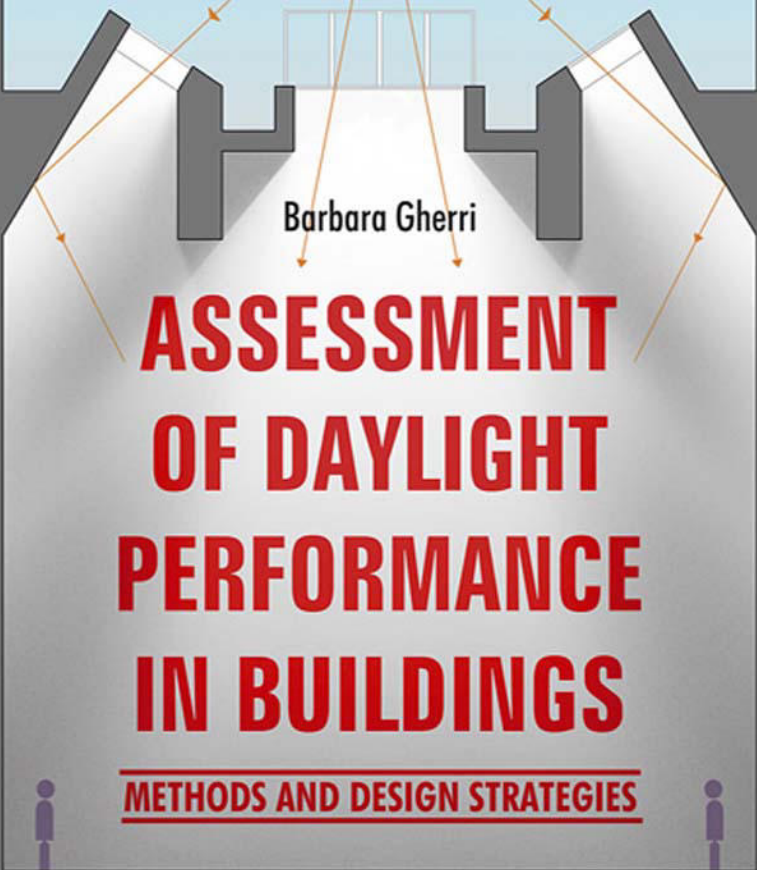

Barbara Gherri

ASSESSMENT OF DAYLIGHT PERFORMANCE IN BUILDINGS

METHODS AND DESIGN STRATEGIES

WIT PRESS

Assessment of Daylight Performance in Buildings

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Her research aims at fostering the linkages between daylight usage, thanks to a qualitative and quantitative daylight appraisal and thanks to the integration of daylight devices in the building envelope, in order to exploit the benefits related to a proper use of natural light as a mean to reduce energy demand and to improve indoor thermal and visual comfort. She has also studied bioclimatic design and other green-passive solutions to be merged in the building envelope to promote a self-sufficient passive design. Her academic and professional research focuses also on environmental certification methods.

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Foreword

Natural light, how to evaluate immateriality

Professor Giovanni Zannoni
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The seemingly limited repertoire of signs with which natural light manifests has for some time convinced the scientific community, and in particular the world of the professionals and scholars of the architecture, to consider light as an element in the basic definition of architectural space and the perception of it.

Issues related to sustainable architecture and the problems of containing energy consumption have recently contributed to the rediscovery and appreciation of some of the many potentials of natural light, through the adoption of systems that leverage this resource in terms of energy, or the creation of spaces that are accessible and pleasant to dwell in where natural light plays a starring role. However, it is surely limitative to think that the quality and performance of this unchanged flow of photons that has reached us daily for millennia from our star of reference can be depleted in a collision with some silicon cell, or by bouncing around inside the glazed system of a greenhouse.

Natural light draws architecture, modulates its spaces, gives rhythm to volumes by emphasising or concealing the interior spaces and details that surround them. Consider it then a mere creative intuition, the representation of an emotional interaction, or the verification of pure physical principles that limits the possible interpretations of this element reducing it to a mechanical, physical or technical calculation, or on the contrary, to the incodificabile sensitivity of a designer. If this twofold antithetical approach has produced numerous excellent works of architecture in which the natural light is a decisive presence, the research that the author presents in this book seeks to deepen the question of light holistically for the first time, surpassing a mere description of luminous performance from an exclusively architectural and/or technological standpoint and including, on the other hand, the question, more exquisitely methodological, of a numerical and procedural approach to an objective evaluation of light.

The choice to speak of ‘Daylight Assessment’ encompasses, in this sense, the need to entrust natural light with a proactive role in integration with other technical skills in order to enhance its high degree of potential. This work seeks to define a process of assessment and analysis, that is as unequivocal as possible, from which to derive an aware and targeted project to get the most out of the luminous performance in interiors, aiming to achieve an adequate level of comfort, both in terms of light and energy, by arranging physical, optical and geometric aspects according to a single analysis protocol. A method that seeks to find application not only in new constructions, where the technological component requested can be more easily integrated with the building envelope but also in existing edifices, in the case of energy retrofit and environmental one. In fact, the well-known implications that connect exploitation of natural light to the possibility of containing electricity consumption, is also complemented by a dawning awareness that recourse to the light of the sun guarantees a general state of wellbeing, including physical effects on the regulation of the circadian rhythm, and favouring concentration and productivity in spaces for work, study and research.

The original account of this book therefore examines various assessment criteria and protocols for the calculation of natural light, devoting space to the question of energy and environmental certification which designers can now turn to (with an eye on possible shortcomings inherent to the application of these methods) to end up by proposing a new integrated assessment protocol that considers all the opportunities to use this form of energy.

Introduction

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New ways in which light can be enhanced and used for the definition of space are made possible by a conscious use of natural light in confined environments, thanks to the many disciplines that are today redefining the roles of natural light with respect to materials, constructed spaces and representation.

The role that natural light plays in this sense, finds itself among definitions of form, the construction of the work of architecture and the perception of space, releasing sunlight from its historic substitutive position, which it has had for centuries, to immerse the constructed space and its occupant in its dynamic and variable flow, which as such, must be analysed and developed.

Research in the field of lighting, as has happened for technological innovation in the same field, encompasses different areas of survey, which are interwoven and involve different areas, from energy saving to a search for visual comfort.

Daylight, with its highly variable and uncertain character, alters, changes appearance and varies with time, giving a space light performances that are always different, environmental qualities that are difficult to predict, but at the same time ensures a comfortable indoor condition that is difficult to achieve with the exclusive use of technological systems. Equally, it is possible to use natural light, direct or indirect, filtered, or reflected, to add emphasis to an architectural accent, to highlight a feature, and for ease of viewing.

The extensive possibilities related to use of sunlight has always interested architecture, both for dwellings and more complex necessities, but rarely has the potential of light as an expressive, visual and energy tool been exploited in a single project.

From these considerations comes one of the most significant misunderstandings inherent to the use of natural light. A question, moreover, that is distorted and deeply rooted – that of confusing architecture built according to Daylighting strategies with an architectural envelope featuring numerous windows or other apertures; in this case, we cannot speak of an 'architecture of the light', built merely to maximise its benefits.

Shapes, spaces and materials must be designed and made from an integrated standpoint, according to a unitary project in which different disciplines and scientific knowledge are interfaced to draw up a formal technological system that will make full room for the natural light project.

The development of the component linked to visual comfort must be set among the fundamental needs to ensure that the final user, together with a comfortable lighting, that it can ensure the best balance between energy savings, reduction in thermal loads and lighting that can be modulated in relation to visual tasks.

A further misunderstanding arises from the way in which light is considered: This is a primary element that is hard to control and manage, whose presence or absence must be provided for prior to the architectural project, to be able, during the practical phase, to take advantage of the benefits and limit shortcomings.

Daylight Assessment therefore is always concentrated in the mere analysis phase at the time of composing the forms, in the instant when the material is taking shape and is being configured as constructed space, that is to say, when the instantaneous presence of the light has been caught and fixed, once and for all, in the figures, spaces and apertures that make up the building. Any modification, change or alteration of the light in the path of the light beam can no longer be questioned.

Although recent studies have shown that the visual and non-visual effects of light have a strong impact on human health and on crucial aspects in terms of energy savings, the technical culture still lacks awareness of the high potential of light and on methods to evaluate and calculate it.

Part 1:

ARCHITECTURE AND DAYLIGHT

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Chapter 1

Natural light in the architectural project

1 Natural light as a construction material

The definition *Architecture of Light* is the one best suited to describe the substantial role that natural light plays in fixing, informing and bringing alive the architecture of the constructed space; the merit goes to Joachim Teichmuller who coined the definition in 1927, on the occasion of a publication in the magazine Licht und Lampe, using the term 'Licht-Architektur'.

The importance of this definition was then sanctioned by the widespread use made of it over the course of the following decades, both to define the architecture of the past, which gave light an active role, but also for those works of architecture that employed new solutions for artificial light in an innovative way.

'There is an architecture of the light. And not only in seed form. Wherever this sprout grows and has already grown with such variety and abundance it is difficult to encompass the entire field and make order in the large amount of manifestations' [1].

Thus was identified a new role for artificial lighting and the use of light fixtures, as well as proposing to give natural light a preponderant role as architectural element, the equal of any other material.

The perceptual question linked to visual and luminous stimuli was, in those years, undergoing definition and experimentation, but it was necessary to trace a road for the conscious use of light at an architectural level, so that it would not be relegated to a simple decorative element.

Although light had always illuminated architecture and given emphasis to form, it was necessary to establish the boundaries, the merits and the possibility of a real science, that blended the historical experience, gained over thousands of years of construction traditions with the new demands of modern man, since it could give rise to variable architectural effects.

Thus, in 1927, the role of an architecture of the light was affirmed, thanks also to Walter Kohler who had the merit of translating into English and giving international renown to the work of Teichmuller, according to whom the concept of an architecture of the light [2] was a natural evolution of the architectural concepts of the ancients who, fully exploiting the potential of sunlight for all their needs, made it into a real construction material.

Today light is, therefore, one of the cardinal themes for architecture, a construction material and key component in the perception of constructed space.

Figure 1: The Milkmaid, Jan Vermeer (credit Dannis Jarvis) and Casa Barragan, Mexico City, Luis Barragan.

The ineffable power of light often relegates it to a secondary element of the architectural project, making it difficult to experience it in a tangible way [5]: 'It is the light that, when it stops being light, becomes matter. All matter is light. Light is the donor of every presence'.

The attention to architecture often seems to reside in the seduction of an image: The purpose of making the form built attractive increasingly results in overlooking care over those formal and technical solutions that help to make the architectural space accessible and comfortable.

Natural light must be first a tool to read architecture, a celebration of the harmony of the parts, an exaltation of shapes and materials, as summed up by the work of Vermeer *The Milkmaid* (1660) and, in a sort of contemporary parallel, *Casa Barragan* in Mexico City (1947) (Fig. 1): In both cases, sunlight permeates the rooms, it exalts and highlights their shapes, colours, sizes and functions; in a moment of revelatory ecstasy, architecture is not simple form, but itself becomes evocative space, as it appears in architectural spaces such as Notre Dame du Haut at Ronchamp, or in the Pavilion of the Nordic countries, in Venice.

Since beauty lies in individual perception, changeable and variable and dependent on the context in which the observation is made, light must assume an essential role in determining the architectural space. The spatial and perceptive relationships that a ray of light creates are not reproducible artificially and it is precisely this original nature that qualifies natural light as a tool to denote the quality of the confined space.

Since matter itself has no form, but it is the work of the architect that bestows dignity and value on a space, the wise and calibrated use of light delineates its image and beauty.

The ceaseless search for the epiphanic power of light and the constructed space by it is garnered by Tadao Ando, according to whom it is the light itself that confers dignity and sense on objects, relating forms to space and, in the same way, as Giedion maintained, eliminating the art of employing daylight involves complex issues, which include not only a calculation of the amount of solar radiation to be ensured inside a building, but also considerations with regard to the comfort and preferences of the users.

The implications brought by the light in architecture are therefore fundamental to fully understanding the essence of architecture. One of the most important achievements in applied sciences between the 19th and 20th centuries was precisely the definition of a method to quantify and codify occupants' needs within a constructed space in relation to sunlight.

Architecture therefore discovers complete fulfilment in its materialising in and through light; architecture as a tactile and visual art demands the presence of light and shade in order to be experienced and appreciated: this is an art that is realised only through the presence of light and time, as epiphanic elements. Without light, the spatial, textural, geometric and visual, tactile and evocative characteristics could not be perceived. Within the constructed space the occupant, whether simply a spectator or an actual user, perceives the space thanks to the presence of its physical limits and of the architectural elements that define the space, and in virtue of the light that illumines, defines and makes it understandable. Within this closed and unchanged system, light plays the predominant role of a catalysing element, which makes it possible for the architecture, and the elements present in it, to take life in space and time, to change and move thanks to the light which delineates the shapes and colours, and which throughout the day and seasons continuously alters.

The relationship of interdependence has always been known to architects and builders who, with the building of the first monoliths, tried to synchronise the movement of the sun and the celestial bodies with their layout.

From those primitive experiences such as Stonehenge, light has been invested with a revelatory role; it draws the space even before the intervention of more tangible materials, filling it with multiple meanings that have varied over the centuries in works of architecture, becoming symbol, stimulus and revelatory element. At the same time, sunlight defines the meaning of the shade, which it itself generates, justifies and reveals.

The sensorial perception of architecture therefore lies in the close link between light and shade, in the continuous mutation of two antithetical poles that are able to generate the sensation of space. From a full awareness of the peculiarities of natural light, the sun, and the stars, primitive man tried to faithfully reproduce the relationship between night and day in constructed spaces, both for religious and everyday purposes.

Light paths, thin beams that sneak into small crevices, into the very mesh of buildings, into the ravines of architecture, which mark symbolic paths, sacred elements or simple visual effects, have always marked works of architecture, eclipsing the creative power of the architect to pay homage to the epiphanic and evocative power of the light.

Light has always been a symbolic material for the composition of architecture; from the oculus of the Pantheon, the windows that illuminate the side chapels of Baroque churches, to the wondrous optical effects of John Soane, recreated to make his residence in Lincoln's Inn-Field a space of hyperbolic suggestion, thanks to the play of materials lit by rays of light cunningly concealed behind architectural elements.

This is a little known repertoire but rich in examples that reflect the 'construction' role of light, on a par with other materials, but with an expressive capacity that usually derives from other elements.

Modern architecture, drawing inspiration from the historical experiences of Classical architecture, has contributed to elevating light and its symbolic use to that of a real construction material, as though it were a major constitutive element.

In this sense, some experiences 'outside the norm' could therefore be, e.g. the works of Nordic architecture, of the great master, Sverre Fehn, whose early works are clearly based on what has been called a key use of light [34], namely, an attempt to concretise the vertical structures. If we look at the *Norwegian Pavilio*n in Brussels (1958) and the *Pavilion of the Nordic Countries* (1962), it is possible to understand his attempt to make the vertical support structures impalpable, almost to the point of vanishing, thanks to the presence of a new building material, i.e. the light, which filters through the beams of the roof and models the space underneath.

Design, architectural and compositional choices have always been influenced by the perception of a material, from the juxtaposition of this with a space, in relation to the light and shade: Builders and architects have long sought to obtain effects of contrast and similarity, building volumes and objects that mimicked others, masking the true function and altering perception and appearance.

The goal is to exalt shapes and textures, but at the same time to deny the intrinsic nature of a material, eagerly exaggerating reflective qualities, by treating rough and porous surfaces to the point of almost obtaining a mirror effect, thanks to grazing light, or employing a zenithal light that floods spaces until it dilates their very confines.

The large rotunda of the Pantheon with its zenithal oculus thus assumes the role of a perfect testimony, a genuine metonymy, to represent the expressive potential of the light, which inundates, gives rhythm, changes and alters the space, materials and, consequently, the sensory perception of the occupant, as Ando described it.

'When the interior of the Pantheon is illuminated by the aperture nine meters in diameter in the centre of the roof, the space is really experienced. In nature, there is nothing similar as regards the light and materials, and what struck me was the power of architecture manifested in this work' [3].

Similarly, canny calibration of shade, be it dense, or just accentuated, makes it possible to hide elements that reveal themselves only in the presence of certain weather conditions or seasonal variations, altering continuously our understanding of an object or volume.

The expressive potential of light and of its opposite, shade, vivifies architecture, renders it continuously changing and articulate.

Suffice to think of the famous stylistic composition that Bernini realised in the *Cornaro Chapel* in the Church of *Santa Maria della Vittoria* in Rome with his *Ecstasy of Saint Teresa* (1647–1651), an emblem of how light constitutes the element of perfect compositional fusion between architecture and sculpture, creating wonderful scenographic effects (Fig. 2).

Figure 2: Ecstasy of Saint Teresa, Gian Lorenzo Bernini (credit Jiuguang Wang).

Bernini's insight represents light's ability to stand as a proper construction element, thanks to the aperture of a small window at the top of the chapel apse, which encompasses the whole scene, and through which the light enters and, concealed from the eyes of the observer, strikes the sculpture making it come alive.

The translation process from the design to the building, towards the realisation of the constructed space, takes life from the moment natural light enters, spreads out and is reflected, creating the sensation and size of the space.

'It is the light that gives the feeling of space. The space is cancelled by the darkness. Light and space are inseparable. If we eliminate the light, the emotional content of the space disappears and it becomes impossible to perceive it' [4].

The process of perceiving space is thus made possible by the revelatory presence of the light and, only secondarily by the effective use of space, as in the *Larking Building* in Buffalo, New York.

'The light glittering through the tubes of a wonderful quality. The effect of the salon is magical. We look up through the light, like fish from the depths of a pond; and the discs seem to be swimming in the flowing glass. The Salone is the most fantastic work to have been designed in the architectural imagination for a long time. In this building, Frank Lloyd Wright creates a new spatial sense by means of a silvery light and a plastic form, without which it is not possible to think in terms of architecture' [4].

It is not possible to unambiguously define the golden rule that binds architecture and light. It has been elaborated by every thinker, creator, artist and architect in response to their own poetic and compositional needs, according to personal taste, a philosophical ideal, or a religious reason; every spatial experiment is generated by personal experience, and is imprinted on the constructed space.

Figure 3: The Kimbell art Museum, Fort Worth, Louis Kahn.

From the heavy walls of the works of architecture described by Vitruvius, to the light spatial arrangements of Baroque architecture, where the light is hidden to the eye of the beholder but manifests like a delicate scenic magic, lighting plays a pivotal role.

Louis Kahn was among the first to express the need to obtain a precise framework of competence in order to express the potential of sunlight in architecture. Kahn believed firmly, to the extent of basing the essence of his architecture on the creative and spatial values of light, that natural light was an indispensable creative element to be taken into account right from the design phase of a work (Fig. 3).

In his lecture, *Law and Rule in Architecture* [5], he explained: 'Every space must have natural light, because it is impossible to read the configurations of a space or shape by having only one or two ways of lighting it. Natural light enters the space released by the choice of construction.'

Kahn's compositional sensitivity, as can be appreciated by the many preparatory drawings for his projects, is realised by calibrating natural light from the early stages of the design process.

The study of how light can penetrate and inform the space is carefully evaluated, just like the arrangement of columns, beams and pillars. It is not simply a matter of defining materials or choosing finishes; for the first time in the modern context, Kahn considered natural light as a construction material, transcending the 19th century tendency of relegating natural lighting to a secondary role, confounded by an inexpressive and often overrated artificial architectural lighting.

The masterful intuition of the vivifying role of the sun's rays in a constructed space found a full definition in the approach of a scientific and at the same time compositional character, linked to the survey of the spectral quality of light for his *First Unitarian Church* project in Rochester, New York (1959–1962).

The project included the design of an ensemble of colourful elements suspended from the ceiling and the walls of the church interior, so that the congregation had the sensation that sunlight was penetrating from mysterious apertures and spreading through the space, like a genesis moment.

The profound knowledge of the expressive, linguistic and textural capacities of light would characterise the entire course of the professional life of Kahn, who came to make a case for the unexpressed potential of light, how it was possible to measure and quantify the creative contribution of a material so impalpable as light.

Similarly, sunlight is given a role as a tangible and pliable material, as found in Ando's architectural vision, in the *Church of the Light*: 'In the way I use it, concrete is devoid of sculptural features and weight; it has the purpose of producing brightness and bringing detail to homogeneous surfaces. The traces of the formwork are treated in a manner that creates smooth surfaces or sharp edges […]. When light is projected onto these, the cold peaceful space surrounded by clearly defined architectural elements becomes cosy and transparent, indifferent to the materials' [6].

In Middle Eastern culture, light is in itself considered an expression of the divine, since it is already inherent within matter. Sunlight in sacred space, in a Muslim setting, is used for various tasks: As an indicator of the privileged orientation towards Mecca, as a decorative system using reflections, when the light rays are channelled and made to filter through the architectural elements, to create games of reflections and shadows, while concealing the direct source of lighting.

In the sacred Islamic space, the function of the light is inextricably linked to the presence of screens, architectural elements that act as a filter between the outside world and the interior, creating views and suggestions that constantly vary, in relation to alterations in external light conditions. Islamic art apparently relies on conditions of a two-dimensional design, which is completed and made three-dimensional by the presence of light, together with the use of reflective materials and shiny glazes that help to create strong contrasts between the colours and textures.

In the eyes of a Western observer like Le Corbusier, the constructed space of Islamic culture is revealed as he himself describes the *Green Mosque*: 'Then you perceive the grandness of the Mosque and your eyes are measuring. You are in a large area of white marble bathed in light. Beyond is another similar space of the same size, full of penumbra, and higher by a few steps (a smaller repetition); from each part two spaces of penumbra still smaller; turn round, two tiny spaces of shadow. From full light to shade, a rhythm' [7].

The light filters through richly perforated surfaces, but does not remain ensnared, on the contrary, it creates gradations of colour and chiaroscuro that are subtle yet defined, accentuating the dynamism of the constructed form.

Islamic art is the only one that can create effective games of contrasts, in denying the direct penetration of natural light; the apparent rejection of the luminous value of the ray of sunshine, on the other hand, is exalted by the complex screen theories.

The light dons a full role as a constituent element of architecture, to delineate the character of the space and the perception of what has been built, the relationship between inside and outside, and the effect of visibility in the penumbra, as centuries later, also Le Corbusier would conclude [8]. 'Architecture in as much a skilful, rigorous and magnificent play of volumes assembled in the light, assigns a task to the architect to bring to life the surfaces that enclose the volumes, without these devouring the volume and absorbing it to their profit, like parasites'.

2 The architectural meanings of natural light

2.1 Connectivity and communication

Natural light creates details, reveals nuances, highlights contrasts and enables us to perceive a space that would otherwise we would not be able to appreciate, unless we used touch. Using sunlight to light a space, a room, a detail, is therefore fundamental to create atmosphere and a correct perception of it; in this sense the amount of sunlight brings life to the building, vivifying and exalting it.

The dualism between light and shade, light and dark, is the first antithesis in the definition of space, for the creation of contrasts in brightness, which, once they traverse the materials creating the constructed space, help to define volumes, textures and material effects.

In the metaphor of the cave in the seventh book of the *The Republic* Plato describes the relationship of close dependency between light, shadow and vision, defining the role of solar radiation in the cognitive and perceptual dimension of man.

In the chiaroscuro world of the cave primitive man's sole possibility of experiencing reality was through appearance, in virtue of the shadows thronging the end of the cavern. The shadows represent, in this metaphor of human knowledge, an extension of the physical reality outside, thanks to which man is able to have prior knowledge of external reality.

The relationship of knowledge created can be realised only through the dualism of light and shade, between the inside and the outside.

The perception of space takes place, therefore, thanks to the decisive presence of light and its opposite, shade. Western culture has over the centuries set aside the role played by shade in the process of perceiving space, reducing the concept to a simple negation of light and taking the term as a synonym of darkness.

Eastern culture, and in particular Japanese knowledge, has instead had the merit of fully recognising darkness, penumbra and obscurity as elements of equal importance in the creation of space.

'We do our walls in neutral colours so that the sad, fragile, dying rays can sink into absolute repose […] A luster here would destroy the soft fragile beauty of the feeble light. We delight in the mere sight of the delicate glow of fading rays clinging to the surface of a dusky wall, there to live of what little life remains to them' [9].

Masters of contemporary architecture, like Ando, refer to shade as a fundamental perceptual element: 'Light alone does not create light. There must be darkness so that the light becomes light, resplendent in dignity and power. The obscurity that refines the splendour of light and reveals its power is an innate part of light'.

For Japanese culture, a simple beam of light has no meaning, either as a revelatory element, or a symbolic object, but only comes to life and takes on a significance when it lands on a significant element, only when it creates a relationship, even fleeting, with an object; its existence is renewed with every variation in intensity and brilliance, just like the moment when the first shadows form and the relationship between light and subject becomes more complex and fluid, until they blur into one another.

The Eastern outlook captures the role of the instantaneous beam of light, the thin breach created between matter and the sun's ray and the changing relations from which the meanings of architecture, space and dimension arise.

This justifies the ecstatic vision that took hold of Tadao Ando on a visit to Europe, while describing the light penetrating through the slits of small windows within a medieval monastery, virtually devoid of decoration, but that appeared to his eyes as one transcendent space, at the instant when the ray settled on the masonry, making it strong and filled with energy at the same time. Japanese architecture, both modern and contemporary, is gradually losing this traditional link with the past, losing the sense of depth and blurring the boundary between light and shade more and more, approaching the tendency of the west to overilluminate.

It has elaborated, as is found in Tanizaki a real aesthetic theory that is totally opposed to the Western culture of apertures, airiness and often uncontrolled brightness, in opposition to the culture of shadows, according to which beauty lies in the path of the shadows, in the antithetical, but fundamentally inseparable relationship between light and its opposite, and in the infinity of nuances that the eye perceives.

'Such is our way of thinking-we find beauty not in the thing itself but in the pattern of shadows, the light and the darkness, that one thing against another creates' [9].

Only a few architects and theoreticians of Western culture have been able to perceive the value of the antithesis between light and dark, and to translate this into finite material elements, in massive constructions that enhance the contrast between light and dark, brightness and gloom.

The light in the works of these masters can reveal the true spatial and tactile nature of surfaces, impressing the retina and fixing the image of what is not there, but what the skilful game of rays has managed to create. Suffice to think of the ability of masters such as Francesco Borromini in *San Carlo alle Quattro Fontane*, Rome, the work that emblematically tells of the theatrical and architectural use of natural light in the Baroque period (Fig. 4).

The characteristic arrangement of the apertures in the Roman church symbolises first the intimate bond of closeness between the spiritual and natural worlds, not counterfeited. The light permeates through the windows in the dome and lantern and spreads through the multifaceted space of the church, revealing its sinuous lines and articulated spatiality. Borromini succeeded

Figure 4: The dome in San Carlo alle Quattro Fontane, Francesco Borromini.

in his attempt to create a sort of theatrical lighting, making use only of the contribution of the sun's rays that spread through the sacred space, managing to conceal lights and shadows behind the scenes, as if on a stage. His extreme compositional skills reached their maximum expressiveness with the creation of the so-called 'chamber of light', an optical device in which the intensity of a beam of natural light was controlled by means of inclined surfaces inside a channel.

The spatiality of the light is enhanced to the point of annulling the massive surface of the wall, which leaves space for windows, arches and decorative elements.

The works of architecture by Bernini and Borromini represent the pinnacle of the skill of the architects and builders to insert light into an architectural context, thanks to lighting of a theatrical type, wherein the light source is hidden from the eye of the beholder, hidden 'behind the scenes', but used as a device to reveal figures.

The perceptual paradox of light lies in the fact that it must necessarily materialise to be accepted as an architectural and material quality; essential to this process is therefore the compositional skills of the designer and then subsequently, the builder, who must manipulate it, channel it, filter it, sometimes hide it and then make it evident again, thanks to a cunning use of reflective and matt materials, windows hidden or exposed.

The culmination of the perceptual research, which seeks to assign a key role to light in the visual process, to comprehend and experience space, has been developed at the construction level by James Turrell, who right from his first works, managed to translate the tactile nature of light in a concrete way, evolving the relationship between communication and connection.

This Californian architect works with the objective of maximising the expressive-space potential of natural light, with state-of-the-art research in the architectural field. The keystones of his research are the optical, visual and spatial characteristics of light: if until that point light had been bent to simple narrative and symbolic ends, Turrell sought to demonstrate that light is something else entirely.

'I basically make spaces that capture light and hold it for your physical sensing […]. It is a realisation that the eyes touch, that the eyes feel. And when the eyes are open and you follow this sensation, touch goes out of the eye like feel' [10].

Turrell became an experimenter with the expressive and linguistic capabilities of daylight in the nineteen-eighties, through continuous spatial research in his special rooms, which he called 'Skyspace'.

The perceptual experience in his works is delineated as a focal point to experiment with the descriptive and revelatory possibilities of light not only considering its effects on the perception of three-dimensionality, but involving the notion that an observer has of him- or herself in a confined space.

Turrell's intention is to materialise light, to make it as pliable as any tangible element and at the same time, to exploit the visual perception, to fully experience the physical and symbolic nature of light. In this sense, Turrell's scientific work has often been misunderstood, by taking his search to convert optical effects into avant-garde architecture to be nothing but foolish artistic aspiration.

The ability to combine the real three-dimensional nature of a room and light projections reached a climax in the unfinished masterpiece of the *Roden Crater*, Arizona; this space – because it is not possible to define the work in any other way – represents the *summa* of optical-perceptive research in a work of architecture, which he himself renamed as 'perceptually malleable'.

The *Ganzfeld*, or homogenous visual field that is often found in *Skyspace*s, is achieved through the construction of a confined space without structure, and which normal perceptual logic is redefined: For the observer, immersed in this room without visual and acoustic stimuli, it is impossible to establish any reference point, due to the presence of a homogeneous light that stands out on the room's surfaces.

The various attempts made over the years included a continuous alteration of the stimuli in the environment: From a variation in depth, to different colouring of the light, by altering the intensity and saturation of the light, the human eye of the spectator is unable to grasp the real shapes and sizes, the shadows and the areas of light, as if he or she were in a sort of impalpable and widespread mist.

In the *Ganzfeld*, Turrell succeeded in his attempt to make vain all the efforts that the Architecture of Light had pursued up until then: the *Ganzfeld* negated the constructed space and restored the full material and tangible value of light.

Among the famous pieces of architectural and luminous research before the *Roden Crater*, as well as in the countless Skypaces, Turrell sought to merge lighting-technique instances, optical and visual demands, and architectural design into a single object, forming a space in which, a simple framing of a quadrant of celestial vault alters the perception of the light, the circadian rhythms of sleeping and waking, the idea of space and the traditional links between visual connection and communication.

‘It’s about perception. For me, it’s using light as a material to influence or affect the medium of perception. I feel that I want to use light as this wonderful and magic elixir that we drink as Vitamin D through the skin – and I mean, we are literally light-eaters – to then affect the way that we see.

We live within this reality we create, and we’re quite unaware of how we create the reality. So the work is often a general loan into how we go about forming this world in which we live, in particular with seeing’ [11].

2.1.1 *Symbiosis and mediation*

Every abstract concept, such as that of light, rather than relying on definitions, needs to be put in common language, in daily experience: this is the only way that a concept can come to life and its value and meaning be understood. So it was for light: only in this way can its intrinsic value find an interpretation.

The amazement that enthrals the viewer in an ecstasy of light in front of the magnificence of places such as the *Hagia Sophia* (Fig. 5) in Istanbul or the *Pantheon* in Rome (Fig. 6) is not related to the space as such, but is the result of the light that illuminates them. The richness of the architectural space lies in the indissoluble union between matter and light, structure and visibility, together with the complex of peculiarities that complement it: the surfaces, the materials, the volumes and the colours.

Light and architecture cannot for any reason be separated, one cannot survive without the other. Architecture is not only volume, it does not occur in the simple action of building to fill a vacuum, to create a functional space; it is not sufficient to create a cavity in matter, or technologically connote a shell without defining what will come to life inside it. If light permeates

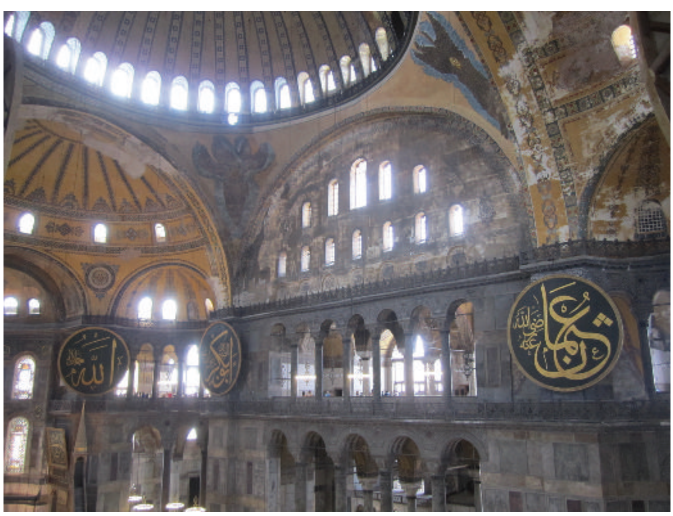

Figure 5: Hagia Sophia, Istanbul.

Figure 6: The Pantheon Dome, Rome.

a vacuum, this becomes space, and only then does it define a function, a purpose, a form. For this space, light and architecture – to paraphrase Giedion – are inextricably linked. The way in which light allows the perception and the subsequent understanding of space coincides with the way, in which space is understood, used, experienced and created.

Only with the advent of artificial light and control devices was it possible to use light in a more flexible way, by modifying the natural alternation of seasonal, daytime and night-time variations of solar radiation.

Light and matter are mutually dependent and, therefore, inseparable, even more so if it means defining an architectural space, perceiving matter, experiencing the dimension constructed.

The way in which architecture enters into a dialogue with natural light is complex and multifaceted, declined according to the poetic needs of whoever is designing and building and, only subsequently, modified and brought alive by those who live in, work in and experience the space.

In this context, it is possible to speak of a ‘physical anthropology’ of light, to fully assess how Daylighting is not a new discipline, but is rather the result of an evolution in style and human needs that have modified construction behaviour and architectural practices. Natural light not only affects the sensory aspects of everyone’s everyday life, but profoundly affects our mood and other aspects related to the chronobiological rhythms of sleeping and waking in relation to the production of hormones.

The fundamental symbiosis between the psychophysical wellbeing of man and the presence of natural light needs to be evaluated and integrated in the design of domestic spaces for study, work or where man spends most of the time. It is not only to respond to biological needs and physiological, but to create a harmony with architectural language, which makes integration and close collaboration possible between architectural, spatial and physiological needs.

Maximising this connection is one of the objectives of the Architecture of Light, in order to create an indispensable link between inside and outside, between the constructed and natural environments, by creating apertures and relationships, to emphasise attention and increase the potency of the view. The objective of *daylight architecture*, i.e. an architecture that does not simply exploit natural light, but raises it to a cornerstone for the definition of space, the creation of an environment that is comfortable and beneficial for the occupants, is to acquire, improve and articulate as far as possible the presence of sunlight. Thus the definition of Daylight Assessment finds its roots in the most ancient forms of construction.

Connectivity and mediation are therefore utterly primitive needs, which find their first examples in the need to create a dialogue between the constructed and the outside world, to ensure a visual and physical connection, to assure continuity between the natural world and the creation of an artificial world that is entirely human.

The challenge to give voice to this primitive need for connection and linking with reality, that is, not merely the constructed and the artificially creations of man, is of great importance today, both for strategies of ecological and biosustainable construction, in line with an approach that harks back to the first construction processes in the ancient architectural practices of the classical and medieval worlds, until the introduction of artificial light.

Connection and communication therefore become primary needs, on a par with the definition of the boundaries of light and shade, for the users of the spaces of today, those *perpetual urban cave dwellers* for whom the view of the outside is for the most part foreclosed by a theory of obstacles and counterfeit visual stimuli, that distract us from the view of the sky.

The yearning to reconnect with the outside world, to create new rapports of connection and dialogue with the outside world, whether natural or artificial, passes through a measured use of natural light, the presence of which prepares the body for a natural alternation between the hours of light and the hours of darkness, between the time of waking and sleeping, to support normal human activities.

It is equally clear that, albeit well-controlled, lit in a uniform and efficient manner, an artificially illuminated environment cannot create a similar ratio of psychological and physical relationships and symbiosis with the outside, making a sense of general wellbeing impossible.

Finally, the diurnal and seasonal variability of natural light, like the changing dynamic of the light stimuli of the sky due to the sun are irreproducible by artificial light equipment, but do contribute in a tangible way to determining a feeling of generic prosperity. From a strictly architectural standpoint, light to illuminate constructed spaces cannot therefore only be evaluated in relation to its effects on the shape of the constructed and space: What needs to be considered as a whole is the positive contribution resulting from physical, physiological, and psychological benefits, as well as from nonvisual effects, equally decisive for the performance of the vital functions.

Having clarified the symbiosis that exists between architecture and light, between human needs and the beneficial effects of lighting with sunlight, the language of architecture must take responsibility to express and articulate the variable amount of natural light through the use of simple components, screens and filters that reflect, filter and govern the light inside. The theme of mediation between inside and outside is a crucial issue in the process of creation and for Daylight Assessment; it is in fact a question of calibrating brightness and contrast, light and shade, the needs and demands of individual users, along with the thermal and energy requirements of the building envelope, without precluding visual contact with the outside.

3 Natural light in architectural projects: written testimonies

In the discussion on the contemporary use of light, deliberately limited in geographic and temporal scope to Europe and North America, it is proposed to investigate some episodes of good architectural practice, in which the issue of integrating daylighting assumed a predominant role in defining the project and associated architectural theories.

It has been intentionally decided to exclude others from the treatise, therefore including only those for which the light is nothing but a simple expedient used to understand the form, a tool for spatial definition, a means of vision and colour perception, a visual and driving phenomenon of the design choices, and to disregard examples in which sunlight embodies symbolic, religious or mystical meanings, which differentiate the approach to, and the definition of the constructed space.

For this reason, it was decided to deliberately exclude from the discussion the question of light in Japanese contexts and all other situations outside mere architectural debate.

In order to provide an extensive overview of the historical contributions relating to the architectural use of natural light, it was considered effective to divide the discussion according to geography and chronology.

3.1 The historical treatises

The history of architectural treatises abounds in systematic research into the use of natural light as a vivifying element and foundational component of constructed space. The innovative idea of treating light as a construction material dates back to primitive construction experiences, but only with classical treaties was the definition of a true and proper role for light reached, both for visual needs and the perception of space through colours and textures.

The analytical assessment of emblematic examples of daylight must be traced back to the grandiose Roman works of architecture, including the Pantheon in Rome. Even earlier must be cited the Middle Eastern examples of Arabian and Iranian mosques, in which the physical nature of the light that penetrates the decorated grilles, assumes a symbolic and tactile role.

To sketch an in-depth *excursus* on the first systematic treatment and the relevant definitions of the 'Architecture of Light', we must assess the historical importance of the thoughts of many authors, from Scamozzi, who, along with the six basic principles of Vitruvius (**Order**, **Symmetry**, **Arrangement**, **Eurhythmy**, **Propriety** and **Economy**), in 1656 was added the *lumen*, until we arrive at Serlio, Piranesi and Bernini.

The massive and spectacular use of natural light in architecture then found its maximum expressiveness in the Baroque and the Enlightenment, as testified by the examples of Francesco Borromini and Bernini, as well as in the examples from Piedmont of Guarino Guarini, Filippo

Juvarra and Bernardo Antonio Vittone and across the Alps in the work of the Frenchman E.T. Boullée, who attributed in construction the task of introducing the effects of light in architecture: 'Émouvoir par les effets de la lumière appartient à l'architecture' [12].

The treatment of light thus reveals a long-time interest in the theme and knowledge of the fundamental principles of lighting and optics that was very advanced for the time; knowledge which translated fully into attempts to use light by means of perforations in the fabric of the wall, the use of oculi and lanterns, atria and arcades.

'The lighting of this monument, which should resemble that on a clear night, is provided by the planets and the stars that decorate the vault of the sky […] The daylight outside filters through these apertures into the gloom of the interior and outlines all the objects in the vault with bright, sparkling lights.

This form of lighting the monument is a perfect reproduction and the effect of the stars could not be more brilliant.

It is easy to imagine the natural effect that would result from the possibility of increasing or decreasing the daylight inside the monument according to the number of stars. It is also easy to imagine how the sombre light that would prevail in this place would favour the illusion' [13].

The historical contribution of these writers therefore lies in the historical-critical analysis that each individual author had the merit to conduct with regard to the use of natural light, thus being among the first to raise light to the rank of a real material for construction, like wood or brick.

Instead, as regards the study of light and different solutions for daylighting between the 15th and 16th centuries, the fascinating essay by Sergio Bettini highlights the substantial absence of a systematic assessment on the topic. The study of natural light remained, at that time, the exclusive prerogative of treatises on theatre and the history of philosophy and art.

Subsequent to the authoritative contribution of Vitruvius, for centuries the architectural value of light was neglected, as was light's inescapably expressive capacity to comprehend space, forgotten by the literature and the critics. The lack of attention to the theme is probably due to the essence of other apparent meanings – mystical and religious – attributed to light. It was necessary to wait for the advent of the 17th century to rediscover fresh interest in the theme of light in the sacred space and the Templars' buildings, a topic that would become major news with the discovery of the remains of the Parthenon [14].

In the Renaissance, Leon Battista Alberti was the first to demonstrate a profound interest in natural light, dedicating himself to discussing it in whole paragraphs, accompanied by exhaustive scientific, optical and architectural discourses, demonstrating how the use of special devices for the dissemination and reflection of light could be used in building.

One of the first testimonies, his *Pittura*, dating to 1435, collected the first complete numbering of the types of light in art, laying the foundations for what was later defined a primordial elaboration of an 'aesthetics of light' [15]. But it was only with the discussion in *De Re Aedificatoria* that Alberti would come to a definition of issues just sketched out by Vitruvius, on the validity of

Figure 7: Interior of Sant'Andrea, Mantua, Leon Battista Alberti.

the use of natural light, on procedures for solar penetration, in relation to functions and visual tasks specific to the setting.

Today, Alberti's description appears much richer and more exhaustive, in virtue of the particular attention paid to the orientation and arrangement of apertures: 'In summer apartments large windows will be made in every direction in the walls facing north, low and narrow in those addressing the midday sun; some will be ventilated, others less vulnerable to the sun; even so the lighting, due to the continuous shining of the sun all around, will be sufficient in places such as these, where the search is, more than for light, of shade. But however we want to introduce the light inside, it is obvious that we must freely look at the sky' [16] (Fig. 7).

'The windows of temples should be modest in size and in a good high position, so that through them we cannot perceive other than the sky, like the celebrants, and the men of prayer are in no way diverted from the thought of the divine' [16].

The theme of an unfettered view of the outside, a fundamental requirement for current strategies of Daylighting, was thoroughly analysed thus by Alberti, who highlighted, for the first time, the need to limit excessive visual stimuli and thermal effects coming from outside.

The architectural and symbolic interest in light, that it is possible to trace in many steps of the treatise, therefore touches on aspects, then considered marginal, of which today it is possible to appreciate the high cultural value: From the precise control of light amounts to the variability of dynamic light, to attempts to reproduce light effects, games of reflection, and attempts to diffuse sunlight, strategies analysed in a decidedly modern key.

Among the subsequent amounts, designed to develop natural light in its many architectural applications, we must recall Sebastiano Serlio, who, among the first defined as builders and designers, was able to intervene in the implementation of perforations in ecclesiastical settings, to ensure the most balanced amount of light in the side chapels, in order to maintain dramatic effects that fostered an atmosphere of meditation and mysticism, necessary to accommodate the faithful: ‘Square chapels shall have the light from the sides: but as to that of the Temple, if there will be at the top of the ceiling an aperture, the diameter of which shall be a fifth part of the Temple, make there above a lantern, as I told of the others’ [17].

Construction practices in relation to visual and spatial effects on the entry of natural light seem to already have been known to Serlio in the 16th century, through the reading of previous treatises and derived from direct experience. Knowledge of the writings of Vitruvius proved useful to the subsequent treatises by Serlio who, albeit in a rather inaccurate and inhomogeneous way, defined the importance of an appropriate arrangement of windows with suitable orientation, for country houses, as he narrated: ‘In the middle of the room there shall be two niches at the top of which there shall be a large window, to take in light and wind’ [18].

The instructions appear immature and ill-defined; these seem to be summary suggestions, derived from experience rather than from extensive physical and optical assessments, however, they clearly demonstrate that the legacy of the first hints of Vitruvius, on the architectural significance and thermal performance related to the use of light for private mansions had not been lost through the centuries.

Instead, to Scamozzi, one of the last great architects of the 16th century in Italy, is due the merit of having first coined the precise distinction between the different types of natural light.

In the season of passage between the age of the great scientific discoveries, before the time of doubts and disputes about the validity of these findings, Scamozzi is an often forgotten author, who has the merit that he paid architectural attention to light by treating it with scientific approach that was then unusual, making it worthy of an extended exposition initially theoretical and then practical, which opened the way to subsequent attempts at classification among his numerous Italian followers.

Scamozzi, a pupil of Palladio, demonstrated his personality by founding his theory and the architectural practice on solid scientific and technical bases, brought together in his work *The Idea of a Universal Architecture*.

Within this weighty scientific treatise, which is abounding in technical details, there is a detailed inquiry, the first, organised in a scientific way and accompanied by drawings and technical plates on the control and management of light from the windows of church side chapels.

In this sense Scamozzi is often considered to be one of the first ‘moderns’, attentive to issues that only with Le Corbusier and Kahn would find worthy positions among purely architectural questions.

‘Natural light is one only but for various reasons, it can be altered not a little: and however, we are going to break it down into six species: i.e. overwhelming or celestial; lumen vivo perpendicular; lumen vivo horizontal; lumen finished; lumen of lumen, or also called secondary or participated lumen, and finally, minimal lumen, that is also said tertiary, namely, lumen reflected or refracted. Lumen in the upper part of the Rotunda expands with much grace, for all parts, as if not stopped by any thing … all is born from the celestial lumen, which by no thing is stopped’ [19].

And again in his book V, light returns to play a beneficial role for the wholesomeness of domestic environments, thereby providing a specific definition for each type of light, in an attempt to provide a primordial scientific cataloguing of the present techniques of Daylighting: ‘Now that we have spoken enough of the air, let us reason something over the lumens, so as to apply them well and conveniently according to the quality of buildings.

Natural light is one only but for various reasons, it can be altered not a little: and however, we are going to break it down into six species: i.e. *overwhelming or celestial; lumen vivo perpendicular; lumen vivo horizontal; lumen finished; lumen of lumen, or also called secondary or participated lumen*, and finally, *minimal lumen*, which we will discuss briefly to our benefit and not curiously or philosophizing’ [20] (Fig. 8).

Natural light in a broad sense is defined for the first time by Scamozzi as ‘*lumen overwhelming and celestial*’, meaning the sum of the amount of direct and reflected light from the celestial vault: ‘By lumen overwhelming and celestial we intend all that from under the open sky we receive abundantly by virtue of the sun above this our part of the air and the earth, by means of which light we see and discern all things here below and without which we would have the darkness of the night’ [20].

Scamozzi also seems to describe for the first time the strategy of zenithal lighting, in precise terms, such as to recall the definition of modern systems of *toplighting*: ‘By lumen vivo and perpendicular we mean that which comes from the open sky and which we receive in the courts or in the apertures of domes, such as the Rotunda of Rome and similar places: which, not being stopped by anything goes proportionally spreading until the ground’.

In the same way the clarification of *lumen horizontal* is one that comes closest, in the history of architectural treatises, to the current characterisation of the technique of *sidelighting*: ‘The lumen free horizontal is what we take every day in front or diagonally from pure heaven and, freely, which, not being prevented by anything, duly illuminates the loggias, halls, lounges, rooms, and other places of the house’.

A lighting accent, focused on a detail or used to underscore is described by Scamozzi under the name *lumen terminated*: ‘The lumen ended is that which, still bright and clear, is nonetheless terminated by some small and enclosed place, as in front of some road, which is stopped on one or both sides by buildings: and therefore this light does not provide much benefit to the inside of the rooms: since it is quite accessible and powerful it arrives in front of a some loggia of not so much width and with high colonnades’.

The exhaustive discussion is not limited to a simple definition of direct lighting strategies, but also goes deeply into the function of secondary strategies of *sidelighting*, as in the case of primeval solutions of *borrowed light*, which are described thus: ‘The lumen of lumen, which can also be called secondary or participated, is what we receive from another near place near lighted by the first lumen and the brightness of the sky: such as loggias, arcades, galleries and similar very open places, that have the true lumen horizontal and diagonal of the pure sky: these places are more or less bright as they approach or leave the brightness of the air, which is found in the first places illuminated. Minimal lumen, which we can also call tertiary, is what we receive from other places not very lighted, i.e. taking even the lumen of lumen, or finally even lumen

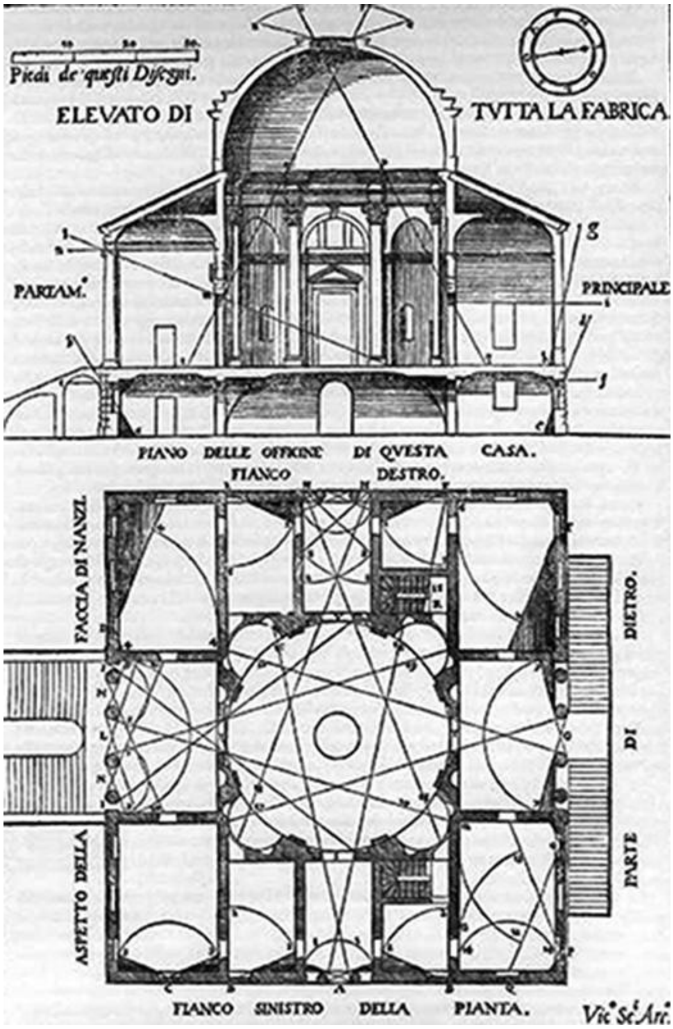

Figure 8: Venetian villa, Section and plan, Vincenzo Scamozzi.

reflected, which is very weak, and therefore is of no use to us, if not in the event of greatest need, for secret stairs, cupboards, places of need and similar other doorways enclosed in rooms' [20].

Scamozzi is therefore, quite rightly, considered a forerunner of that peculiar 16th- and 17th-century sensitivity for the use of and interest in the effects of light, which enhanced not only 'its tonal values', but also it luminous effects that it can create within the architectural space, such as to be a precursor of the luminous dynamism of Baroque architecture [21].

The experience of Scamozzi in the theoretical study and practice of light and its different uses inspired subsequent authors to experiment with the expressive potential of direct light, filtered light and light hidden behind architectural elements.

The many experiences of the Italian Baroque contributed in great measure to increasing the use of light as a construction material, and, only afterwards, were more daring experiments conducted in other countries. The famous lessons in architecture of John Soane were to introduce to the countries of northern Europe a new focus on the compelling possibilities related to the use of natural light in home environments and public buildings.

The renowned example of his classroom built at *Lincoln's Inn Fields* in London represents the *summa* of Soane's light concepts, brought to the maximum expressiveness thanks to the calibrated use of what he called '*lumière mysterieuse*'.

The project for a private residence in *Lincoln's Inn Fields* served for years as an experimental laboratory in which Soane tested his insights into the use of direct and indirect light, and the effects of diffused and reflected light, by putting into practice the instructions he had culled from classical texts: 'Palladio, Scamozzi, Phibert de l'Orme, and many other great architects, gave us their different views on the shape and proportions of the windows, but, from the moment that the windows must be of appropriate proportions to particular climates in which we must build, and from the moment that the observations of those great men related to a warmer climate than ours, their directives may be of little help [...] Our windows are also larger than they have been in the past and, being constructed so as to open the centre, the general effect is very good; in this way more air and light are entering, and an appearance of greater habitability is conferred on the apartment' [22].

Soane's interest vis-à-vis the evocative power of light, as a true creator of spaces and volumes, together with his faith in the transfiguring power of the light beam, developed from historical knowledge of the Vitruvian treatise.

The cultural debt to the skilful compositional mastery over natural light is reflected in the search for an architectural declination of incoming rays, that are reflected and illuminate the interiors in complex games of refractions, a global poetic of light, clearly traceable in every smallest detail of the house, from the dining room up to the dome hidden on the outside, defined a 'baldachin' by Soane himself, namely a room with zenithal lighting, with a glazed octagonal skylight and two smaller skylights arranged at the sides.

His curiosity for the creative and deforming potential of optical devices impelled Soane to place mirrors on the walls of his residence-laboratory, strategically positioned to follow the path of the sun and reflect in many directions the coloured light of the zenithal skylights, creating evocative and unexpected glimpses, and using that simplest of technical tricks, natural light.

'The architect will do well to examine different ways adopted by painters to get the light in their studies.

The *lumière mysterieuse*, applied so successfully by the French artist, is a very powerful tool in the hands of a man of genius, and this power can never be too inclusive, nor too highly appreciated' [22].

The definition of *lumière mysterieuse* is thus used by Soane himself to experience the infinite possibilities of natural light, concealed from view or coming from lateral apertures, to create evocative coloured and luminous effects. Perhaps inspired by the fascinating engravings of Piranesi, Soane created the interior spaces of his London residence with the ability of a sculptor, using light as a punch with which to chisel the surfaces.

As a result of Soane's innovative experiences, other benefits inherent to the presence of sunlight within spaces were investigated from an environmental, architectural and luminous standpoint, which enabled many subsequent architects to reach a definition of a new use of natural light, as a technical expedient for the attainment of the much sought-after sense of structural lightness, thanks to which, personalities such as Horta, Labrouste and Mackintosh were to magnify the sense of lightness of the constructed space, obtained with the use of iron and cast iron, through a cunning use of apertures to the outside.

The exact distinction between *lumière naturelle* and *lumière artificielle* can therefore be placed in the trough of a vast collection of direct experiences and treatises on architecture that define, in relation to different epochs and geographic regions, architectural trends, stylistic notes and good building practices for sunlight, founding the bases of the modern definition of *Daylight Architecture* and *Daylight Assessment*.

In the following centuries, Soane's eclectic and innovative experience was to radically mark, in Anglo Saxon circles, the development of the multiple tendencies to enhance the expressive and spatial use of natural light, as well as strategies of illumination, while attempts at defining space through management of sunlight continue to echo today, in the works of architects such as Louis Kahn, who makes his knowledge of the arrangement of the apertures for natural light diffused and poetic, as in the case of the *Kimbell Art Museum* in Fort Worth, Texas. Likewise, as regards exterior lighting, assessment of the perceptual impact of light on the surrounding landscape can be attributed to the research that developed around the 60s and 70s by Louis Kahn, e.g. at the *Yale Centre for British Art*, where the architect produced specific assessments, accompanied by a wide-ranging theoretical discussion:

'It is light which, when it stops being light, becomes matter. All matter is light. Light is the donor of every presence' [23].

3.2 The Italian experience

The Italian architectural tradition, from the Classical era to the Renaissance period, up to the scenographic practices of the Baroque, has its roots in a context in which natural light constantly affirms its presence, determines the form of the constructed space and its variable glimpses, never the same twice, and because of this unique and unrepeatable.

Great modern masters made this natural constant their own, through formal subtleties that allow us to glimpse an awareness very close to the techniques of Daylight Assessment, or by putting forward proven solutions from secular experiences unwittingly, the fruit of a deeply rooted cultural heritage.

Among the most admirable ambassadors of this representative capacity through light, Ignazio Gardella makes the theme of the articulated treatment of surfaces and light as a tool of spatial composition his own.

Reflecting on the implications that light plays in the Italian scenario, also Carlo Scarpa represents an incarnation of that architectural mastery which is able to guide the eye towards an understanding of the elements denoting and connoting the space of his creations.

The architectural light that Scarpa used gradually dissolves the box-like space of the environments while the declination of the light rays on the surfaces projects visions that are always new and different from one another. Scarpa succeeded, in this sense, to shape light as if it was *solid light* [24], as he himself describes to explain his famous angular window used in Possagno, 'the edge glazing is a blue block pushing upwards' [25].

Scarpa's compositional and material skill lies therefore in maximising the expressive potential of natural light within architecture thanks to which he came to obtain stunning plastic, tangible and chromatic effects: 'What I want to say is that sense of space is not communicated by a pictorial order but always by physical phenomena, that is by matter, by sense of mass, the weight of the wall. This is why I assert that is the apertures, openings and orifices that create spatial relationships' [25].

The light alone defines the dimensions of the space, thereby altering perception without changing the setting's volumetric system. Scarpa manages, with brilliant skill, to cope with the uncontrollable variability of the sunlight, releasing it from the position of the observer, so as to offer perceptive angles that are constantly new and unexpected.

Among the most significant examples of the use of light, the project for the *Brion Tomb* is emblematic of the poetics of Scarpa, where the theory of small windows along with a further aperture at the foot of the dome, light up the altar (Fig. 9).

And once again the spatial definition of the box-like volumes and the works exhibited at the *Palazzo Abatellis* in Palermo, is articulated by virtue of the incoming light.

The uncontrollable dynamism of the Mediterranean light makes it possible for Scarpa to play with the perceptual mechanism of observers in motion, in such a way as to create a symbiosis between the modulations of the sunlight and the subjective perceptions, so as not to alter the composition of forms and figures, but evoke continuously changing suggestions.

'The visitor, who comes from the double-faced room of the chapel, is first attracted by the chiaroscuro game of the outline, three-quarters illuminated, then is urged to move around the bust feeling its volumetric implications, and is ultimately directed by the dynamics of the gaze towards subsequent stations along the route' [25].

Daylight, as a spontaneous element of architectural expression, is also realised in complex games of blendings, duplications, transmutations and negations, through the architectural use of solar radiation, in the works of Franco Purini.

The architect himself reveals his deference towards sunlight, for its creative and descriptive value, which Mediterranean architecture cannot ignore: 'Light is the closest thing to the idea of the divine that it is possible to know. It is indeed the divine essence of the world. It is an intangible thing, an incorporeal phenomenon translated into a conceptual oxymoron, in an experience of abstraction that literally coincides with beauty' [26].

The constant references to light in the theory and practice of Purini reveal an in-depth theoretical research in respect of an impalpable instrument, which finds its maximum tangible

Figure 9: Brion-Vega Cemetery, San Vito d'Altivole, Carlo Scarpa (credit Seier+Seier).

expression in the creative process of art and architecture, in as much as it constitutes the founding sign for the understanding of space.

The light separates, establishes differences and confers identity. It arouses by isolating, creates by dispersing. In this showing of its diversity among the things it reveals its hostile side, turning to the representation of what there is at the end of the irreducible, in the difference. Coinciding with truth, light is in fact where contrasts subside. But at the same time that they become recognisable, they remain indefinitely: light is therefore constant contradiction, immutable insolubility.

The opportunities inherent in the architectural, creative and revelatory use of light collide with the need to properly calibrate its variable contribution, through a simple but intuitive approach to Daylight Assessment, as Purini himself stresses in his writings

'Obstructing the light in its liquid pervasiveness, excluding it, therefore, is necessary but not sufficient: it is necessary that the architect removes its ability to represent and recount by attenuating its emotional outcomes and reducing it to a logical size. Indeed theological.

The architectural light, the light of architecture, is then a cold and distant current, a passionate but frozen fluid, a classical and heroic voice, Davidian, measuring weights and distances […]. Light coincides with space' [26].

Awareness of the compositional possibilities of the beam of light due to the multiple meanings of Mediterranean light then evolved in the works of Paolo Portoghesi, whose celebrated *Mosque* *in Rome* (1984–1995), takes on the role of a manifesto of a real poetic of architectural light at the service of Mediterranean light, connoting and denoting element underlining meanings and confined spaces.

'In the Mosque of Rome the concept of *light from light* of the Koran has been translated into a dual presence of light: as indicator of privileged orientation and a system of light reflection in which the architectural elements serve as mirrors channelling light, concealing its direct sources' [27].

3.3 The experience of Central Europe

In Europe the most significant experiences in relation to light experimentation assign a diminished role to Daylighting strategies, for the most part integrated with artificial light sources, due to the large variability of natural light in the daytime and in the summer season.

The exaltation of form and the definition of the quality of materials can only be done through light: having exhausted the attention to artificial light as the only possibility to illuminate spaces, the 20th century saw sunlight resurfacing as an eloquent, dynamic and variable tool of representation. The architects wanted to ensure their works an added value derived from performance linked to natural light, without which architecture itself does not exist.

Among the most important testimonies, Le Corbusier had the merit of reflecting fully on the impact and exploitation of natural light in the confined space project. The evocative power of light for the representation of articulated spaces, able to evoke complex and variable sensations in response to its inconstancy becomes an integral part of his creations (Fig. 10).

'We want to create a place of architecture made of materials, light, and proportions, in which room can be found for works of another emotional potential, works that are dense and strong and from which emanates the power of thought or emotion' [28].

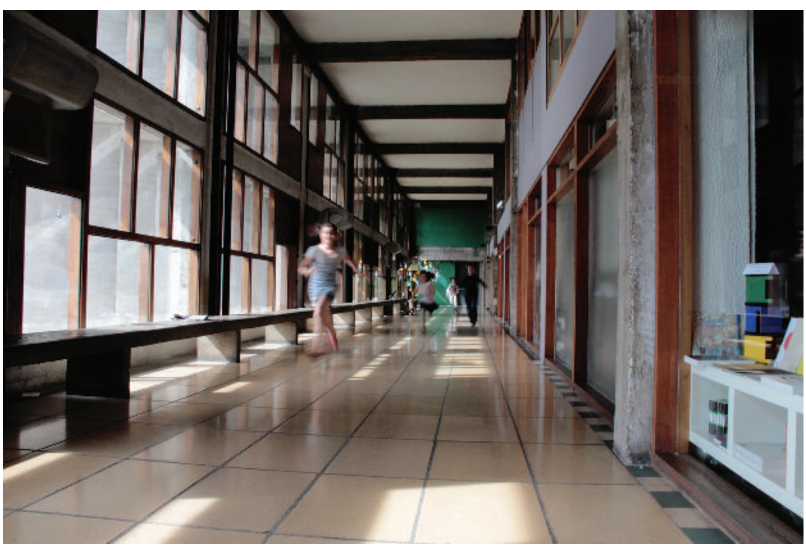

Figure 10: Unité d'Habitation, Marseille, Le Corbusier (credit Lisa Lorenzini).

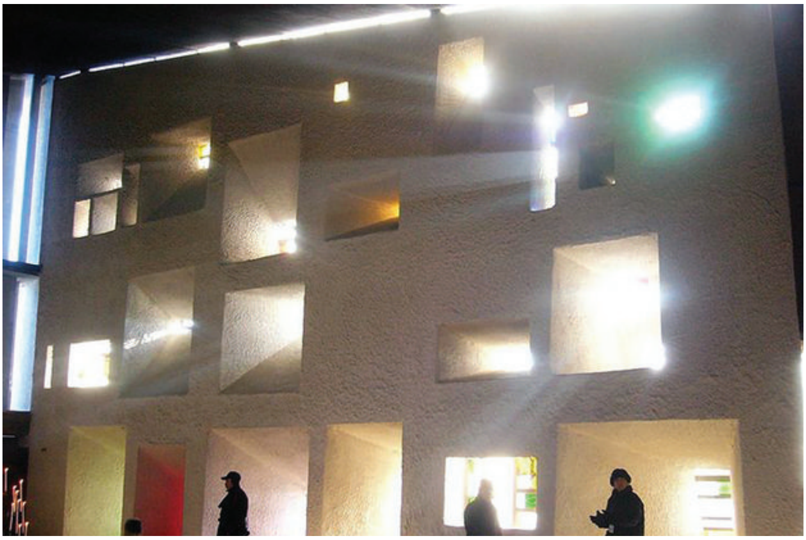

Figure 11: Notre Dame du Haute, Ronchamp, Le Corbusier (credit elyullo).

The artistic treatment of light, devices with a shading or illuminating function are what distinguish Le Corbusier's projects, becoming instruments to calibrate and modulate light, which is cleverly concealed or integrated with the constructed form and distributed like a veil over the surfaces.

It is therefore extremely simplistic and inaccurate to bring the architectural identity of Le Corbusier, like so many other masters in the same period, down to a single geometric question of form, just as it would appear unproductive to produce an assessment focusing solely on the technical innovations of his projects, given that light remains a central milestone of his poetic complex, as he himself admits: 'there is no doubt that I am making abundant use of light; light is, in my opinion, the basic element of architecture. I compose with light' [28].

The symbolic and spatial use of light reaches its culmination in the complex arrangement of apertures for *Notre Dame du Haute* in Ronchamp (1950–1955), in which Le Corbusier seems to want to reinterpret the articulation of light in Italian Renaissance chapels, one of the first examples of the scenic use of natural light (Fig. 11).

'In the interior, I imagine a symphony of shadow, of light and shade materialised in a rough epidermis of sprayed plaster, entirely covered with the milk of lime white. The needs of worship intervene here in just a few things. The natures of the forms were a response to the psycho-physiology of the sensation' [29].

The cadence of articulated lights and shadows, and the game of the reflections on the rough materials of the interior surfaces thus characterise some of the projects of the Swiss master.

Similarly, the creations of Mies van der Rohe are distinguished by the strict simplicity of forms, which is equally reflected in colour choices and the desire to encourage the pure essence of the light as much as possible. In contrast to some of his contemporaries, it is not possible to affirm that Mies evaluated a true strategy of natural illumination, but rather, it is clear how he preferred to use natural light as a tool for the enhancement of the surfaces, a means to control the plasticity of form.

The difference in approach between the poetics of Mies and those of Le Corbusier as regards light as an expressive medium and creator of form can also be identified in the essentiality with which Mies employed holes in the masonry.

The compositional potential of light for Mies lies in games of reflection of light onto materials to affirm that reflection and diffusion are more important than the light itself, including the extreme exploitation that light represents through the transparency and reflections of glass.

For Mies, the architecture of the light means light filtered through glass, and transparencies: 'In the hands of Mies *the primitive obscurity* of crude constructions is truly transformed into its counter image: it acquired a crystalline elegance of great simplicity in design, which allowed *one hundred percent architecture of the light* on the basis of a high level of technological culture, without which Mies' visions could not have developed' [30].

3.4 The experience of Northern Europe

The discussion on the use of natural light and its capacity as an expressive, formal and instrumental vehicle for the plastic modelling of surfaces has been developed in the works of architecture of the Nordic regions, according to the so-called *Nordic Light* approach.

Many theoreticians and architects have looked into the issue and in particular on the actual existence of a 'northern light'. With the term *Nordic Light* there is a tendency to define, not only the light at higher latitudes, but the set of all the design and technology processes that relate to the choice of the arrangement of apertures in relation to the variability of the light. The dispute is still open, and there continues to be discussion of the validity of such a definition, as well as the concrete applicability of specific strategies for *Nordic Light*.

In the case of works of architecture located in high latitudes, the light plays a very different role compared to the consolidated situation in middle latitudes.

The presence of diffuse light for long periods of the year and the different distribution of light radiation makes a radically different approach necessary: the primary requirement remains to convey the greatest amount of natural light as possible and spread it in depth, at the same time ensuring greater solar gains and thermal loads.

Experiments concerning the use of light as a creative and vivifying tool in Nordic architecture has permeated many projects, from dwellings to public buildings, in which the expressiveness of white light and translucent reflections reached its apex.

The relativism of the architecture of Alvar Aalto, viewed from the perspective of daylight, symbolically represents the synthesis of the relationship between architecture and northern light.

'Architecture is usually understood as a visual syntax, but it can also be conceived through a sequence of human situations and encounters. Authentic architectural experiences derive from real or ideated bodily confrontations rather than visually observed entities' [31].

The historical development of the techniques of representing space in Scandinavian, specifically, is intimately linked to the development of architecture itself, and to the perspective understanding of space: In this case, we can speak of a genuine architecture of vision, oriented to multiperspective realisations in which the light, albeit weak and faint, envelops the viewer, as not even the warm and collected Mediterranean light manages to do.

The projects of Aalto base their spatial and perceptual essence on the light source which, in a country paradoxically deficient in natural light for most of the year, must necessarily be integrated by artificial light. In the projects for the libraries of *Viipuri* (1927, 1933–1935) and *Saynatsalo* (1949, 1950–1952) can be identified the beginnings of complex zenithal devices to diffuse the light, which take the form of skylights and other light sources, affirming the use of a primitive 'Daylight Assessment', that allowed Aalto to analyse more accurately the angle of light rays in relation to the vision to obtain the interior spaces.

The same process of preliminary analysis on the presence and effects of natural light that permeates the reading rooms by means of systems of *toplighting* and *sidelighting* is also found in many subsequent projects: 'The lighting of the library at Saynatsalo was resolved with large windows facing south. These are located above the shelves of the libraries, to give them a sufficient size, the slanting ceiling rises precisely towards the south. But given that the direct light from the south is unsuitable both for books and the eyes, to screen it partially, the windows were equipped with dense slats of dark wood' [32].

The windows of Aalto, as can be seen in the *Stockmann bookstore*, defined by the architect himself as *solar windows*, almost as if to emphasise the vital function of the same in capturing the unequalled power of sunlight, are placed on the roof, where the incident radiation is greater in those latitudes, causing an evocative and shocking effect, as if 'enormous pieces of ice were trying to pierce through the roof' [32].

The *library of Wolfsburg* embodies a successful attempt to design a space bathed in zenithal light that pervades obliquely from the roof the reading space below and is then reflected from the texture of the side walls, creating the illusion of a space in full light, a sensation that Aalto himself defines *permanent stability*.

In a large part of Aalto's repertoire of construction (Fig. 12), it is easy to identify the constant tension for the search of a suitable use of light, both from an architectural and perceptual standpoint to solicit the attention of the users and facilitate the visual task. His writings and design research focussed in particular on the spaces for reading and study, where the amount of the light must be constant and rendered harmonious in its time variations, via the games of reflections from the surrounding surfaces. Within the Nordic architectural context, where natural light is so scarce as to be considered a valuable asset for the definition of spatial functions, Aalto does not limit himself to simple theoretical speculation, but applies to his projects the concept of visual comfort for a specific task.

The visual function is elevated to a fundamental theme both for the formation of space, and for the subsequent enjoyment: The awareness that a library should be well-lit and technically functional gives way to the question of how it can be regarded as humanly and architecturally complete, to meet the needs of reading.

Figure 12: The Stokmann bookstore, Helsinki, Alvar Aalto (credit Jean-Pierre Dalbéra).

Aalto's sensitivity to light was born in the wake of a general trend that relegates the performance aspect of interiors to a secondary question: The rationality of Aalto's construction approach and lighting lies in the quantitative and qualitative definition, defined on a human scale, of integrated systems of zenithal and artificial lighting, to ensure 'A light that is mixed, reflected and diffused by the tapered walls of the skylights, which is extremely suitable for reading' [33].

It seems correct to trace in this type of design approach the germs of a modern design of a dynamic type that is designed to investigate the time and seasonal variations of light, an approach that today is found in early attempts at validating dynamic analysis based on the weather. Might we find in Aalto's architectural practice a first attempt to provide precise answers to the complex issues of Daylight Assessment, both from the point of view of a quantitative and qualitative approach?

Aware of the profound changeability of Nordic light, Scandinavian architects, from Aalto to Fehn, have experimented with luminous solutions and material textures that developed the amount of natural light in constructed spaces, playing on the size of apertures, the colours and spatial articulation. The obsessive search for light has produced outstanding examples of architecture in which each element is aimed to maximise the amount of incoming light, through diffusing elements that direct diffuse radiation in distance and depth.

'If you build in Greece it is the light itself that creates your architecture. Just scratch the surface of marble with a fingernail, that scratch remains visible, while up there, under the northern light, it wouldn't. These factors mean that our architectural world has no shadows […] each material has its own shadow. The shadow of stone does not resemble that of a brittle autumn leaf. The shadow enters the material and radiates its message' [34].

Figure 13: Nordic pavilion, Venice, Sverre Fehn (credit Frans Drewniak).

Curiously, Fehn's compositional skill with natural light reaches its culmination in a project context far from the Scandinavian world, namely, the *Pavilion of the Nordic Countries* in the gardens of the Venice Biennial, built in 1962, with the chief intention of transforming Mediterranean light into an atmosphere of the North. The typical treatment of Nordic light is transposed to the Mediterranean context with amazing results as regards perceptions of space and the spectacular effects of the light, in an exhibition context; this is a room with a square base, whose roofing is made with close beams of concrete, but made light-permeable, characterising the pavilion from a structural and formal point of view: 'Crossing the double order of the roofing beams, the intense light of the lagoon undergoes a magical metamorphosis, and transforms into a homogeneous light, without shadows, as creeping as that of Nordic countries' [34] (Fig. 13).

As has been observed by Paolo Giardiello, the key question for the Scandinavian world, is not the continuous struggle to search for light, but rather the Nordic treatment of the light-shadow relationship and of its mutual relations with the constructed space; the correspondences that are created between closed and covered spaces and the presence of natural light are summarised in the image of the umbrella, under the shade of which the key game is played out between the light and the spatial relationship defined by the constant antithesis of the shade [35].

The psychological potential of the light-diaphragm-shadow ratio in Fehn's works of architecture therefore represent the perfect synthesis of the relationship between Nordic architecture and daylight.

In the diaphragm that is born where the shadow line leaves room for the brilliance of the light, is found the architectural and spatial search of many Nordic masters, whose goal is to establish the correct amount of light, through the use of the variable strategies of Daylighting, not to undermine the quality of the radiation, but to accentuate its flexible and variable nature.

Both in projects for dwellings, and in projects for exhibition spaces, Nordic light fully acquires role of creative tool and construction material; simplicity and discretion in the geometric and spatial composition of the apertures, as well as attempts to diffuse the light with devices oriented to the path of the sun alternate, through a search for formal solutions and innovative techniques, which are designed to enhance the natural rhythms of light and darkness.

'Bare areas, along the perimeter wall, bathed in light contrast areas marked by shadows and penumbra created by means of translucent panels positioned between the high laminated wood beams. It is thus that the places inside are exclusively obtained by modulations and nuances of light' [34].

3.5 The U.S. experience

In the contemporary U.S. panorama, the experiences related to the use of natural light are not very dissimilar from those mentioned previously on a European scale, apart from complying with specific solutions of Daylighting belonging to theories and architectural trends that originated there.

On the one hand, the aesthetics of the skyscrapers, the grand constructions and the extended and multifunctional shells, on the other, the transparency of the shell, split between the need for aperture to the outside and protection from excessive sunshine and heat, became the challenge that U.S. architects had to tackle for over a century.

In this sense, we owe to Colin Rowe, among others, the merit of having defined the concept of *transparency*, in close relation to the themes of natural light and the issues of Daylight Assessment.

Thus was a revised concept of transparency evolved, as a synonym for brightness, to be applied in architectural and artistic fields.

Thus *literal transparency* concerned the representation of translucent objects in deep spaces, while the *phenomenological transparency* [35] belonged to the representation in abstract, non-natural spaces of objects aligned frontally and arranged with respect to a shallow depth.

The discussion therefore re-examined the fundamental difference subtended to the two terms associated with the concept of transparency, but sharing the idea that transparency and, consequently light, were essential tools of organisation and spatial definition, essential for the interpretation of space.

The spatiality of the construction, whether small or large-scale, can be changed and altered through contractions and expansions in virtue of the characteristics of their own shell, which can appear transparent to light, letting enter large quantities of it, or aperture up to slender rays of light. According to this logic, even the idea of transparency related to apertures and the use of transparent materials found numerous examples in North-American architecture.

An expressive medium and construction foundation, in the U.S. context light is therefore closely linked to the very existence of the skyscrapers, which originated in the United States.

'The skyscraper is therefore, in the penumbra, a sparkling vertical prismatic form, a veil of gauze of a festive scene, which descends against the black backdrop of the night to dazzle, entertain and amaze, in large masses.

Lighted interiors transpire from the veil exuding a sense of life and wellbeing.

The city then seems living.

It lives as illusion lives' [36].

The skyscraper becomes a testing ground, both in terms of transparency during daytime and in the treatment of the immense glazed surfaces during the night. The intensive use of glass allowed, on the one hand to experiment with new strategies to manage daylight, on the other, it raised issues of great importance, for shading and shading needs.

Among the greatest U.S. leaders to be a spokesman of innovative application solutions on the use of natural light in architecture was Louis Kahn, master in the use of geometric shapes, whose plasticity is exalted by the knowing use of natural light.

Kahn's innovative contribution resides in his compositional skills, which enabled him to calibrate simple geometric shapes in buildings made of reinforced concrete that are seemingly cold and detached. The use of light in these discordant contexts assumed the form of a complex, detailed and evocative spatiality.

Taking to the extreme both the structural system and the potential inherent in the materials, Kahn grasped the full potential of an architecture that went beyond its own formal limits, to open up to new expressions through the use of natural light, which is the key to ensuring satisfaction of the functions to be realised for the comfort of the building's occupants.

The description of the *Kimbell Art Museum* in Fort Worth, Texas (1971), clearly shows that, in spite of the structure being based on the creative intuition of cycloid vaults, as technological and formal solutions to roof the exhibition halls, the essence of the project rests entirely on the changing and dynamic effects of the light, which defines the interior space and its functions (Fig. 14).

'No space, architecturally, is a space unless it has natural light … I am designing an art museum in Texas. Here I felt that the light in the rooms structured in concrete will have the luminosity of silver. […]

This light will give a glow of silver to the room without touching the objects directly, yet give the comforting feeling of knowing the time of the day […] Rather than a new way of calling something; it is a new word entirely.

It is actually a modifier of the light, sufficiently so that the injurious effects of the light are controlled to weather the degree of control now possible' [23].

In this specific case, prior to the lighting design specific knowledge is assumed of the varying effects of natural light in relation to the hourly and seasonal fluctuations and the precise effects that it may cause on the objects on display in the rooms of the museum, and for the constraints that Daylighting might inflict on the occupants.

Therefore this is a case where Daylight Assessment is integrated initially in the design, in relation to the optical possibilities offered by the geometric shapes and finishing materials, which play an essential role in determining the interior luminous effects.

Kahn's attention to the theme of light as a building material in the same way as reinforced concrete, widely used in those same years to realise his creations, highlights an accurate assessment of the problems related to the management and use of solar radiation, developing its use in complex and in a certain sense avant-garde poetics, that consider light as the only source of illumination to vivify the spaces.

Figure 14: The Kimbell Art Museum, detail of the clear-span cycloid concrete shell, Louis Kahn.

Knowledge of the optical perceptive effects of light, in relation to the human eye urged Kahn's project to embrace knowledge of the nonvisual effects of natural light on an individual's general sense of wellbeing in a space designed to be illuminated by daylight.

'A man with a book always goes toward the light; this is the beginning of a library.

That man will not travel more than 15 metres to reach the light of a light bulb. The table on which he reads and the niche that might originate the ordering of the space and its structure. In a library the column always comes from the light' [37] (Fig. 15).

Natural light in his projects is an integral part of the design and programming related to the use of the building. The first director of the Kimbell, Richard Brown, expressed significant doubts about the use of natural light in an exhibition space.

According to the conventions then consolidated, natural light distracted the visual experience of the spectator from the observation of works of art: Kahn refuted this theory, demonstrating how integrated design, which would require a preliminary survey of the daylight, enabled the achievement of effects of natural zenithal light, diffused and reflected, which enhanced the objects on show and made the visual experience of the spectator unrepeatable and comfortable.

Among the most significant works for the use of natural light, and compositional and technological choices for the creation of interior spaces, the *Philip Exeter Library* in Exeter, New Hampshire, must be mentioned.

Figure 15: Interior of the Philip Exeter Library, Exeter, Louis Kahn (credit Kathia Shieh).

The zenithal light that spreads from above allowed Kahn to subvert the traditional structures of libraries, allowing him to organise the reading rooms on four levels around an open well in the centre, from which the light spreads in continuous variations of light and shade, without affecting the stored books.

The different internal spatial articulation builds on the needs to light the rooms, while the niches for reading arranged along the sides; specially designed shielding elements, offer the possibility to modulate the amount of incoming natural light.

The arrangement of the roofing responds to the needs dictated by an in-depth analysis of light boundary conditions and provides a zenithal lighting that is never direct, but rather a light that is reflected and scattered, thanks to shading and diffusing elements, together with a careful choice of interior finishing materials. The light does not have the role of a simple functional element, but expresses the natural material thanks to which the form is revealed and draws motivation, while the direction, and the way in which is modulated, reveal the building's symbolic value.

Richard Meier, one of the most prolific American architects, and a profound connoisseur of the aesthetics of light, also expressed the spatial value of his buildings through the vibration of light, an element that makes the materials used alive and bright, on the basis of his profound admiration for the works of Borromini.

'For me, daylight is the key. Daylight is the protagonist of this church and daylight will emanate from the skylights above and will also bounce off and spill around the walls in the shells of the church. It is the light that accentuates the curved forms. The light creates atmosphere. And the interior of the church is constantly permeated by light, and the white concrete shells subtly reflect this palette' [27].

3.6 The experience at low latitudes

The use of sunlight in tropical and subtropical countries has always been an element inherent to architectural design since, where light plays a predominant role, precise measures are required for protection from the sun, long before accentuating expressive and compositional peculiarities.

At low latitudes the incessant amount of light radiation during the day and in different seasons represents a constant that architecture always has to deal with.

Daylight Assessment in contexts of this type constitutes an indispensable preliminary tool for correct design and subsequent management of the apertures, and at the same time the necessary shading and shading systems that must actively cooperate to provide refuge from excessive illumination and thermal overload.

In this situation, the activity of Luis Barragan reveals itself among the most emblematic for the function he attributes to light in the Mexican context, where solar radiation is conceived as a problem to be mitigated, rather than a resource to be exploited. Barragan's works of architecture draw strength and vitality from two essential materials and from the mutual relationships they create: light and water, as can be seen in *Casa Gonzaléz Luna*, in Guadalajara.

Both these natural elements become the fundamental constitutive engine and raison d'être of the design of the famous *Casa Gilardi* (1975–1977) and *Villa Valdez* (1982–1984), in which sunlight becomes a construction material to all effects and purposes, and also a surface finish, a veil that covers all the surfaces and alters the perception of them through colours and different textures (Fig. 16).

Emblematic as regards the use of light is the *Convent of the Capuchin Sisters of Tlalpan* (1954–1959), often compared to Tadao Ando's famous *Church of the Light*. If on the one hand the parallel picks

Figure 16: Casa Gonzaléz Luna, Guadalajara, Luis Barragan (credit Elisa Abati).

Figure 17: Interior of Capuchinas Chapel, Tlalpan, Luis Barragan (credit Armando Rosado).

up on the similarities in the treatment of materials and the value assigned to the natural light that filters through slits in the massive surface of the roof, on the other hand it does not take into account the inherent differences linked to the value of the light, itself an epiphanic element and life-giver, as a direct evocation of the presence of God.

The purpose of Barragan's design, through the calibrated use of light in the chapel is to recreate an atmosphere of meditation and contemplation, a goal that could scarcely have been reached in the presence of high levels of illumination (Fig. 17).

'He thought that the light that pervades a cathedral was not intended for the eyes, but for reason, reflection and an echo of the divinity, not a mere visual effect but a rational evocation of a presence […] inside the convent he made the central patio the dominant light source and the place for communication between the closed environments and the sky' [38].

The filtering and shading system becomes fundamental in Barragan's architecture, not a simple secondary system, but a tool to manage direct light and identify the project itself.

'The light filtered by a grid that concludes the triangular space on the opposite side of the nave laterally illuminates the cross […] But Man is not permitted to look at the light directly, but only through the mediation of the cross, which, in the chapel, carries out this fundamental function. The whole building coincides with an apparatus that precisely filters the light' [38]. The principles underlying Barragan's works are openly declared: The weightiness of the material and the stone are highlighted and at the same time denied by the presence of a light that is specially filtered and then directed towards the objects, almost as if wanting to upset the natural order of things.

Gravity, light and time also feature in the Spanish works of architecture of Alberto Campo Baeza, become elements through which the material textures, interwoven with light, bring to life the architecture of complex spaces.

'Light is a material. It lets the constructed space and man relate.

Light *wakes up* matter, which is dormant. Only true architecture can *wake up* and begin to express its own value. Everything that is not architecture continues to sleep remains insignificant' [39].

The a-temporal value of the light is an essential fulcrum in architectural composition, as can be read in the many theoretical contributions that reveal the role of Daylighting: Natural radiation, so abundant and inherent to the culture of Campo Baeza, plays a decisive role in the definition and use of space, drawing inspiration from Classical examples of great power, such as the Pantheon in Rome, an absolute and unrepeatable reference, a model to aspire to: 'Gravity builds the space, Light builds the time, makes Time right. Here are the central issues of architecture: the control of Gravity and the dialogue with Light.

The future of Architecture will depend on a potential new understanding of these two phenomena' [40].

Collaboration with the colour white becomes an archetypal element for the whole of architecture at Campo Baeza, in whose realisations the finishing treatment in white is made even more blinding by the skimming light that covers the interiors with horizontal, oblique and variable beams, according to the principle that light is: 'The supreme principle of architectural structuring and spatial qualification' [20].

Particular interest among architects and critics arose regarding the concept of 'structural light', to be found in the works at Campo Baeza, a subject to which Alberto Morell Sixto devoted a sweeping critical analysis, suggesting how the idea of making an intangible and authentically natural element like sunlight a supporting structure for the definition of architecture, redefines the logic of composition and surface treatments.

In this sense, the most effective example is that of the *Caja General de Ahorros* in Granada (1998–2001), a work in which the relationship between structural materials and light is achieved clearly, and defines the poetics of Campo Baeza with simplicity and naturalness.

The massive presence of opaque and heavy reinforced concrete, which provides a perception of colour and texture that is always the same, is altered and enhanced by the fluid light, which helps to lighten the solid material *par excellence* and make it inexplicably ethereal.

Daylight Assessment arranged on the basis of the needs of the geographic context and in tune with the desire to alter the perception of materials such as reinforced concrete, induces the architect to use multiple light beams, differently angled, reflected and refracted, to the extent of losing individual directions and points of origin.

'Many times we forget that the light inside a building is a summation of the inclined luminous beams that rotate throughout the day. Without a doubt, in this building, all its constituent elements, fullnesses, voids, stairways, structure and material, are composed and ordered around the angle and rotation of the light. It is not that the space is different and that the light passes through it diagonally, as usually happens, but it is the space that is diagonal to receive the light: as if to say that the space becomes light' [20].

The handling of the light in a context that is strongly lit in a concentrated and diffuse way demands precise demands in managing the apertures in the shell: The inclusion of shading elements, essential to manage the light, and create internal scenographic effects.

The architect must therefore anticipate the effects of the light, allowing light rays to permeate space only after a thorough preliminary analysis. Nothing can be left to chance, nor to the natural hourly and seasonal variations: The light cannot be passively suffered, but must be put to work to define the space.

4 Daylighting between the project and definition of space

It was Kepes who first delineated a *grammar and syntax of vision*, emblematically outlining the importance that light plays at the moment of the architectural process, the stages of design and creation, and the subsequent use by its occupants: 'we live in the centre of a vortex of light quality. From this whirling confusion we build unified entities, those forms of experience called visual images. To see a picture is to participate in a formative process; it is a creative act' [41].

The dynamism and flexibility demanded today of a built space cannot be divorced from a dynamic use of light, not only as a simple tool for the vision of space, but as a means to continuously vary the perception of it.

Natural light, in a strictly architectural key, must therefore cover a twofold function: spatial and visual connotation.

In a large uninterrupted space, natural light acts as a tool to define the spatial limits, ignore the boundaries or amplify the extremities; the rays of the sun impress on the space on which they insist, an imperceptible dynamism, even in the case of a more modest size and with the assumption that the user remains still in the given environment.

The intangible element *par excellence*, without artifice or optical tricks, becomes the substance and as such, corporeal and experiential, as in Turrell's spatial experiences.

'What interests me is the possibility of building the space with light even more than with any other material, I am interested in the way in which space forms depending on where the light falls and how this building up relates to us' [42].

The spatial effect obtained dilates the confined space beyond the limits of the material, denoting one continuous space, but difficult to identify as concluded. Spectators within his installations are thus compelled to a perceptual effort to discern an apparent phenomenon of the optical type, which tends to fade continuously in a real vision, as if these were homogeneous fields of dynamic coloured light that constantly change.

Otherwise, in the small fragmented space, the measured use of light may be used architecturally to confer a sense of unity and conclusion on a space, thanks to the presence of light coming from different sources, that interrupts the path and that defines the boundaries between darkness, light and penumbra.

The unexpected entrance of the light and the dynamic variables of the shielding establish additional parameters to be taken into account in the realisation of the areas illuminated naturally.

The question of Daylight Assessment demonstrates how different strategies need to combine in a comprehensive and integrated approach that takes into account many factors, from local, geographic, meteorological and climatic aspects, to optical and perceptive needs linked to the sensation it is intended to give the environment, in addition to the requirements to connote a space that is concluded and accessible, by means of the light that illuminates it.

Understanding the multiform possibilities offered by natural light in architecture means taking a cue from the many historical experiences, which have their roots in construction practices that are distant in time and space, to achieve a new orientation, one that cherishes the intuitive approach to develop a scientific discipline, and that includes aspects of spatial and formal research.

The experiments of the past make evident the incongruity of an approach that focuses exclusively on the question of constructed geometric form, as it likewise seems unproductive to reflect exclusively on technological systems with which to check, calibrate and manage the light.

The natural evolution on the compositional and technological plane of architecture responds to more complex demands, that are necessarily articulated according to a multidisciplinary approach, open to new contexts, in which space is connoted in relation to function, the variable demands of the user, and, last but not least, to the demands of the changing nature of the light.

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Chapter 2

Daylighting, architectural strategies compared

1 Daylighting techniques and other devices for daylighting

For centuries, from the first construction experiences, natural light was used to illuminate spaces by optimising the amount of incoming light radiation, maximising the evocative effects of the light being projected onto the interior walls, from zenithal apertures and any other device that allowed exploitation of solar radiation, to view, heat and define the space.

Architecture has always been dominated by the need to create efficient systems to let light enter environments, without interfering with the composition and design of the façade, interacting in an optimal manner with the articulation of the volumes.

The challenge of the natural light project is, therefore, to be able to communicate stylistic and compositional needs with those of size and energy, with respect to the apertures in the building envelope.

From the ancient caves used as a primordial shelter to today's buildings, passing via the complex operations of recovery and energy retrofit, the theme of natural light is a challenge for both the architect and the builder: It is the light that defines our lives, regulates our existence and controls individual responses in relation to the surrounding environment.

Treating natural light as a building material, as a strategy to ensure interior comfort and energy savings, actualises a challenge that involves architecture as a whole, the design of interiors and the design of the shell.

The history of architecture is inextricably linked to evolution of the shape, size and technology of the apertures in the shell building envelope, be they windows, skylights, zenithal oculi or any other device that has been used for Daylighting: From the windows constructed in the first residences, to the slots of medieval churches, to the spatial articulation of the apertures in domes of Baroque architecture, up to *la fenêtre en longeur*, a true emblem of modern architectural theory from Le Corbusier onwards.

The choice of materials, dimensions and positioning are only some of the technological issues to be analysed for the construction of windows, transparent façades, glazed atria, that is, all the apertures in a building's shell to allow the light to illuminate, heat and circumscribe the space within (Fig. 18).

In the following description the intention is to give room to those systems that are predominantly of a passive type, without mechanised or electrical elements for natural light.

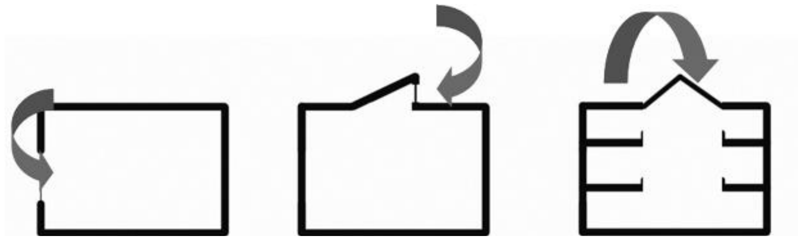

Figure 18: Daylight techniques: Sidelighting, Toplighting and Corelighting.

1.1 Sidelighting

With the term *sidelighting,* does it mean a vast system of architectural solutions that include side windows only on one or more fronts, as exclusive means to provide natural lighting.

The techniques of *sidelighting* envisage the use of vertical windows to allow natural light to enter; unlike other techniques such as *toplighting* and *corelighting*, *sidelighting* is co-responsible for numerous problems related to the excessive heating of the areas near the apertures and irritating dazzling phenomena in the vicinity of these.

Solutions of *sidelighting* most easily suit buildings that are oriented east–west or towards the south, since they can ensure direct solar gain and provide constant illumination all day (Fig. 19).

In order to illuminate a room from one side only, the mechanisms to be taken into account are the correct design of the aperture, an adequate size and the positioning, with respect to the morphology of the interior space and the façade.

The actual distance natural light can cover from the time it enters an interior – in the case of glazed apertures on only one side of the room – is rather limited and closely dependent on the width of the window itself, the depth of the room, and the presence of obstacles inside and outside.

In the case of buildings with a ratio of about 1:2 between the surface of the floor and the usable height of the ceiling, the solution with sidelighting from the front only ensures a potential level of illumination sufficient for most visual tasks; instead, in the case of different and more complex spatial configurations the sidelighting solution on only one front is greatly lacking.

In cases where the height-width ratio of the room exceeds the ratio 1:2 by about 25%, the difference in brightness between the zone immediately facing the window and the central part of the room will be considerable.

Due to the fact that the human eye is able to adapt very quickly to changes in brightness, thus accommodating the contrasts in illumination present in the room, the perception of darkness and irritating dazzling phenomena must be attributed to a general lack of brightness along the length of the room.

To compensate for a possible absence of uniformity in illumination it is possible to use two different strategies, to be adapted according to the specific visual and luminous requirements of the room.

Figure 19: Different types of sidelight solutions.

The depth of the interior should be as small as possible in relation to the size of the fenestrated front, in order to ensure a good level of homogeneity.

Alternatively, in cases where this ratio is unfavourable, it is necessary to use other types of lighting, whether natural or artificial.

Horizontal windows provide the largest amount of illumination for an equal size, especially in the absence of internal or external obstructions that threaten to restrict the penetration of solar radiation.

The greater the height of the aperture, the more chance the sun's rays will have to penetrate deep into the room and be reflected off finishing materials and objects.

At the same time, it is necessary to bear in mind that a position that is too high with respect to the floor may deleteriously affect the view of the outside, creating disagreeable effects of disorientation and discomfort.

The most suitable configuration to satisfy these needs is therefore the horizontal window that develops along the whole length of the exterior of the room, in line with the 19th century tradition that included this type of aperture especially for industrial buildings, to guarantee an adequate level of lighting for the workers inside.

More evolved solutions in the case of sidelighting strategies on only one front are windows with a clerestory, that is, high windows that provide light predominantly in depth, and avoid problems of discomfort glare, being positioned higher up than the eye of the occupant.

A successive development of the window for sidelighting is the full-length window, a technological and formal solution that has marked the development of numerous architectural trends, together with the appropriate technical solutions to overcome problems such as excessive illumination or overheating in warm weather, resulting in the development of new shading systems, films and glass to control incoming solar radiation. In the case of a solution with a double-fenestrated front, the complexities increase and particular attention needs to be paid to balancing the luminous variables arising from multiple sources [43]. It is desirable that windows, regardless of their shape, are arranged along the highest part of the wall, since the distance covered by incoming sunlight is equal to one and a half times the height of the window itself.

It is preferable to provide continuous clerestory windows for deeper solar penetration of the room, in order to ensure greater uniformity in illuminance levels. This solution allows separate control over the operations of aperture up and darkening of the room in relation to the visual tasks to be performed there.

Where possible, windows should be distributed on several fronts; windows should be positioned near interior walls to reduce the contrast in brightness between the windows and the walls themselves; other preferred solutions are ones that filter direct natural light before passing through the window. Lastly it is recommended to include moving shading devices, in particular on the south front.

1.2 Toplighting

One of the most common methods to regulate natural light in interiors consists of solutions of *toplighting*, that is, through skylights or roof monitors that can be opened or are fixed to the roof, which represent only a narrow range of the systems available to achieve illumination from the top down.

The main advantage of this technique of Daylighting is the possibility of having a uniform light that comes from the brightest part of the sky, the zenith, without incurring any reflections or encountering obstacles; this ensures a much more extensive availability of light, regardless of the type of glass used.

It can be affirmed that toplighting is the strategy of natural light that most resembles the performance offered by artificial light, due to the fact that it ensures direct illumination, neither filtered nor reflected, from top to bottom (Fig. 20).

For this reason, many of the principles relating to lighting techniques are also used for the design and arrangement of individual toplighting systems.

On the other hand, the management of incoming zenithal light through toplighting devices can cause problems of glare and overheating in the area just below the aperture, where there are no control or shading systems. In addition, the use of zenithal light systems is highly advantageous only for the floors immediately beneath the roof, while it is totally ineffective in the case of multi-storey buildings.

A further restriction in the case of similar solutions is the absence of a view of the outside, with negative effects on the perception of the alternation of day and night, accompanied by effects of discomfort for the occupant.

When designing toplighting systems, particular care should be dedicated to the sizing and positioning of the apertures, in addition to the selection of individual devices and technical solutions as regards finishing materials and their degree of reflection, to avoid irritating dazzling phenomena.

Figure 20: Interior of the Nasher Sculpture Centre, Dallas, with toplight solution.

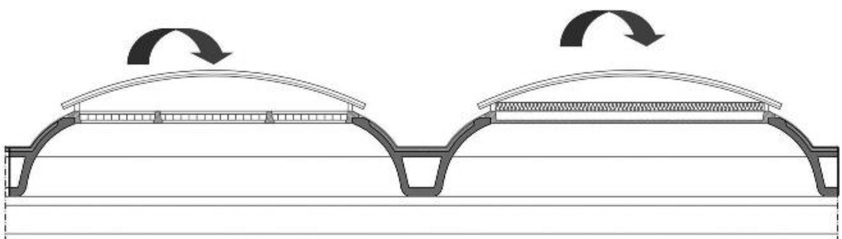

Figure 21: Skylights.

Many systems are used for toplighting solutions, classified in relation to the luminous performance they offer, and the uses they can be put to.

Skylights or domes are realised through horizontal or slightly inclined glazed apertures in the roof. Skylights offer the chance to see a wide swathe of the sky from a location that is free of obstacles and transfers within almost all of the incident light (Fig. 21).

Where it is necessary to control a quota of incoming solar radiation, it is possible to treat the surface of the skylight with translucent or reflective material, to encourage internal diffusion. The sizing and positioning of skylights is closely dependent on the climate, the geographic location and even more on the prevalent sky conditions, in addition to the type of building being worked on.

So-called sawtooth skylights, or sawtooth roofs, consist of a succession of slanting zenithal apertures, all oriented in the same direction (Fig. 22).

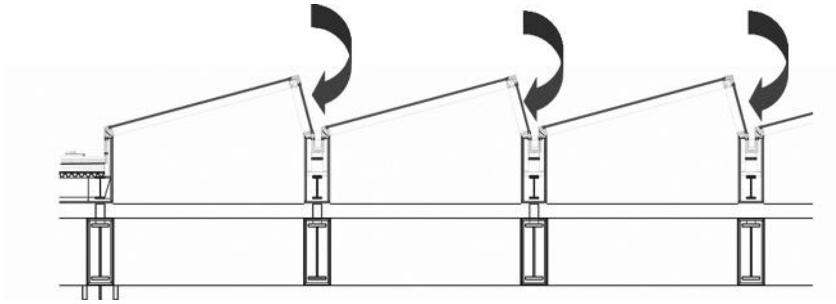

Figure 22: Saw tooth skylights.

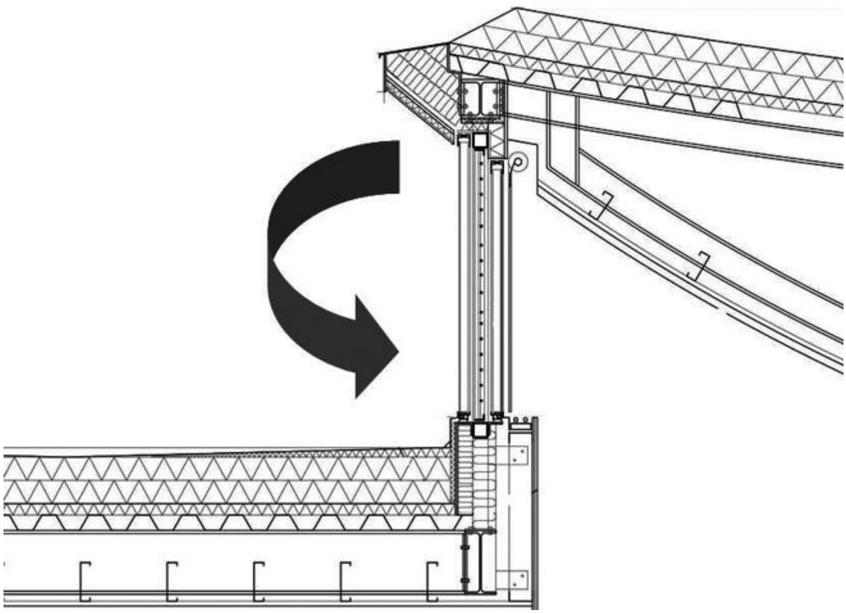

Figure 23: Clerestory window scheme.

This strategy allows natural light to penetrate into the environment according to a homogeneous, evenly distributed flow, obtaining a type of *wall-washer* lighting, thanks to the system of spontaneous reflections between the inclined surfaces the light is shed on, to then be directed onto the opposite wall below.

Therefore a decisive choice remains, namely, the correct orientation and degree of inclination to angle the surfaces of skylights arranged in series: Pointing them southwards will provide a greater quota of daylight in the interior space, but at the same time will require shading systems for the hours of maximum solar insolation. On the other hand, in the case of apertures towards the north, the flow of light channelled to the interiors will be more constant and uniform, but provide illumination levels lower than the annual average of south-facing apertures. For this reason, it is desirable to provide an interior with both technical solutions.

The use of these devices for toplighting is normally reserved for large environments, in which is sought a homogeneous diffuse illumination, and in which the presence of large free spaces between the floors reduces the luminance contrast which, inevitably, is created in the vicinity of the zenithal apertures.

Roof monitors or zenithal skylights, are systems that can be produced with vertical, horizontal or inclined sections with respect to the surface of the ceiling they are resting on. These are hybrid systems between skylights and high windows (*clerestory*), made to assimilate the benefits and advantages of each of their respective systems (Fig. 23).

These devices allow homogeneous, controlled illumination in the central part of the room, instead of a perimeter lighting obtainable only with clerestory windows. Clerestory or high windows can currently be used to realise both *toplighting* and *sidelighting* systems.

In cases where the positioning of the window happen approximately one-third of the way up the height of the wall, we talk of high windows.

The benefit of this type of window is the large quota of daylight, which is able to spread in depth through the room.

Clerestory windows do not allow a view of the outside, being located higher than the eye of the occupant: this feature limits its use to large public spaces where natural light is not the only source of light, but does make it possible to maintain eye and perceptive contact with the external environment.

1.3 Corelighting

The term *corelighting* refers to the most complex of the Daylighting techniques, which makes use of both architectural systems and optical devices to naturally illuminate interior spaces.

Despite the development of specific technologies for corelighting having undergone a process of considerable evolution over the past decades, especially for the optical systems of collection and distribution of the light, the origin of the first devices has to be traced back to Ancient Egyptian culture, when the primitive attempts to provide tunnels and rooms with direct light opened the road to research into the optical properties of lenses and mirrors to channel the sun's rays. As is the case for sidelighting and toplighting systems, corelighting too includes the use of active and passive systems, in order to transport the light inside complex and articulated spaces, also to the floors under the roof, down to the edifice's lowest floor.

Corelighting techniques essentially include the use of light duct systems, to illuminate the central core of the building, in the absence of other systems or apertures that allow contact with the outside.

It is usual to distinguish between optical ducts, atria and internal courtyards.

The *light court* or *open court* is the simplest system to implement the corelighting strategy, since this is a simple space open towards the celestial vault, for use in both private and public buildings. It can assume various shapes in relation to the interior lighting needs (Fig. 24).

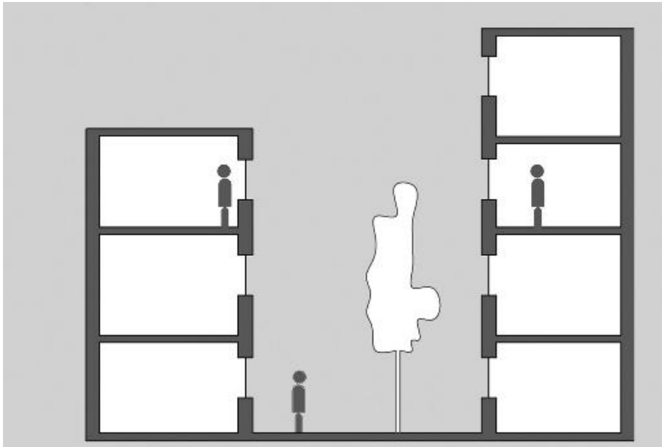

Figure 24: Light Court scheme.

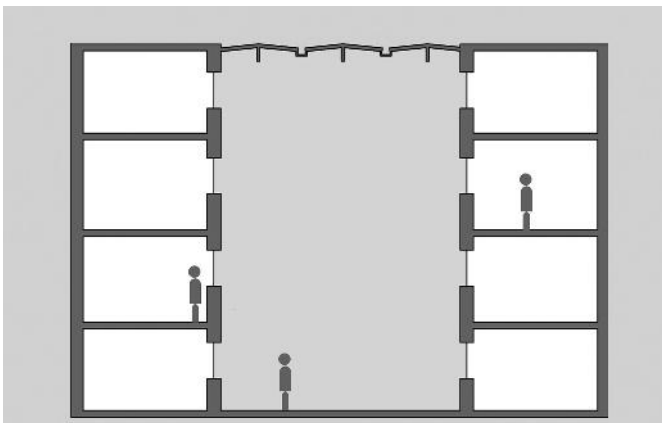

Figure 25: Light well scheme.

Properly designing a glazed atrium or *light well* can, in itself, constitute an important expedient for the control and management of natural light in the case of central plan buildings. The main difference between an open atrium and a *light court* consists in the possibilities inherent in the latter to ensure levels of illumination for spaces adjacent to the glazed court (Fig. 25).

The atrium or light well, is a technique of basic lighting that is used in modern buildings with several storeys. The core of the building is open to the outside through an element that is glazed or transparent at the top, while the building's shell must feature numerous apertures that provide light to perimeter rooms, through techniques of *sidelighting*.

A basic rule of intuitive design consists in relating the height of the atrium to the breadth of the building: This means that the two dimensions should be as similar as possible, to ensure the penetration of light even in the innermost part. The ratio between the height and width of a glazed atrium must therefore be no greater than 2:1.

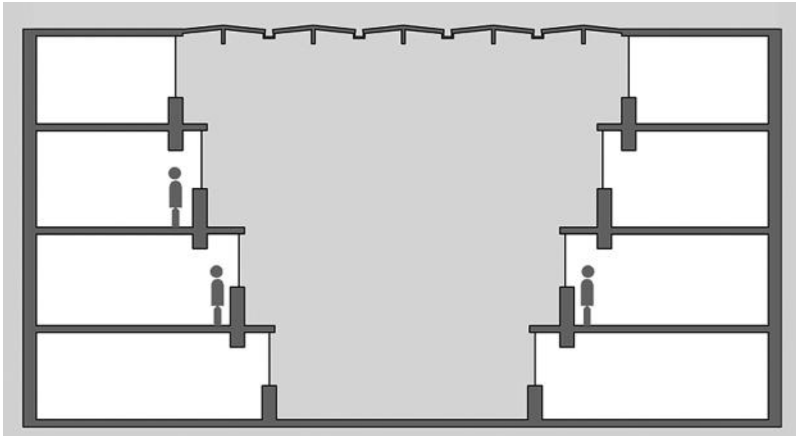

Figure 26: Litrium scheme.

However, in the case that this ratio cannot be guaranteed, it is advisable to use reflectors and interior diffusers suspended in the central space below the glass roof to facilitate dissemination in several directions.

A considerably efficient solution in achieving adequate levels of interior lighting can be achieved with translucent and highly reflective interior fittings that accentuate the interior lighting.

The glazed atrium therefore has considerable advantages: It ensures homogeneous interior lighting with a profoundly natural effect in areas that would otherwise require artificial light. In addition, the constant visual and perceptual contact with the external world ensures a good level of visual and psychological comfort for the occupants.

The *litrium*, from the English *light* and *atrium* consists of a foyer, whose shape tapers towards the bottom, that is, in which the open surface decreases towards the lower floor, in order to maximise solar penetration from the top of the light well (Fig. 26).

In these glazed atria with their particular shape closed at the bottom, the sunlight, coming directly from the sky, is usually directed towards the walls rather than the ceiling of the confined rooms overlooking the atrium.

The question of greater weight in selecting the most appropriate Daylighting strategy depends essentially on the most appropriate size for the spaces around the corelighting device.

The choice of the geometry of an atrium is regulated by some parametric formulae, such as SAR - *Section Aspect Ratio* - PAR - *Plan Aspect Ratio* - and WIR - *Well Index Ratio* [44,45].

On the basis of these devices employed to maximise the amount of natural light in a glazed atrium in relation to its geometric shape, numerous studies have attempted to define a unique method to develop a relationship between the methods of forecasting the availability of Daylighting and the design tools related to them [46].

In addition to the formal and architectural solutions, the solution strategies for corelighting also concern active systems made using optical devices, through which the light is captured and collected by heliostats, that is, mirrors and independent optics regulated by photosensitive cells, which enable the system to follow the daily track of the sun and to concentrate the light beam in confined environments by passing through closed ducts.

To transport solar radiation it is possible to take advantage of the multiple reflections of incident sunbeams, collected by Fresnel lenses through a pickup head and then routed long distance into the ducts coated with reflective materials and lenses that avoid dispersing – in terms of both quantity and efficiency – the sunlight picked up at the top.

Finally, the emission system concludes with the introduction of the light into the room through circular or other shaped apertures of variable diameter.

In deciding the size of the system, in addition to the selection of the most suitable length of the inner duct, it is useful to assess the integration of shading systems for the pickup head outside, to shelter it from excessive summer insolation and overheating, just as it is equally advisable to provide devices that encourage absorption in the event of predominantly overcast conditions or for the winter months.

2 A dichotomic question: solar penetration versus solar screens

Rational and conscious design to facilitate the application of architectural and energy strategies for daylight essentially concern the initial stages of an architectural project: assessment of the most effective solutions to introduce technological systems for the control of solar penetration.

Strategies to provide a suitable amount of natural light within an architectural space are implemented, first, by means of a design oriented towards maximum exploitation of solar radiation, by resorting to shading systems or other architectural elements to integrate the roof.

Technical considerations and assessments on the nature of the site are therefore vital preliminary steps in order to ensure, in the first instance, optimal exploitation of the sun's rays and, secondly, the technological choices best suited to safeguarding the building from excessive overheating in the summer.

To consider all the factors that contribute individually to the access of light and its diffusion from apertures, skylights or glazed atria, is virtually possible at the design stage, however, at the construction stage, managing such discordant and random factors often constitutes an obstacle.

The visual comfort challenge in a confined environment is therefore characterised by attempts to integrate into the design aspects that are apparently secondary – from the preliminary to the executive step – in order to ensure a comprehensive approach to the questions of indoor comfort and energy saving.

The factors to be taken into account in a design process can include: the configuration and arrangement of the apertures, the percentage ratio between the surface area of the floor and

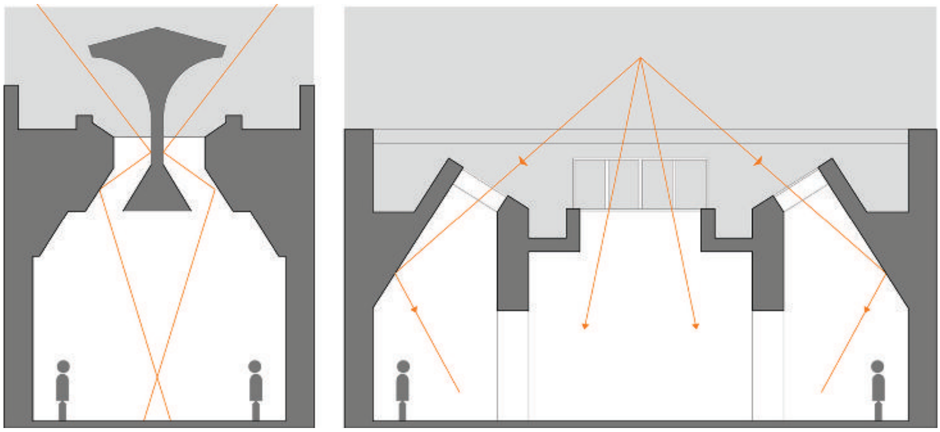

Figure 27: Scheme of daylighting penetration via toplighting devices.

the fenestrated surface, the shading conditions, the orientation of the apertures in relation to whatever visual task will take place, the presence or absence of fixed or mobile partitions, the presence of manually or mechanically operated shading devices (Fig. 27).

The integration of aspects that are so different from one another and the involvement of disciplines belonging to different areas make it very difficult to manage solar radiation, both in the case where it is wished to encourage solar penetration, and when a system of screens instead proves indispensable.

The dichotomous question of management between the two opposing polarities is always a pivotal theme of architecture.

This concerns equally Mediterranean and Nordic architecture; despite the availability of sunlight being highly variable and greatly dependent on geographic latitude, questions relating to systems to manage and control sunlight can be found in all episodes of the history of architecture.

'Winter triclinia and bathrooms look to the winter west, due to the fact that it is necessary to use the evening light there, moreover, as also the waning sun emanates light from the front, increasing the heat it makes this orientation warmer in the evening. Bedrooms and libraries must look to the east, because the morning use requires lighting, and also the books do not rot in libraries' [47].

The choice of the orientation and, even before that, an assessment and analysis of the site are essential to ensure a good supply of sunlight and visual comfort for the functions that are to be carried out inside the built environment.

These concepts date back to the most ancient architectural experiences but, like other knowledge of good design practice, have often been ignored over the centuries, disrupted by purely stylistic and expressive demands. At the same time, the concepts of good design practice are difficult to apply in a unique way, however specific solutions can be applied to different situations, as Palladio wrote in his treatise, highlighting the impossibility of setting absolute standards.

'In doing the windows, you should be aware that the more or less light you capture, shall be no rarer, nor denser than, that the need seeks. So the result is that a large room needs more light, so that is bright and well-lit, than a small one: and if we make the windows smaller and rarer than what is suitable, this will make the places dark: and also if they are excessive in size' [48].

Awareness of the problems relating to over-illumination acquired great significance in the literature and treatises above all as a result of the invention of the incandescent bulb.

Until the industrial revolution, and with the spread of oil lamps and electrical appliances, the term 'shading' was often assimilated – if not often used as a synonym – with the term 'shielding'.

The technical solutions used were mainly oriented to darkening the rooms during the night-time hours, or to offer shelter from the weather, while devices and systems for shading in the summertime consisted of simple curtains or porticoes.

Otherwise, the countries at low latitudes still show today valid examples of bioclimatic design to protect from excessive solar radiation and to ensure a constant exchange of air, thus avoiding excessive heat loads.

In the case of works of architecture at low latitudes, light assumes instead a different weight, accentuated also by the need to exploit up to extreme consequences, the constructive and epiphanic power of sunlight, in conjunction with the needs of shelter and protection from the sun's rays.

The most emblematic examples that make the binomial light-shade explicit in compositional forms and laws, that is, the dichotomy between penetration and solar shading, can be sought in those works of liminal, tropical or Nordic architecture, where the excessive or deficient availability of natural light makes it difficult to arrange for technological devices that maximise the opportunities offered by daylight.

Therefore, any daylighting strategy, regardless of the latitude and geographic context, cannot overlook a careful assessment of the distribution of luminance, the component of the sky, the surrounding buildings and the quota of radiation reflected from the ground and from the materials used for the interior space.

2.1 Apertures and interior finish to facilitate solar penetration

Analyses of the site and the microclimatic conditions are instruments of preliminary analysis; however, these are not sufficient to ensure an environment that is properly illuminated and for this reason, they cannot be separated from an assessment of the internal finishing materials. Just as there is an assessment of the obstructions outside the building, also particular architectural choices that concern the internal layouts can help increase or decrease the availability of sunlight.

Therefore, the objectives that must be pursued to illuminate, satisfy the visual task and produce a feeling of comfort for the occupant, to provide a pleasant environment and optimise the consumption of electric energy, are closely interdependent on the architectural choices taken, and the management of daylighting control systems.

Visual, architectural-spatial and thermal-energy performances linked to Daylighting for an enclosed space depend essentially on the light availability that invests the building envelope and that determines the possibility of exploiting natural light inside it; on the physical and geometric characteristics of the building envelope, such as the presence of projections, loggias, balconies and other obstructions, as well as the arrangement of the windows, and other apertures; and on the physical and geometric characteristics of the internal space, in addition to the optical properties of finishing materials and objects present in the interior space.

The windows, seen not as mere apertures but as real technological elements of the building envelope, play an increasingly crucial role in defining the architectural form, and, more importantly, control over the light.

Technological innovations have above all focused on the windows and the structures of the frame, as determinant elements for optimising penetration and at the same time modulating the entry of light radiation.

The specific choice of the frame and of the related type of glass (opaline, Low-E, triple coated glass etc.) is not only an aesthetic and purely architectural issue but a technological choice that has a direct influence on the amount of incoming light.

The subsystem of windows, doors, shading and shading elements contributes to creating the organism as a whole through which it is possible to control, and get the maximum benefits from, the exploitation of sunlight.

Visual contact with the outside world must also be ensured by the global nature of the subsystem and the individual elements that constitute it.

Together with these choices, a crucial contribution to the question of the distribution of illumination is identifiable in the choice of materials for interior finishings, which can be reflective, diffusing or absorbent, in order to ensure maximum visual performance, and avoid irritating and harmful glare.

Although the impact of this type of choice falls primarily within the range of interior design, the contribution made by each finishing material must not be overlooked as regards the proportion of sunlight reflected or absorbed.

A preference for materials traditionally used for interior finishing can often be detrimental if not carefully weighed up in relation to other choices for the definition of the illuminated area, of course.

Suffice to think of an instance where a significant amount of solar radiation enters a room during the summer through large, full-height glass façades, and spreads diffusely through a room featuring light-coloured plaster or reflective surfaces, creating irritating reverberations and irritating glare.

Similarly, opting for a floor treatment using materials such as enamel paints or gloss resins can cause irritating effects in especially bright rooms, for which it would be more appropriate to choose satin varnishes or porous coatings.

Causing a rigorous interaction between the architectural choices relating to finishes and those relating to the shell would therefore help control the ratios of luminance between the surfaces directly and ensure greater emphasis on the chromatic yield of each object.

2.2 The role of shading in architectural design

The issue of integration between the building envelope, sunshades and darkening systems, already finds its first examples in vernacular forms of architecture.

It is complex to historically date the first examples in which specific devices were developed with the purpose of deliberately shading solar radiation; the first forms of control over natural light were born with the purpose of adjusting the light inside a built environment; however, with the passage of time and the occurrence of precise requirements by occupants, the need arose for integrated systems, modular and movable in relation to the sun, which did not completely darken the environments they were arranged in.

Screens, porticoes, awnings and simple projections made their first appearance in the earliest examples of architecture, especially in those contexts where the sunlight was for most of the year excessive or unpleasant.

Techniques of bioclimatic architecture and passive systems have always included the use of simple technologies to integrate with the shell, allowing control and mitigation of daily solar penetration within a building throughout the seasons. These were simple expedients, derived and developed from common experience, then refined and improved, leading to today's technology of active systems.

The first elements that functioned as sun screens (think of the porticoes and triclinia of Roman times) arose from direct experience and the need to screen the summer sun and favour the penetration of sunlight during the winter. These were fully integrated into the building and allowed the occupant to exploit solar input in different ways, in accord with the seasons and thermal requirements.

The very shape of the building and the architectural design were created simultaneously, according to a passive design, to increase the potential of solar penetration and ventilation.

Not only European architecture, but also the vernacular building tradition of the Americas experimented with numerous revivals of Greek and Roman architecture, replicating double height porticoes for public and civic buildings.

Variations on protruding and shading elements were adapted in relation to the climatic conditions of the different places: Where a hot, humid climate required a larger amount of natural ventilation, there was a preference for shallow porticoes and shielding systems to be applied directly to the windows, such as reticles and perforated screens.

In traditional Italian architecture there are many examples of simple shading devices, which were made at the same time of the building, often as integral elements of the architecture itself, and ending up as stylistic connotations.

Systems made by resorting to modular elements in brick, such as the *mandolato* of terracotta tiles typical of the Tuscan countryside or the apertures with shutters, envisaged that the bricks would be placed obliquely in ribs, so as to allow the entrance of both sunlight and air.

Similar systems were adopted over the centuries in rural areas: these were different types of screens, used as a filter to sift and modulate natural light, but that at the same time connoting an element of the outer shell.

In works of architecture in hot and humid countries, preference was given instead to archaic shading systems, inside cloisters, first as protection elements and then applied to individual apertures as screens of perforated stone, as in the case of Moorish and Muslim architecture.

Arab-style screens carried out the dual function of promoting cooling, ventilation and evaporation, while allowing the right amount of sunlight to illuminate the interior space.

Among the first examples of bioclimatic design that reveal a particular attention to orientation and screens are to be found in the settlements of the indigenous peoples of Mesa Verde, Colorado (Fig. 28).

In the 13th century, natives realised their homes by exploiting the beneficial presence of the sun, while at the same time ensuring constant protect from excessive solar radiation by building their homes in the cutting of a rock peak on a canyon facing south, a sheltered position during the summer and exposed during the winter.

The thermal inertia of the rock behind, as well as the arrangement of the peak on the gully, ensured a constant supply of heat and natural ventilation.

Figure 28: Mesa Verde settlement, Colorado.

Figure 29: Wind Tower, Old Dubai.

A different bioclimatic strategy for sunscreens was adopted by the people of the Caribbean, who made the porticoes and large overhangs in inlaid wood of the farmhouses a hallmark of their homes.

Some of the buildings of Middle-Eastern culture, such as Iranian or Pakistani constructions, still use today examples of devices for protection from the sun and excessive sunlight, such as the wind towers, the so-called *baud geers*, examples of vertical chimneys, divided into several sections, where the air and light can enter and meet in the various rooms of the building (Fig. 29). At intermediate latitudes, shading and shielding devices are only required in certain periods of the year, but traditional architecture has always used simple steps in order to exploit the solar contribution, as in the case of dovecotes and roof terraces.

The architecture of the great masters of the 20th century reflects knowledge of local tradition and appropriated it, inserting sun screens and protection devices into buildings, as real elements of design, hallmarks of the architectural project.

Projecting roofs and aperture systems that follow the path of the sun became hallmarks of Frank Lloyd Wright's *Prairie House*, protecting the occupants from hot and humid weather and ensuring solar penetration into the rooms.

In particular, Wright's ability to manage the quotas of radiation and incoming shade are reflected in the projecting and covering roofs that he designed for the *Robie House* in Chicago, where the projection of the roof is elaborated in such a way as to protect from excessive heat without denying the right degree of brightness for the rooms below.

The ability to act in perfect harmony with the surrounding natural scenery marked all of Wright's work, along with his particular sensitivity to the theme of natural light. Indeed, organic

Figure 30: Chandigarh High Court interior, Le Corbusier (credit Aleksandr Zykov).

architecture aspired to a more complete integration between shading and shielding elements with the shape of the building.

The founding values of organic architecture blended with local tradition and the technological possibilities of the time, to obtain admirable compositional effects: 'Stage by stage, we are creating the contemporary architectural revolution. And here we are in front of the stunning story of the window. I have allowed myself the *de-Vignolizing* of architecture with this prosaic statement: architecture consists of illuminated floors' [49].

In light of this deeply rooted awareness, Le Corbusier himself used several times in his constructions sunshade elements to protect the interiors, ending up connoting these as emblems of the architecture itself, as in the case of *High Court of Chandigarh* (Fig. 30). Buildings for the new city followed a mostly horizontal pattern, and Le Corbusier succeeded in transforming a simple element of protection from the sun typical of the place, into a recognisable symbol of the project: a projection in the shape of the crescent moon pointing up, translated from tradition local construction, gave impetus to the design of elaborate *brise-soleil*.

In the monumental realisation of *Chandigarh*, the grazing light is therefore a pivotal element which, exalted or damped, thanks also to the presence of large basins of water placed at the foot of the *High Court*, is made dynamic and changeable by the articulated perforated screens, arranged along the sunnier sides of the building.

This project of Le Corbusier, outside of the better-known places where in those years he was experimenting with new solutions for shells, emblematically embodies the possibility of an effective integration between the architecture of the shell, and the definition of the interior space through natural light and local construction traditions.

Daylighting as a strategy for visual comfort, environmental and energy-saving measures, was therefore subject to mutations that have helped make it, over the years, an aspect of primary importance.

The building envelope can now also act as an adaptive skin that performs multiple functions through different functional levels: Its performance varies in relation to external stimuli, including climate, heat and light, to adapt to the needs of the occupants.

The end user is now able to make precise changes to specific elements of the building envelope separately or jointly, in response to particular needs.

The role of the designer assumes more and more weight, in the context of actively combining architectural and technological instances, to the satisfaction of the end user, who lives in and continuously changes the constructed space.

The integrated design approach is the one best suited to different techniques of solar shading and other devices designed to facilitate Daylighting.

The culture gap that today permeates architectural works in terms of solar shading appears almost paradoxical, considering how many simple expedients could be derived from vernacular architecture and how many have been used over the centuries to prevent too much daylight from entering the buildings.

The spread of extremely sectorial technical skills has often made the basic knowledge of bioarchitecture, in use for millennia, quite unnecessary as simple design tools.

3 Internal and external shading systems

Shading systems can be divided into different categories depending on use – internal or external, the type of shielding provided and the operation – mechanical, manual or mixed.

The choice of one system with respect to another must be determined in relation to the needs of the shell, its architectural features and in accordance with requests of the user.

The functionality and performance offered by individual systems are variable and in continuous evolution, because they respond to more and more specific needs related to the overall performance of the envelope and the activities that will be carried out inside.

They can perform the functions of

- shading from sunlight;
- protecting the interiors from dazzling phenomena;
- avoiding overheating;
- encouraging solar penetration up to the maximum depth of the environment, by directing natural light right to the end.

At the same time, an essential feature to ensure a sense of comfort inside is the possibility offered by some shading systems, both internal and external, of enjoying the view of the outside.

Even if it is not an essential function, numerous joint studies have demonstrated that the view of the outside increases concentration and makes unfavourable microclimatic conditions more acceptable. Therefore, guaranteeing constant contact with the outside from the visual point of view allows keeping attention high, stimulating sight and providing constant production of melanin to adjust the natural sleeping-waking cycles.

In this sense, shading systems can be subdivided in relation to the contact they create with the outside:

- Systems that ensure a view of the outside without obstacles and optical distortions.
- Systems that provide a partial view of the outside, for example, apertures at the top of the window.
- Systems that guarantee an occasional view of the outside, but that can be operated at the discretion of the occupant.
- Systems that offer full shielding, hiding the view of the outside completely.

Therefore, as regards shading systems and their operation, it is possible to distinguish two further sub-families:

- Systems that allow management of levels of variable shielding in relation to the needs of the user and climatic conditions.
- Systems which, in addition to the shading function, can pick up the light and direct it into the desired regions (e.g., regions that are under-lit), to create indirect lighting, by exploiting the contribution of a reflective ceiling or other interior surfaces.

Shading systems therefore perform two functions seemingly separate: shielding and providing a proper amount of natural light in specific areas, in addition to secondary functions of heating and reduction of glare.

As regards strictly luminous systems, it is therefore possible to distinguish between [50]

- systems that favour the presence and distribution of diffused light;
- systems that facilitate the presence of direct light;
- systems that distribute natural light in a random manner;
- systems that transport natural light.

If we wish to set up the peculiarities of each system, the following table summarises the key features of currently available shading systems, in relation to the type of aperture to which they may be applied, as shown in the following table, where the symbol D stays for *depends*, V stands for *yes* and X stands for *no* (Table 1).

Table 1: Review of the main shading systems.

Shielding systems – Toplighting								
		System performance						
System	Position	Glare protection	External view	Deflected light	Homogeneous distribution	Energy saving	Manual/automatic operation
Prismatic panels	Vertical windows and skylights	D	X	D	D	D	D
Prismatic panels	Vertical windows	V	V	X	V	V	V
Louvre and blade systems	Skylights	D	X	X	V	X	X
Anidolic zenithal systems and anidolic ceilings	Skylights and glass roofing	V	V	X	V	V	X
Lightshelf	Vertical windows and skylights	D	V	X	D	V	V
Systems and windows for directing sunlight	Vertical windows and skylights	D	V	X	V	V	V
Direct lighting systems							
Guided diffusion systems	Transparent windows	V	V	D	D	D	X
Louvres and Venetian blinds	Vertical windows	V	D	V	V	V	V
Lightshelf	Vertical windows	D	V	–	V	V	D
Glazing and holographic optical element (HOE) systems	Vertical windows	D	D	D	D	D	X
Skylights with laser-cut panels	Vertical windows	D	–	D	V	V	D
Lightshelf	Vertical windows and skylights	D	D	D	D	D	V
Venetian blinds with anidolic systems	Vertical windows	V	D	D	V	D	D

(*Continued*)

		System performance					
System	Position	Glare protection	External view	Deflected light	Homogeneous distribution	Energy saving	Manual/automatic operation
Lightshelf	Vertical windows	D	V	D	D	D	X
Integrated anidolic systems	Vertical windows	X	V	V	V	V	X
Anidolic ceilings	Transparent façades	–	V	V	V	V	X
Fish system	Vertical windows	V	D	V	V	V	X
Glazing and HOE systems	Transparent façades in glazed courtyards	–	V	V	V	V	X
	Systems for indirect light						
Laser-cut panels	Vertical windows and skylights	X	V	V	V	V	X
Prismatic panels	Vertical windows and skylights	D	D	D	V	D	D
Glazing and HOE systems for skylights	Skylights	D	V	V	D	V	X

3.1 Lightshelf

Among the most efficient systems to ensure visual and energy performance is the *lightshelf*.

This term refers to those shading devices consisting of a horizontal shelf positioned inside or outside an aperture (Fig. 31).

The oldest examples of lightshelf can be traced back to some constructions in Ancient Egypt, when these simple shading devices were used to create shade and shelter from excessive radiation reflected or directly from the sky.

Therefore, these are systems that can adapt to any size and shape of aperture to which they can be fitted: It is usually preferable to install this device on the outside of a room.

The height at which the shelf is positioned depends on the interior demands and possible additions of the device to the building's shell. The lightshelf usually divides the area of the window into two parts, of which the lower one is situated at a height that ensures a view of the outside while the upper part becomes a clerestory.

In addition, there are several systems of lightshelf that can be integrated within optical systems to redirect the light in depth, in order to create indirect but homogenous lighting for the furthest corners of a room.

The inclusion of an internal lightshelf thus allows reduction in the percentage of Daylight Factor, as a result of the decrease in the effective fenestrated area for the purposes of geometric computation, while the integration in the building's shell of an external lightshelf permits mitigation of the amount of incoming light and ensures the ability to transmit a greater share of solar radiation towards the furthest corners of an interior.

Integration of these devices results in substantial alterations in the design of a façade and, more generally, on the compositional aspect of the building: which is why the application of

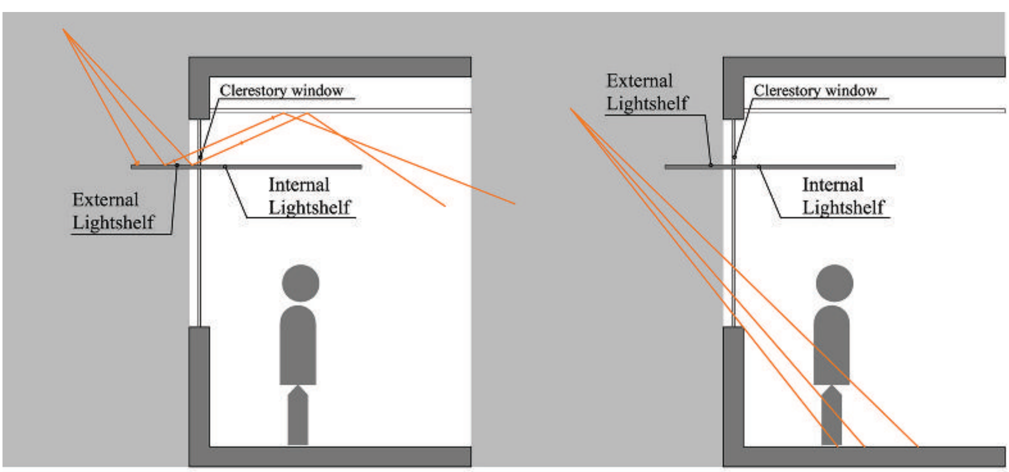

Figure 31: External and internal lightshelf in case of summer and winter sun.

Figure 32: External lightshelves in Dubai.

lightshelves in the case of a building already in use can produce significant alterations in the building envelope.

The realisation of a lighshelf must arise from careful assessment of the needs of the interior space and the final user, to adapt the most appropriate solution to the orientation of the window, the configuration of the room and the geographic latitude, and to determine the most appropriate depth for its projection and inclination. Recourse to this type of device has proved particularly effective where the apertures in the shell are mainly arranged north-south, while they prove less effective along an east–west axis, referring to exposure in the northern hemisphere (Fig. 32).

The use of these solar shelves is recommended for rooms that mainly develop in depth with respect to a fenestrated front and are oriented southwards; in these cases, the shading solution proves very effective in the area around the window, by reducing the amount of direct radiation and heat, ensuring greater light distribution in the furthest part of the room.

Better performance can be obtained in the case of lightshelves that are movable and can be orientated mechanically or manually, and which offer the possibility of changing the angle of the slat in response to external light conditions. This type of device can also be made with a system that can adapt to climatic changes and solar tilt, while it may also have a surface treatment that enhances the optical properties.

Normally the solar shelf has two different surfaces, either in glass or in another non-transparent material: The lower surface provides protection from glare and excessive exposure to the sun by projecting a shadow, while the upper surface is coated with diffusing materials to capture direct solar radiation, sending it towards the roof area and also acting as a reflective element.

One particularly interesting characteristic relating to the use of the lightshelf is the possibility of integrating it into existing buildings. In order to add the new device efficiently to an existing façade or within an environment already in use, particular attention needs to be paid to the positioning and the angulation of the slat, whether fixed or mobile. An angle that is too slight

Figure 33: Residential application of external lightshelves, Darmstadt.

may in fact prove disadvantageous since it will limit both solar penetration and direct radiation, as well as reducing the extent of the view outside. For these reasons, the width and height of a lightshelf need to be studied in relation to geographic latitude and the prevailing climatic conditions. At high latitudes, where the solar height is lower compared to the horizon and in the case of a building oriented to the prevailing east–west axis, a considerable amount of direct solar radiation will always manage to penetrate through the gap left between the lightshelf and the ceiling.

Furthermore, the slat may be inclined downwards to minimise the radiation reflected towards the ceiling, just as an inclination upwards will increase solar penetration in the lower part of a room, to the detriment of the shading effect.

In general then, it is possible to say that having shading systems like the lightshelf is the best compromise to ensure a gradual and adjustable level of shading, which at the same time facilitates indirect and homogeneous lighting in the depths of a room. Where these devices are to be used in intermediate latitudes, numerous simulations and tests have shown that the maximum shading effectiveness is achieved with the installation of external systems, equipped with reflective surfaces in combination with internal surfaces with high reflectivity (Fig. 33).

Instead, where internal lightshelves are used, the shading effect is too high for most of the year, thereby tending to decrease the average illumination in areas furthest from fenestrated fronts. The surface treatment of the shelf is very significant not so much in its shading capacity, as in the reflectiveness of the element, in particular as regards the amount of reflected light and its degree of homogeneity. An optical treatment, in order to ensure maximum reflectance from the upper surface of a lightshelf is therefore particularly effective in countries with low latitude or that are particularly sunny: Treatments that offer semi-specular or high reflectance

Table 2: Features of lightshelf system.

Advantages	Disadvantages
Traditional lightshelves	
Reduce thermal loads in summer	Can potentially cause glare during the winter
Maximise solar gains in winter	Performance reduced in the case of sun low on the horizon
Avoid irritating dazzling phenomena	Reduced performance in the case of overcast skies
Evenly distribute illumination	Reduced performance along the east–west axis
Ensure a view of the outside	Reduced performance in case of use in a room with a depth of more than 3.5 meters
Affect the composition of façades	Problems of maintenance and cleaning in the case of external application
Direct natural light in depth	
Optically treated lightshelves	
Shielding from direct light in any condition of the sky, both in summer and winter	Very expensive from an economic point of view
Increase levels of illumination up to 10 meters from a fenestrated façade	Implementation and technological research very expensive
Effective for depths of more than 2.5 meters	Problems of maintenance and cleaning in the case of external application
Sun tracking lightshelves	
Shielding from direct light in any condition of the sky, both in summer and winter	Very expensive from an economic point of view
Increase uniformity of illumination	These systems are still being developed to optimise their technological performance

surfaces can be obtained using optical films to be applied to the lighshelf, to preserve the brightness of the interior space with a maximum extension of 10 meters from the fenestrated front.

It is possible to obtain similar performance even in cases of non-horizontal surfaces, but with curved or segmented surfaces that reflect the sunlight thanks to simple arrangements of a passive type.

A common peculiarity of a lightshelf with optical treatment is, instead, to offer constant adaptability to external conditions by blocking direct solar radiation, thus increasing illumination and minimising thermal loads in confined spaces where they are applied.

Finally, the new technologies are now concentrating on the development of the so-called *sun-tracking light shelf system*, an automated system that adapts to the path of the sun, offering variable inclinations in relation to the movement of the light. Following is a table that summarises the peculiarities of the use of the three main families of lightshelf [51] (Table 2).

3.2 Louvre

Louvres, slats for ventilation and solar penetration, comparable to awnings, are the most popular solar shading devices for protection against overheating and to redirect the sunlight within a constructed interior.

Louvres and other types of adjustable slats make use of horizontal, vertical and inclined elements, with shapes and surfaces optically treated.

It is possible to realise sun-louvers in galvanised or anodised steel, or aluminium, which meet both architectural and compositional needs, as in many cases of public and private buildings.

The arrangement of internal slats is more difficult to manage: It is preferable to use less invasive systems, consisting mainly of slats in PVC or aluminium, in which the individual elements are curved or straight.

As for the angle of inclination of the individual slats, the shading system offers the possibility to obtain total shielding or partial protection from the sun's rays, with a limited view of the outside (Fig. 34).

Slats and awnings are, to date, among the systems with the greatest possibilities and widespread use, particularly if applied to existing surfaces and buildings with extensive transparent surfaces; their effectiveness proves high, managing to reduce up to 70% of the incident solar radiation on a surface in summer, while during the winter period, manual and automatic management of the slats makes it possible to increase the quota of direct and indirect radiation that penetrates a confined space.

The maximum efficacy of these systems is mainly linked to the shading capacity, since they are able to eliminate solar radiation before it reaches the glass, thus preventing a greenhouse effect in the vicinity of the transparent surface. The correct positioning of these shading systems ensures the highest performance in applications outside the building's shell, while the diffusing

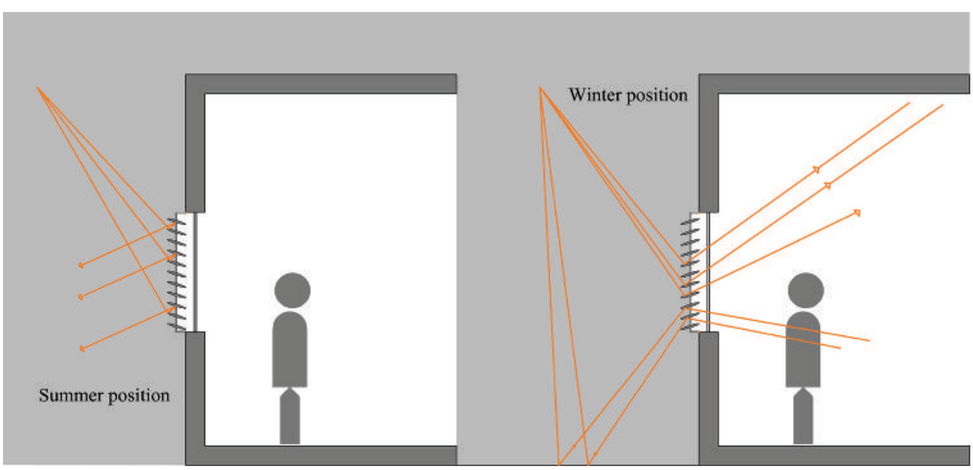

Figure 34: Louvre system in case of summer and winter sun.

Figure 35: Horizontal adjustable louvres, Darwin.

performance is weak due to the limited surface of each single slat and the closeness between individual elements.

The sizing of the type of slat and the free angle of inclination for each element, as well as the pattern of the elements, are data to be assessed and to choose from in relation to the shading needs, the prevailing climate, as well as the latitude of the site, to optimise the passive behaviour of the building in both summer and in winter, thereby reducing the thermal loads (Fig. 35).

External horizontal slats offer the maximum shading effectiveness if installed on the southern front of the building envelope, shading or attenuating the amount of direct radiation during the middle of the day, but allowing light to enter the interiors during the winter season. Slats and slats fitted vertically are to be preferred in the absence of pre-existing shading elements, in the case of surrounding buildings or trees.

These vertical systems, fixed or movable, of the *brise soleil* type, make it possible to modify the aperture angle to control the amount of radiation entering the interior space (Fig. 36). The maximum effectiveness can only be guaranteed by horizontal systems that not only offer protection from dazzling light and overheating but can also be used throughout the year to obtain variable shielding of the interior spaces.

A similar distinction must be made between internal and external systems: Maximum solar efficacy is guaranteed by external systems, the only ones that can ensure full protection from overheating.

Among the most innovative adjustable slat systems, *Fish systems* are created with horizontal slats featuring a triangular cross-section and with a micro-perforated concave surface, which is aligned by means of two connecting elements belonging to the slat itself (Fig. 37).

Figure 36: Vertical louvres, Dubai.

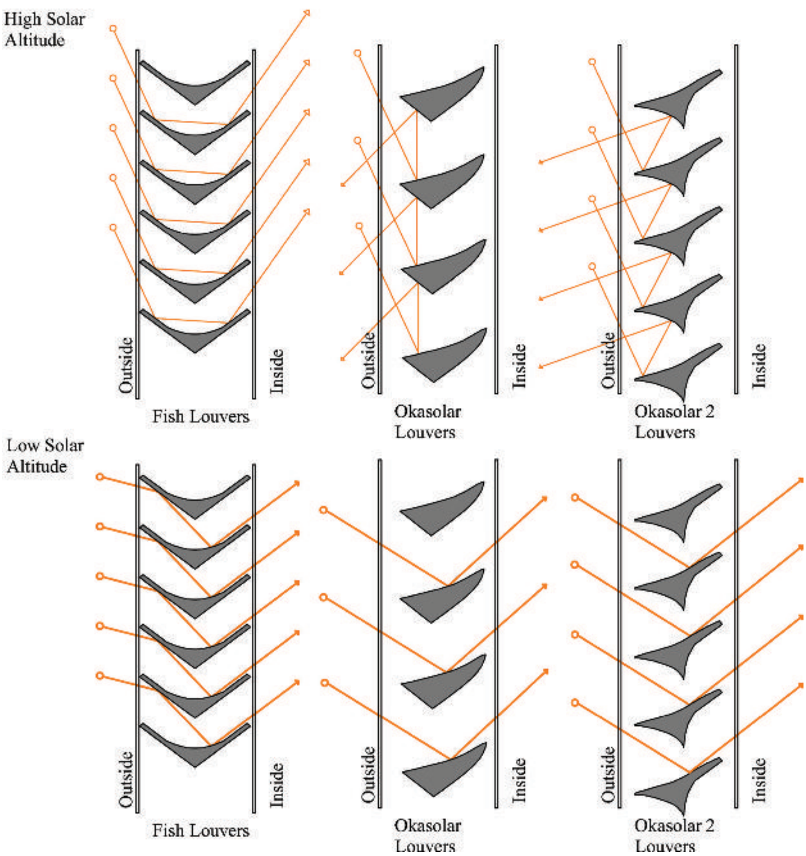

Figure 37: Diagrams of Fish, Okasolar and Okasolar 2 system operation, in summer sun and winter sun.

The upper concave surface of the slat is able to capture different angles of incident radiation and then direct the light within.

Direct glare is instead mitigated during the day and throughout the year.

This shading system can only be used for vertical windows to prevent glare and to diffuse the light: for this reason it is usually associated with other systems, wherever additional shielding and protection from overheating are called for, especially at low latitudes and in warm climates [52] (Table 3).

Also *Okasolar*, among the fixed systems, consist in a series of planks made of highly reflective materials arranged with a small pitch within two glazed surfaces.

Table 3: Features of louvre systems.

Advantages	Disadvantages
Louvres with fixed and mobile blades	
Maximum effectiveness as shielding	Do not offer the possibility of intervening in the angle of inclination
Maximum protection against overheating	Do not scatter solar radiation in the environment in winter
Ability to direct natural light in depth in the environment concerned	Reduced performance in the case of overcast skies
Offer flexibility and adaptability to the external conditions	Effective system if applied in a room with a depth not less than 3.5 meters from a fenestrated façade
View of the outside	Problems of maintenance and cleaning in the case of external application
Maximum effectiveness as shielding	Do not offer the possibility of intervening in the angle of inclination
Translucent strips	
Shielding from direct light in any condition of the sky, both in summer and winter	Very expensive from an economic point of view
Transmit a small fraction of solar radiation even when closed thanks to the translucent materials	Costly systems from the point of view of technological research
If backlit, constitute a source of direct lighting	Difficult to adapt to existing buildings
Ensure high levels of illumination, both in the case of clear and overcast skies, especially when the sun's rays approaching the normal of the glazed surface	Complex maintenance
Light directing louvers	
Usually used in the window interspace	Very expensive from an economic point of view
Maximise the amount of radiation reflected within towards the ceiling	Expensive from the point of view of technological research
Offer significant levels of energy efficiency with respect to the consumption of electricity	When angled offer no view of the outside

They reflect the light towards the surface of the roof in the winter and offer good shading level during the summer.

The design and installation of *Okasolar* must be suitably programmed to adapt to the solar path at different latitudes, on the basis of the prevailing climatic conditions.

3.3 Prismatic panels

Prismatic panels are mainly employed in temperate climates to direct and reflect incident light onto the façade and transparent portions of a shell. These systems are intended to be used mainly for solar control in summer (Fig. 38).

The two faces of the panels each have a different coating: the exterior is made with triangular prisms that help divert a quota of incident solar radiation, while the inner face of the panel is smooth.

Linear prismatic panels offer luminous performance by virtue of the presence of a series of tiny prisms, the faces of which offer a reflective surface, and therefore shading, for a wide range of inclinations.

This type of panel is usually inserted between two glazed surfaces, which protect the prisms and reduce the need for maintenance. Prismatic panels may be fixed or mobile, according to the shading requirements of the shell on which they are installed. In a fixed conformation, which is the most widespread, these systems need to be integrated with other shading structures.

The flexibility in the use of these panels lies in the different behaviour in relation to the seasons, and during the summer most of the incident radiation is reflected and diverted, thus deflecting the sun's rays from the shell and avoiding glare and overheating; during the winter, the rays with a lower slope manage to pass through the prisms past the panel, spreading into the interior (Table 4).

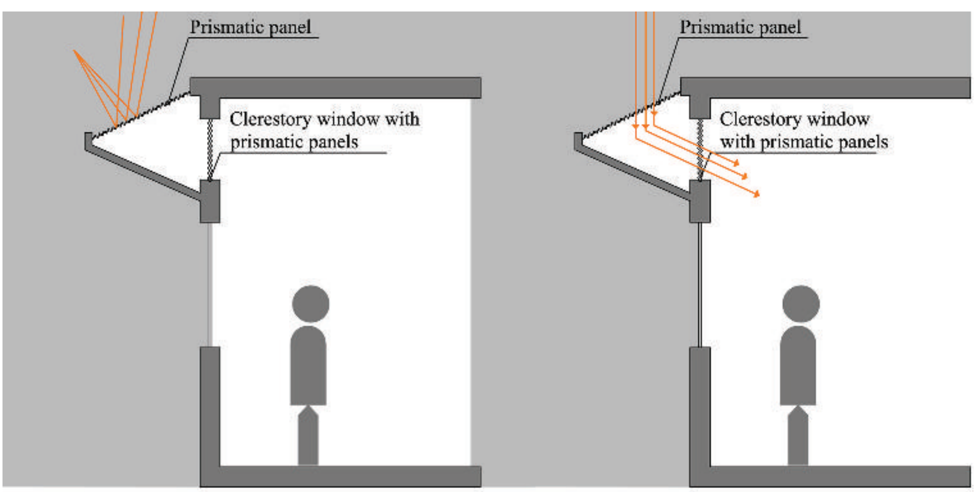

Figure 38: Prismatic panels.

Table 4: Features of prismatic panels.

Advantages	Disadvantages
	Prismatic panels
Reduce thermal loads in summer	Possible presence of irritating dazzling phenomena if prisms are oriented in a manner that does not conform to the solar path
Maximise solar gain in winter	High costs for installation and to be made to measure for each latitude
Protection from irritating glare	Reduced availability of natural light in standard overcast conditions
Uniform distribution of illumination	Require additional shielding components
Ability to provide tailored angling of the prisms	
Reduced maintenance when cleaning the panel in which they are inserted	
Direct natural light in depth in the room and reduction in artificial sources	

In the winter, the efficacy of the panels is therefore due to the greater share of solar radiation transmitted, which increases the levels of illumination and reduces costs for artificial light.

Therefore, to obtain the maximum effectiveness, the panel should be able to function at a wide range of angles: for example, an angle of 15° with respect to the horizontal enables reflection of the light, so that a substantial proportion of radiation exceeds the barrier of the device, preventing glare.

Determining the angles of inclination of the triangular face that form the prisms must be based on the path of the sun in the locality where the panels will be used. Consider also that, in the presence of a standard overcast sky, the prismatic panels work to reduce by up to 20–30% the illumination of the interior, just as brightness in the upper part of the fenestrated or transparent surface is greatly reduced (Fig. 39).

In the presence of clear skies the reflecting and diffusing action of the prisms ensures a remarkable homogeneity of illumination in the areas surrounding the panel, protecting also from an increase in the average E_m levels in the depths of the room, in proportion to the reflectivity of the ceiling.

During the solstice and the vernal equinox, at our latitudes, solar radiation with a low angle on the horizon is able to filter through the panels and to illuminate the room, even in depth, while circumventing glare in the vicinity of the transparent surface.

3.4 Laser cut panels

Laser cut panels perform the task of re-directing incident light; they are also counted among the shading systems, by virtue of their inherent ability to manage particular incident angles of light,

Figure 39: Translucent prismatic panels canopy, Yankee stadium, New York.

within whose range the optical properties of the panels allow reflection of the full quota of light, thus protecting interiors from glare and overheating.

These are thin panels cut by laser to create prismatic surfaces of infinitesimal size in a transparent acrylic material, PMMA – Polymethyl methacrylate, capable of directing natural light.

When incident light is inclined at an angle of about 30°, all the rays are reflected towards the outside, while with inclinations equal to or less than 20° from the horizontal, light is directed towards the surfaces of the ceiling and diffused towards the bottom of the interior space, far from the apertures.

Thanks to this configuration, laser cut panels possess a variable dynamic behaviour that guarantees maximum protection from incident rays during the summer, and a greater level of illumination than plain transparent glass during the winter (Fig. 40).

The path the light follows within the prismatic surfaces cut by the laser is composed of multiple refractions, to ensure maximum effectiveness of diffusion and shading.

Usually, laser cut panels are engraved with an inclination perpendicular to the surface of the panel, but it is also possible to realise other angles to respond to special illumination needs using Daylighting.

This particular system is used between glazed panels, to create a fixed system that cannot be modified once installed. Customised angling of the panel guarantees maximum efficiency for the device. On the other hand, the physical conformation of the panel prevents perfect vision of

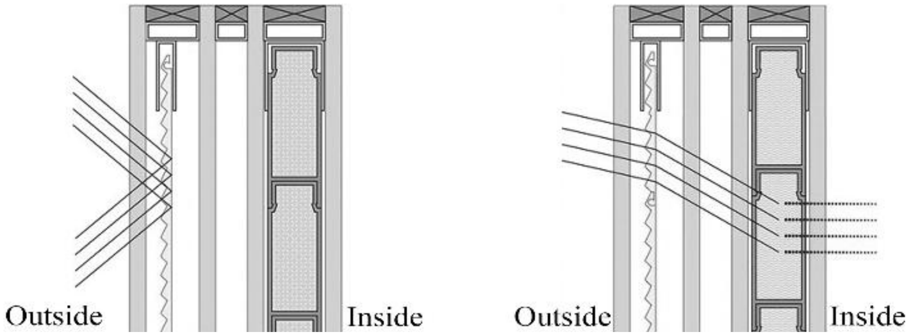

Figure 40: Laser cut panels, system of operation.

Figure 41: Façade cladded with laser cut panels, London.

the outside: the view is often compromised or distorted by the optical properties of the panel. For this reason, it is preferable to use it for the upper part of the windows, or in the case of transparent glass, at a height greater than that of the eye. Since the incident solar ray is naturally inclined downwards by the cutting of the panel, the external view is often compromised.

The main uses of these devices is as reflector systems that can be used either vertically or horizontally: In both cases, the peculiarity that makes them so effective is the ability to consistently reduce glare in the vicinity of the transparent surface, by virtue of the fact that the diverted ray is directed upwards, while the radiation not diverted continues its journey downwards, together with the incident light (Fig. 41).

The quota of light dispersed is considerably reduced by the absence of curved surfaces, eliminated in the production stage by the laser. It should be understood that the most appropriate positioning is therefore in the upper part of windows (Table 5).

Table 5: Features of laser cut panels.

Advantages	Disadvantages
	Laser-cut panels
Reduce thermal loads in summer	Possible irritating dazzling phenomena if panel is placed at height of the eye of the beholder
Maximise solar gain in winter	Need additional protection against direct sunlight
Protection from irritating glare	Distorted view of the outside
High availability of natural light as the sole source of lighting	High costs for installation and customisation for each latitude
Direct natural light in depth in a room, with deviation of 120°	

3.5 Light guiding shades

This Daylighting system works primarily as a tool for the diffusion of light in interiors and, only secondarily, as a tool for shading. The *light guiding shade* consists of an outer screen that conveys light and directs it according to a pre-determined angle towards the ceiling.

The system is constructed in such a way as to cover a range of angles that extend from horizontal up to a maximum of 60°, with a minimum inclination of 0° in order to avoid any risk of glare.

The device has the appearance of an external slat – a lightshelf, but features a screen fixed towards direct radiation, with the difference that the slat is coated with more sophisticated materials to ensure a wide range of tilt angles, so that the deflected light is directed towards the reflective surface of the ceiling.

The finishing material of the light guiding shade is highly reflective to ensure maximum optical efficiency.

Particularly advanced light guiding shade solutions are usually positioned at a height equal to one-third of the light from the aperture, while a further slat consists of an aperture of diffusing glass and two reflectors, designed to drive the light into a channel that is created towards the inside of the room.

The complexity of the device and the inherent cost of the materials used, make light guiding shades rather expensive, but very effective, even though they may suffer from some problems of rainwater infiltration, which collects within the slat and can percolate inside or onto the glass.

The main use of these devices for Daylighting is to diffuse the sunlight according to a pre-determined angle, while at the same time offering shading from direct light; this peculiarity makes them particularly suitable for tropical and sub-tropical climes, where the direct solar radiation is excessively strong and simple shading systems threaten to plunge closed environments into total darkness.

For this reason it is recommended for these climates to have diffusion angles with an amplitude that can ensure the correct amount of diffused light to carry out visual tasks, without having to resort to the contribution of artificial light (Fig. 42).

Figure 42: Light guiding shades for residential use, Cape Town.

In these specific cases, the efficiency of light-guiding shades is also optimal to reduce thermal loads from overheating, without precluding the presence of adequate levels of illumination within rooms to which they are fitted.

Light-guiding shades can be used in any building that includes external shading systems, because these act as a barrier to direct incident light, but provide a quota of reflected light directed towards the ceiling that meets the needs for homogeneous and indirect illumination (Fig. 43). It is considered that an excessively shaded window offers an average illuminance equal to 50 lux, while if a light-guiding shade has been fitted, it is possible to reach 1000 lux at a depth of about 5 meters from the fenestrated front in the case of clear skies, and up to 250 lux in the presence of a standard overcast sky.

The direct light that strikes a light-guiding shade and enters and spreads through an interior, can strike the slat according to such a broad spectrum of angles that it would be impossible to check all the possible directions of reflection.

The diffusion treatment that the inner surface of the device can be created with ensures control over the particular direction with which the light is diverted into the interior space, according to a variable angle that depends on the illumination needs.

Therefore, particular attention needs to be given to the selection of the most effective aperture angle for the device, as well as the choice of diffusing and reflecting optical materials used to treat the surfaces of the slats and the surfaces of the ceilings and walls.

The high performance of these systems lies in the fact that they can ensure remarkable savings in terms of energy (Table 6).

Figure 43: Light guiding shades with treated optical glass, Dubai.

Table 6: Features of light guiding shades.

Advantages	Disadvantages
Light guiding shades	
Reduce thermal loads in summer	High production costs
Protection from irritating glare	Need additional protection against direct sunlight
Uniform distribution of illumination even in tropical climates	High costs for installation and customisation for each latitude
High availability of natural light as sole source of lighting despite the outer shield	
Reduced maintenance	
Direct natural light in depth into a room	
Do not affect the external view	

3.6 Sun-directing glass

Despite being an evolved glazing system, *sun-directing glass* deserves to be counted among the daylighting devices. It is made by sealing together concave acrylic elements vertically arranged on top of one another, to allow direct incident light to be directed and angled towards the ceiling, in a pre-established direction.

To prevent the device totally excluding the view of the outside, sun-directing glass is normally fitted at the top of a window, so as not to preclude the view or alter the colour, while the lower portion of the window is made from double standard glass and possibly shaded using traditional systems.

Figure 44: SMUD HQ, Sacramento, one of the first examples of the use of sun-directing glass in a public building (credit Dreyfuss & Balckford Architects).

It is usual to fit a sinusoidal structure to the inner surface of the glass in order to be able to diffuse the light with a reduced horizontal angle, while the outer surface of the glass is treated with film to capture incident light and concentrate it according to a precise angle.

The peculiarity of optical devices of this kind is the shape of the acrylic elements with which the double pane is made: the concave elements are cut onto a holographic film by a laser beam, similar to what happens for a sinusoidal surface.

Sun-directing glass offers considerable flexibility in application: it can be inserted above the height of an unobstructed view, either inside or outside a window, on an existing window or even onto transparent façades, where retrofit operations are necessary (Fig. 44).

They can also be effective for horizontal apertures in the case of toplighting, in the presence of skylights and glazed atria, as long as the system is tilted to a minimum angle of 20° to encourage solar penetration, but avoid irritating glare and direct the solar rays deflected downwards.

The best orientation for sun-directing glass is south, in temperate climates. In the case of use with east–west orientation, the maximum effectiveness of the system is obtained in the early hours of the morning and in the afternoon.

The ability to redirect the light protects against excessive illumination ensuring homogeneity in the areas surrounding the fenestrated front, while the illumination at the bottom finds no particular benefits, especially in the case of very long rooms (Table 7).

Table 7: Features of sun-direct glass.

Advantages	Disadvantages
Sun directing glass	
Effective for all solar heights	High production costs
Protection from irritating glare	Need additional protection against direct sunlight in the lower slotted part
Uniform distribution of illumination in depth	Alter the view of the outside
Integrate with other shielding systems	Give a milky or opaline appearance to façades
Can be used in cases of energy retrofit	
Direct natural light in depth into a room, in the presence of diffusing finishing materials	
May be installed inside or outside	

We must bear in mind that the operation of sun-directing glass is guaranteed both in the case of vertical and horizontal inclination, in relation to the type of curvature used for the concave acrylic elements interposed in the glass.

The variable behaviour of this glass, by virtue of its own composition, together with the optical properties of the holographic film affixed to it, alters the transparency, modifying the perception of colours and giving the façade a milky, opaline appearance that must be carefully evaluated in the overall design for the building's shell.

3.7 Glazing and shading systems that employ HOE materials

Systems employing holographic materials in the form of films applied to windows allow incident light to be distributed in depth in the interiors, especially in the case of zenithal illumination. The film coating is made from a polymeric material, which, through the reticules of which it is made, reflects the light according to precise directions. The HOEs direct incoming diffused light allowing the achievement of high thresholds of illumination.

The limitation of this type of window is the restricted field of use: In fact it is effective only in the case of diffused light, since, once it has been struck by direct solar radiation, it creates glare and uncontrolled disturbances in the light.

A further limitation is the slight deformation produced, making this type of glass unsuitable for use on large transparent surfaces, where the view of the outside should be unhindered; in fact, it is preferable to employ it in the upper part of larger apertures.

On the other hand, in the case of zenithal light this type of glass offers a good response when the inclination is around 45° (Fig. 45).

The use of systems and windows that employ HOE film is advisable in situations where the view of the sky is strongly precluded, whether because of the presence of obstructions, for example, in strongly urbanised contexts, or in cases where the sky is predominantly overcast throughout the year. In the latter case, composite systems or simple light-guiding glass can direct natural light into the interior space using an inclination of about 45° with respect to the

Figure 45: HOE glass and light guiding shades, Administrative Building of UCSD, San Diego.

plane of the façade, thereby increasing light levels. The addition of reflective materials, for both walls and ceilings, is essential to complete the diffraction effect of the film applied to the windows.

Installation of HOE glazing is very sensitive therefore as regards the angle of incidence of the sunlight due to the conformation of the holographic film, which requires an optimal angle of solar height around 5°. Some experimental tests, for example, some HOE glass installed on the fifth floor of the *Hartley Library* at Southampton University, mainly concentrated on quantifying the performance of HOE in ideal conditions. The assessments focused on investigating differing performance in relation to specific positions of the sun with respect to the inclination of the HOE glass.

In addition to a simple application for the production of glazing panels, HOE film can be used for the construction of complex systems, such as in the case of transparent sun breakers made from selective holographic glass.

The advantage consists in the interoperability with other systems and with vast transparent surfaces, both for façades and roofing elements, in addition to notable ease of maintenance.

In this way, in addition to ensuring penetration of natural light into the depths of a room, it prevents overheating and irritating glare near the fenestrated front.

Unlike the installation of simple HOE glass, systems of louvres or lightshelves which make use of holographic films, need to be integrated with an automatic, mechanical system that modifies the inclination of the slats, following the direction and the path of the sun, to optimise performance and ensure a proper angle, both in the case of vertical and horizontal mounting (Table 8).

Table 8: Features of HOE windows and systems.

Advantages	Disadvantages
Glazing and shielding systems that employ HOE	
Savings in terms of reduction in artificial lighting	Solar gains cancelled during the winter
Protection from irritating glare	Complex maintenance
Integrate with other manual and mechanical shielding systems	Alteration of colours
Can be used in cases of energy retrofit	
Re-direct natural light in depth into a room, in the presence of diffusing finishing materials	
Can be placed inside or outside	
Savings in terms of reduction in artificial lighting	

The movement that an integrated mechanical system provides, therefore, allows inclination along a single axis, an angle that is selected based on the average height of the sun for the site in question.

A further sub-category of products that employ holographic film is *sunlight-concentrating system.*

In this case, the effectiveness of a single device is maximised: from a simple shading system, it becomes a daylighting device that makes it possible to take full advantage of diffused light and the same time to produce energy, thanks to the presence of photovoltaic elements.

3.8 Zenithal anidolic systems and anidolic ceilings

Zenithal anidolic systems, better known as anidolic ceilings or *Anidolic Daylighting Systems* (ADS) capture the diffused light from a large portion of the celestial vault and transmit it within a building, at the same time screening out direct radiation for visual and thermal comfort inside [53] (Fig. 46).

This system makes it possible to reach a homogeneous and constant level of illuminance for most of the daytime hours, both in the case of clear and standard overcast skies [54].

The optical facilities of these zenithal systems make use of parabolic concentrators that collect the diffused daylight coming from the sky and then direct it towards a specular light duct above the ceiling, which transmits the light captured to the end of the room.

These systems, created for non-residential applications, make it possible to build systems that focus and intensify the incident radiation and then direct it into optical channels and concentrators that operate differently from traditional mirrors, since the final product is not an image but a concentrated ray.

The element that makes the system particularly efficient is a compound parabolic concentrator, which governs a wide range of reflectors for natural light, to be used for horizontal roof structures, that is, anidolic ceilings.

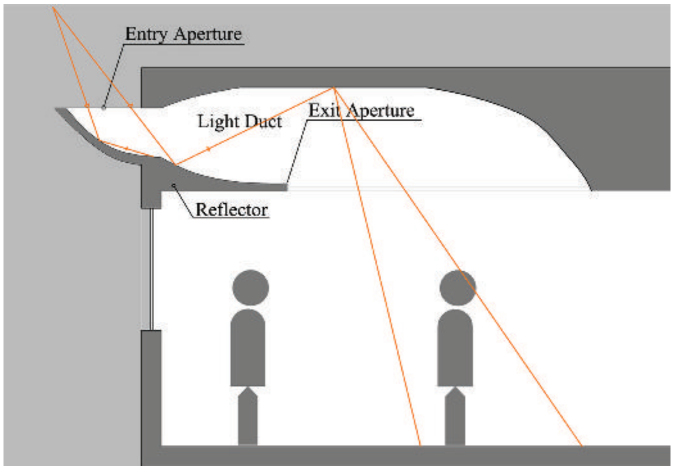

Figure 46: Scheme of an anidolic ceiling system.

The spread of these complex systems has found fertile ground especially in metropolitan areas, where solutions of sidelighting are far from efficient, due to the proximity of the buildings and the large number of obstructions along the paths of light.

A convenient solution for strategies of Daylighting, therefore, consists of anidolic systems, applicable to cases where windows alone are not sufficient to ensure adequate levels of illumination.

The zenithal anidolic system consists essentially of three subsystems: an external manifold, a solar tunnel and a diffusing element for the interior space. The concentrator is positioned on the roof, to receive the diffused light from the celestial vault, where it captures diffused sunlight, regardless of the sky conditions.

Each element of the subsystem performs a specific function: The manifold has the task of collecting the flow of sunlight, which is then transported through the optical duct into individual rooms, where it is distributed. The luminous performance resulting from the use of these zenithal systems is greater the more light the manifold manages to gather.

The illumination at the back of the room is lower, as are the overall lighting levels, due to the lowering of the height of the ceiling.

Recent assessments and tests on mock-up rooms, performed in the department coordinated by professor Scartezzini, have shown that the maximum effectiveness of systems of this type are for interiors with depths of more than 6 meters. Within this family of optical devices should be mentioned anidolic solar screens, made from a succession of hollow reflective elements coupled with two tiny three-dimensional parabolic concentrators (Fig. 47).

The maximum shading and diffusing effectiveness is obtained by using these optical bodies in a lateral position, in order to control the amount of light that enters through the windows by selecting only useful angles, hence they are also called *anidolic solar blinds* (Table 9).

Figure 47: LESO Solar Experimental Building, EPFL Campus, Lausanne (credit Chantal Basurto).

Table 9: Features of anidolic devices.

Advantages	Disadvantages
Anidolic Daylighting systems and anidolic ceilings	
Uniform distribution of illumination in depth	Solar gains cancelled
Protection from glare	Tough integration in case of retrofit operations in existing buildings
Re-direct natural light in depth into a room, in the presence of diffusing finishing materials	
Maximum effectiveness regardless of the conditions of the sky both overcast and clear	
Possibility of integration with other systems of an existing building, but only in the event that a suspended ceiling is used across the full width and depth	
Also applicable in the case of obstructions and limited portion of sky	
Ensures unobstructed view of the outside	
Savings in terms of reduction in artificial lighting	

The slats of *anidolic solar blinds* are part of a fixed system applied to windows, or to be affixed to the upper part of an aperture, so as not to obstruct the view of the outside, while providing a variable amount of natural light inside the shaded environment. Systems of anidolic slats control the radiation on entry and regulate the thermal quotas during the winter and summer, especially in the case of façades looking south.

In both applications, the slats are enclosed within a glass interspace to avoid exposing them to dust and inclement weather, thus guaranteeing enduring constant use and facilitating maintenance.

The most evident shading performance is obtained in hot countries that are mainly sunny, due to the inherent nature of the slats, which once positioned, cannot be adjusted.

To increase solar gain in sunny climates, it is possible to angle the slats with respect to the vertical up to an angle of approximately 18°, along an axis that will also lead to an increase in levels of illumination.

4 The role of Daylighting in environmental and energy certification procedures

In accordance with recent policies aimed at fostering sustainable development, to reduce the emission of pollutants, and consciously exploit natural resources, Daylighting can act as a crucial element to maximise the input of sunlight and exploit its beneficial contribution in terms of energy consumption and indoor health.

There is now widespread awareness that the controlled use of sunlight, wherever possible, is one of the most important strategies in terms of energy saving, not only because of the reduction in energy consumption due to a lower quota of artificial light, but also because of the reduction in thermal loads related to conditioning. The potential related to the quota of electricity and thermal energy savings must lay the foundations for an informed integrated approach between different professional skills, suitable to carry out a project in which Daylighting is included from the early stages of the project.

Although the preconditions to the question depend on the definition of multidisciplinary approaches in order to promote energy savings, the fundamental question has rarely been investigated thoroughly, and in effect, few examples of valid integration of daylighting strategies are to be found in energy-saving policies.

Instead, there is a rather diffuse idea that, ‘good sunlight’ is a method in itself sufficient to address the issue of energy saving, without addressing the problem of weighing up and providing adequate systems of solar penetration, shading and artificial lighting.

Potential savings in electricity were then obtained by analysis of the levels of the Daylight Factor [55] for the illumination of an interior [56], information that was then aggregated to manage the first artificial light control models.

The first apparatus proposed envisaged manually turning on and off switches and appliances for artificial light, based on levels of user satisfaction.

The inherent limits of this type of practice were understood very early on, which often, instead of promoting energy saving and creating an environment that was comfortable from a lighting and thermal point of view, created overheating and overloading of the whole electrical system. Some primitive forms of automated control to dim artificial light on the basis of the needs of the user were proposed for public buildings, together with theoretical formulations on the possible behaviour patterns of occupants in relation to natural and artificial light.

The design of complex systems for the control and management of lighting equipment and sensors to detect the occupation of working environments has considerably improved over the course of the last thirty years, also thanks to POE – *Post Occupancy Evaluation*.

In addition to assessments concerning the real preferences of occupants, it is also important to pay attention to the control of electrical and thermal power consumption in the cooling and heating of buildings, in particular public buildings, schools and offices, where energy loads are considerably higher.

These various considerations must therefore be merged in a policy that integrates skills, in which natural and artificial light, mechanical devices or ones that are automated and manually adjustable by users can be controlled to provide the maximum in energy and indoor environment performance.

The methodology proposed in recent years is therefore one of synergistically bringing together new dynamic parameters according to the CBDM dynamic model, along with a specific thermal modelling of the building, its various areas and its environments, making it desirable to have a realistic and reliable simulation to provide genuine savings in terms of electricity [57].

The help offered by specific software for the dynamic climate simulation also makes it possible to resolve precise solutions both in the design phase *ex novo*, and energy retrofits, by evaluating also the overall environmental performance of a building.

In the context of environmental certifications of the Anglo-Saxon matrix, we can in fact find numerous parameters for assessment and verification that suggest and encourage exploitation of natural light.

Among the targets to be achieved to ensure achievement of the thresholds set and the subsequent attainment of relevant scores, is that of a design, as integrated as possible, at different stages and applied to various building components. In this way, attention must be paid to the selection of finishing materials, surface treatments and colours; crucial choices to vary light distribution in a confined environment.

A further practice to ensure energy effectiveness and saving is based on a *component-level* approach, which includes an effective combination of active and passive approaches to control the light, through the most state-of-the-art solutions of *toplighting*, *sidelighting* and *corelighting*.

Therefore, the concretisation of an excellent level of integration between elements of the building and the availability of natural light must occur at the earliest design stages, so that the building envelope and the other systems involved will collaborate smoothly.

4.1 Natural light in environmental assessment procedures: protocols and certifications

Accreditation programs and systems for environmental certification of buildings are currently burgeoning, including both mechanisms and scores of a voluntary nature, and the adoption of certain legally binding requirements that are capable of influencing the inherent processes of the design and management of buildings.

Environmental Certification includes Life Cycle Assessment, which takes a holistic approach to the environmental sustainability of a building.

The purpose of this type of procedure is to assess the totality of energy consumed and the totality of the environmental impacts, with a view to an improvement in overall performance of an edifice.

Among the most widespread systems, and among the first to include categories that contribute to the formation of a natural light score, is the US system called LEED, *Leadership in Energy and Environmental Design*.

LEED is used today to certify almost all types of building on the basis of the prevailing functions, from public buildings, schools, and offices, to buildings for cultural pursuits and research.

This system of accreditation is voluntary, and is therefore based on the acquisition of scores relating to six categories, used to declare the achievement of a standard level, which also considers daylight.

Among the categories of requirements the system is based upon is *Indoor Environmental Quality*, which assesses the presence and effectiveness of solutions for the exploitation of natural light.

Specifically, this awards a credit upon reaching the minimum level of illumination of at least 2% of Daylight Factor over 75% of the area in question (according to a test *in situ*), on the other hand, if a computer simulation is used, the achievement of at least 25 candles per square foot must be achieved, with reference to 75% of the area of assessment; a further credit may be scored in the presence of transparent fenestrated apertures, that ensure a vision of the outside environment for 90% of the surface of calculation.

Daylighting Credit 8.1 quantitatively assesses the efficacy of adequate levels of illumination capable of ensuring optimal conditions of environmental and visual comfort indoors, while always preserving a view of the outside from each work or rest station.

Despite the U.S. origin of this accreditation system, where the debate on the validation of new units of measurement and assessment systems for natural light is more lively and productive, incredibly, the LEED system still includes recourse to the static DF parameter which, as will be explained subsequently, provides no indication of the quality and variability over time and space of natural light.

Assuming different methods of calculating the credit 8.1 as valid therefore means a risk of considerable variations from one measurement to another, considering also the absence of a verification protocol in the assessment methodology itself.

In addition to establishing the criteria through which to give scores, some possible strategies are suggested to increase the amount of natural light in interiors, by promoting the use of systems designed to maximise the efficiency of shading devices, encouraging integration with combined natural ventilation systems, to bring the maximum possible benefit to indoor climates.

Similarly, practical guidance is also provided on the most appropriate choice of finishing materials and on the type of glazed panel to be used for windows.

Among the most important features derived from the approach provided by the LEED system are some guidelines, which are proposed as support for a new Daylighting project, but that can also be adapted to working with an existing system.

There is also an emphasis, in addition, on the vital urgency to integrate systems using natural light, not only with the architectural envelope, but with the utility networks, in order to derive the maximum possible gain through close collaboration between various subsystems.

For the first time in a voluntary certification scheme, attention is paid not only to the amount of light but also to the quality of the visual environment.

Similar in approach to the LEED system, is the British BREEAM – *Building Research Establishment Environmental Assessment Method* – which, for the most part, accepts as valid the requirements demanded by British building regulations, giving scores related to the achievement of a pre-determined standard.

This is a system of certification of a voluntary type, based on the acquisition of credits that defines the standards to be pursued for the achievement of high standards of sustainability for the construction industry, from individual components, to a consideration of the system in its entirety.

Specifically, a BREEAM credit is assigned if the availability of natural light is such that it covers 80% of the light requirements of the area under consideration, in relation to the requirements of the prevalent visual task that takes place there; in addition, a DF of at least 2% must be detected on the working plane, with a uniformity of at least 40% in the distribution of the illumination; additional credits are also assigned if the view of the outside is preserved.

Additional suggestions for good practice are provided for Daylight Assessment in a residential area, for which the assignable credits are three.

In response to the need to adapt the Italian and European regulatory landscape, the EU directive 2002/91/EC on energy efficiency in the building sector, in addition to a calculation of the requirements of the building, includes the introduction of a section for assessment of electrical consumption related to artificially lit environments.

In Italy, the Directive 2002/91/EC was transposed through several legislative acts: Legislative Decree 19/08/2005 no.194 (then modified as Legislative Decree 29/12/2006 no.311), Legislative Decree 30/05/2008 no.115 and with the corresponding Presidential Decree 02/04/2009 59, as well as the Ministerial Decree 26/06/2009, which instead, established national guidelines for the energy certification of buildings.

Again in Italy, the current status of regulations and ordinances for energy certification has been further transferred to the initiative of individual regions, which, through their own mechanisms and on the basis of the afore-listed directives, define methods and ranges of values with which to carry out classification. Although currently these assessments only determine the energy needs of a building's shell, there will soon be further considerations to calculate primary energy needs for air-conditioning and lighting.

Instead, the EN 15193 standard (2008) introduced the parameter LENI, *Lighting Energy Numeric Indicator*, for the assessment of energy performance of buildings as regards lighting.

Criteria were established to calculate the amount of lighting installations in terms of energy consumption, both in the case of existing buildings and new constructions.

The LENI indicator thus makes it possible to calculate energy consumption in accordance with EN 15193, in the same manner as the calculation of consumption related to heating, air-conditioning and sanitary hot water production. The LENI, in other words, is calculated as the ratio between the energy consumption for lighting and surface of the environment, and is therefore measured in kWh/m^2 per year. It can be calculated from the annual amount of electricity consumed W_{light}:

$$LENI = \frac{W_{light}}{A}\left[kWh / m^2 year\right] \quad (1)$$

LENI is therefore significantly influenced by the amount of natural light present that reduces energy consumption, as well as the possibility of manually or automatically operating systems to control the natural light, shading devices and by the combination of natural and artificial light.

In addition to the quantitative-type indicator there is a further parameter, created for artificial lighting, which is useful for qualitative assessment of visual comfort.

This is the ELI – *Ergonomic Lighting Indicator* – which makes it possible to evaluate the level of quality of a lit environment, based on five parameters, whose aggregate provides a good basis to prepare improved Daylighting strategies: scores are ranked by visual performance, overall look, visual comfort, vitality, individuality and flexibility.

Finally, mention must be made of the contribution in terms of environmental assessment provided by the ITACA protocol, applicable in a limited number of Italian regions and used to assess the sustainability of buildings, according to the proposed methodology and approved by the Decree 760/2009.

This protocol is a system to evaluate an analysis of the overall performance of a building according to several criteria that can be assigned a score, from which comes an aggregate.

Among the criteria that make up the areas of assessment, can be found numerous parameters relating to the quality of light in a confined environment: in the requirement of Table 4, under the heading 4.1 – Visual Comfort – there is a comprehensive analysis of natural light, through verification of compliance with the requirements 4.1.1: Natural Lighting, 4.1.2: Penetration of direct sunlight and 4.1.3: Uniformity of illumination.

For each requirement, the ITACA protocol expects minimum indicators of performance, just as each category of inquiry is supported by specific strategies of reference to be followed. In particular, Requirement 4.1.1 evaluates the exploitation of natural light for the purposes of energy-saving and of visual comfort through the use of the parameter DF_m, on the basis of which a reference scale has been drawn up that combines at determined intervals of DF_m percentages, scores in a range from 2 to 5 points.

The main objective of the survey is therefore to examine the architectural choices, from the preferred orientation of the façades of the building, to the layout of the interior space and the selection of the type of apertures to be used.

5 Daylighting between the architectural design and the management of light

The technological question, concerning both the choice of diffusing systems and shading devices, parallel to the need to integrate in the design of the building shell – choices that will meet the requirements of visual and thermal indoor comfort, shows the need to deal with the question of managing Daylighting according to a complex and well-constructed practice.

A key role in strategies for light definition is also played by the finishing materials and the choice of colours for these; fundamental in determining the distribution pattern of the sunlight, assessed on the actual demands of the space.

Management of the optical properties of the materials is considered an issue of vital importance at the time of design, at a technological level, both with respect to the optical properties of the apparatus to diffuse the light, and of those involved in shading.

The technological solutions previously addressed are mainly suitable for large buildings, where multiple and variable needs over the course of the day, and in relation to the type of user, must be able to offer different and variable shading solutions for positioning with respect to the windows, to be arranged at the outset of the assessment, or designed from scratch.

Natural light, filtered, screened and directed, becomes a central theme in the designing of a space, since different multi-criteria assessments have helped us understand that the preference for natural light is a factor of individual inclination, just as the predilection for different levels of natural light depends on a multitude of factors.

The use of these devices allows, in the first place the designer, and secondly the user, to measure their own preferences against their real needs in a flexible way. The most coherent approach is therefore geared towards maximum adaptability, arranging for complex and integrated solutions.

While the new architectural trends are intended to meet, where possible, the majority of the needs of the occupant, thanks to the integration of automated control systems for the management of domestic devices, the management of natural light simply follows natural and organic paradigms which, if properly evaluated and used, can also contribute significantly to the creation of comfortable and energetically advantageous environments within the overall budget of a dwelling or a public building.

Lighting design, seen in the context of the most effective combination of devices for artificial light, devices for natural light and automatic and adaptable systems for the shell, can only be entrusted to professional figures whose profile is capable of combining architectural, plant and environmental instances.

By drawing on experiences of good practice from traditional and local construction traditions, it is also possible to orient the management of natural light to permeate the constructed space with an eye on energy savings and sustainable environmental management of the building.

Lighting design, the timely management of solar contributions together with the assessment of spatial and energy aspects cannot only cover the optimisation of the shell, the apertures and the devices to manage the light and shade but must deal with defining a global system of assessment that can define the limits of the field of action, as well as matching the variable instances to the exact needs of the occupants in relation to a particular visual task.

The question of Daylight Assessment demonstrates how different strategies need to combine in a comprehensive and integrated approach that takes account of complex factors, from local geographic, meteorological and variable aspects, to optical and perceptive needs linked to the mood to be given to the environment, in addition to the requirements to define a space that is concluded and accessible through the light that illuminates it.

Architecture in its broadest sense must therefore necessarily tackle the most contradictory challenge between two primitive and extreme requests: it must mediate between change and tradition, reconciling the request for innovative and technological solutions with the difficulties in management and integration that these entail. But, primarily, daylight architecture must know to deal with the unpredictable: to be flexible and adaptable to the constant variability of users' requests, the technologies of the shell and solutions for the reduction of energy consumption.

In this sense, Daylight Assessment can also be described as a complex system of critical assessment that makes the architectural space somewhere that is never concluded, but is changing, dynamic and never standardised, in virtue of natural light.

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Part 2:

THE CALCULATION OF NATURAL LIGHT – FROM THE STATIC TO THE DYNAMIC MODEL

Chapter 3

Daylight assessment: the evolution of static model

1 Introduction

Defining the performance and the expressive possibilities of natural light in architecture is the task of a multi-criteria assessment, which is able to take into account the complex performance related to the use of daylight, not only in an architectural context, but also linguistic and formal. An analytical system based on an assessment of the static type, to assess the persistence of prevailing conditions in levels of lighting, glare and visual comfort in a confined environment, constitutes most widespread the approach today.

Daylight Assessment according to the static model, envisages that an optimal level of natural light is possible to explain simply through the achievement of threshold levels established *a priori*, in relation to the prevalent visual task expected to be carried out in a given environment.

An approach of this type appear excessively restrictive and inconsistent, since it does not take into account the conditions of extreme volatility and dynamism of the sky conditions, variability in the functions and tasks that an interior may house, in addition to not taking into account a possible, and probably necessary, integration with appliances for artificial light.

The role of light, according to the static approach, remains confined to a simple element that enriches the environment, by virtue of the possibilities of integration between light, shape and colour in a space, creating new configurations, flexible and always renewable scenarios, capable of conferring emotionality on a constructed space.

Static analysis at this point appears reductive and imprecise, incapable of representing actual lighting conditions, distributions of the light, and the potential inherent in the appropriate use of direct and indirect radiation for energy saving strategies.

While the focus towards the creation and management of illuminated spaces naturally evolves in a constant manner, both to meet the needs of energy saving, and to deal with requests for indoor comfort for occupants, the definition of new parameters for a fresh approach to the assessment of natural light still seems stuck at the initial characterisations.

Assessment according to a quantitative approach of natural light in a confined environment is relatively recent: the first attempts at measurement of external ambient lighting in fact date from 1895 [58].

The first to introduce the Daylight Factor concept was the English physicist Trotter who, at the same time as the first attempts to systematically measure the illumination of the sky, tried to define the geometric parameter, of which today we know the exact definition thanks to it being elaborated by Hopkinson. To define the amount of natural illumination of a horizontal surface within an environment, numerous studies came subsequently to different systems of analysis.

In 1955, Ketteler came up with a formula to calculate the luminous distribution of the sky, which is essential for studies of the various models of the sky, which was then followed by the diagrams of Waldram, elaborated by Peter and Michael Waldram to assess the components of the sky.

Proposed in the United Kingdom in the early 1900s and subsequently taken as a basic parameter for the definition of light analysis in closed environments, the Daylight Factor (DF), was set up in the current version in 1963 [59]: 'The Daylight Factor is defined as the ratio between the daylight illumination at a point in the interior and the simultaneous exterior illumination available on a horizontal surface from an unobstructed hemisphere of overcast sky (excluding direct sunlight) expressed as a percentage'.

Therefore, by DF is meant the ratio between the illumination inside detected on a horizontal plane in CIE standard overcast conditions and the corresponding illumination outside.

The studies by Hopkinson took as valid two criteria to calculate Daylight Factor: If, on the one hand, the DF is definable as a percentage of the relationship between internal illumination and the simultaneous illumination level outside, measured in the absence of obstacles and with an unhindered view of the sky, on the other, it is also possible to define it as the summation of three individual contributions that take into account the *Sky Component* (SC), the *External Reflected Component* (ERC) and the *Internal Reflected Component* (IRC).

At the present time, the greater part of luminous assessments on the performance of natural light consider the DF as the only valid criterion, according to a methodology of a *snapshot* or *single-point-in-time* type, ignoring in both cases the real influence of the sky conditions and the temporal and climatic variations linked to the geographic location.

The DF, in fact, excludes, by definition, the contribution of the light coming directly from the sun, considering only the diffused component, i.e. that reflected from the sky, according to the standard approved by *Commission Internationale de l'Eclaraige* (CIE), in overcast conditions.

Some scholars have tried to deeply understand the diffusion path of sunlight in a confined environment through study of the solar path, using a *sun path diagram*, thanks also to dynamic analysis of shading systems, but systematically excluding the contribution of direct sunlight, in favour of the single sky component.

Because of these limitations, calculation using the static approach always produces a relative value, independent of the extensive range of possible weather conditions. It is therefore of great importance to specify the real distinction that exists between direct light, coming straight from the sun, and diffused light, coming from the whole sky, diffused and reflected by it.

In this connection, reference should be made to the preceding scheme, useful to understand the range of applicability and its limitations related to the use of the DF as the sole criterion for the assessment of the luminous performance with only natural light. This diagram shows the different components of natural light and their respective contributions with respect to the static model.

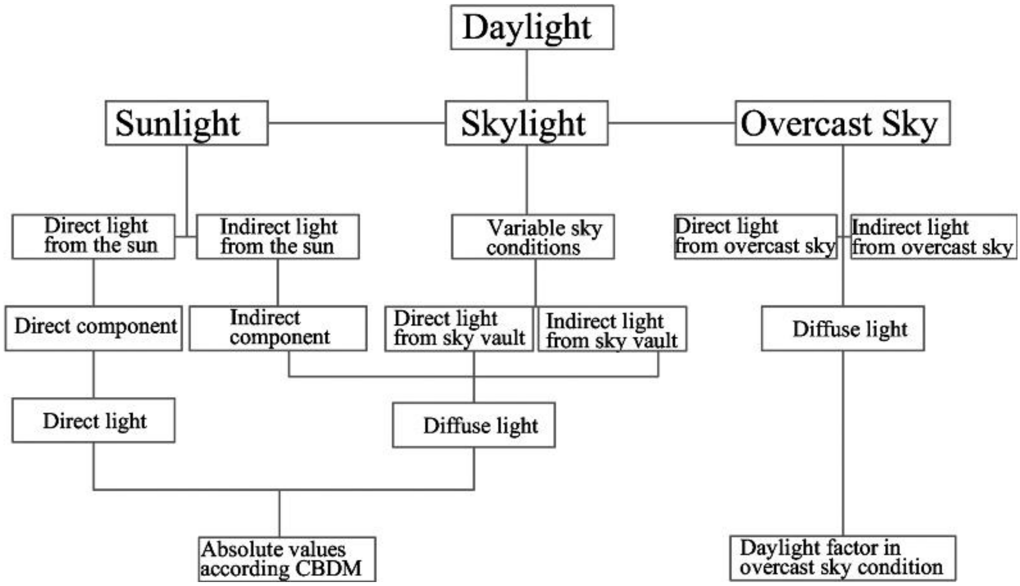


Figure 48: Daylight components.

Natural light is therefore formed from two essential components, the proportion coming from the sun and the quota from the sky (Fig. 48).

Since light can reach a point on the Earth's surface directly or indirectly, direct lighting is defined as the quota of solar radiation that reaches the surface from the source, without intercepting any kind of obstacle; while if a light beam reaches the point of calculation as a result of several reflections, we talk of indirect light.

Although it is correct to consider as sources of natural light both the sun and the sky, the light coming directly from the sun must be considered in a distinct manner, due to its reduced angle and its high illumination potential. Meanwhile, the proportion of light reflected several times from the sky, cannot be considered properly indirect light, but rather diffused light.

The first studies on the nature of the sky and the wide variety of light conditions associated with it, were performed by Kimbell in Chicago and Washington, in order to collect a vast amount of data, to create an extensive overview of the real sky conditions over a sample period of three years, from 1921 to 1923.

As a result, two prevailing models of the sky were defined – still in use today – the model of the *standard overcast sky*, and the model of the *clear sky* [60].

As a result, scholars such as Pokrowski [61] implemented existing models, arriving in 1929 at the definition of a new formula for calculating the luminous distribution of a cloudless sky, similarly to that obtained by Moon and Spencer, with the calculation of an empirical formula for a graphic representation of the standard overcast sky, to which was added finally the mathematical formula to represent the luminous distribution of the standard overcast sky by McDermott and Gordon-Smith in 1951.

Only in 1955 was a definitive validation by the CIE made of the formula of Moon-Spencer to calculate the luminous distribution of an overcast sky, thanks to which it was immediately clear that this contribution was crucial for the assessment of natural light.

Despite the widespread use and the popularity gained by the DF parameter, especially in relation to recent trends aimed at enhancing passive technologies as much as possible, including exploitation of sunlight as a prevalent source of lighting in indoor environments, it is evident that some substantial limitations are obvious in the very definition of the Daylight Factor.

2 The Daylight Factor: methods and tools

The Daylight Factor (DF) is not a unit of measurement on the good quality of light in a confined environment, but is a parameter to assess the satisfaction of a minimum threshold of natural light.

The DF stands as the most widespread unit of measure for estimating luminous performance, just as any qualitative or quantitative consideration for the measurement of natural light cannot do without the DF today.

Several methods are currently being validated to calculate the Daylight Factor. Illumination achieved through sunlight can be expressed in absolute terms as the value of illumination expressed in lumens per square metre, or as a percentage of the natural lighting available in the presence of a standard overcast sky.

Natural light that strikes an object or that affects a horizontal surface in a confined space is not composed only of the quota of light coming from the portion of the sky visible through the window or door frame, but also by the amount of light reflected from the ground and the surrounding elements that reaches the point in question after a journey of multiple reflections.

The global value of the Daylight Factor can be defined by the sum of these different contributions; however, the numerous methods for calculating DF can essentially be divided into graphic, geometric and analytical.

2.1 Graphic methods

Among the graphic methods in use to estimate DF, the best known is the *Waldram Diagram* for the assessment of the Sky Component, SC [62].

The use of this graph-type tool refers to a condition of the sky with uniform radiance, thus compelling simplification in considering the actual conditions of the celestial vault. The Waldram Diagram can be used to estimate the direct lighting from the sky for a single point.

This method is usually employed, often using specific software, for a preliminary estimate of the availability of a sufficient quota of natural light in the design stage of a building, or in the case of volumetric increase or increase of the volume of a nearby building, operations which could influence the presence of light for a given room and in the case of complex fenestrated apertures.

The Waldram Diagram consists of a rectangular field that represents half of the celestial vault, in which the vertical axes correspond to the altitude and the horizontal axes represent the azimuthal angle between the wall and the sky (Fig. 49).

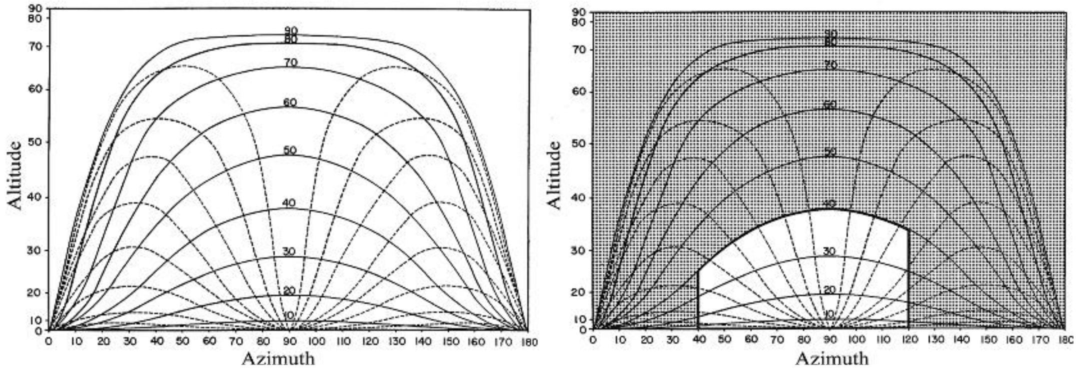


Figure 49: Waldram diagram and example of graphic calculation.

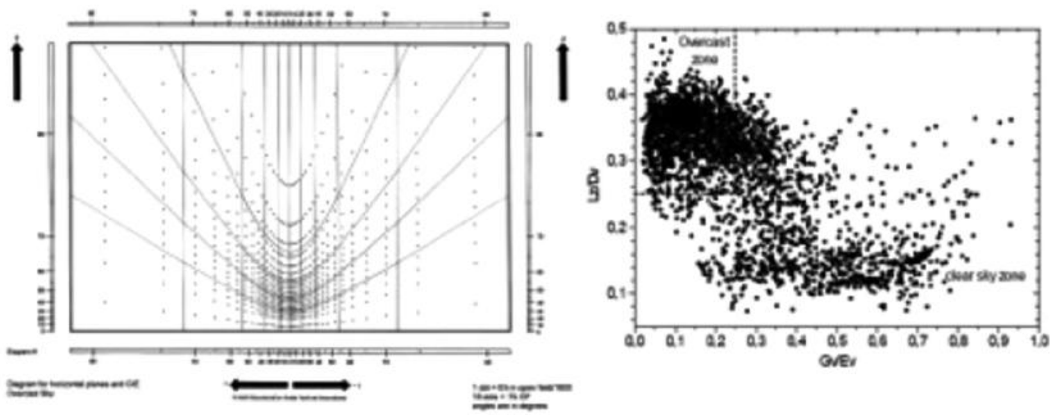


Figure 50: Pepper-pot diagram and Turner diagram.

The peculiarity of this graphic system lies in the fact that the vertical representation axis is different from the horizontal one, making it possible to compare measurements that are otherwise too different: in this way, the areas that are formed on the graph represent quotas equivalent to the radiance of the sky. The graph makes it possible to represent the space taken by a room and the positioning of the relevant apertures, in such a way as to evaluate the portion of sky visible through them, without any obstacles that may intercept the incoming light.

The ratio of the area enclosed in the projection of the portion of sky viewed from the point in question and that of the entire diagram considered twice, gives the percentage value of the Sky Component, SC.

This simplification is feasible in virtue of the fact that the chart is divided by a grid of squares in multiples of fifty.

Another graphic system that can be used to assess the DF in a room is the Pleijel or pepper-pot diagram, first presented in 1954, for standard overcast conditions, very similar to the graph of Turner, in which clouds of points are used to represent distribution of the sky's luminance [63] (Fig. 50).

2.2 Geometric methods

Among the geometric instruments, goniometers for the assessment of components of internal and external reflection are characterised by their ease of use, apart from the complexity of the apertures to calculate the amount of light. The goniometer geometric method is used to estimate the proportion of light reflected from the sky and interior finishing elements, in the presence of either standard overcast or clear skies. Goniometers are laid directly on a plan view of the interior space.

The so-called 'primary goniometer' is a graphic scale on which to read the value of a component directly, while on an auxiliary goniometer, corrective factors can be found in relation to the geometric and physical characteristics of a window sash (Fig. 51).

The analytical formula that the goniometer geometric method assessment is based on makes reference to the principle of solid angle projection.

These tools base their operation on the concept that the internal distribution model of illumination depends essentially on certain variables: the luminance of the source, the apparent angle between the source, the floor whose luminance is being assessed and the relative position of the source with respect to the point considered. The goniometers used are known as *SAB protractors* and include five different types for horizontal and vertical windows to be used in the case of a uniform sky, and five for the CIE overcast sky model [64] (Table 10).

Other goniometers are used for aperture with vertical and horizontal angles of inclination up to 300° and in the case of an absence of glass. Depending on the prevailing condition of the sky and the type of aperture, the most suitable protractor must be chosen to obtain the value of the external reflective component.

Among the many models of goniometers available for Daylight Assessment, we must also consider *Bryan goniometers* for clear sky conditions.

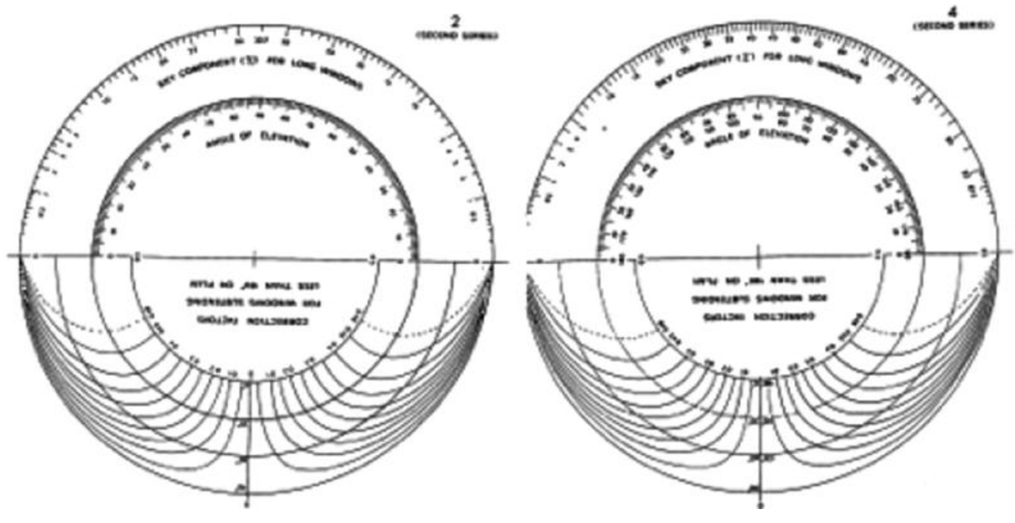


Figure 51: BRS Sky component goniometer for vertical glazing (CIE overcast sky) and BRS Sky component goniometer for horizontal glazing (CIE overcast sky).

The *9 Bryan goniometers* for clear skies were developed by Bryan and Carlsberg in 1982, by revisiting the best-known goniometers of the BRS system, but which, unlike the previous ones, are used exclusively in the presence of clear sky conditions.

Table 10: Use of goniometers.

	Series 1: Clear uniform skies	Series 2: Overcast sky CIE standard
Vertical openings	1	2
Horizontal openings	3	4
Openings with an inclination of 30° from the horizontal	5	6
Openings with an inclination of 60° from the horizontal	7	8
Openings without glazing	9	10

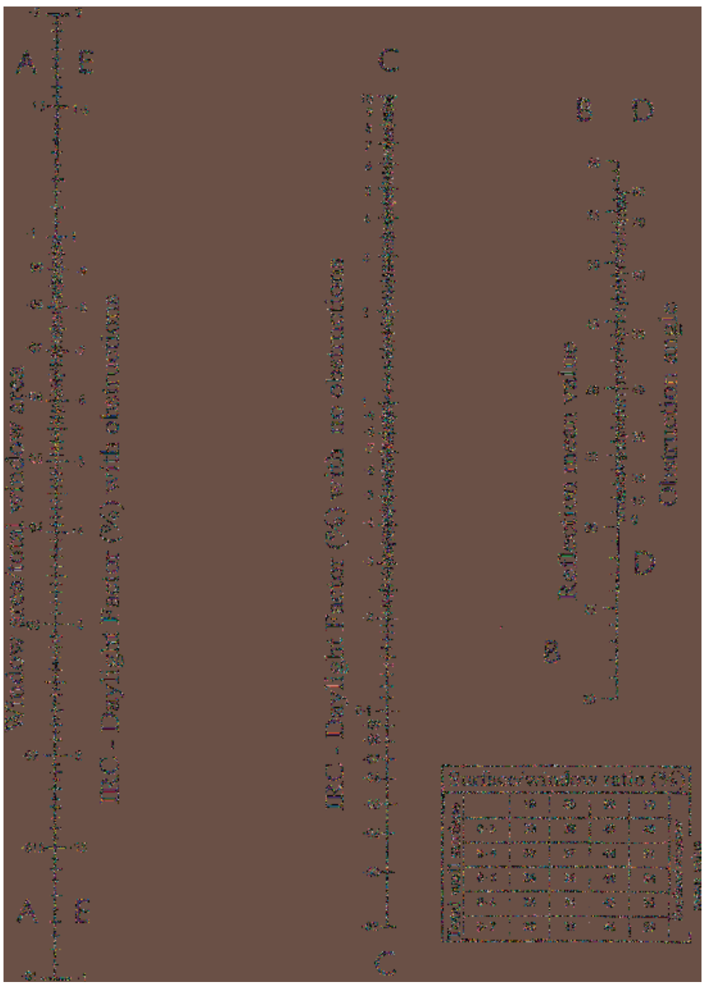


Figure 52: Nomograms for the calculation of the IRC component in case of sidelighting, illumination from vertical windows and in case of toplighting.

They provide data on the individual components of reflection, to be read in relation to the angles formed on the goniometer, less the IRC component that is instead derived from special tables.

The restrictions on the application of these goniometers exclude their use in the presence of horizontal apertures and strongly inclined glazed panels.

A further method to calculate the percentage of DF is known as *BRS Daylight Factor*, using tools such as nomograms.

The method of calculation is among the geometric methods, since it uses instruments similar to rulers to calculate the reflective component inside a room, based on extensive measurements performed to calibrate these tools themselves, rather than by resorting to empirical formulae.

The applicability of tools such as BRS nomograms is limited to cases of standard artificial sky, in which the distribution of brightness is therefore controlled, as a faithful replica of the conditions of the standard overcast sky in accord with the CIE model and in relation to certain specific situations.

Nomograms are deemed reliable where the light reflection coefficients of the finishing surfaces of floors and ceilings are equal respectively to 15 and 70%, with a luminance of the ground outside and the entirety of the obstructions near the window equal to approximately one-tenth of the average of the sky, in the presence of continuous external obstructions or ones that are horizontal with respect to the front of the room being assessed.

The first valid nomogram to calculate the average IRC reflected component is used in the case of vertical windows and in the presence of sidelighting from one side only.

The nomogram to calculate the reflected internal IRC component to be used in the case of vertical windows requires inclusion of the ratio between the glazed surface and the total area of the outer shell, as well as the average coefficient of reflection of the room's surfaces.

Instead, the last BRS nomogram is used to calculate the percentage of IRC in the presence of toplighting devices, including both horizontal and inclined skylights.

Unlike the preceding nomograms, it is necessary in this case to evaluate some corrective factors that take account of the inclination of the window and the angles that are formed with respect to the horizontal due to the presence of external obstructions.

For this case, use is made of tabular values that list the correction factors as a function of the angle of obstruction for vertical skylights and ones with glass inclined at 30° and 60° with respect to the horizontal plane.

2.3 Analytical methods

For the calculation of natural lighting through analytical methods and mathematical formulae, it is possible to single out two different methods: the *DF Method* and the *Lumen Method*, based on an analysis of the coefficient of utilisation, mainly developed and used in the United States.

Analytical calculation of the DF consists in a comparative assessment of the compliance of the DF percentage value calculated with respect to predefined thresholds, in relation to the visual task carried out in the room in question.

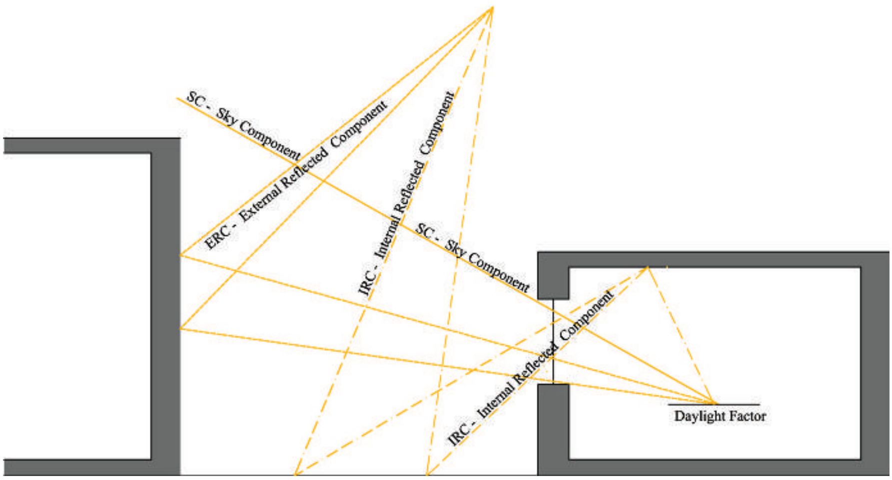


Figure 53: Determining contributions of direct light, internal and external reflection quota.

In this regard, it is necessary to evaluate how the incident luminous flux on a surface within a given environment depends on two components: the direct one, entering through the window, and the indirect or reflected one from interior surfaces, which reaches the calculation point after repeated reflections. The direct component can be considered as the summation of the sky component – the amount of light coming directly from the sky, and the exterior reflectance component.

It is inferred that the Daylight Factor is composed of three factors (Fig. 53):

$$DF = SC + ERC + IRC \quad (2)$$

in which are distinguished: the SC, *Sky Component*; the ERC, *Exterior Reflectance Component*; the IRC, *Interior Reflectance Component*.

For the determination of the individual components that make up the DF value, it is possible to resort to graphic, geometric or analytical methods.

In particular, to determine the Sky Component SC and the Exterior Reflectance Component ERC, it is possible to opt for the reading of SC values on a Waldram Diagram, on goniometers, or on *Pilkington pepper pot* diagrams, whereas for the ERC quota, reference can be made to tabular values.

To determine the IRC value, however, it is possible to use the relevant analytical formula, tabular values provided by the BRE or through a graphic interpolation on BRE nomograms.

By analysing the amount individually, it is possible to note how the Sky Component SC represents the greater input in relation to the reflected component, whether internal or external.

The quota of direct SC radiation depends on the area of sky visible from the point in question and, in the case of assessing the CIE condition of the sky, also from the position of the area in the subdivision of the celestial vault.

It is usual to proceed through a reading of the angle relative to the portion of sky visible from the point considered, choosing an appropriate goniometer in relation to the type of aperture and the geometry of the room.

Table 11: Assessment of the coefficient C in relation to the angle of obstruction.

Angle of obstruction	0°	10°	20°	30°	40°	50°	60°	70°	80°
Coefficient C	39	35	31	25	20	14	10	7	5

Instead, to define the quota of ERC, the Exterior Reflectance Component, values from the BRE Tables are used, in reference to external obstructions, the shape and the prevailing material; otherwise a graphic quantification is used.

The reflectance component that requires the most analytical effort is that of the interior IRC, whose value is obtained by the BRS formula, which in simplified form is:

$$IRC = \frac{0.85 \times A}{S_{tot} \times (1 - r_m)} \times (C \times d_{mb} \times 5 \times d_m) \tag{3}$$

in which: A represents only the surface of the glass of the apertures excluding the frames; S_{tot} represents the sum of the areas that delimit the interior space, including the area of the apertures; r_m represents the average coefficient of light reflection surfaces S, according to the relevant table; δ_m represents the average coefficient of light reflection of the interior surfaces situated in the lower part of the space in question; δ_{mb} represents the average coefficient of light reflection of the inner surfaces situated at the top of the space in question; C represents the coefficient to determine the degree of obstruction outside, which can be deduced from the appropriate table (Table 11).

The determination of the IRC comes from the studies in 1954 of Hopkins, Longmore and Petherbridge, which had the merit of introducing, among others, a further method of calculation known as the *split-flux method*, which was realised through the processing of a specific relationship to assess the IRC.

The basic concept was, as in the eqn (3), to split the amount of the ray of incoming light from the aperture into two separate amounts, one above the horizontal axis of the window and one below. The component involving the upper part is the one that comes from the sun and the sky without external obstacles; while the second is represented by the quota of light reflected from the ground without any obstacles. Determination of the percentage value of DF can be made through an assessment of the following quotient, which represents the original definition provided by Hopkinson:

$$DF = \frac{E_{in}}{E_{out}} [\%] \tag{4}$$

where E_{in} represents the average illuminance obtained only with the amount of natural light at a considered point inside the room; E_{out} represents the simultaneous illuminance value measured outside on a horizontal plane without obstructions or obstacles exposed toward the sky, in the case of a standard overcast sky.

The average Daylight Factor, which is the usual reference, must also refer to the physical and geometric characteristics of the room in question. For this reason, the following formula is used to estimate the average DF value:

$$DF_m = \frac{A_w \times t \times q}{A_{tot} \times (1 - r_m^2)} \tag{5}$$

in which the contributions are: A_w which represents the area of the windows and the glass apertures; t which represents the light transmission of the panes, θ which represents the angle of the sky visible from the point in question; A_{tot} which represents the total area of all the surfaces that define the interior space, including the area of the windows and other transparent apertures; e.g. skylights or high windows; r^2_m which indicates the weighted average of the reflection coefficients of all the finishing materials that define the environment.

The formula, processed as a simplification compared to the one proposed by Littlefair in 1996, is applicable to small rooms with a maximum depth of 6 metres, mostly quadrangular; on the other hand, in the case of complex ground plans it is necessary to split the area into rectangular portions on which to apply eqn (5).

Subsequent experiments underlined that the formula was actually attributable to a wider range of environments and that at the same time, it was possible to improve the performance resulting from the calculation by replacing the value of the total area with a simpler variable, i.e. the floor area, considering the calculation plane conventionally positioned at a standard height of 85 cm from the ground, assuming this measurement as the average height of windowsills.

With these premises the simplified formula was introduced, expressed by the relationship:

$$DF_{avg} = 0.30 \times \frac{A_w \times t \times q}{A_{tot} \times (1 - r_m)} \quad (6)$$

From eqn (5) came the introduction of a further formula to calculate the DF:

$$DF_m = \frac{A_w \times t \times e}{A_{tot}(1 - r_m)} \quad (7)$$

The value of the angle of the portion of the sky visible from the window is replaced by the coefficient ε, i.e. the *window coefficient*, obtainable from the appropriate table, while the weighted average of the reflection coefficients of the interior surfaces is considered once only.

In 1998, Littlefair published his research on the measurements made in two identical rooms, which showed a fenestrated front facing north and another facing south, analysing the results of the cumulative values of the interior illumination.

The rooms he measured did not feature shading systems, and were not occupied by people. The results of the tests showed that an illumination of about 200 lux could be reached in 58% of the cases for the room facing north, and in 68% of the cases for the one with windows facing south. The same was found for the threshold of illuminance of 400 lux, verifiable in 12% of the measurements of the sample room facing north, and in 51% of those for the sample room facing south.

This showed how the variability of the conditions related to the sky, the exposure and the quality of the shell considerably affected the DF percentage value, making the pre-set thresholds difficult to reach and insignificant in terms of luminous comfort.

The surveys of Littelfair and numerous other direct assessments soon attested the ineffectiveness of a static approach based on DF, i.e. based on the reaching of limits and thresholds often conflicting with the design criteria (e.g. thermal parameters and strategies relating to solar gains), but inherent to the very nature of the parameter, unresponsive to the orientation and the climatic conditions.

A further method to calculate DF, which uses an empirical formula, is the *Lumen Method*, elaborated by Fruhling in 1928.

The decidedly innovative approach that the method employed was a system identical to that used to calculate artificial light, but that was in this case used to determine the value of DF in a room illuminated only with natural light. The formula developed by Fruhling introduced for the first time the contribution of the Coefficient of Use CU, to quantify which the author defined appropriate tabular values. In an initial formulation, the illumination was calculated as follows:

$$E = \frac{n \times N \times F \times UF \times LLF}{A} \tag{8}$$

where the terms represent: E is the average illuminance over the horizontal working plane; n is the number of lamps in each luminaire; N is the number of luminaire; F is the lighting design lumens per lamp; UF is the utilisation factor for the horizontal working plane; LLF is the light loss factor; A in the area of the horizontal working plane.

The *lumen method* also has strong similarities with the zonal cavity method, used to assess electric light.

This suggests the system to predict interior illumination by natural light via skylights or windows. The basic premise is that the environment is of a regular geometric shape and rectangular, featuring simple daylighting systems, but provided with shading devices [65].

The *lumen method* [66], also known as the *total flux method*, thus allows an evaluation of the distribution of light arriving from multiple sources and diversified entry points.

The lumen method, unlike its precedents, makes it possible to carry out more complex assessment of illumination, that include the presence of *sidelighting* on several fronts, or in presence of *toplighting* systems, with lightshelves. The method consists of certain fundamental steps: Firstly, an assessment of the external illumination, measured in the vicinity of the windows and skylights, and then a calculation of the level of reduction in the amount of natural light through the apertures, in virtue of the transmission factor of glazing and other reductive elements, dependent on the optical properties of the finishing materials; the Coefficients of Use, previously mentioned, therefore make it possible to count the average illumination on the work surface. In this case it is necessary to distinguish between solutions of *toplighting* and *sidelighting*, which employ different coefficients:

$$E_i = E_{x>h} \times t \times CU \times \frac{A_s}{A_w} \tag{9}$$

in which: E_i represents the internal incident illumination on the work surface (in lux); E_{xh} represents the external illumination in lux calculated horizontally; τ represents the net factor of light transmission of the glass, including loss of light transmission due to other elements present in the room; CU represents the *Coefficient of Use* of the room, on the basis of the prevalent visual task; A_s is the gross area of the aperture of the zenithal system in m^2; A_w represents the area of the work surface in m^2.

In a similar way, in the presence of *sidelighting* solutions, standard values of reflection are assumed for horizontal floor and ceiling surfaces: the distribution and levels of natural light indoors are evaluated in reference to five calculation points, arranged according to a regular grid on a calculation plane perpendicular to the position of the windows.

In this case, a simplified formula applies that does not take into account either internal or external shading solutions.

$$E_i = E_{X \times V} \times \tau \times CU \quad (10)$$

In this case E_i represents the horizontal illumination inside calculated for each of the five points of reference, E_{xv} represents the vertical external illumination measured near the fenestrated front; τ represents the net transmission factor of the light transmission of the glass, including loss of light transmission due to other elements present in the room; CU represents the Coefficient of Use of the interior space, on the basis of the prevalent visual task.

The Daylight Coefficient (DC) parameter was instead introduced on the international scene thanks to the studies of Tregenza and Water [67].

This method was born from the discovery, which took place from simultaneous measurements of the levels of daylight in a room, that the relationship between the internal illumination E_{in} and that outside E_{out}, underwent considerable changes if calculated in real sky conditions, due to the meteorological changes in the sky.

The conventional method to calculate the DF gave, as a reference value, the percentage of illumination relative to a given point, situated on a horizontal plane, on which the measurement was made.

The concept on which DC is based, however, comes from the insightful idea of dividing the celestial vault into a discrete number of smaller skies, to be precise, into 145 portions, with a conical aperture of 10°15′, to cover 68% of the celestial dome.

This subdivision also made it possible to consider the lighting of a point as the sum of contributions arising from each portion of the sky.

The total illumination that can be precisely measured E(x) is thus obtained as a linear superimposition of the contribution of each coefficient of DC natural light, together with the luminance variable for the corresponding segment, according to the relationship:

$$E(x) = \sum_{n=1}^{N} DC_n(X) \times L_n \times \Delta S_n \quad (11)$$

The advantage, in terms of calculation, from this subdivision of the sky is that it allows a precise measurement of the illumination in any sky condition, considering only one spherical segment.

Tregenza specified that the DC parameter could be divided into distinct components ERC, IRC and SC, taking into account the dispersion of the light through the atmosphere.

According to Reinhart's assessment of 2006, the definition of the DC parameter represents the first attempt at characterising a dynamic approach to the issue of Daylight Assessment in a confined environment.

2.4 Rules of thumb

According to studies conducted among professionals from the sector, in addition to the previous methods, validated by analytical studies, direct experience in the field together with the practical rules of good building seem to represent two of the design methods most widely used to assess the distribution and quality of natural light in interiors [68].

The characteristic that makes these established methods of practice so attractive, even though they have never been set up and formalised, is the ease inherent in the assessment approach, independent of specific considerations relating to the actual involvement of materials and visual tasks present in the interior space being evaluated.

The formulation of these empirical, non-standardised rules is therefore bound to their simplicity of use, particularly if compared to traditional graphic, geometric and analytical methods, and even if they do not provide accurate or absolutely reliable data for each situation; they are among the most widespread in architectural practice.

The study of *Daylight Feasibility* [69] offers, among other things, some practical directions for a preliminary assessment concerning the availability and subsequent diffusion of natural light in a confined environment, by analysing the potential level of natural lighting.

The essential characteristics that are taken into consideration for an empirical calculation primarily concern the geometric peculiarities of the building envelope, the presence of obstructions, and the orientation of the apertures.

The dissemination of this practical tool, especially in North America, has had the merit of defining some specific parameters for preliminary assessments, such as, e.g. the AEA – *Adjusted Effective Aperture* – i.e. the actual efficiency of an aperture and the DFF – *Daylight Feasibility Factor* – which measures the effectiveness of illumination using natural light, according to a formula that takes into account the presence of apertures and external obstructions, like in eqn (12).

In eqn (12) the term OF represents the Obstruction Factor, while the WWR is defined as the sum of all the transparent or translucent surfaces present in the shell, including window frames and any stanchions, broken down for the outer area of the façade concerned, while τ_{vis} indicates the mean value of the light transmission coefficients of the transparent elements.

$$AEA = WWR \times \tau \times OF \geq DDF \tag{12}$$

The Obstruction Factor (OF) therefore represents the best approximation of the effects produced by external obstacles and is determined as a function of the percentage of free view, which would be produced by a window in the absence of external obstructions.

Thus are distinguished four different percentages of OF which summarise some of the most likely real situations: if the view is obstructed by 50%, OF = 1 (case a); if the view is obstructed by a percentage ranging between 50% and 70%, OF = 0.85 (case b); if the view is obstructed from

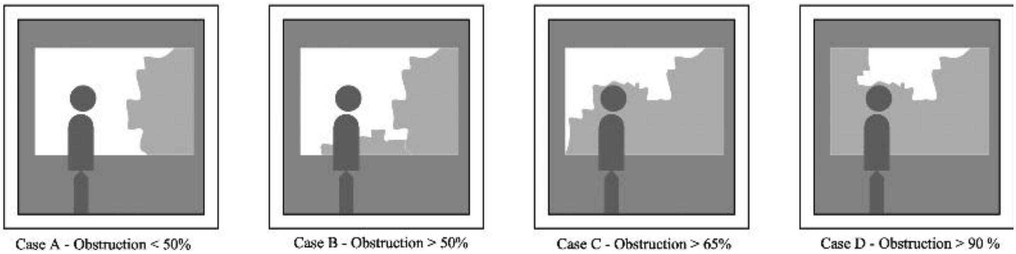


Figure 54: Obstruction Factor types.

70% to 90%, OF = 0.65 (case c), while if external obstacles obstruct the view for more than 90%, then OF = 0.4 (case d) (Fig. 54).

Despite eqn (12) never having been validated through specific studies, among designers it enjoys considerable appreciation, thanks to its ease of use, and because it is able to offer differentiated assessments in relation to the possible external configurations.

For the prediction of potential distribution of natural light in bright side-lit environments it is also possible to use the uniformity of natural light method, which relates the latter to the depth of the room under examination.

For these environments, the fundamental question is whether the quota of direct and diffused radiation in the proximity of the fenestrated front does not cause overheating or irritating glare, contributing, at the same time, to significantly raising the average DF value in the room.

To overcome this limitation, the formula introduced by Lynes proposes a rule of thumb to easily obtain the most suitable depth of the room, such that it is proportionate to the width of the fenestrated front and the height of the aperture with respect to the plane of the floor.

$$D_{Lynes} = \frac{2}{1 - R_{mean}} / \left(\frac{1}{W} + \frac{1}{h_{wind-head-height}} \right) \tag{13}$$

The terms that appear in eqn (13) are: W, the net interior width; h wind-head-height the distance between the floor and the highest height of the window; R_{mean} the average weighted reflection coefficient of the interior finishing elements, including glazed parts. In this manner, it is possible to calculate the maximum useful depth of the room, to ensure the uniform distribution of natural light, on the basis of the assumption that, if the ratio between the average DF in the first half of the room – including the fenestrated front – and the average DF at the rear exceeds three times the value of D_{Lynes}, then the geometry of the room is inadequate [70].

In this way, in the presence of external obstructions, the eqn (13) limits the depth of the room at a pre-determined distance, beyond which it is impossible to see the horizon line from the calculation plane:

$$D_{noskyline} = (h_{wind\text{-}head\text{-}height} - workplan_{height}) \times \tan(\theta) \tag{14}$$

This approximation is based on a calculation of the angle θ, or of the external angle formed between the upper half of the window area and the angle generated by the external obstruction (Fig. 55).

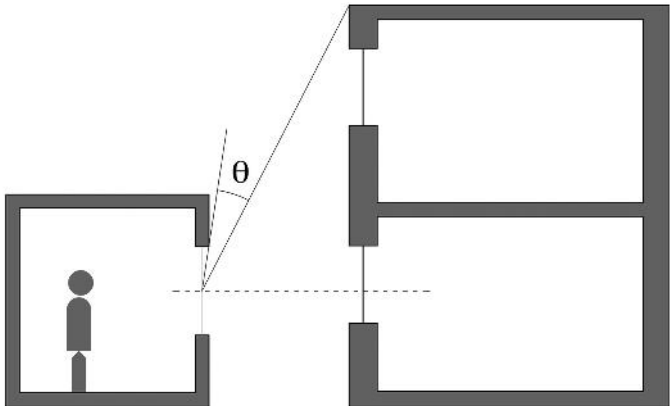


Figure 55: External obstruction angle.

The sequence of empirical rules and assessments arising out of planning experience analysed in this section are in reality only a small part of the numerous rules of thumbs; although they may appear easy to apply in any case, we must be aware of some substantial limitations, the most important of which is the assumption of a standard overcast sky condition.

In addition, it is necessary to consider that, to calculate the DF, it is possible to carry out the assessment only for regular morphological conformations for the most part rectangular, besides the fact that the considerations presented are valid only for environments with side lighting on only one front, while the external obstructions are represented by a single item within the formula, thereby greatly simplifying the actual presence of obstacles on several fronts.

3 Limits of applicability of the static approach

To date, there have been no calculations, formulations or methods to assess the Daylight Factor unless in the presence of a standard overcast, intermediate, or clear sky, according to the classification accepted and validated by the CIE: this means that the distributions of sky luminance used to calculate the DF constitute simplifications that bear no relation to real sky conditions.

These images represent only a narrow range of possible sky conditions, from the completely clear to overcast and allow, through a *fish-eye* vision, to capture the entire hemisphere with the horizon marked on the edge of the sphere and the zenith at the centre of the image.

The *Commission Internationale de l'Eclairage* CIE, therefore developed a series of mathematical models of ideal light distribution, that can describe the most likely sky conditions, of which the three most common are overcast, uniform and clear, on which depend variations in the distribution of illumination and luminance (Fig. 56).

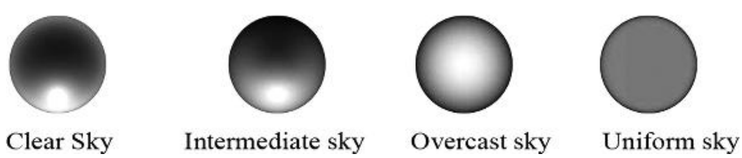


Figure 56: Some sky types.

Models of the sky therefore concern only the distribution of luminance values across the sky, but not the total amount of light coming from it, i.e. the illumination coming from the sky, for which it is also necessary to consider the geographic latitude.

The term *standard overcast* indicates a prevailing condition of the sky in which there is only the quota of diffuse light and in which the maximum luminance is at the zenith, with luminance that decreases until the horizon, in the vicinity of which it shows values equal to about one third of those recorded at the zenith, regardless of the position of the sun, while an average value is recorded at a solar height of around 42°.

Meanwhile, the equation for *standard clear skies* takes into consideration the actual conditions of diffusion and refraction of the light in an atmosphere that is perfectly serene and cloudless: Normally in this model of the sky there is maximum luminance at the sun and in the position opposite to it, just as the maximum luminance is seen at the horizon with respect to the zenith.

In all the calculation methods previously analysed there is always reference to a particular condition of the sky, considered as the one that occurs most frequently in our latitudes: This is the so-called *standard overcast sky* in which the sky is considered completely covered by clouds; the passage of the sun's radiation through the overcast sky produces an effect of diffused white light, while the sky itself may appear with a colour tending to yellow with perfectly symmetrical distribution.

The *uniform sky*, meanwhile, represents a simplified condition in which the celestial vault is assumed to have a constant luminance equal to 1. In spite of the simplifications introduced, it is very evident that in reality it is necessary to evaluate the distribution of luminance in the sky in a timely manner over the entire hemispherical dome.

The aforementioned models of the sky provide a simple mapping of the distribution of luminance values across the sky, but not the total amount of light coming from the hemispherical dome, i.e. that which defines *sky illuminance*.

DF is, in this sense, a parameter that is inaccurate and unreliable because the percentage value of the DF cannot faithfully represent the changes in level of indoor illumination, since it does not take into account the temporal variations in the sky's luminance.

In addition, the DF value is totally insensitive to the orientation of the building, due to the symmetry of the simplified sky, and it is also independent of the orientation of the building's sides.

In other words, the DF value is identical both where the building has a large glazed surface exposed to the north (at a high latitude), or one that has a wide wall looking south (at a low latitude).

In addition, since the sun is not being considered, any data concerning the different positions of the sun, on its angle of incidence or intensity, or any other real variations in the light have no influence on the calculation.

The main reason why there is recourse to a percentage value of DF rather than an absolute one arises from the need to overcome the problem of the numerous and frequent fluctuations in values and in the intensity of the amount of natural light.

The simplifications introduced by this system do not facilitate the task of the designer, who is forced to forecast the multiple light reflections in the interior of the room, taking into consideration the individual amounts due to the materials present internally and externally.

If on the one hand, these simplified methods give the designer some information regarding the way in which light is distributed in the space in question, on the other, there is a need to perform the calculation considering specifically the visual tasks that will be carried out there and including the optical characteristics of the finishing materials that will be used. An intuitive summary of the luminous performance of the lit area is therefore extremely inaccurate and risky, just as an *a priori* assessment might appear too daring.

In the final analysis, the increasing number of types of software designed to calculate the DF has further highlighted an intrinsic difficulty in comparing the output data of the programmes and the results that can be obtained through direct survey or scale models.

For these reasons, the scientific debate now concentrates on an attempt to develop new dynamic parameters, metrics, and unified criteria to assess the component of natural light. The question on which the international community is now focussed therefore regards the possibility of correctly employing new daylight metrics to adequately define the daylight in a confined environment.

The inadequacy of the DF parameter arises, in addition to the previous methodological and procedural inaccuracies, also from the self-evident inability to translate in a clear manner the complexity of lighting levels and the overall degree of luminous comfort in a room.

Therefore, as long as the definition of a 'naturally well-lit environment' is delegated to an unspecified number of units of measurement and geometric parameters in relation to the average frequency of prevailing sky conditions, arriving at the formulation of a unique datum regardless of surrounding conditions, any method will prove inadequate to describe daylight conditions.

4 The current status of the legislation on Daylighting: European and international codes

The definition of a standard corpus at a European level that regulates the use of natural light and that fixes the minimum limits to be satisfied is currently being outlined.

Codes and standards for building and national land-use regulations tend to define limits, restrictions and requirements that govern the use of sunlight, in order to safeguard the health, safety and comfort of occupants. Over the course of the last few decades the corpus has evolved significantly, thanks also to the close correlation, by now well-known, between sunlight and the benefits in terms of energy savings and improvement in luminous performance.

Despite the increasing attention to these issues, codes and standards for lighting design appear to be significantly lagging behind, afflicted by serious deficiencies and excessive simplifications. Among the issues of greatest importance is, first and foremost, the need to set up some parameters to evaluate light performance in a reliable and realistic way.

Despite the awareness that the possibility of performing a visual task is strongly influenced, not only by the levels of illumination, but also by relationships of luminance, contrast and control of glare, current assessments are essentially based on the analysis of compliance of illumination levels compared to pre-determined thresholds, often determined superficially with respect to the prevalent visual task.

4.1 Standards and requirements based on illuminance levels

The most widespread standards are those based on an assessment of illuminance levels, as EN 12464-1:2011, *Light and Lighting. Lighting of work places – part one*, recommends, assumed as substantial parameters for analysis of luminous performance in a confined environment [71].

Also in the United States, where the search for the definition of new parameters and units of measurement is directed towards the validation of the so-called dynamic approach DDS, the most widespread requirements come out of transposing the BOCA [72], which defines the minimum guaranteed levels dwelling spaces, with the exclusion of environments with a high concentration of users. It is not explicitly specified what the individual amount of natural light should be, imagining as possible a constant integration with equipment for artificial light.

The ASHRAE 189.1 [73] standard provides some useful indications for the control and management of Daylighting, inside of a very wide corpus of requirements designed to maximise the effects and benefits of a sustainable energy approach for new constructions.

Although including design indications, from the preliminary phase to the phase of managing the building, from site selection to the determination of the energy recovery systems using sustainable and eco-compatible technologies, it does contain some guidelines regarding the use of Daylighting strategies.

The ASHRAE standard includes – among the first to do so – Daylighting strategies within an overall view of systems and methods of energy efficiency, by correlating the visual and thermal performance of natural light in a wide range of sustainable solutions for the construction of new buildings, as demonstrated by Article 7.4.2.9 *Fenestration Orientation*, which requires the integration of natural light with occupancy sensors, in order to reduce the quota of artificial light to be used, as well as to reduce solar gains from east and west, in different climate zones.

'Lighting in daylight zones, including daylight zones under skylights and daylight zones adjacent to vertical fenestration, where the combined daylight zones for enclosed space is greater than 250ft^2 (25m^2), thereunder shall be provided with controls that automatically reduce lighting power in response to available daylight'.

The standard also specifies the illuminance levels to be ensured in a given environment, ASHRAE 8.3.4, *Daylighting by Toplighting*, in relation to the Daylighting system selected; in the presence of light from above, it should be noted that: 'There shall be a minimum fenestration area providing daylighting by toplighting for large enclosed spaces. In buildings three stories and less above grade, conditioned or unconditioned enclosed spaces that are greater than 20,000 ft^2 (2000 m^2) directly under a roof with finished ceiling heights greater than 15 ft (4 m) and that have a lighting power allowance for general lighting equal to or greater than 0.5 W/ft^2 (5.5 W/m^2)'.

Table 12: European Standard specifies Daylight Factors in indoor work places.

	$FLD_m > 1\%$	$FLD_m > 2\%$	$FLD_m > 3\%$
Homes without distinction of function	–	All rooms regardless of visual task	–
Schools	Offices, stairs and spaces for connection and distribution	Gymnasiums and cafeterias	Classrooms and laboratories regardless of visual task
Hospitals	Offices, stairs and spaces for connection and distribution	Wards	Wards, laboratories, spaces for diagnosis

Furthermore in ASHRAE 8.3.4.1, *Minimum Daylight Zone by Toplighting*: 'A minimum of 50% of the floor area directly under a roof in spaces with a W/m^2) shall be in the *daylight zone*. Areas that are daylit shall have a minimum *toplighting* area to *daylight zone* area ratio as shown in Table 8.3.4.1. For purposes of compliance with Table 8.3.4.1, the greater of the space lighting power density and the space *lighting power allowance* shall be used'.

In a different manner, the *Department of Public Works of Canada*, recommends an average daylight level to be guaranteed for work spaces, without establishing what type of room it is, or what strategies are being used to promote Daylighting, with the sole purpose of offering some guidelines for the management of the daylight.

The European situation presents considerable similarities, as in the case of the aforementioned Italian legislation (Table 12).

In Germany, DIN 5034 [74] set out, for the first time, a set of definitions and calculation methods specific to natural light only [75], providing limits and recommendations for Daylighting [76], although it did not establish a precise distinction between visual tasks for each function.

Among the specific recommendations for the workplace, illuminance levels were fixed in France through the *Décret no.83-722-1983*, where ample room is given to measures to ensure a proper supply of artificial light, while more coherent is the *Lettre-circulaire DRT 90/11-1990*, concerning Daylighting and possible strategies to promote visual comfort.

The first prescription fixed maximum limits for lighting levels to ensure a narrow range of four types of confined space, although, even in this case, the average levels to be maintained in the rooms are not legally binding, but are regarded as voluntary requirements and simple recommendations to increase the value of the constructed space.

4.2 Standards and requirements based on the Daylight Factor

Starting from the ISO standard 15469: 2004 *Spatial distribution of daylight – CIE standard general sky*, as defined by the CIE to circumscribe how to check the spatial distribution of natural light, in the presence of standard clear and overcast skies, arrived the transposition by each national legislation of specific EC directives.

None of the standards, codes, or legally binding or voluntary provisions that consider the DF as a valid parameter, has determined a precise level to reach, but rather a percentage, derived from application of the Sumpner equation, regardless of external lighting conditions.

The French method, in addition to the already mentioned recommendations, lists in the *Cahier des Recommendations Techniques de Construction (Ministère de l'Education, 1977)* some observations on the school environment to ensure compliance with a DF percentage higher than the 1.5% for teaching premises, different to that stipulated for Italy in the Ministerial Decree of 18/12/75, *'Updated technical regulations for school building, including the indexes of minimum functionality for teaching, building and town planning to be observed in the execution of works of scholastic building'*, in which there is a distinction between classrooms (2%), laboratories (3%), connecting spaces and gyms (1%), devoting much more attention to artificial lighting.

From this point of view, it is to be understood that UNI 10380: 1994 remains the most comprehensive Italian treatise on the lighting issue.

The Anglo-Saxon context appears to be equally backward as regards the specific definition of a law for Daylighting: the current situation makes reference to a rich corpus of non-binding requirements in compliance with the British Standard 8206 [77]: 'If electric lighting is not normally to be used during daytime, the average Daylight Factor should not be less than 5%. If electric lighting is to be used throughout daytime, the average Daylight Factor should be not less than 2% if a predominantly daylit appearance is wanted'.

Unlike the approach based on calculation of the DF value by means of Sumpner's formula, British law recommends the achievement of a threshold not less than 27% for the *Vertical Sky Component* for apertures to be created in a residential area, a value that has its origin in the standard height of a single-family or terraced dwelling and the distances to be maintained on the street front.

The *Illuminating Engineering Society of North America* has defined with precision via document IESNA RP-5-99 [78] the different technological solutions and the new tools to increase the amount of daylight, through strategies that improve the calculation of the DF in interiors [79].

'When an average Daylight Factor is 5% or greater an interior space will appear to be well lighted. When the average Daylight Factor is less than 2%, the interior space will seem dimly lighted'.

In the document are also stipulated the calculation rules linked to a definition of the heights of the work surfaces, to carry out the assessments on, as well as specifying the visual tasks for each interior space.

For the first time the regulatory corpus also decreed how to calculate the energy saving potential that can be obtained through the use of natural light as the sole lighting system, reserving new attention to the containment of electric consumption and the preservation of the health and comfort of occupants.

Also defined and promoted are the potentials related to the use of *sidelighting* and *toplighting* techniques, in relation to variable inputs of available natural light.

4.3 Standards and requirements based on the sizing of windows

Another type of prescription regards the sizing of windows, which relates – albeit indirectly – the amount of natural light with the geometric characteristics of the interior space. This type of approach is born sooner with the objective of defining standards that are useful to ensure correct exchange of air and a view of the outside and only secondarily to ensure sufficient levels of natural light.

These requirements are identified increasingly often among building regulations and national laws to promote energy-saving policies: Appreciation for this type of approach derives from notable ease of application that it allows, even at a preliminary stage, to have a good degree of control over the sizing of apertures and the areas to be illuminated, of course.

Although the regulations may seem sufficiently detailed in defining relations between transparent areas and the variable percentages as a function of visual tasks, they disregard in reality any type of assessment of the context, the external conditions, the climate, or the orientation of the building.

The already mentioned ASHRAE 189.1 also provides, in addition to minimum levels of illumination in relation to the daylighting strategy chosen, interesting design suggestions on the adequate sizing of fenestrated apertures, proposing limits and materials, as can be read at point 8.4.1.1 *Minimum Effective Apertures*, specifying which further screening and shading systems are allowed, according to the characteristics of the interior space and its prevalent function [79] (Table 13).

'Office spaces and classrooms shall comply with the following criteria: all north, south, and east-facing facades for those spaces shall have a minimum effective aperture for vertical fenestration (EAvf) as prescribed in Table 8.4.1.1; b. Opaque interior surfaces in daylight zones shall have visible light reflectance greater than or equal to 80% for ceilings and 70% for partitions higher than 56 in. (1.54 m) in daylight'.

In the Anglo-Saxon panorama we must also recall the British Code BR 8206 (Part 2), according to which, in the case of premises that measure less than 8 meters in depth, the windows must cover at least 20% of the outer area of the wall, while for greater depths up to 14 meters, the levels of daylight illumination must be maintained through apertures that cover at least 35% of the surface of the outer wall.

As regards buildings for the tertiary sector, in particular, office environments, British law assumes that apertures should be 35% of the area of the wall exposed, in the case of public buildings, 25% in the case of private buildings, as Littlefair has reported [80].

Table 13: Minimum effective aperture for sidelighting by vertical fenestration.

Climate zone	Maximum effective aperture for sidelighting by vertical fenestration
1, 2, 3A, 3B	0,10
3C, 4, 5, 6, 7, 8	0,15

In Germany, the DIN 5034 standard reserves a specific section, part 4, *Daylight in interiors, Simplified regulation for minimum window sizes* to discussion of possible strategies for daylighting to be implemented in a confined environment, paying particular attention to the correct sizing of the windows. The standard also sets dimensional limits for each type of environment, in relation to the prevalent visual task.

The *Building Code of Australia* [81] suggests preliminary criteria for the sizing, according to which the area of a transparent fenestrated surface in the case of residential buildings must constitute at least 10% of the floor area.

Specific dimensional rules are instead provided by Japanese building regulations, which establish different percentage values for areas to be reserved for transparent fenestrated apertures, in relation to the function of the interior space, promoting, in residential buildings with the continuous presence of people, the realisation of a transparent area of at least 14% of the floor surface, and in any case not less than 1/7, while, in the case of public buildings, this ratio must be around 20–40% in relation to the prevailing activity carried out [82].

The *New Zealand Building Code (NZBC), Clause G7 Natural Light* [83], recently revised and valid form February 2014 assumes a formula to verify the minimum illuminance maintained, using the formula of the BRE method and suggesting some general guidelines for preliminary sizing of the windows, as described in NSZ 6703.

In particular [84], it prescribes a sizing of vertical apertures greater than 10% of the surface they are inserted in, to provide approximately a minimum level of 33 lux at floor level for 75% of the duration of the standard year. The New Zealand standard also reserves special attention to ensuring the possibility in the residential and tertiary sectors to enjoy a view of the outside, by requiring that at least 50% of the fenestrated area is provided with transparent glass, to be placed at a height of between 90 and 220 cm from the floor surface, defining fully, for the first time in the civil area, so-called *Visual Awareness Zone*.

4.4 Standards and requirements based on solar zoning building regulations

Some interesting prescriptions can be found in so-called *solar zoning legislation*, with regard to the management and control of solar radiation in areas with large buildings, especially in big cities.

Requirements of this kind amass guidelines for the planning and control of natural light to be respected in tall buildings and areas of high urban density. In this sense, many countries have regulations that are designed to respond to the need to provide a proper amount of natural light.

The most famous example of zoning for the urban environment dates back to 1916, with the *Zoning Ordinance of New York City*: This is a corpus of regulations designed to preserve access to direct light and ventilation in skyscrapers under construction, defining the principle of *setback*, i.e. the progressive retraction of façades, which has become characteristic of the profile of New York and many other US cities.

The principle of *set back* evolved further through the definition by Knowles in 1980 of the *solar envelope*, according to which the profile and shape of the building had to be determined in relation to the possibility of the sun to filter through the tall buildings to reach the street.

In this way, the question of access to sunlight became an essential requirement, an inalienable right to be guaranteed in every circumstance. Solar zoning solar and the related regulations progressively spread to the various states, in agreement with local *set back requirements*, which spread quickly even outside the United States.

In Japan, e.g. in addition to the above-mentioned requirements for individual interior spaces, strict rules for constructions had already appeared around 1600, when they established charges and fines for those who, by planting trees and building close to the border, obstructed the view of the sky from neighbouring properties, and for this reason, had to pay compensation, the *kage-shiro* or charge for the shadow procured.

Attention to the theme of natural light, as a tool not only of lighting, but guaranteeing well-being for indoor environments, was even defined with a specific term in Japanese language, *Nissho-ken*, the right to the sun.

5 The need for a new international paradigm

The static approach to the lighting issue is currently contaminated by numerous limitations, deriving both from geometric simplifications, and simplified assumptions for the analysis of external conditions, confined to the use of a model of the standard overcast sky.

Instead, a detailed analysis of the prevailing sky conditions for each region clearly shows the need to adopt a different approach to the assessment of the prevailing sky condition.

Also an analysis at a European scale shows the high potential of illumination in relation to the quota of reflected sunlight, which, for about 60% of the time, in the months from April to August, can be used, as a source of predominant lighting for interior spaces. In the remainder of the year those European countries situated on a latitude above 50° fail to exploit sufficiently direct radiation or reflected sunlight, unlike the south of Europe, where the proportion of reflected light manages to ensure a significant contribution to ambient lighting for about 40% of the working hours, calculated on an annual basis.

In-depth reading of distribution maps of illumination and direct and diffused radiation underlines the thesis that the Daylight Factor on its own is severely limiting in representing actual dynamic changes in sky conditions, and to indicate light distribution in virtue of the geographic location of the site; basic conditions to provide an effective reading of lighting conditions, making it essential to introduce a new dynamic approach, based on the prevailing weather conditions at a local level.

The definition of a new paradigm, according to the meaning suggested by Thomas Kuhn in this regard, is ever more necessary.

Understanding the paradigm as ‘the practices that define a scientific discipline at certain point in time’, research is the sector must be designed to highlight limits and shortcomings of the well-established model now in use, in order to reach the definition of an innovative approach to Daylight Assessment, so that we can achieve a true surpassing of the paradigm in use, dictated 'by the immense difficulties often encountered in developing points of contact between theory and nature' [85].

It is precisely from the emergence of mismatches between actual lighting conditions and energy and environmental needs that emerge in tackling the luminance issue, that validation of the CBDM model, according to the Dynamic Daylight Simulation, DDS method becomes the first step towards a true methodological revolution.

The transition from the internationally known static system to the dynamic DDS system therefore constitutes the passage from one paradigm to another, i.e. a change towards a new policy.

It is possible to say that the current paradigm, which is the only one validated and accepted, as well as still being in use, despite being born with the principal characteristics of a paradigm, i.e. as a model that is functionally and universally valid, over the years has sown up weaknesses and limitations, which were then taken as simplifications useful for calculation, by transforming the fault into an average for the benefit of the assessment.

The obvious differences detectable today regarding the reliability of the static model are born from the awareness that the simplifications implemented up until now produce, in the majority of cases, simulations that are unreliable, if not downright wrong, that impose inconsistent choices on designers and architects.

The application of and the subsequent changes to the static model that Daylight Assessment is based on have helped to develop new technologies, from computer simulation to annual meteorological knowledge, highlighting the so-called anomalies, which are an essential requirement for the paradigm shift.

The current situation of Daylight Assessment and the methods of survey seems to lie today in that interim period, in which, although the limitations of the approach in use are evident, the corpus of new units of measurement and the new tools of inquiry is being subjected to verification by the scientific community.

Today, the international panorama is seeing the emergence of a new orientation which, based on differences in the static system, proposes a differentiated analysis based on geography and meteorology: the term 'dynamic' therefore indicates, a datum that changes over time, on a daily and annual basis in relation to climate datasets, which take into consideration the changes in the sky conditions, in stark contrast to the concepts of static modelling and simulation, as in the case of the Daylight Factor.

A uniform standard at a European level is currently in the process of being defined through the *Lighting Technology Standards Committee* in cooperation with the German *DIN (Deutsches Institut für Normung)*, to develop a supranational standard for use in the assessment of natural and artificial light, with particular attention to the definitions of methods of unitary analysis, for the acquisition of a common terminology; elements that should facilitate the approach to a conscious use of light, to facilitate the policies to achieve energy savings and to safeguard the visual comfort of occupants.

In particular, the evaluating commission representing 10 countries responsible for the creation of the new European standard CEN/TC 169/WG 11 [86] is currently working on the wording of the paragraph 11 whose subject is daylight, to establish useful indications for the implementation and assessment of natural light in working environments, schools, residential buildings, prisons, hospitals and for particular target groups.

The proposal will be based for the first time on the implementation of the dynamic method known as *Climate-Based Daylight Modelling* (CBDM), but without completely excluding the static DF parameter – still deeply rooted in common practice, but including correction factors to analyse the availability of daylight. The complete adoption of systems and units of measurement relating to the CBDM method would lead to the acquisition of some standard boundaries and thresholds for all European countries, ignoring natural differences in terms of luminous availability that is extremely variable in relation to latitude. The ultimate goal of the Commission is to integrate static and dynamic systems and provide general guidance that can be adapted by individual countries in different geographic contexts.

The final objective is thus to establish a corpus of guidelines that are valid in a unique way for all European countries, which includes appropriate simplifications for all the climatic zones and can be adapted to national standards already in force.

Chapter 4

Daylight Assessment: definition of dynamic model

1 Introduction

The inefficiency of the methods currently used for Daylight Assessment comes from the obvious inadequacy of the current approach in quantifying absolute doses for natural light, as a result using percentages to be compared with pre-established thresholds.

The most significant element that hinders the adoption of a shared approach to the assessment of the proper amount of sunlight to be guaranteed in a confined environment comes from the absence of a system that assesses the real surrounding conditions and that therefore leaves aside preliminary assumptions and geometric simplifications.

This need becomes even more urgent in virtue of the potential use of natural light to optimise energy-saving strategies, reduce polluting emissions and create comfortable visual environments.

The informed approach to an architectural project, whether it be a construction intervention *ex-novo*, an intervention to retrofit or recover an existing edifice, must be directed to a practice that maximises the use of natural light, allows the attainment of high levels of comfort for the occupant from a thermal and visual point of view, making for a highly desirable integration with other systems of the building.

The dynamic assessment of natural light, through the approach called Climate-Based Daylight Modelling (CBDM), therefore relies on the possibility of predicting the continuous variations in terms of quantity and quality of light radiation, analysing precisely the sky conditions and the sun, taking them from the weather datasets on a daily, monthly and yearly basis.

The name CBDM *Climate-Based Daylight Modelling* has not yet been formally validated by the international community, despite the obvious advantages associated with it, starting from its first formulation in 2006 by Mardaljevic [87]: 'The CBDM is the prediction of various radiant or luminous quantities (e.g. irradiance, illuminance, radiance and luminance) using sun and sky conditions that are derived from standard meteorological datasets.

CBDM delivers predictions of absolute quantities (e.g. illuminance) that are dependent both on the locale (i.e. geographically-specific climate data is used) and the building orientation (i.e. the illumination effect of the sun and non-overcast sky conditions are included), in addition to the building's composition and configuration'.

Climate modelling of natural light provides forecasts of absolute amounts of illumination in real sun and sky conditions, via estimates on a geographic basis and on the basis of the actual orientation of the apertures in building envelope.

Assessments using software simulations have in fact demonstrated that daylight can effectively be analysed through an analysis of specific coefficients able to accurately calculate time series of illumination and luminance in buildings [88].

The function of precisely defining the amount of solar radiation for each location is therefore entrusted to the CBDM model, which uses models of real skies in the presence of the sun, basing the modelling on climate files that permit absolute forecasts of illuminance, through overall light levels, considering the quotas of both diffused light and direct sunlight.

The CBDM model therefore considers both amounts, since it counts the actual days of overcast and clear sky, enabling computation of the exact period in which light levels are sufficient to carry out a particular visual task to predict the moments when it is appropriate to complement natural light with the lighting fixtures.

In this way, the geometric limitations, the formal approximations and the forecast data on climate data are replaced by articulated climate files on a base of 10 years, capable of providing a fairly reliable datum for a precise location at a specific time of the year.

The Daylight Factor is therefore currently in the process of being revised, in order to define a complete and comprehensive dynamic approach.

Under consideration of the international commissions therefore is the Dynamic Daylight Simulation (DDS) system based on CBDM simulation, both based on the reading of an annual series of climate data that can easily be integrated with a more complex performance analysis to include analysis of thermal and luminous comfort.

The dynamic model makes it possible to interface internal luminous analysis with the varying performance of any internal and external shading systems, as well as evaluating the lighting pattern in dense urban environments, in which the façades of buildings are directly affected by the presence of shadows from the surrounding buildings, and can therefore finally evaluate the most advantageous design solutions to prevent the 'canyon effect'.

The methodological innovations, for the moment only proposals to the international community, are certainly innovative, while still awakening strong perplexity about what the design phase is responsible for, not to mention the many barriers that still separate the possibility of seeing new metrics applied along with complex approaches to evaluate Daylight Assessment.

The dynamic method involves the use of distinct simulation environments, specific software with excessively complex interfaces, which make the approach laborious and time-consuming; dynamic simulation requires long timelines to complete the calculation, especially where the simulation environment relies on *raytrace* methods; the dynamic simulation approach is likely to be burdened by procedural errors and defects of interpretation, in particular in the face of the large amount of numerical data of a meteorological variety, which can lead an inexperienced analyst into error.

Simultaneously, other obstacles that slow the change of paradigm can be identified in different systems of environmental and energy assessment, which do not give sufficient weight to the assessment of daylight as an added value to the building and, by still resorting to static assessments, make any effort to promote the adoption of Dynamic Daylight Simulation methods ineffective.

Lastly, the inability to interpret the output data of the dynamic simulation in a synthetic manner and translate it into graphic languages and architectural representations is a major obstacle to the eventual adoption of the CBDM system.

2 Climate-Based Daylight Modelling

The term CBDM, although not yet accepted in a definitive way, means a simulation of the distribution of natural light in a confined environment, considering the totality of the amount of direct sunlight and reflected light from the sky, on the basis of a temporal series of the geographic location in question.

This means that the data related to the individual amounts of daylight are calculated on an annual basis, from climate datasets that contain at least 8,760 hourly observations for the entire calendar year.

Unlike the static approach, the DDS method takes its cue from effective integration between the artificial and natural lighting components, since it finds its definition of new criteria on verification of a quite distinct luminous threshold and, where these are not completely or are only partially achieved, it has been suggested to make progressive use of variable quotas of artificial light.

The annual amount of natural light that spreads into a confined space is therefore evaluated in a global manner by the CBDM simulation, which uses brand new parameters of a new definition starting from annual illumination profiles, through statistical analysis of annual and historical series, on a 10 years basis.

The first requirement is to make usable for the intended aim, a mass of climate data, which must necessarily be converted into intuitive parameters, capable of interfacing with an architectural and construction system that is already very complex.

Given the changing and dynamic nature of the seasonal model relative to the availability of sunlight, an assessment extended throughout the year, is in reality the only possible option, in order to have data that can be considered reliable.

The model of the hourly and sub-hourly values of illumination and luminance for each geographic location is for this reason deduced from meteorological datasets, according to a specific data format.

The meteorological data needed for the creation of climate datasets have been obtained from files known as *Test Reference Years* or *Typical Meteorological Years*.

The simulation that makes use of this set of complex files is able to provide hourly predictions for each point it is desired to evaluate. For sub-hourly forecasts the reduced variability of irradiation conditions makes it necessary to resort to statistical models.

It has become clear that only through an hourly forecast it is possible to obtain a reliable and realistic estimate of the actual illumination in variable sky conditions. A dataset with a number of restricted hourly profiles can be considered valid for analysis using the dynamic method, in spite of the fact that it risks introducing some inaccuracies into the calculations.

From these observations it has been assumed that the best method to prevent mistakes or excessive simplification, similarly to what commonly happens with the static approach, is to consider the climate files in their entirety.

Only in this way can the time variations found in the sky and luminous conditions be computed over an entire year, allowing the inclusion in the calculation, of the entire range of climatic and luminous conditions, in both the short and long term. The choice of the minimum number of illuminations to carry out the calculation is around 4,000 point surveys for each hourly threshold.

If, alternatively, it is desired to consider a calculation based on minutes, the number of necessary data increases exponentially, arriving at about $2{,}4\text{x}10^5$ precise observations.

These numbers can be reduced if an assessment is chosen that takes into account the sunshine hours included in the arc of normal working hours, probably from 8 to 18, as is the case for most dynamic analyses conducted with the new parameters.

2.1 Typical meteorological year climate data for the formulation of dynamic parameters and methods of application

The procedure that is therefore best suited to the need to describe variations in light distribution hourly over the duration of the year, is based on local Typical Meteorological Year (TMY) climate files [also known as *Design Reference Year* (DRY)], to determine which requires sequences of 8,670 values, calculated for each hour of daylight. The methodology currently in use is based on the first analytical assessments [89] and successive revisions and refinements [90].

The procedure that has helped define the specific climate datasets for each calendar year is based on a selection of hourly data for each month of the year, in order to guarantee the calculation algorithm maximum reliability.

One of the first selection procedures was developed in North America, by Stamper in 1977, in order to be able to carry out assessments on energy consumption in buildings and on their energy-saving potential. The method for the definition of the reference year and for the climatic assessments, known as TRY, *Test Reference Year* or TMY, *Typical Meteorological Year*, initially provided for the elimination of those months where anomalies were found within the series analysed, until the definition of the reference year.

The TRY method is therefore based on the aggregation of data relating to the 12 months that are typical from a meteorological perspective, selected from the data collected in annual historical series.

The selection of the TMM, *Typical Meteorological Month*, is based on statistical analysis of the particularly significant variables for the overall representation of the standard year, including direct solar radiation known as GSR, *Global Solar Radiation* [91].

The simple arithmetic average of the measured values throughout the year would appear, therefore, not very representative of the real complexity and variable sky conditions' brightness. The data that refer to the month that best represents the monthly average of the measurement period are then chosen as TMM values for that specific month of the year. An identical process is then repeated for each monthly dataset in order to determine the most appropriate value for each of the 12 months, to sample only one year.

The procedure for the selection of the most suitable daily and monthly data take place through the choice of that calendar month, which proves to be more similar to the average polyennial trend of the month in question. This may result in a set of TMY data for a given month being the aggregation of data acquired by series pertaining to separate years.

We should point out that there is no strict criterion for the determination of TMY sample values, for this reason, special databases with free access have been set up, that provide validated data for each location, in order to ensure uniformity of input data at the start of light analysis using the dynamic method.

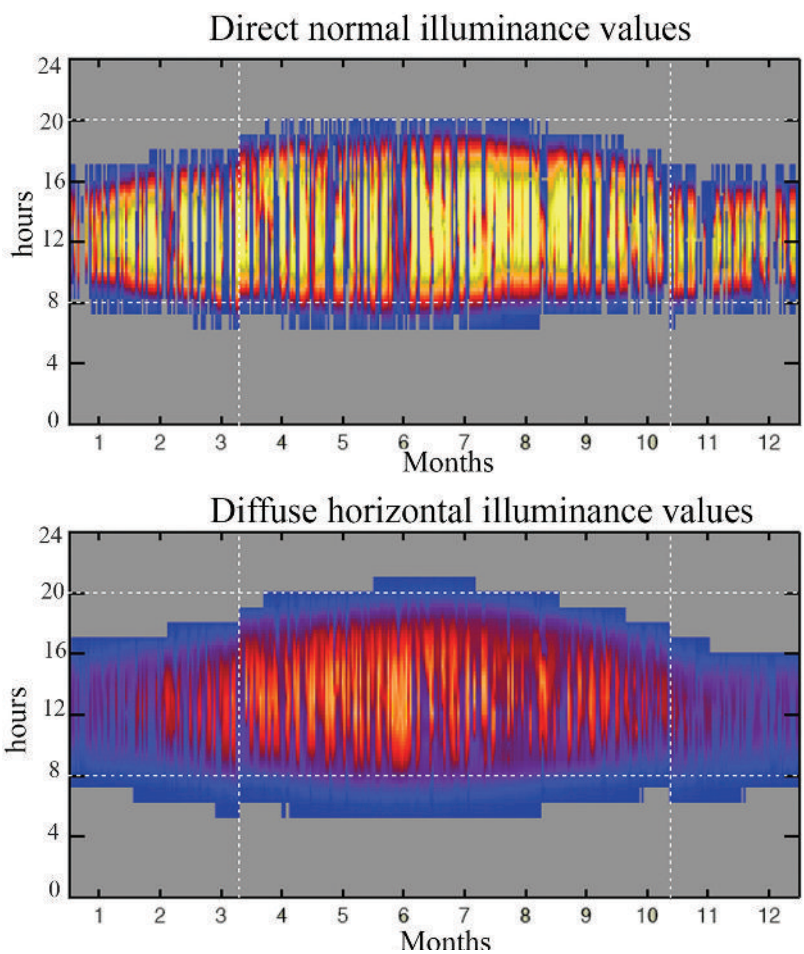


Figure 57: Illuminances values according to a TRY file.

The graphic representation of these climate datasets (Fig. 57) must be made so that it ensures comparisons between the enormous amount of hourly data, making analysis easier.

The graph therefore makes use of a field divided into 365 vertical rectangular sections to represent the days of the year on the abscissa axis, while the ordinate axis shows the distribution of brightness over the 24 hours of the day. The matrix thus represented employs a variable colour map to represent the thresholds of illumination expressed in lux, as illustrated in Fig. 57.

The shading and colour variations allow a representation of the hourly, daily and monthly fluctuations for a location over the entire course of the year, while the areas with a uniform grey pattern indicate the hours of the night, with brightness close to or similar to zero.

The graphic representation therefore collects a set of raw data, grouped into a unique representation for each point of calculation: the advantage of this type of representation is that it allows an appreciation of the variability in the pattern of light distribution throughout the year. In the same way, the hourly and sub-hourly variations are immediately identifiable and easily comparable with other datasets for different geographic locations.

Implementation carried out as part of Mardaljevic's research into the coefficients of daylighting and the definition of new inquiry parameters thus provides for separate computation of direct and indirect lighting, so as to ensure an analysis of each amount according too absolute and comparable quantities, in order to arrive at a design approach directed to mitigate or absolve precise shading or diffusing needs for sunlight.

In purely architectural terms, this type of survey allows, for the first time, to perform an analysis on an annual basis, in relation to the most likely condition of the sky, allowing designers to make the choices and prepare specific solutions in response to predictable needs over the day or on an hourly basis.

In the same way, a greater awareness of solar dynamics and climate is particularly convenient for analysis of energy consumption and the real needs of each building shell. As is evident, the approach on an hourly and sub-hourly basis, if on the one hand it requires the use of a large amount of raw data, to be calculated using complex algorithms, on the other it makes it possible to simulate even before the executive or practical phases, the real behaviour of a building or environment, from both the light and energy points of view.

The use of climate datasets through TMY data for each geographic location then allows the adoption of two methodological approaches from which to choose: the *cumulative method* and the *series method*.

Analysis of a cumulative type on an hourly basis (or on a fraction of an hour) is based on estimates of aggregate measurements of illumination, as occurs, e.g. for the parameter of *Total Annual Illuminance*, i.e. a cumulative assessment of the luminance or irradiation of the sky.

The *cumulative method* usually prefers analysis on an annual, seasonal or monthly basis, while recourse to intervals of calculation under one month are to be excluded, in as much as the results are not very significant if related on an annual basis, since they represent a pattern of light distribution that is not statistically valid.

The cumulative system is usual used to assess micro-climate aspects or to assess solar access in dense urban environments, as well as long-term assessment of the exposure to sunlight of works of art to evaluate the effects it has caused, as well as qualitative and quantitative surveys for the design of shielding or shading devices.

The *series method* offers instantaneous forecasts presences of precise measurements such as the illumination values, based on values taken hourly or in fractions of an hour within the specific annual TMY dataset for the location.

Unlike the previous one, this approach may be exploited to evaluate the potential of the *Overall Daylighting Potential* of a building or a room, or the occurrence of excessive illumination or related phenomena.

The assessments made are therefore crucial in influencing the design of the building, the design choices related to the treatment of the finishings and the glazed or transparent parts, and in the choice of devices designed to control or manage the natural light.

Subsequent modifications to the TMY method have been made by various scholars and led to the establishment of the so-called TMY2 model, which introduces, as a main novelty, the direct solar radiation variable, resolutive for the processing of new units of measurement and of the new parameters as formulated by Mardaljevic.

The TMY2 encompasses in its formulation a greater number of data on direct solar radiation and illumination as compared with the previous formats TMY and TRY.

Recently further research has been conducted for the formulation of the TMY3 method, according to which solar radiation should not be measured directly, but calculated on the basis of statistical analysis from the data of historical stations on databases of 10 or 15 years. The TMY3 format collects climate data for localities solely in the USA, by means of measurements carried out more recently [92].

Among the most widespread codes that must also be mentioned is the IWEC – *International Weather for Energy Calculation*, a meteorological file that comes out of the results of the *ASHRAE Research Project 1015* [93], as climate data according to the ASCII format, which is better suited to energy simulations for the buildings, but that provides data on sunny places in Canada and the USA, thereby limiting its international use, with just 227 overseas locations. The IWEC format is based on a weather database listing 18 years of measurements, making data available on solar radiation and temperatures. The files on solar radiation are estimated on an hourly basis, according to the prevailing sky conditions. IWEC files also contain weather observations on an hourly scale essential to make global energy assessments of a building, including information such as the dry-bulb temperature, dew-point temperature, wind speed and direction of the wind, as well as data on illumination.

The ESP-r code is a further example of a built-in tool for the multiscale energy assessment of buildings, including also the luminous, acoustic and thermal analysis of a confined environment. The system is based on the use of codes supported by a number of platforms and operating systems, thanks to the interface, which allows non-stop implementation on the part of users, taking into consideration also those factors that influence the energy and environmental performance of buildings.

In order to make simulations easier by using software in recent years a further generalised climate data format has been developed, which is very widespread and linked to the use of programmes and systems for energy and environmental assessments.

The new format called EPW, *Energy Plus Weather format*, uses the ASCII format, today among the most popular, almost to the extent of replacing the TMY2 format, and is used as input data for simulations conducted with ESP-r.

The advantage of this special format derives from the fact that all data are expressed in SI units, making it a relatively simple tool, text-based and with the data separated by commas. The source data for the processing of the EPW type files are derived from the TMY2 format, suitably re-managed to facilitate their use.

The EPW format also refers for the first time to the *Infrared Sky* model, which makes it possible to calculate the actual temperature of the sky, in order to obtain data on nocturnal irradiation. A further difference is that the file format in EPW has no need of complete data throughout the year, therefore the number of hours evaluated, usually amounting to 8,760, is no longer necessary, but is replaced by reduced subsets of selected years.

2.2 The project to define an Italian TRY and the last frontier of dynamic calculation through Real-Time Weather Date

The ongoing renewal process is also reflected in Italy where the well-known advantages linked to energy and environmental assessments according to the dynamic approach, have focused attention on the need to develop a model of national reference, from which to create real and reliable analysis models.

The first climate data to employ the coding system of the reference year type date back to a project funded by the IFA the Institute of Atmosphere Physics of the CNR, in 1979.

The research program, for the creation of the *Giovanni De Giorgio* data bank for national climate data attempted to encode the collected values in a vast time span, from 1951 to 1970, through analysis of weather data collected from the Weather Service of the Italian Airforce via 68 stations scattered across the country.

Among the measurements was therefore selected the most significant month type with mean values and variances more readily comparable with the measured values, from which was to be inferred the year of reference-type, by aggregating the more significant sample months.

The weather stations that the data were collected and analysed from, proved insufficient, since the measurements contained numerous shortcomings and inaccuracies, as well as a substantial overestimation in the amount of direct radiation.

In recent years, the most decisive contribution was provided by a project carried out in collaboration with the company NIER Engineering S.p.A., and by the Department of Energy and Nuclear Engineering, and Environmental Control (DIENCA) of the University of Bologna, in the context of the research programme 'Environmental TRY for Innovative Dynamic Environmental and Energetic Analyses'.

The project, which began at the end of 2010, is still being completed, and has the goal of implementing the data bank on *Test Reference Years* for Italy, to support environmental and energy analyses, for approximately 1,000 national locations.

The originality of the Italian approach lies in the creation of appropriate models of annual reference to respond to different applications, including environmental, photovoltaic and solar-thermal TRYs, through a separate selection of data, based on meteorological variables relevant to the specific application, and appropriately weighted.

The method of data selection, carried out on the findings of more than 1,000 Italian locations, seeks to identify the most representative month from a historical series, thereby producing a year of weather data consisting of significant monthly factors that can also belong to distinct years.

The lack highlighted, both in climate dataset of a few places in Italy, and in the backwardness of the survey methodology, makes the project of considerable importance, an indispensable step towards the adoption of a dynamic approach to energy and environmental assessments – including Daylight Assessment.

In addition to the significant experiences designed to renew or to create datasets *ex novo* for TRY or TMY climate models, the most evolved frontier as regards the dynamic simulation of luminous performance with natural light, is represented by *Real-Time Weather Date*.

All data can be freely consulted for the main geographic locations worldwide in a common database that transforms the data collected according to GMT in different time zones, as well as LST, to make the necessary data available for every fraction of an hour throughout the calendar year, so that they can be used for precise assessment.

The main objective of the scientific research into natural light and the performance associated with its use, is now concentrated in an attempt to provide conclusive definitions in the search for a new series of parameters that surpass the current generic qualitative criteria.

The ultimate aim is therefore to move from generic assumptions to real units of measurement, which are useful in analysing the energy performance of buildings and assessing the condition of interior comfort for the occupants of naturally lit buildings.

Once the parameters relating to natural light, assessment criteria and limits of applicability have been defined, approval at an international level needs to be sought.

3 New Metrics

3.1 Useful Daylight Illuminance

Among the new units of measurement proposed to meet the requirements dictated by the dynamic approach based on climate, in accordance with the procedures previously described of the CBDM type, the best known is UDI, *Useful Daylight Illuminance* or *Useful Daylight Index*.

Natural illumination of a work surface involves continuous variations and consequently significant differences, both from the spatial and temporal points of view, just as the levels of illumination differ greatly when evaluated near a fenestrated front or with respect to the most distant point, as happens from one instant to the next as a result of a change in external weather conditions.

Precisely by virtue of this inhomogeneity and the impossibility to assuming the standard CIE overcast sky as an unequivocal condition, a new metrics has been defined appropriately designed for dynamic analysis, which provides data that can be used immediately and are valid on more extended temporal arcs. Among the new parameters introduced with the advent of the dynamic method based on CBDM, was the UDI paradigm, defined with the objective of facilitating the interpretation and reading of illumination levels recorded in an interior space, initially on an hourly basis and then extended to an annual basis.

The schema to assess the values of *Useful Daylight Illuminance* is designed to make it easy to understand the absolute values of natural illumination in a confined environment and define thresholds that would otherwise be difficult to compare.

The novelty of the approach lies in the fact that, for the first time, rather than analysing the large amount of illuminance values through static geometric simulations, this relates the levels of daylight in a room according to the prevalent visual task.

If the method based on the DF produces only a percentage value, valid for each point in space, mediating between the different values calculated at the level of the surface of calculation, on the contrary, the UDI metric, while maintaining simplicity in interpreting the DF, bases its analysis on a forecast of the lighting for every hour of the day throughout the year, and for each considered point. The main advantage linked to the introduction of this new parameter consists in the huge reduction in volume of the output data, along with the ease of interpreting thresholds in relation to the visual task to be assessed.

Instead of a minimum threshold, Nabil and Mardaljevic, responsible for defining the UDI value, propose a parameter that indicates the attainment of levels of natural illumination considered useful, abandoning the concept of *target illumination*, usually associated with 500 lux to base their approach on verification of a series of pre-determined illuminations (Fig. 58).

According to this method, the UDI paradigm provides data, not only on the levels of useful daylight illumination, but also with regard to a propensity to attain excessive levels of natural light, mostly associated with forms of visual discomfort, irritating glare and overheating.

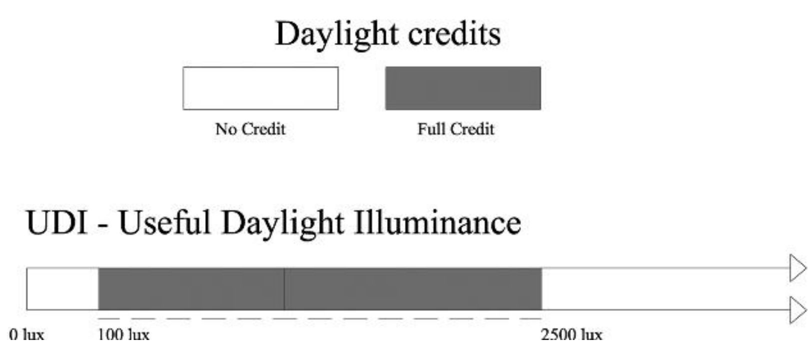


Figure 58: UDI scheme.

UDI is therefore based on an exact assessment of the frequency with which sunlight sits within a range of pre-determined illuminance. Considering the enormous variability with which sunlight can change in one day and throughout the duration of the year, the UDI approach reflects these variations in a fairly realistic way, calculating the trend over the 12 months, in a much more reliable way than the Daylight Factor.

From a practical point of view, UDI is defined as the set of those illuminations that lie within the range from 100 to 2,500 lux [94]: in fact, it has been established that daily illuminations that fall within the 100–2,500 lux interval can generically be defined as *useful*.

The UDI range is further subdivided into segments known as *UDI supplementary* and *UDI autonomous*.

The former indicates the occurrence of situations in which the levels of natural illumination lie in the range between 100 and 300–500 lux.

In the case of a level of annual average illuminance whose value falls in the first interval, it is usually necessary to integrate it with artificial light, especially for activities requiring precision, reading and writing.

Instead, *UDI autonomous* indicates the attainment of a threshold between 300–500 and 2,500 lux, in the presence of which artificial light is almost never required, nor is necessary.

The UDI assessment scheme is applied to determine the illumination at each calculation point present in the vicinity of the useful surface and to demonstrate the achievement of predetermined levels of daylight, according to the following breakdown:

- If the illumination is less than 100 lux, it is defined *UDI fell-short* (UDI-f), an insufficient value to be used as the sole source of lighting, such as to require constant integration with artificial light sources;
- If the illumination is higher than 100 lux, but lower than 300–500 lux, it is defined *UDI supplementary* (UDI-s): this is judged as an adequate level of illumination and an effective source only in certain circumstances, though requiring the contribution of artificial light in certain situations;
- If the illumination is greater than 300–500 lux but less than 2,500 lux, it is defined *UDI autonomous* (UDI-a), i.e. it is assumed to be a satisfactory target level for most circumstances;
- If the illumination is higher than 2,500 lux it is called *UDI exceeded*, i.e. one exceeds the useful range and is the cause, with a reasonable approximation, of certain phenomena of glare and overheating.

According to these definitions, the introduction of the UDI parameter allows the use of only three indicators to effectively describe the daily, hourly and annual levels of fluctuations in illumination in a confined environment and for each point of calculation.

Instead of a single threshold value, there is a distinct range of illuminations, calculated on an annual basis in real sky conditions; this new approach should therefore check in which interval the illumination point is established, leading to eventual integration with a quota of artificial light.

In particular, if the level calculated according to the dynamic approach is lower than necessary, it cannot contribute in any way to the completion of the visual function and the correct perception of the environment, and therefore cannot be considered in the range of useful daylight doses. On the contrary, if the annual levels, calculated in the period of time in question, are extremely high, these can be the cause of troublesome phenomena to occupants, both from visual and heat points of view, involving the psycho-physical sphere in general.

The raw data on illuminance levels identified throughout the year in the daylight hours are calculated as fundamental values to determine the percentage of the working year in which there is actually UDI.

The most advantageous use for the raw data is on the horizontal plane to indicate the times of the day when there is UDI, evaluating with what percentage a threshold limit is reached. The value resulting from the calculation indicates how many times over the course of the working year it will be necessary to resort to artificial light. The real computation, performed with the aid of specific software, therefore offers an overview of the recurrence to natural and artificial illumination needed on the working plane during the period of the entire working year, on an hourly basis.

The UDI paradigm preserves therefore in its formulation efficacy an ease of interpretation that belonged to the static approach of the Daylight Factor, in virtue of the introduction of just three new units of measurement, representative of the illuminance levels achieved, which are at the same time able to provide crucial information as regards a propensity to situations of visual discomfort and overheating in the vicinity of a fenestrated front. In a different manner from DF, the UDI parameter and the smaller ranges of illumination UDI-f, UDI-s and UDI-a, are based on representation of absolute values of illumination for a period of one year.

Unlike the other recently proposed parameter, *Daylight Autonomy*, UDI for the first time also gives a precise function to illuminance values lower than the usual threshold of 500 lux, bringing significant benefits in terms of energy savings, since it shows that illuminance levels lower than 500 lux are still sufficient for some specific visual tasks, without necessarily resorting to integration with artificial light.

This aspect brings considerable results, especially in the daylight assessment of work spaces, such as open space offices, schools, and large environments with systems of natural light.

The substantial facilitation of this new parameter therefore consists in the methodology itself, which makes it possible to determine the intervals of the illumination UDI-s, UDI, and UDI-a, through surveys carried out via multiple research on samples of naturally lit offices [95].

Although no examples are available in the literature that correlate in a determinant way the relationship between natural light and the level of psychophysical satisfaction among occupants, numerous experimental studies have shown that users prefer environments lit naturally, since they aid concentration and productivity [96].

The more indicative surveys, such as those conducted on the levels of preference in terms of natural light and the levels of attention and productivity found in US schools, derive from reports by Heschong on K-12 schools in three areas of the United States [97].

The CISBE committee, after extensive surveys, found that the most appropriate levels of illumination for workspaces should be around 500 lux in the case of both artificial and natural light [98].

In a similar manner the IES and Canadian research institutes concluded that the majority of the interviewees prefer illumination greater than or equal to 150 lux, significantly lowering the threshold of the traditional 500 lux prescribed as an optimum threshold value: This means, therefore, that it is possible to use levels of natural light suitable for the visual task well below the requirements of the standards, as demonstrated by the transposition of a US regulation, which stipulates precise illumination of 50–150 lux to be provided to improve the so-called *visual task area*. In most of the tests conducted during the research campaigns it has been found that, unexpectedly, most of the subjects claimed to feel a general sense of visual comfort if subject to levels of natural light around 100 lux, well below the levels usually recommended.

It has been demonstrated that subjects tend to adapt more easily to minimum levels of natural illumination rather than levels of artificial light, especially in the second part of the workday, when of course the brightness drops [99].

An aggregate reading of these assessments shows that the majority of subjects who work in bright environments with devices for *sidelighting* declare themselves to be more satisfied and productive in the presence of natural rather than artificial light, although some individuals do demonstrate a propensity for lower light levels, even if it causes discomfort [100].

At the same time it has been found that illuminance levels higher than those usually prescribed – around 500 lux – are well tolerated by subjects, even though they may be the cause of irritating glare.

It has also been observed that illumination that falls in the range between 700 and 1,800 lux, apparently well above the standard, are however accepted in relation to special visual tasks, including computer activity or reading.

Daylight Assessment therefore draws considerable benefits from the application of this new parameter by virtue of the very nature of UDI, which makes it possible to assess the most appropriate solution to optimise strategies of *solar shading*. In the same way as the inverse relationship between UDI and electricity is a crucial indicator for the energy-saving potential of a building naturally lit.

The UDI therefore offers the means to communicate important characteristics in variations in internal illumination through concise formulation for any type of Daylight Assessment.

3.2 Daylight Autonomy – DA and continuous Daylight Autonomy – cDA

The *Daylight Autonomy* was initially used to generically evaluate the availability of sunlight, for a dynamic approach according to the CBDM method. Daylight Autonomy was in fact conceived among the first metrics developed for the dynamic approach to assessing natural light, and represents the percentage of daylight hours over the arc of the entire year in which illuminations lie above a pre-determined threshold (Fig. 59).

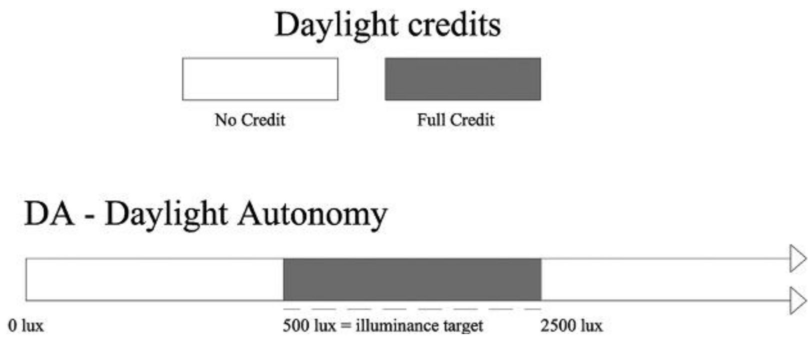


Figure 59: DA scheme.

It was originally proposed by the *Association Suisse des Electriciens* in 1989 and, subsequently, became the object of research by Reinhart between 2001 and 2004.

DA is a measurement of the annual percentage frequency at which a pre-determined minimum level, usually 500 lux of illumination, can be maintained on the working plane thanks to only natural light. Unlike what was previously described for the UDI parameter, which is based on an assessment of the percentage frequency with which it is possible to reach a pre-determined range of illumination, the DA metric seems more simplistic.

It must also be considered that *Daylight Autonomy* proves unsatisfactory in giving value and meaning to those illuminations that fall below the threshold of 500 lux, despite the fact that even in those circumstances the quota of sunlight is useful to carry out some activities, and is nonetheless an appreciable amount in terms of reducing energy loads.

Secondly, DA does not take into account the overall amount of illumination over a pre-determined threshold and how much this is exceeded for each instant of time: this want produces considerable impact, as does not give weight to the occurrence of possible phenomena of visual discomfort or glare.

As is the case for the calculation of UDI, assessment on an annual scale of the parameter to be obtained through joint analysis of the climate file of the locality in question, assuming standard working hours from 9 am to 6 pm, on which range the calculation of values is made for a grid of points placed at the workplane height.

Similarly to the distribution of the DF values, it is to be noted that the DA parameter progressively decreases with a distancing from the fenestrated front but, unlike the uniform distribution of DF illuminations, *Daylight Autonomy* does not have a symmetrical distribution, since the calculation also considers changes made by users, usually characterised by an absence of stable or symmetrical patterns.

Calculation of DA is therefore proposed to quantify the daylight saturation in a room and to determine the percentage of direct sunlight.

In this sense, two distinct methods have been proposed to calculate DA, both to be made through calculation on an hourly basis for the entire duration of the year.

The incremental method, or method of the incremental summing, introduced in 2002 by Reinhart [99], includes an assessment of only those points where illumination exceeds the reference threshold of 500 lux.

This implies that, in the case of a surface of calculation where the expected illumination level has not been reached at a given instant of time, the surface is assigned a score equal to 0%, while for the instants in which the target is achieved, and conceivably exceeded, a score of 100% is given.

Instead, the continuous method, dating back to surveys from 2006, also considers the smaller fractions of illumination available so that, in the case of an illuminance of 300 lux on the plane of calculation, a score is given equal to the fraction 300/500, i.e. 60 percentage points. According to this criterion, thresholds of illumination below the target value are also counted and it is possible to determine the variable amount of artificial light at specific moments of the day, only for the hours the space is actually used (Fig. 60).

This calculation method is particularly useful in the event that assessments are necessary of the energy-saving potential related to the electrical consumption of spaces, in order to jointly determine aspects such as indoor comfort and the level of productivity.

To tackle a correct analysis of the DA parameter in a confined environment particular attention must be paid to some of the variables essential for calculating, such as the time period, spatial analysis, the choice of the target light and further estimates on the orientation of the apertures.

The choice of the interval of time within which to perform the survey is also crucial for the reliability of the DA value.

In this sense, the night hours must be excluded from the count, so that the DA percentage score is not distorted or mediated by excessively low values. For spaces occupied day and night it is helpful to consider only the temporal arc with sunlight, in order to be able to provide a reliable analysis; in the same way, in the morning the DA calculation may prove useful to arrange actions to optimise the incoming light, just as in the afternoon it is possible to accurately establish how much artificial light will be required.

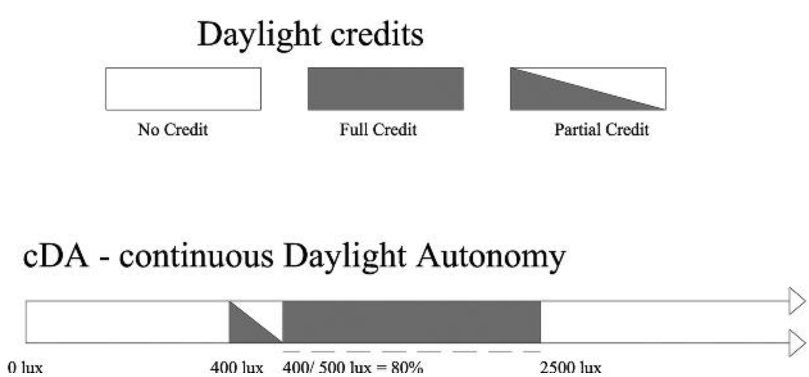


Figure 60: cDA scheme.

In 2006, Rogers [101] also defined a new parameter as a result of a survey campaign performed on school spaces: the cDA, *Continuous Daylight Autonomy*, assigns partial credits thereby introducing illumination thresholds lower than previous ones, useful to analyse specific visual tasks, which do not necessarily require the attainment of the 500 lux foreseen traditionally by DA (Fig. 59).

If, for example, a limit is fixed for the assessment at a value of DA500 and the point to be analysed is affected by a illumination of only 400 lux, the cDA will give a partial score given by the ratio 400/500 = 0.8.

In other words, if a point in the space of calculation registers 150 lux at a given instant, according to the DA method, a score of 0 will be given, while according to the cDA parameter, the score to give is equal to the ratio between the illumination maintained and the threshold value, i.e. 150/300 = 0.5 points.

The most interesting outcome of the new metric lies in the fact that, rather than defining a threshold that clearly differentiates between compliant and non-compliant results with respect to the objective of the project, the limit becomes more transient and helps to establish variable terms in relation to the needs of the user and lighting preferences.

The percentage values that are being used for the graphic representation of the cDA show the percentage of points, measured at the workplane, in which the illumination exceeds 50% of the limit value of 300 lux.

For the sake of completeness it is necessary to briefly mention the DAmax parameter, defined by Rogers as *Maximum Daylight Autonomy*; this was born as the result of incremental summing method, mentioned previously, fixing the maximum value of the illumination reached as a threshold limit.

On the basis of the actual period of occupation, it establishes the moment when illumination is at a maximum, and this target sets a limiting condition in which phenomena such as irritating glare and overheating of the environment are very likely to occur.

The threshold that it prescribes is, in this way, about 10 times greater than the average of the normal values.

3.3 Other parameters: daylight saturation percentage, annual sunlight exposure and spatial daylight autonomy

In addition to the earlier metrics defined for dynamic analysis, further parameters have recently been developed, derived directly from UDI or defined to evaluate specific aspects in relation to particular visual tasks.

Daylight Saturation Percentage DSP, e.g. can be understood as a change in the UDI parameter, because it displaces the minimum limit of illumination that can be evaluated to 40 candles, equivalent to 430 lux, simultaneously raising the upper limit to 400 candles, equal to 4,300 lux, compared to the previous 2,500 lux (Fig. 61).

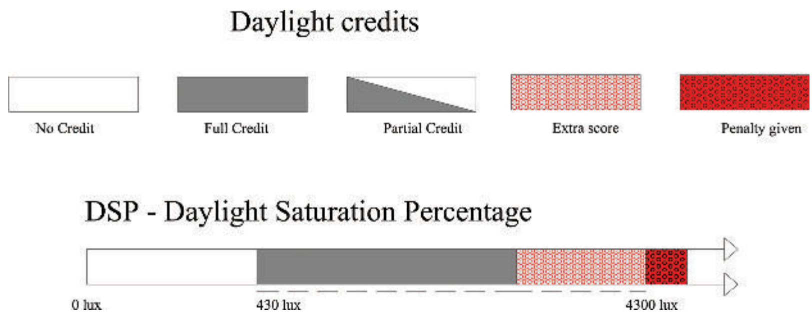


Figure 61: DSP scheme.

This parameter was developed with the specific purpose of carrying out surveys of maximum precision for schools and classrooms. The calculation to determine DSP is frequently employed in the field for studies on illumination levels maintained in school classrooms, from 8 in the morning until 3 in the afternoon, from Monday to Friday, during the school year, from August 15 to June 15.

The *Daylight Saturation Percentage* DSP, comes from a combination of several calculation methods used to assess the DA, as defined in the mathematical relationship:

$$DSP = DSP40 - 2 \cdot DSP400 \tag{15}$$

Where the term DSP40 represents the saturation rate of natural light at 40 candles, the term DSP400 indicates the incremental value of DA at 400 lux, considered to be the equivalent to 10 times the illumination obtainable from 40 candles, and therefore also definable as DA_{max}.

A parameter often mistakenly associated with the new unit of measurement, given that it considers percentages concerning the risk of excessive exposure to sunlight occurring, is instead the ASE *Annual Sunlight Exposure*, i.e. the annual amount of natural light to which an object, by virtue of its characteristics, can be subject. In particular, ASE is defined as the percentage of space affected by more than 250 hours of direct illumination per year, where ‘direct illumination’ means a quantity higher than 100 lux through the apertures, excluding secondary reflections and the quota intercepted by shading devices.

Therefore, this term usually indicates the annual amount of incident light visible at a detection point, calculated for an entire year, in such a way as to provide a reliable estimate of the amount of harmful radiation to which an object is subjected with reference to the presence of sources of visual discomfort.

The definition of the metric was born in the lighting engineering context to define the most suitable illuminance threshold for specific materials, in the event that they are subject to artificial radiation for long periods of time.

The IES commission has further refined the concept of ASE for museum displays, officially approving the definition in January 2013, through the criterion TC3.22 ‘Museum lighting and protection against radiation damage’, recommending the maximum permissible annual amounts of radiation with regard to the objects exhibited.

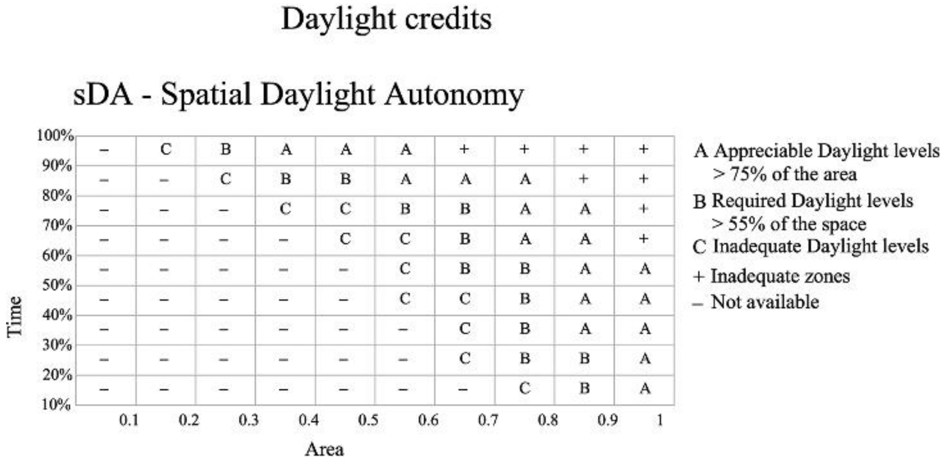


Figure 62: DA scheme.

In October 2012, the IES definitively validated the effectiveness of a further unit of measurement the sDA *Spatial Daylight Autonomy*, introduced by Lisa Heschong and her research team. This parameter is defined as the percentage of the work area or the plane of calculation on which fall 300 lux for at least 50% of the year, basing the calculation on a working day of 10 hours.

The novelty of the parameter lies in the fact that for the first time it takes into account the spatial component and the geometry of the area on which the limit value of 300 lux insists over a pre-determined range of hours per year (usually equal to 50% of the time interval considered for working, i.e. between 8 am and 6 pm); in this way, it is possible to define time zones and the times of the year during which to intervene with a variable quota and supplementary artificial light, in support of natural radiation.

As can be read in the diagram in Fig. 62, created as part of preparatory assessments performed by Heschong for a series of naturally lit interior spaces, the term sDA300 followed by the percentage value indicates when, in the course of a year, the surface meets, at least, 300 lux.

The sDA therefore uses as reference threshold an illuminance of 300 lux on the horizontal surface, evaluating the number of hours per year in which each point of analysis meets or exceeds this limit value.

The complete wording to define the sDA uses more indices, which indicate whether the point of analysis meets or exceeds the threshold of 300 lux for 50% of the time of calculation, as in the wording for sDA300/50%.

Previous graphic representations of the different daylight metrics shows how daylight analysis based on the sDA parameter allows a precise reading of varying conditions on the work surface, creating micro areas that make it possible to distinguish the areas where the sDA has been achieved and where the percentage is sufficient, acceptable or satisfactory.

In this way it is possible, especially for daylight assessment of work and study environments, to distinguish between areas affected by a greater illumination in distinct periods, and to arrange for an estimate of how much artificial light is necessary in order to compensate for the lack of natural light and to forecast any dynamic movement of occupants within the environment, on an annual scale. In accord with the assessments still undergoing definition, Heschong's team of researchers is still working to propose further clarifications of the parameter, through the distinction of two classes, marked by the letter A, in which the illuminance of 300 lux is adjustable to 75% of the area, with extensive measurements on an annual basis while the normal working hours, spread over 10 hours a day and by the letter B, in which the area involved in this illumination affects 55–75% of the time of calculation. The sDA metric was also recently introduced among the requirements used by the LEED environmental assessment system, in the criteria used to allocate scores relating to the quality of the indoor environment. At the same time as the final arrangement of this new parameter, US research is also directed towards further methods of measurement, which are essential to complete assessment of the level of indoor comfort attainable in buildings in the presence of natural light.

3.4 Comparative analysis of the dynamic parameters

One of the first comparative studies, conducted by Nabil and Mardaljevic [95] was designed to compare, from the point of view of graphic and architectural representation, the benefits and potential of the new UDI dynamic parameters compared to the traditional DF (Fig. 63).

The simulation carried out for a sample building compares the full potential of the three daylight metrics, *Daylight Factor*, *Daylight Autonomy* and *Useful Daylight Illuminance*, through analysis of

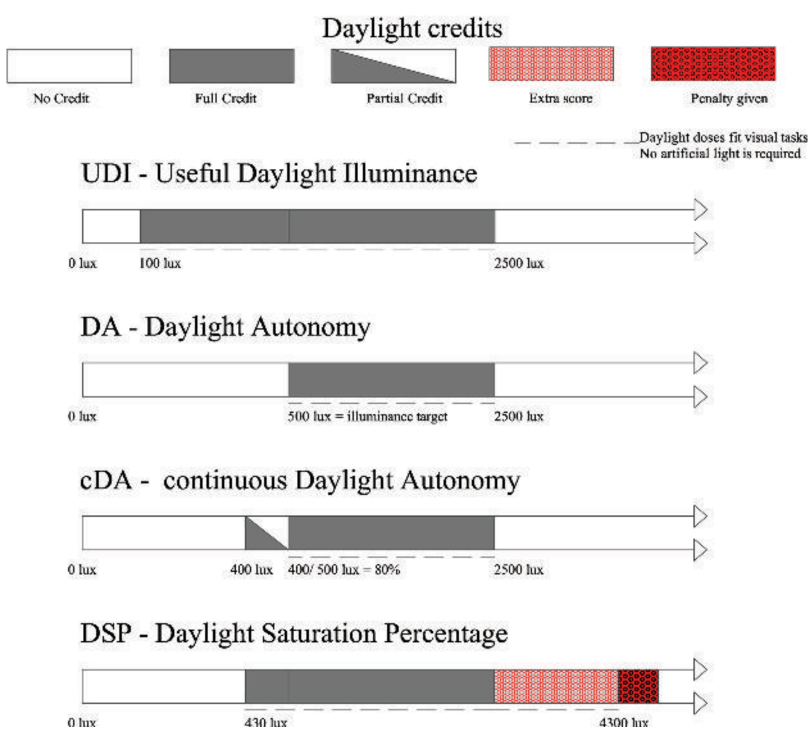


Figure 63: Daylight metrics comparison.

the respective sensitivity in determining the changes induced by the introduction of shading devices or to encourage solar penetration.

The results of computer simulations on an office building in London (Fig. 64), use building plans with falsified colour and graphs to represent the patterns of the three daylight metrics, to investigate similarities and differences in behaviour with respect to the real situation, measured *in situ*.

The reproduction of the prevailing trends of the three luminous parameters makes it possible to grasp the most significant differences.

The campaign of simulations first consider the existing building through a simplified three-dimensional model, to which changes are gradually introduced, through the inclusion of external lugs, or central light wells, so as to verify how the individual parameters fit in depicting the luminous variations following the inclusion of individual devices.

A comparative study performed using the software called *Radiance*, employs generic reflection coefficients: 0.5 for walls, 0.7 for ceilings, 0.3 for floors and 0.7 for external horizontal projections, while for glazed façades an average coefficient of transmission medium equal to 81% is used, as well as a single surface of calculation, equal to the floor quota.

On the surface of calculation is fixed a grid of 900 points and sensors, following a 30 × 30 square arrangement, which is indispensable to simulate the presence of virtual photometers, and through which the survey is usually made; the data supplied by these sensors therefore determines the light distribution dynamics, according to the three available parameters.

Starting from model [a], which represents the building free of shading devices, with a square zenithal skylight, two variants are then proposed.

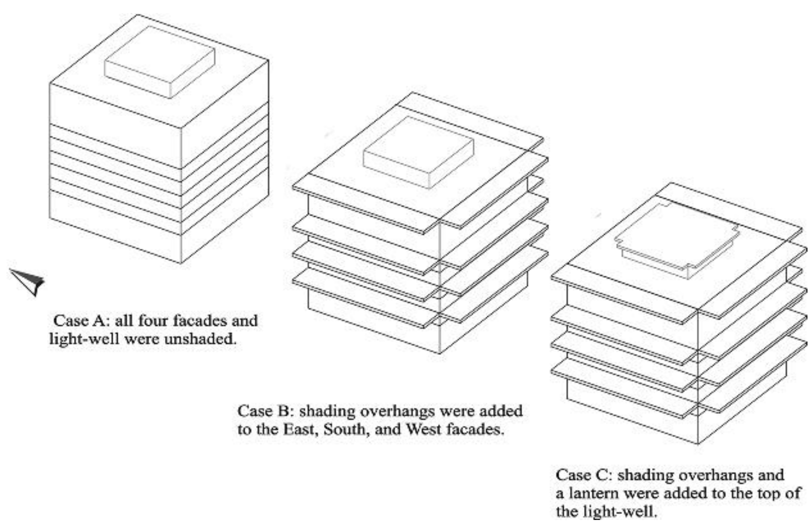


Figure 64: Building model and design variants.

Version [b] provides for the inclusion of horizontal slats and protection of windows on three of the four fronts of the building, i.e. on the south, east and west, the north being excluded since the simulation is performed in the northern hemisphere.

The horizontal slats form a projection of about 60 centimetres from the fenestrated front and are located at a height of 2.7 meters from floor level.

The second variant [c] provides, in addition to horizontal slats, the inclusion of a lantern on the roof of the building, corresponding to the skylight already present.

The simulation uses a dynamic analysis based on climate, using the specific weather file of the city of London, both for the assessment of UDI and DA, while for analysis of DF a simplified standard overcast condition is considered. Comparison of the daylight data performed makes it possible to appreciate the almost symmetrical trend between east and west for the DF value, a result that derives from the insensitivity of the parameter to the orientation of fenestrated fronts: in variants [a], [b] and [c] the distribution of the Daylight Factor appears symmetrically identical with respect to the central core of the building, the axis of symmetry of the model.

The target value is reached in about 80% of the measurements, considering only the working day from 9 am to 6 pm. The areas near the corners instead showed a greater amount of illumination where the threshold of 500 lux is almost always guaranteed. The annual percentage of DA decreases instead when moving away from the fenestrated front. The asymmetry characteristic of the DA value highlights a considerable variation in the vicinity of the north-east quadrant in which, in both variants [b] and [c], the threshold value of 500 lux is exceeded in 20% of the cases and further decreases in case [c] in the presence of horizontal projections and the inclusion of the zenithal lantern.

This therefore shows that the integration of fixed horizontal shades on three fronts can significantly affect the DA value, as well as the inclusion of the lantern [c] is responsible for a decrease of 85% to 50% of illumination values in the central area of the building.

Lastly, the same hourly data on illuminations were calculated in accordance with the pre-set thresholds for UDI, further subdivided into *UDI achieved*, *UDI exceeded* and *UDI fell short*. Contrary to what happens with DA, in peripheral areas of the building there is a smaller percentage (20%) that increases towards the central core.

This is because, in the absence of external shading devices, an *UDI exceeded* is found for about 60% of the year, whilst in variants [b] and [c] the inclusion of devices to control solar penetration ensures a reduction in the UDI value, in particular in the vicinity of the east and west wings, which reaches the optimal range for 50% of the year.

The variant [c] with the lantern in opaque glass shows a rise in the UDI percentage value to 75%, approximately.

It is therefore possible to say that the spatial distribution of the UDI value follows an opposite trend with respect to what happens to the DF and the DA, since the UDI is at a minimum, at least in the vicinity of the fenestrated fronts where other parameters instead showed maximum values.

In conclusion, therefore, the highest levels of illumination calculated for DA and DF are found in variant [a], without shielding systems and central lantern, while UDI shows levels exceeding the threshold of 2,500 lux for a major part of the working year. The DF, which would seem then to prove the presence of optimal conditions of brightness, with values well above the required limits of 2–5%, does not meet the data provided by the UDI, according to which the unshaded solution [a] is the most disadvantageous configuration with illuminance levels higher than those considered useful for 60% of the year, within a distance of about 5 meters from the windows, a value which further increases below the skylight, where the *UDI exceeded* equals 50%, while opposite values are read according to the *UDI achieved* scale.

If these data are compared with the experimental findings concerning the degree of satisfaction of the occupants, they denote high levels of overall discomfort, in particular discomfort related to excessive brightness and glare, demonstrating once again the total inadequacy of the static DF parameter in representing actual conditions of visual comfort.

3.5 Daylight Assessment and dynamic performance metrics: issues worthy to be clarified

The different dynamic metrics according the CBDM approach offer many advantages. The UDI has, e.g. a simple and exhaustive scheme in depicting energy-saving potential in relation to actual luminous needs.

If compared with the traditional DF scheme, according to the static method, the dynamic approach is more articulate and only apparently more complex, but is able to express a comprehensive overview of the luminous dynamics on an hourly, daily and yearly basis. In particular, it provides, for the first time, relevant information in terms of a propensity to meet high levels of illumination that can be related to phenomena of thermal and visual discomfort.

In a totally innovative way, the new dynamic approach is calibrated to the needs of the occupants, resorting, as explains Mardaljevic himself, to 'human-factor based daylight metric' [102].

This type of practice integrated to the resolution of daylight assessment makes it possible to define the confines of a genuine revolution in the system of assessing natural light.

The CBDM scheme, more generally, employs a variety of different means to take into account the most significant features of the local climate firstly, and then to deploy these in a thermal and luminous design for a building or a single interior space.

The question which the international scientific community is now occupied with, in addition to the validation and final adoption of dynamic parameters, is the adoption of shared threshold levels for the determination of *UDI exceeded*, *UDI achieved* and *UDI fell short*, in order to determine whether high levels of *UDI exceeded* are realistic indicators of an actual reduction in the quota of electric lighting to be used.

The dynamic approach based on local climate allows for the first time to provide, prior to the design and the actual usage phase of the building, a clear and realistic forecast of luminous performance and electrical consumption that occur therein.

The persistence of certain uncertainties, together with a widespread scepticism regarding such an innovative approach to the luminous question has allowed the static-geometric method founded on DF to remain rooted in design practice, as the dominant assessment system, thanks to its intrinsic simplicity, rather than because of its realism or the reliability of the results provided.

For the majority of professionals, the examination of any measurement relating to daylight comes to an end with the verification of compliance with the average Daylight Factor.

Despite the obvious lack of effectiveness in the representation of luminous data, professionals prefer to adopt the average Daylight Factor (Fig. 65), supported by the fact that most of the systems of energy or environmental assessment still resort exclusively to this static parameter.

Daylight Assessment according to the dynamic model (Fig. 66) today appears as a real discipline that is the bearer of necessary changes which, to focus attention on the anomaly inherent in the static system, takes its inspiration to initiate reforms and radical changes, in order to set up a scheme that is uniquely valid and applicable in a differentiated manner for every requirement.

The necessary step towards the definitive assumption of the new dynamic approach, therefore, needs a process of systematisation at an international level.

The proposed metrics must be organised, compared with the real needs of designers, manufacturers and end-users, and made available to conclude efficient calculation on a local and climate

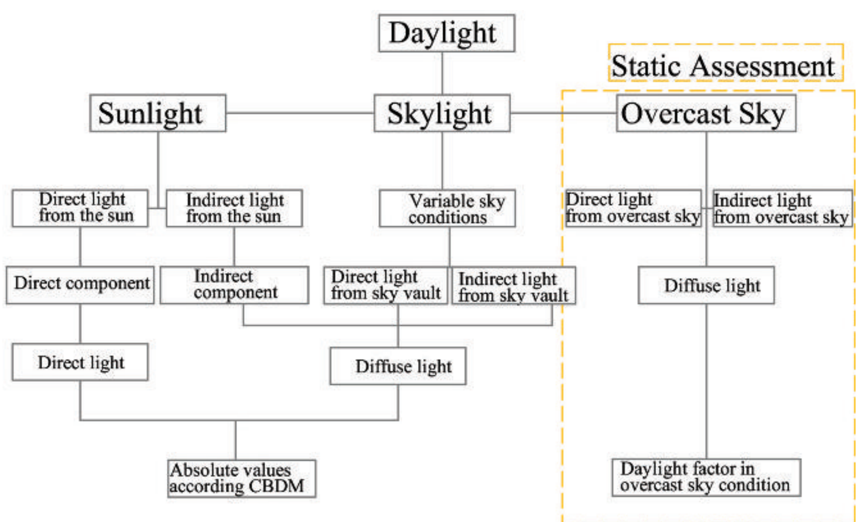


Figure 65: Diagram of the components that the static evaluation method considers.

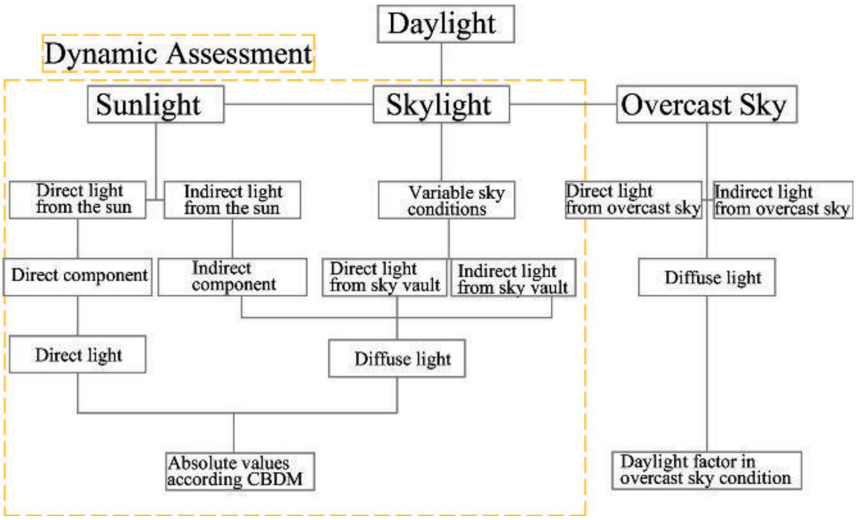


Figure 66: Diagram of the components that the dynamic evaluation method considers.

basis that is able to provide as output data, easy-to-use information and graphic representations, and can generate spatial and temporal maps of the actual distribution of illumination for a confined environment.

It is to be hoped therefore that an approach will be adopted that is unique but applicable to different geographic locations, that can assess the physical and meteorological specificities of a place and provide a concise parametric assessment for other energy quotas, as well as providing a link between their expressive and energy potential linked to indoor wellbeing obtainable with natural light.

The drivers useful in raising awareness of the need to validate this new dynamic paradigm must therefore be inspired by the knowledge that natural light, considered and controlled, can firstly reduce the energy load within a building, ensure a pleasant and calming environment for those who stop by or live there, that is healthy from luminous, visual and thermal standpoints, increasing productivity and raising the levels of attention, ending by being curative in the presence of diseases and disorders of different kinds, through so-called non-visual effects on the circadian system.

Chapter 5

A new paradigm for Daylight Assessment

1 Defining a protocol to optimise the Daylight Assessment procedure

The new approach to Daylight Assessment can be defined according to a 'bottom up' methodology, i.e. one based on the principle that, in accordance with the requirements to be pursued, it is necessary to determine the limits and thresholds within which the brightness needs to be established to satisfy not only visual task needs, but also the global wellbeing of users.

The search for conditions of indoor visual comfort usually includes a consecutive reading of some of the parameters and the verification of pre-set conditions: sources of natural direct illumination are identified, together with other factors that might influence the distribution of light; the annual and daily quotas of natural light that users and objects will be subject to are defined and, as a result, the threshold values to compare these with, in relation to the prescribed amount.

Using this approach and considering the use of the conventional static method, through the Daylight Factor (DF) parameter only, inevitably the complexity and vastness of the stimuli and environmental parameters is disregarded, both inside and outside the confined environment, making Daylight Assessment completely ineffective as a response to multiple requirements.

As a result, in the last 20 years new solutions for Daylight Assessment have been investigated according to a holistic system that would surpass the above critical issues.

The first, and most obvious obstacle in addressing the question is the lack of a unique system with regard to the choice of physical parameters to be considered: With respect to the first approach, based on simple rules of common sense or inferred from consolidated construction practices, only recently have local guidelines made it compulsory to assume the geometric DF parameter which, as has been analysed in the previous sections, is not only limiting and imperfect, but often provides values that are totally misleading and inadequate.

If we assume as valid other parameters of the static type, there is an equal risk of excessive simplification, always leaving aside environmental assessment and the degree of user satisfaction.

The complex apportionment that binds together the different parameters of a new definition must instead be supported by a genuine framework of analysis, suitable to describe in a comprehensive and comparable manner, different relationships that link aspects such as light distribution, visual comfort, the architectural quality of the environment, and respect of requirements that promote energy saving.

Resorting to simple indicators of a qualitative type, such as identifying the peculiarities of a confined environment through quantitative indices to be compared with pre-set values has so far been found unreliable.

From these considerations comes a proposal to set up a new verification protocol, which is remarkable for its integrated approach, able to offer a reading simultaneously on multiple levels of lighting conditions, environmental and visual comfort, and to assess the energy performance of a confined environment lit by natural light.

The analysis proposed below will arrive at the formulation of a *cascade analysis framework*, which is useful for the survey of existing edifices, and indispensable for a preliminary assessment at the planning stage.

According to this type of method, the individual components under survey are evaluated simultaneously, despite belonging to different systems or disciplines. In fact, the integrated system should operate simultaneously, by establishing comparable common limits and parameters to link different subsystems, such as assessment of hourly and sub-hourly illumination, analysis of dynamic parameters that combine natural and artificial light performance, assessment of visual comfort and the general perception of the environment by the occupants.

The analysis framework is undoubtedly more complex than the mono-disciplinary approach, but it does work as a single system of assessment, through the aggregation of separate synergistic subsystems, which relate to the different areas of inquiry.

The integrated approach seeks to define a practice that permits the taking into consideration of the needs of the user, the regulatory requirements and energy-type needs all at the same time, according to a method that provides for the adoption of the new CBDM system, tailored to the needs of the context and in relation to energy-saving strategies.

In this way, it leads to the definition of a single verification system, applicable both in preliminary stages and in the case of energy retrofit, to test the potential of the distribution of natural light in the interior spaces, from the point of view of quality and quantity.

The limitation of the integrated method proposed now regards essentially its range of applicability, it is obvious that a system which evaluates on several levels subsystems that are different from one another, in terms of indices to be respected and critical thresholds to be compared with, is easier to use on large complex buildings, where the needs of the user are differentiated and distinguishable.

In other words, the system will be proposed and better adapted to the daylight assessment of public buildings, in particular offices, schools and large spaces, where the stay of the users is prolonged in time and the visual tasks can be defined for specific areas, while the method is more difficult to use for the daylight assessment of residential buildings where it is not possible to actually differentiate the visual tasks among the interior spaces and application of the protocol would be more burdensome.

1.1 An integrated protocol for the dynamic assessment of natural light in confined spaces: a cascade framework in line with qualitative and quantitative aspects

Analysis of the environmental and energy performance of a confined environment can therefore benefit greatly from the introduction of the new dynamic parameters, which are able to jointly express relationships between visual function, climate and microclimate aspects, and performance and energy requirements.

The proper application of these new CBDM parameters within an integrated system of assessment allows an overall comprehensive assessment that takes into account the particularities of climatic context, of visual tasks, and in the interior space in question can be concluded, calibrating the variable amount of artificial light.

What remains excluded from the process of existing dynamic analysis is instead a comprehensive assessment of the preferences of the occupant, which may vary not only in relation to the target audiences, but also on the position that the subject occupies in the room.

The analysis procedure hitherto adopted (Fig. 69) essentially brings together data from the static approach, comparing the average DF values together with the geometric peculiarities of the interior space considered; only later on can the assessment be integrated with data relating to the requirements of comfort and energy saving, complex relationships that are formalised through the identification of certain limit values, in relation to which the compliance is assessed.

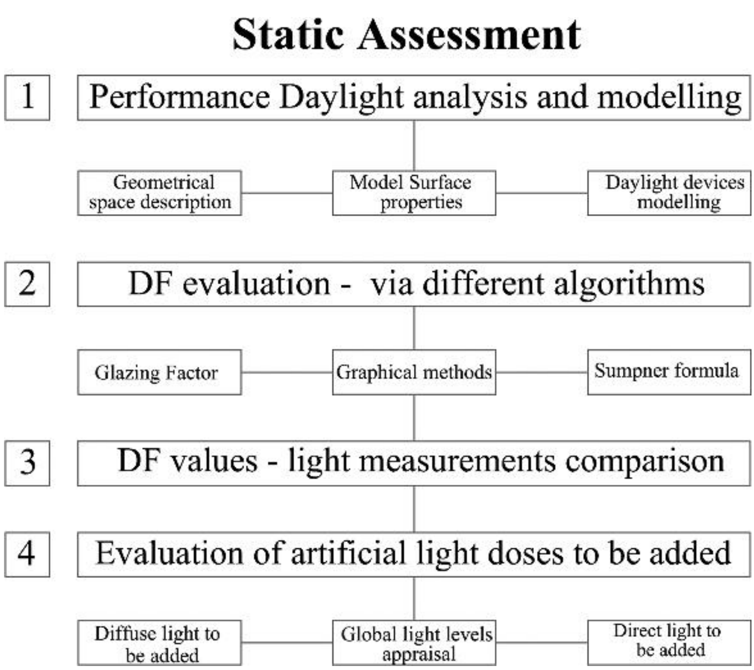


Figure 67: Analysis phases according to the currently valid approach.

The standard procedure (Fig. 67) that includes use of the static method is divided into two distinct parts: on the one hand it requires a precise description of the space in question, through the determination of opaque and transparent areas, and considering any optical and reflective peculiarities (step 1). Then from among the different methods to perform the luminous assessment one must be chosen, through the DF, using the simplified formula of Sumpner or resorting to calculation of the three components, DC, IRC and ERC (step 2).

In the case of existing buildings, the test can be performed *in situ* under the prescribed conditions, i.e. in the presence of a standard overcast sky, measuring the internal and external illumination to verify any agreements or anomalies in the light distribution.

This step can thus be integrated with previous ones, just as it can be followed by an energy-type assessment, for the determination of the integrative component of electricity.

As can be deduced from the scheme in Fig. 67, the major steps of assessment are mutually disjointed and in particular, steps 2 and 3 do not provide any type of reciprocal relationship, i.e. the amount of light required for artificial lighting is not directly dependent on the DF quota, this being hardly comparable to the actual lighting situation.

The limitations inherent in this type of practice, already defined in the previous section, are further increased by the absence of an assessment of comfort as perceived by the occupants.

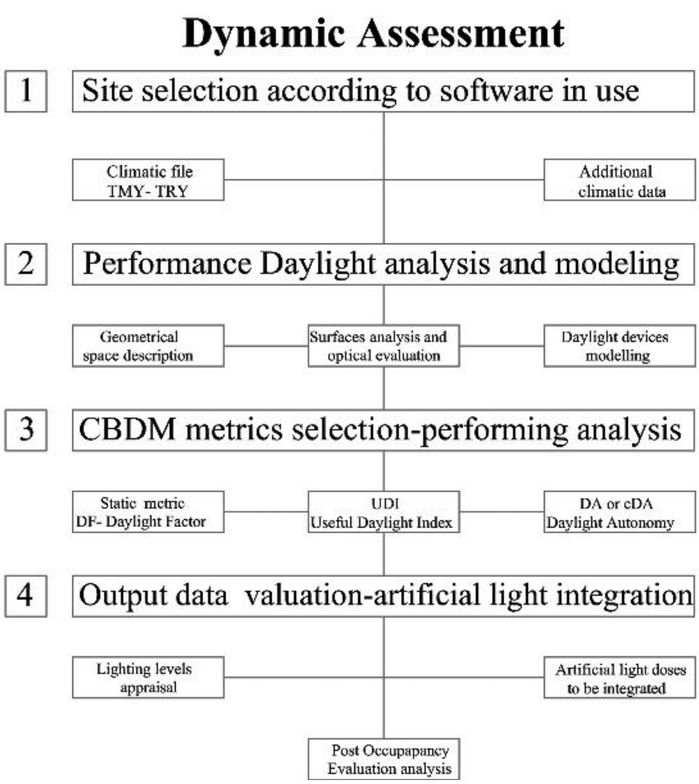


Figure 68: Analysis phases according to dynamic model.

Daylight Assessment according to the dynamic approach (Fig. 68) is differently characterised by a complex cascade process, which is divided into four phases, in which the flow of the project is carried out at separate times.

Specific analysis of geometric, physical and optical requirements is preceded by the choice of a climate file, which contains information relating to the average annual climate and the amount of light radiation available for the location in question.

The adoption of a cascade process requires a precise order of execution in the analysis itself, where each phase begins only when the previous one has been completed, making the flow of information highly controllable and turning it into a reliable assessment. If the strictly geometrical and defining phase of the model can be equated to the static method, the successive steps turn to new dynamic parameters that can also be used at the same time to arrange for a more comprehensive assessment in relation to the prevailing functions that take place in the space.

The geometrical and physical analysis of the space is thus supplemented by observation of precise hourly distributions in reference to pre-established limits, through identification of the areas most affected by excessive illumination and areas that are under-lit. In this case a choice is made from the dynamic parameters Useful Daylight Illuminance (UDI), Daylight Autonomy (DA) and continuous Daylight Autonomy (cDA) according to which is the most appropriate for the survey (phase 3). This stage can be followed by a further survey to collect additional information to correlate the presence of natural light with the subjective perception of the occupants (phase 4).

Examination of the level of perceived comfort usually relies on an assessment of the POE, *Post Occupancy Evaluation* type, which processes data on the level of comfort perceived by the occupants through the administration of standard questionnaires.

The inherent limitation in this phase of subjective analysis lies in the generic nature of the survey among users, who are interviewed in relation to general preferences without establishing a real correlation between the questions on the form, the actual areas of light distribution, and the relative position of the subject in the room.

A more correct approach to this type of survey must therefore relate the actual climatic and meteorological conditions and physical environment with a precise analysis of the geometry of the building, thus obtaining a unambiguous mapping of results over a complete year, data that give a whole picture to compare with the results from the tests.

Daylight Assessment according to the integrated dynamic approach shown in Fig. 69 instead, outlines a new paradigm, which includes in one single process, an assessment of the light distribution of the interior space and an analysis of users' preferences, in order to implement energy-saving strategies by reducing consumption for artificial lighting, cooling and heating.

For the first time, the integrated framework applied through this procedure combines the possibilities of the CBDM system on a large-scale, allowing a cascade reading on multiple levels, i.e. a vertical reading of steps consequential to one another, depending on the choice of reference parameter. The procedure that follows therefore collects in a single protocol a

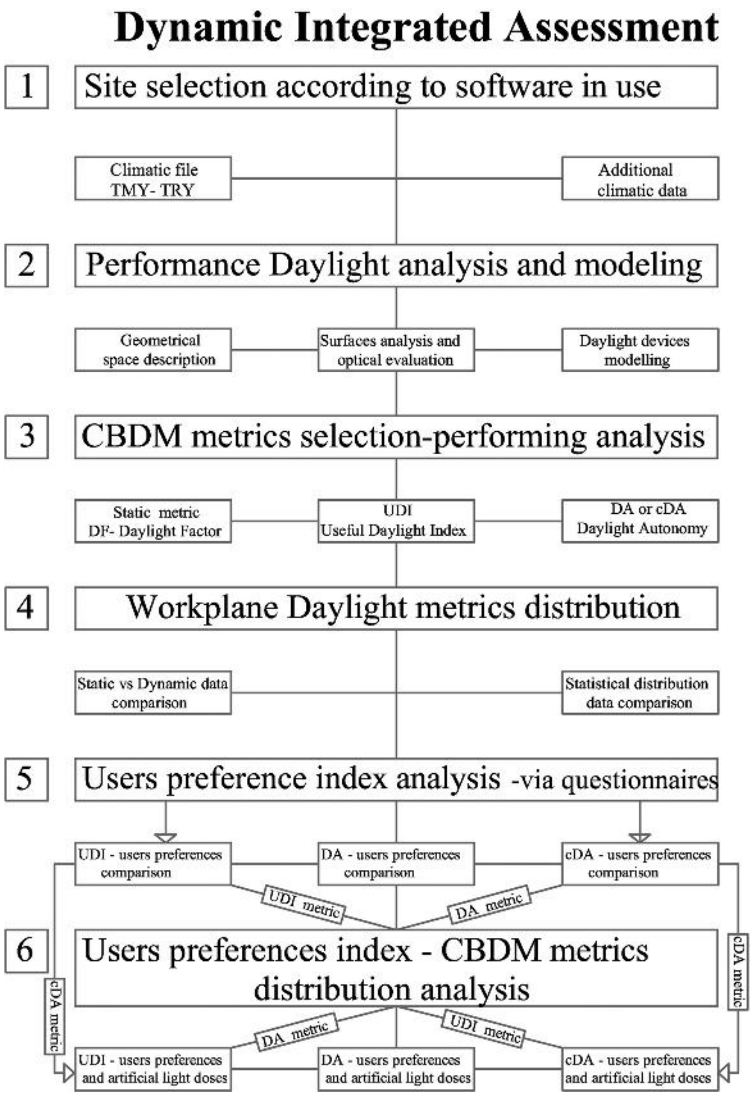


Figure 69: Analysis phases according to the dynamic integrated system.

simultaneous qualitative and quantitative reading, thanks to the use of the newly defined dynamic metrics.

As previously discussed, the potentialities expressed by the CBDM method are enhanced in this scheme by readings made on the basis of maps of light distribution, which can be made to order using the tests of users' preferences, creating a comprehensive picture of the actual lighting conditions, potentially harmful situations in terms of glare and local overheating, from which to derive targeted actions to reduce or increase the amount of variable light.

For the first time, it is possible to disregard any *in situ* measurements, which in this context appears simplistic and too tied to the specific measurement conditions, replaced instead by a direct survey of the preferences of the occupants, which in this way provides a qualitative assessment for the specific interior space.

The quantitative data, obtained from the distribution of light levels and the percentages of DA and UDI recommended, can be compared to qualitative data through a reading of the preferences expressed by the occupants themselves. The model of usage on which the qualitative survey is based can also be predicted, in the design or verification phases, to develop distribution and movement patterns, by modelling some possible configurations, simulating the individual amounts of direct control over diffusing, shielding or shading systems, upon which users can intervene.

The specific analysis, starting from step 4 (Fig. 69), may proceed either with a cascade flow, which provides a progressive reading of all the aggregated parameters, or on the basis of a single parameter, in relation to the selected unit of measure, crossing the different parameters.

Vice versa, from step 5 onwards, it is possible to proceed with an aggregate reading of all the dynamic parameters by grouping and comparing multiple units of measurement.

The method is thus based on the possibility of reading individual layers or aggregates of information, on luminous and geometrical bases, independently of each other, without excluding the possibility of re-associating the information obtained from each single phase, superimposing the output data on it.

From an operational point of view, it is possible to use different software packages that are interfaced in a precise manner, starting from *Daysim*, a freeware software, developed by the Lighting Group of the National Research Council Canada and Solar Building Design Group, at the Fraunhofer Institute for Solar Energy System, under the supervision of Christoph Reinhart, that can calculate illumination levels, thanks to local climate annual datasets and using the dynamic parameters.

On the basis of the information provided by the annual illumination profile and the Annual Light Exposure, *Daysim* can generate hourly distributions related to the usage patterns for both electrical loads and the variable amounts from shading devices. The annual quota of light calculated for a point in space corresponds to the sum of all the illuminance levels that affect a calculation point in space throughout the year and measured in lux per year. The importance of this type of parameter lies in the calculation method with which the data is obtained, since it considers the contribution of variable direct and indirect light, as well as that filtered through any screening devices.

These simulations must then be made system with other simulations to obtain additional information to complete the survey energy. Usually surveys of this type can be carried out using softwares like *TRNSYS*, *EnergyPlus*, *eQuest* and *Esp-r* which are able to collect the luminous results provided by the dynamic approach through simulations of thermal and electrical loads.

The final phase of the integrated dynamic survey is completed with a simultaneous reading of the results obtained from specific questionnaires, through the development of realistic lighting profiles, so-called Occupancy Profiles.

In the same way, *Ecotect* software can be used for this type of assessment and to display the results, with the limitation, however, of having to exclude multiple reflections from the calculation, as a result, underestimating the quota of indirect light

1.2 Quantitative analysis through simulation by software and the models in use. Methods, algorithms and interoperability of resources

Carrying out a cascade survey like the one proposed here requires the use of a complex network of software tools that ensure interoperability on multiple levels.

Daysim, created to operate based on climate, incorporates the new metrics of the CBDM dynamic system, basing its predictions of the annual availability of natural light on TMY files.

The initial stages of the assessment are the crucial moment for the simulation, passing first via a choice of the correct climate file, in order to be able to include data relating to geographic coordinates in the calculation, which are essential to describe the place where the building or the interior space under survey are located.

The essential starting point for a system of holistic assessment, which includes the steps shown in Fig. 69, must consequently be implemented through an effective collaboration between software, units of measurement and dynamic policy.

The contribution of the software that allow you to study the potential for energy savings is therefore linked to the expectations that they are able to provide regarding the actions of individual users, who are free to choose to move or stand in a particular area of the space, as well as being able to intervene manually or through automated mechanisms on the shading devices.

The quantitative analysis comes from a reading of the annual illumination profiles, from which to calculate the dynamic UDI, DA and cDA metrics, together with prediction of possible situations of irritating glare.

Through a parallel and simultaneous reading of this information it is possible to analyse and predict patterns of behaviour of the occupants, and to gauge interventions for the improvement of indoor comfort.

Recent years have been marked by a proliferation of numerous software packages that have enabled researchers to investigate more deeply relations of interdependence between the units of measurement, and profiles of light and thermal distribution, related to the movements of end users, while the global performance of naturally lit spaces still appear complex and difficult to implement for the moment. These complex assessments have mainly involved theoretical studies, however, and remain for this reason disjoined from architectural practice and especially distant from design applications.

The engineering community is reluctant to accept these tips, thereby opposing use of the integrated dynamic method.

Considerable technical limitations still close the road to a full validation of the system: From the lack of a user-friendly shared interface that allows designers, architects and engineers to learn rapidly and move easily among the simulations, to the long time required between calculation and graphic rendering, which makes the static approach preferable to the dynamic one, to the complexity inherent in the step preceding the simulation, make this type of analysis framework far from attractive, despite its obvious advantages [103].

From the eighties to the present day numerous software packages have been developed to perform joint analysis on the comfort of indoor confined interior spaces, paying attention to the luminous aspects.

In the last 10 years, the potential of these instruments has been greatly increased, and they can now offer a wide choice to sector professionals.

The reliability of the software has made it increasingly less common to use physical models that require, on the contrary, an enormous effort to recreate the physical and optical conditions of the interior space, in addition to a considerable amount of time and resources.

Some comparative assessments have shown quantitatively, and from an operational point of view, the advantages and limitations of the main commercially available software packages, such as *Radiance*, *Superlite*, *Lumen Micro* and *Lightscape*.

More recent surveys have instead developed more advanced versions of specific new software, distinguishing the precise differences in the values found among the different DF thresholds in a sample room, on which have been conducted simulations using *Desktop Radiance 2.0*, *Lightscape*, *Ecotect*, *Lumen Micro 7.5*, *Dialux 4.4* and *Ecotect 5.5*.

Additional considerations should be also reserved for the comparison between software simulations and data observable from simulations performed on small-scale models, in of real or simplified sky conditions [104].

The major contribution of this study lies also in the subsequent comparison between the results of different simulations carried out on a real model, bringing attention to a debate long open on the validity and reliability of the measurements, the comparability between illumination values and other parameters, using both small-scale models and in the presence of an artificial sky. From observation of the results of the software simulations it is possible to say that the most obvious limitation of the scope of the integrated dynamic assessment according to the proposed new approach derives, in large measure, from the difficulty of interpreting and properly using the data produced by computer simulation, the only tool possible to approach Daylight Assessment according to the new methodology.

1.3 Qualitative analysis through the subjective assessment component and POEs

Assessment of a qualitative type, which we usually rely on, can now be carried out by direct detection, using questionnaires of subjective assessment, whose precise purpose is to investigate the real perception of light, levels of luminance, contrast and any visual discomfort among occupants.

In agreement with Daylight Assessment according to the dynamic model, the tool most widely used consists of the assessment questionnaires known as POE, which measure the degree of satisfaction of end-users after staying for a given period of time within the interior space under survey.

The POE method therefore implies a general assessment concerning opinions that the subjects involved can express on the interior space, i.e. are arranged to represent the perceptions of users on the performance offered by luminous and shading systems in an interior space.

The POE tests differ in many aspects compared to conventional surveys and market research: in fact, they make use of direct surveys and observations with reference to an experience just ended on which the subject expresses an immediate judgement.

The advantages of the critical reading of the results of these subjective survey tools are more easily interpretable for large or public buildings, where the end-user stays for a long period. By means of the POE it is possible to understand the as yet unexploited potential of a building, increasing its receptive capacities and developing its different component, specifically, devices for daylighting, appliances for artificial light and systems for shielding or shading.

In the same way, the results obtained from these assessments can be used to improve the design of buildings or interior spaces that are designed from scratch, for the retrofit of existing interior spaces and for the transformation of others.

The critical reading of the results is facilitated by the fact that the questions in the questionnaire are compiled with the final goal in mind.

The preparation of the test usually takes place through three distinct phases: the initial phase of preparation of the questionnaire, where the goals are identified and the field of survey is split up; to follow the true fields of survey through the administration of the test to groups of users who can then add to the format of the questionnaire, their own impressions and reflections; finally, all the documentation is collected and compiled into a final report.

In the light of the system described, the traditional POE is used today to study the overall perception of a building and to assess the degree of comfort reached in the interior space, without distinguishing between the different aspects that contribute in defining the space, or the relations of interdependence between the technological, environmental and energy systems [105]. The standard questionnaires, all constructed in the same way, independent of the object and subject of the assessment, feature a scale of values from 1 to 7, from the lowest degree of satisfaction (1) to the highest level of appreciation (7).

The limit of these subjective assessments is the fact that the environmental parameters investigated are too interconnected, so much so that it is difficult to separate the individual quotas to relate them to strategies for precise interventions, even if directed to the improvement of only one aspect be it environmental, thermo hygrometric or luminous comfort.

Even though, in some cases, the result deduced from a reading of the results is exhaustive as regards the level of overall comfort reached, the results are difficult to compare never mind apply for specific strategies concerning individual technological systems.

In recent years, some of these limitations and inconsistencies have been partially remedied and the forms adapted to the needs of Daylight Assessment in a confined environment [106].

In this context, with the arranging of the integrated assessment framework, a specific questionnaire has been compiled exclusively to assess natural light and other luminous parameters to gauge the level of visual comfort achieved.

The reading of the questionnaire results will be much more comprehensive, the greater the degree of freedom left to the users: in this way, the so-called model of *adaptive comfort* is analysed, according to which subjects tend to adapt their preferences in relation to the prevailing conditions of the interior space they find themselves in.

The adaptive model introduces for the evaluation of visual and luminous comfort, specific algorithms of control and response, to improve the level of comfort, responding to the diverse needs of the occupants, even becoming an indispensable tool to implement strategies for energy-saving in buildings.

In the adaptive comfort model, the subject, consciously or unconsciously, plays an active role in the achievement of a condition of satisfaction with respect to the microclimate in which he or she is located. The same subject interacts in the process of individual adaptation, reducing his or her individual reactions to environmental stimuli, so that it is possible to distinguish two types of adaptation: physiological and behavioural.

2 Application of the new assessment protocol: dynamic simulation for a case study

The definition of the integrated dynamic analysis model requires, after fine-tuning, a precise verification of the feasibility and efficacy of the procedure thus defined.

To this end, it was chosen to conduct this verification on a case study that would allow the testing of each step in a large interior space, with a considerable influx of users, and where natural light plays a leading role to accomplish visual tasks.

The applicatory case verified concerned some classrooms at the Faculty of Engineering of the University of Parma.

These spaces demand a careful, well-gauged design both from an architectural point of view, as regards the technological choice of daylighting devices, and for the arranging of strategies to encourage the concentration and attention of those who sit in the classrooms.

Numerous studies have been carried out on school premises, through surveys and simulations for kindergarten, primary, and secondary schools, as well as universities [107].

The continued presence of students in classrooms and study rooms has made it possible to carry out accurate and reliable surveys on the dynamics that govern concentration and student productivity, in relation to the amount of natural light present, variations in distribution of the light, coming from daylighting devices, to develop strategies for energy-saving and improving indoor comfort.

From the preliminary analysis carried out in the case of the premises of the Faculty of Engineering (Fig. 70) the need emerged to define standard procedures that could integrate various design interventions and any recovery.

The objective of the survey was to deduce, starting from analysis of objective luminous parameters and assessing the degree of comfort associated with them, the overall degree of environmental acceptability of the interior spaces examined, starting from a direct comparison of measured data of a subjective nature (distribution of questionnaires) and an objective nature

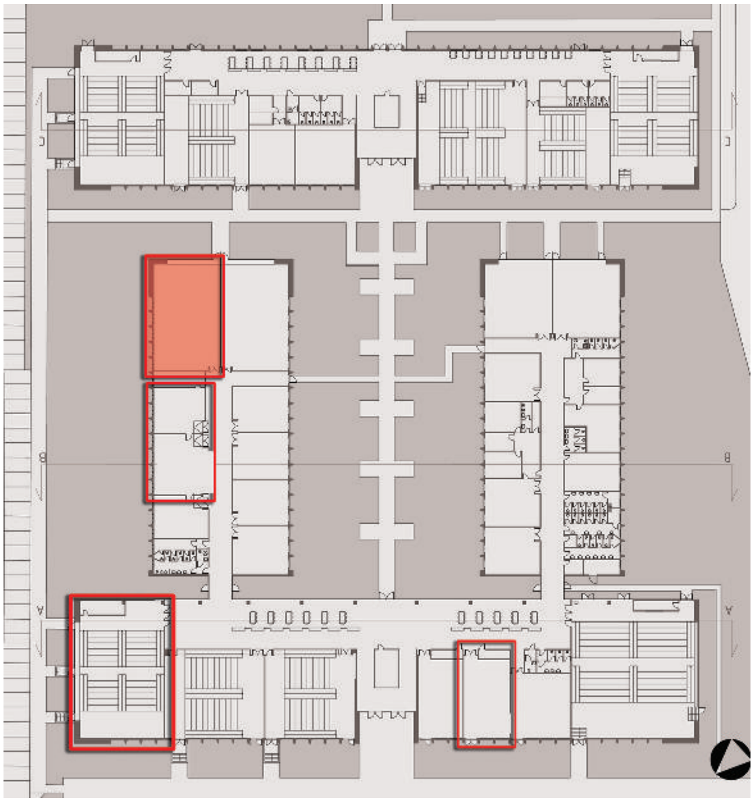


Figure 70: University of Parma, Faculty of Engineering, Classrooms plan.

(measurements and calculations according to the CBDM method), with the limits imposed by the regulations on luminous wellbeing in buildings intended for education.

The preliminary analysis phase was carried out by choosing from among the classrooms ones that exhibited distinct morphological and typological features and that housed different functions. By way of example, only one classroom is presented here, as indicated in Fig. 70.

This is a classroom designed for workshops and design, and is equipped with special tables that are not fixed, so that students can move freely among the workstations, in accordance with variable positions. For this reason, the simulation does not take into account the drawing tables, but considers a workplane that is located at a height of approximately 85 cm from the floor (Fig. 71).

The survey protocol initially envisaged a geometric survey of the classroom and the physical and optical characteristics of the finishing materials present inside. The survey served to find all relevant information relating to the interior space, to be inserted into a three-dimensional model produced by software. The simulation makes use of climate files specific to the locality in question, thereby incorporating prevailing climate data.

The next step is based instead on the choice of the parameter to be adopted and the limits within which to establish thresholds of analysis for the new dynamic-type unit of measurement. In this case it was considered interesting, in order to better understand the potential inherent in the

Figure 71: The classroom tested.

CBDM approach, for the sake of completeness to calculate also the static parameters, such as the DF and illuminance levels, and then compare these with the new dynamic metrics.

The static simulation was carried out thanks to *Ecotect* software, whose three-dimensional model was then imported in *Daysim* to calculate the dynamic parameters, such as DA, cDA and UDI, which were further considered in UDI fell-short, UDI achieved and UDI exceeded, in the intervals respectively of 100 lux, 100–2,000 lux and 2,000+ lux.

In the graphic representation with false colours, through the use of isolux lines it is possible to represent precise values according to the calculation grid used, set at the pre-determined height of the calculation plane.

To compare precisely the real illumination conditions at certain hourly thresholds, with findings from the questionnaires administered simultaneously, *Dialux* software was used, the only one that makes it possible to obtain mappings concerning the DF values and illumination levels for the date and locality concerned, so as to be able to compare quantitative data according to the static model, with those relating to the annual climate base of the dynamic model and, furthermore, with the aggregate results of qualitative surveys using questionnaires.

This is followed by a simultaneous reading of all the results obtained, using a comparison on the basis of the individual parameters UDI, DA and cDA, or by comparing individual opinions on single areas and sub-areas of the interior space, assuming as valid only one parameter at a time.

This method of reading is made possible by the very nature of the dynamic metrics: It is possible to acquire useful information assuming as valid only one dynamic parameter, e.g. UDI or DA, and aggregating the information that each of these provides with the values for the potential for energy savings, to meet pre-determined thresholds, considered acceptable or otherwise, and therefore responsible for attaining situations of visual comfort.

Then there is a simultaneous analysis of the reviews of preference and visual satisfaction obtainable from suitable questionnaires, after they have been grouped by sub-areas and separated according to visual assessment indices.

The final phase is the implementation of more unfavourable and irritating visual and luminous conditions, for which an intervention of mitigation is required.

Both through the graphic readout, which facilitates comparison of the entire layout of the room, considering the individual zones into which the room is divided, it is possible to define the areas that are effectively over- or under-lit, those at risk of glare, and those where there may be overheating or areas of generalised discomfort from a visual point of view.

By interpreting the distribution preferences of interviewees with respect to different areas of the interior space, it is possible to understand what lighting dynamics are preferred by users in relation to the prevalent visual task, providing strategies for illumination or shielding. Supported by quantitative data and maps showing the distribution of both brightness and users, the designer can now select devices for daylighting or for shading, specially calibrated for the diverse demands of the space.

2.1 Results of quantitative analysis of the static parameters and the new dynamic schemes

After completion of Phase 1 of the protocol, come Phases 2 and 3, as in Fig. 72. The results of the quantitative analysis phase were obtained by integrating several reprocessing steps, using two different software packages, *Ecotect* and *Dialux*. Numerical estimations performed with the software made it possible to evaluate the quotas due to direct radiation from the sun and the sky, starting from a study of the path of the sun, on a daily and annual basis, related to the geographic location in question, from the climate type file.

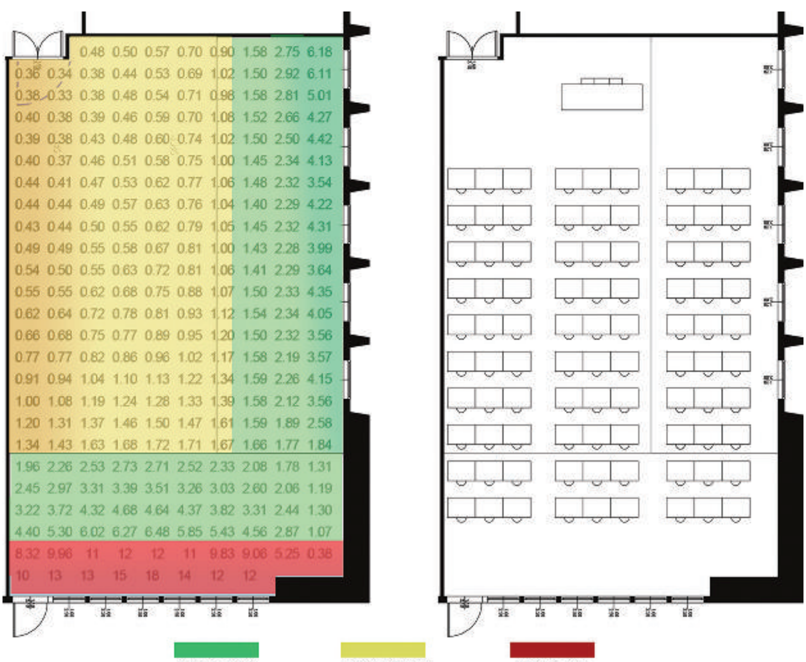


Figure 72: DF values distribution in the classroom.

The first simulations carried out used, as a sole term of analysis, the DF and subsequently Daylighting Levels, which are represented graphically through isolux lines. The assessment carried out for the design classroom of the Faculty of Engineering at the University of Parma highlighted the following output data, related to four significant dates during which the calculation was performed (Tables 14 to 17). As can be understood from the results concerning the DF parameter, the distribution of the percentage values is heavily inhomogeneous: in areas close to the fenestrated fronts DF values are around 20%, and then start to decline significantly, reaching

Table 14: Average illumination values E_m on the main calculation surfaces.

21st March at noon					
Surface areas	Average illumination			Reflection coefficient	Average luminance
	Direct	Indirect	Total		Cd/sqm
Useful surface	427	60	497	–	–
Calculation surface 1	419	79	48,338	–	–
Floor	481	69	560	20	36
Ceiling	0	96	96	70	21
Wall 1	13	138	152	50	24
Wall 2	622	148	770	50	123
Wall 3	12	87	99	50	16
Wall 4	82	95	176	50	28
Wall 5	34	88	122	50	19
Wall 6	167	62	228	50	36
Wall 7	69	54	123	50	20
Wall 8	48	47	95	50	15
Wall 9	173	79	252	50	40

Table 15: Average illumination values E_m on the main calculation surfaces.

21st June at noon					
Surface areas	Average illumination			Reflection coefficient	Average luminance
	Direct	Indirect	Total		Cd/sqm
Useful surface	323	53	376	–	–
Calculation surface 1	317	52	369	–	–
Floor	364	60	424	20	27
Ceiling	0	72	72	70	16
Wall 1	10	105	115	50	18
Wall 2	470	112	583	50	93
Wall 3	9.01	66	75	50	12
Wall 4	62	72	134	50	21
Wall 5	26	66	134	50	15
Wall 6	126	47	173	50	28
Wall 7	52	41	93	50	15
Wall 8	37	35	72	50	11
Wall 9	131	60	190	50	30

Table 16: Average illumination values E_m on the main calculation surfaces.

21st September at noon					
Surface areas	Average illumination			Reflection coefficient	Average luminance
	Direct	Indirect	Total		Cd/sqm
Useful surface	427	70	497	–	–
Calculation surface 1	419	69	488	–	–
Floor	481	79	560	20	36
Ceiling	0	96	96	70	21
Wall 1	13	138	152	50	24
Wall 2	622	148	770	50	123
Wall 3	12	87	99	50	16
Wall 4	82	95	176	50	28
Wall 5	34	88	122	50	19
Wall 6	167	62	228	50	36
Wall 7	69	54	123	50	20
Wall 8	48	47	95	50	15
Wall 9	173	79	252	50	40

Table 17: Average illumination values E_m on the main calculation surfaces.

21st December at noon					
Surface areas	Average illumination			Reflection coefficient	Average luminance
	Direct	Indirect	Total		Cd/sqm
Useful surface	426	70	496	–	–
Calculation surface 1	418	69	487	–	–
Floor	479	79	558	20	36
Ceiling	0	95	95	70	21
Wall 1	13	138	151	50	24
Wall 2	620	148	768	50	122
Wall 3	12	87	99	50	16
Wall 4	82	94	176	50	28
Wall 5	34	87	121	50	19
Wall 6	166	62	228	50	36
Wall 7	69	54	122	50	19
Wall 8	48	47	95	50	15
Wall 9	172	79	251	50	40

an optimal value in a restricted area, located about two meters from the windows, until ending around an almost homogeneous but insufficient value of 1–2%.

A similar pattern of light distribution is identifiable from a reading of the average DF values, represented in plan (Fig. 72), while precise values on a workplane placed about 85 cm above the floor, are legible in average amounts of illumination detected in the 4 time thresholds selected, as well as from *Dialux* results (Tables 14 to 17), i.e. for the days of 21 March, 21 June, 21 September and 21 December at noon.

Also in this case, it is clear that the interior space is subject to widespread over-lighting, particularly in areas adjacent to the two fenestrated fronts, while more distant areas are heavily under-lit.

In this first phase of analysis there is a clear tendency to over-simplify the output data obtained through the static approach.

The only possibility to precisely evaluate average illuminances (E_m) is obtained by processing maps of the distributions instantaneous presences that are not representative as compared to the actual values, because they consider as a basic condition for the calculation a simplified situation of CIE standard overcast sky. The measurement of the mean values of DF also offers no type of additional information useful to intervene in individual cases, in the case of screening or shading solutions, due to the well-known shortcomings of the parameter. Having demonstrated the inadequacy of the data processed, the new metrics of the CBDM method were employed, such as the DA, cDA UDI and the three sub-parameters UDI exceeded, UDI fell-short and UDI achieved, according to step 3 of the protocol.

The three-dimensional model previously made by *Ecotect* must now be imported into *Daysim*, which is able to compute, from WDF, *Weather Data Files*, for the chosen location, the actual weather conditions on an annual basis. *Daysim* takes into account the quota of direct and reflected light from the sky and that coming directly from the sun, thanks to the calculation of *ambient bounces*, i.e. the bounces the light is subjected to in the calculation of indirect lighting.

The advantage inherent in the calculation procedure derives from the fact that it is possible at the same time to take into account the interaction of the light that filters from the outside towards the inside, thanks to the DCs that combine these data with the values of insolation and direct and diffused radiation.

The strong limitation connected to the use of software such as *Daysim* lies mainly in the difficulty of reading the output data.

In fact, these are raw data expressed in complex tables (Table 18), in which each row shows the data collected in the room in the vicinity of virtual sensors that the calculation uses.

The table shows the numerical values for all luminous parameters, both static and dynamic, calculated for each point in space.

Table 18: Excerpt of output data as supplied by Daysim software.

x	y	z	DF %	DA %	CDA %	DA_{max}%	UDI_{100} %	$UDI_{100–2,000}$ %	$UDI_{2,000}$%	DSP
1.23	5.88	0.09	14.8	93	96	16	3	35	62	62
1.29	5.88	0.09	10.8	91	95	11	3	50	47	81
1.35	5.88	0.09	7.8	88	94	6	3	65	32	87
1.40	5.88	0.09	5.3	83	92	3	4	76	21	86
1.46	5.88	0.09	3.6	75	88	2	5	82	14	79
1.51	5.88	0.09	2.5	66	84	2	6	85	9	71
1.57	5.88	0.09	2.2	62	82	2	7	87	5	58
1.57	5.88	0.09	1.8	53	78	2	8	87	2	54
1.63	5.88	0.09	1.6	49	76	0	9	89	1	52

The simulation of the sample classroom shows an average DF value of more than 2% on 45% of the calculation area.

As regards analysis of DA (Fig. 73) it can be seen from an examination of the dedicated column (Table 18) that the DA values change from a minimum of 0% to 96%, i.e. there are points in which, over the course of the year, the prescribed presence of 500 lux is never reached, while at other points in space the limit is reached in 96% of cases.

As regards analysis of *Useful Daylight Illuminance*, values are grouped according to three sub-parameters: UDI < 100, recorded in about 51% of the area, while UDI 100–2,000 is almost never

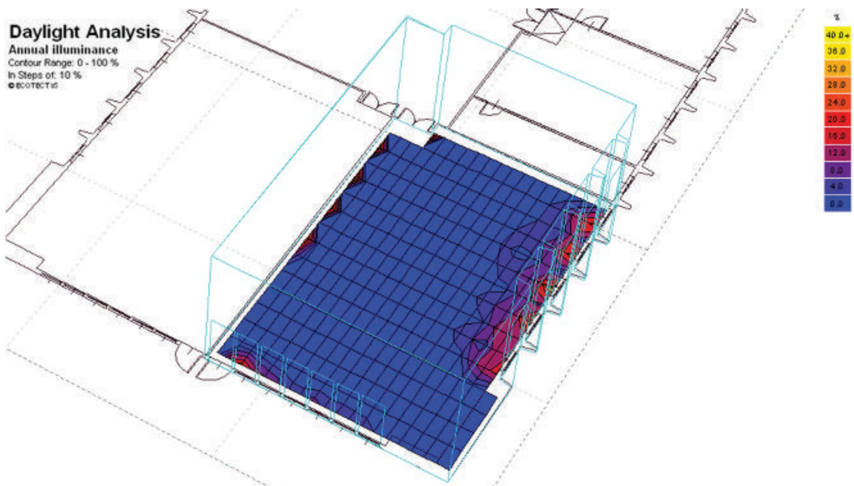


Figure 73: DA values.

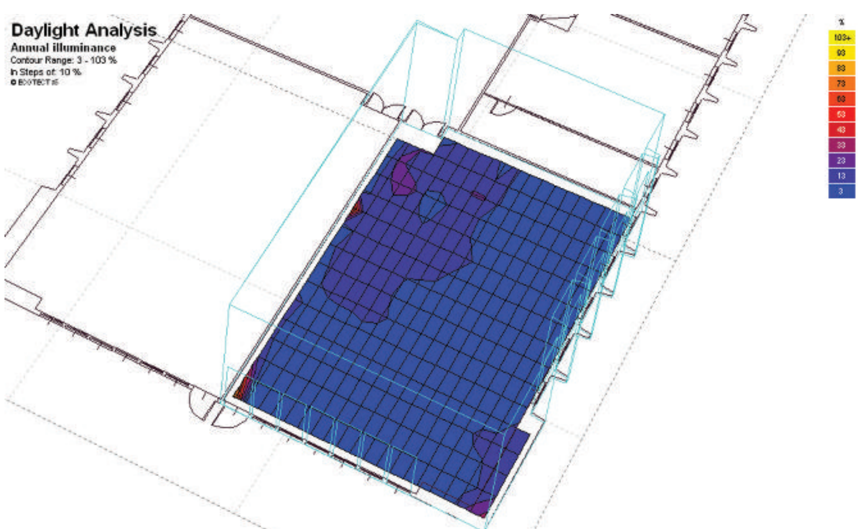


Figure 74: UDI 100 values.

reached in the room (0%), and finally UDI > 2,000 is found in 49% of the points, that is to say, in their virtual sensors (Figs. 74 to 76).

This clearly shows that, given the environment of the workplace from Monday to Friday, from 9 am to about 6 pm, with three breaks lasting about half an hour, over the course of the year the room has a deeply inhomogeneous pattern of light distribution, with some regions heavily over-lit, with the likelihood of overheating and irritating glare, while the other half of the room does not receive enough natural light.

This shows that, despite the DF value for 45% of the space, with a percentage taken that seemingly reveals a proper quota of natural light, the dynamic analysis totally refutes the static one.

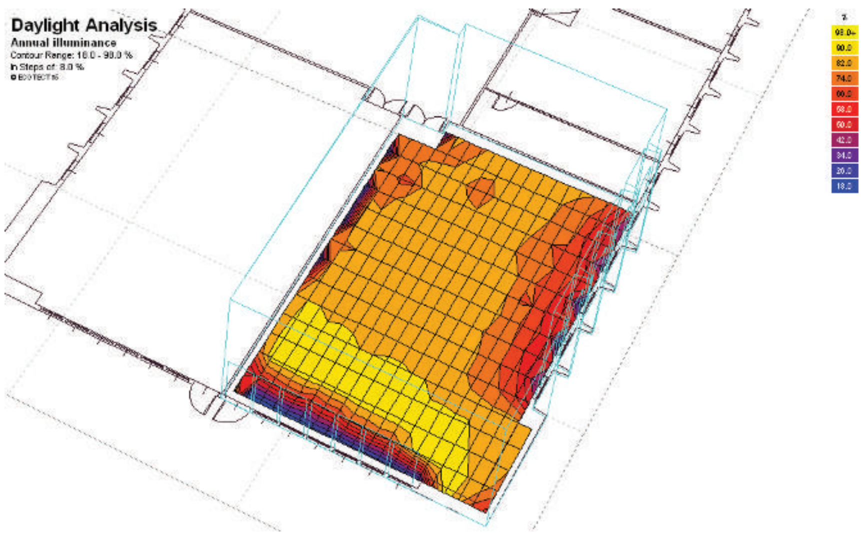


Figure 75: UDI 100–2,000 values.

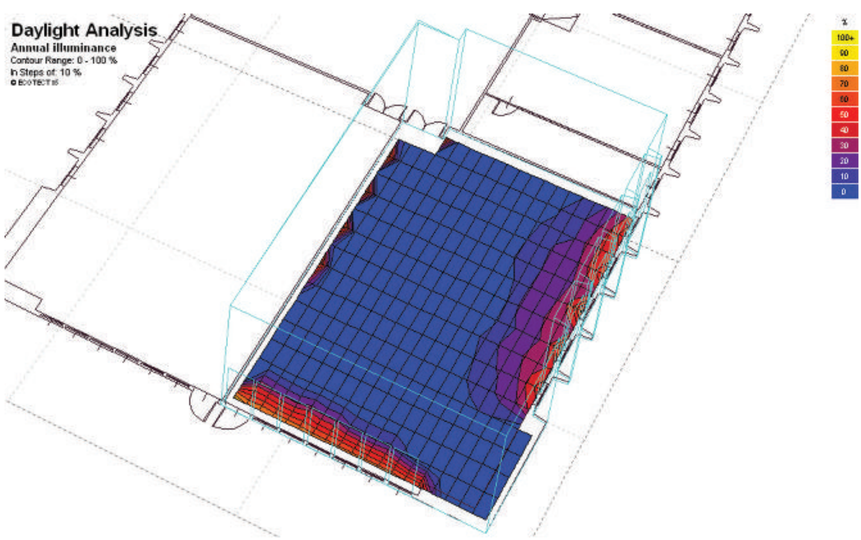


Figure 76: UDI 2,000 values.

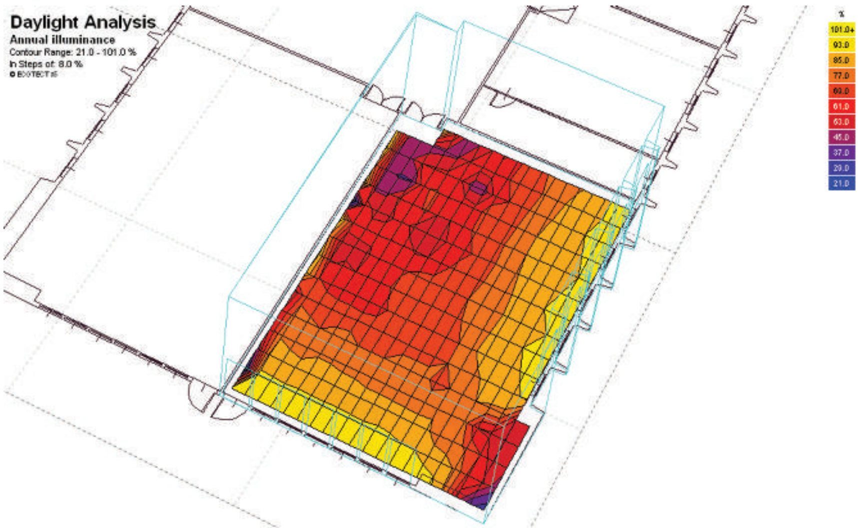


Figure 77: cDA values.

Finally the last dynamic parameter to be evaluated is the *continuous Daylight Autonomy*, together with the DA_{max}.

In this respect, it should be noted that 88% of the virtual sensors recorded cDA values higher than 60% (Fig. 77), while 19% of the sensors detect a DA_{max} above 5% (Fig. 78).

In other words, this means that, in accordance with the provisions of the cDA definition, partial credits can be given to areas with a cDA above the pre-determined limit of 500 lux, as in this case, in which 88% of the points in space exceed the threshold of 500 lux by about 60%.

Similarly, having set 500 lux as a maximum limit of illumination, the DA_{max} shows that 19% of the sensors exceed the limit of 500 lux with an average increase of 5%.

Finally, on the basis of the average occupation time considered for the simulation, the programme stipulates that the amount of electricity required satisfying the quota of natural light in the annual time band considered is approximately 2.9 kWh per unit area.

This hypothetical value refers to the use of electricity in an identical environment to the one considered, in the event that it is occupied by two types of different users: on the one hand, it is assumed that users have the chance to adjust the intensity of light on the basis of the external light conditions, being able to act in the same way on any internal or external shading devices; the second hypothesis takes into account users who use only artificial lighting, regardless of the external lighting conditions for the entire duration of the day, in the presence of shading devices that are always activated.

The aggregate read of these complexes parameters must necessarily find an easy-to-read graphic illustration that makes the dynamic analysis easily comparable with the previous static analysis. To this end, it is necessary to import, through a reverse process, the numerical data from *Daysim* to *Ecotect*. Some graphic representations of three-dimensional simulations are given on the following pages.

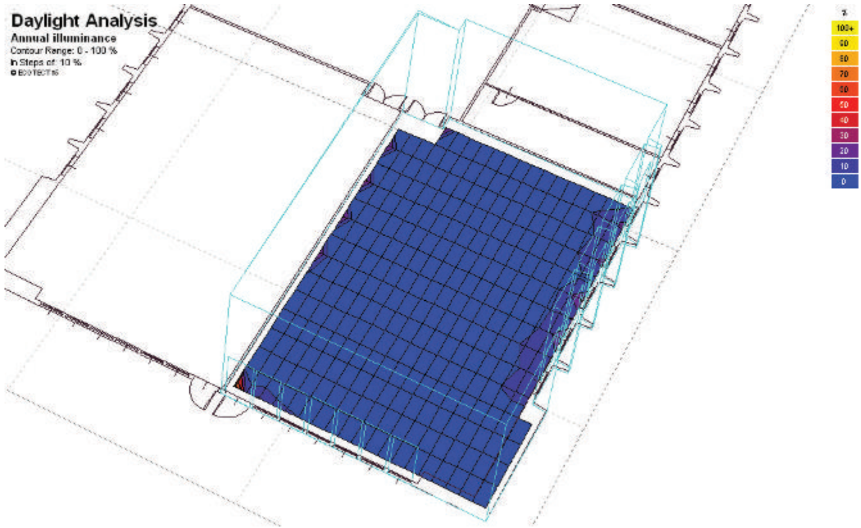


Figure 78: DA_{max500} values.

Despite the ease of representing on the groundplan colours that correspond to the different levels of DA (Fig. 78), examination of the individual cells that the surface of calculation is divided into remains rather laborious.

As regards the colour coding, the blue areas represent areas where the pre-set illumination target of 500 lux was not reached. This means, not so much that the hatched area was not illuminated by sunlight, but that the quota of daylight was insufficient to accomplish the visual task.

Gradually the colours of the graphic scale shift towards yellow to indicate illuminance levels approaching those pre-set. The percentage value associated with the colour of the cell indicates the percentage of time during which it reaches the set point fixed, thanks only to the amount of natural light and considering the hours of actual occupancy of the room during the year. It is usual to consider a percentage of autonomy of natural light equal to 40–60% as a condition of optimal illumination.

It is also to be considered that cells affected by a percentage greater than 70% are often subject to dazzling phenomena and overheating, in the event that solar control glass or systems of external shading have not been arranged.

The colour reproduction for the distribution of DA_{max} (Fig. 78), used to analyse the areas affected by an excessive presence of light during the hours of calculation, indicates in an indirect manner the presence of zones of glare. In fact, this parameter shows areas subject to direct radiation from the source, in this case the red and yellow cells will be, with great probability, over-lit. The particular orientation of the interior space and the arrangement of the windows mean that in a restricted area of the classroom, the windows should be screened for about 10% of the year, to prevent the zone becoming unusable.

Bearing in mind that the term DA_{max500} indicates the attainment of an illuminance equal to 10 times higher than that pre-set, it therefore highlights an annual percentage with illumination greater than 5,000 lux.

For the sake of completeness, the cDA parameter was also calculated: among the units of a dynamic origin the latter can be defined as the most appropriate for analysis of spaces for teaching, since this came precisely from studies by Rogers on some school classes. Unlike the data supplied by the DA, it confers partial credits also to time intervals during which the illumination point is below the threshold level.

Unlike the previous graphic representations, the cells that represent the distribution of cDA (Fig. 77) are more easily read and interpreted. The yellow cells have obtained a credit, in other words they indicate the points at which it is possible to reach 500 lux for 100% of the time of calculation; using the cDA it is not, however, possible to recognise areas excessively illuminated, i.e. 500 lux above the set point.

From a detailed reading of the parameter it can be observed that, up to about one third of the depth of the room, there are partial cDA credits (80%), represented by the orange areas.

For the areas in which the partial credits are less than 90%, a designer who uses the cDA tool has a precise indicator that shows, cell by cell and potentially for each point in space, the quota of missing artificial light alongside the partial credit to reach 500 lux. This makes it possible to intervene with a lighting design targeted to the real needs of the space and to install diversified equipment with different power levels, without risking to unnecessarily exceed the illuminance levels really needed.

Other considerations may be deduced from a reading of the graphic representations of the values of UDI and the sub-parameters UDI exceeded, UDI achieved and UDI fell-short (Figs. 74 to 76). The UDI is the most useful parameter to identify most of the times of the year when the levels of natural light are considered *useful*, i.e. sufficient to accomplish the visual task.

UDI fell-short regards areas with an average illumination lower than 100 lux where the use of artificial light is essential, while UDI exceeded regards the percentage of areas affected by an average illumination over 2,000 lux, around which precise dazzling phenomena are likely to occur.

The main purpose in identifying this threshold is to be able to determine when an excess of daylight can generate conditions of visual discomfort and heat. Finally, we consider the percentage time when illumination lies between 100 and 2,000 lux, i.e. UDI achieved.

From illustrations in false colours relating to the different UDI, it can be deduced that the area near the door, that is to say, that most distant from both fenestrated fronts, has a 13% of possibility of being under-lit until reaching a point where the percentage increases to 26%.

Despite the average illumination always being higher than 100 lux, throughout the course of the period in question, it should be understood that this does not ensure an optimum condition from an illumination point of view.

The distribution of illumination levels that fall within the range considered useful, i.e. between 100 and 2,000 lux (Fig. 75), makes it possible to appreciate the cells, or sub-areas, where artificial light is not needed.

These percentage values facilitate reading and thanks to these we can say that the central part of the classroom can be illuminated using only natural light. On the other hand, this value makes it difficult to understand the real light situation, thus it is preferable to use the information provided by the cDA and DA_{max500} parameters.

Values that exceed the threshold value of 2,000 lux are represented through the parameter $UDI_{2,000}$ or UDI exceeded, which identifies in the space how many and which areas are over-lit (Fig. 79).

For about a quarter of the depth of the room towards the eastern front, can be observed areas progressively affected for 50% of the time by excessive illumination, which wanes towards the centre of the room. On the southern front, also because of the presence of a narrow passage between the building and the obstacle in front of it, the distribution of illumination is homogeneous.

Ultimately, also precise values can be analysed for each point in space, in relation to the parameter DSP – *Daylight Saturation Percentage*.

The DSP changes the values of the UDI parameter, increasing the limit values in the range between 430 and 4,300 lux.

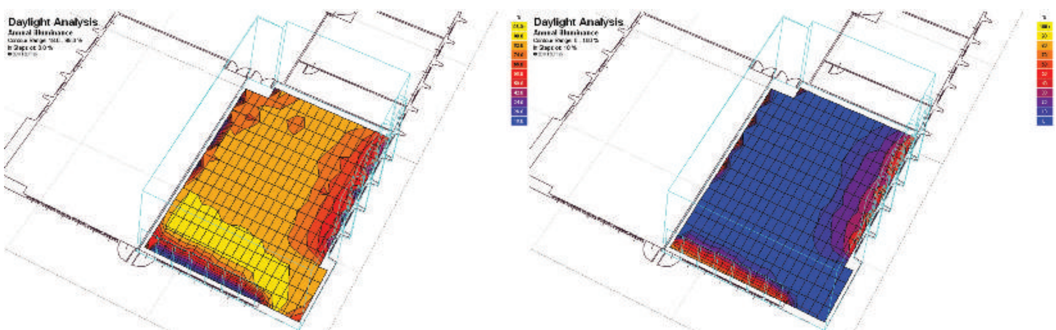


Figure 79: UDI values comparison.

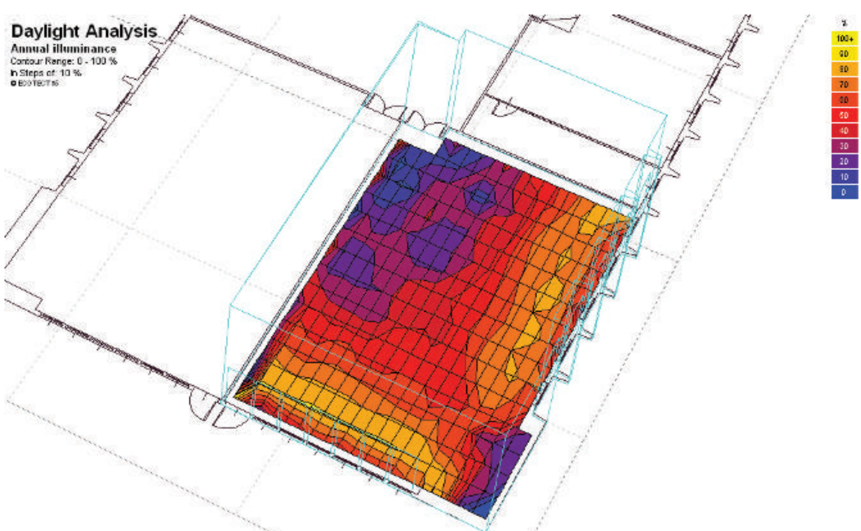


Figure 80: DSP values.

The graphic representation of Fig. 80, obtainable from a numeric computation, indicates that for at least 50% of the time, the pre-set values are achieved. In this case, a less homogeneous distribution is evident compared to previous assessments, but at the same time, the areas where there are percentages of high DSP are more extensive as a result of enlargement of the range of useful illumination and the raising of the minimum threshold.

2.2 Results of qualitative analysis of visual comfort through subjective assessments

This phase of the qualitative survey, in accordance with step 5 of the protocol (Fig. 69), includes, at this point, a comparative reading of the luminous data previously acquired and information on usership distribution obtained from a critical reading of questionnaires.

To analyse the case study specific questionnaires were drawn up in order to optimise the aggregate read of the individual preferences of the subjects, with regard to their stay in the classroom and, in particular, external conditions.

At the time of administering the questionnaires, tests were simultaneously performed to study the main thermal, hygrometric and luminous parameters in the absence of artificial light.

The questionnaire suitably adapted for the purpose of the survey consisted of two distinct sections, one on the sensorial perception of each individual, and one on the so-called 'emotional quality of places'.

Based on ASHRAE 55/1992, in accordance with ISO 7730/1994, and referring to national technical standards requirements on luminous wellbeing, the anonymous test aimed to investigate the differences between the situations perceived by users in their immediate surroundings compared to the results of numerical simulation.

The first part of the questionnaire was drawn up on indications of the UNI EN ISO 10551, with some useful additions to understand subjects' degree of visual satisfaction.

Among the questions was a reference to the possibility of occupants being able to directly control the heating and lighting of their surroundings: from the scores obtained it was possible to infer the level of satisfaction, and, as a result, assess corrective or mitigating actions to influence users' future behaviour.

In order to complete the survey from the point of view of the perception of the individual of the thermal and visual environment, the second part of the questionnaire focussed on the so-called *emotional quality of places*, something able to highlight a statistically non-indicative relationship, although useful to the survey, in assessing the quality of the architectural, social and functional aspects of the environments analysed [108].

The purpose of this complex survey is therefore to provide the technician with tools not only for the environment and lighting fixtures, but also a likely pattern of distribution of the subjects inside the room, on the basis of a sample of users expressing a subjective estimate on their level of comfort in line with the model of adaptive comfort.

The research, hitherto carried out on a small number of interior spaces for teaching, was a first attempt to combine traditional quantitative data with a review of the individual preferences that guide users' choices, integrating a cognitive-emotional assessment with a regular environmental analysis.

Below is the model of the questionnaire, developed for the specific requirements to evaluate each classroom.

This anonymous test includes a part on the demographics of the subject, as well as a graphic part in which subjects have to indicate their position at the time of compilation on a simplified plan of the room.

The latter proved extremely important to be able to provide a differentiated reading for certain areas of the classrooms, aggregating the results in relation to the position the subject occupied.

The second part of the questionnaire is instead devoted to an assessment of the perception of 'emotional quality', using a different scale from the one usually used in POEs, elaborated through assessment of 48 adjectives referring to the possible range of emotions provoked by the interior space on the mood of the occupants.

The questionnaire, adapted from the original model in English, contains a list of adjectives that can be divided into four subgroups, relaxing vs. stressful, pleasant vs. unpleasant, exciting vs. depressing, stimulating vs. boring, with a score from 1, *do not agree at all* to 5, *agree totally*.

The final analysis of the results from this second part gave results on different classrooms and different subjects in the classroom taken as a representative example.

From the results, the main quality in describing the classroom is strongly negative more than positive: the highest score was in fact attributed to the adjective *soporific*.

The comparative reading of the pairs of adjectives leads to the conclusion that even the adjective *stimulating*, the opposite of *soporific* achieved a higher average, inducing the thought that the environment is perceived more in the direction of the adjective *soporific* rather than *stimulating,* without a strong connotation towards one or the other, as can be read in the aggregate outcomes in Table 19.

With respect to the reading the other two polarities of adjectives, *relaxing* vs. *stressful* and *exciting* vs. *depressing*, the higher scores were recorded for 'stressful' and 'exciting', as if the dynamism

Table 19: Results of the questionnaire on the emotional quality of the places.

Positive qualities	Average of the values	Negative qualities	Average of the values
Relaxing	1.14	Stressful	2.4
Exciting	2.16	Depressing	1.5
Stimulating	2.66	Soporific	2.81
Total positives	5.96	Total negatives	6.71

and movement which were perceived in the classroom as prevalent sensations were instead identified as phenomena of disturbance and agitation by the students.

The administration of the questionnaire and the instrumental surveys began after a time interval of about 30 minutes, to allow the occupants to adapt to the existing climatic conditions.

On the basis of this information, the aggregate read of data obtained for each classroom surveyed was combined to obtain some significant parameters referring to three indices for specific questions in the survey (Table 20).

In order to better understand significant data for the final goal of the survey, the questions followed three indicators to assess the quality of the lighting:

- An *Index of Dissatisfaction with the lighting* (%), assessed as the proportion of subjects who responded to the questions: The lighting is too intense for the tasks that I have to perform; the lighting is too low for the use I require in this environment; overall, the lighting is comfortable;

- An *Index of Discomfort due to the lighting* (%), assessed as the proportion of subjects who responded to the questions: the lighting is poorly distributed; the lighting creates shadows; reflections from the windows hinder my work; direct glare from the windows hinders my work; direct sunlight hinders my work; the flickering of the artificial light hinders my work; comfortable environmental conditions allow me to learn in an efficient manner;

- An *Index of Lighting preference* (%), assessed as the proportion of subjects who responded to the questions: I can change the conditions of the environment in which I find myself; other people control the conditions of the environment in which I find myself; I have a certain degree of control over the lighting; being able to modify the conditions of the environment in which I find myself makes me feel better.

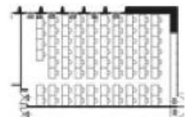
The preferences expressed by the interviewees show above all a strong variability in the results, as can be deduced from the graphic representation on the plan of the classroom.

In the classroom taken as a sample for the purpose of the survey, as well as in other classrooms part of an overall assessment, the questionnaires were administered to students of different ages in such a way as to cover a wide range of interviewees.

Although the results from the experimental campaign of measurements detected some areas affected by over illumination, such as to present the risk of glare for a large part of the year, many of the interviewees stated a discrete appreciation for these levels of illumination, without complaining of any kind of discomfort. Above all, the results of the experimental surveys demonstrated strong discrepancies with respect to the experimental values calculated by the software, as well as in the subjective preferences of the sample of occupants interviewed.

The results from the questionnaires were then aggregated in the three indices of *Dissatisfaction with the Lighting*, *Discomfort due to the Lighting* and *Lighting Preference*, each of which was further investigated in relation to the three areas in which the classroom was divided virtually (Fronts 1, 2 and Interior Wall), to allow easier reading of the percentage values with respect to the position of each occupant with respect to the three areas.

Table 20: Questionnaire on the thermal and luminous quality of the classroom.

Demographic data of the subject					
Age:					
Sex:			M		F
Have you taken caffeine-containing beverages and/or protein in the last hour?			S		N
Indicate the position you occupy in the classroom at this moment: 					
Please indicate with a cross how much you agree with each statement, from 1 (strongly agree) to 5 (strongly disagree).					
The classroom in which you are:					
Is well-ventilated	1	2	3	4	5
Is aesthetically pleasing	1	2	3	4	5
In the classroom you are in:					
It is cold	1	2	3	4	5
I have been able to choose where to sit	1	2	3	4	5
It is pleasant to stay there	1	2	3	4	5
The temperature is comfortable	1	2	3	4	5
The air is cool and pleasant	1	2	3	4	5
I can change the conditions of the environment where I am	1	2	3	4	5
I can feel irritating air currents	1	2	3	4	5
The air I am breathing is dry	1	2	3	4	5
I feel discomfort in the respiratory tract	1	2	3	4	5
Other people control the environmental conditions of the classroom.	1	2	3	4	5
Comfortable environmental conditions allow me to learn efficiently	1	2	3	4	5
Ability to change conditions around me makes you feel better	1	2	3	4	5
I have a certain degree of control over the lighting	1	2	3	4	5
My achievements in studying depend entirely on me	1	2	3	4	5
Overall, the lighting is comfortable	1	2	3	4	5
The lighting is too intense for the tasks I have to do	1	2	3	4	5
The lighting is too low for the tasks I have to do	1	2	3	4	5
The lighting is poorly distributed	1	2	3	4	5
The lighting creates shadows	1	2	3	4	5
Reflections from the windows hinder my work	1	2	3	4	5
Direct glare from the windows hinders my work	1	2	3	4	5
Direct sunlight hinders my work	1	2	3	4	5
The view outside is pleasant	1	2	3	4	5
The sunlight entering at this moment is pleasant	1	2	3	4	5
The sunlight distracts me	1	2	3	4	5
The flickering of the artificial light hinders my work	1	2	3	4	5
The flickering of the natural light obstructs my view of the whiteboard	1	2	3	4	5
How satisfied are you with the classroom you are in from a thermal point of view?	1	2	3	4	5
How satisfied are you with the classroom you are in from a lighting point of view?	1	2	3	4	5
How happy are you with the classroom you are in compared to the other environments of the faculty of engineering and architecture?	1	2	3	4	5
How satisfied are you with the spaces for teaching in this building?	1	2	3	4	5

On the Index of Dissatisfaction with the lighting (Table 21), referring to the aggregate values of the questions about the sensation perceived by the occupants in respect of illumination levels, to the possible presence of irritating dazzling phenomena, irritating reflections and other manifestations of over- or under-illumination, it can be deduced that the majority of the interior space is characterised by poorly lit areas.

Only a small number of interviewees, seated in the vicinity of the two fenestrated fronts expressed discomfort due to the presence of an excessive amount of incoming light (7% and 12%).

This result, if on the one hand it has to be assessed as the outcome of a questionnaire still needing to be perfected, on the other it does show strong discrepancies between what the instruments measured and what the occupants perceived.

Table 21: Results related to the Index of Dissatisfaction with the lighting.

Quality of the lighting	Fenestrated façade 1	Fenestrated façade 2	Inner wall
Excessive	7%	12%	12%
Bearable	31%	20%	20%
Agreeable	27%	15%	15%
Insufficient	31%	40%	40%
Almost absent	4%	13%	13%

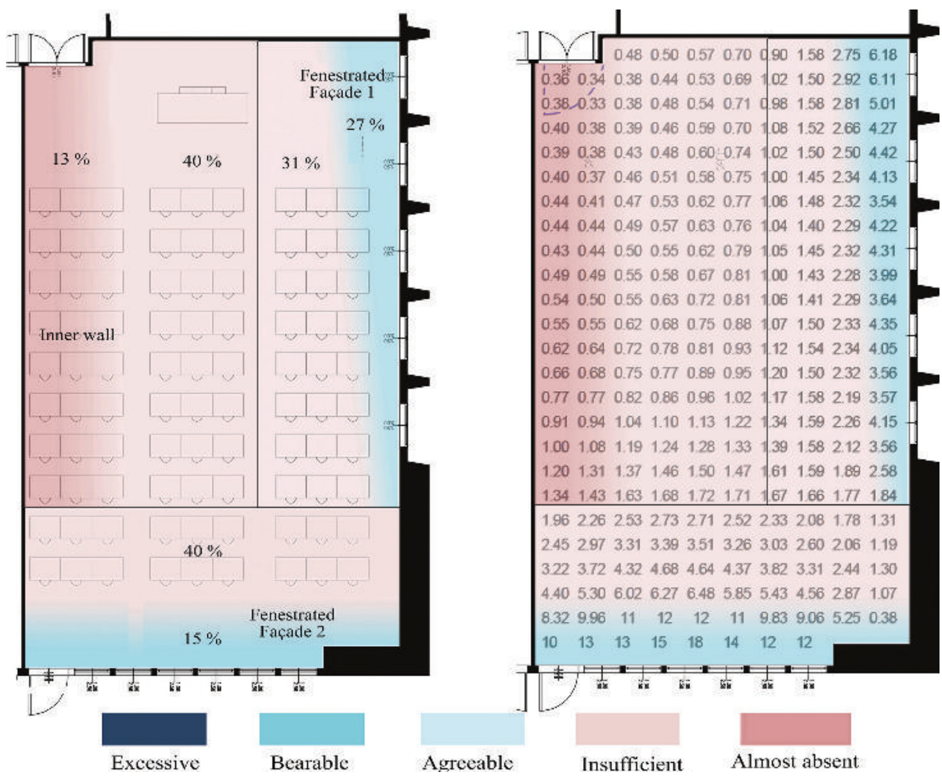


Figure 81: Index of Dissatisfaction with the lighting and DF values distribution.

It is immediately evident, despite the absence of sources of direct light, that for the wall opposite the fenestrated front, where DF values are equal to 0.5% (Fig. 72) a small share of interviewees perceived excessive lighting (20% and 12%), while the values of dissatisfaction with the lighting (Fig. 81) show general appreciation from those sitting in the vicinity of the windows.

In the same way, the close proximity of some subjects to Front 2 where the percentage of DF medium is fairly high (12–18%) did not cause discomfort among the interviewees, expressing instead favourable opinions, declaring an absence of discomfort despite a high value of illumination, from 15% to 20%, i.e. appreciable. This discrepancy is made evident by the plans in Fig. 81, in which are shown the results of the Index of Dissatisfaction with the lighting in the vicinity of the three areas, successively compared with the corresponding DF values calculated.

Table 22: Results related to the Index of Discomfort due to the lighting.

Quality of the lighting	Fenestrated façade 1	Fenestrated façade 2	Inner wall
Optimal	8%	6%	15%
Pleasant	48%	60%	43%
Agreeable	19%	17%	14%
Irritating	4%	13%	21%
Unbearable	21%	4%	7%

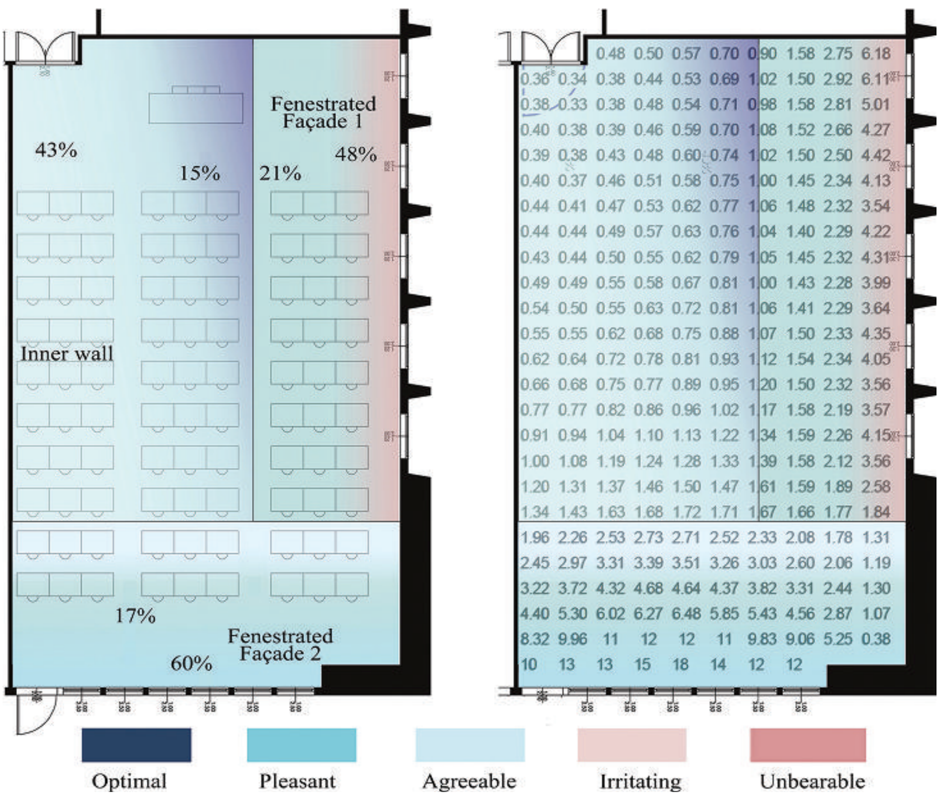


Figure 82: Index of Discomfort with the lighting and DF values.

Aggregated values relating to visual discomfort (Table 22) are pointed up by a general propensity of the subjects to express positive opinions, assessing the natural lighting in the vicinity of Front 1 and Front 2 pleasant or appreciable (in blue), both in the areas immediately adjacent to the windows where the DF exceeds the recommended threshold of 3%, and in the remoter areas, where the lighting is virtually absent, as can be seen in Fig. 82.

A small percentage of votes testifies to the occurrence of irritating and unbearable lighting situations, especially for those seats behind the south front (Front 2), which seem, however, not to suffer from excessively high levels of illumination.

Despite the absence of manual or automatic devices to control the illumination, the Index of Lighting preference (Fig. 83) still seems far from reliable (Table 23). With respect to Front 1, 33%

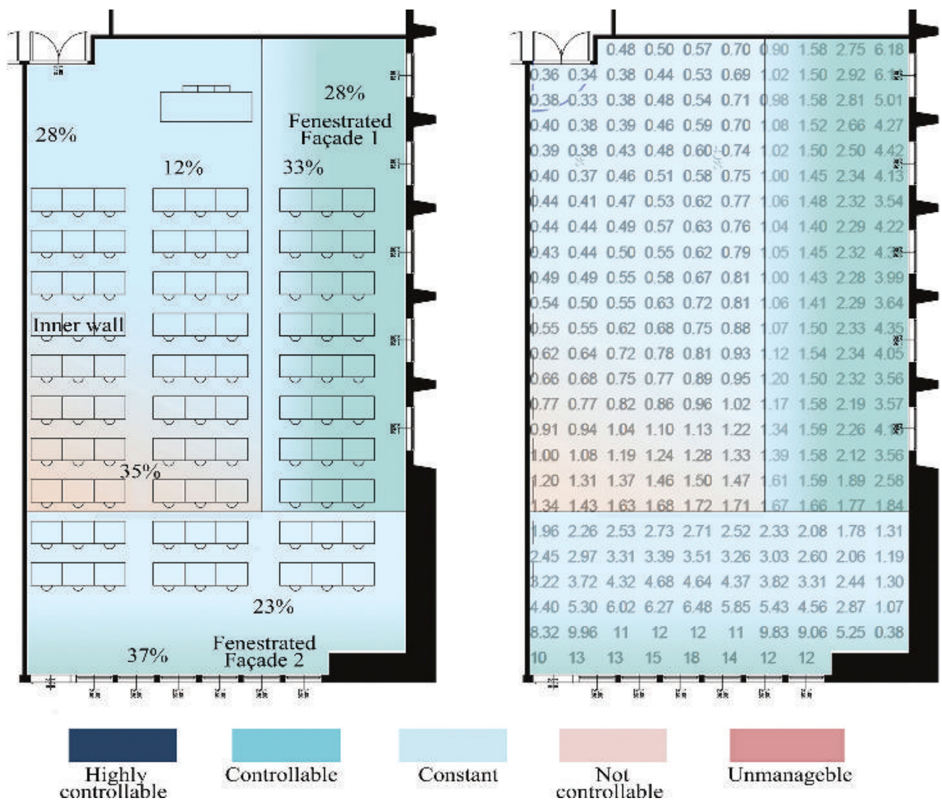


Figure 83: Index of Lighting preference and DF values.

Table 23: Results related to the Index of Lighting preference.

Quality of the lighting	Fenestrated façade 1	Fenestrated façade 2	Inner wall
Highly controllable	6%	3%	5%
Controllable	28%	37%	12%
Constant	33%	23%	28%
Not controllable	11%	27%	35%
Unmanageable	22%	10%	20%

and 28% of interviewees declared they could act with respect to the excessive brightness of the fronts, while those subjects far from the fronts, declared that it was impossible to intervene on the levels of illumination.

The outcome of the comparison between the values to calculate DF and the aggregated results of the test of appreciation shows that most users prefer to remain in the over-lit areas facing south, near Front 2, as is clear from a comparison between the plans in Fig. 83.

Similarly, positive votes and general appreciation were also expressed for those areas that, despite not reaching the prescribed value of 500 lux or the 3% threshold for DF, and settling instead on much lower levels, show again how the prescribed terms are not very reliable and are very distant from the actual needs of those occupying the space.

The strip in the vicinity of the fenestrated fronts where the DF stood around a value of 1.5% (insufficient for the legislation in force), was instead the area preferred by users, as is evident in the comparison in Fig. 81, between the distribution of the values of DF and its representation in colour of the Index of Dissatisfaction with the lighting.

The synchronous analysis of the data, subdivided by area and intervals of illumination, makes it possible to provide timely and targeted interventions, differentiating specific strategies aimed at enhancing the illumination or to screen areas that are excessively lit, revealing itself

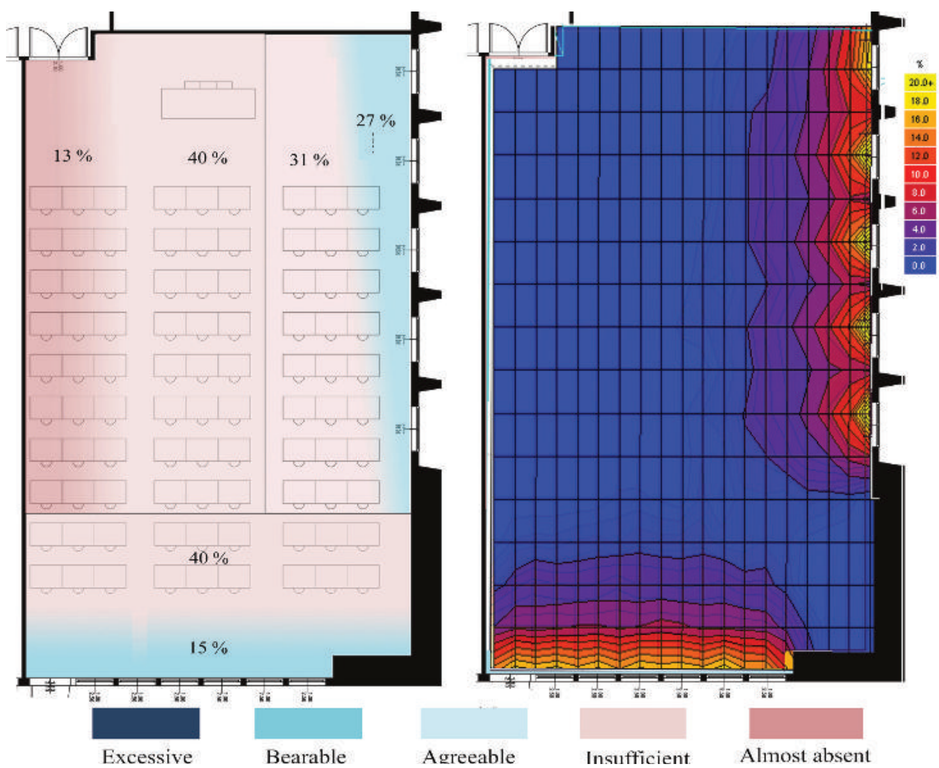


Figure 84: DF values distribution and the users assessed and Dissatisfaction Index with the lighting in the classroom.

as indispensable to provide integration with technological solutions designed to increase the uniformity of the illumination or prepare specific solutions of artificial lighting, to contain both electrical consumption and to help the overall energy saving of the confined environment. Such a comparison makes it possible to ensure that, in agreement with what was described by the interviewees regarding the central area of the room, the area between the fenestrated front 1 and the interior wall, seems to have illumination conditions that are welcomed by occupants.

Instead what came out of the comparison between DA_{500} and the index of dissatisfaction with the lighting is that the threshold target of 500 lux, evaluated as optimal for visual tasks, is actually only reached 20–30% of the time (Fig. 84).

Therefore, it would seem useful to intervene to maximise the percentages relating to the DA_{500} and to ensure uniform light distribution in this area.

As demonstrated by this comparison, a reading combining dynamic metrics and values from the subjective questionnaire can better disentangle information arising from a strictly qualitative assessment from those of a quantitative variety to complete Daylight Assessment.

3 Considerations on implementation of the new paradigm

As has been demonstrated, implementation of the integrated cascade protocol makes it possible to obtain a vast amount of data, first in raw form and then processed in a differentiated way, to obtain a comprehensive range of information to be used for architectural and technological ends.

The potential inherent in the very nature of the new dynamic parameters are increased by comparison with data resulting from a thorough reading of the assessment questionnaires, thereby obtaining a multi-level analysis that makes it possible to conduct an assessment of a diversified type, but that encloses all the data necessary for a Daylight Assessment that can identify strategies and systems to improve the shell or the building/plant system, to improve performance or carry out a retrofit.

The data show that a classroom with a prescribed average illuminance of 500 lux can be deemed acceptable by users even in the presence of a light level much lower than the target threshold.

Similarly, by using the dynamic CBDM metrics, it is possible to globally assess the real needs for natural light and the variable quota in terms of time and space of artificial light, in order to meet deficiencies of illumination, or to locate an appropriate shielding system, where necessary.

The dynamic assessment based on climate and has been precisely designed as a tool to ensure realistic estimates of natural light and to be able to deal with the process of Daylight Assessment through systematic and reliable criteria.

The subsequent categorisation proposed here makes it possible to assess individual zones of the interior space being considered, in order to determine positive or negative aspects, in relation to the parameters evaluated.

In this way, it is possible to provide a global retrofit of the building envelope, as well as ad hoc solutions that ensure shielding or shading where required in the room, without incurring irritating dazzling phenomena or overheating, at the same time evaluating the proportion of artificial light to be ensured for each area or sub-area, in order to address the failure to reach a comfortable level of uniform illumination, without unnecessary and unjustified electrical consumption.

The approach of this type of simulation proved highly adaptable in virtue of the integrated procedure, which enables a differentiation between the analysis phases: in fact, it is possible to evaluate a diversified strategy that takes into account the evolution of the illumination over the entire working year, examining only those hourly intervals in which the interior space is actually occupied and in which the subjects remain there, or by evaluating a single zone at a time, up to a single cell on the floor of computation, in relation to a single parameter, from the precise illumination to the indices of visual preference and visual satisfaction. The ability to perform rigorous analysis area by area or through a survey of individual cells is feasible thanks to the presence of an adjustable analysis grid, to better evaluate in detail the specific characteristics of the individual cells, ensuring the ability to intervene more effectively in the event of requiring screening and shading solutions, or to increase light levels at a precise point in space.

Since the precise management of daylight illumination is notoriously one of the most difficult challenges the designer must face to improve overall energy performance and to enhance indoor comfort, the codification of a protocol for Daylight Assessment makes it possible to obtain direct control over the main aspects related to the question. In addition to proposing a valid strategy to balance the growing demand for primary energy, the proper use of natural light enables reduction in electrical consumption in larger spaces through effective use of daylight, together with systems for shading and shielding.

A further peculiarity of the integrated approach on a climate base consists of the possibility to choose the time interval and season to perform the calculation on. Although the calculation is usually performed during the daytime hours over the course of the entire calendar year, it is more appropriate, as in the simulation carried out in this chapter, to consider only the daytime hours of actual occupation, to be able to compare the output data with those obtained by direct observations, static calculations and a reading of the aggregate preference ratings from the subjective questionnaires.

Another prerogative of the analysis framework is to be able to adapt easily to a stage of preliminary or final design, in addition to that of a retrofit on the extant buildings.

Although born and defined to meet the growing demand for tools to be used in retrofits and functional recovery, it can be adapted to the verification phase of a project to certify compliance of illumination parameters in a confined environment.

In case it is required to intervene on the classroom analysed with a specific retrofit intervention, joint analysis of the criticalities shows that it is appropriate to proceed with the inclusion of certain devices that mitigate conditions of excessive illumination in the vicinity of the fenestrated fronts, to avoid effects of overheating and irritating glare, and safeguarding, at the same time, a homogeneous distribution of illumination at the end of the room.

Therefore, it would seem useful to intervene to maximise the percentages relating to the DA_{500} and to ensure uniform light distribution in this area.

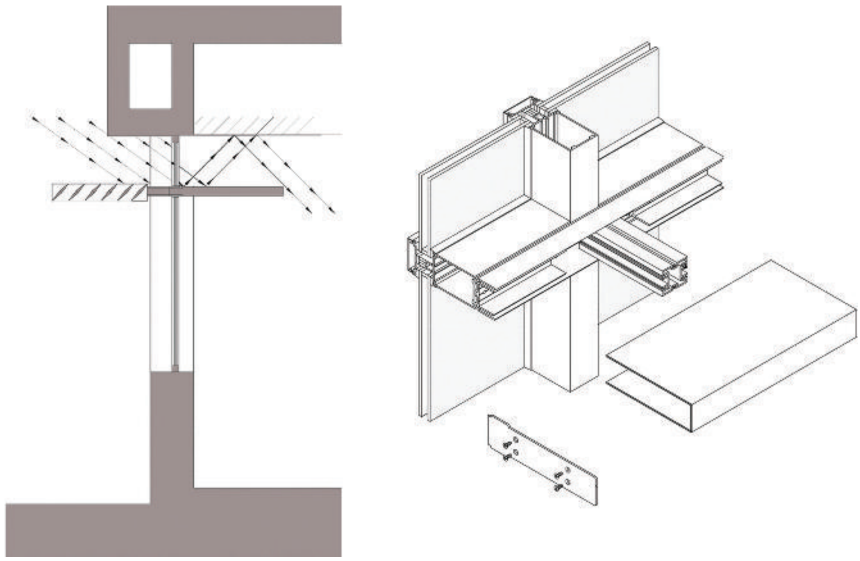


Figure 85: Interior and exterior lighshelf inclusion in each classroom windows.

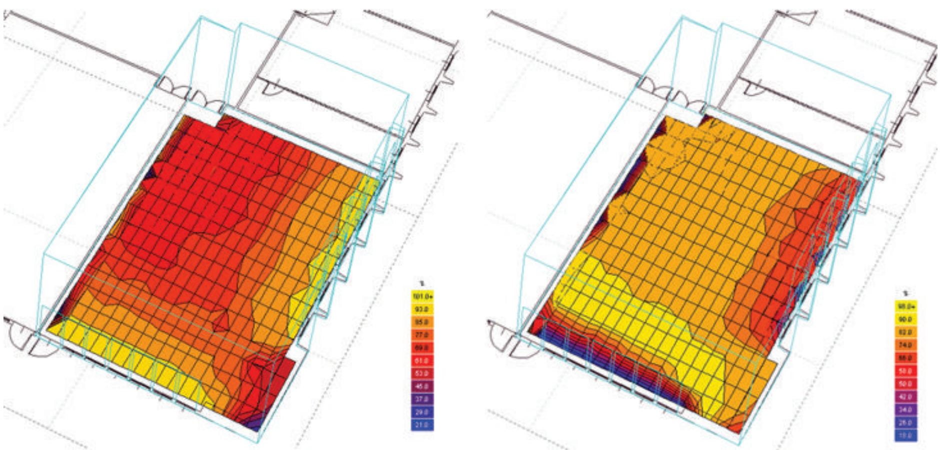


Figure 86: cDA_{500} and $UDI_{100–2,000}$ values after the lightshelves intervention.

As demonstrated by this comparison, a reading combining dynamic parameters and values from the subjective questionnaire can better disentangle information arising from a strictly qualitative assessment from those of a quantitative variety to complete Daylight Assessment.

The reading of this information makes it possible to prepare both architectural and technological differentiated strategies, to implement, e.g. interventions to reduce the illumination in the vicinity of the fenestrated front 1, contextually facilitating the re-direction of a share of natural light towards the end of the room, on the opposite wall.

On the basis of the need to make minimally invasive changes so as not to alter the existing building envelope, one of the feasible solutions could be the inclusion of some interior lightshelves, as shown schematically (Fig. 85), with a variable overhang, equipped with external shelves and directional slats, to limit the excessive radiation penetrating the immediate area around the windows and that can address a large quota of light rays towards the back of the room, thanks to reflections directed onto the ceiling and into the depths.

To demonstrate the efficacy of this mitigation intervention of a check was subsequently made on the performance of an internal lightshelf, about 120 cm deep with adjustable external slats, to be applied to the eastern wall, thanks to additional testing and simulations.

The simulation, according to the afore-described steps, produced some significant results that demonstrate how it is possible to intervene precisely on sensitive areas of the interior space (Fig. 86).

It is to be understood that additional processes of refinement are feasible, however, by looking at the choice of appropriate shading or diffusing devices, as well as finishing materials for the surfaces. Where satisfactory improvements have not been found, even following the introduction of active or passive devices, the survey can be directed towards the development of a lighting design using artificial devices, on the basis of the values supplied for each single cell, and in relation to the values analysed; if cDA is taken as a survey parameter, it is possible to determine the proportion of missing illumination to achieve the predetermined threshold as a target value.

4 Extension of the field of the phenomenology of daylight

The careful use of light makes it possible to give a sense of unity and conclusion to the space. Thanks to control of the light coming from different sources, able to define the boundaries between dark, light and shade, it is possible to achieve a computed size for a confined space, taking into account the necessary dynamic variables of shielding and shading.

Understanding the multiform possibilities offered by natural light in architecture means take a cue from historical experience, whose roots lie in construction practices that are distant in time and space, to reach a new orientation that cherishes the intuitive approach to develop a complex discipline of spatial and formal research.

The question of Daylight Assessment treated so far demonstrates how the different strategies and the analysis procedures available today need to fuse into a systematic method of global and integrated survey, to take account of complex factors that include local, geographic and meteorological aspects, the optical and perceptive needs of users, and the dynamics resulting from processes of adaptive comfort. In particular, it must be considered that the handling of the light as environmental performance of a space is inherent to the nature of the location. This means that the designer can never have generic solutions to apply to resolve special problems, and must therefore adapt to local needs, developing differentiated solutions.

The formal experimentation of the recent past points up the incongruity of a universal approach that concentrates exclusively on the geometric issue of the building, just as the development of the technological systems to be applied to the shell has erroneously led to considering these devices as the sole means of controlling, calibrating, and managing the light.

The inconsistencies arising from approaches of a static and geometric type are reflected accordingly international regulatory scenario, which is not devoid of inaccuracies and inconsistencies. These complexities have highlighted the need to radically alter the approach to analysis and calculation, and at the same time, the design of daylighting, in particular in the case of an energy retrofit.

On the other hand, natural light, filtered, screen and addressed, assumes a central role in the design of any space, to the extent of being a fundamental factor for indoor comfort and energy-saving strategies. The urgency to respond to these different needs, to provide a model of correct analysis, appropriate to the physical reality of natural light and its distributions, has led to a reformulation of the assessment process, through a dynamic model, based on local climate and on the introduction of new measurement metrics.

In the light of the observations made, the designer can therefore manage the necessary tools to make editing, mitigation and corrective actions on the levels of interior light distribution, increasing visual comfort and avoiding the risk of disturbing phenomena, whether optical or thermal.

The implementation of the protocol defined herein demonstrates that effective collaboration between the numerical data resulting from a dynamic assessment of parameters such as DA, cDA and UDI, together with a reading of preference ratings collected from evaluative questionnaires among users, make the process of analysis particularly effective, allowing targeted actions with respect to the highly variable needs of a confined space in relation to the prevailing visual task.

The decisive contribution to the question lies in the first instance in the adoption of the new integrated dynamic paradigm and the related new metrics that can further be implemented by making each parameter suitable to meet the needs of lighting design, as well as definition of a quota of supplementary electric lighting needed to satisfy the final requirements.

The discussion regarding the possible uses of new parameters of a climatic origin then suggests that the dynamic system can become a valid alternative to static factors, gradually replacing the DF.

The numerical results and graphs arising from the formulation of the verification protocol, thus demonstrate the need for validation at an international level of the new CBDM metrics, to be followed by a systematisation of verification tests and simulation, in order make them suitable for a wide range of building types, and accessible to numerous professional figures.

Stimuli useful in raising awareness of the need to validate the new dynamic paradigm must therefore come from the knowledge that natural light, properly weighted and controlled, can reduce the energy load of a building to ensure a pleasant and calming environment for those who visit and live there, that is healthy from luminous, visual and thermal points of view, and can positively affect productivity and levels of attention.

Issues that remain to be defined include, among others, those relating to a definition of absolute reference levels, through which to circumscribe the confines of the dynamic analysis and reference parameters.

The audit trail on some exemplary cases, as demonstrated by the case study presented, has allowed critical testing of the analytical protocol, to which will be added repeated experimental verifications to prove its efficacy in different contexts and improve the complex integrated path.

The relationship of close dependency between the luminous phenomenon, various aspects of energy and the perceptive questions allow a further broadening of the question, in order to obtain maximum performance from the new approach and to enhance the studies relating to the relationships between light/energy-saving, light/human health and light/perception.

Afterword

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The explanation given by the author demonstrates how the theme of daylighting opens the way to important developments in design. The denial of natural light as a foundational aspect of the architectural project and, in particular, lack of knowledge of the possibility that it can be governed as a physical entity, that it can be calculated and predicted through simulations and predictive analytics, has often produced buildings that are completely indifferent to this aspect. Now, not only the prospect of containing energy consumption rather than the specific content performance of the light, as well as the direct fallout that it exerts on the quality of indoor comfort are sufficient elements to elicit increasing interest. The aid of dedicated calculation tools, moreover, defines natural light as a typical physical parameter of the confined space that can be managed just like any other project datum.

Beyond the methodological issues and regulations, more or less legally binding and variously articulated according to the national contexts, meticulously explained, the underlying message from the work remains strong: the building/environment system, in particular in the relationship between confined space and daylighting, between the closed dimension of architecture and the open dimension *par excellence*, that of light, offers high design potential. Certainly, the refined and refinable tools that are described here in their wide range of features and opportunities make the work of architects extremely attractive, when they wish to use natural light as an effective component of their work, indeed, constitute a stimulus to achieve as much control as possible over the phenomenon of natural light – including the desired intensity, where, and when.

One fundamental question remains open, perhaps inevitably – in addition to others properly investigated by the author – relating to the quantification of energy-saving; estimation of the increase in healthiness and effective user perception – and more exquisitely of a design nature: the choice of a morpho-technological solution that the building must assume in order to ensure the desired luminous performance, in response to local climatic conditions and the functions provided for the confined spaces. In particular, which integrated systems between form and technology can physically give rise to the desired *light architecture*? Which materials and which combinations of surfaces to define spaces, which systems to control natural light and which apertures, will ensure the planned quality of light?

The phenomenology of the light that the author outlines here in its founding aspects and that with precision seeks to govern through the development of a detailed calculation protocol based on a hypothesis of the dynamic type, leads us into a dimension of advanced architectural design which we can no longer ignore. The issue of the environment, first and foremost, and the search for increasingly sustainable indoor comfort, make this work an essential tool for the verification and prediction of the luminous component of architecture design.

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Glossary

The glossary of terms related to Daylight Assessment has the essential purpose of facilitating understanding of the terminology commonly used in the architectural and technological fields, providing for each term a concise and simple definition.

In view of the complexity of the terminology, this glossary is not intended to be comprehensive, but rather seeks to provide a tool to understanding for those approaching the issue of the technology and methodology of daylighting in architecture for the first time.

Adaptive Comfort: complex system that covers different principles of adaptation to ambient conditions, through behavioural, physiological and psychological adaptation. According to the Adaptive Comfort model, the occupant of an environment is not simply intended as a passive person, but as an actor who interacts with the environment in which he or she is located, through the aforementioned three levels. At the base of the model of Adaptive Comfort is the firmly rooted belief that the subject personally determines the environmental, thermal and visual conditions that he or she prefers, through a process of adaptation and a gradual decrease in individual reactions to environmental stimuli.

Angle of Incidence: angle between the ray of light that strikes a surface and the normal of the same surface.

Anidolic Systems: systems for ceilings and apertures, consisting of special mirrors and reflective surfaces to facilitate the diffusion of light, produced on the basis of the principles of 'non-imaging optics'. The crucial element underlying these technologies is the so-called compound parabolic concentrator, an efficient reflector commonly called an anidolic concentrator, from the Greek *an*: without and *eidolon*: image. Among the systems are anidolic ceilings and blinds with anidolic slats.

Artificial Sky: tool that makes it possible to simulate the luminance distribution of the celestial vault, in accordance with the recommendations of the CIE, i.e. according to the most widespread luminance distribution, and usually used for natural lighting design. The Artificial Sky enables the study and evaluation of the amount of natural light in an architectural project in scale models from 1:10 to 1:12.

Atrium: vast entrance space of private or public buildings, open or closed, usually used as the focal point of a building or an area of connection, where public functions are concentrated. Among the daylighting techniques, a glazed atrium is used when it is wished to convey the maximum amount of light into the central areas of the building, according to the *Corelighting* technique. The atrium is spoken of in terms of daylighting strategies in the presence of lateral closed spaces where the roofing is made from a surface that is transparent or translucent and allows light to filter down to the lowest floor.

Azimuth: the angle between the vertical plane that contains the sun, and a vertical plane facing northwards.

Brightness: generic term, associated with the phenomena of visual perception, often misused as a synonym of physical quantities such as luminance, luminance factor, brilliance and clarity. Indicates a visual sensation that allows the observer to grasp the degree to which a surface appears to emit or reflect light. Since this is an objective sensation, it does not define a characteristic magnitude.

Brise Soleil: shading system to be mounted on a façade in the presence of large fenestrated areas to check phenomena of over-lighting, glare, and undesirable solar gain, especially for exposure southwards. These can be external or internal, and are realised using slats of varying kinds and morphology, to be affixed to the façade.

Candle: unit of measurement for light intensity, indicated by CD. One candle is equal to the luminous intensity in a given direction of a source that emits monochromatic radiation of a frequency equal to 540–1,012 Hz.

CBDM: acronym for *Climate-Based Daylight Modelling*. Climate based daylight modelling is the prediction of various radiant or luminous quantities, like irradiance, radiance, luminance and illuminance, using sky and sun conditions. The prevailing conditions of sun and sky are deducible from standard sets of meteorological data. Climate-Based Daylight Modelling thus provides forecasts of absolute amounts for illumination, that depend on both the geographic location and specific data on the local climate, taking into account the morphology of the building and its internal configuration. The CBDM does not yet have a formally accepted definition and Mardaljevic first defined it in 2006.

CIE Standard Clear Sky: model of the sky defined by the *Commission Internationale de l'Eclairage*. Conventionally, it defines a sky that is completely serene, clear of clouds. In this model, the lower luminances are located in the vicinity of a sector that forms an angle of 90° relative to the sun.

CIE Standard Overcast Sky: model of the sky defined by the *Commission Internationale de l'Eclairage*. This is a model of sky completely covered by clouds. According to this model, the luminance at the zenith is three times higher than that recorded on the horizon.

Clerestory: a high window. An aperture for daylight created in the highest part of the outer wall.

Continuous Daylight Autonomy – cDA: proposed as a variation of Daylight Autonomy by Zach Rogers in 2006, this assigns partial credits if the daylit environment reaches values less than that imposed as a DA threshold, or is lower than 500 or 300 lux.

Contrast: visual difference between the colour or brightness of two surfaces if observed at the same time. Excessive contrast levels can be the cause of glare.

Corelighting: among the systems for illuminating with natural light, corelighting includes the use of a source of natural light that comes directly from the top and can penetrate the depths of the building, in the central core. The light can be channelled through the use of ducts or by resorting to atria and glazed courtyards.

Daylight Autonomy – DA: hourly or annual frequency during which natural light reaches a certain threshold, such as to ensure illumination by exclusive use of natural light, and excluding artificial light. This was the first new unit of measure based on climatic and dynamic to be defined. It represents the annual percentage of hours during the day in which, in a given point in space, there are illumination values above a pre-set limit, usually equal to 500 lux.

Daylight Availability – DA: luminous flux coming from the sun and the celestial vault that arrives at a specific location for a given time and sky condition.

Daylight Factor – DF: ratio, measured for a given point or on a given surface, between the interior illumination, that directly or indirectly received from the sky, and the simultaneous exterior illumination, calculated on a work surface. In this case, the amount of direct sunlight is excluded.

Daylight Saturation Percentage – DSP: percentage of saturation of daylight. A further elaboration of the UDI value, according to which the lower limit is raised to 40 candles per square foot (precisely 430 lux), as well as the upper limit, which marks the useful range, raised to 400 candles per square foot (precisely 4,300 lux).

Daylight: a set of the entire global radiation visible, i.e. composed of direct and reflected sunlight, plus light from the celestial vault. Part of global solar radiation capable of causing a visual sensation.

Debilitating Glare: form of visual discomfort that may lead to a worsening of the functions of the visual apparatus until a reduction of sensitivity in perceiving contrasts.

Diffused Light: secondary component of sunlight, or the light diffused by the earth's atmosphere.

Direct Light: sunlight, generated directly by the sun, which reaches the earth's surface after being filtered by the atmosphere.

Direct Solar Radiation: solar radiation which, after selective attenuation by the atmosphere, reaches the earth.

Discomfort Glare: a type of glare usually to be found in indoor environments, which causes a feeling of discomfort. According to the CIE definition, this is 'glare that produces an unpleasant sensation without necessarily impeding vision'.

External Reflected Component – ERC: ratio of that part of the illuminance at a point on a given plane in an interior which is received directly from external reflecting surfaces illuminated directly or indirectly by a sky of assumed or known luminance distribution, to the illuminance on a horizontal plane due to an unobstructed hemisphere of this sky, where the contribution of direct sunlight to both illuminances is excluded.

External View: if available, this guarantees a high level of comfort for occupants, ensuring constant contact with the outside, allowing them to perceive the effects of the flow of time. Fluctuations in light levels throughout the day may turn out relaxing or stimulating for the observer.

Flickering Effect: rapid variation of light coming from download sources caused by the electrical current, which can cause sensations of visual discomfort.

Glare: condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or by extreme contrasts. Irritating Glare is usually defined for artificial fixtures, and can be calculated using the CIE tabular method of UGR (Unified Glare Rating), depending on the type of environment, the activity, and the visual task. It is possible to distinguish between direct glare, or glare generated by unshaded sources that enters the visual field (the case of windows), and indirect glare, caused by the presence of light rays in which the reflection falls directly on the eye of the beholder.

Global Solar Radiation: amount of solar radiation that derives from a combination of direct and diffuse solar radiation.

High Window: see Clerestory.

Illumination: amount of light that reaches a point on a given plane in an interior, or the flow of light, measured in lumens, that strikes a unit surface area of one square metre. The unit of measurement of illumination is the lux.

Indirect Light: proportion of natural light that reaches a surface after different paths of reflection, inner and outer, due to different types of obstructions and reflective surfaces.

Internal Reflected Component – IRC: ratio of that part of the illuminance at a point on a given plane in an interior which is received directly from internal reflecting surfaces illuminated directly or indirectly by a sky of assumed or known luminance distribution, to the illuminance on a horizontal plane due to an unobstructed hemisphere of this sky, where the contribution of direct sunlight to both illuminances is excluded.

Isolux Lines: a set of curves or lines that connect points having the same illumination in lux.

Laser–cut Panel: panel used for daylight systems to redirect the light thanks to the presence of variously inclined surfaces, made by laser on a thin panel in transparent acrylic material.

Light Pipe: physical structures used for transporting or distributing natural light for the purpose of illumination, making use of a hemispherical transparent dome that picks up the light and conveys it inside the tube through a complex path of reflection created with lenses of the Fresnel type, reducing dispersion of light radiation to the maximum.

Light Transmission: percentage amount of sunlight that the glass allows to pass with respect to the incident light hitting it. Therefore concerns the flow of light transmitted through a glass window in relation to the incident light flux.

Light-guiding Shades: external shading system that redirects sunlight towards the ceiling and into the depths of an environment.

Lightshelf: device, which can be likened to a shelf, to be installed within an environment in the vicinity of the highest part of the window. In most applications, it must be combined with other devices to avoid the glare of the sunlight that enters from the bottom of the window. The lightshelf therefore avoids the glare problem, exploiting natural light that is conveyed towards the bottom of the environment. Can also be applied to the exterior, and submitted to different finishing treatments.

Louvre: device that acts as a baffle against incident solar radiation. Created in the presence of a window, through the use of horizontal slats, angled to allow the entry of natural light and air, and offering protection from the rain and direct sunlight.

Lumen: unit of measurement of luminous flux. A lumen, indicated by the symbol lm, and equal to a luminous flux emitted in a solid angle of one steradian, from a point source with the luminous intensity of one candle.

Luminance or Brightness: ratio between the emitted intensity in a certain direction from the light source and the emitting surface normal to the direction considered. Measured in cd/sq m.

Luminous Efficiency: refers to light sources of an artificial type. Used to express the ratio between the total luminous flux emitted by a source and the total power input to the same source. Expressed in lumens/watt.

Luminous Flux: luminous power emitted by a source or received by a surface, expressed in lumen (lm). Usually taken into consideration is the flux emitted by the solid angle of one steradian (sr) from a point source, with the light intensity of one candle.

Luminous Intensity: light flow, measured in lumens, emitted by a point source in a particular direction in a unitary solid angle.

Luminous Retrofit: any luminous revamping of a building or single environment to improve lighting performance and, consequently, to increase visual comfort and more generally indoor comfort, by rationalising all the energy flows. Actions of retrofitting may range from the simple substitution of doors, windows or glazing, up to the installation of devices for shielding and directing light.

Lux: unit of measurement of illumination. A lux, indicated with the symbol lx, is equal to the illumination produced by a luminous flux of one lumen distributed over a unit area of one square metre.

Obstruction: any natural or artificial object that prevents direct and indirect natural light from entering an environment. The presence of any kind of obstruction generates shadows that affect light distribution within the environment.

Partially Covered Sky: variable condition of the sky with a percentage of between 30% and 70% cloud cover.

Prismatic Panel: thin flat panel, used for windows or skylights, which is made from clear acrylic. Used in temperate climates to redirect and/or reflect natural light. Can also be used as a shading system, since it can reflect sunlight and transmit diffused light into an interior.

Radiance: measures the intensity of a beam of light and is defined as the power per unitary solid angle per projected area. The unit of measurement of radiance is $W/sr\ m^2$.

Radiosity Method: physical lighting model that evaluates all the surfaces involved that reflect, i.e. diffused light, assuming that the interactions between them can be solved using linear equations. A linear equation solution is the final output to produce a rendering of the surfaces of the scene.

Raytracing Method: a method based on the observation that, among all the light rays that spread from a source, only those that reach the observer actually help to form the image. The Raytracing Method therefore only traces the path taken by the ray of light from the point of view of the observer, by reversing its trajectory and considering only those rays that depart from the position of the observer.

Roof Monitor: device for toplighting, used especially for large buildings, to provide uniform illumination and eliminate glare.

Selective Glass: low-emissive glass that can filter part of the incident radiation, reducing the transmission of heat by radiation.

Shading Coefficient: indicates the peculiar properties of heat transmission of glazed surface in the presence of solar radiation (known as the total solar heat transmittance). The coefficients are calculated by comparing the properties of the glass with those of a clear float glass with a total transmission equal to 0.87.

Shading: any device or system designed to screen and create shading effects. Can be applied both inside and outside a room, for solutions of *sidelighting*, *toplighting* and *corelighting*.

Sidelighting: natural lighting system where the light filters into the environment thanks to the presence of lateral apertures made in a building's shell. Sidelighting is defined as simple if there are windows and other apertures on one side only, while bilateral sidelighting means the presence of apertures on two fronts.

Sky Component – SC: in the calculation of natural light, the Sky Component is usually the most consistent between the reflected external component and the internal component. Its magnitude depends on the portion of sky visible from the point considered.

Sky lighting: light received from the entire celestial vault of the sky, on the basis of changes in the sky, of the seasons and of the hour of the day, ignoring sunlight, and, by association, also toplighting devices.

Skylight: device among the most common to bring sunlight into an environment in the absence of windows or other apertures. Originally defined a simple aperture on a flat or inclined roof that makes it possible to give light to rooms without windows.

Solar Chart: path of the sun on its orbit with reference to the changes and time and seasonal variations linked to the position of the sun with respect to its path. Also spoken of are stereometric solar charts or solar graphs, which can be identified for each location, to represent the projection on a horizontal plane of the apparent path of the sun on the celestial vault.

Solar Control Glass: glass that reduces the transmission of input energy emitted by the sun, thanks to the presence of surface deposits applied to its outer surface.

Solar duct: see Light Pipe.

Solar Gain: achieved by means of passive solar systems and defined as the difference between the amounts of solar energy that enters the building and the loss of heat from the same building.

Solar Protection: simple device or complex system that can provide variable protection from direct sunlight, and that allows, again in a variable manner, shading and shielding the area immediately surrounding the aperture to the outside.

Static and Dynamic Parameters: static parameters include Daylight Factor or DF_m. Based on a uniquely determined condition of the sky, that is independent of the geographic position and the real sky conditions. To make static calculations only the geometric, morphological and optical parameters of the environment in question are considered. Dynamic parameters based on climate consider instead the actual sky conditions, with recourse to complex meteorological data on a statistical basis for each location, i.e. they consider all the possible sky conditions that occur in a year-type for the given site.

Sun-directing Glass: concave acrylic elements stacked vertically inside double glass, to redirect the sunlight coming from all angles of incidence towards the ceiling.

Task Lighting: natural or artificial light that is used to complete a given visual task; usually refers to the lighting of offices, schools or environments that require particular concentrated illumination, to increase the illumination in reading areas.

Test Reference Year – TRY: typical year of weather reference. The TRY is composed of a sequence of meteorological data schedules, measured in reality and selected within a historical series of at least ten years, through a method of selection of a statistical nature. This leads to the creation of a vast amount of hourly data that merge into a year-type, used for models of analysis and the forecasting of complex phenomena including dynamic simulation of the distribution of sunlight.

Toplighting: among the daylighting strategies, this offers significant opportunities to arrange both simple and complex solutions. Toplighting systems can only be used on the top of the buildings to illuminate the floor below, thanks to the use of skylights and other types of zenithal area apertures, both flat and sloping. Traditionally, toplighting strategies are used in areas where there is a predominantly overcast sky, to channel as much light as possible into a room.

Typical Meteorological Year – TMY: Reference year for weather.

Uniformity of Illumination: correct distribution of the illumination in an area, given by the ratio between illumination of the area in which activities take place and illumination of the surrounding areas. Provided by calibrating in a manner consistent with the visual task, the task area, and the surrounding area. It is possible to determine a correct ratio of uniformity by resorting to the relationship between precise minimum illumination and the average illumination of the surrounding area.

Useful Daylight Illuminance – UDI: unit of measurement designed to make easily understandable the output data of the dynamic simulations based on climate, without reducing the many useful data contained in the results of the simulation. Defined as the percentage of annual illumination that falls within the range considered useful, in relation to a given visual task.

Visible radiation: portion of the electromagnetic spectrum with wavelengths of visible light between 380 and 760 nm.

Visual Acuity: defines the visual dimension of the threshold, that is, the size of an object that can be identified only 50% of the time, in certain conditions of observation. Also defined as the reciprocal of the visual dimension.

Visual Comfort: optimum condition of lighting, whether natural or artificial, that must be ensured through the fulfilment of certain fundamental requirements, including an adequate level of illumination, proper uniformity of illumination, and an efficient distribution of luminance values, in order to prevent glare. In the context of strategies to maximise the visual comfort of an environment by using natural light, the visual relationship between the inside and outside must also be considered. The windows, and other types of apertures, not only have to procure the light needed for an activity, but also allow the view of the outside.

Visual Performance: ability to carry out a visual task, which depends on the way in which the eye can perceive the details of a task. Determinant factors for visibility of the details of the task therefore include size, luminance, contrast and glare.

Visual Task: this defines observation of details and objects in relation to the performance of an activity according the needs of the visual system to complete such a task, both in relation to a view of the surrounding objects, and the immediate background comprised in the observer's visual field.

Workplane: for the calculation of natural light this is an ideal plane located at a height of 85 cm above floor level.

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