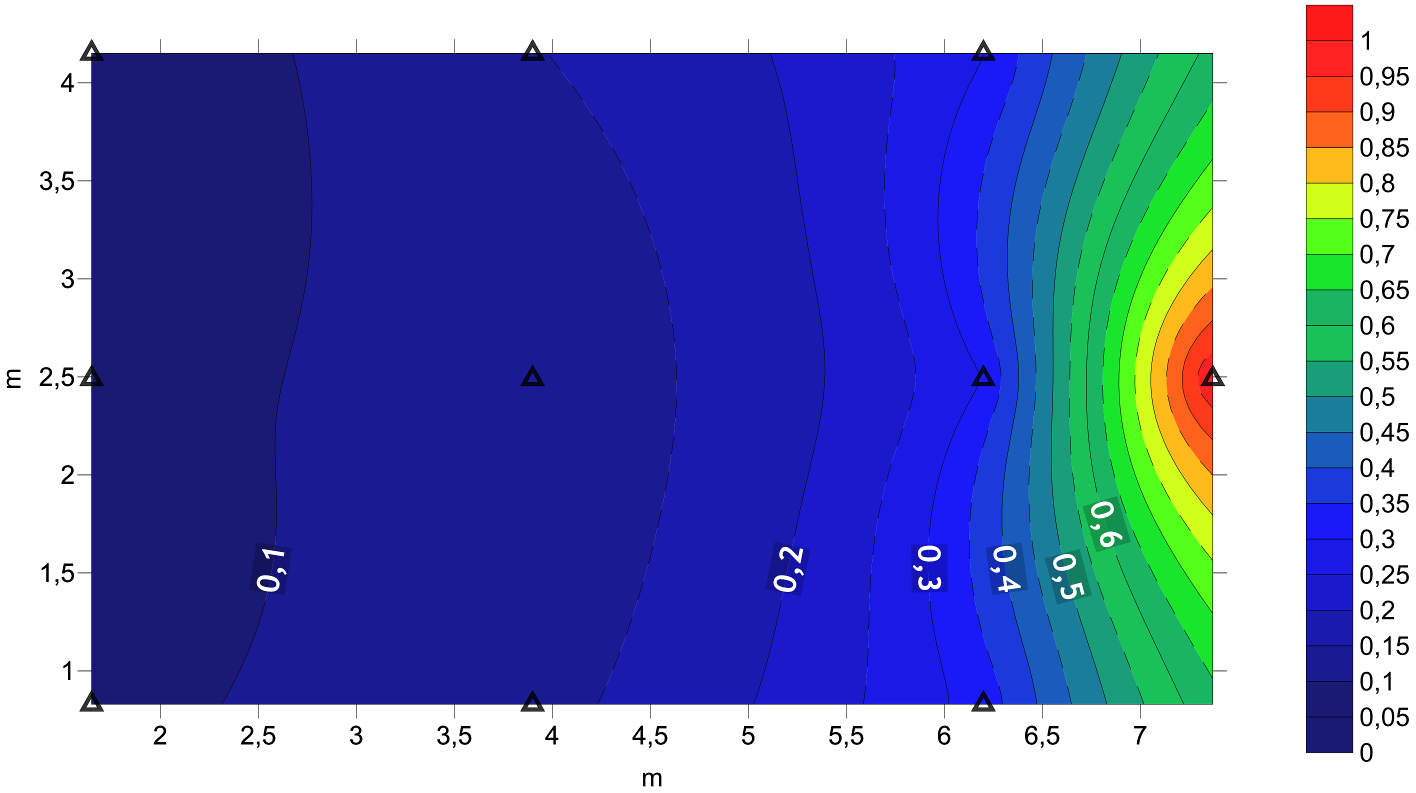

SUNNY h 9 DF_m
m
m
0,1
0,2
0,3
0,4
0,5
0,6
1
0,95
0,9
0,85
0,8
0,75
0,7
0,65
0,6
0,55
0,5
0,45
0,4
0,35
0,3
0,25
0,2
0,15
0,1
0,05
0


SUNNY h 9 DF_s
m
m
0,2
0,3
0,4
0,5
0,6
0,7
1
0,95
0,9
0,85
0,8
0,75
0,7
0,65
0,6
0,55
0,5
0,45
0,4
0,35
0,3
0,25
0,2
0,15
0,1
0,05
0

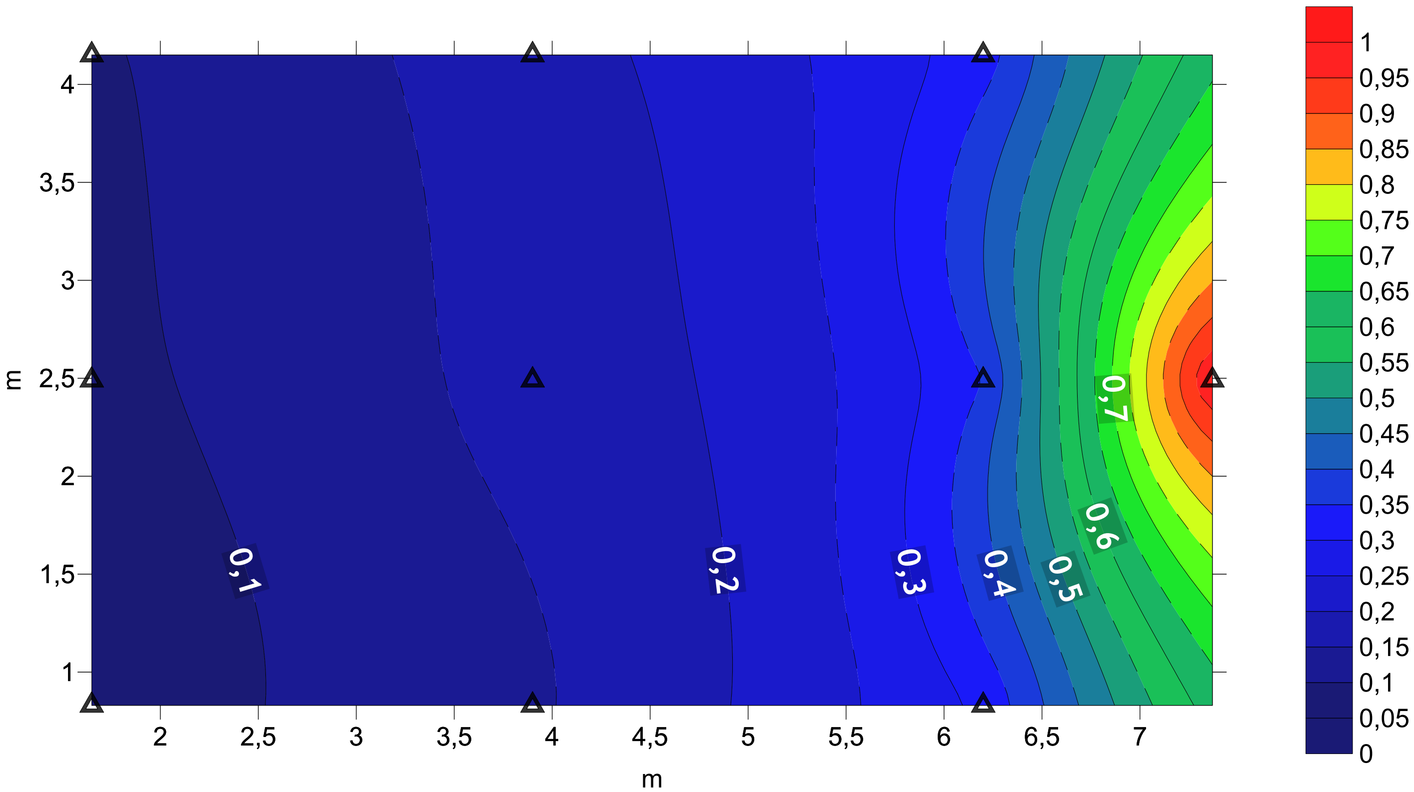

PARTLY CLOUDY h 9 DF_m
m
m
0,1
0,2
0,2
0,3
0,3
0,4
0,4
0,5
0,6
0,7
1
0,95
0,9
0,85
0,8
0,75
0,7
0,65
0,6
0,55
0,5
0,45
0,4
0,35
0,3
0,25
0,2
0,15
0,1
0,05
0

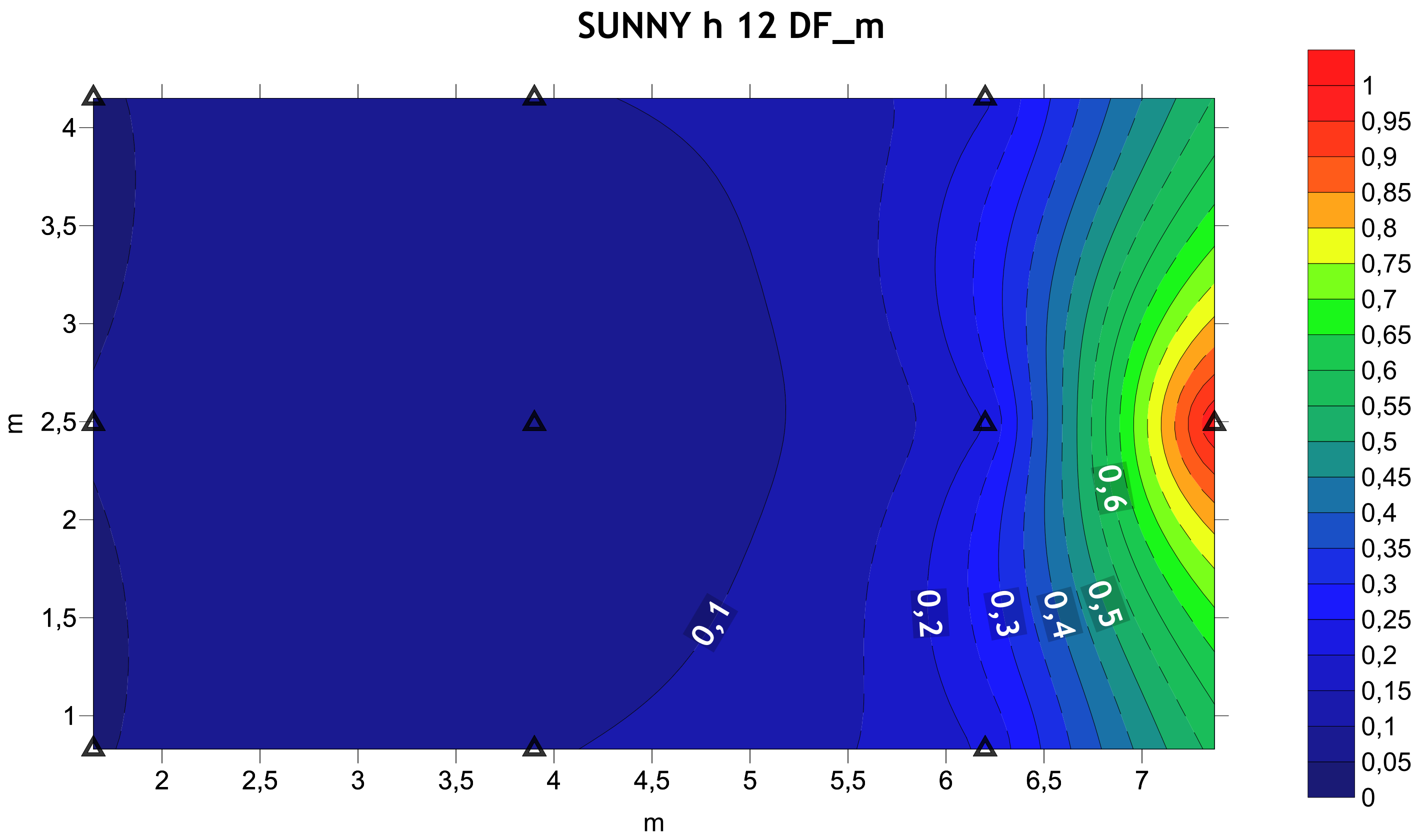

PARTLY CLOUDY h 9 DF_s
m
m
0,1
0,2
0,3
0,4
0,5
0,6
0,7
1
0,95
0,9
0,85
0,8
0,75
0,7
0,65
0,6
0,55
0,5
0,45
0,4
0,35
0,3
0,25
0,2
0,15
0,1
0,05
0

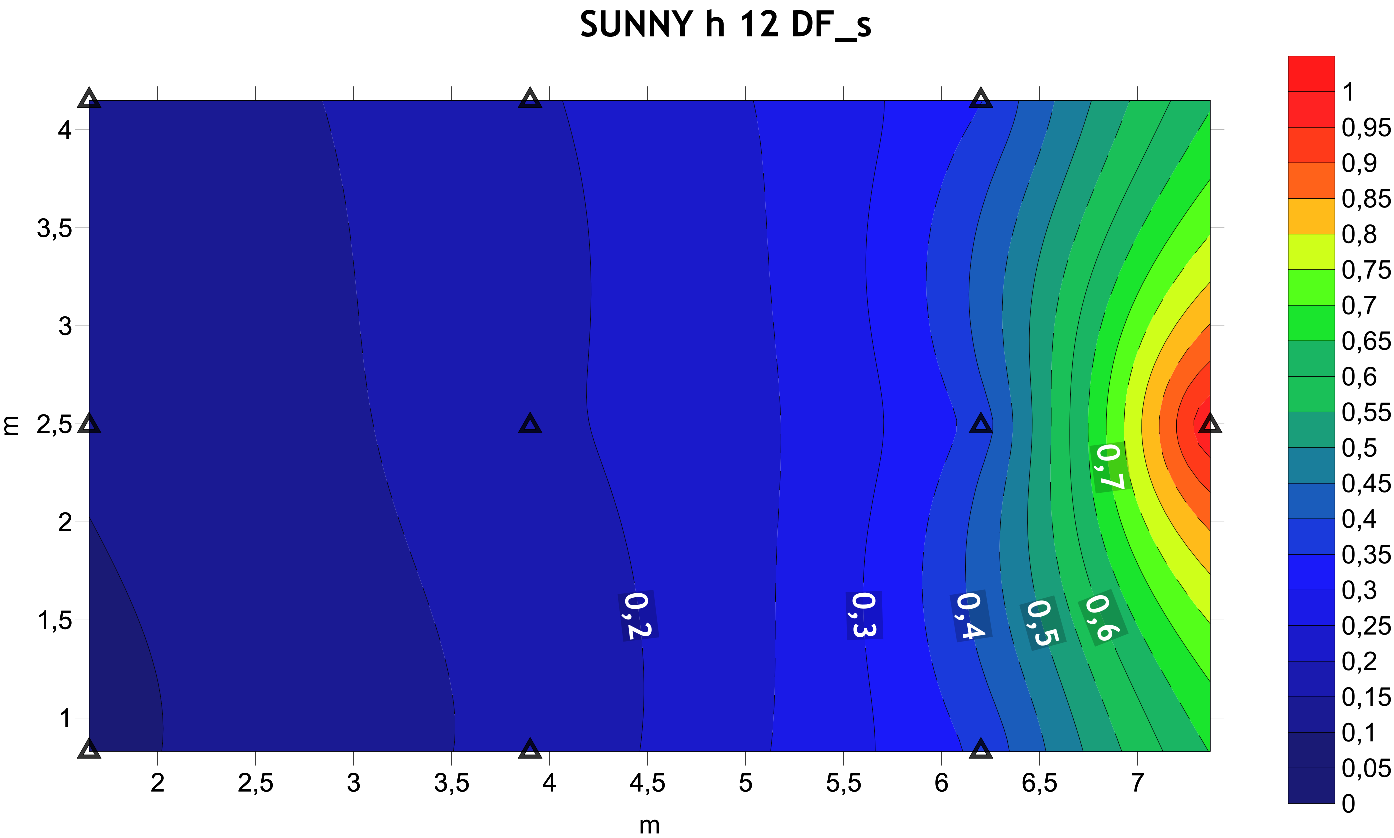
CLOUDY h 9 DF_m



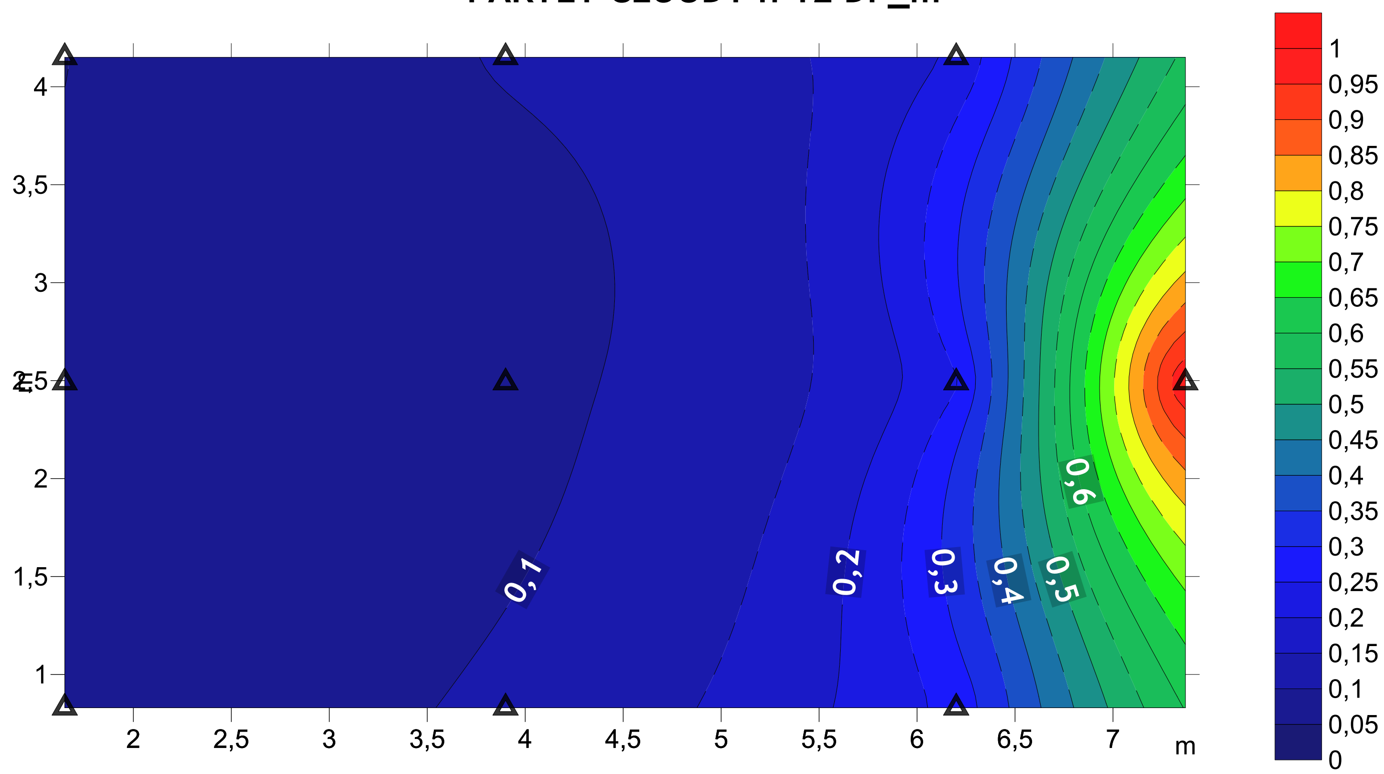
CLOUDY h 9 DF_s



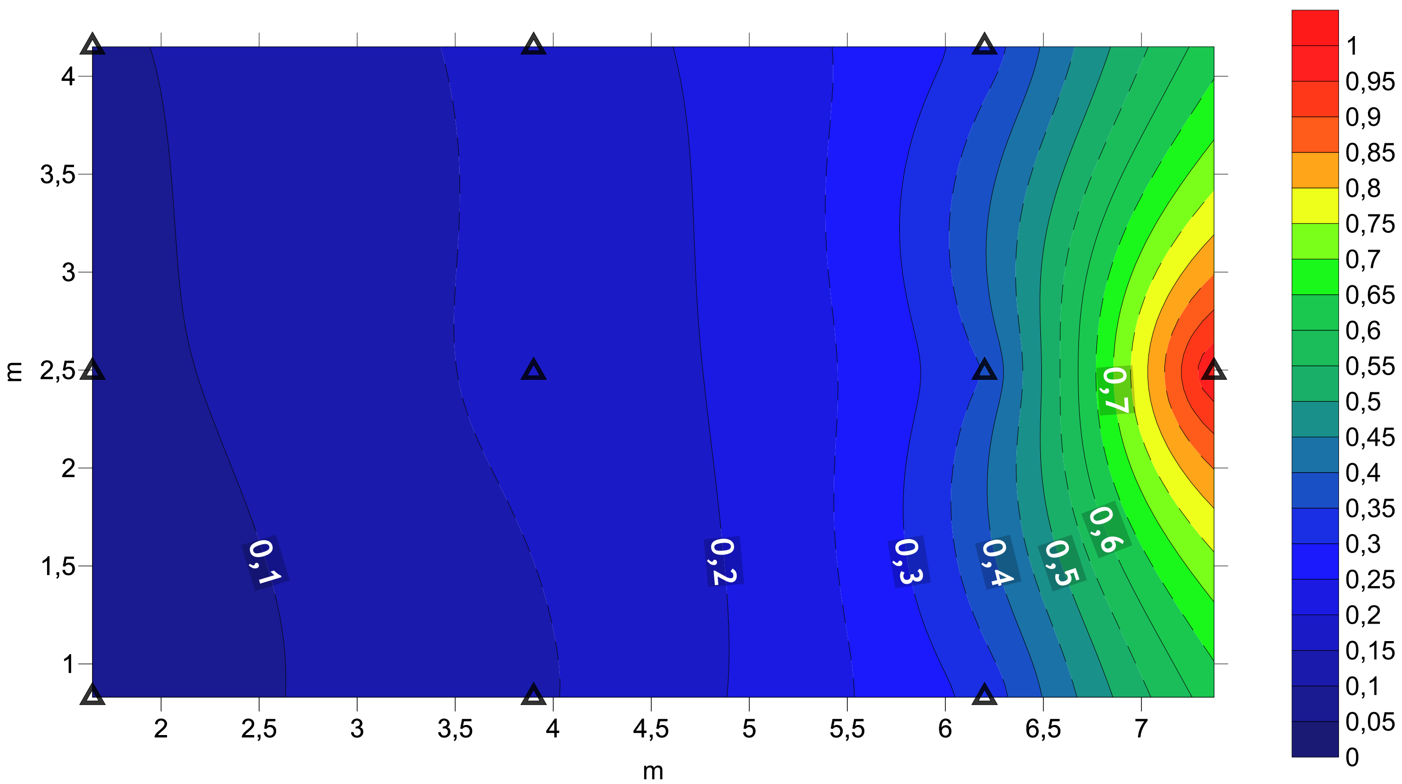

SUNNY h 12 DF_m
m
m
0,1
0,2
0,3
0,4
0,5
0,6


SUNNY h 12 DF_s
m
m
0,2
0,3
0,4
0,5
0,6
0,7

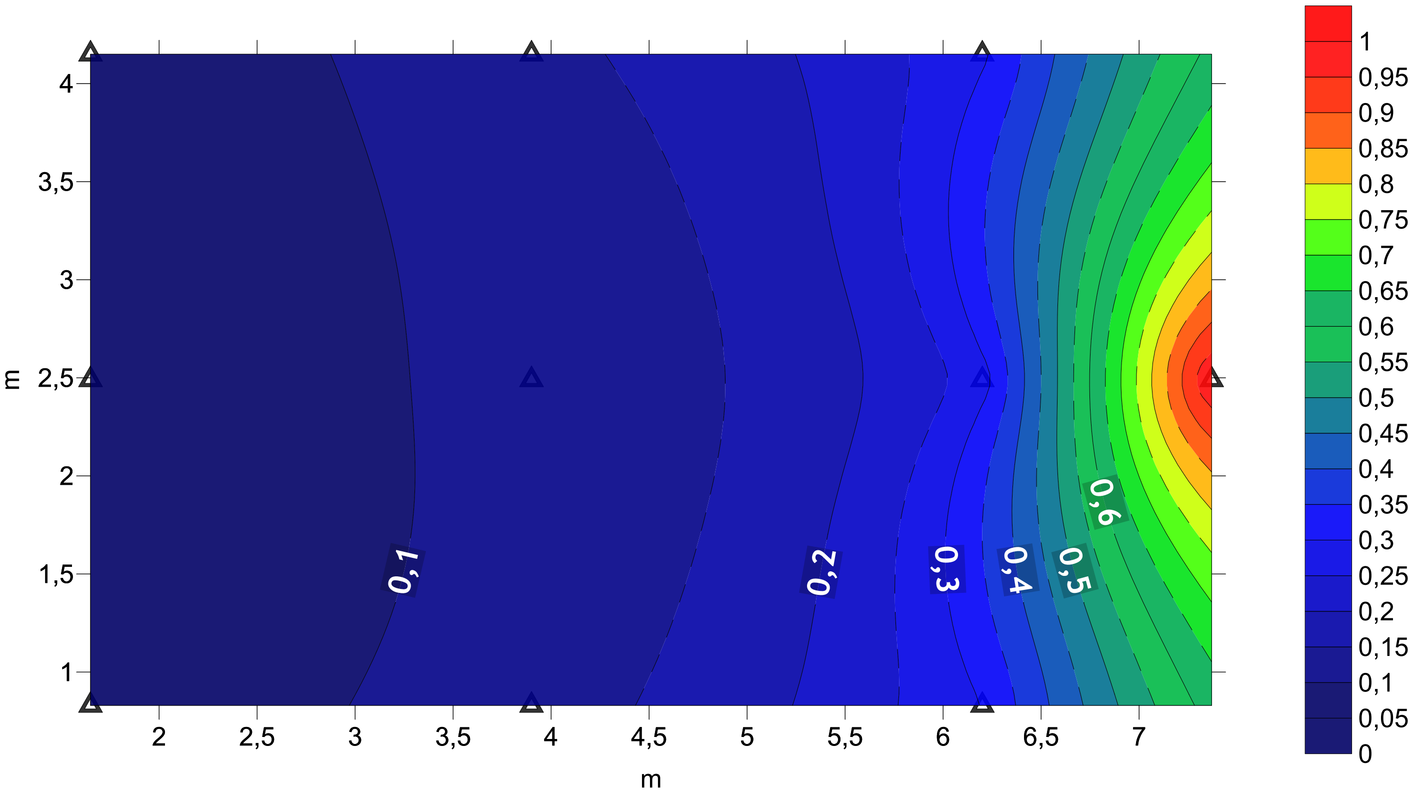
PARTLY CLOUDY h 12 DF_m



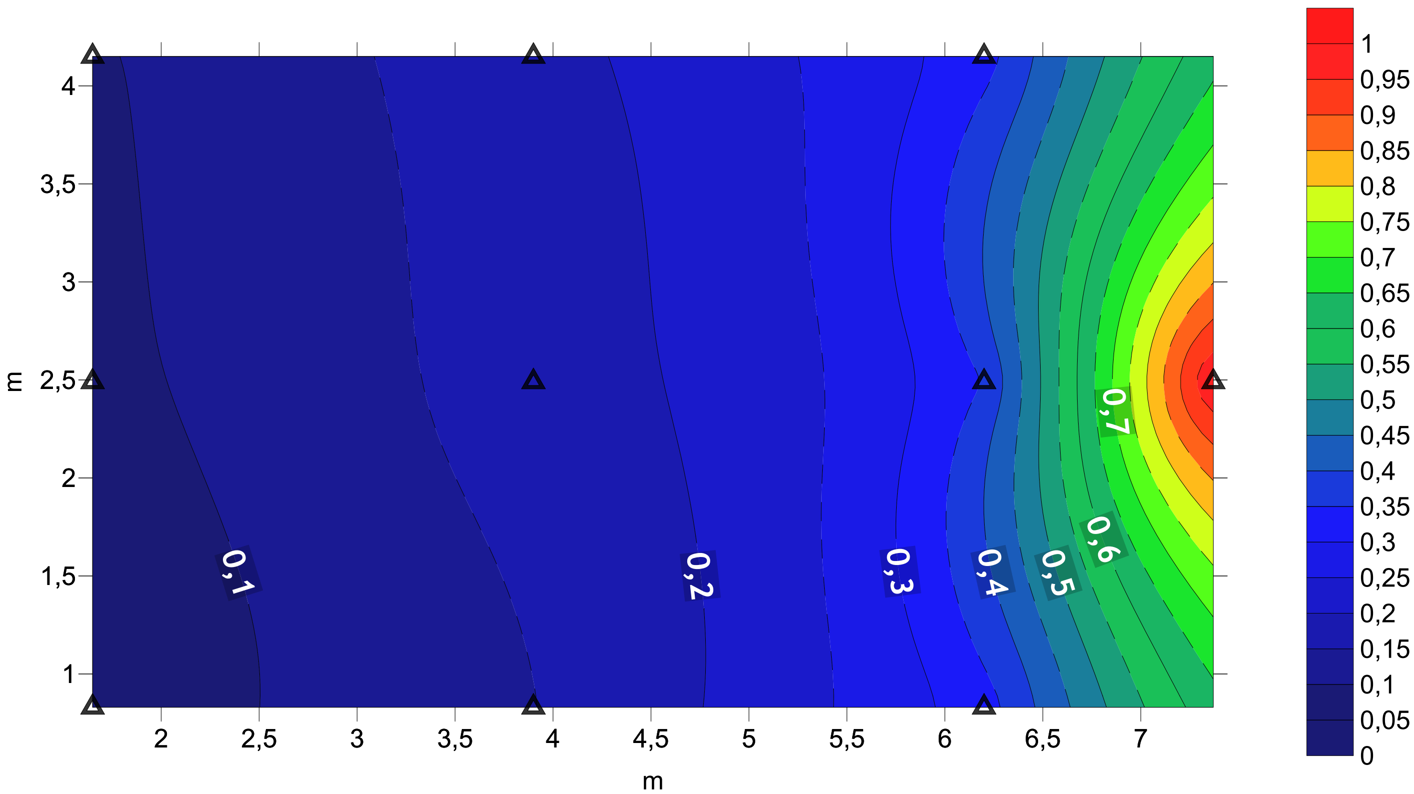
PARTLY CLOUDY h 12 DF_s

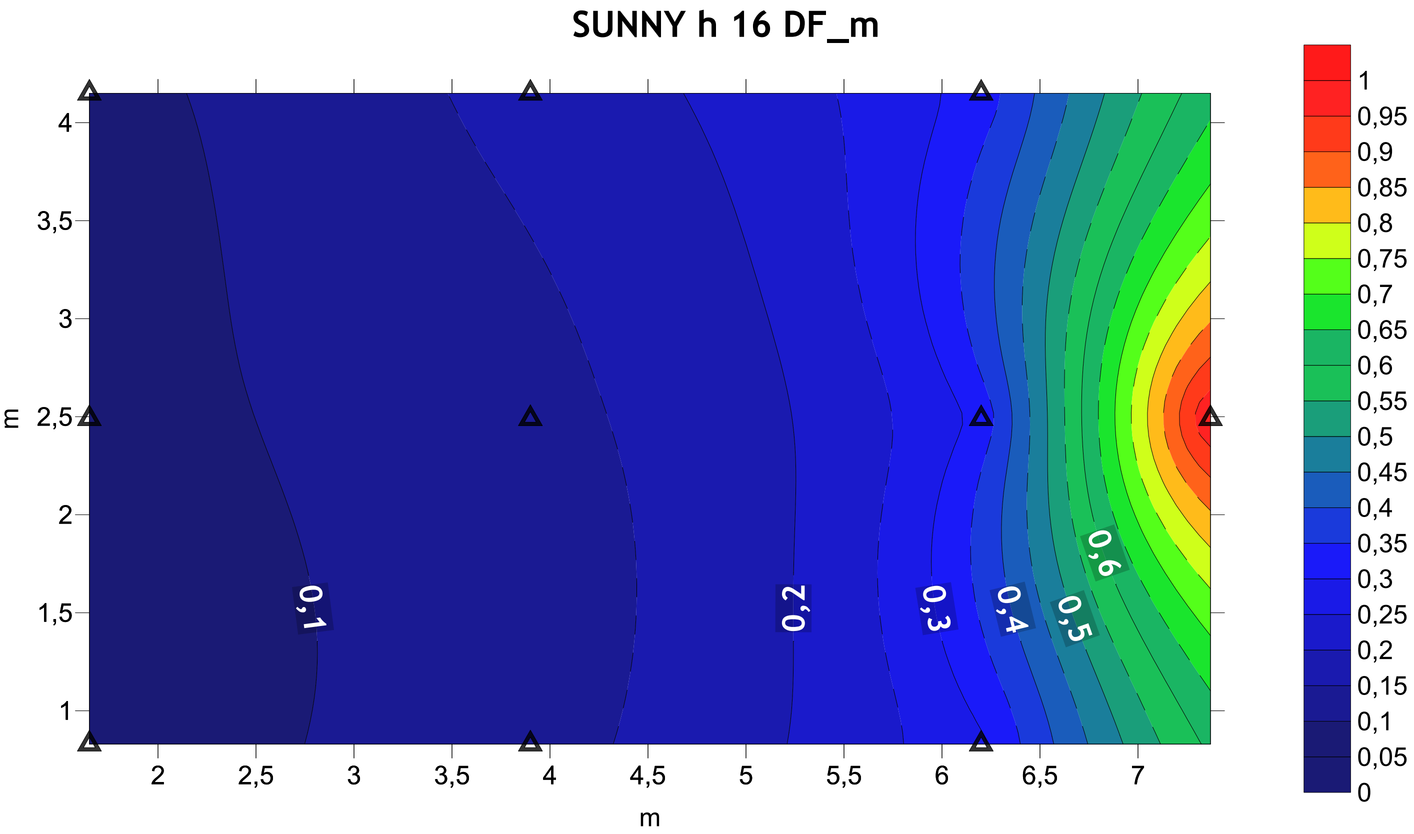


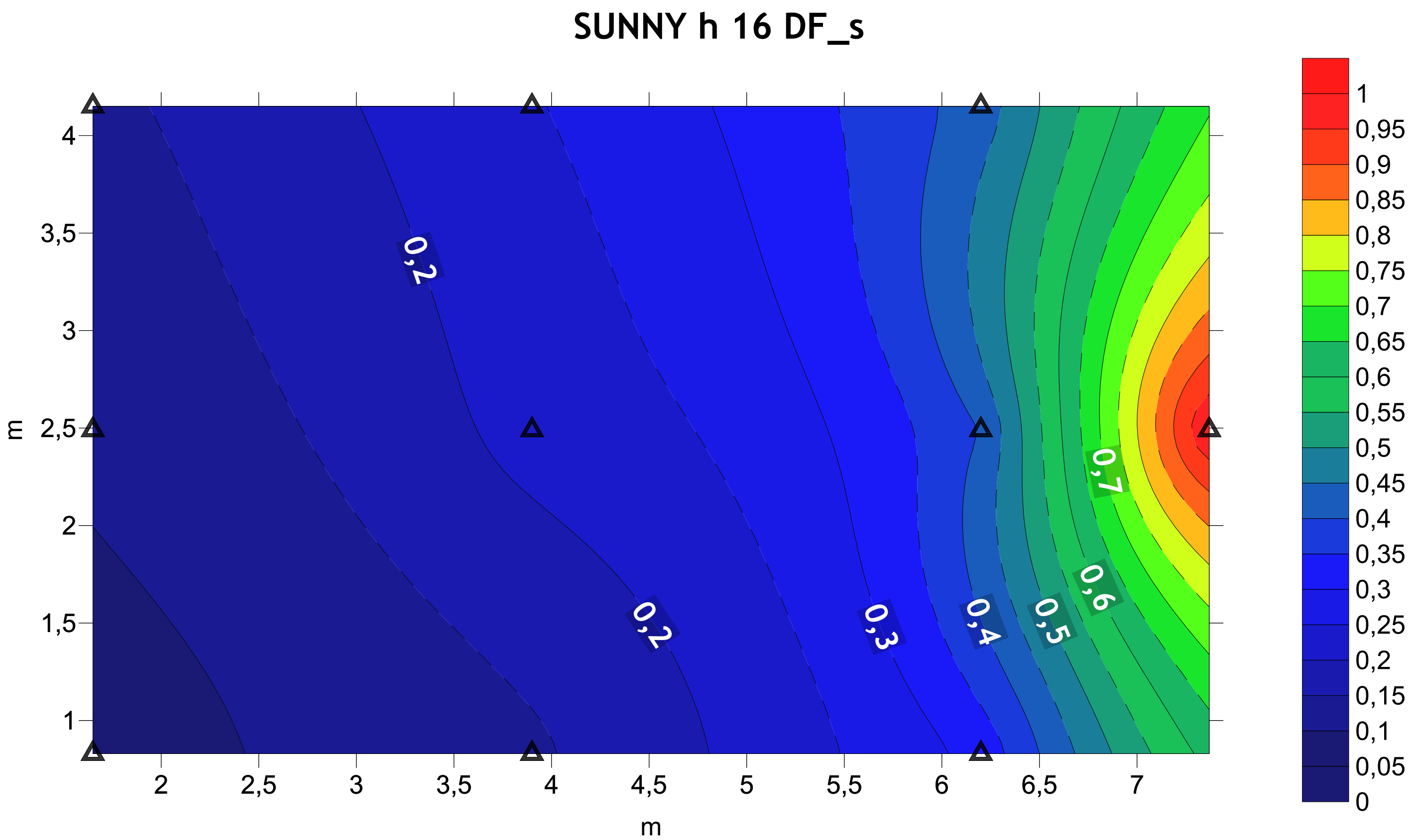
CLOUDY h 12 DF_m

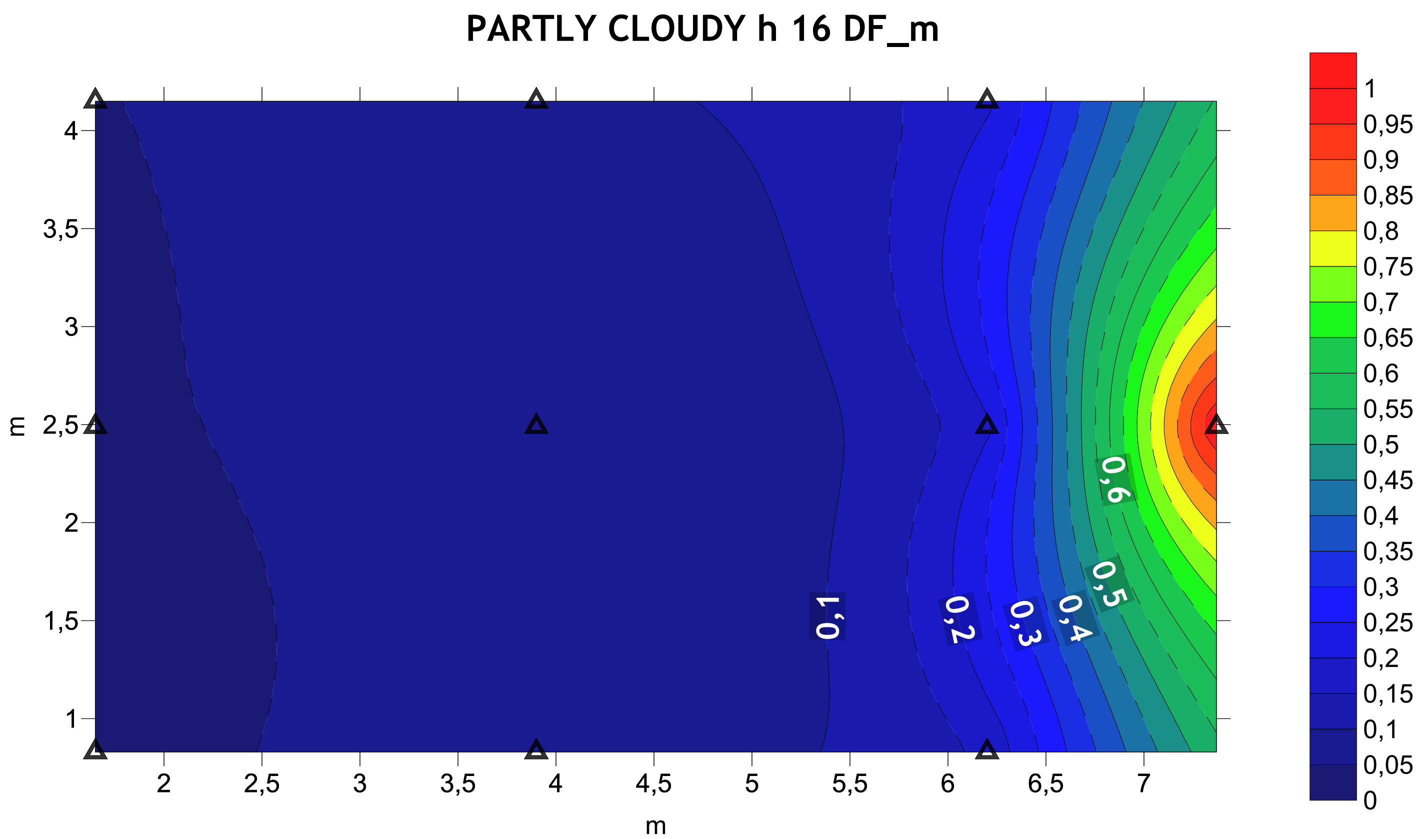


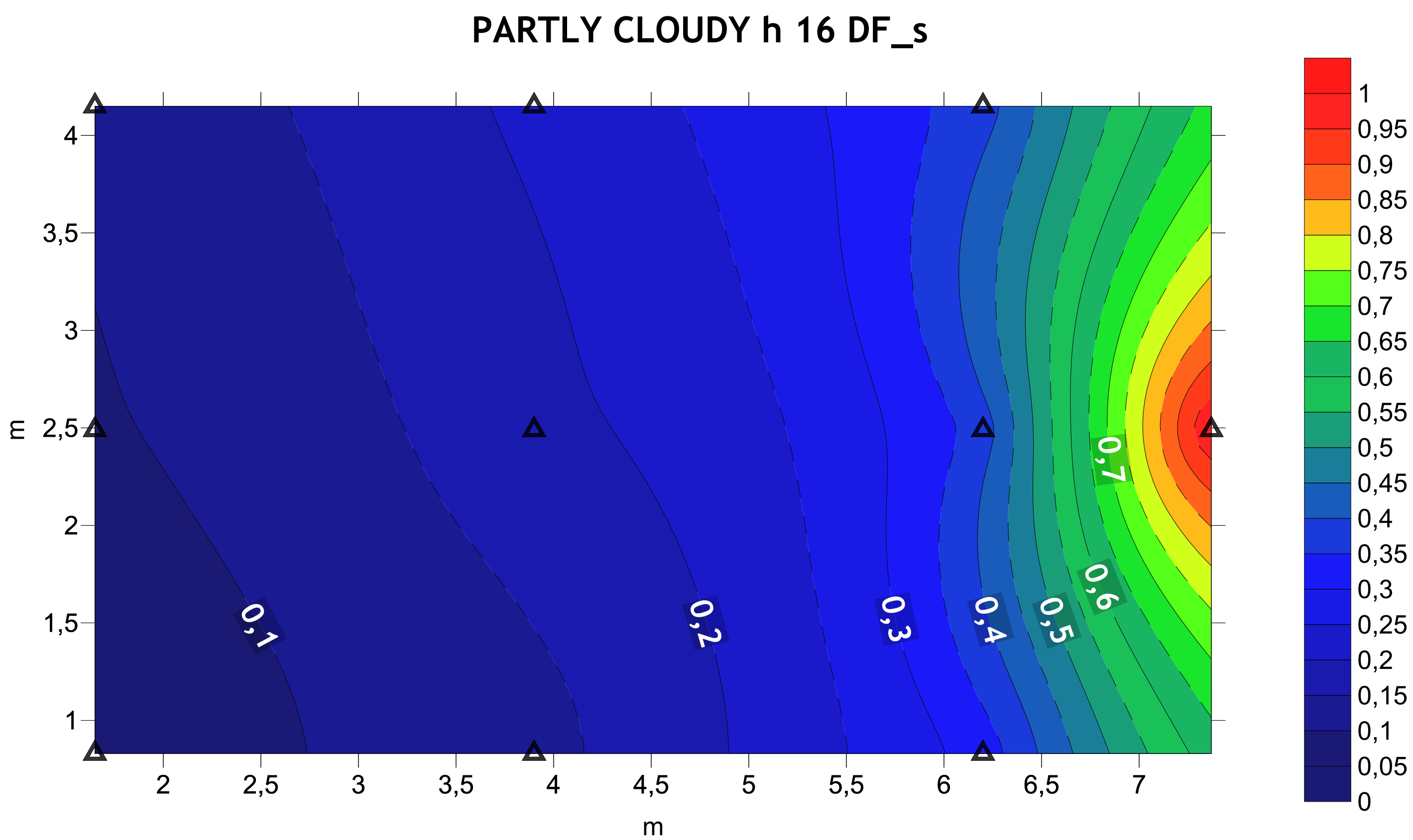
CLOUDY h 12 DF_s

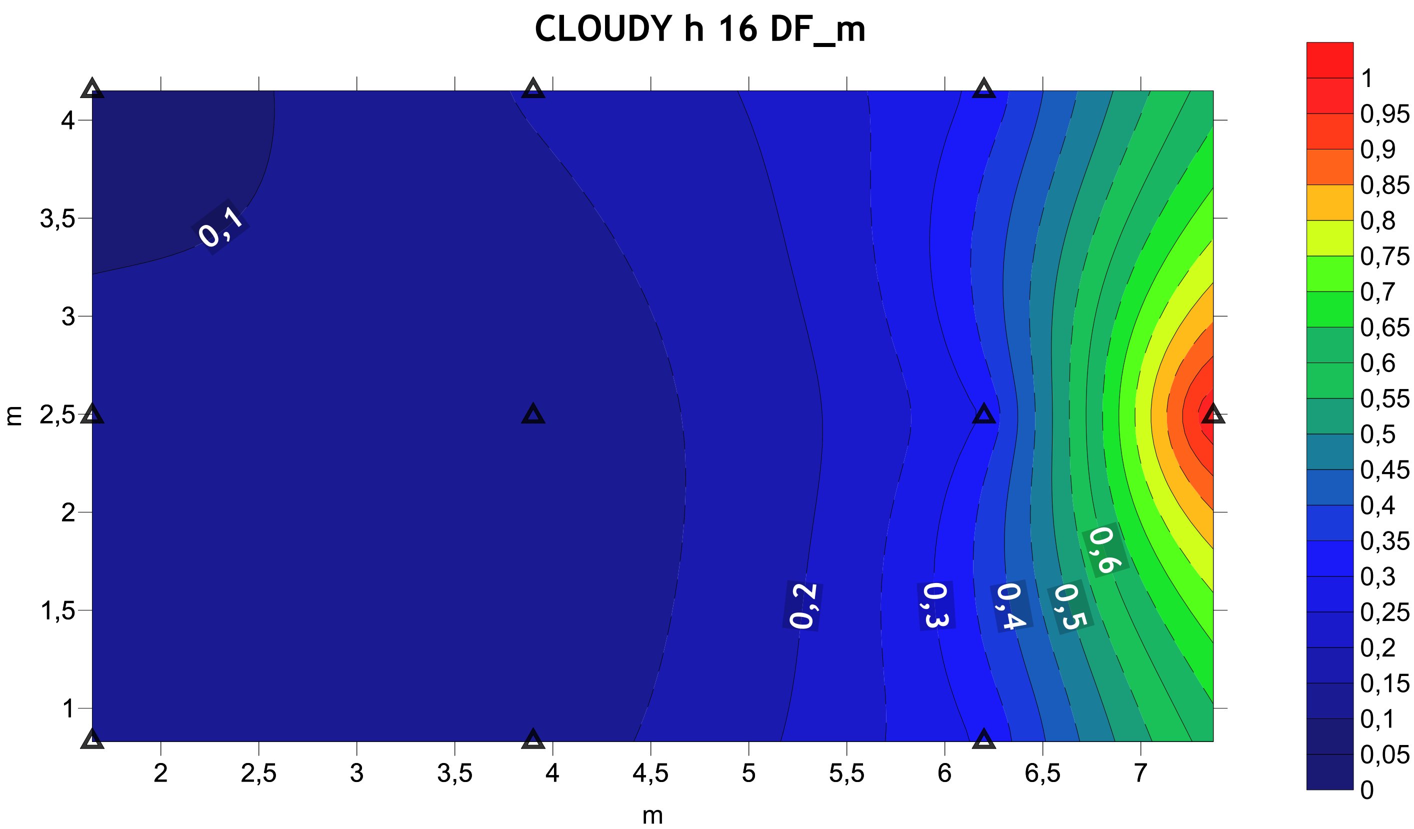


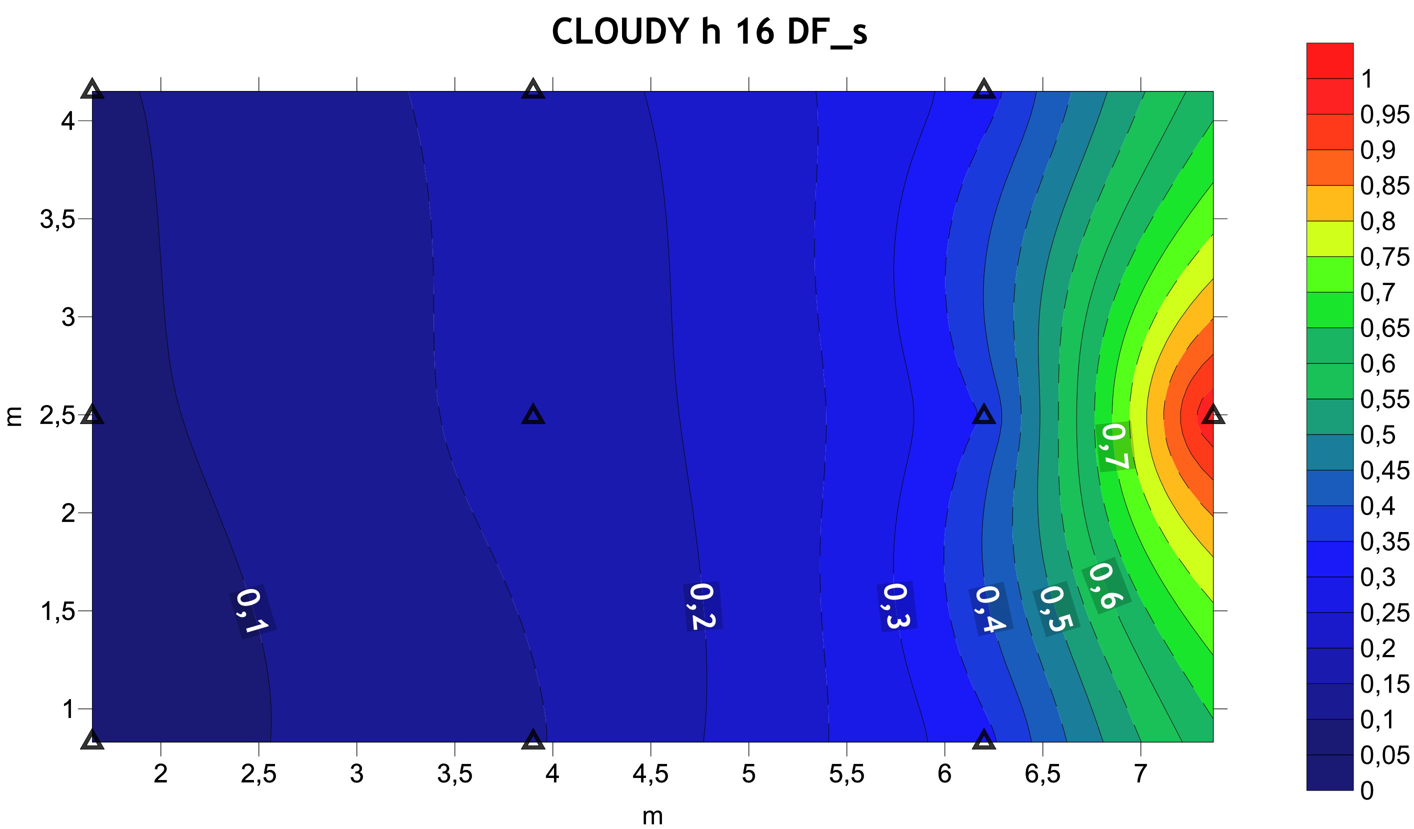

SUNNY h 16 DF_m
m
m
0,1
0,2
0,3
0,4
0,5
0,6

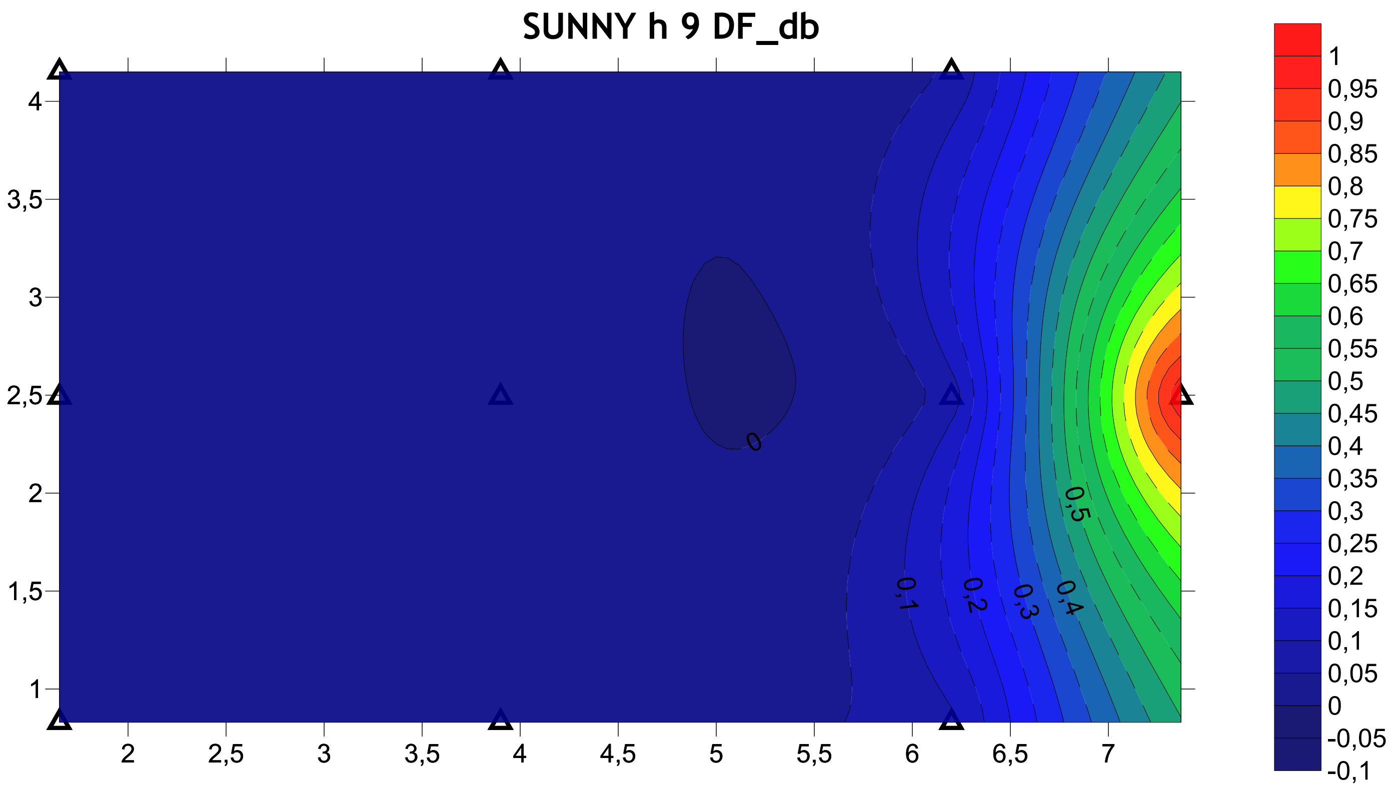

SUNNY h 16 DF_s
m
m
0,2
0,2
0,3
0,4
0,5
0,6
0,7

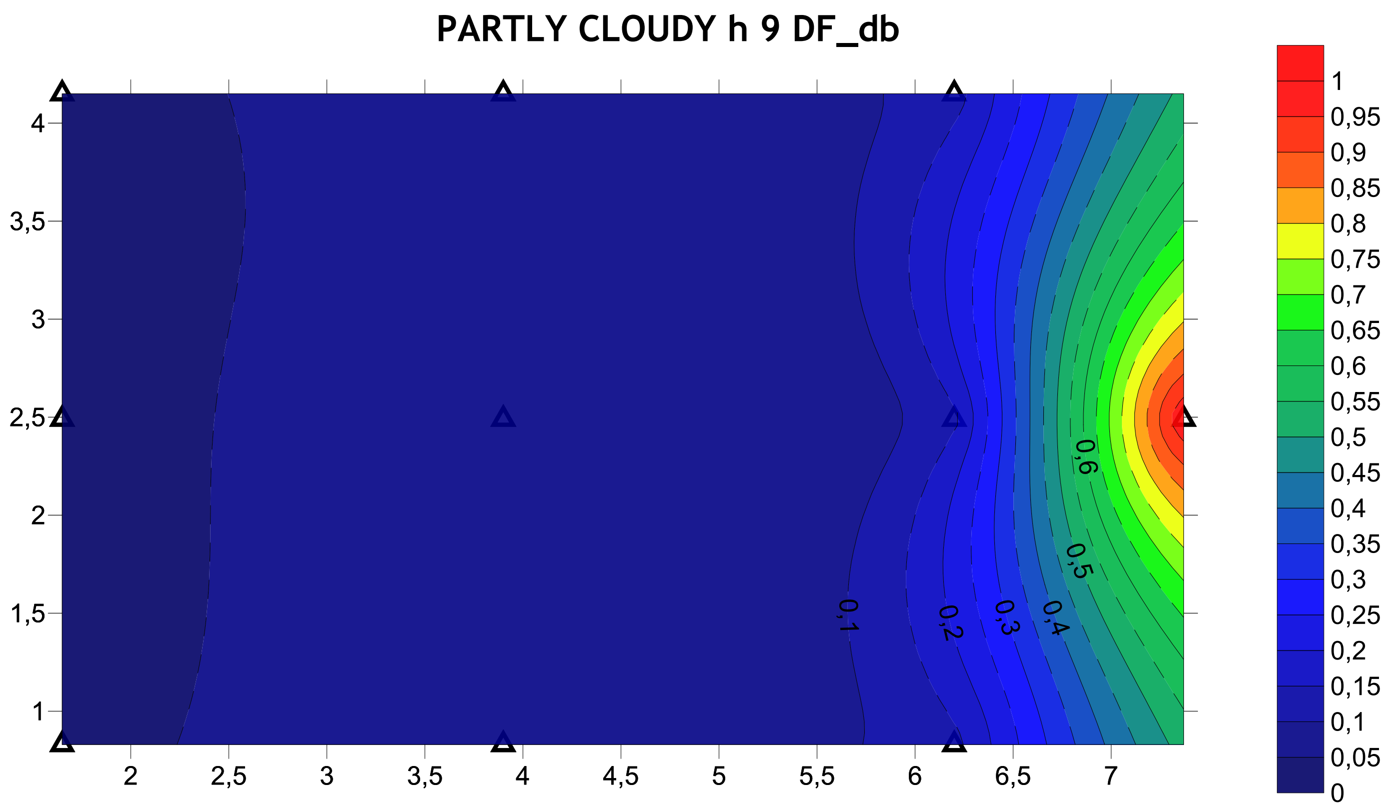

PARTLY CLOUDY h 16 DF_m
m
m
0,1
0,2
0,3
0,4
0,5
0,6

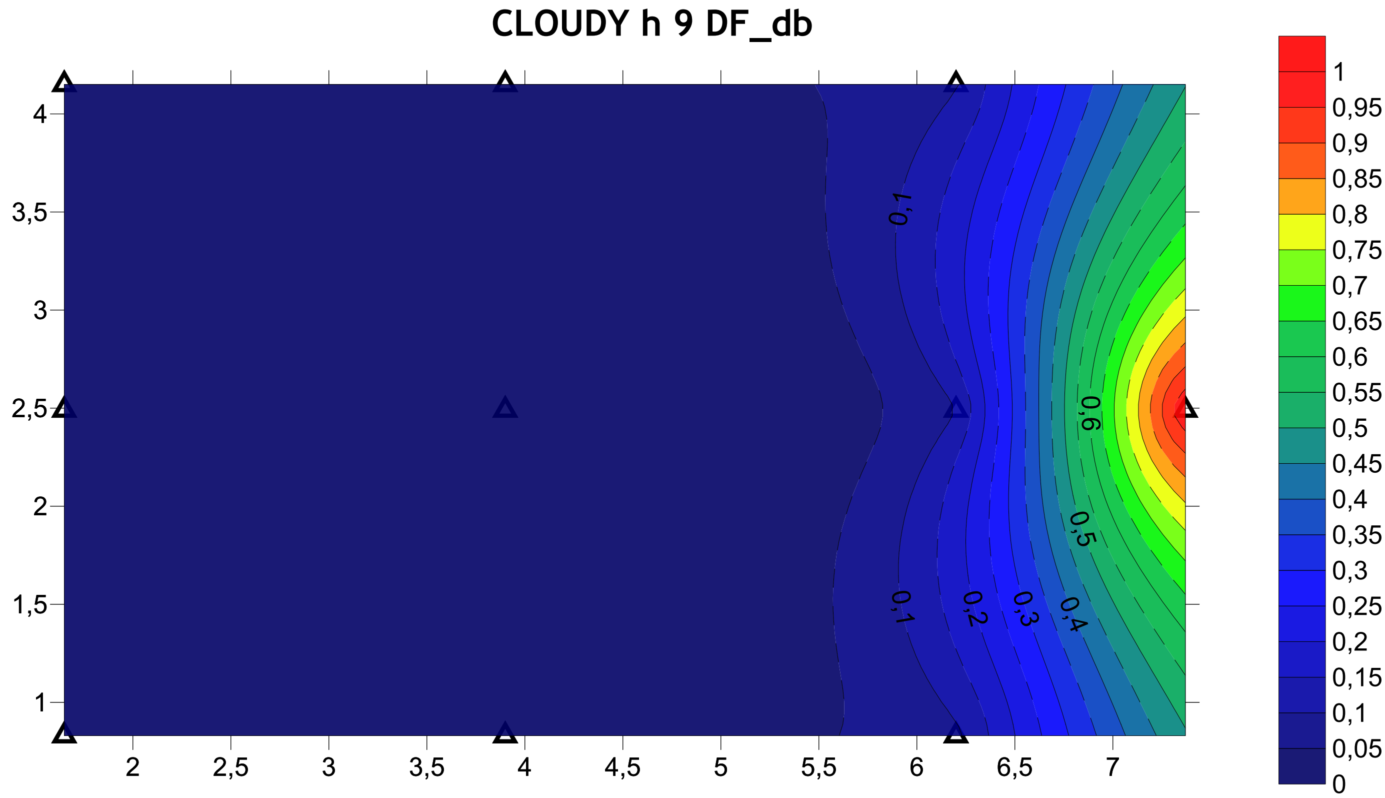

PARTLY CLOUDY h 16 DF_s
m
m
0,1
0,2
0,3
0,4
0,5
0,6
0,7


CLOUDY h 16 DF_m
m
m
0,1
0,2
0,3
0,4
0,5
0,6

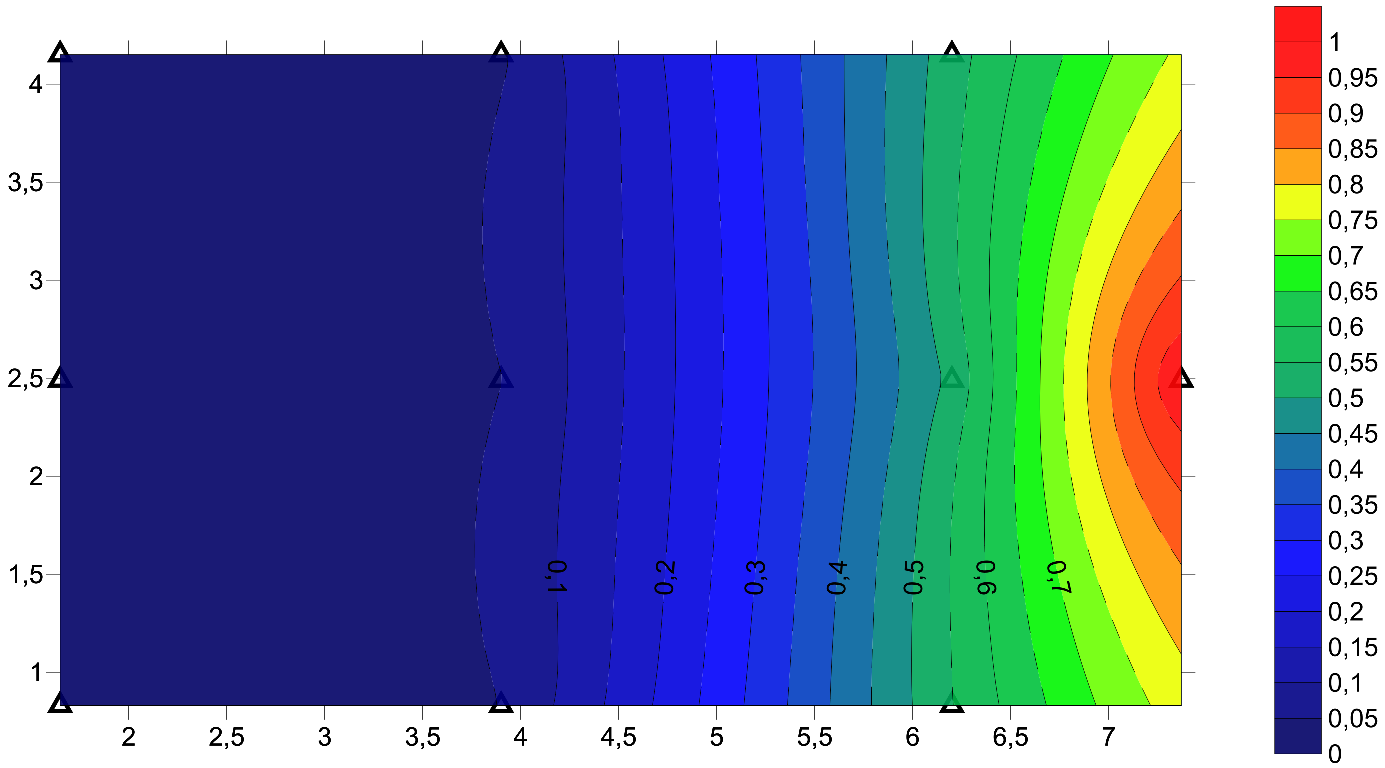

CLOUDY h 16 DF_s
m
m
0,1
0,2
0,3
0,4
0,5
0,6
0,7


SUNNY h 9 DF_db
0
0,1
0,2
0,3
0,4
0,5
1
0,95
0,9
0,85
0,8
0,75
0,7
0,65
0,6
0,55
0,5
0,45
0,4
0,35
0,3
0,25
0,2
0,15
0,1
0,05
0
-0,05
-0,1

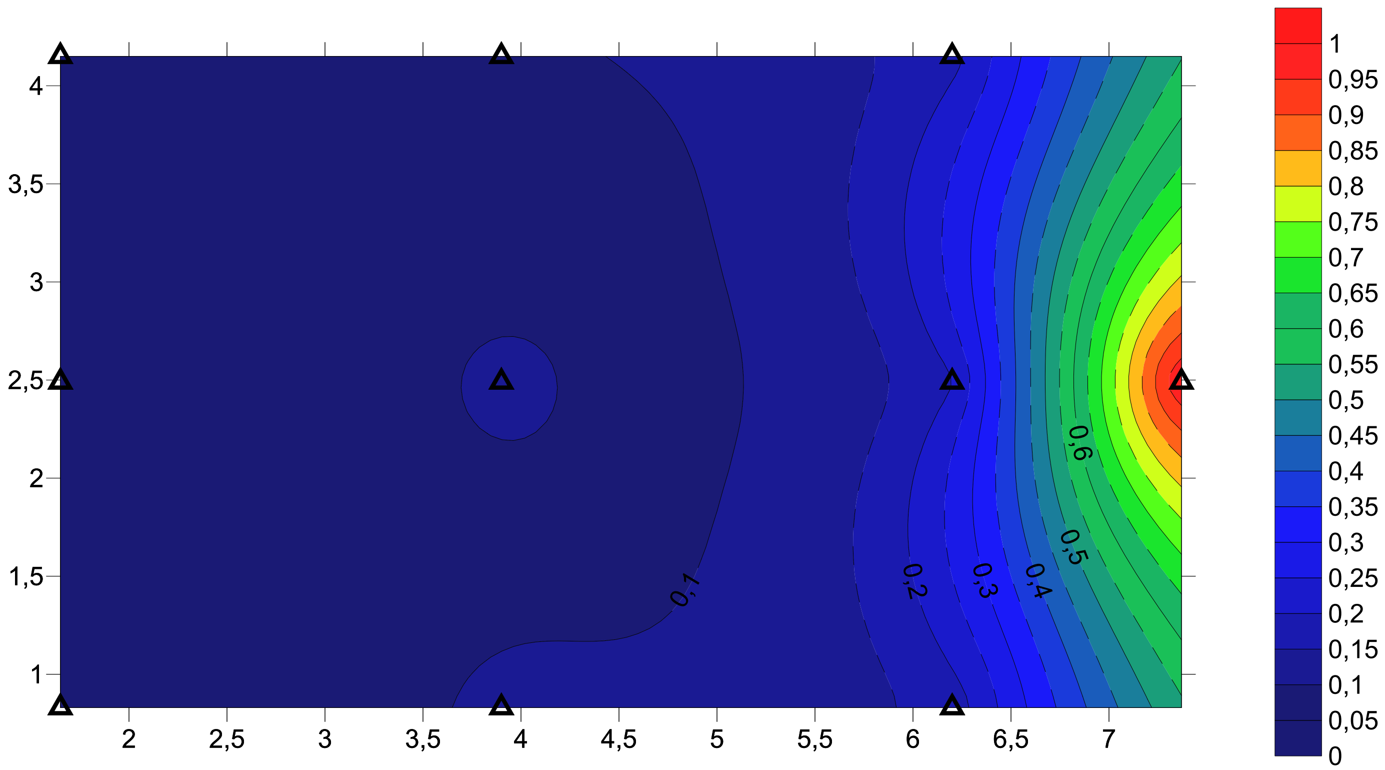

PARTLY CLOUDY h 9 DF_db
0,1
0,2
0,3
0,4
0,5
0,6
1
0,95
0,9
0,85
0,8
0,75
0,7
0,65
0,6
0,55
0,5
0,45
0,4
0,35
0,3
0,25
0,2
0,15
0,1
0,05
0


CLOUDY h 9 DF_db
4
3,5
3
2,5
2
1,5
1
2
2,5
3
3,5
4
4,5
5
5,5
6
6,5
7
0,1
0,2
0,3
0,4
0,5
0,6
1
0,95
0,9
0,85
0,8
0,75
0,7
0,65
0,6
0,55
0,5
0,45
0,4
0,35
0,3
0,25
0,2
0,15
0,1
0,05
0

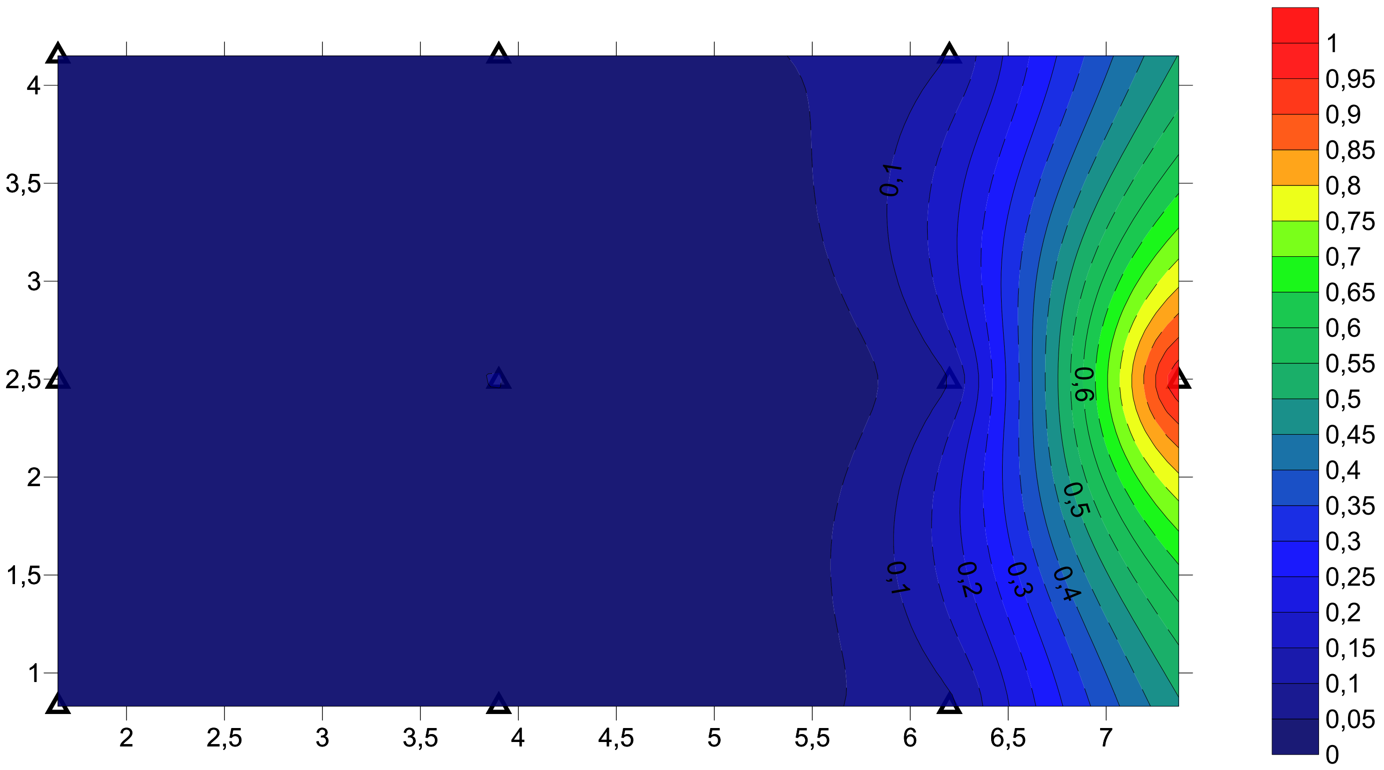
SUNNY h 12 DF_db



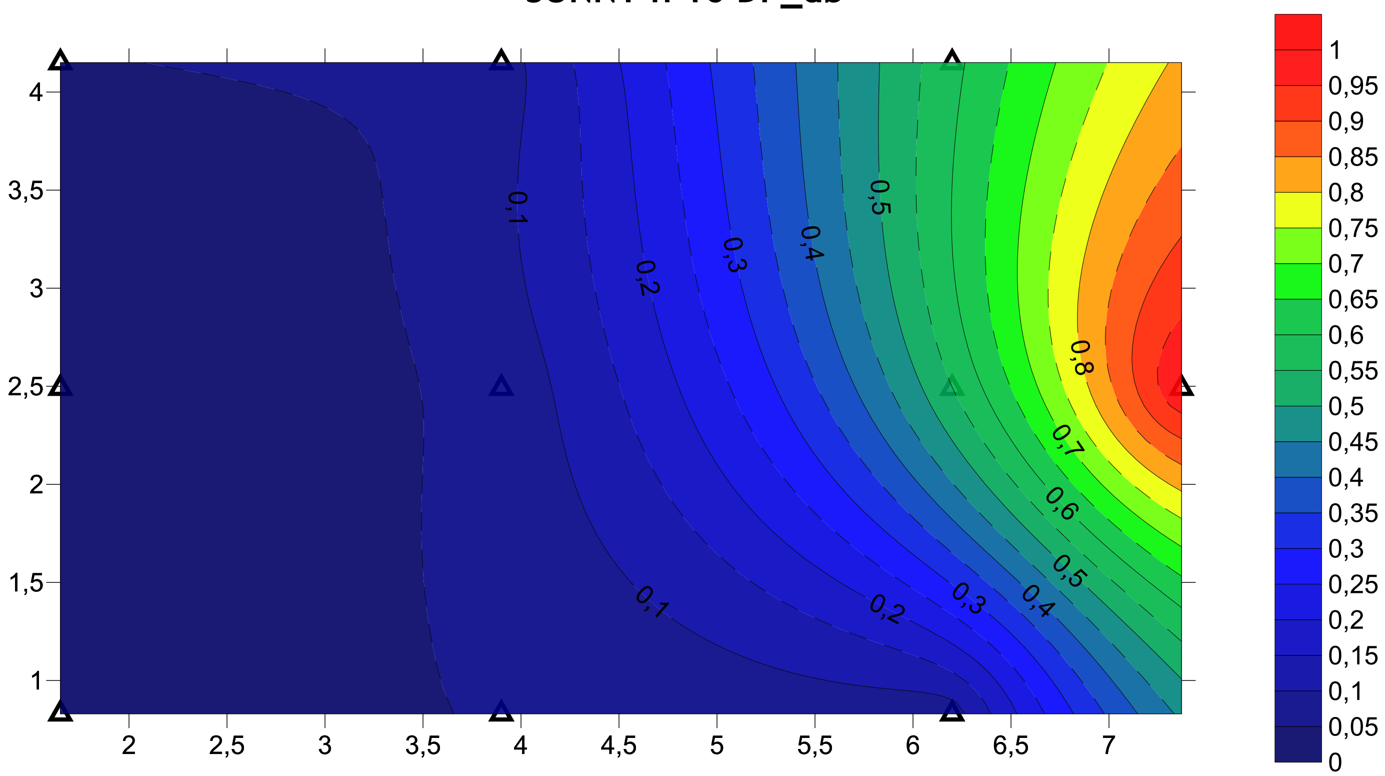
PARTLY CLOUDY h 12 DF_db



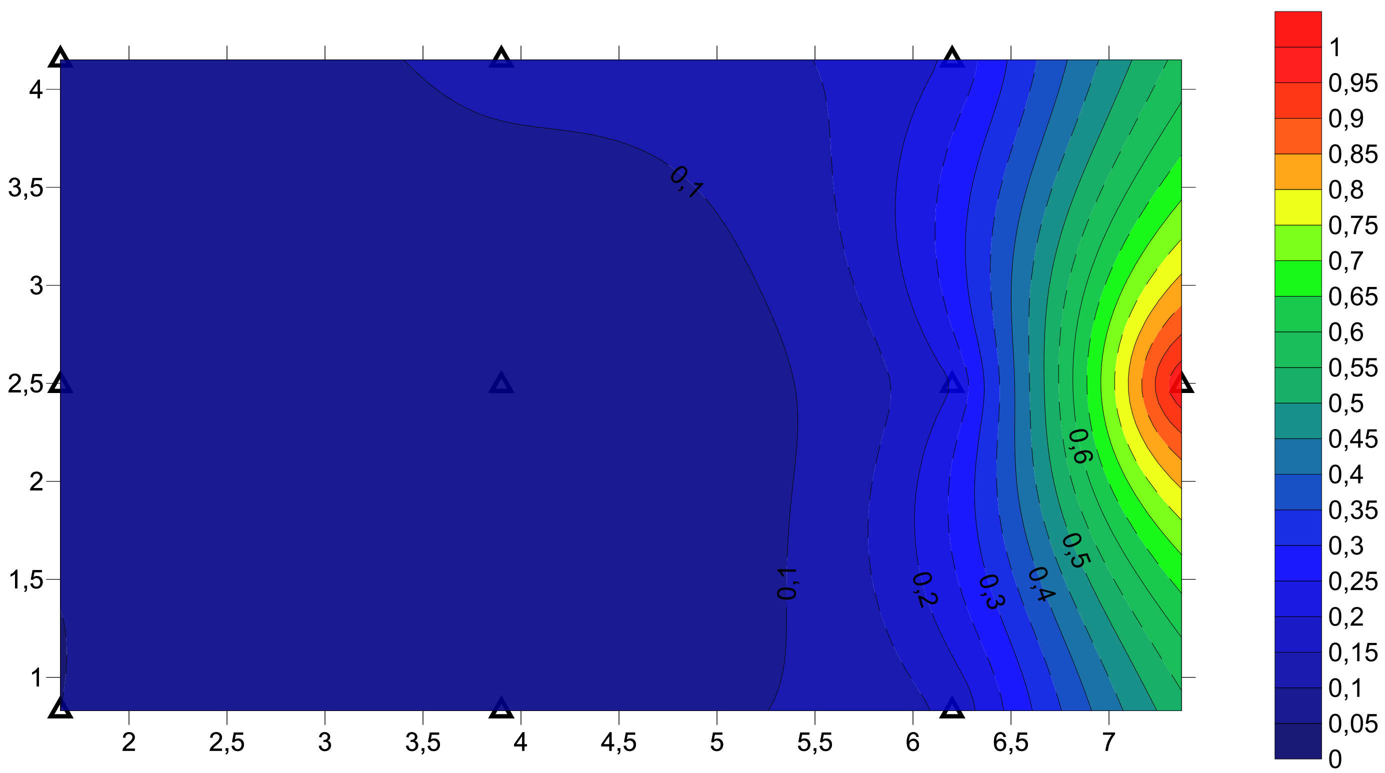
CLOUDY h 12 DF_db



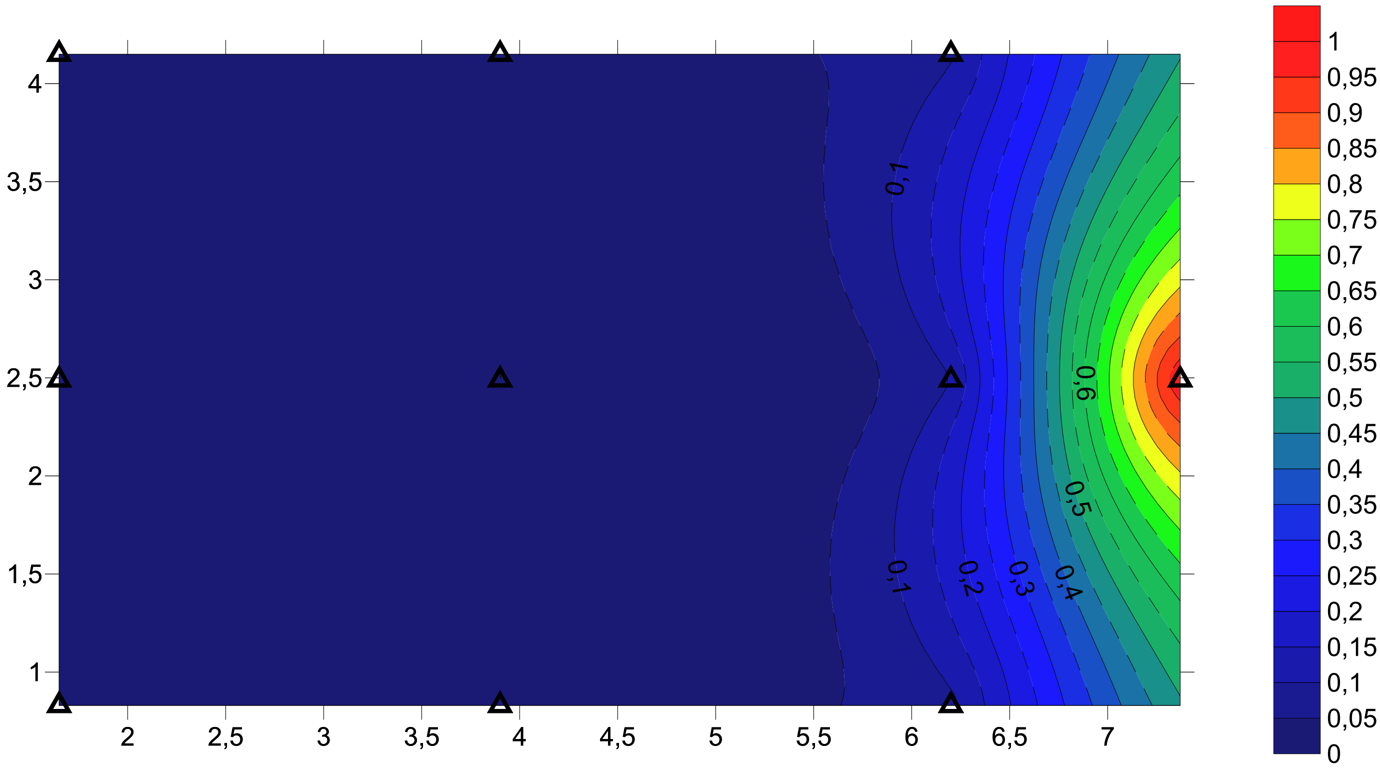
SUNNY h 16 DF_db



PARTLY CLOUDY h 16 DF_db



CLOUDY h 16 DF_db

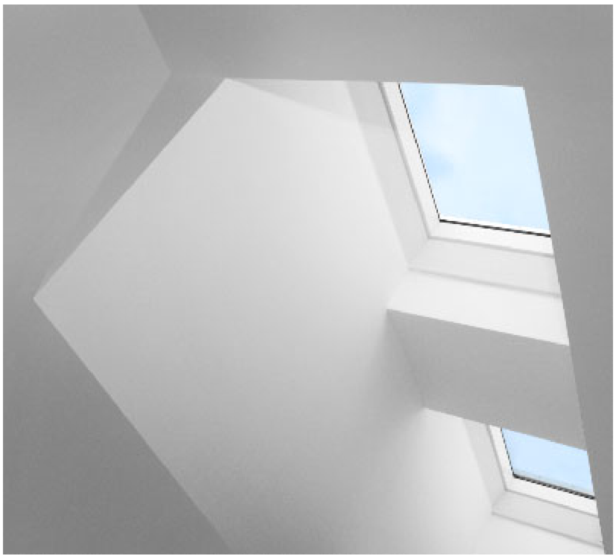


Attachment E

Data Sheets

Specifiche tecniche

Finestra per tetti piani VELUX CFP fissa con vetro piano



Descrizione del prodotto

- Finestra per tetti piani fissa
- Resistente all'acqua, telaio in PVC bianco
- Vetrata interna stratificata con trattamento basso-emissivo
- Vetrata esterna di rivestimento piana con trattamento auto-pulente, minimizza la necessità di pulizia del vetro esterno.
- Superfici senza necessità di manutenzione

Pendenza del tetto

- Può essere installata con pendenze comprese tra 2° e 15°

Materiali

- Basamento e battente in PVC estruso di colore bianco (RAL 9016)
- Vetro stratificato interno
- Isolamento interno in polistirene
- Vetro temprato esterno di rivestimento con bordo serigrafato e profili perimetrali in alluminio estruso

Per le istruzioni di installazione, dettagli tecnici CAD, voci di capitolato, consultare il sito www.velux.it

Indice Scheda Tecnica

Garanzia

10 ANNI GARANZIA

VELUX garantisce la produzione in fabbriche certificate ISO 9001 e ISO 14001

VELUX®

Dimensioni disponibili e vetro visibile

	600 mm	800 mm	900 mm	1000 mm	1200 mm	1500 mm
600 mm	**CFP 060060** (0.19)					
800 mm		**CFP 080080** (0.40)				
900 mm	**CFP 060090** (0.32)		**CFP 090090** (0.54)			
1000 mm				**CFP 100100** (0.70)		
1200 mm			**CFP 090120** (0.76)		**CFP 120120** (1.07)	
1500 mm				**CFP 100150** (1.11)		

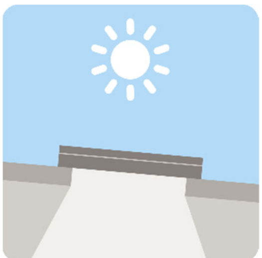
( ) = Vetro visibile, m^2

Dimensioni per finitura interna

Misura	Dimensioni interne (mm)
060060	559x559
080080	759x759
060090	559x859
090090	859x859
090120	859x1159
100100	959x959
100150	959x1459
120120	1159x1159

Dimensioni del foro

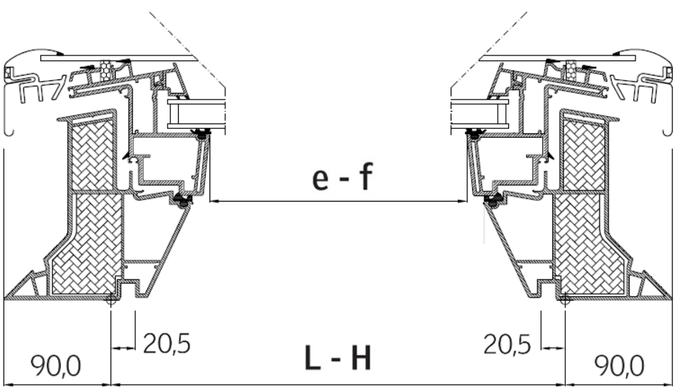
Misura	L x H (mm)
060060	600x600
080080	800x800
060090	600x900
090090	900x900
090120	900x1200
100100	1000x1000
100150	1000x1500
120120	1200x1200



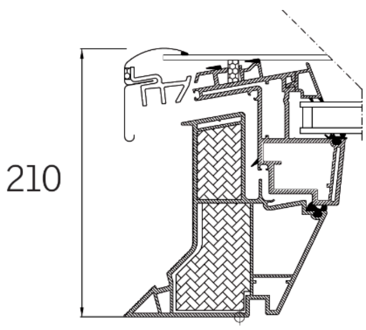
La finestra per tetti piani VELUX CVP fissa con vetro piano

- È fissa – non è possibile l'apertura per la ventilazione
- conferisce un'estetica elegante al contesto nel quale viene inserito ed un integrazione nella copertura
- Può essere inserita in combinazione con la finestra per tetti piani apribile elettricamente e manualmente

Dettaglio tecnico di prodotto (Sezione trasversale)



Dettaglio tecnico di prodotto (Altezza)



Caratteristiche dimensionali	Misure							
	060060	**060090**	**080080**	**090090**	**090120**	**100100**	**100150**	**120120**
Vetro visibile (e x f) in mm	435x435	435x735	635x635	735x735	735x1035	835x835	835x1335	1035x1035
Vetro visibile (e x f) in m²	0.19	0.32	0.40	0.54	0.76	0.70	1.11	1.07

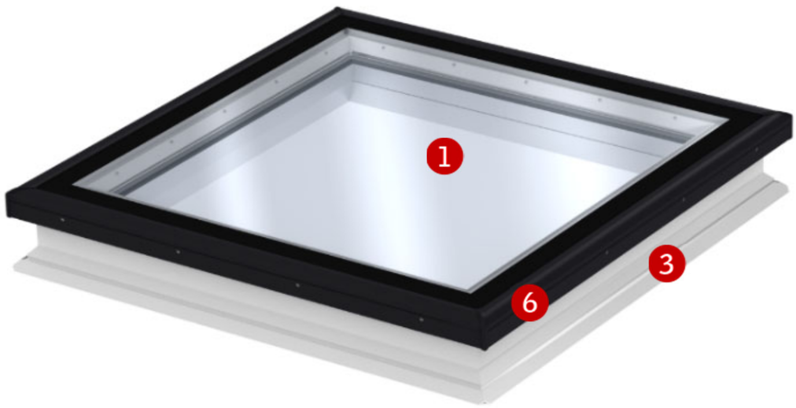
Prestazioni tecniche

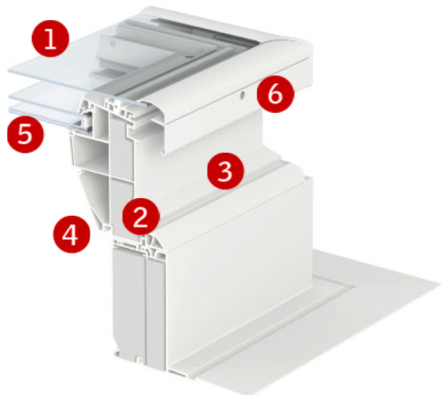
	Vetro bassoemissivo –73U	**Vetro stratificato antieffrazione –73QV**
	Vetro piano esterno ISD 2093	**Vetro piano esterno ISD 2093**
Trasmittanza Termica infisso [W/m²K]	$U_{rc,ref300}$ =0.87 $A_{rc,ref300}$: 3,4m² (EN 1873:2014)	$U_{rc,ref300}$ =0.79 $A_{rc,ref300}$: 3,4m² (EN 1873:2014)
R_w [dB]	36	36
g [ ]	0.54	0.52
τ_v [ ]	0.72	0.72
Permeabilità all'aria [classe]	3	3

Composizione vetrate

	Vetro bassoemissivo –73U	**Vetro stratificato antieffrazione –73QV**
Vetro interno	2 x 3 mm stratificato di sicurezza con due pellicole di PVB interno (0,76 mm)	2 x 3 mm stratificato di sicurezza con quattro pellicole di PVB interno (1,52 mm) con trattamento bassoemissivo
Vetro esterno	4 mm con trattamento bassoemissivo	4 mm con trattamento bassoemissivo
Intercapedine	14.5 mm	14.5 mm
Tipo di vetro	Doppio (Argon)	Doppio (Argon)

Caratteristiche





1 Vetro piano esterno

- 4 mm temprata
- Riduzione del rumore da impatto per un eccellente isolamento acustico
- Protezione delle vetrata stratificata sottostante
- Trattamento autopulente

2 Isolamento

- Telaio isolato con polistirene per una migliore performance

3 Telaio

- Basamento in PVC estruso
- Facilità di pulizia
- Non necessita manutenzione

4 Finitura interna

- Scalanatura di rivestimento per la realizzazione di un imbotte di finitura interna

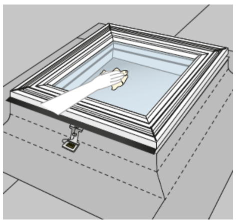
5 Vetrata interna

- Vetrata stratificata di sicurezza nella variante standard o antieffrazione

6 Fissaggio

- Guarnizioni, viti e staffe fornite per un corretto fissaggio del vetro piano

Pulizia e manutenzione



Per la pulizia del vetro piano di rivestimento è sufficiente semplice acqua. Non applicare i normali detergenti.

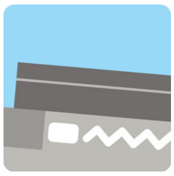
Per la pulizia del vetro stratificato sul lato esterno è necessario rimuovere il vetro piano dal telaio.

Vetro piano di rivestimento

Vetro piano:

- alta trasmissione della luce per ambienti con esigenze visive
- resistenza ai graffi
- massima integrazione nella copertura

Schermature



Schermature interne

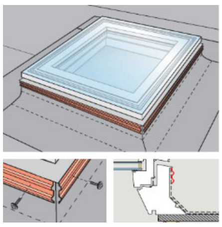
Tenda filtrante plissettata ★
Tenda oscurante plissettata ▲

★ Disponibile nella versione elettrica
▲ Disponibile nella versione ad energia solare

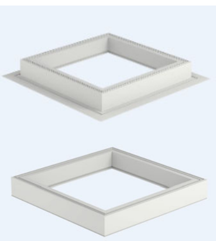
Finitura interna

Profili in PVC bianchi	NCS standard: S 0500-N, RAL standard: 9016

Accessori



Profili blocca guaina ZZZ 210 per il fissaggio meccanico dell'impermeabilizzazione sul prodotto.



Rialzo opzionale con basamento ZCE 0015 per un'altezza aggiuntiva del telaio di 15cm.

Rialzo opzionale senza basamento ZCE 1015 può essere combinato con il rialzo ZCE 0015 per ottenere altezza aggiuntiva del telaio superiore a 30cm.

Un rialzo ZCE 0015 può essere combinato con massimo tre ZCE 1015.

Prodotti elettrici

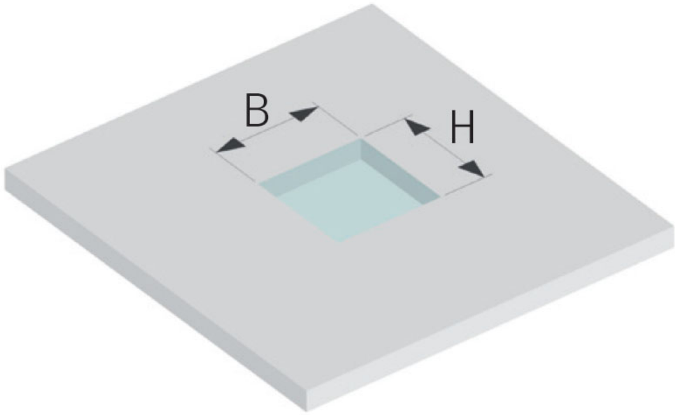
KUX 110	Unità di alimentazione per schermature interne elettriche

Note

Per ulteriori informazioni in merito a questo o ad altri prodotti della gamma VELUX consultare velux.it

Predisposizione del foro strutturale in cantiere

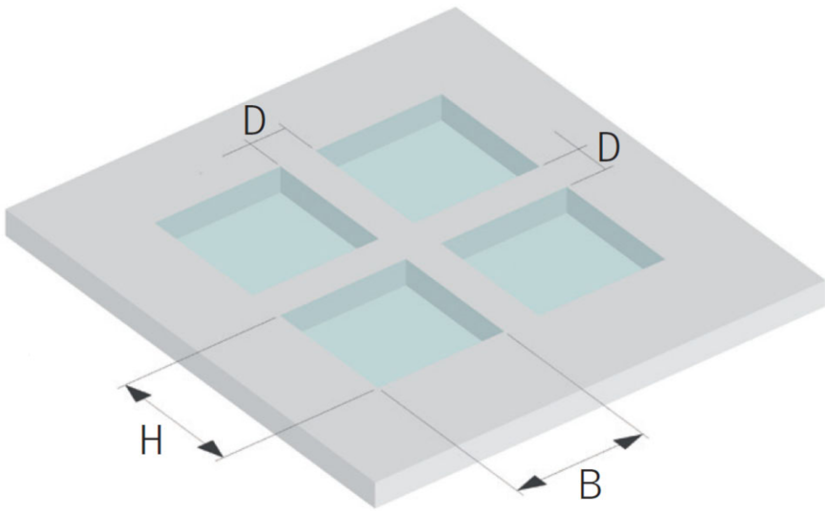
In caso di soluzione singola seguire le indicazioni in tabella in base alla misura scelta.



Dimensioni foro strutturale

Misura	B x H (cm)
060060	60x60
060090	60x90
080080	80x80
090090	90x90
090120	90x120
100100	100x100
100150	100x150
120120	120x120

In caso di soluzioni in combinazione seguire le indicazioni in tabella in base alla misura scelta.



Dimensioni foro strutturale

Misura	B x H (cm)	Distanza D minima tra i fori (cm)
060060	60x60	25
060090	60x90	
080080	80x80	
090090	90x90	
090120	90x120	
100100	100x100	
100150	100x150	
120120	120x120	