Development of an integrated methodology for the daylight assessment of commercial buildings employing dynamic shading devices or kinetic envelope systems

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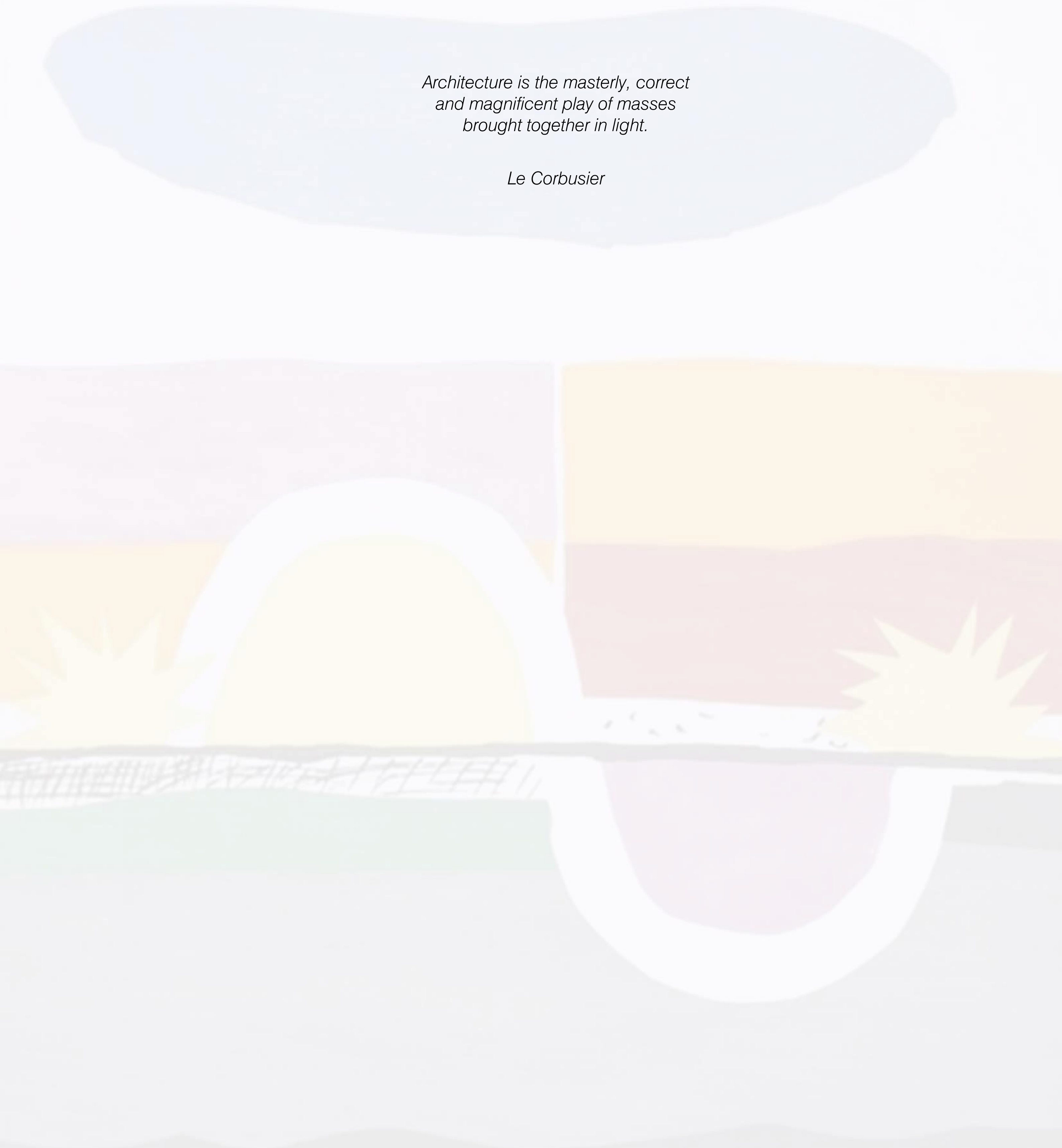
Architecture is the masterly, correct
and magnificent play of masses
brought together in light.

Le Corbusier



Charles Édouard Jeanneret (Le Corbusier), European; Swiss, 1887 -. 1955. Untitled, pg. 17, in the book Le Poéme de l'angle droit by Edmond Jeanneret (Le Corbusier) (Paris: Tériade Éditeur, 1955). Prints, lithograph. Place: Fine Arts Museums of San Francisco, San Francisco, California, USA, Gift of the Reva and David Logan Foundation, 1998.40.27.13, http://www.thinker.org/. http://library.artstor.org/asset/AMICO_SAN_FRANCISCO_103848941.

Abstract

Natural light has many positive effects on the human behavior, physiology and psychology by influencing our visual and non-visual systems, regulating the circadian clock, tough it might be the cause of several discomfort issues, such as eye strain, sleep/wake shifting, glare and so on. Lately, the importance of daylight in commercial buildings has been reconsidered and the best way to enhance it is through high performance envelopes: dynamic shadings, kinetic facades, adaptive skins, etc… represent the most stressed field of innovation in today's architecture, allowing to achieve optimized solutions for a good distribution of daylight and reduced energy loads thanks to climate-based analyses, integrated design strategies and the adoption of efficient artificial lighting sources equipped with advanced control systems. The issue linked to these architectural solutions is the unavailability of a digital analysis tool able to directly assess their preliminary daylight and energy performance due to limitations of the existing software.

The work developed consists in the definition of a strategy for the evaluation of the daylight metrics achieved in those buildings where dynamic envelopes are involved: after modelling the room and the shading geometries, including each shading configuration available, a set of annual simulations is run for each shading position (considered as a static one) and eventually, through post-processing operations, the results are used to define an optimized schedule represented by the shading configurations assumed at each time-step, which can be used to assess the daylight and energy performances achieved through the adoption of a specific dynamic shading optimized on a single (or multiple) parameter.

The results deriving from the application of the method to a case study show that the proposed workflow can be very accurate and allows designers to understand the potential of a dynamic shading device, including the possibility of enhancements or adjustments of the same.

Abstract

Il lavoro illustrato nelle seguenti pagine si ispira alle tematiche affrontate durante il corso di BIO-Design, promosso dalla Prof.ssa. Dr. Eugenia V. Ellis della Drexel University e la Prof.ssa Dr. Giuliana Iannaccone, in particolare ai moduli relativi allo studio dell'apparato visivo umano ed alla cronobiologia, che hanno catturato il mio interesse facendomi capire l'importanza che la luce naturale esercita nella vita quotidiana di tutti noi. Allo stesso modo, i contenuti trattati nel corso "*Building Envelope Design Lab",* tenuto dal Prof. Dr. Marco Pesenti, hanno ricalcato argomenti simili ai suddetti, aiutandomi a delineare la struttura del lavoro svolto. Escludendo l'interesse sviluppato per il tema, la motivazione dietro tale lavoro è promuovere l'uso della luce naturale negli ambienti di lavoro, invitando i progettisti a valutare le prestazioni raggiungibili con l'uso di un particolare oscuramento dinamico già durante le fasi iniziali della progettazione, con lo scopo di ridurre tempi, costi ed il consumo di energia, migliorando sia le condizioni di comfort che di salute per chi vive gli spazi dell'edificio.

Oggigiorno il compito dell'involucro edilizio si è evoluto da semplice barriera verso l'ambiente a mediatore di variabili esterne (come la radiazione solare), assumendo quindi un ruolo più attivo nel controllo delle condizioni di comfort visivo e termico all'interno di un edificio; negli ultimi anni l'avanzamento tecnologico ha coinvolto diverse sfere della ricerca, tra cui caratteristiche dei materiali, tipi di attuatori, dispositivi di oscuramento complessi, sistemi di illuminazione e controllo, etc ... consentendo di ridurre il quantitativo di apporti solari, aumentare la trasmissione di luce visibile, abbassare i costi di manutenzione e propensione ad un miglior adattamento al variare degli stimoli ambientali esterni, delineando quindi un'ormai chiara direzione in cui la tipologia di involucro impiegata in nuove costruzioni sta virando.

La luce naturale gioca un ruolo importante su salute e psiche umana: aiuta il nostro organismo a regolare i vari cicli circadiani presenti in esso, inibisce l'insorgere di forme di depressione stagionali, stimola la produzione di vitamine D tramite irraggiamento della cute, stimola le capacità cognitive e la prontezza. D'altro canto, agli effetti positivi appena riportati se ne affiancano di negativi, come l'abbagliamento (diretto o per contrasto di luminanze), il surriscaldamento dell'ambiente per la porzione di radiazione infrarossa e talvolta bruciature dell'epidermide.

Gli indici di valutazione sulla qualità di illuminamento all'interno degli ambienti di lavoro, stabiliti dalle norme vigenti, si basano su metodi (*DF*) che considerano le condizioni del cielo costanti per tutto il tempo (cielo coperto), sottostimando eventuali livelli eccessivi raggiungibili in condizioni di cielo sereno che possono causare discomfort; negli ultimi anni l'interesse di alcuni ricercatori ha contribuito a sensibilizzare i progettisti nell' adottare metodi di analisi più avanzati, che tengano conto delle condizioni atmosferiche del luogo scelto, e nel definire il livello di prestazione mediante indici più idonei a livello qualitativo (*DA, UDI, sDA, ASE*).

Ad oggi, l'analisi prestazionale di ambienti provvisti di oscuramenti dinamici risulta complicata per via di limitazioni nei software utilizzati per le simulazioni: il cambio di configurazione geometrica, per esempio, da un time-step al successivo farebbe ricominciare l'intera simulazione creando così un'iterazione infinta, inoltre non sarebbero disponibili informazioni sulle configurazioni assunte dal sistema oscurante e programmate per ogni time-step, se non tramite una definizione a priori del progettista.

Le informazioni sopra riportate mostrano che nell'architettura odierna si sta delineando una chiara tendenza al dinamismo, all'efficienza energetica, all'ottimizzazione, ad analisi basate sul clima locale ed al crescente interesse nell'efficienza luminosa. Il lavoro proposto è quindi finalizzato alla definizione di un metodo di analisi standardizzato da applicare ogni qualvolta oscuramenti, o involucri, dinamici siano inseriti durante la progettazione di un edificio, con lo scopo di valutare le prestazioni di illuminamento (ed energia) nella fase di progettazione preliminare: la valutazione viene definita tramite l'ottimizzazione di uno o più indici (che definiscono la qualità dell'illuminamento all'interno dell'ambiente di analisi)

strettamente legati alla specifica configurazione geometrica assunta dall'oscuramento dinamico. Questo metodo consente di visualizzare l'effettivo potenziale sistema ombreggiante adottato e permette al progettista di capire se siano necessarie ulteriori regolazioni o migliorie per raggiungere risultati migliori, sia per la prestazione di illuminamento naturale che per la prestazione energetica.

Il lavoro descritto parte analizzando le caratteristiche, l'influenza, i benefici ed i disagi legati alla luce naturale, nonché i suoi effetti sul comportamento umano, la produttività, la fisiologia e la psicologia (cap. 2). Le nuove tendenze nella progettazione di edifici per uffici sono introdotte nel capitolo 3, in cui vengono marcate le ragioni per cui vengono preferite a soluzioni statiche; successivamente, si illustrano i sistemi di illuminazione più diffusi negli edifici per uffici ed il loro impatto energetico, i sistemi di controllo dell'illuminazione più comuni, ed infine l'influenza che il comportamento degli utenti esercita sui precedenti (cap. 4). Nel capitolo 5 il flusso di lavoro adottato viene descritto ed illustrato, partendo dalla definizione digitale delle geometrie coinvolte e da tutte le configurazioni definite per l'oscuramento dinamico, seguite da simulazioni annuali (per illuminamento naturale e consumo energetico), estrapolazione dei risultati ottenuti ed infine la post-elaborazione dei valori ottenuti per definire un programma orario ottimizzato delle configurazioni assunte (cap. 5). Infine, viene effettuata una valutazione finale delle prestazioni energetiche, di illuminamento naturale e delle condizioni favorevoli alla regolazione del ritmo circadiano legati all'ambiente analizzato ed ottimizzato.

Il metodo proposto è stato applicato ad un caso di studio consistente in un ambiente interno standard – lo IEA BESTEST – a cui viene applicato in facciata un oscuramento dinamico esistente (sprovvisto di valutazione di illuminamento/consumo energetico), valutato per verificare l'accuratezza del flusso di lavoro definito precedentemente. Le simulazioni sono state effettuate per lo stesso caso studio secondo tre orientamenti diversi (Est, Sud, Ovest) e confrontati con un caso base uguale a quello definito, ma sprovvisto di oscuramenti e dotato di un sistema di illuminazione artificiale tradizionale.

I risultati ottenuti non evidenziano errori di forma legati alla modellazione digitale od alla definizione del programma ottimizzato delle configurazioni assunte dall'oscuramento, al contrario risultano affidabili e fluttuano tra gli estremi ipotizzati: con tale metodo un progettista può essere in grado di stimare l'efficacia di un oscuramento e di valutarne la validità, la sostituzione od il suo miglioramento. I risultati derivanti dall'analisi dei livelli di illuminamento utili alla regolazione del ritmo circadiano degli utenti possono fornire importanti informazioni sulla qualità dell'ambiente di lavoro, tuttavia una restituzione grafica più efficiente si rende necessaria per capire al meglio la questione.

Il DGP è un indice molto utile per stimare la potenziale insorgenza di fenomeni di abbagliamento ed è considerato il più affidabile tra i vari indici disponibili, tuttavia è noto che, nel caso in cui la luce solare ricada direttamente sull'utente, l'accuratezza risulti ridotta.

Contents

Chapter 1

Introduction

The work developed in these pages took inspiration from the topics faced during the *BIO-Design global classroom* held in the 4th semester (A.Y. 2016/2017) with the promotion of *Prof. Dr. Eugenia V. Ellis* and *Prof. Dr. Giuliana Iannaccone,* in a collaboration between *Drexel University* and *Politecnico di Milano*; in particular, the modules related to the human visual system, the chronobiology and the non-visual system caught my full interest and made me realize the actual importance and the impact of natural light on our lives.

At the same time, the attendance of the course held by *Prof. Dr. Marco Pesenti* in the same semester, dealing with some of the topics treated during the BIO-Design global classroom, helped me visualizing the possible outline of the work presented here, giving me a very solid background as starting point and good management skills for the work-flow.

Apart from the evolved interest for the topic, the motivation that made me pursue this work was to promote the daylight issue in commercial buildings and sensitize architects/engineers to consider it in the design and pre-assessment phases, whit the purpose of reducing time, cost and energy loads, and, simultaneously, increase comfort and health conditions for the occupants of the building.

1.1 Forward

Today's building envelopes are addressed to the main task of providing a barrier able to define thermal and visual comfort in the spaces we live and spend time in, and not only a separation between the interior and the exterior environments. When it's up to sustainable and high-performance facades, these optimal comfort targets must be achieved with the less amount of energy employed: firstly, designers should take into considerations many aspects like a climate-based design approach, employment of solar shadings, evaluation of discomfort glare, daylighting levels, moisture content and transport phenomena, materials to employ, thermal performances, etc…; secondly, designers should examine systematically a wide range of design options in which it is possible to quantify the effects of all the aspects listed before and eventually select the optimal solution based on specific fixed targets.

In the last few decades, technological improvements for advanced envelope systems have changed the scenario related to glazing and material properties, actuators, shading devices, lighting systems and their control, etc… allowing to reduce solar gains, increase the visible light transmission, lower the maintenance costs and adapt to changing climate stimuli, therefore a new path for the future design of high performance envelopes is almost well delineated.

Daylighting in buildings plays an important role and needs for an integrated design approach to fulfill its scope, however nowadays the initial assessment of the daylight (and energy) performance needs a tortuous workflow for its definition, especially due to limits in the digital tools that perform the analyses, such as the impossibility to change the geometric configuration of the shading once the simulation started.

At present, and maybe in the future too, it is not possible to follow generalized guidelines or rule-of-thumbs for both design definition and performance assessment, because high-performance facades usually consist in stand-alone cases defined by a very specific assembly of shape, materials and control strategies, in particular when the climate factor is involved.

1.2 Goal and scope

The contents described above show a clear tendency in today's architecture to dynamism, energy efficiency, climate-based approaches and increasing interest in lighting efficiency, however a workflow to follow for the definition of precise assessment of daylight (and energy) performance is not available for software-related problems.

The proposed work is aimed at the definition of a standardized analysis method to apply whenever dynamic shadings or kinetic envelopes are involved in the design of a building in order to assess the daylight (and energy) performance at the early stage of design for the analyzed environment. The assessment is pursued through a preliminary optimization of the desired daylight metrics, registered in the interior space, strictly dependent on the specific geometric configuration of the dynamic shading device considered for the design.

This method permits clearly to understand which is the actual potential of the employed dynamic shading according to the optimized parameter and if further adjustments or implementations are needed to achieve better results on both sides of daylight and energy performances. In this way it is possible to perform an integrated design with a fast feedback on the energy loads and the daylight quality by means of climate-based analysis, allowing to reduce energy costs and CO_2 production, to consider more features and aspects concerning daylight

1.3 Outline

The structure of the dissertation starts by analyzing the characteristics, influence, benefits and discomfort related to natural light and its effects on the human behavior, productivity, physiology and psychology, followed in chapter 3 by the illustration of the new trends in the design of office building facades that involve dynamism, and why these inclinations are preferred over static solutions.

Another section of the work analyzes the most diffused lighting system in office buildings, focusing on their impact on the energy consumption, and the most diffused lighting control systems and the influence of users' behavior on their efficiency.

In chapter 5 the workflow of the proposed method is explained and illustrated, starting from the digital definition of the involved geometries and all the available shading configurations, followed by daylight and energy annual simulations, extrapolation of the obtained results and post-processing operation to define the optimized hourly configuration schedule for the entire year, and eventually a final assessment of the energy and daylight performances of the analyzed environment provided with the optimized configuration schedule.

The proposed method is applied to a case study consisting in a standardized interior environment – IEA BESTEST building – to which an existing shading device (no daylight/energy assessment available) is applied on the façade and evaluated to check the accuracy and the workflow. South, East and West orientations were considered for the analyses in addition to the comparison with another IEA BESTEST building deprived of shading devices.

Results are then presented and discussed to check if their accuracy might be acceptable or not, and eventually final conclusions on the method and its application to a case study are provided.

Chapter 2

The importance of natural light

Light in general can be described as the electromagnetic radiation, which is a flow of energy travelling through free space or mediums, perceived by the human eye, spanning within a wide range of wavelengths. Usually, we refer to light as the very narrow band of wavelengths 400-700 nm that identify visible light and its adjacent spectral regions, corresponding to ultraviolet and infrared (figure 1). Light theory went through many scientific investigations during the past (and still nowadays) about its structure, nature and behavior (rays, waves, electromagnetic radiation, quanta), but not only scientists and engineers are concerned about this topic: alternatively, artists take part in the exploration of the many features related to the aesthetic appreciation of the visual world since spatial and temporal information are delivered through light.

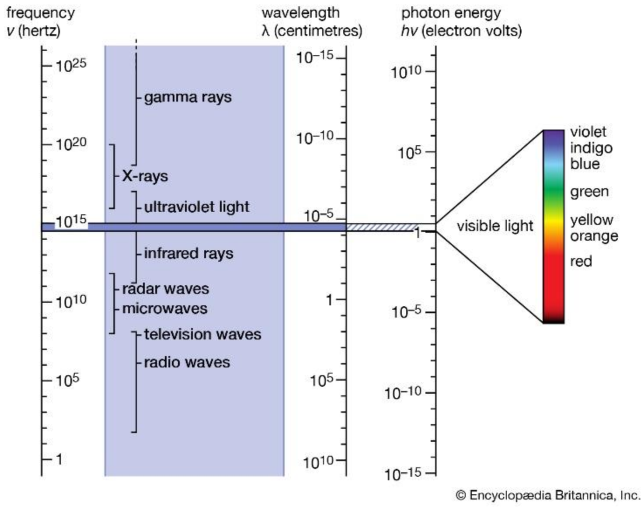


Figure 1 - Electromagnetic spectrum: position of light in the electromagnetic spectrum, Image, from Encyclopædia Britannica, accessed March 21, 2018, https://academic.eb.com/levels/collegiate/assembly/view/73677.

A good approximation of light properties can be found in the electromagnetism theory, where light is assumed as the combination of an electric and a magnetic field travelling through space or mediums in the form of waves that can store and transport energy, which is fundamental for the life on Earth: air temperature, weather patterns and photosynthesis are the main factors that allow life on the planet due to the involved physical and chemical processes. Energy from light is defined as irradiance (or intensity), a measure that represents the amount of energy that reaches a unit area perpendicular to the wave direction of propagation, and the main source of natural light available in nature, the Sun, provides a constant irradiance at the top of the atmosphere, called solar constant, which equals a value of 1350 W/m^2.

Light and its cycles are also responsible of recurrent physiological alterations in living organisms by regulating many endocrine functions like the secretion of melatonin by the pineal gland, which is accountable for the regulation of the sleep-wake cycles, in addition the controlled ultraviolet exposition of skin enhance the conversion of ergosterol into vitamin D which plays an important role in the normal deposition of calcium in growing bones.

2.1 Non-visual effects of daylight on human health

> *"Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity"*[1]

The definition of health provided by the WHO does not point out specific requirements and makes it necessary to analyze many aspects, researches and investigations on human health to outline and collect the leading factors that contribute to its enhancing or alterations, eventually adopting adequate strategies to guarantee positive conditions.

Surely, emotions in human health play an important role in the management of the brain's activities and homeostatic equilibrium: indeed, an emotion can be described as the response produced by the brain to a certain stimulus, interior and exterior, and it's produced by chemicals and neurological activities with the intent of maintaining the body homeostasis, differing from feelings that represent simple interpretations of the emotions by the brain activity. Emotions are generated by coordinated activities in different regions of the brain aimed at the definition of neural patterns and, considering the relevance of the emotions on the human well-being and the little research activity pursed to identify the variables present in the built environment that affect our emotions, architects, and designers in general, should investigate the topic and aim at building pleasant environments not only considering the appearance of the world we live, but also the possible effects on our emotions.

Natural light, or daylight, deeply affects the activities that take place in our brain and, consequently, our body, determining also related changes in emotions and mood. Light activates the visual system through the absorption of photons by the photoreceptors present in the retina, which triggers a series of neurochemical reactions: all the living organisms respond to light stimuli through a specific biological process called *phototransduction*, which comprises the absorption of light by photoactive molecules called *chromophores* and the subsequent physiological responses (the chromophores are characterized by a spectral absorption of light and, like a fingerprint, they are unique within each molecule). These responses contribute in the setting of biological rhythms in a multitude of living organisms, spanning from thermal regulation to sleep/wake cycles, defining the so called circadian rhythm (figure 2).

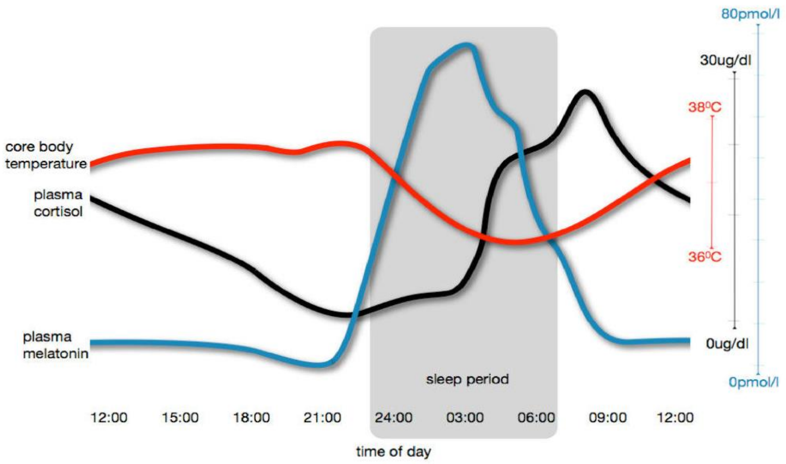


Figure 2 - Relationships between sleep and daytime activity and varying levels of cortisol, melatonin and body temperature. Image credits: https://bmcmedicine.biomedcentral.com/articles/10.1186/1741-7015-11-79#Abs1, last accessed March 25, 2018

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[1] Preamble to the Constitution of WHO as adopted by the International Health Conference, New York, 19 June - 22 July 1946; signed on 22 July 1946 by the representatives of 61 States (Official Records of WHO, no. 2, p. 100) and entered into force on 7 April 1948. The definition has not been amended since 1948.

Circadian physiology started to be explored after the discovery, about 50 years ago, that light plays a primary role in the regulation of the pineal gland functions and the melatonin levels; through the first analyses involving polychromatic stimuli it resulted that the light spectrum between 450 nm and 550 nm strongly influence the circadian response in mammals and afterwards the analytic action spectra helped in defining the wavelength sensitivity with higher precisions and identifying in an accurate way the photopigments involved in the phototransduction process.

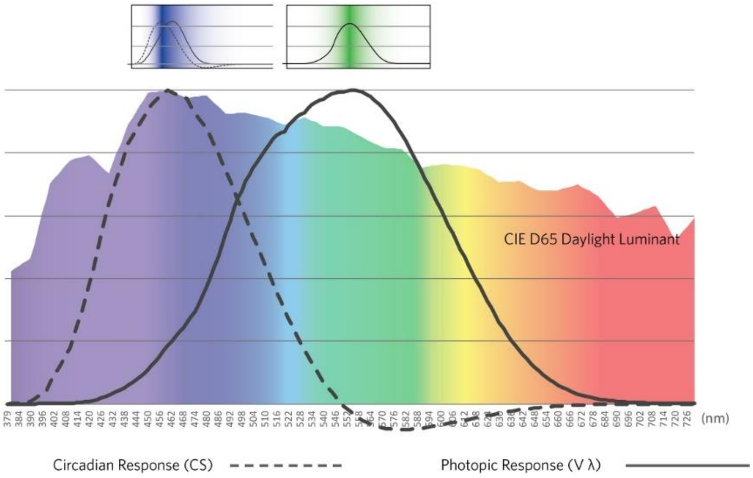


Figure 3 - Spectral variation of receptors in the daylight spectrum (colored). Image credits: http://www.metropolismag.com/interiors/healthcare-interiors/why-light-matters-designing-with-circadian-health-in-mind/, last accessed March 25, 2018

Many studies developed in the past assessed that *rods* and *cones*, the main photoreceptors in the retina aimed at capturing visual information and send it to the brain for the elaboration of images, do not take part in the circadian regulation of living organisms, but the discovery of a different kind of photoreceptors at the beginning of the millennium, called *intrinsically photosensitive retinal ganglion cells (ipRGC)* (figure 4), that use melanopsin for the phototransduction process, showed their participation in the synchronization of the circadian clock and, at the same time, also contribute to human vision altogether with rods and cones at the retinal level by perceiving blue light: these photoreceptors are believed to affect also learning and memory skills, opening up an entire field of study about the engineering of lighting system and their correct applications by using adequate light wavelengths for medical or educational purposes. The ipRGCs deliver a part of information to the suprachiasmatic nuclei (SCN) of the hypothalamus, which serves as the circadian clock in an organism: the circadian rhythm (from Latin, *circa* = nearly, *dies* = a day) controls many vital functions and it is strongly influenced by sleep/wake and light/dark cycles.

The humans' circadian clock is usually set on a 24-h averaged cycle, it responds to a complex series of neuroendocrine changes and hormone oscillations that induce acute effects on the most physiological functions of the body (figure 5). Among these we can find the secretion of melatonin, the hormone secreted by the pineal gland aimed at the regulation of sleep cycle: during the day, natural light suppresses the melatonin production in our organism, while during the late afternoon and the beginning of the evening, when the retina detects a reduction of daylight, the blood concentrations increase and reach their peak around 2 – 4 am. However, exposition to bright light, and especially blue lights, during night time could suppress the production of melatonin (such as happens during the daytime), altering the circadian rhythm and consequently the sleep cycle periods, but anyways a research that investigated the effects of daylight on disrupted circadian cycles concluded exposition to natural light during the morning reduces the melatonin suppression effects during night caused by bright lights.

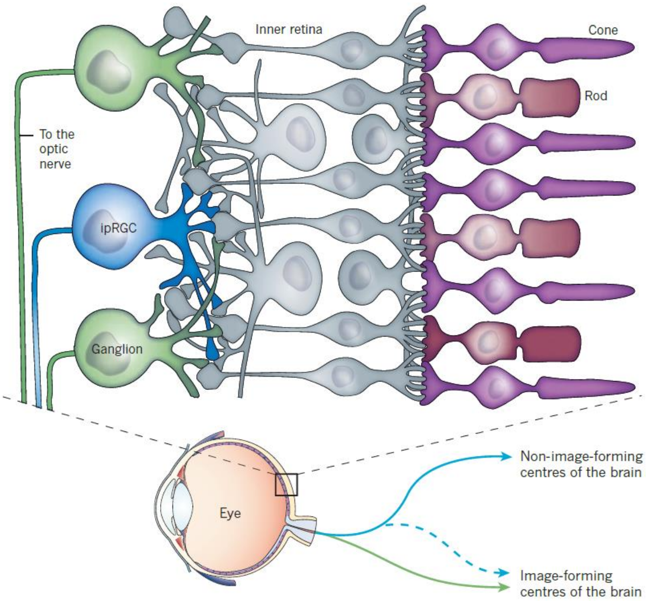


Figure 4 - Illustration of the retinal structure of the human eye, with indications on the type of information collected and distributed to the brain, Image Credit: Published online 19 January 2011 | Nature 469, 284-285 (2011) | doi:10.1038/469284a

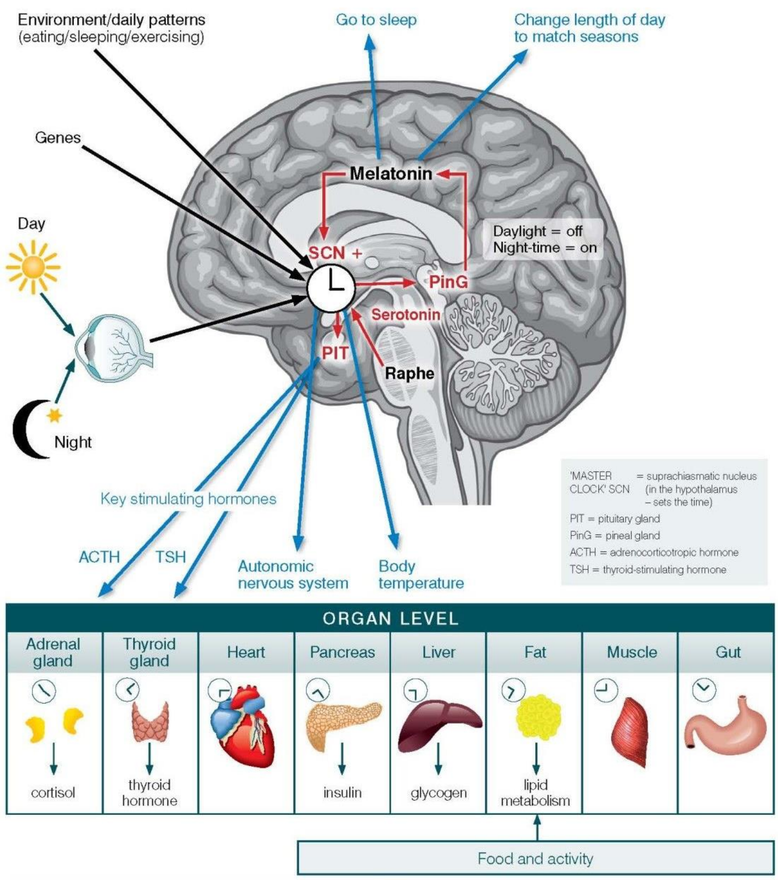


Figure 5 - The master circadian clock in the human brain.
Image credits: https://bmcmedicine.biomedcentral.com/articles/10.1186/1741-7015-11-79#Abs1, last accessed March 25,2018

Visible light, hence, can contribute both in regulating and disrupting the circadian clock of humans, especially the consequences related to air travel, indoor light conditions and working during the normal sleep hours may lead to a series of emotional and physiological diseases. Among these we can find the *seasonal affective disorder* (SAD), a form of major depressive disorder that corresponds to a seasonal depression state occurring in not particularly stressed conditions, but it has been discovered a direct relation with the shorter duration of the days from fall to spring and the consequent less availability of natural light during the day: approximately 14% of Oslo population is affected by SAD and this disease is commonly diffused in northern climates all over the world, moreover a lesser form is widely diffused affecting a higher range of people, known as "winter blues". People affected by SAD can be cured, among different treatments, with light therapy, consisting in a forced exposition to a white fluorescent light source emitting about 10˙000 lux for a certain time-laps varying for each patient. Even though most of the light therapy uses have focused on SAD, additional applications can be extended to non-seasonal depression, various sleep disorders, menstrual cycle–related problems and bulimia nervosa; moreover, the therapy allows to reduce the circadian disruption associated jet lags and shift work.

Daylight also affects the immune response, which is susceptible to stress, seasons, mood alterations and the circadian rhythm, by activating the suprachiasmatic nucleus and the related triggers for the pineal gland and pituitary, with the consequent production of hormones like cortisol, serotonin and dopamine, and, at the same time, suppressing the melatonin production: observations on this topics helped in the definition of chronotherapy, which is adopted whenever specific timings and preferred time of the day are considered to enhance the efficacy of a medical treatment, especially when related to autoimmune disorders, heart disease and diabetes.

In a similar way, also the ultraviolet part of the visible light can induce some benefits in human health by a skin (figure 6) mediated response rather than the visual system: UV A could be very effective in atopic dermatitis treatments and some autoimmune diseases, while UV B is widely known for the induced photoproduction of vitamin D that helps in the calcium and bone metabolism.

Alternatively, infrared radiation can be very harmful for tissues and can damage the retina, which is reachable on the contrary of the ultraviolet radiation; the most diffuse disease is the *chorio-retinal damage*, a thermal effect that concern the retina and lead to the creation of blind spots in the sight.

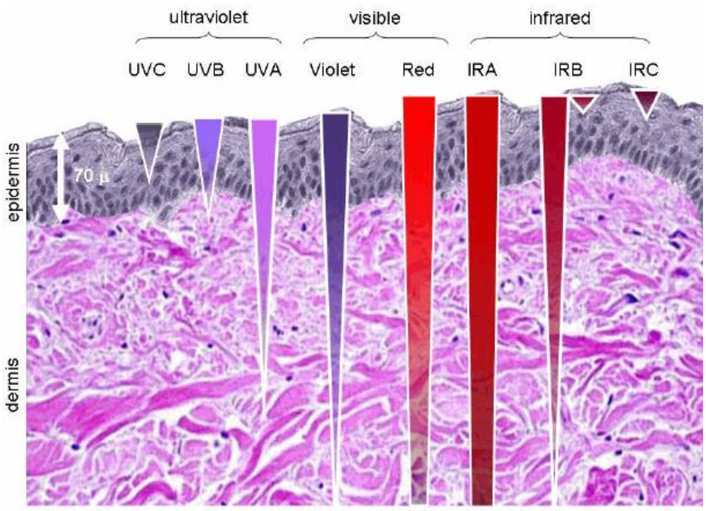


Figure 6 - Skin penetration by light, transmission of different wavelengths of radiation through the skin. Image credit: https://copublications.greenfacts.org/en/artificial-light/figtableboxes/8.htm, last accessed March 25, 2018

2.2 Productivity, visual comfort and energy savings related to daylight

Daylight affects users' satisfaction, productivity and perceived visual comfort. The productivity of individuals is strongly influenced by the system factors and particularly by the indoor environment quality, which includes lighting conditions (figure 7) acting on both the visual, circadian and perceptual systems, on the other hand the performance of the visual system is affected by visual size, color difference, retinal illumination and image quality, and contrast, which are all parameters that allow to identify and correctly detect a stimulus. The exposition to bright lights before and during shift works enhance productivity of workers by increasing alertness, but it is very important to not act only during working hours, but way before in the afternoon to make the treatment effective. The perceptual system instead derives from personal evaluations on the properties of the task area since good lighting conditions might not be sufficient even when respecting the minimum required illuminance levels, or maybe the light color.

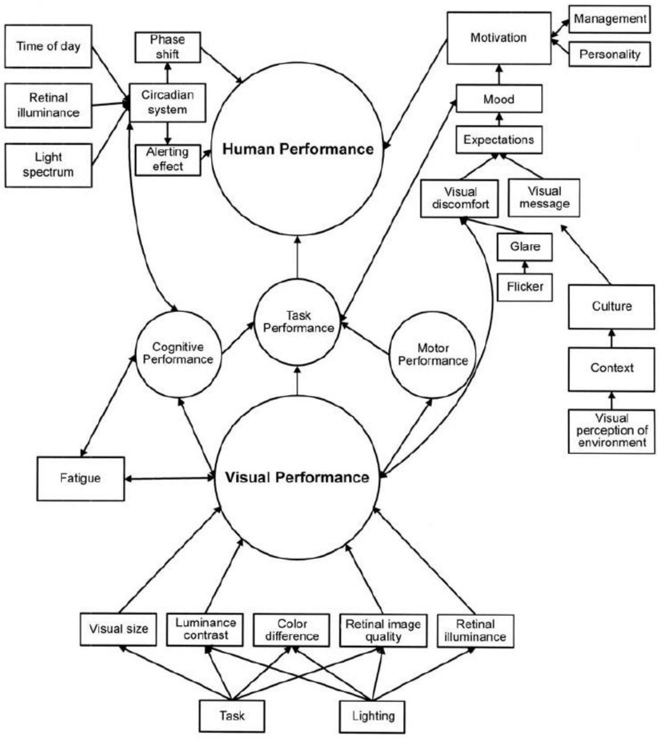


Figure 7 – Illustration of all the possible influences that light could apply to the human performance. Image from http://thedaylightsite.com/wp-content/uploads/papers/DaylightBenefits.pdf, last accessed March 21, 2018

Natural light is very important when the visual tasks involve fine color discrimination because it span the whole spectrum, but in the general case daylight is not inherently superior to artificial light when dealing with visual tasks and human performances, unless specifically and critically designed by the architect, which should avoid color saturated interior surfaces, strong shadows, low levels of illuminances. However, on the basis of the perceptual system, daylight results to be totally preferred by users against artificial lighting, probably because the presence of windows allows ventilation, view towards outside and access to environmental information such as the passing of the day and the weather conditions; people also tend to improve their mood when working in offices provided with large window, therefore it can be assumed that better moods could lead to higher work performances, moreover there is evidence that people in stressful situations that have access to a natural view make fewer calls on the healthcare provider than those who don't have such a view.

Visual comfort depends on the task and many related variables, when it is not achieved some diseases might be encountered: eyestrain is among the most diffused effects of lighting through the visual system with symptoms that include irritation of eyes, double vision, blurred vision, etc… It might derive from poor lighting, the specific task and its surroundings, or specific problems previously affecting the user, and its mechanism can be induced by the muscular strain of the ocularmotor system (pupils' dilatation and contraction, convergence of the eye, etc…), by poor illumination of the visual task area, the presence of flickers or other stress-causing situations, and these might lead to detractions to productivity of workers.

Some groups of people are very sensitive to lighting conditions, i.e. photoepileptic people could be driven to seizure in case of fluctuating artificial lighting at a certain frequency, which can be mostly avoided when daylight is involved for interior illumination. Another special group of people might often suffer of migraine and experience higher sensibility to light and especially low tolerances to sunlight through windows.

Sleep disorders derive from the disruption of the circadian system of people due to the night exposure to bright or blue light, causing shifting in the sleep phase of people (especially young) and the consequent chronic sleep debt makes people feel permanently tired, undermining the work efficiency.

Stress is also tightly related to workers productivity: prolonged experiences of stress could bring to undesirable health issues and also changes in behavior, such as absenteeism, lower performance and higher turnover of employees, however it seems that the view through a window (real or even of artificial construction) could help in relieving stress.

The visual comfort, being a personal perception, needs to be identified under a common reference method for the indoor environmental quality of buildings, therefore different metrics based on daylighting have been defined since now (and still going on) for the assessment of well-lit ambient. About 50 years ago, the *daylight factor* (DF) was proposed as the metric that would better define the daylight assessment of buildings, and right now it is the required metric to calculate by many codes: the daylight factor is defined as the ratio between the illuminance measured at a certain point inside a room and the illuminance measured outside without presence of any obstruction, evaluated under overcast sky conditions and assuming a constant distribution of the sky brightness. This parameter, being calculated in overcast conditions, does not take into consideration the varying glazing orientation, sun position, time of the day, season and actual sky luminance, however the returned DF is usually used to portray the worst-case scenario for illuminance levels on cloudy days, so to allow designers to present an adequate solution that can satisfy the minimum required values, but no indications are available about glare phenomena and overheating.

In relatively recent years, new climate-based analysis method has been proposed as substitution the DF method: climate-based daylight modelling (CBDM) is effective because it relies on realistic sun and sky conditions defined by typically registered values incorporated in weather files, allowing to generate and analyze new metrics such as the daylight autonomy (DA), the useful daylight illuminances (UDI), the spatial daylight autonomy (sDA), etc….

The *daylight autonomy* (DA) is a coefficient that represents the percentage of time during the year that a minimum illuminance threshold value is reached by just daylight, on the base of the occupancy schedule and the varying sky conditions in time: on the contrary to daylight factor, daylight autonomy is strictly linked to artificial lighting energy need because lower DA values corresponds to higher energy consumption and vice versa. Mentioned for the first time in 1989 in a Swiss norm, this parameter nowadays has been implemented by considering in the calculations the presence of manual blinds whose motion can be scheduled throughout the year. The typical threshold value is assumed at 300 lux, which is also adopted by the LEED guidelines for the definition of the spatial daylight autonomy.

The *spatial daylight autonomy* (sDA) relies on the previous DA values calculated for a specific work plane defined by an analysis mesh: being one of the crediting parameters defined in the LEED guidelines, this daylight metrics represents the percentage of the work plane achieving the minimum illuminance level of 300 lux for at least the 50% of the occupied hours (indicated as $sDA_{300,50\%}$). Avoiding an upper boundary, sDA is usually coupled with another a metric called annual sunlight exposure (ASE), since it is more related to visual comfort.

The *annual sunlight exposure* (ASE) is a daylight metric very similar to the sDA, previously defined, to which is strictly linked. The ASE represents the portion of the work plane that exceeds the illuminance level of 1000lux for at least 250 occupied hours during the entire year; the metric should always be presented along with the sDA, in this way it can give the designers some preliminary feedbacks on their work about the risk of glare phenomena or overheating, especially during the first design phase of the project. The LEED guidelines suggest limiting the ASE to 10% of the total area (indicated as $ASE_{1000,250h}$).

The *useful daylight illuminance* (UDI), proposed by Mardaljevic and Nabil in 2005, is very similar to the DA and it indicates the percentage of occupied hours in which the illuminance levels reach or do not reach certain thresholds: a low bound set to 100 lux, under which the UDI is fell-short and the ambient is too dark, a high bound set to 2000 lux, above which the excess of daylight could trigger glare phenomena and overheating of the ambient, while all the values included within the boundaries are considered to meet the UDI. It is also possible to look for a further subdivision of the UDI range, adding the UDI-supplementary and UDI-autonomous: the first one shows the amount of time when the daylight illuminance levels are between 100 and 500 lux, where the need for artificial lighting may be reported or not according to the task level, while the second one span from 500 and 2000 lux and usually is related to all those moments when artificial lighting is not needed at all. This metric is outlined by ranges drawn from occupants' surveys that reflect their preferences about the daylight quality of the work environment.

Currently, no minimum requirements have been defined for the support of the circadian entrainment, though some researchers suggest designers to guarantee to the building users the availability of 180 lux at the eye level for at least 1 h in the morning or 226 lux for at least 4 h (continuously, at any point of the day.

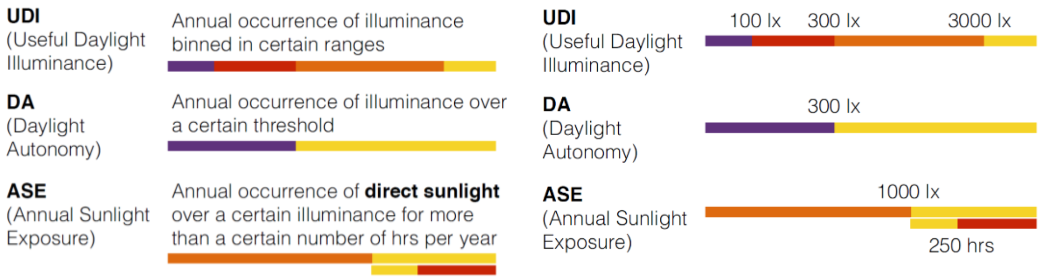


Figure 8 - Illustration of some of the climate-based metrics used for the daylight assessment of interior spaces. Image credit: Eleonora Brembilla & John Mardaljevic (2016), "Climate-Based Daylight Modelling The What, the Why and the How - Part 2", last accessed March 25, 2018; https://www.researchgate.net/publication/294573316_Climate-Based_Daylight_Modelling_The_What_the_Why_and_the_How_-_Part_2

The adoption of daylight harvesting strategies through large fenestration systems could enhance energy savings for mainly two aspects: reduced solar gains and artificial lighting. High solar gains contribute in increasing the peak design load for the HVAC system leading to consequent higher costs for the system components, installation and energy required in order to guarantee the thermal comfort for the users.

Even though artificial lighting technologies have been highly improved in the last decades, the sun still remains the most efficient light source known by mankind, emitting a luminance of about 100˙000 lm in bright sun conditions and 20-30˙000 lm on a cloudy day, on the contrary the typical fluorescent lamp has a luminance of 4˙500 lm, however, considering that the typical values needed on working areas should roam around 300-500 lm/m^2, the need to control the external light source becomes very important. The use of lowered lighting power density (LPD) systems can help in reducing the internal gains and save energy for artificial lighting, allowing in extreme cases to halve the electric energy consumption that should be aimed at reaching a value of 8 W/m^2 according to the European standard NS-EN 15193 *Energy performance of buildings – Energy requirements for lighting*.

2.3 Discomfort effects of daylight: glare phenomena

Glare can be defined as the *"condition of vision in which there is discomfort or a reduction in the ability to see details or object, caused by an unsuitable distribution or range of luminance, or to extreme contrast"*[2]; glare discomfort is related to the visible sky luminance perceived by the users and the vertical illuminance registered near glazing, it occurs more frequently in ambient with high WWR and in the areas closer to the façade and might be experienced also with lower sky luminance combined to a high contrast of the visual task area.

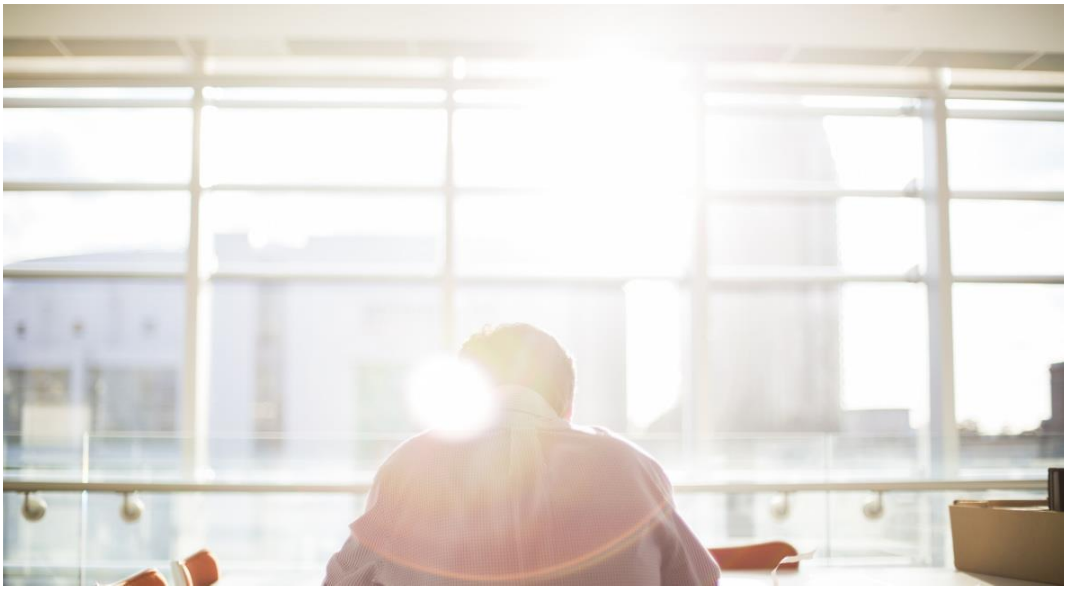


Figure 9 - An example of discomfort glare perceived by the building occupants.
Image credit: https://www.blackdiamondtint.com/single-post/reduce-office-heat-and-glare-with-window-tinting

Glare control became an essential feature to be integrated in the innovative daylight systems, especially when responsive controls are embraced, by predicting the occurrence of visual discomfort through experimental formulas and indexes. A reliable unique metric for the evaluation of glare does not exist yet, however the two most diffused methods included during the daylight analyses are the Daylight Glare Index (DGI) and the Daylight Glare Probability (DGP): in case of non-uniform light source and more in general, the DGI seems not to represent correctly the discomfort glare effects, showing results often not coherent with the users' perception, on the contrary the DGP seems to correlate more to the users' perception and the vertical illuminance at the glazing, though, if detailed predictions are needed, the thresholds should be arranged for every single analysis.

[2] CIBSE Lighting Guide LG7, 2005

The discomfort index related to glare can be calculated with the DGP method through the equation proposed by Wienold and Christoffersen in 2006, which combines the modified glare index formula with the vertical illuminance, defined as following:

$$DGP = c_1 \cdot E_v + c_2 \cdot \log(1 + \sum_i \frac{L_{s,i}^2 \cdot \omega_{s,i}}{E_v^{a_1} \cdot P_i^2}) + c_3$$

E_v:	vertical Eye illuminance [lux]	$c_1 = 5.87 \cdot 10^{-5}$
L_s:	Luminance of source [cd/m²]	$c_2 = 9.18 \cdot 10^{-2}$
ω_s:	solid angle of source [-]	$c_3 = 0.16$
P:	Position index [-]	$a_1 = 1.87$

Usually, the daylight glare probability is determined by image-based simulations relying on HDR images, built as hemispherical fish-eye frames, that evaluate the vertical luminance of the background and the task area to determine the occurrence of visual discomfort at a certain time and date and related environmental inputs. This method, performed by Evalglare[3], is not suitable for annual simulations because it would be necessary to capture around 4000 images per time-step hour, resulting in a considerable computation overhead for the machine, therefore the previous formula for the definition of the DGP has been redefined to make it suitable for running annual analyses: the simplified new version doesn't consider the contact of direct sun (or its specular reflection) with the user eye, so the middle term of the equation is ignored and the vertical illuminance at the eye remains the key parameter, resulting in the following simplified equation:

$$DGPs = (6.22 \cdot 10^{-5} \cdot E_v) + 0.184$$

According to different surveys, three glare classes have been outlined on the basis of thresholds set to 95% percentile of discomfort perceived as listed in table 1. It is again reminded that this assessment doesn't guarantee to achieve a precise prediction because it is affected by many factors (user's perception, behavior, sky luminance, etc…), therefore post-occupancy evaluations are always important to understand if the control adopted to prevent discomfort glare are actually effective.

	A Best class	B Good class	C Reasonable class
DGP limit	≤0.35	≤0.40	≤0.45
Average DGP	0.38	0.42	0.53

Table 1 - Suggestion of glare classes for interior environments, proposed by Wienold

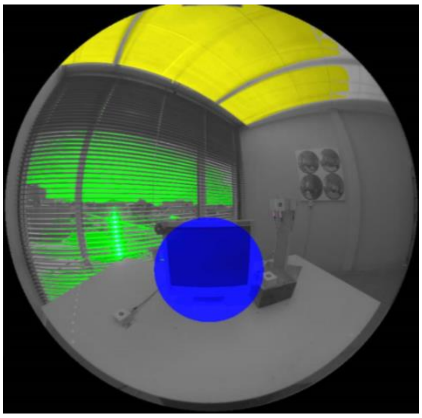


Figure 10 - Example of the HDR image defined and analyzed with Evalglare; the blue circle represents the task area. Image credit: https://www.radiance-online.org/community/workshops/2013-golden-co/wienold_glare_rad_ws2013.pdf, last accessed March 25, 2018

[3] Evalglare is a Radiance based tool for the evaluation of glare in interior environment developed by Jan Wienold.

Chapter 3

Daylight control and enhancement through the building envelope

The main function of buildings is to shield people from the exterior conditions and to supply them a certain level of comfort, it is possible to state that the users and their needs are the main focus points for what concerns the energy consumption of a built environment, making the building envelope the actual parameter to deal with when energy reductions are necessary.

The distribution of daylight in interior spaces relies on daily sky conditions and many geometric constraints related to the surrounding context (like other buildings, trees, etc…) and the orientation, the main shape and the envelope of the considered building: for the latter feature, the daylight penetration depth in a specific room is be strictly linked to a series of design considerations that should be kept in mind, which especially include the characteristics of the glazed portion of the envelope. Referring to an exterior wall, the window-to-wall ratio (WWR), representing the percentage of glazed surfaces on the total wall, strongly affects the daylight distribution, as well as the dimensions and location of the windows: as a general rule, the window head height can be considered as one of the main features that influence the daylight penetration in the room (figure 11), especially when combined with sloped ceilings, moreover in the wall portion located under the window sill (i.e. usually placed at a height of 0.9 – 1.0 m) the installation of glazing gives little to no contribution to the penetration depth of natural light but it can actually increase the amount of solar gains.

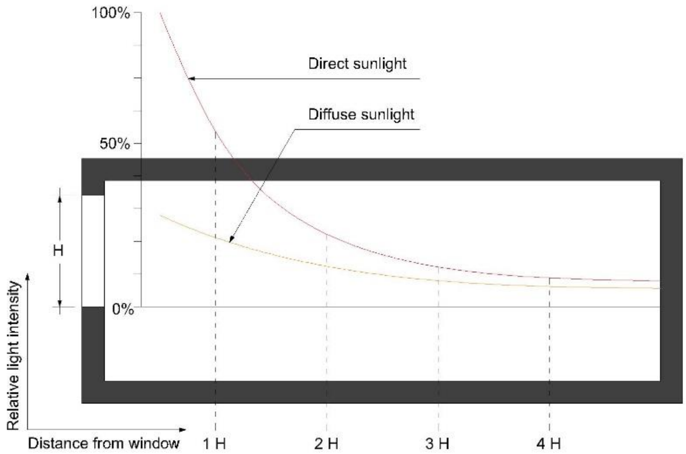


Figure 11 - Correlation between daylight relative intensity and room depth

In the design of today's office buildings, daylight availability is considered a fundamental feature, believed to increase the building value, stimulate workers productivity and decrease the energy consumption related to artificial lighting, therefore designers started to provide high WWR to new constructions, so to enhance this daylight component of the overall interior environment quality. Unfortunately, this design characteristic, if not defined with an integrated approach, could lead to a boost in cooling loads, due to the related increase in solar gains, and the rise of glare problems, especially in Mediterranean areas: in fact, natural light, as previously said, stores and transports energy that is transmitted by the glazing to the interior surfaces, then absorbed and re-irradiated as infrared radiation inside the room, leading to an increase of the surface temperature of the hit surface and, consequently, the interior air. High energy demands lead to high primary energy use, thus high CO_2 emissions and air pollution: the built environment is responsible of about one-third of the carbon dioxide production, in particular office buildings can be accountable of about one-fifth of the total urban electric energy consumption. It is then clear the importance of controlling and reducing the energy needs of these kind of buildings, so to reduce their environmental impact and fight climate change.

Solar shadings are clearly addressed as the most effective solution to overheating phenomena occurring in indoor environment, allowing strong reductions of the cooling energy needs by reducing the peak loads and therefore the HVAC system capacity and operating time, especially in those cases where an integrated shading/architectural design is approached. The side effect of the majority of blind systems is the total block of the direct solar radiation, followed by a decreased illumination inside the room: hence, a good design of the shading element shall be provided, so to reach both requirements of reducing the solar gains and increasing the daylight penetration in the room by guaranteeing protection from glare phenomena. This explains why many shading devices are also designed as daylighting systems, improving visual conditions in the further areas from the glazing especially by reflecting direct sunlight; in overcast sky conditions this role can't take place, therefore no increase of daylight contribution in deeper areas is met, especially when the system is static. Adjustable systems perform very well in mid-seasons thanks to the possible adaptation to varying sun-path conditions, moreover, shading devices show better performances when installed on the exterior side of the envelope rather than the interior one since in the latter case it would also act as a heat storage, consequently re-irradiating the absorbed energy to the interior ambient.

At present, in the early stage of design it is possible to predict correctly the main performances of a building provided with shadings such as energy needs for heating and cooling, solar gains, daylight illuminance levels and, in relation to the latter, the artificial lighting energy need and this general assessment is achievable thanks to many available software that could be involved in the design process, allowing to link daylight simulations to energy ones.

Following, the main categories of shading elements (figure 12) are described, highlighting the main pro and cons, and examples will be given.

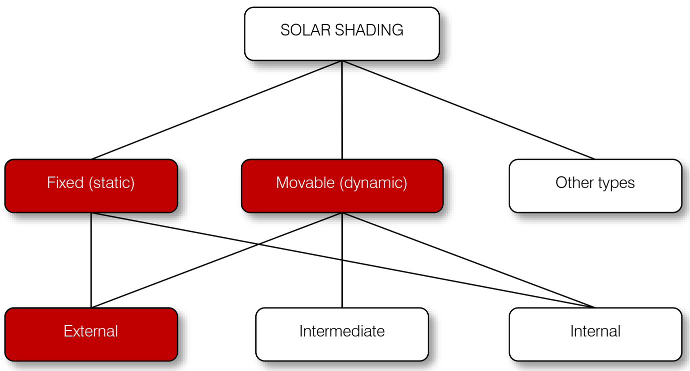


Figure 12 - Solar shading systems for buildings: a possible classification

3.1 Static approach: drawbacks of an outdated design attitude

Static shadings are widely employed all over the world since years for their simplicity, relatively cheap cost, easy maintenance and good performances: there are many types of static devices, such as overhangs, vertical fins, eggcrate structures, louvers, loggias, balconies and roofs, and their application strongly depend on the direction faced by the glazing that needs to be shaded. In fact, vertical static elements result to be efficient for east/west orientations (figure 14), while horizontal shadings are suitable for south exposures and both of them achieve very poor performances if employed for glazing facing different directions, making necessary to install different devices for different exterior walls. This fact doesn't mean that this type of shading isn't able to achieve good performance, on the contrary it is possible to achieve the best efficiency of a static shading and very good results through its optimization, allowing consequently to increase the daylight comfort inside the building and reducing the energy demand, meaning lower CO_2 emissions. The adoption of static devices can be useful in cooling dominated climates, achieving good results in both thermal comfort and energy savings, however if we analyze their employment in mild and heating dominated climates the total energy demand would increase because of the lower amount of solar gains.

Figure 13 - Example of a typical fixed shading consisting in a horizontal louver. Image from Archdaily.com, last accessed March 22, 2018; https://www.archdaily.com/catalog/us/products/11876/solar-shading-reynaers-aluminium/111493

Fixed external shadings need lower maintenance, can be low-tech, economic and, if adequately designed, might increase the daylight depth penetration inside the room, but unfortunately the optimization of the system would be defined only on a specific design period (usually the worst scenario according to the climate) and a seasonal or monthly shading optimization wouldn't achieve the best performance possible for the whole annual environmental conditions.

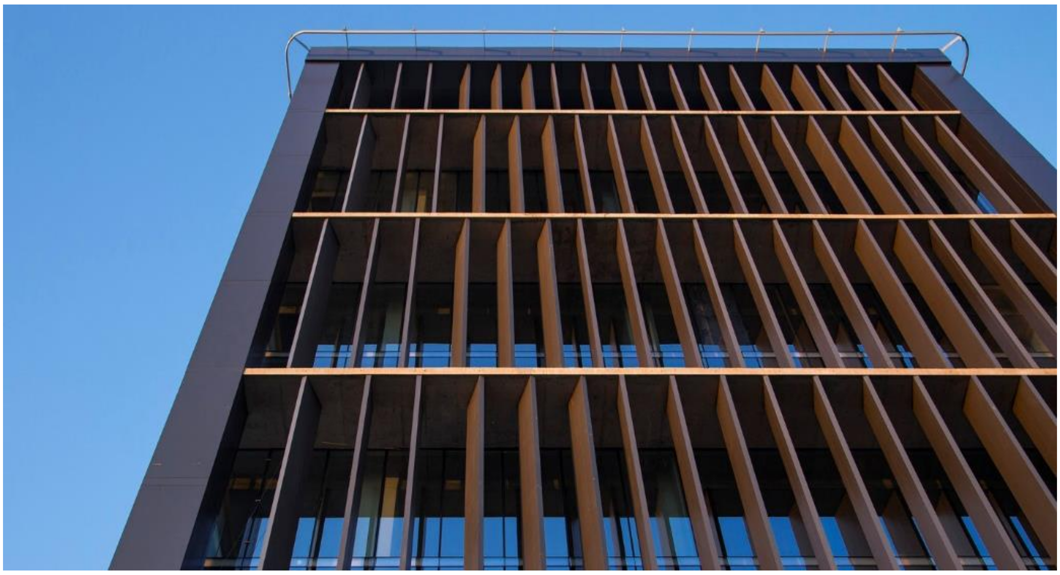


Figure 14 - Example of a fixed shading consisting in vertical fins. Photo credits to Marcos Mendizabal, https://www.archdaily.com/768087/office-building-kennedy-wisconsin-alemparte-morelli-y-asociados/557245d5e58ece23c8000108-office-building-kennedy-wisconsin-alem

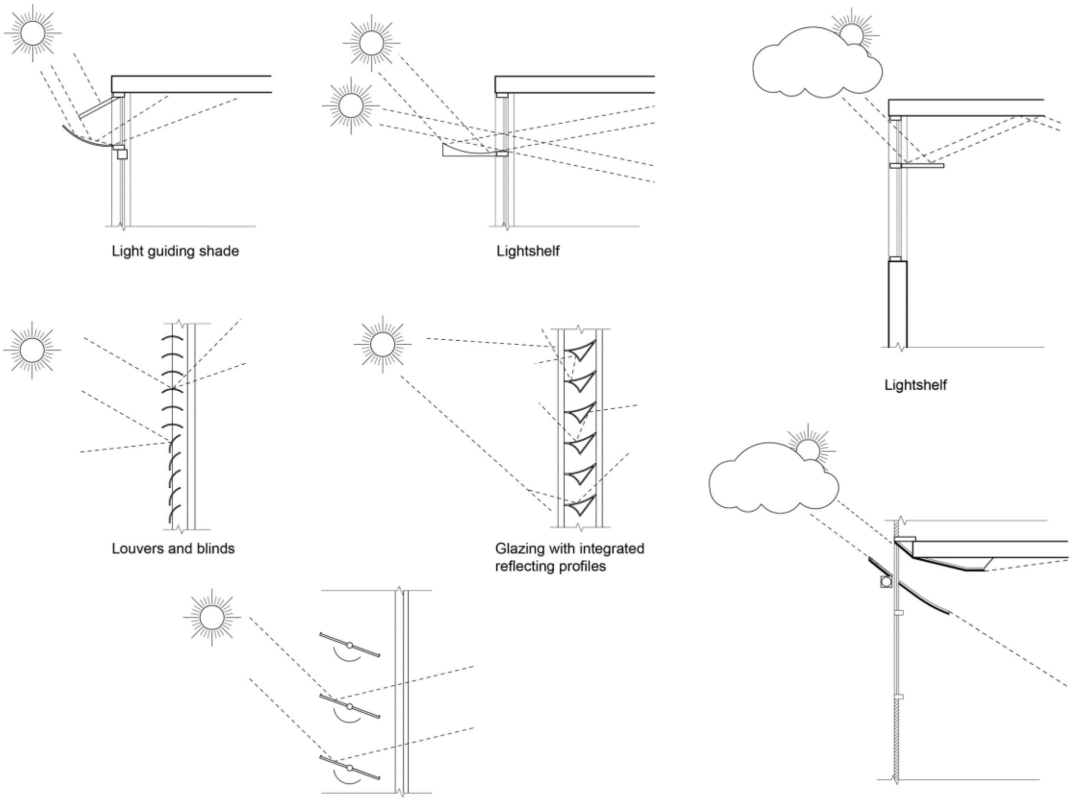


Figure 15 - Light-redirecting mechanisms for locations with predominantly sunny sky conditions and light-directing mechanisms for locations with predominantly cloudy sky conditions; image credits to Aksamija (2016), "Design methods for sustainable, high performance building facades"

3.2 Advanced solutions: kinetic facades, responsive envelopes and CABS.

Many studies have noted that the major cause of the high energy consumption – even in cold climates – of highly insulated residential buildings is represented by the overheating phenomenon that occurs during summer and the intermediate seasons. According to this, it might be reasonable to assume that office buildings as well could be affected in the same way by the same problem: in fact, the typical office buildings built nowadays are provided with large glazing to enhance the daylight penetration depth in the interior spaces and to add value to the construction (figure 16), however this solution implies an increase of solar gains and the consequent amplification of cooling energy demand (in both summer and intermediate seasons) and glare risk.

Figure 16 - Typical architectural features involved in the design of today's commercial buildings: the provision of high WWR is very common and widespread all over the world. Free stock image, last accessed March 23, 2018; https://stocksnap.io/photo/YWJJ8BCZE4

Many researchers claim that the adoption of dynamic shading systems would define the best daylight scenarios among many available solutions and, in comparison to static shadings, lower energy consumption can also be achieved, especially when these systems can automatically adjust to the most favorable position during the day and the interval of movements is frequent, then the provision of an automatic control – in particular if user-accepted – could help in defining more realistic predictions about the system performances than when manual controls are involved (they are usually not well actuated by the users).

However, dynamic shadings are characterized by a remarkable contradiction: the accomplishment of reaching high performances for daylighting and energy savings is subordinated to an energy consumption derived, in the first instance, to the actuation of the components aimed at developing the motion, hence the actual improvement of the overall performances of the building involving dynamic shadings shall be assessed at the early stage of design, when it is possible to change or improve the adopted system without negative consequences on the final design development. Dynamic shadings can be divided in two categories, in which the first one comprises systems that block the radiation and diffuses light, and the second one redirects the radiation to deeper ambient areas.

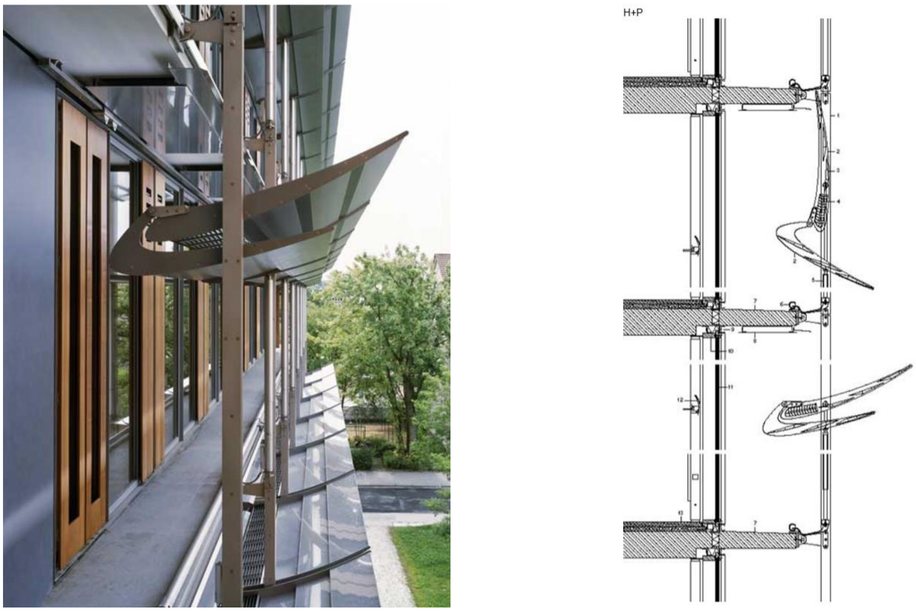


Figure 17 - Example of a dynamic shading device consisting in horizontal lamellas able to block radiation or enhance it by reflection (project by Thomas Herzog). Photo credits to P. Bonfig, last accessed March 22, 2018, http://www.iuav.it/Ateneo1/docenti/architettu/docenti-st/Carbonari-/materiali-1/Materiali-2/dispens

The dynamic approach can be considered as function-based on environmental goals and indoor environmental quality by means of spatial transformations through real movements, or non-spatial transformation through materials deformation, encouraging the adoption of integrated design methods, innovation and development of advanced technologies to pursue energy-saving behavior. This explains why kinetic architecture is capturing attention nowadays: its applications have been made possible thanks to the recent improvements in technology and an increased interest in the research for comfort, flexibility, adaptability and improved management of natural resources. The approach pursued in kinetic architecture follows the mutable social functions that take place before and after occupancy and requires a strong design interconnection among materials, structural elements and mechanical joints, making it necessary to approach data updating to avoid risks of failure of the kinetic system.

Kinetic architecture obviously leads to higher construction costs due to the increase of complexity and the need for responsiveness, but the right optimization of the components and motions according to the various environmental inputs, i.e. sunlight or natural ventilation, allows to reduce in a faster way the running costs during the building life-time: the sustainability target is reached whenever the energy employed to trigger sensors and actuators results to be lower than the total energy savings achieved, taking into account also embodied energy of some components.

It is possible to distinguish among these dynamic solutions Climate Adaptive Building Shells (CABS) that automatically adapt to the users' needs or the current climatic conditions, Acclimated Kinetic Envelopes (AKE) whose adaptation takes place through reversible, incremental and mobile ways of change, and Adaptive skins which are able to adapt themselves to changing situations without needing external interferences: these solutions represent the most advanced concept of building envelopes and still are under definition and evolution, no standard idea or workflow is shared and all the built applications are stand-alone architectural pioneering experiences.

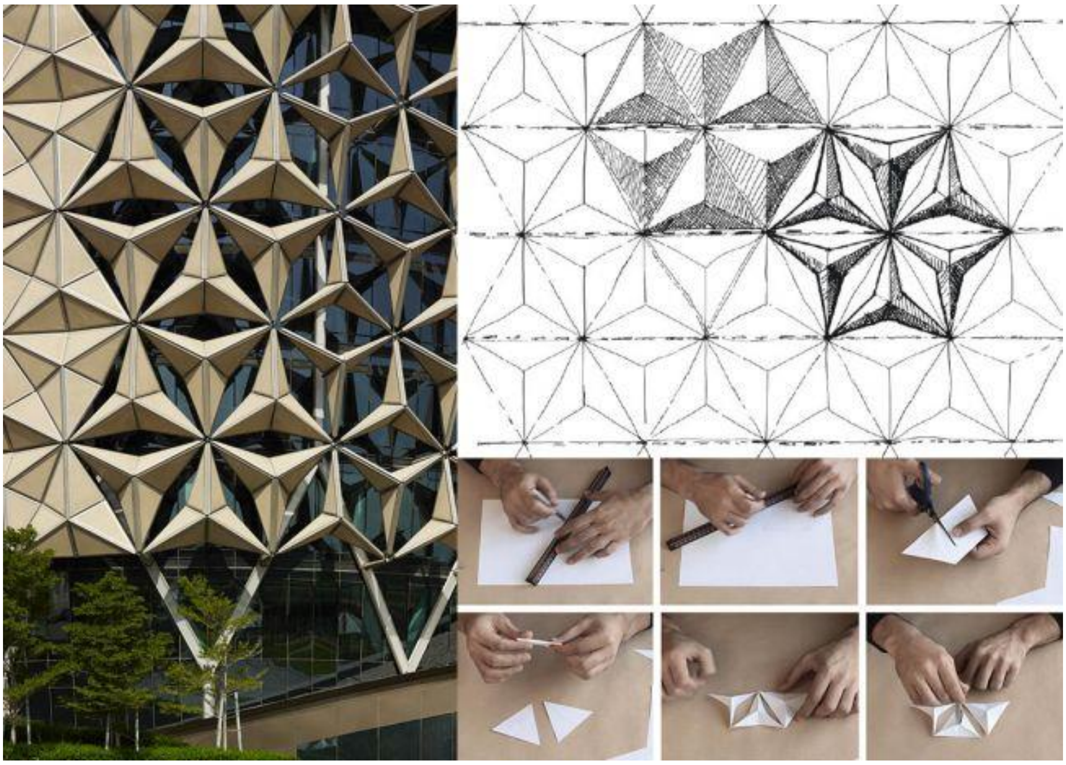


Figure 18 - Example of kinetic facade, Al Bahar Towers, Abu Dhabi. Image credit to http://www.infobuildenergia.it/progetti/al-bahar-towers-torri-abu-dhabi-facciata-solare-intelligente-477.html

Adaptive facades are strongly connected and influenced by the climate context, therefore it is not possible nowadays to make a categorization of these technological systems and their assessment is not easy to accomplish. Responsive envelopes deal with multiple environmental data, measured and processed to perform a predefined response that satisfies the users' preferences and needs, according to the evolving environmental conditions. Seasonally adaptable facades can enhance energy savings and achieve better thermal comfort conditions when compared to static facades, also improving the view to the outside by involving higher WWR in the design phase.

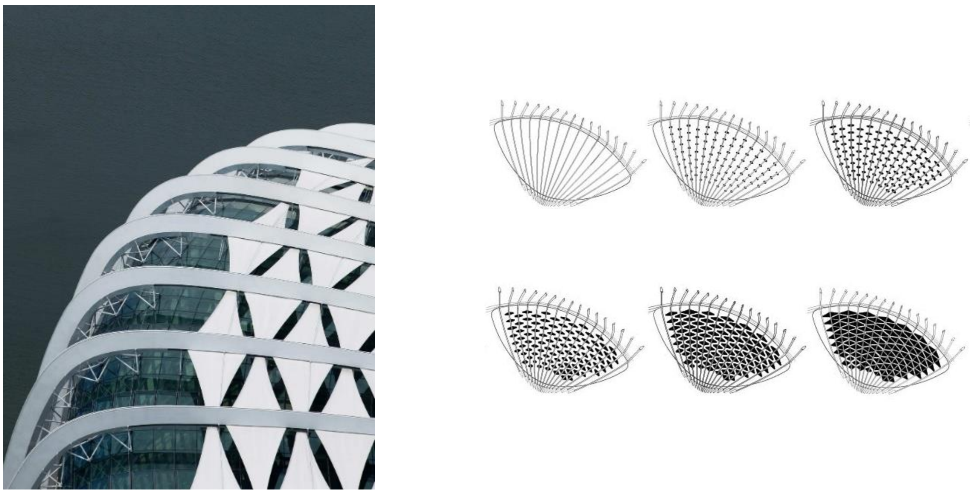


Figure 19 - Example of kinetic facade, Cooled Conservatories, Gardens by the Bay, Singapore. Image credit to WilkinsonEyre2018, last accessed March 22, 2018; http://www.wilkinsoneyre.com/projects/cooled-conservatories-gardens-by-the-bay

Chapter 4

Daylight control, occupant behavior and artificial lighting

4.1 Artificial lighting system and energy savings

In the U.S. artificial lighting is accounted for 25% of the total electricity used in buildings, where an average lighting power density (LPD) of 9.1 W/m^2 indicates a wide use of incandescent lightbulbs (figure 20) and their coupling to a traditional switch control system: the main problem with traditional incandescent lightbulbs is related to their poor lighting efficiency that makes them irradiate the most of the energy under infrared radiation (figure 21), then other lighting systems have been investigated and introduced allowing way better performances as shown in table 2.

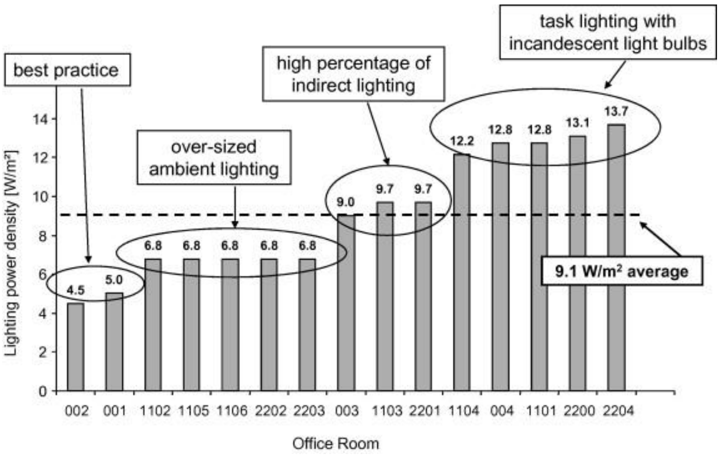


Figure 20 - Lighting power densities of 15 office rooms. Image credit to Linhart F, Scartezzini J., "Minimizing lighting power density in office rooms equipped with Anidolic Daylighting Systems"

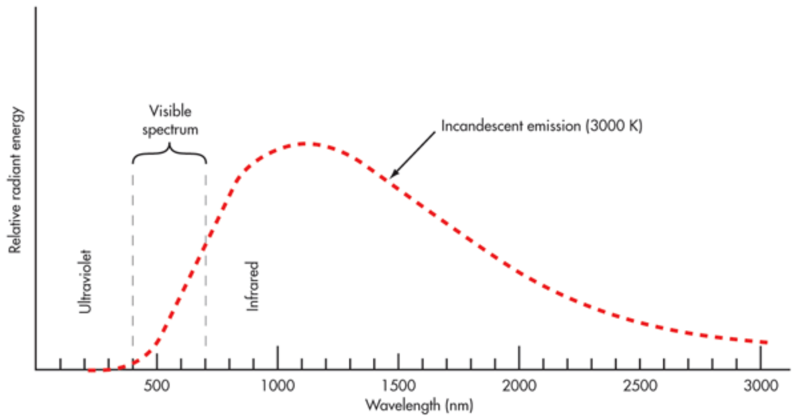


Figure 21 – Illustration of the spectrum of a typical incandescent lightbulb (red dotted line) according to the relative radiation energy. Image credits to Laszlo Liesz, last accessed March 24, 2018; https://www.quora.com/Which-part-of-the-spectrum-does-an-incandescent-light-bulb-emit

	Incandescent	Halogen	CFL	LED
Power	*60 W*	*43 W*	*15 W*	*12 W*
Energy $ Saved (%)	–	~25%	~75%	~75%-80%
Annual Energy Cost*	$4.80	$3.50	$1.20	$1.00
Bulb Life	1000 hours	1000 to 3000 hours	10,000 hours	25,000 hours
**Based on 2 hrs/day of usage, an electricity rate of 11 cents per kilowatt-hour, shown in U.S. dollars*				

Table 2 - Comparisons between Traditional Incandescents, Halogen Incandescents, CFLs, and LEDs. Credits to the U.S. Energy department, last accessed March 24, 2018; https://www.energy.gov/energysaver/save-electricity-and-fuel/lighting-choices-save-you-money/how-en

In addition to the high energy consumption, the most diffused lighting system show a poor performance in the stimulation of the circadian rhythm or the photopic vision as shown in figure 22: the photopic vision is mediated by the cone cells and it's activated in well-lit environments, allowing better color perception, higher visual acuity and resolution. It results that incandescent lights achieve poor performances against LED or phosphorescent light bulbs.

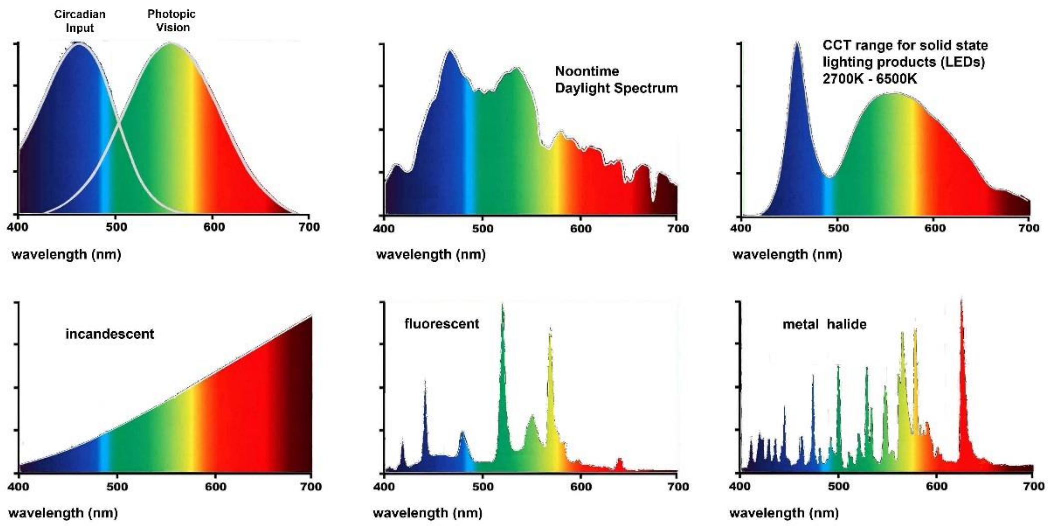


Figure 22 - Light Spectrums Associated with Vision and Circadian Timekeeping; green light is associated to the peak of photopic vision, while blue light is associated to the peak of the circadian input.
Image credit: http://www.bauarchitecture.com/research.chronobioengineering.shtml, last accessed March 25,2018

4.2 Control systems and occupant behavior

From the beginning of the new millennium, the increasing interest on daylight in buildings made researchers focus on how to lower the energy consumption of electric lighting systems and at the same time guaranteeing the reaching of an adequate visual comfort, including also glare effects on the users. Though, it results very complicated to estimate visual comfort conditions for the users since it is a personal feeling and varies for each individual: many non-physical motivations lead users to interact with the artificial lighting or the shading system, such as the perception of daylight, the need for privacy, the need to freely access the windows and see outside, and, eventually, also the contribution of the HVAC system, which affects the control behavior of the building occupants, i.e. a higher acceptance of poor daylight conditions is observed when air conditioning is provided to the ambient.

Figure 23 – Users need to access the window and see the outer environment: this feature contributes in relieving stress and make the room ambient more enjoyable. Free stock images, last accessed March 24, 2018; on the left https://stocksnap.io/photo/ASR3IXBDTR; on the right https://www.pexels.com/photo/buildings-businessman-city-cityscape-561458/

The main advantage of manual controls is that they allow the users to set the shading device (internal or external) at their will and according to their personal visual and, sometimes, thermal comfort, however, in this way the shadings are rarely operated as a response to varying external variables such as the sun position, because users tend to control the devices just when discomfort is perceived (such as glare) and then leave it in that position for the remaining time without further adjustments. Users often override the control system for experienced discomfort or just the desire to customize the interior environment and this attitude contributes in the definition of a "worst case scenario" for most of the occupied hours, resulting in fixed stances along the daytime and causing strong reductions in both energy savings and daylighting conditions.

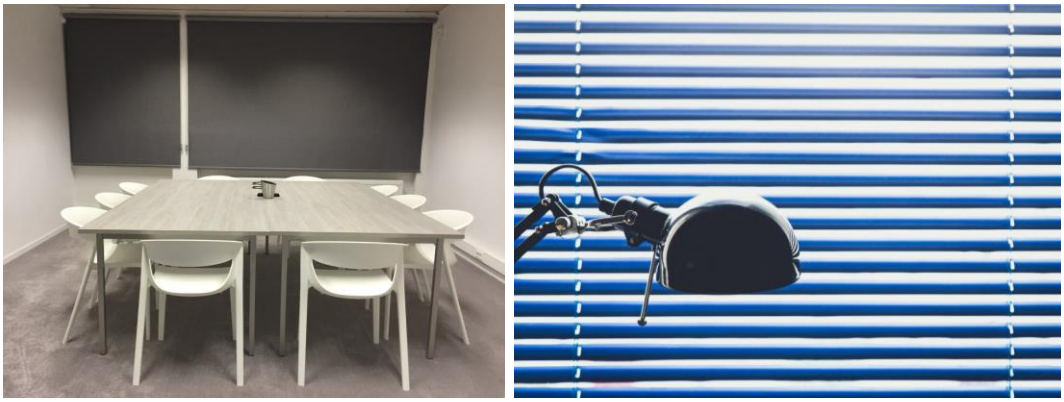


Figure 24 - Typical manual blinds installed in office work-places, roller blinds on the left and venetian blinds on the right. Free stock image, last accessed March 23, 2018; https://stocksnap.io/photo/DB4QVRZJXC, https://www.pexels.com/photo/black-and-white-blackboard-blinds-chairs-260928/

The adoption of daylight responsive control strategies allows to achieve increased savings in the energy consumption, both for daylighting through dimming and switching lights according to the illuminance level needed on the work plane, and cooling load by blocking the radiation. As already mentioned, user's satisfaction influences the control pattern and the overall daylight and energy performances: the building occupants usually show low tolerance about outer changes related to automatically controlled shadings and, consequently, override the predefined settings, hence it might be helpful to consider the avoidance of too frequent adjustments of automatic shading devices. Even though the adoption of automated blinds can help in avoiding this kind of problem, it must always be considered during the design of the control system, especially if automated, that users prefer the possibility to override the blind position, which help them in accepting the automated system.

Typical daylight automatic controls can be grouped in *closed-loop* and *open-loop* controls: the first one needs the placement of a consistent number of photosensors inside the room (looking downward at the work plane) to sense the illumination achieved through both artificial lighting and daylight, then it adjusts the dimming level (or switch on the lamp) to guarantee the minimum illumination required; the second one consists in the location of a photosensor on the exterior that senses the available daylight and performs a mere estimation of the illumination reached on the work plane inside, then, according to that, it regulates the dimming level or switch on/off the lamps. The choice of the automated control type usually depends on the scale of the system and the installation of photosensors in the controlled room.

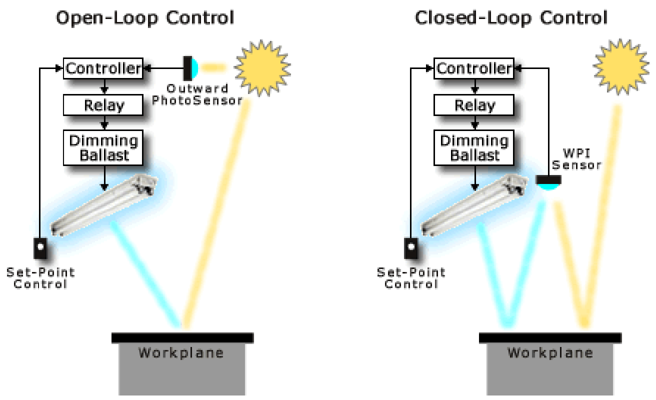


Figure 25 - Open-loop versus closed-loop lighting control.
Image credit to http://intelliblinds.com/daylightharvesting.html, last accessed March 24, 2018

In conditions where occupants' behavior cannot influence the control system, energy savings related to the draw upon daylighting can potentially rise between 20-60%. As it has been evinced, artificial lighting plays a main role in the definition of the total electric energy use of commercial buildings such as offices, frequently due to inappropriate control strategies relying on solely occupant direct control, which are very likely to maintain light switched on in daylight environment, nevertheless a good control strategy could involve the adoption of light emitting diode (LED) lamps which are suitable for dimming operations and consumes less in comparison to traditional light-bulbs.

Chapter 5

Definition of a dynamic evaluation strategy and application to a case study

5.1 Target pursued and overview

Kinetics and dynamic shading devices applied to architectural solutions potentially play an important role in the definition and the optimization of the interior environmental quality in buildings, especially when climate-based analyses are involved to guarantee the best response to variable environmental factors for visual comfort and reduced energy consumption.

Presently, the most diffused analysis tools show some limitations in the performance assessment of dynamic shading systems at the early stage of design, which are related to the complexity of the system itself. The design workflow starts from the geometric definition of the dynamic shading, its possible motions and the configurations that can be assumed – the dynamism can be assumed as a sequence of static positions. At this stage, designers can either set a deployment or configuration schedule *a priori,* based on a simple architectural aspect, or aim at climate-based solutions in which the shading element responds to certain environmental inputs: in both cases, it is still impossible to define a detailed performance assessment during the early stages of design using parametric modelling tools, since changes in the geometry inputs will restart the annual simulations and create a loop in the analyses.

The prefixed target is the outline of a workflow aimed at developing the hourly configuration schedule of a dynamic shading system through the optimization of the internal daylight comfort parameters and assess the global performance about visual comfort and energy loads achieved.

This workflow starts from the digital definition of the involved geometries and all the available shading configurations, followed by daylight and energy annual simulations carried out for each geometric configuration alone, considered as a static solution for the whole annual analysis, whose hourly results are then exported to a set of spreadsheets and compared to highlight the most performing ones. Once the optimized hourly configuration schedule is defined for the entire year, the data related to each hourly result is then acquired to outline the energy and daylight performances of the analyzed environment through specific parameters.

The target defined can be very suitable for commercial buildings, where the assessment of daylight comfort parameters might be among the requirements that need to be fulfilled to comply with the standards or where daylight can contribute to achieve better environmental conditions for workers and other users. Eventually, a case study will be developed to show the achievable results.

5.2 Digital tools

Grasshopper is a graphical algorithm editor used by designers to create parametric/algorithmic models and to perform actions inside the Rhinoceros digital environment. Each action, from the creation of a point to the division of a curve, is performed by a predefined component representing a specific algorithm with inputs and outputs, therefore engineers and architects can express their will by using these predefined components, otherwise they can directly write the algorithms using Python if necessary. The high number of available plug-ins for this software allows to do almost everything a designer needs for his/her work.

Ladybug and Honeybee are among the said plug-ins and both are object-oriented application programming interfaces (API): the first one allows to import EnergyPlus weather files and to perform weather analyses such as solar radiation studies, view analyses, sunlight hours modeling, etc… which can be supported with 2D and 3D graphics during the early stages of the design process, while the latter is used to create, run and visualize daylight simulations using Radiance and/or energy simulations with EnergyPlus, besides it can also investigate energy flows through construction elements using Therm.

Microsoft Excel is a spreadsheet very useful to visualize, manage and analyze large amounts of data and that's why it results very suitable for combined uses with the previously mentioned software and plug-ins, which are able to produce large quantities of results to analyze according to specific needs.

5.3 Modelling the geometry

With Grasshopper for Rhino it is possible to perform parametric modelling and identify almost infinite solutions to represent single geometric elements, therefore designers usually focus on the definition of the easiest way to do that by simplifying the connections between the involved components summarizing algorithmic functions.

The simulations rely on EnergyPlus and Radiance, so it is not possible to run any kind of analysis by connecting the mere geometry to the Honeybee components that run the simulations since many input parameters, such as the materials properties, would be missing for both energy and daylight analyses.

5.3.1 The interior environment

The internal spaces of buildings must be represented by the component "HB zone", namely defined by a collection of HB surfaces that must create a closed boundary representation (or brep) of the space.

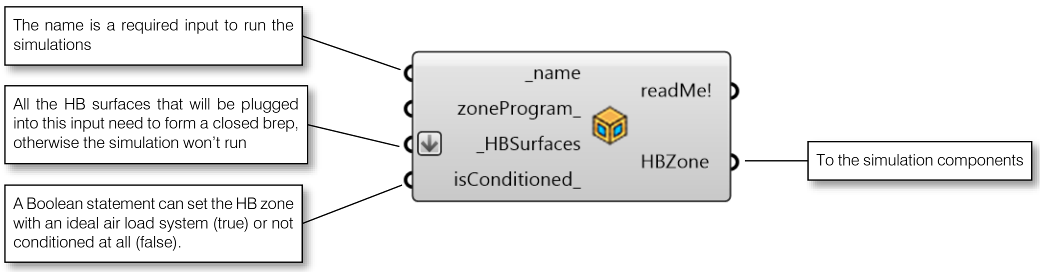


Figure 26 - Description of the component HB zone, representing the ambient to be simulated during the daylight and energy analyses

The definition of a name through a text string is fundamental to avoid running errors and the zone program is an optional input that represents predefined parameters for schedules, occupancy, systems, etc… and, in case deeper analyses are involved, it could be avoided if all the necessary parameters are lately considered by means of specific components described later.

The HB surfaces are the proxy between plain geometries and simulation elements, allowing to merge a large set of information such as Radiance materials and EnergyPlus construction parameters with the geometric element. Each construction part of the internal ambient must be represented by a single HB surface containing all the related physical characteristics.

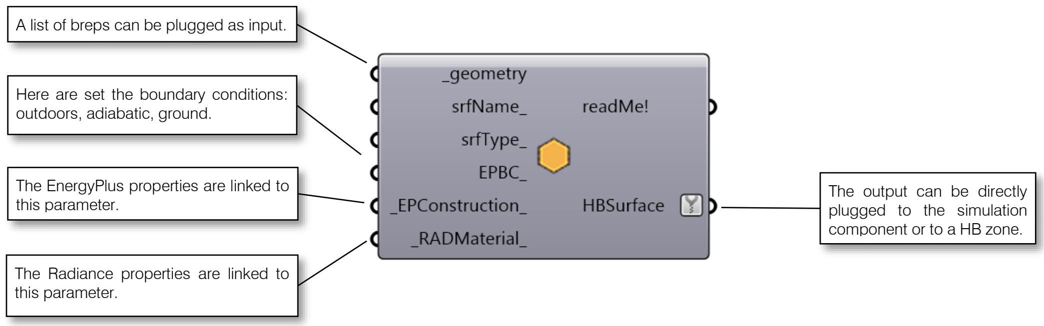


Figure 27 - Description of the component HB surface, representing the proxy between the geometry designed in Grasshopper and the simulation components

The component "EP construction" is used to portray the composition of the construction elements assigned to specific surfaces and it provides a detailed description of each layer properties such as thermal resistance, weight, specific heat, thickness, etc… related to that construction element through the definition of each EP material of every layer present. Layers can be added by zooming-in in the component and hit the sign "+", moreover it is important to remember that the last layer in the input list is always the innermost one, while the first one is always the outermost.

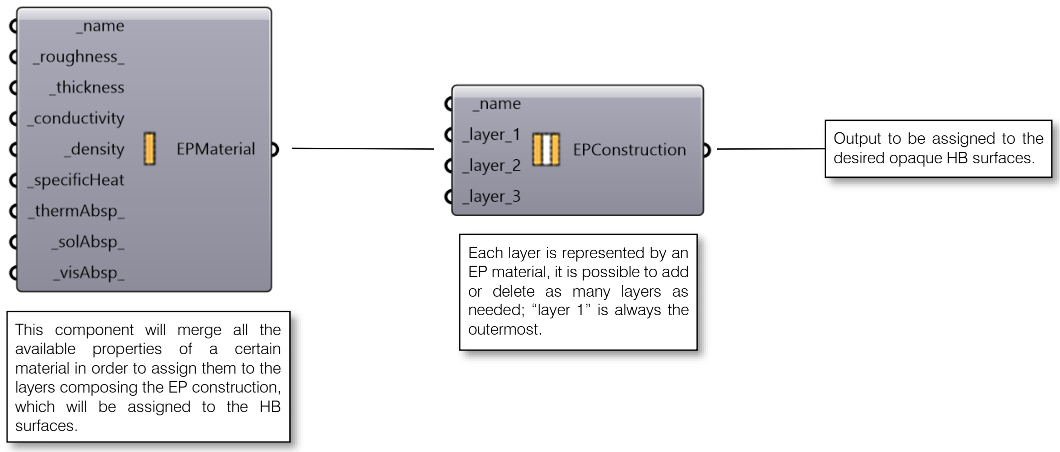


Figure 28 - Description of the components needed to define the EP construction properties and the related layers (opaque elements)

The glazing modelling follows a slightly different construction path because it is not possible to create a transparent element standing by itself because it necessarily needs a host surface, therefore the assigned component asks to specify in the inputs the HB surface that will host the glazing and the brep representing the shape of the desired window. The EP construction of windows will be then defined by a single layer connected to the EP window material component without mass, where it is possible to specify the main parameters related to thermal transmittance, solar heat gain coefficient and the visual transmittance of the glazing; the absence of mass may lead to imprecisions in the model analysis, so if it's needed it is possible to define a glazing with mass through the component "EP transparent material".

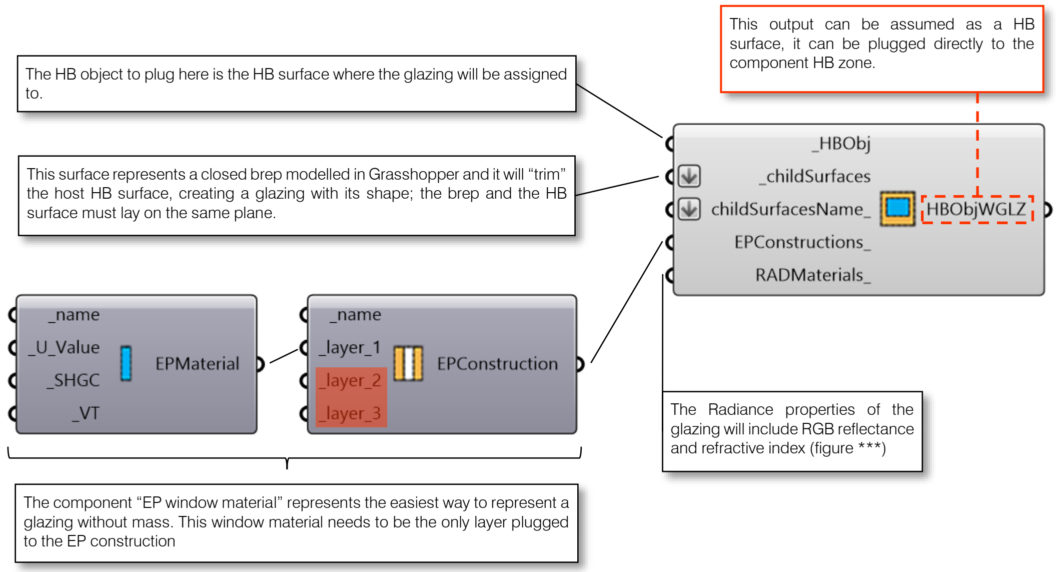


Figure 29 – Description of the main steps to follow in the creation of glazing elements.

The component "RAD material" is instead meant to define the average diffuse reflectance of the analyzed opaque material/construction element or the transmittance of transparent surfaces. Typical reflectance values adopted in Radiance simulations might be 0.2 for floorings, 0.5 for vertical partitions and 0.7 for ceilings, while the light transmittance depends on the type of glazing designed.

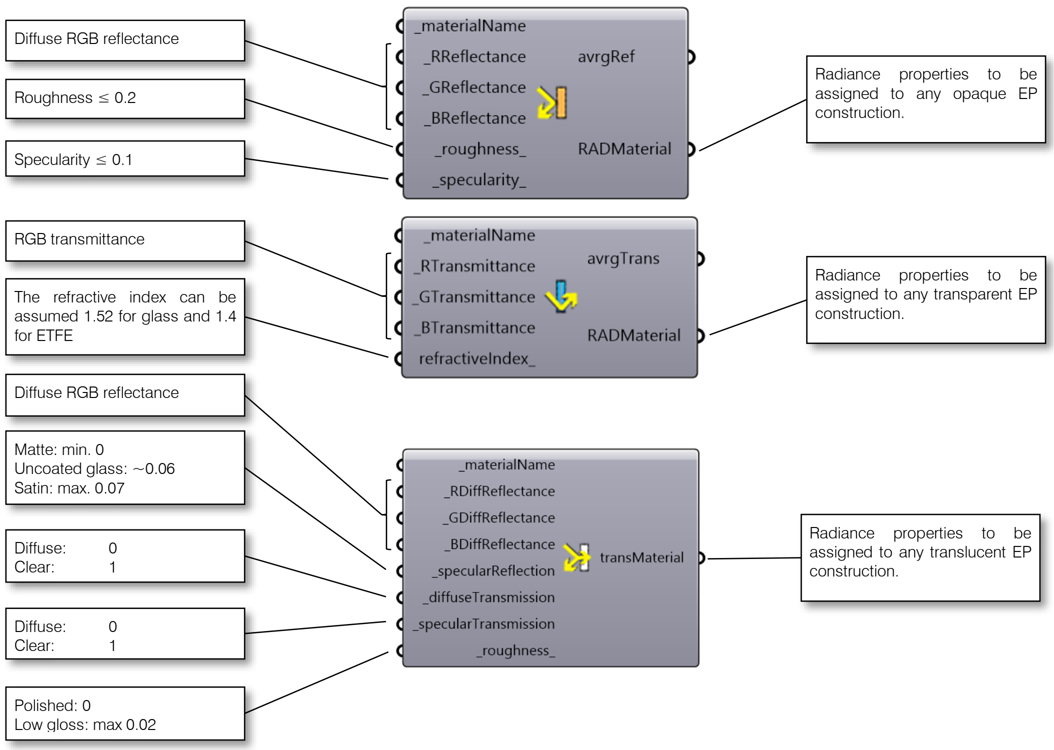


Figure 30 - Description of the Radiance material properties that could be assigned to opaque, transparent and translucent materials that constitute the EP surface

5.3.2 The exterior environment and the exterior shadings

The geometric elements that are not part of the interior ambient and that still can influence the energy and daylight performances by providing shade on the conditioned ambient can be considered as placed "outside" and can have a natural or artificial origin. Natural shadings include essentially the nearby vegetation elements or terrain conformations, while the artificial elements can be either the surrounding buildings and/or the provided external shading system and all these entities will need to be defined by Energy plus and Radiance parameters in order to perform the necessary analyses, as well as previously done with the interior ambient definition.

Then, the procedure to be followed for these external shades consists in the translation of the breps that define the involved geometries into HB context surfaces: the adopted component allows to manage the Radiance parameters for daylight analyses and it provides the possibility to define a transparency schedule for deciduous vegetation that won't influence the ambient performances in the same way all along the year.

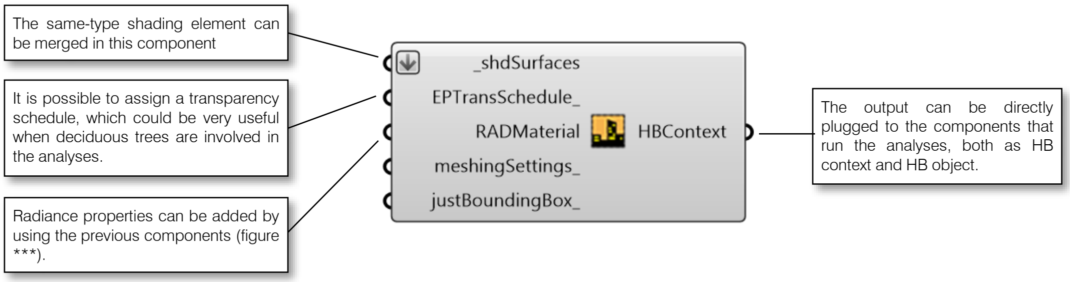


Figure 31 - Description of the main components needed to define a context surface, adoptable as HB surface or directly connectable to the simulation components

5.4 Modelling the daylight analysis components

The steps concerning this stage of daylight assessment start from the generation of the analysis mesh on which performing the annual analyses through the component "generate test points" (figure 32), usually represented by an ideal surface parallel to the floor with specific offset and grid size according to the designer's needs. The mesh dimension is important because it defines the total amount of test points generated, remind that a 0.50 m mesh creates 4 test points/m^2. The generated points, vector and mesh will be then connected to the analysis recipe represented by the component annual daylight simulation", which precedes the actual component that runs the simulation and writes the result files. The analysis recipe collects all the necessary parameters that will outline the daylight simulation by means of Radiance and Daysim settings, weather data file for the climate-based approach and the analysis mesh to be tested.

The orientation considered during the simulation can either be input as an angle in degrees (north is 0°) or by rotating the whole geometry in case problems in the simulation would occur, then the weather file can be linked through a simple file path or directly downloaded with Ladybug from the EnergyPlus website.

The Daysim parameters are defined to incorporate in the analysis recipe the evaluation of glare phenomena, so being this an image based analysis it is required to assign a Rhino view to the component. If venetian blinds or roller blinds are provided it is possible to include them into this component through the inputs "dynamic shading group".

The Radiance parameters (table 3) define the desired quality needed by the designers for the simulation to be performed and these values can influence both the results accuracy and the analysis duration. The parameters involved are:

- *ambient bounces* (-ab), which indicates the number of diffuse bounces of each sunray;
- *ambient divisions* (-ad), which denotes the number of projected sunrays from each point towards the sky for the definition of the indirect radiation;
- *ambient super-samples* (-as), which represents the number of extra rays identified between two samples differing by 10% of sunray projections;
- *ambient resolution* (-ar), which refers to the density of ambient values;
- *ambient accuracy* (-aa), which shows the percentage error of the ambient interpolations.

Parameter	Minimum	Fast	Accurate	Very accurate	Maximum
-ab	0	0	2	5	8
-ad	0	32	512	2048	4096
-as	0	32	256	512	1024
-ar	8	32	128	512	0
-aa	0.5	0.2	0.15	0.08	0

Table 3 - Typical Radiance parameters used for the definition of the analysis recipe to run the daylight simulation

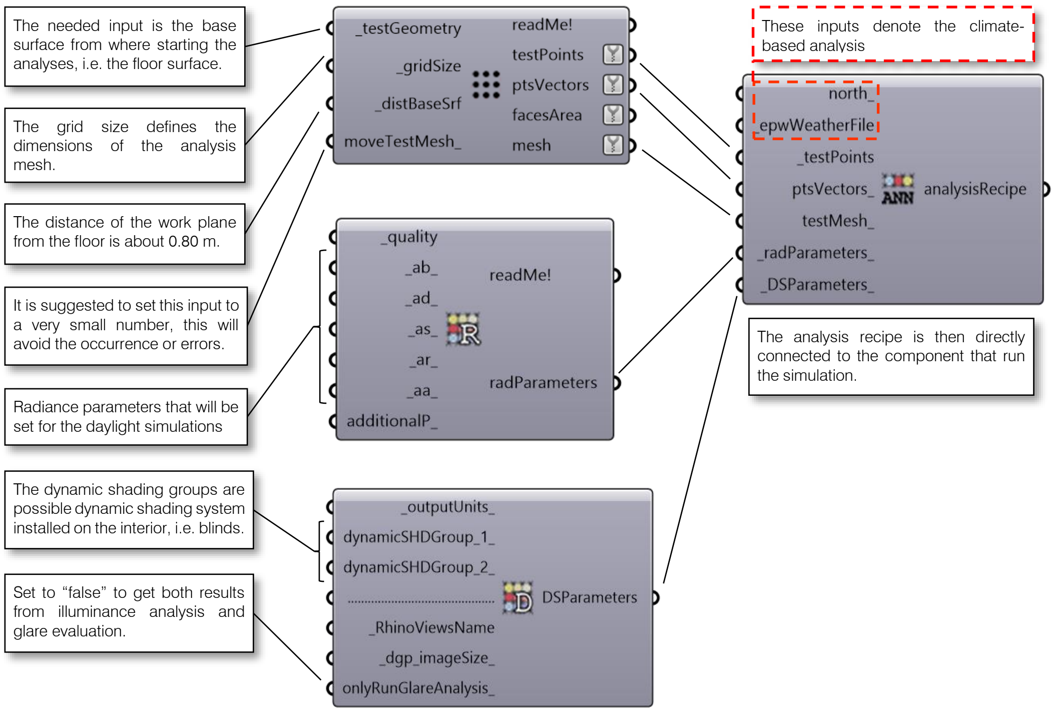


Figure 32 - Definition of the main components and parameters needed to set the analysis recipe for the annual daylight simulation

For the definition of an accurate view from a seated user it is possible to create a mannequin from the Ladybug component "comfort mannequin", which can be assigned to a desired position inside the interior ambient, oriented to the needed direction and from which it is possible to set the view direction, then in the Rhino digital environment it will be necessary to save the novel view and name it as the name assigned to the text string in the "Daysim parameters" component (figure 33).

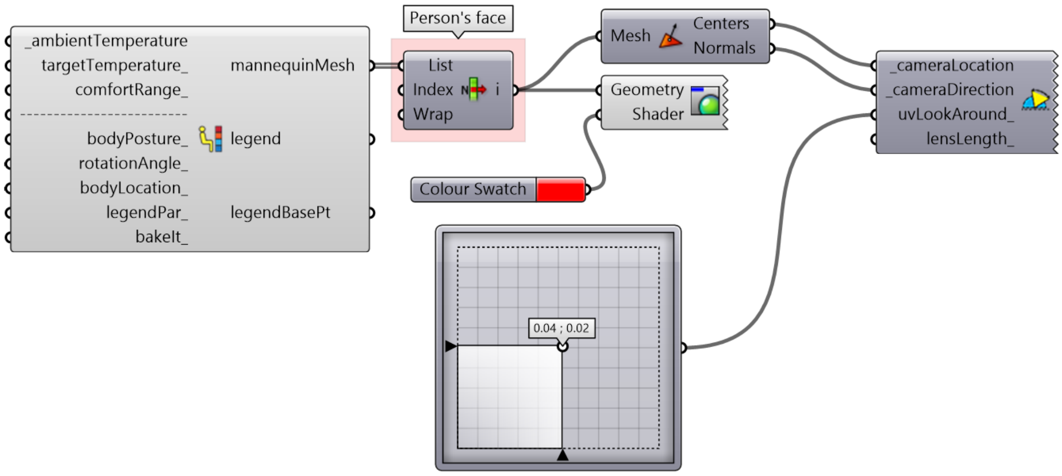


Figure 33 - Useful solution to define the view of a seated user to evaluate glare phenomena

It is now possible to connect properly all the necessary inputs to the component that actually run the daylight simulation and where all the information related to the simulation parameters merge into the annual analysis recipe and the geometries involved are taken into consideration, namely the HB zone and the HB context surfaces, all flowing into the same input "HB objects". Note that is fundamental to set the number of involved processors in the daylight simulation to "1", otherwise after running the simulation for the annual DGPs values the component will stop and the illuminance values won't be calculated.

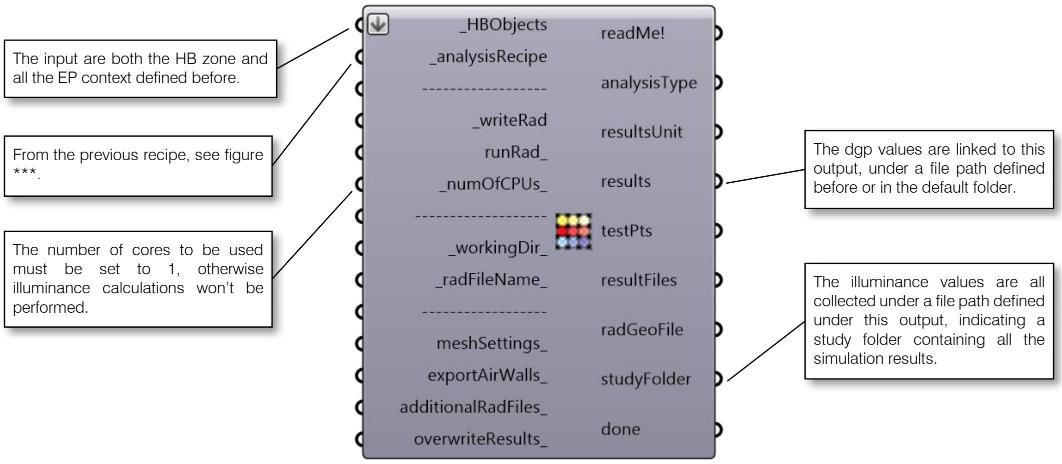


Figure 34 - Description of the main inputs and outputs related to the component that run the daylight simulations

In this way, the hourly illuminances are defined for each test point and the hourly dgp values (during the whole year) for the modelled mannequin, so the data are available in the assigned folder under the specified project name, but no information about the electric lighting use is still available: with the HB component "read annual results I" it is possible to write a fractional schedule for the use of artificial lighting that activates whenever a certain daylight threshold is not met, then the output can be connected to the input of the lighting schedule provided during the energy analysis, making the calculation of the consumed electric energy possible.

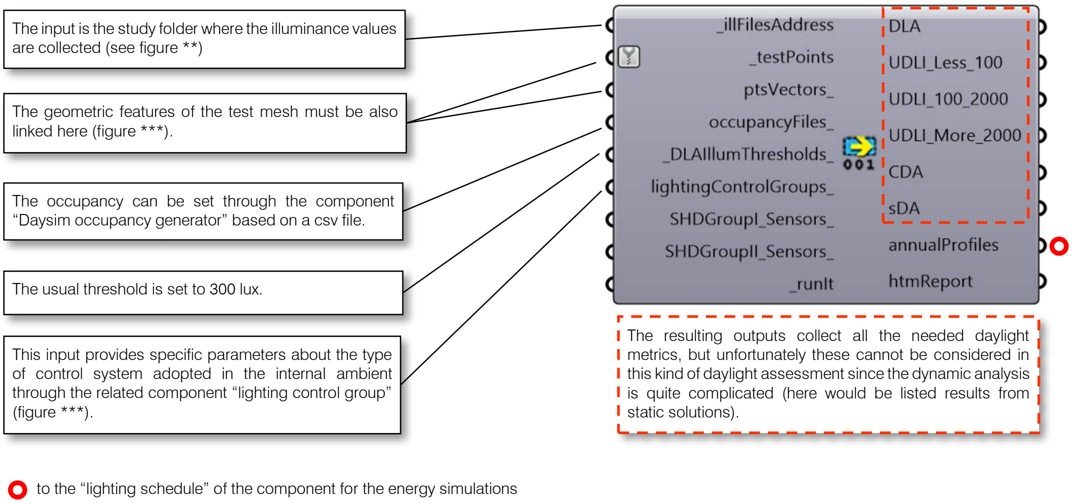


Figure 35 – Definition of the necessary parameters to read the annual results and define a lighting schedule to use for the later energy assessment for the artificial lighting load

The needed files address corresponds to the study folder where all the hourly illuminance values are written and located, the occupancy file represents a Daysim schedule that lists at each hour the users' presence inside the building and consequently indicate if the artificial lighting should be provided or not considering also a daylight autonomy threshold, set by default to 300 lux. The daylight metrics calculated and listed in the outputs are very useful when static external shadings alone or in combination with simple dynamic internal shadings (roller and venetian blinds, however, since this workflow is assumed for exterior dynamic shadings evaluation, these outputs will be defined in a different way, which will be explained in the following paragraphs. Moreover, it is also necessary to reconsider as inputs the analysis mesh parameters to correctly run the component, while the shading group sensors inputs are optional and refer to the presence of automated dynamic internal shadings such as roller blinds or venetian blinds.

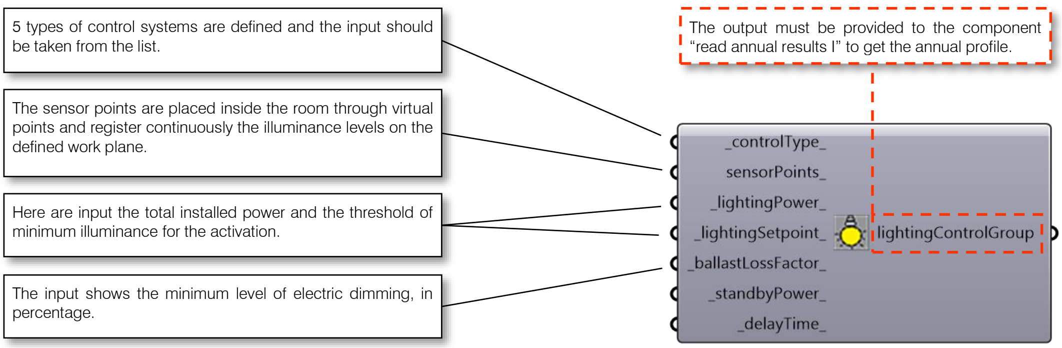


Figure 36 - Definition of the necessary parameters that characterize the artificial lighting control system

The component "lighting control group" define the characteristics related to the artificial lighting system such as the control type, the installed power, the illuminance set point, etc.… The conceived control strategies can be identified as:

- manual switch on/off (reference system), which corresponds to a standard manually controlled lighting system with a single on/off switch;

– automated with switch off occupancy sensor, which corresponds to a lighting system that need a manual activation and can be either be switched off manually or when users are not present anymore;
– automated with switch on/off occupancy sensor, which results to be a lighting system always in stand-by mode activating and switching off according to users' presence in the building;
– photosensor-controlled dimmed lighting system, which corresponds to a system that need to be manually activated via a single on/off switch and the photocell dims the lighting until the work plane illuminance reaches a minimum predefined threshold;
– dimmed lighting system with an energy-efficient occupancy sensor, which is a system that need a manual activation, equipped with a photocell that dims the lighting until the work plane illuminance reaches a minimum predefined threshold and can be either be switched off manually or when users are not present anymore;
– combined with an on/off switch and an occupancy sensor, which is a system that need a manual activation, equipped with a photocell that dims the lighting until the work plane illuminance reaches a minimum predefined threshold, though the system is always in stand-by mode and switch on/off according to users' presence in the building.

5.5 Modelling the energy analysis components

The energy analysis should be performed after the daylight simulation since, as explained right before, it is possible to get from the latter the annual profiles for the artificial lighting which take into account the natural light contribution on the work plane illuminance levels.

The component that runs the energy analysis using EnergyPlus merge the environmental data from the weather file with the geometries involved in the design, properly translated into HB objects and implemented with the adequate data to allow the simulation to run (figure 37). Substantially, the most important parameters in this component are the ones related to the HB zone, which needs to be implemented with information about energy loads, schedules and systems, the HB context, merging all the surrounding elements and the external shading systems, the eventual energy generators such as photovoltaic elements and the definition of the searched output parameters.

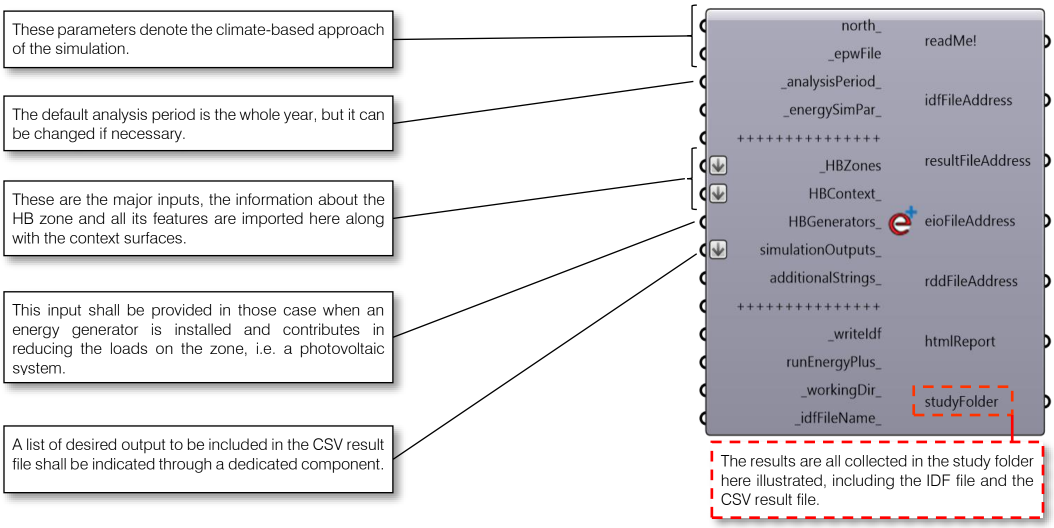


Figure 37 - Description of the main parameters to consider during the energy simulations

The predefined energy simulation parameters consider 6 time-step per hour, an averaged shadow calculation on 30 days adopting 3000 points maximum, both contributions of interior and exterior light reflections in solar energy calculations and a city terrain.

The definition of the HB zone goes through many "overriding" of the zone itself, by connecting the HB zone output of a component, i.e. the zone loads, to the HB zone input of another, i.e. the zone schedules (figure 38). The data to input as zone loads rely on the designer assumptions and can be assigned by connecting simple text strings, while the zone schedules need to be created or selected from the default ones, either are valuable method that should reflect the designer will. The component concerning the designed HVAC systems needs to specify the type of system installed and this is possible either by selecting the desired template from a list of predefined HVAC systems or adding detailed components according to the necessities of the designers. After the definition of the parameters mentioned above, by connecting all these components it will happen a merging of all the information about the investigated HB zone without loss of data.

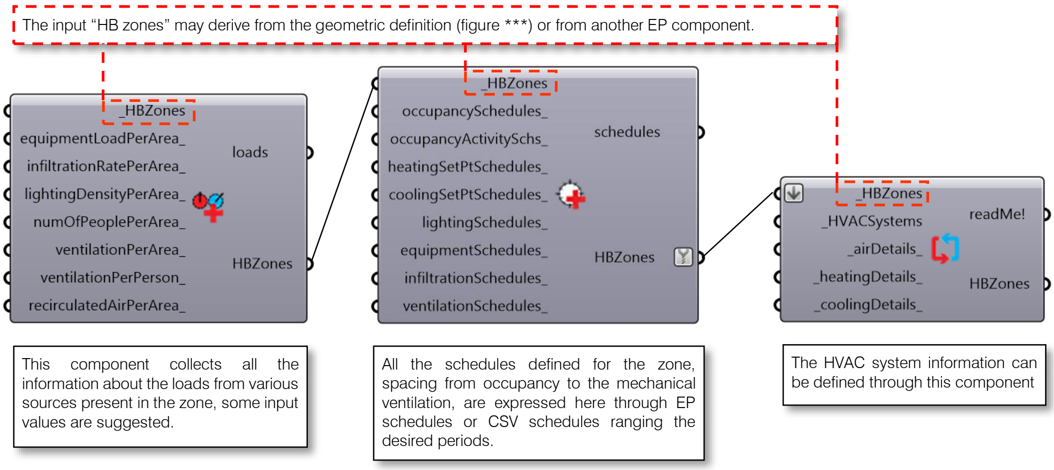


Figure 38 - Description of some of the components that define the EnergyPlus features of a certain geometry to analyse: from left it is shown the "set EP zone loads", "set EP zone schedule" and "assign HVAC system"

For the energy simulations it is also necessary to define the simulation outputs to be included in the csv file containing the analysis results and this possible by connecting the component "simulation outputs" and defining for each instance a Boolean input.

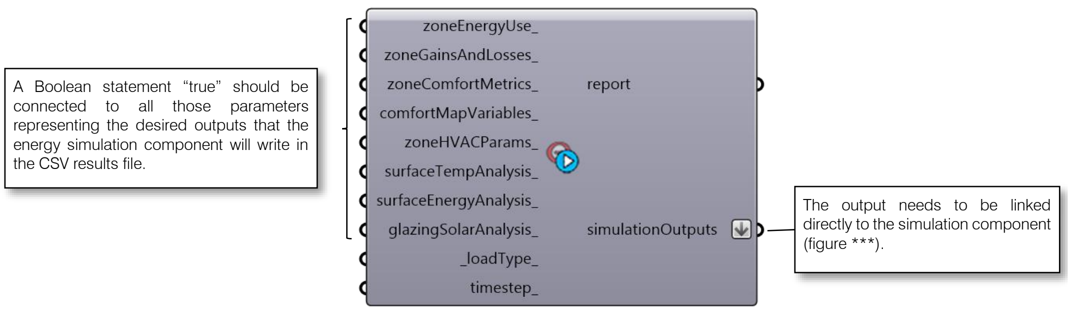


Figure 39 - Description of the component that generate the needed simulation outputs and the way to define its parameters

The HB context surfaces are the same defined for the daylight simulation phase and shall be simply connected to the right input, but in the case of geometries defined by non-planar surfaces, errors might occur during the simulation, sometimes not even advised by the typical red flag provided by

Grasshopper, with the consequent impossibility to write the csv file containing the simulation results. The error could be the outcome of a wrong assumption of the geometry by EnergyPlus, therefore it is suggested to re-mesh the Grasshopper object before linking it to a HB context surface to avoid this kind of problem.

5.6 The dynamic evaluation process

5.6.1 An overview on the post-processing

In the previous paragraphs there has been shown the main components needed to run daylight and energy simulations in Grasshopper by means of the plug-ins Honeybee and Ladybug, moreover it has been indicated the main parameters to provide them in order to make the whole script work. Therefore, once the components are placed on the canvas, correctly compiled and interconnected, it is possible to start the simulations phase: the dynamic shading will be defined by a set of deployment or configuration states, according to the designers' necessities, and it is required to run both daylight and energy simulations for each assumed positions of the shading system. The components that run the analyses will eventually write the annual hourly results in the specified folders defined by the user, into particular files, which are:

- a comma-separated values file (*.csv) for each energy analysis, containing all the simulation outputs defined before with the specific component;
- an annual illuminance profile (*.ill) for each daylight analysis, listing the indoor illuminance for each test point defined before with the specific component;
- an annual daylight glare probability profile (*.dgp) for each daylight analysis, displaying the daylight glare probability for each specified Rhino view.

Reminding that the scope of this work is the definition of an evaluation method for buildings employing dynamic shading devices, the suggested procedure starts from gathering, for each defined configuration, the annual hourly results listed in the above-mentioned files and converting them into Excel format files, neglecting some data when not needed in order to avoid working with overloaded spreadsheets that could make the following data management more complicated because of the reduced computer speed. Afterwards, the selection of a shading configuration schedule (based on hourly comparisons) should fulfill a given selection rule defined by the designers' will, through which it is possible to promote some parameters, i.e. the maximum illuminance or the minimum DGP value for each hour, or a combination of them. Eventually, the values of the parameters for each hour related to the best shading configuration are copied on a different spreadsheet and then analyzed for the building general assessment, defining parameters such as sDA, ASE, DA, UDI, minimum useful illuminance for the regulation of the circadian rhythm, DGPs and energy consumption.
The workflow regarding the post-processing of the results can be summarized with the following phases:

1. Running of daylight and energy simulations for each possible position of the shading device and generation of annual hourly results;
2. Collection of the annual hourly results for each simulation into Excel files;
3. Definition of a selection rule to determine the best shading configuration among all for a specified time-step, related to the promotion or avoidance of a certain parameter;
4. Selection of the best shading configuration for each time-step, according to the defined selection rule, and copy/pasting of all the related parameter values;
5. Analysis of the values of the optimized schedule and definition of the main parameters for the general assessment (sDA, ASE, DA, UDI, aUDI, $E_{circadian}$, DGPs, energy consumption).

5.6.2 Extrapolation of the hourly results

The results of each daylight and energy simulations can be found in the folder that has been specified through a text string in the input parameter of both components designated to run the analyses, otherwise it is possible to find it by connecting a simple panel to the appropriate output and making a simple search in the computer browser.

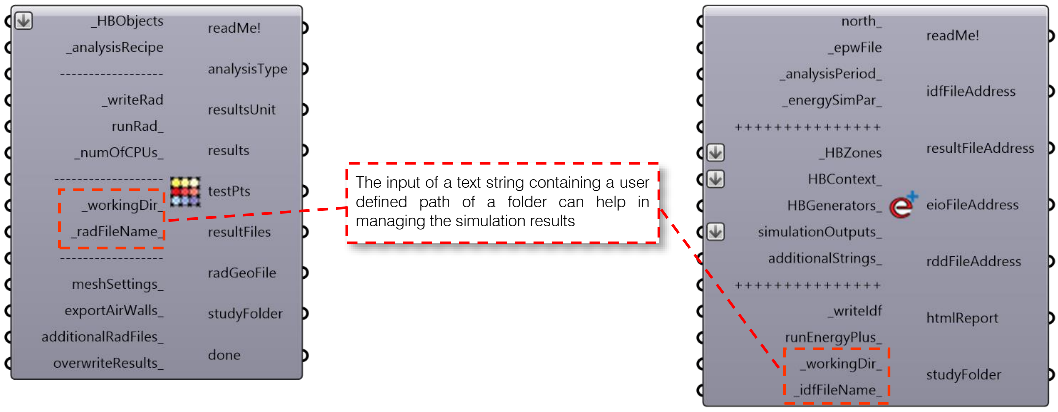


Figure 40 - Definition of a user specified folder to create for the simulations where all the results will be collected

The daylighting results files are defined by the extensions *.ill or *.dgp, while the energy ones are defined by the extension *.csv and these data can be visualized and analyzed on Excel in two ways. The first method considers a drag and drop operation of the desired file into an already open spreadsheet through which the results data are imported as a single column containing the entire set of values, then the separation of these data can be fulfilled by selecting the whole column and using the command “text to columns” in the tab “Data” and by selecting the text option “delimited” in the wizard: for the daylight result files the separator is “space”, while for the energy ones the separator is “comma”. The second way to import the results into Excel is by using the command “from text/CSV” in the tab “Data”, then browsing the desired file and importing it with the predefined settings.

The results data are presented as a list of 8760 hourly values for each parameter linked to a single column, i.e. the heating load, but the illuminances results are organized in a different way: each column represents a sensor point on the analysis mesh and the amount of points (and consequently columns) can vary according to the mesh dimensions and the floor area of the analyzed building.

It might be useful for later operations to collect the results files under single Excel spreadsheets for each extension file defined before, which means that there will be three separate Excel files containing namely all the illuminances, the daylight glare probability values and energy needs associated to each shading configuration provided for the simulations.

5.6.3 Definition of rules to determine an optimized schedule

Once the simulation results are all gathered in three separated Excel files according to their type – illuminances, DGPs, energy needs – it can start the analysis phase through which it will be possible to determine the shading configuration, for each hour, that better satisfies specific requirements established by the designers, according to their scope.

The first step is denoted by the choice of a noteworthy parameter (or more) followed by the definition of a desired target that the designers want to achieve, i.e. having the maximum illuminance values for all the occupied hours or avoiding completely the occurrence of glare phenomena. Afterwards, it shall be created a new Excel file on which it will be organized the selection of the hourly shading configurations through a user-defined rule based on the formula “IF” or “IFS” and containing all the conditional statements and the references of the results files defined before with the importing operations, eventually returning a result represented by a label (such as a name, a code, a rotation angle, etc…) that makes clear which shading configuration fulfills the requirements outlined among all the available ones at the same time-step hour. The writing of the formula can be done for a single cell, then extended and applied to the lower 8760 cells by selecting them, editing the active cell by pressing “F2” and applying the formula to all the cells by pressing “Cntrl+Enter” to input the same data into multiple cells.

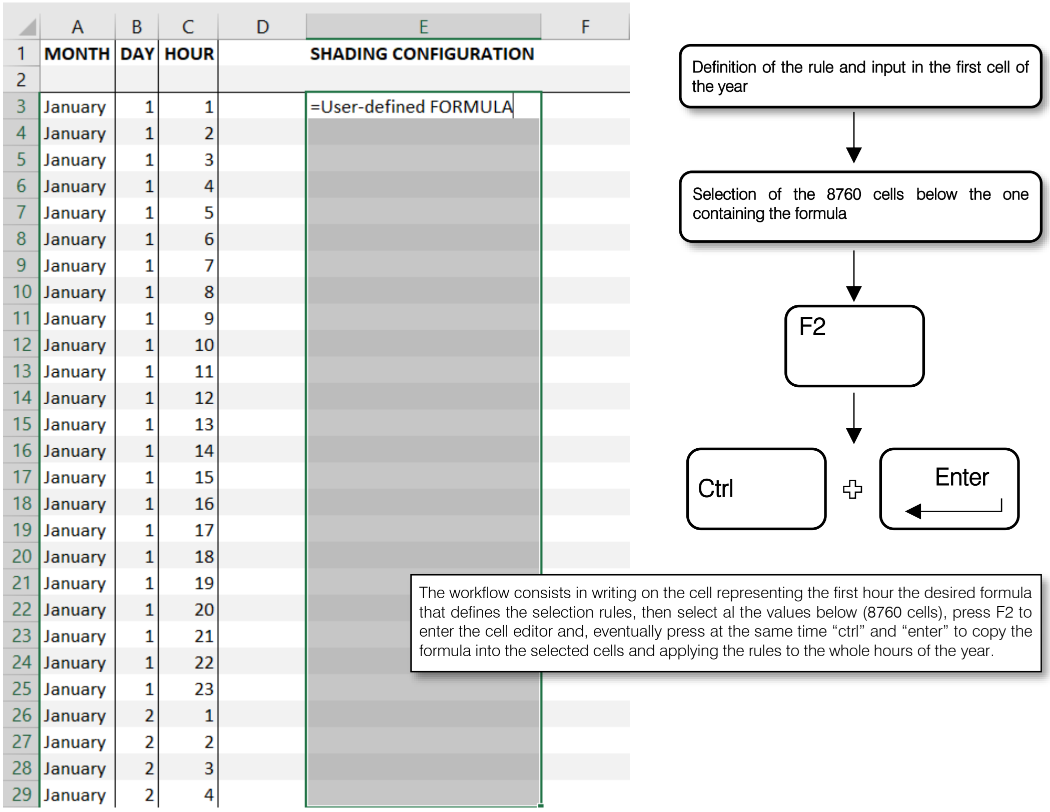


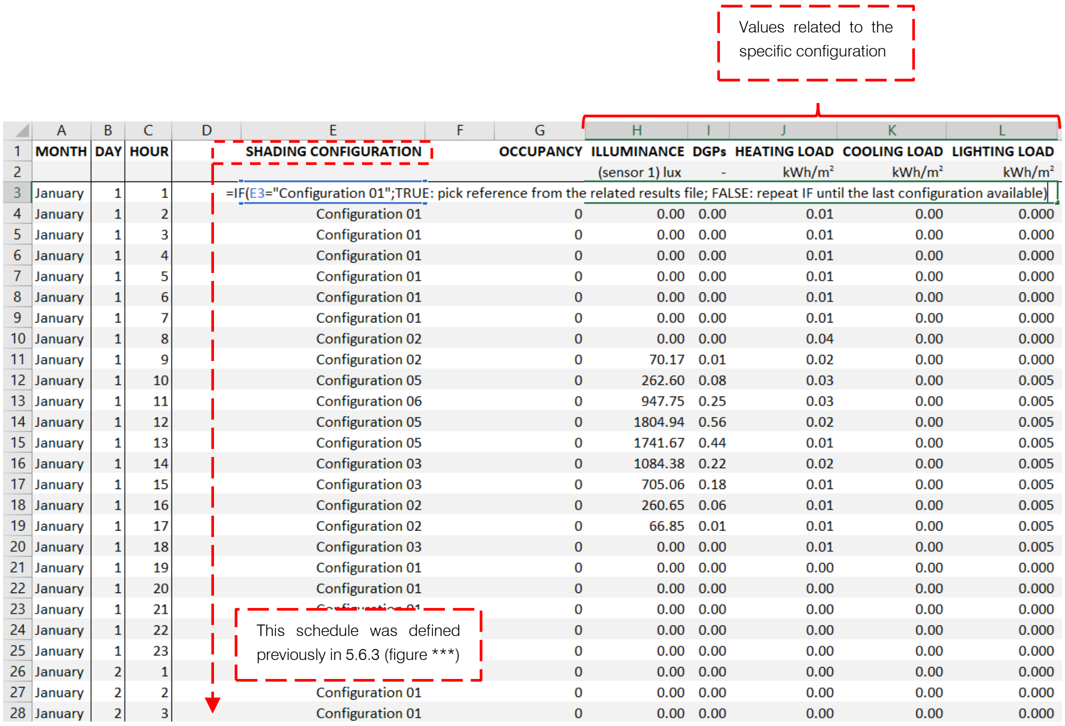
Figure 41 – Possible layout of an excel file on which defining the selection rules to achieve an optimized configuration schedule

5.6.4 Analysis of the optimized hourly set of data

The definition of the shading configuration schedule is followed by a new set-up operation of the side cells in the same spreadsheet with the intent of reporting the results linked to the configuration at that specific time-step hour. Each column is associated to a main parameter – illuminance, DGPs, heating demand, cooling demand, lighting demand – and the number of columns/parameters can vary according to the designers’ need, then the side cells, representing a single time-step for each row, will be defined by an “IF” formula that reports the parameter value referred to the configuration label expressed in the optimized schedule for that time-step and that specific parameter.

The formula “IF” is structured as [*test*; *if true*; *if false*], therefore it will test if the first content of the column that reports the shading configuration schedule corresponds to the first configuration defined: if the statement is true, the formula will show the value of the same parameter and time-step of the results file related to that shading configuration, otherwise, if the statement is false, it will test the second configuration with the same previous formula and will loop for each shading configuration until the statement is true. Considering the example file presented in figure 42 the formula could be written as:

=IF($E3="Configuration 1";[Daylight analysis results]Configuration 1'!F3;IF($E3="Configuration 2";[Daylight analysis results]Configuration 2'!F3;…;IF($E3="Configuration n";[Daylight analysis results]Configuration n'!F3;"error")))



	A	B	C	D	E	F	G	H	I	J	K	L
1	MONTH	DAY	HOUR		SHADING CONFIGURATION		OCCUPANCY	ILLUMINANCE	DGPs	HEATING LOAD	COOLING LOAD	LIGHTING LOAD
2								(sensor 1) lux	-	kWh/m²	kWh/m²	kWh/m²
3	January	1	1		=IF(E3="Configuration 01";TRUE: pick reference from the related results file; FALSE: repeat IF until the last configuration available)							
4	January	1	2		Configuration 01		0	0.00	0.00	0.01	0.00	0.000
5	January	1	3		Configuration 01		0	0.00	0.00	0.01	0.00	0.000
6	January	1	4		Configuration 01		0	0.00	0.00	0.01	0.00	0.000
7	January	1	5		Configuration 01		0	0.00	0.00	0.01	0.00	0.000
8	January	1	6		Configuration 01		0	0.00	0.00	0.01	0.00	0.000
9	January	1	7		Configuration 01		0	0.00	0.00	0.01	0.00	0.000
10	January	1	8		Configuration 02		0	0.00	0.00	0.04	0.00	0.000
11	January	1	9		Configuration 02		0	70.17	0.01	0.02	0.00	0.000
12	January	1	10		Configuration 05		0	262.60	0.08	0.03	0.00	0.005
13	January	1	11		Configuration 06		0	947.75	0.25	0.03	0.00	0.005
14	January	1	12		Configuration 05		0	1804.94	0.56	0.02	0.00	0.005
15	January	1	13		Configuration 05		0	1741.67	0.44	0.01	0.00	0.005
16	January	1	14		Configuration 03		0	1084.38	0.22	0.02	0.00	0.005
17	January	1	15		Configuration 03		0	705.06	0.18	0.01	0.00	0.005
18	January	1	16		Configuration 02		0	260.65	0.06	0.01	0.00	0.005
19	January	1	17		Configuration 02		0	66.85	0.01	0.01	0.00	0.005
20	January	1	18		Configuration 03		0	0.00	0.00	0.01	0.00	0.005
21	January	1	19		Configuration 01		0	0.00	0.00	0.00	0.00	0.000
22	January	1	20		Configuration 01		0	0.00	0.00	0.00	0.00	0.000
23	January	1	21		[illegible]		0	0.00	0.00	0.00	0.00	0.000
24	January	1	22				0	0.00	0.00	0.00	0.00	0.000
25	January	1	23				0	0.00	0.00	0.00	0.00	0.000
26	January	2	1				0	0.00	0.00	0.00	0.00	0.000
27	January	2	2		Configuration 01		0	0.00	0.00	0.00	0.00	0.000
28	January	2	3		Configuration 01		0	0.00	0.00	0.00	0.00	0.000

Figure 42 - Example of a set-up file collecting all the parameters related to the new hourly configuration schedule through which it is possible to assess the building performance

After reporting all the data related to the optimized schedule it is possible to show the results achieved through graphs.

The energy loads should be analyzed separately (heating, cooling, artificial lighting) and can be summed up to get monthly and yearly energy assessments, then showing the results or monthly trends by adopting bar charts, line charts, etc… (figure 43).

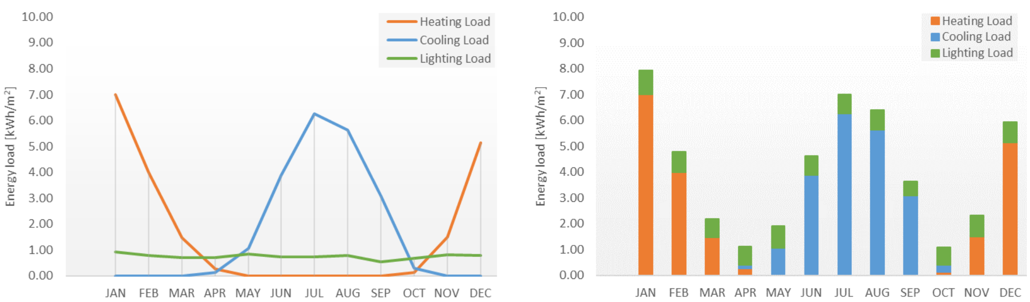


Figure 43 - Possible ways to show monthly and annual trends of energy loads

The DGPs values are defined for a specific view, as previously described in figure 33, and are represented by a column with 8760 values; the most effective way to show these results could be a graph representing the 24h values on a daily basis, meaning to define a portion of cells formatted with a color scale with dimensions 24 rows by 365 columns (see example in figure 44). The construction of this temporal graph can be made by using a macro acting on the hourly values: for examples, if the hourly DGPs are placed in the range [I3:I8763] and the graph with formatted cells would be placed in another sheet “DGPs”, then the macro named “DGP” would be formatted as shown in figure 45. The color scale should be presented from dark colors to bright ones, where blue stands either for no light or no glare, yellow set the lower limit of the perception (DGPs=0.35) and red intolerable conditions (DGPs>0.45).

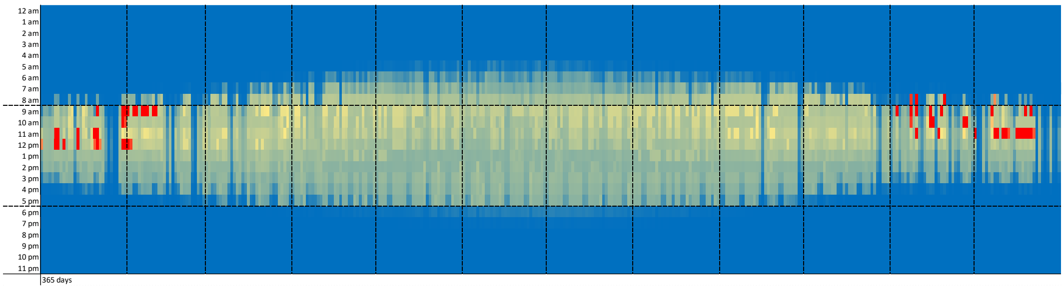


Figure 44 - Example of DGPs graphic representation for the whole year, showing the 24 hours in the rows and the 365 days in the columns

```
Sub DGP()
'
' DGP Macro
'

'
a = 3
b = 26
c = 1

Do
    Range(Cells(a, 9), Cells(b, 9)).Select
    Selection.Copy
    Sheets("DGPs").Select
    Cells(1, c).Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    Application.CutCopyMode = False

a = a + 24
b = b + 24
c = c + 1

Loop Until a > 8770

End Sub
```

Figure 45 - Example for the definition of a macro command for the DGPs values representation

For what concerns the results related to the illuminance values, the path would be a little more laborious: reminding that each column represents a test point and each row an hourly value, the graphical representations will actually concern the result values obtained from the definition of daylight autonomies, useful daylight illuminances, etc… which are values that consider all the hourly data for each test point and need to be defined. Therefore, by following the descriptions of the interested parameters (DA_{300}, UDI, aUDI) it is possible to identify them at the end of the 8760 hourly values through a formula like:

=COUNT.IFS ($E:$E;1;F:F;">=300")/COUNT.IF($E:$E;1)

which in this specific case would define the daylight autonomy for the test point in the example in figure 42, and that can be modified in its structure to find all the necessary parameters as shown in table 4.

Daylight metric	Symbol	Low bound	High Bound
Daylight autonomy	DA	300 lux	-
Useful daylight illuminance – fell short	UDI-f	0 lux	100 lux
Useful daylight illuminance – supplementary	UDI-s	100 lux	300 lux
Useful daylight illuminance – autonomous	UDI-a	300 lux	2000 lux
Useful daylight illuminance – exceeded	UDI-e	2000 lux	-
Adapted Useful daylight illuminance – autonomous	AUDI-a	300 lux	1000 lux
Adapted Useful daylight illuminance – exceeded	aUDI-e	1000 lux	-

Table 4 - Daylight metric related to the illuminance values registered by each test point and related boundaries

	A	B	C	D	E	F	G	H	I	J	K	L	M	Y
1	**MONTH**	**DAY**	**HOUR**	**SHADING CONFIGURATION**	**OCCUPANCY**	**SENSOR 1**	**SENSOR 2**	**SENSOR 3**	**SENSOR 4**	**SENSOR 5**	**SENSOR 6**	**SENSOR 7**	**...**	**SENSOR n**
11	January	1	9	Configuration 02	0	70.17	20.17	10.17	40.17	15.17	25.17	20.17	...	20.17
12	January	1	10	Configuration 05	0	262.60	212.60	202.60	232.60	207.60	217.60	212.60	...	212.60
13	January	1	11	Configuration 06	0	947.75	897.75	887.75	917.75	892.75	902.75	897.75	...	897.75
14	January	1	12	Configuration 05	0	1804.94	1754.94	1744.94	1774.94	1749.94	1759.94	1754.94	...	1754.94
15	January	1	13	Configuration 05	0	1741.67	1691.67	1681.67	1711.67	1686.67	1696.67	1691.67	...	1691.67
16	January	1	14	Configuration 03	0	1084.38	1034.38	1024.38	1054.38	1029.38	1039.38	1034.38	...	1034.38
8755	...	...	...	...	...	...	...	...	...	...	...	...	...	...
8756	December	31	15	Configuration 05	1	5016.00	6344.00	7373.00	8210.00	8833.000	9259	9826	...	10450.00
8757	December	31	16	Configuration 03	1	4065.00	5176.00	6056.00	6782.00	7390.000	7773	8076	...	8503.00
8758	December	31	17	Configuration 03	1	2471.00	3188.00	3781.00	4273.00	4613.000	4841	4993	...	5240.00
8759	December	31	18	Configuration 01	1	587.00	734.00	844.00	928.00	985.000	1023	1048	...	1092.00
8760	December	31	19	Configuration 01	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	...	0.00
8761	December	31	20	Configuration 01	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	...	0.00
8762	December	31	21	Configuration 01	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	...	0.00
8763	December	31	22	Configuration 01	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	...	0.00
8764	December	31	23	Configuration 01	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	...	0.00
8765														
8766					**AUDI-f**	54%	5%	5%	4%	5%	5%	5%	...	59%
8767					**AUDI-s**	34%	4%	4%	4%	4%	4%	4%	...	29%
8768					**AUDI-a**	11%	25%	29%	32%	26%	28%	30%	...	11%
8769					**AUDI-e**	0%	66%	62%	60%	66%	63%	61%	...	1%
8770					**DA**	11%	91%	92%	92%	92%	91%	91%	...	12%
8771					**UDI-a**	11%	62%	70%	71%	58%	62%	62%	...	12%
8772					**UDI-s+a**	46%	66%	74%	75%	62%	66%	65%	...	41%
8773					**AUDI-s+a**	46%	29%	33%	36%	29%	32%	34%	...	39%
8774					n° h > 1000lux	0.0	1508.0	1421.0	1358.0	1502.0	1438.0	1388.0	...	0.0

Figure 46 - Example file management for the definition of the daylight metrics inherent to the illuminance values registered

Afterwards, the definition of the spatial daylight autonomy and the annual sunlight exposure can be calculated in excel by using the daylight autonomies found right before and adding another row of formulas that just count the number of hours above 1000 lux for each sensor point. Then, by adopting the formulas:

=COUNT.IF(F8770:Y8770;">=0.5")/COUNTA(F8770:Y8770) for the sDA,

=COUNT.IF(F8774:Y8774;">250")/COUNTA(F8774:Y8774) for the ASE,

which in this specific case relate to the example in figure 46, it is possible to calculate both spatial daylight autonomy and annual sunlight exposure for the test room.

Eventually, the evaluation of the daylight conditions according to the benefits for the circadian rhythms of the users can be assessed through a graphical representation of the minimum illuminance levels by adopting the same format as for the DGPs (figure 48) in order to have a clear idea on the occurrence of good daylighting conditions along the year. This graphical assessment has been defined in a different way from the other metrics related to the illuminance values because a spatial representation of the achieved values during the yeas wouldn't be enough consistent to understand if good conditions are achieved or not: the nature of this investigation rely on the fact that an internal ambient can be considered to achieve good conditions for the stimulation of the circadian rhythm when the illuminance reaches a minimum threshold for a certain period with a good frequency along the year, on the contrary the application of the same formula defined for the spatial daylight autonomy can return an inconsistent value, i.e. a 40% final result means that less than half of the interior space achieve the minimum daylight illuminances for the 50% of the occupied hours, but this wouldn't show whether this result is well distributed or not during the year and potentially it could mean that for 6 months straight the conditions are met and for the rest of the year they are not, and the latter condition cannot help in the regulation of the circadian rhythm. Therefore, after the definition of the average illuminance for the whole space, or its portions, at each hour (figure 47), the construction of the temporal graph could be made by using a macro acting on the mean hourly values: for examples, looking at the information in figure 47, if the hourly $E_{circadian}$ are placed in the range [Z3:Z8763] and the graph with formatted cells would be placed in another sheet "E_circad", then the macro named "Circadian" would be formatted as shown in figure 49. The color scale should be presented from dark colors to bright ones, where blue show too low illuminances, red represents the minimum threshold needed during morning (180 lux) and eventually yellow shows all the results above 226 lux. Higher accuracy can be achieved by subdividing the interior space in a certain number of sectors and analyzing the related average illuminances.

Average value of the illuminance values of each test point highlighted

	A	B	C	D	E	F	G	H	I	J	K	L	M	Y	Z
1	MONTH	DAY	HOUR	SHADING CONFIGURATION	OCCUPANCY	SENSOR 1	SENSOR 2	SENSOR 3	SENSOR 4	SENSOR 5	SENSOR 6	SENSOR 7	...	SENSOR n	Average illuminance
8	January	1	6	Configuration 01	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	...	0.00	0.00
9	January	1	7	Configuration 01	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	...	0.00	0.00
10	January	1	8	Configuration 02	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	...	0.00	0.00
11	January	1	9	Configuration 02	0	70.17	20.17	10.17	40.17	15.17	25.17	20.17	...	20.17	21.71
12	January	1	10	Configuration 05	0	262.60	212.60	202.60	232.60	207.60	217.60	212.60	...	212.60	86.05
13	January	1	11	Configuration 06	0	947.75	897.75	887.75	917.75	892.75	902.75	897.75	...	897.75	165.71
14	January	1	12	Configuration 05	0	1804.94	1754.94	1744.94	1774.94	1749.94	1759.94	1754.94	...	1754.94	685.97
15	January	1	13	Configuration 05	0	1741.67	1691.67	1681.67	1711.67	1686.67	1696.67	1691.67	...	1691.67	654.58
16	January	1	14	Configuration 03	0	1084.38	1034.38	1024.38	1054.38	1029.38	1039.38	1034.38	...	1034.38	212.94
8755	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
8756	December	31	15	Configuration 05	1	5016.00	6344.00	7373.00	8210.00	8833.000	9259	9826	...	10450.00	138.60
8757	December	31	16	Configuration 03	1	4065.00	5176.00	6056.00	6782.00	7390.000	7773	8076	...	8503.00	28.32
8758	December	31	17	Configuration 03	1	2471.00	3188.00	3781.00	4273.00	4613.000	4841	4993	...	5240.00	0.00
8759	December	31	18	Configuration 01	1	587.00	734.00	844.00	928.00	985.000	1023	1048	...	1092.00	0.00
8760	December	31	19	Configuration 01	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	...	0.00	0.00
8761	December	31	20	Configuration 01	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	...	0.00	0.00
8762	December	31	21	Configuration 01	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	...	0.00	0.00
8763	December	31	22	Configuration 01	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	...	0.00	0.00
8764	December	31	23	Configuration 01	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	...	0.00	0.00
8765															
8766					AUDI-f	54%	5%	5%	4%	5%	5%	5%	...	59%	
8767					AUDI-s	34%	4%	4%	4%	4%	4%	4%	...	29%	
8768					AUDI-a	11%	25%	29%	32%	26%	28%	30%	...	11%	
8769					AUDI-e	0%	66%	62%	60%	66%	63%	61%	...	1%	
8770					DA	11%	91%	92%	92%	92%	91%	91%	...	12%	
8771					UDI-a	11%	62%	70%	71%	58%	62%	62%	...	12%	
8772					UDI-s+a	46%	66%	74%	75%	62%	66%	65%	...	41%	
8773					AUDI-s+a	46%	29%	33%	36%	29%	32%	34%	...	39%	

Figure 47 - Addition of an end column that defines the average hourly illuminances of the whole space

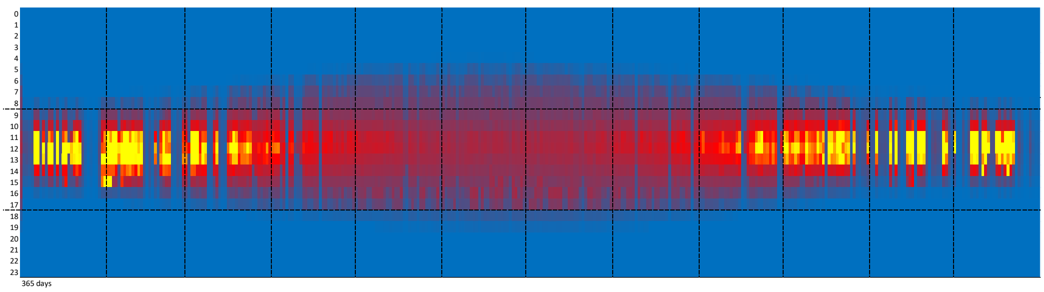


Figure 48 - Example of the graphic representation of the useful illuminances that stimulate the circadian rhythm for the whole year, showing the 24 hours in the rows and the 365 days in the columns

```
Sub DGP()
'
' Circadian Macro
'

'
a = 3
b = 26
c = 1

Do
    Range(Cells(a, 26), Cells(b, 26)).Select
    Selection.Copy
    Cells(4, c).Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    Sheets("E_circad").Select
    Cells(1, c).Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    Application.CutCopyMode = False

a = a + 24
b = b + 24
c = c + 1

Loop Until a > 8770

End Sub
```

Figure 49 - Example definition of the macro command for the graphical representation of the useful illuminance values for the stimulation of the circadian rhythm

5.7 Application of the method to a case study

The present case study has been developed starting from a validated standard model of an interior ambient and applying to it an existing dynamic shading technology. Ensuing the contents introduced in the first chapters that highlight the pro and cons of well daylit work environments, the following evaluation model has been delineated as an office workplace, which is the place where people usually spend the most of their time during diurnal hours, and therefore an initial assessment of the shading system could facilitate the prediction of users' comfort or the definition of a possible implementation of the shading.

The performed analyses follow a climate-based approach and Milan has been selected for the test location to assess the building daylight and energy performances, taking advantage of the familiarities developed with the chosen location. An identical test building devoid of the shading system has been also assessed in order to check the accuracy of the post-processing operations defined in the previous paragraphs for the illuminance results, considering the amount of data analyzed.

The performed analyses will focus primarily on the optimization of the illuminance levels and the avoidance of glare phenomena, the energy loads are simply evaluated as following values. In the next chapter, the results gained from the analysis of the test ambient provided with dynamic shadings will be eventually compared to the ones of the test building lacking the shading device and the possible pro and cons will be shown, moreover the daylight and energy assessment will be defined for different orientations – south, east and west.

5.7.1 The shading device: brief description and digital modelling

The selected shading system is employed since 2013 in a commercial building of Shanghai designated to multipurpose uses, such as showcase for organic food products, restaurant and food stores; the devices, installed in groups of single modules, can be classified as vertical shadings whose peculiarities lie on the two sets of 23 vertical strings fastened at each end to metallic mullions, whom the one at the lower end can rotate around the axis of the module and gives a remarkable contribution in the creation of a moiré effect in combination with the different coloration of the two sets of strings.

Figure 50 - External views of the dynamic shading (photo credits to Bartosz Kolonko)

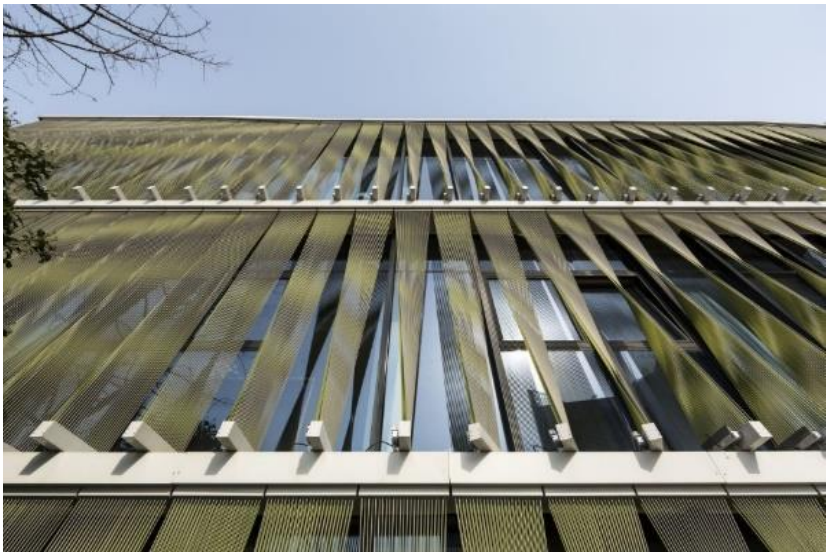


Figure 51 - Shading device appearance (photo credits to Bartosz Kolonko)

From the little reachable information about this shading system it is possible to state that its main functions are the provision of privacy to the building users and shading the solar radiation to reduce the heat gains, though no indications on the energy performance is provided and the real effectiveness of the sun-shading purpose can't be checked. According to the available information gathered from the design studio, the adoption of separate strings allows to manage in a better way the tensions in the rotated device in comparison to a whole fabric, but no specific data about the components and actuators is provided.

The digital modelling starts from the definition of proportions and dimensions of the interested elements by looking at the references available from the designer website (figure 50-51), then a simplified model is approached by focusing on the two main components of the shading system, namely the vertical strings and the metallic elements that retain them. The modelling workflow proceeds with the virtual construction of a module consisting in the geometrical definition of the said elements and the provision of the rotational motion, then the application of the system to the façade will pass through the repetition of the shading module and its correct position in the space. Eventually it is needed to assign the shading geometries to HB components, namely HB context, in order to include them into the simulation processes.

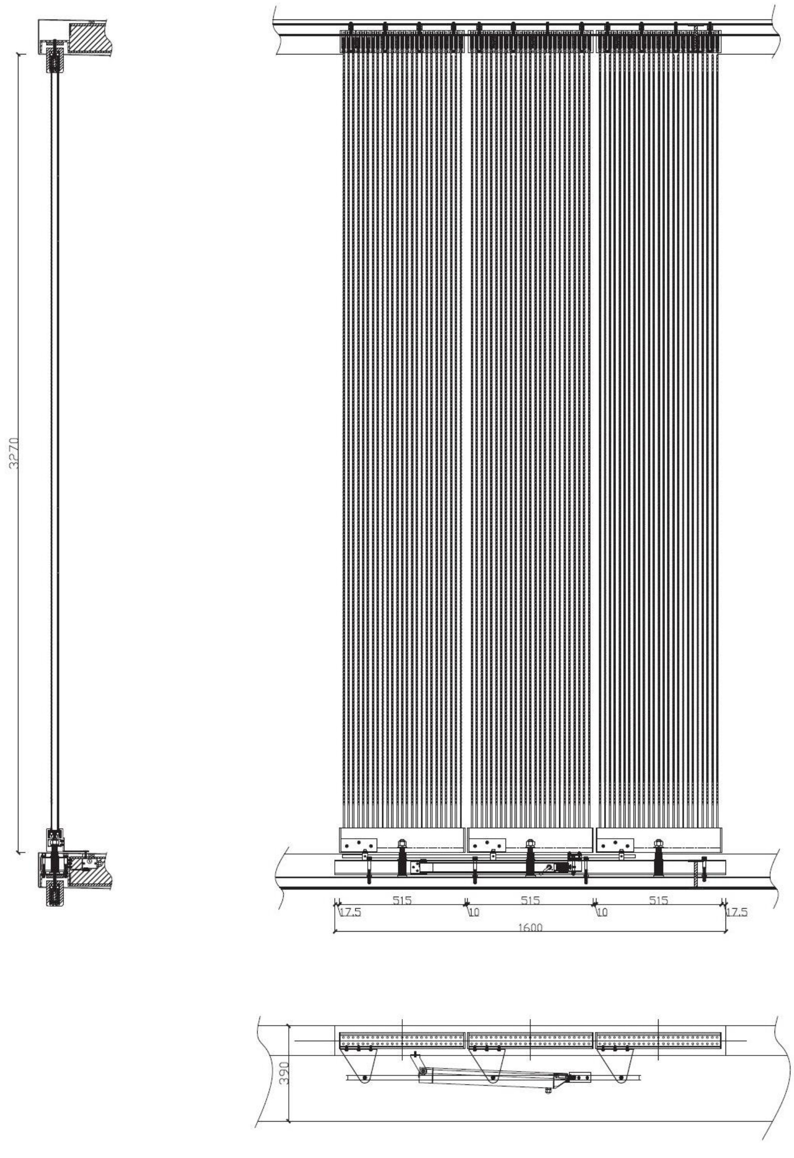


Figure 52 - Representation of the shading device (http://www.playze.com/978464/tony39s-organic-house)

The module's measures have been derived from the only geometric information available (figure 52 or assumed from that reference and also considering the dimensions of the designed construction elements – walls, ceiling, etc… – to obtain a perfect fit for the later combination of the shading system and the test ambient. The metal transoms that retain the strings are defined by simple boxes obtained from the extrusion of rectangles with dimensions 51.5 cm x 7.5 cm and 10 cm height;

the motion is performed through the rotation around the vertical axis passing from the barycenter of the element. The 46 strings are grouped in two sets of 23 items each and are placed in between the metal transoms that block the\m at each end, while the supposed wires section is circular with a diameter of 1 cm. The location of the strings is parametrically linked to the transom geometry, so the two sets lie on the lower and upper thirds of the transom width and are evenly distributed along the 24 subdivision spaces of the transom length. A rendered picture of the shading device and its configurations is presented in figure 54.

Considering that both Radiance and EnergyPlus face difficulties in dealing with curved surfaces, the shape of the vertical strings, which present a circular section, has been re-dimensioned to a square section: a size of 8 mm per length has been defined to guarantee the most similar shading surface to the original design – 3.20 dm^2/m_{square} againts 3.14 $dm^2/m_{circular}$ (figure 53).

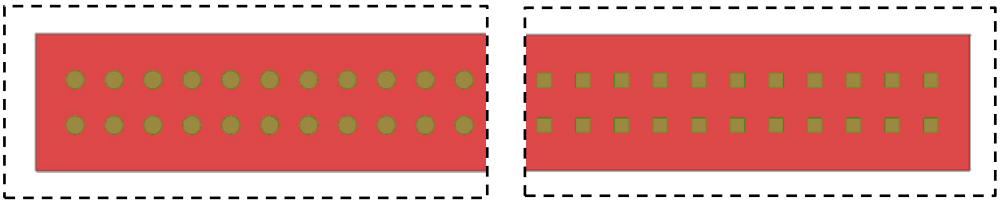


Figure 53 - Modification of the strings section: on the left the actual solution, on the right the approximated one to comply with the simulation engine requirements

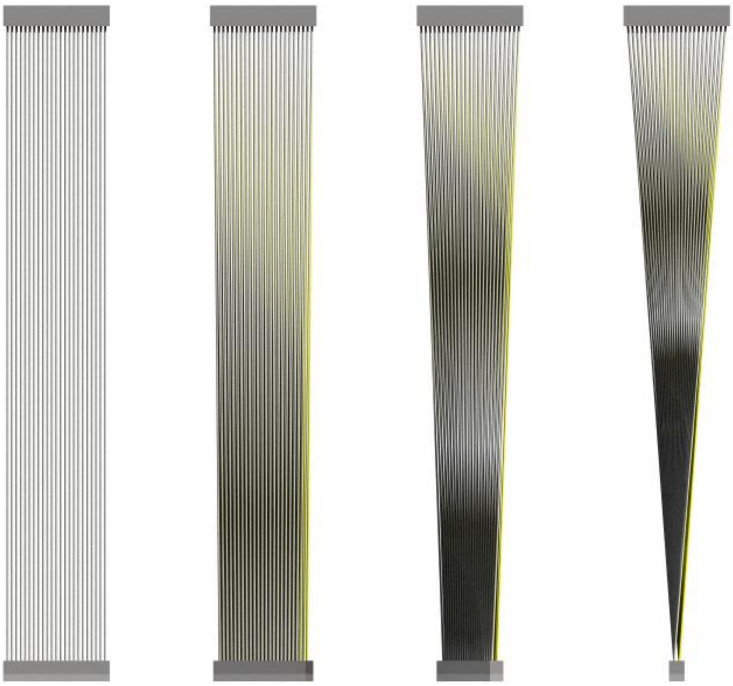


Figure 54 - Deployment stages of the digitally modelled shading device, rendered with Neon; from left to right 0°, 30°, 60°, 90°

Another issue arisen during the first analysis tests was due to the impossibility to run energy simulations for the selected geometry, even though a triangulation was provided: therefore, for the only energy analyses, the geometries related to the two sets of 23 strings have been substituted with two ideal plain surfaces, the triangulation components have been kept and the Radiance material properties have been defined as translucent material (figure 56). The properties of the translucent material (figure 55) have been assessed through many attempts aiming at reaching the same sDA (or a close value) of the original shading device for the south orientation and in a parallel position to the envelope, which eventually have been set as specified in table 5.

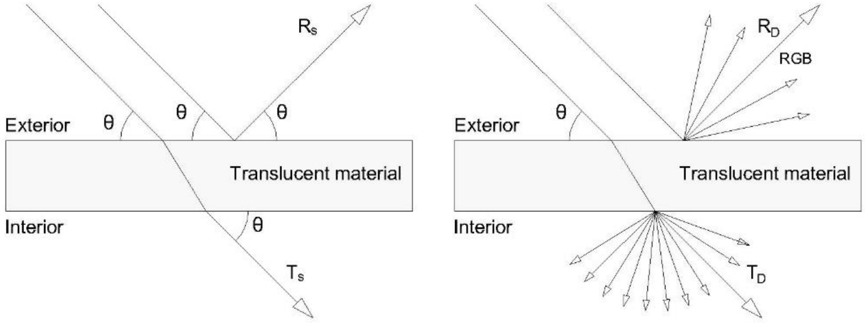


Figure 55 - Graphical representation of the properties defined for the translucent material

Parameter	Symbol	Value
RGB reflectance	R_D	0.50
Specular reflection	R_S	0.05
Diffuse transmission	T_D	0.24
Specular transmission	T_S	0.20
sDA	-	21.35% (-7%)

Table 5 - Radiance material properties assigned to the equivalent translucent material defined for the whole surface that substitute the vertical strings in the energy simulations

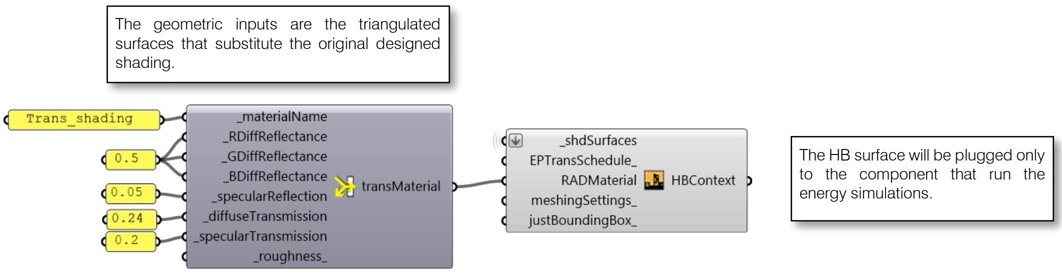


Figure 56 - Description of the component that substitute the original shading device with an approximated translucent surface

Since the main focus for the case study is related to the daylight assessment and to the optimization of the hourly configuration schedule of the shading system, it has been decided to run the daylight simulations with the original design and the energy ones with the modified shading surface, being aware of the discrepancies and accepting them.

The shading group will count 23 elements placed at 0.8 m from the building façade and they are all characterized by the same motion and the contemporaneity.

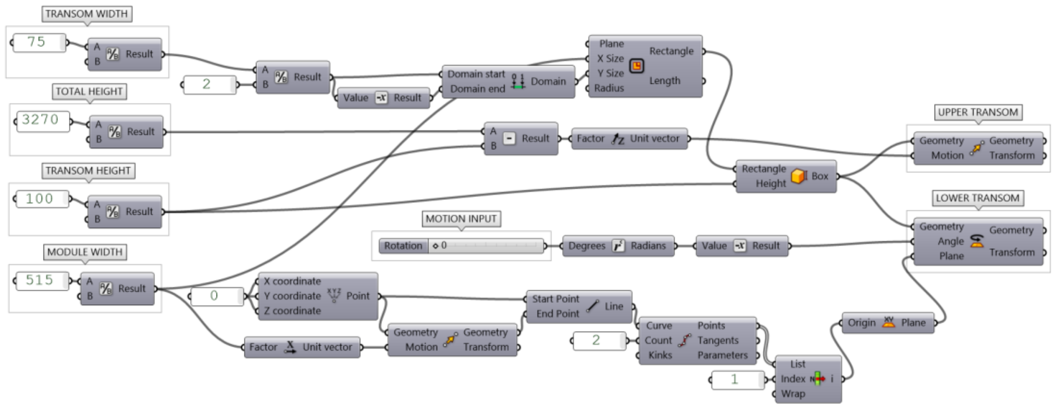


Figure 57 - Script components employed for the geometric definition of the metallic transoms that retains the strings

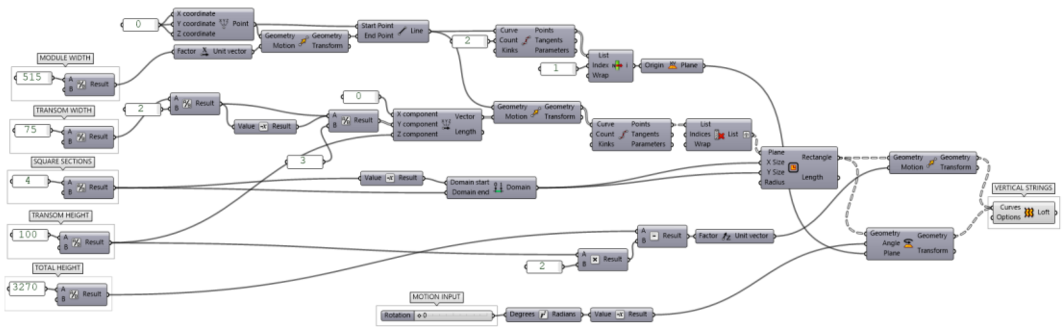


Figure 58 - Script components employed for the geometric definition of the vertical strings

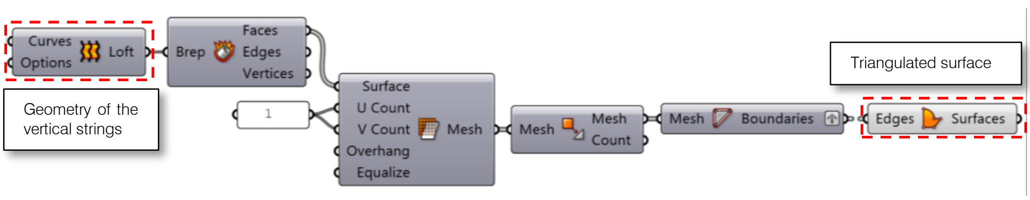


Figure 59 - Set of components defined to triangulate the non-planar surfaces generated in the geometry during the motion

5.7.2 The test ambient: brief description and digital modelling

The IEA BESTEST building (figure 60) is a standard building developed about 20 years ago and frequently used for energy simulations where development of systems or envelope components are involved. The choice fell on this geometry for a matter of similarities with the current design trends regarding office buildings, whose peculiarity may be found in the high window-to wall ratios adopted, which in this case is around 56%, leading to possible excessive daylight scenarios and resulting discomfort effects such as glare phenomena.

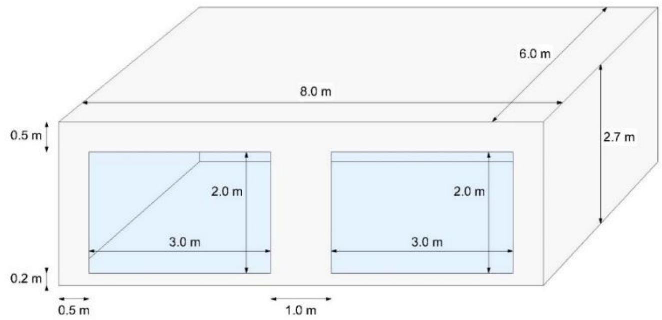


Figure 60 - The IEA BESTEST building defined for the case study

The building has internal dimensions of 8.0 m x 6.0 m, 2.7 m height and presents two windows with dimensions of 2.0 x 3.0 m, which are south-oriented by default setting; for this case study, the ambient has been considered as a central portion of a multistory building, therefore the glazing has been considered placed on the only construction element interfacing the exterior environment while all the other boundary surfaces have been defined as adiabatic since the adjacent ambient are interior spaces too and meet the same room conditions as the case study.

The pursued building assessment finds its basis on guaranteeing the users' daylight visual comfort, though it is not possible to totally neglect the thermal aspects – and the related energy consumption – considering the remarkable contribution in the users' comfort assessment, therefore the boundaries defining the test ambient have been identified by high-performance construction elements. The opaque elements have been designed as stratified layer systems, which stress considerable advantages in comparison with traditional technologies – reduced thickness, weight, and water consumption during the construction phase, easier recycling of disused materials, improved quality thanks to the employment of skilled workers. All these features allow to reach better performances for the building energy consumption, which can be translated as a strong reduction of CO_2 emissions.

The exterior wall (figure 61) is composed by two main layers having a structure made by U and C-shaped aluminum profiles, whose interior space is filled with a layer of insulating material and enclosed by gypsum plasterboards, or fiber-cement panels when facing the outdoor environment; in between these two elements is provided a gap in which another insulating layer is placed and closed in, while a vapor-barrier is inserted between the two inner plasterboards. Some of the main properties of this construction element and the involved layers are listed in table 6.

		T [mm]	λ [W/mK]	δ [kg/m³]	c [J/kgK]
	Interior	-	-	-	-
1	Gypsum board	12.5	0.200	680.0	1030
2	Gypsum board	12.5	0.200	680.0	1030
3	Mineral wool	75.0	0.035	19.4	1030
4	Mineral wool	40.0	0.035	19.4	1030
5	Gypsum board	12.5	0.200	680.0	1030
6	Mineral wool	100.0	0.035	19.4	1030
7	Fiber-cement board	12.5	0.600	1200.0	1030
8	Fiber-cement board	12.5	0.600	1200.0	1030
	Exterior	-	-	-	-

Total thickness	27.75 cm
Thermal transmittance - U	0.153 W/m²K
Thermal resistance – R	6.54 m²K/W
Total weight	59.67 kg/ m²

Table 6 – List of the main layers adopted for the exterior wall and primary properties

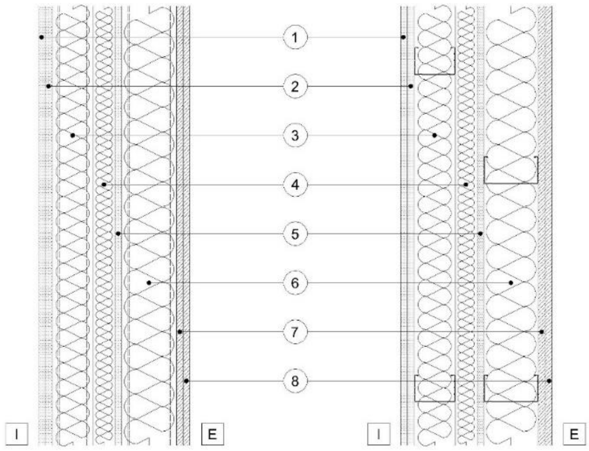


Figure 61 - Exterior wall construction: vertical section on the left, horizontal section on the right

The interior wall's structure still adopts U and C-shaped aluminum profiles filled with insulating material and enclosed by gypsum plasterboards. Some of the main properties of this construction element and the involved layers are listed in table 7.

		T [mm]	λ [W/mK]	δ [kg/m³]	c [J/kgK]
	Interior	-	-	-	-
1	Gypsum board	12.5	0.200	680.0	1030
2	Gypsum board	12.5	0.200	680.0	1030
3	Mineral wool	55.0	0.035	19.4	1030
4	Gypsum board	12.5	0.200	680.0	1030
5	Gypsum board	12.5	0.200	680.0	1030
	Interior	-	-	-	-

	Total thickness	10.05 cm
	Thermal transmittance - U	0.500 W/m²K
	Thermal resistance – R	1.99 m²K/W
	Total weight	35.07 kg/ m²

Table 7 - List of the main layers adopted for the interior walls and primary characteristics

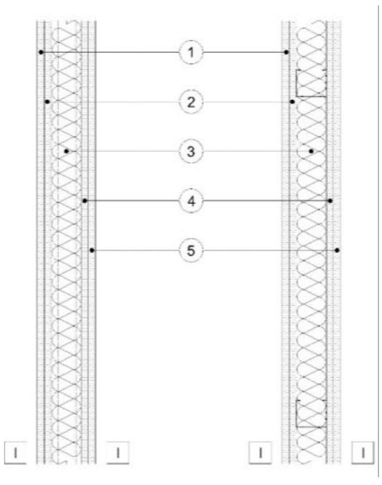


Figure 62 - Interior wall construction: vertical section on the left, horizontal section on the right

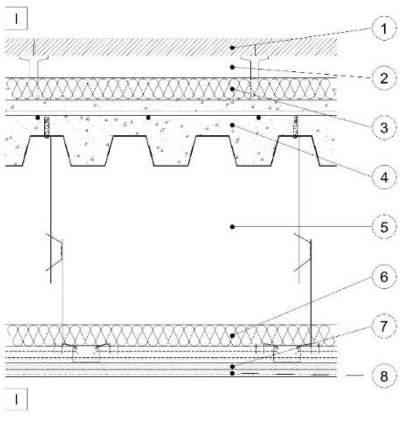


Figure 63 – Interior floor construction: vertical section

The floor and the ceiling of the test ambient share the same construction technology: the main structure consists in a metal deck combined with a reinforced concrete cover above which is placed a raised floor, while below it is provided a suspended ceiling that allows the passage of HVAC system. Some of the main properties of this construction element and the involved layers are listed in table 8.

		T [mm]	λ [W/mK]	δ [kg/m^3]	c [J/kgK]
	Interior – upper side	-	-	-	-
1	Wooden tiles	30.0	0.220	850.0	1360
2	Air layer	40.0	-	-	-
3	Mineral wool	40.0	0.035	19.4	1030
4	Metal deck + concrete	65.0 ÷ 120.0	2.300	2500.0	650
5	Air layer	300.0	-	-	-
6	Mineral wool	40.0	0.035	19.4	1030
7	Gypsum board	12.5	0.200	680.0	1030
8	Gypsum board	12.5	0.200	680.0	1030
	Interior – lower side	-	-	-	-

Total thickness	**61.75 cm**
Thermal transmittance - U	**0.330 W/m^{2}K**
Thermal resistance – R	**3.02 m^{2}K/W**
Total weight	**275.30 kg/ m^2**

Table 8 - List of the main layers adopted for the horizontal partitions and primary characteristics

Reminding that the analysis pursued is related to a preliminary assessment, the windows have been assumed as ideal glazing systems and many details have not been investigated, from the size of the frame to the dimension of the sill, though the main properties considered for the input glazing have been derived by starting from a double-glazing system (90% Argon filled) whose technology was more oriented to the thermal insulation issue, therefore the parameters that have been considered have been assumed as following:

Parameter	Symbol	Value
Visible light transmittance	Tvl	0.80
Thermal transmittance	U_{global}	1.70 W/m^{2}K
Solar heat gain coefficient	SHGC	0.60

Table 9 - Main parameters defined for the shading system

The digital model has been defined as shown in figure64 starting from the construction of a simple box and following the illustrated flow, namely consisting in deconstructing the geometry and listing its faces to identify each part of the envelope that needs to be considered for the definition of the single HB surfaces. It is brought then the attention on another group of components showed again in figure 64 and used to define a particular shading element representing a sort of frame for the exterior facade: the resulting brep will "wrap" the upper, lower and side parts of the dynamic shading system and should represent, in a real case scenario, the shade offered by the elements found in the space between the envelope and the shading devices (i.e. a maintenance path), however boundary surfaces should always be provided in order to perform more realistic simulations and avoid wrong considerations about the system efficacy. This geometric element will be therefore included in the simulations as HB context surface as displayed in figure 65 and assigning a reflectance value of 0.2.

Back to the test ambient modelling, the running operations for both daylight and energy simulations depend on the provision of all the necessary parameters, that allow EnergyPlus and

Radiance to properly run the analyses, to each EP material employed for the definition of the EP constructions, then it just remains to connect correctly all the components that flow into the HB zone to end the zone modelling (figures 66-67-68).

HB Surface	Assigned EP construction	Reflectance (RAD material)	Transmittance (RAD material)
Floor	00_Interior floor	0.2	-
Ceiling	00_Interior ceiling	0.7	-
Interior walls	00_Interior wall	0.5	-
Exterior wall (opaque)	00_Exterior wall	0.5	-
Exterior wall (glazing)	00_Exterior window	-	0.8

Table 10 - List of relevant properties assigned to the HB surfaces delimiting the test building (EnergyPlus and Radiance material definition)

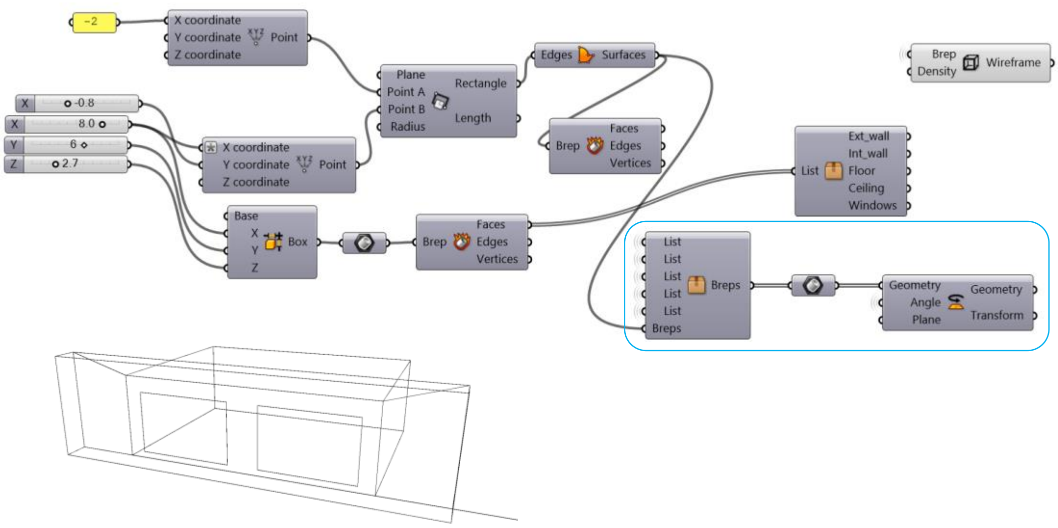
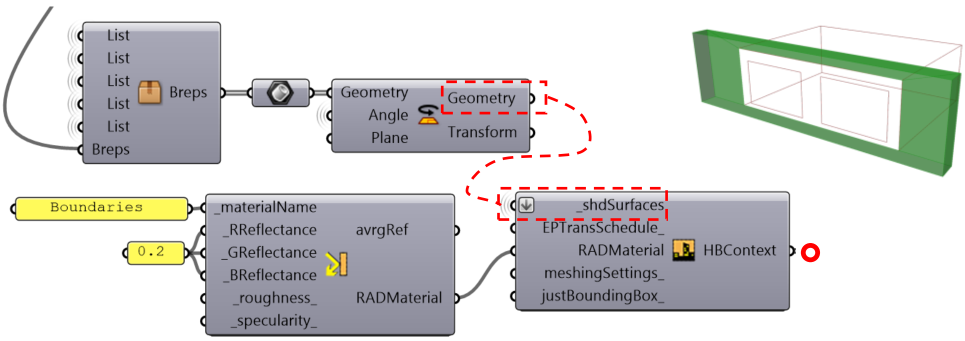


Figure 64 - Illustration of the components used to define geometrically the test ambient and the wireframe representation of the result, before defining the HB objects used for the simulations



to the simulation components

Figure 65 – Conversion into HB context surface of the brep representing the shading element defined by the components placed in the gap between the shading system and the building envelope

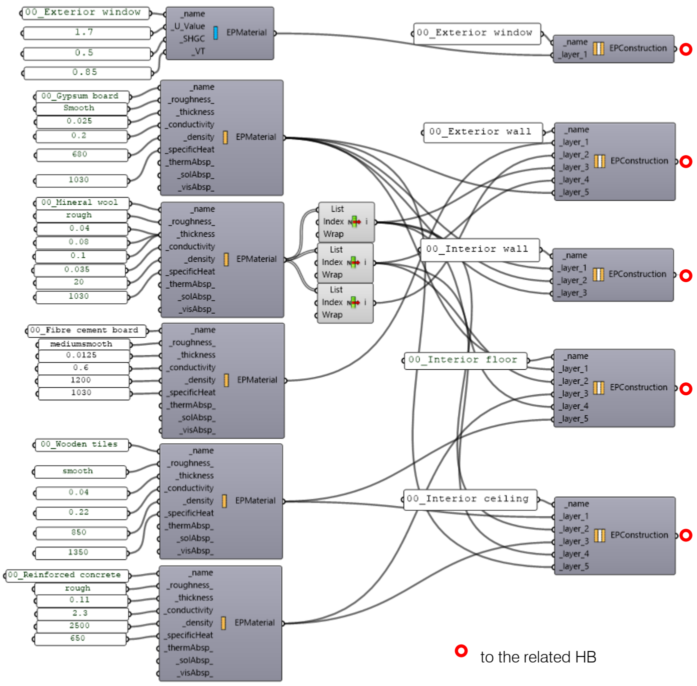


Figure 66 - Illustration of the parameters used to define the employed EP materials adopted for the definition of the EP construction components; blank input parameters assume default values from the component.

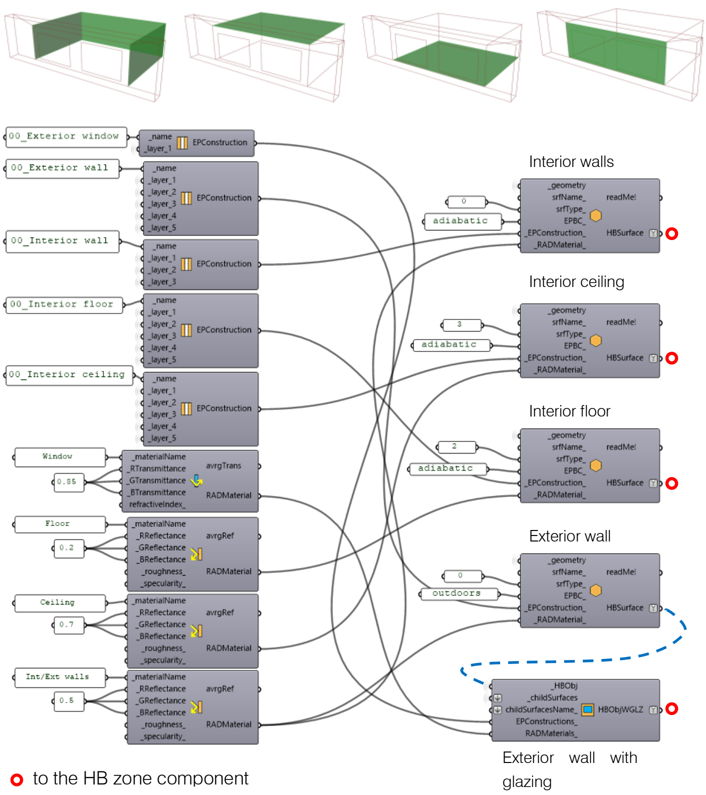


Figure 67 – Illustration of all the Radiance and EnergyPlus properties assigned to the HB surfaces.

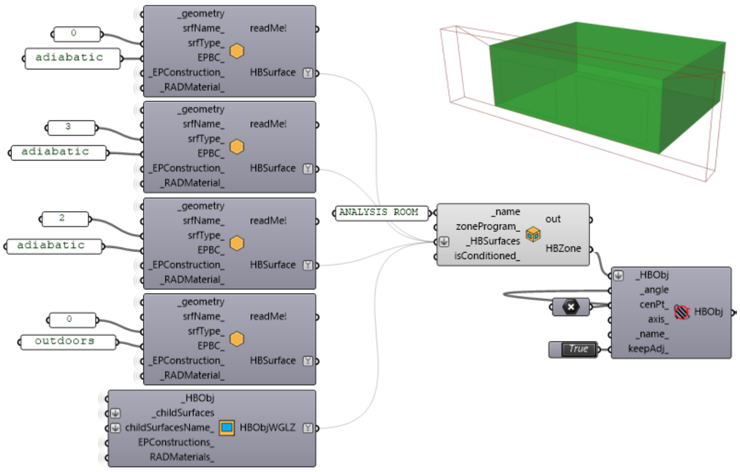


Figure 68 - Final step for the definition of the HB zone that will represent the test ambient; the rotation component is included to allow further analyses for different orientations of the building

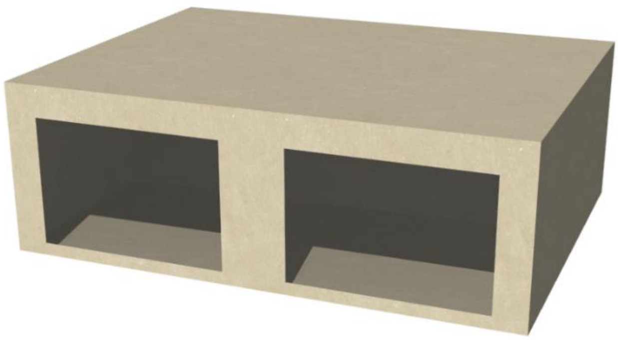


Figure 69 – Rendered representation of the IEA BESTEST building modelled with Grasshopper

5.7.3 Daylight simulations parameters

The analysis mesh on which performing the analyses is based on the floor geometry raised at 0.8 m height and a square grid size of 0.5 m: the total amount of test points results to be 192 for the 48 m^2 of the test ambient floor.

The Radiance parameters listed in table 11 have been set for the daylight analysis, although it would have been better to consider different values to get very accurate analyses and results as previously seen (table 3): unfortunately, the simulation related to very accurate parameters were very prolonged in time, namely about 3 h for a single simulation considering only 2 ambient bounces, otherwise for higher -ab, i.e. 3, it was not possible to even estimate the analysis duration. The reflectance defined for the geometries involved in the daylight analyses have been assumed as the typical values reported in table 10. The Daysim parameters won't provide any dynamic shading group, the Rhino view has been set to "Glare" (check 5.4 for the procedure) and the image size input is 300 px.

	Symbol	Value
Ambient bounces	-ab	2
Ambient divisions	-ad	512
Ambient super-samples	-as	512
Ambient resolution	-ar	256
Ambient accuracy	-aa	0.1

Table 11 - Radiance parameters set for the daylight simulation

The artificial lighting has been devised as a supporting system that should intervene in case daylight comfort conditions are not met, therefore the light sources assumed for the simulations are high efficiency LED lightbulbs with an installed power of 250 W, corresponding to a lighting density of about 5.2 W/m^2, while the lighting control is developed through a photosensor-controlled dimmed lighting system, corresponding to a system that needs to be manually activated via a single on/off switch and the photocell dims the lighting until the work plane illuminance reaches 300 lux. Afterwards, through the component "read annual results I" it is possible to record into a csv file (under the output "annual profiles") the fractional use schedule of the artificial lighting system adopted, which will be linked to the following energy analysis to determine the annual energy consumption for the artificial lighting.

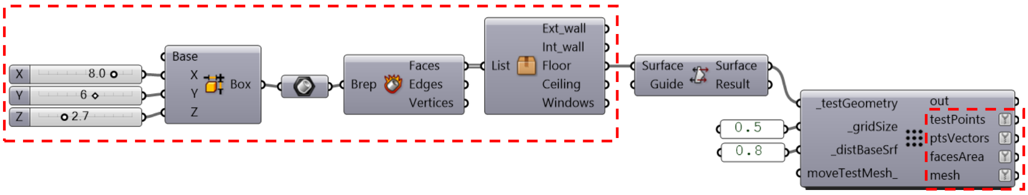


Figure 70 - Setting of the test points generator, main components and parameters adopted

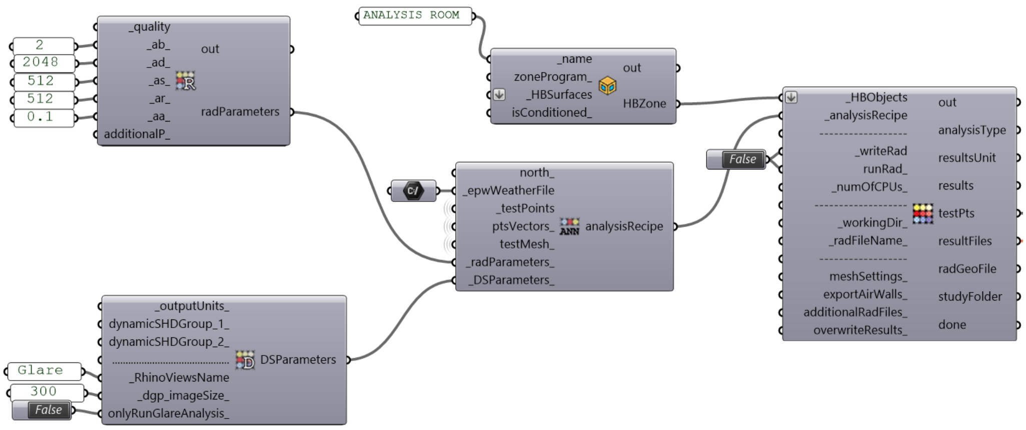


Figure 71 - Setting of the daylight annual analysis to run the simulation, major inputs and components

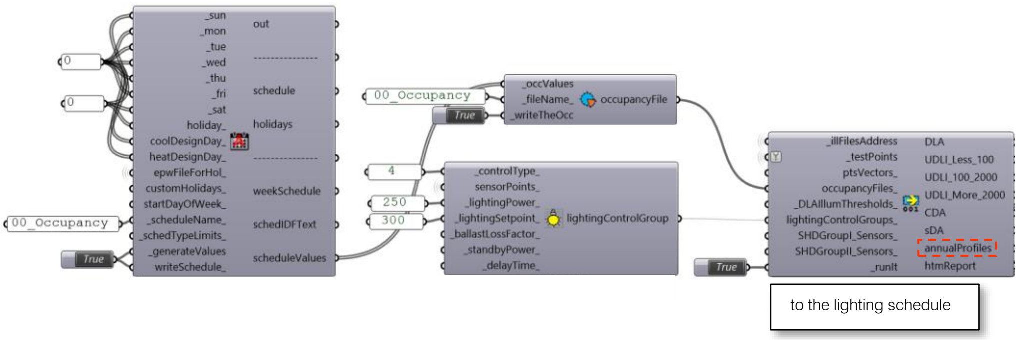


Figure 72 - Description of all the necessary components and inputs to define the annual profile for the artificial lighting use

5.7.4 Energy simulations parameters

Reminding the precondition that the building assessment would focus especially on the daylight performances, the HVAC system has been assumed working with ideal air loads and any further development has been neglected. However, the HB zone has been provided with energy loads (figure 73) and assigned schedules (figure 74) reported in table 12.

Almost all the schedules provided for the ambient test are related to the users' presence, whose work time has been set from 9am to 6 pm with a lunch break, from Monday to Friday: consequently, the mechanical ventilation and the appliances use are linked to that schedule, as well as the HVAC system working hours. Air infiltrations have been considered constant and always present and assuming a value that reflects that of a medium air permeability, though the value, presented in m^3/s per m^2 of façade need to be converted to m^3/s per m^2 of floor (figure 73). The artificial lighting schedule has not been defined because it derives from the daylight simulation which contributes in the creation of a fractional schedule considering the reaching of an illuminance level of 300 lux on the work plane located at 0.80 m from the floor.

The thermal performance is linked to a set-point temperature and a set-back temperature: the first one represents the minimum (or maximum) temperature at which the HVAC system activates during occupied hours, while the latter denotes the minimum (or maximum) temperature at which the HVAC system activates during unoccupied hours to control the environment, avoiding free floating. During the heating period the set-point temperature has been set to 20°C and the set-back temperature to 16°C, while during the cooling period they have been namely set to 26°C and 30°C.

	Value	Unit	Type of schedule	Active period
Equipment load	12.00	W/m^2	On/Off	9am–6pm, Mon-Fri (no holydays)
Infiltration rate	0.0003	$m^3/s \cdot m^2_{facade}$	On/Off	Always on
Lighting density	5.208	W/m^2	Fractional	Dependent on daylight analysis
N° of people	0.125	pp/m^2	On/Off	9am–6pm, Mon-Fri (no holydays)
Ventilation rate	0.001	$m^3/(s\ m^2)$	On/Off	9am–6pm, Mon-Fri (no holydays)
Heating set-point	20.0	°C	Temperature	9am-1pm, 2pm-6pm
Heating set-back	16.0	°C	Temperature	12am-9am, 1pm-2pm, 6pm-12pm
Cooling set-point	26.0	°C	Temperature	9am-1pm, 2pm-6pm
Cooling set-back	30.0	°C	Temperature	12am-9am, 1pm-2pm, 6pm-12pm

Table 12 - Definition of the EnergyPlus parameters related to energy loads and schedules assigned to the analyzed HB zone

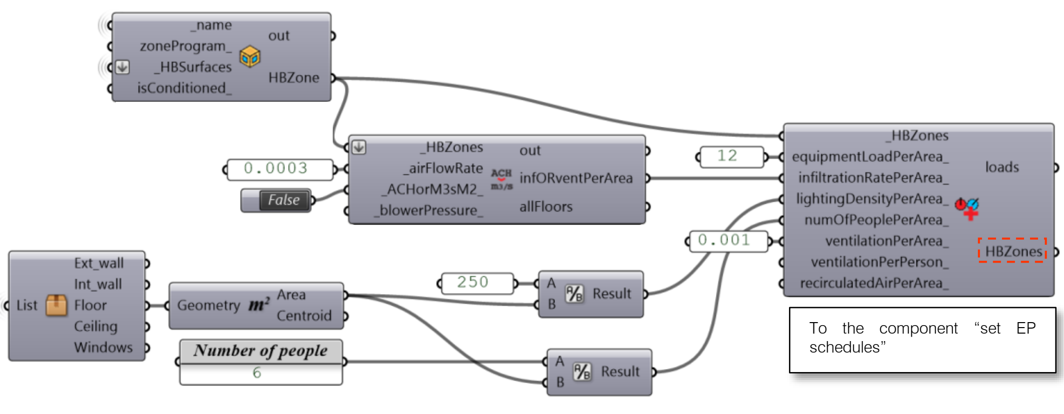


Figure 73 - Setting of the component aimed to define the HB zone energy loads

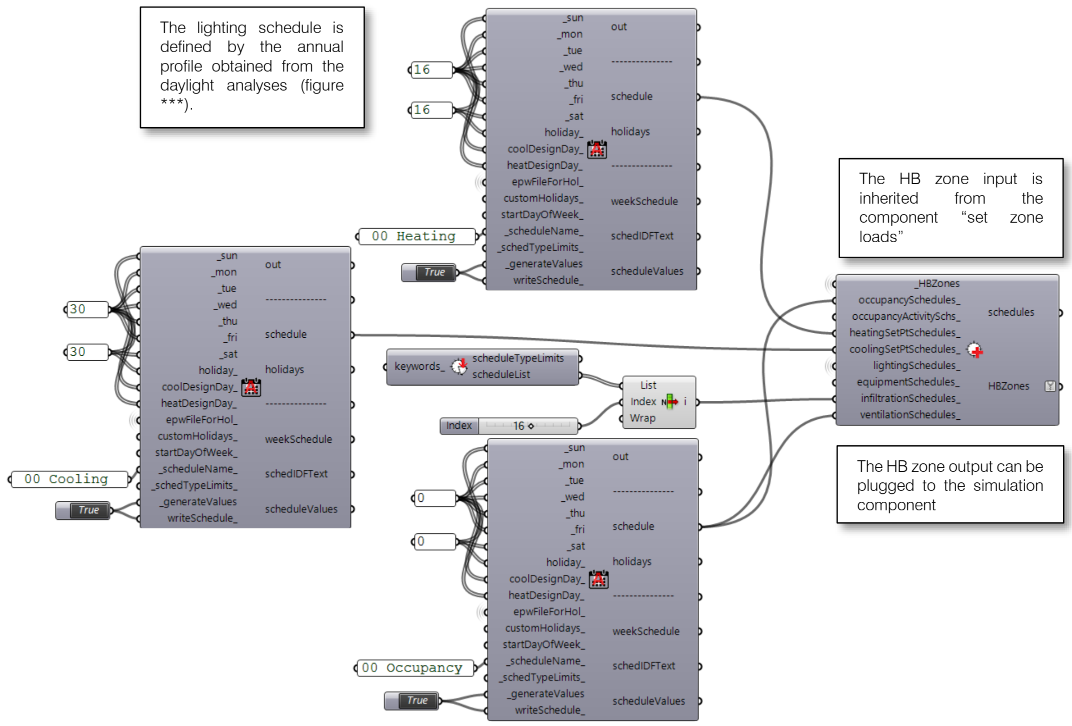


Figure 74 - Setting of the different schedules provided

As previously mentioned – and illustrated in figure 72 – the lighting control will be performed adopting automatic dimmers with switch-off occupancy sensors: dimmers can control the lighting intensity by reducing the wattage and output of lightbulbs, occupancy sensors can detect the activity presence and turn on/off the lights according to that. Both control system and light sources defined can contribute a lot for the reduction of the artificial lighting energy use.

5.7.5 Post-processing of the result data

The daylight and energy simulations have been run for the case study – the BESTEST building provided with the dynamic shading system – and for another base-case represented by the same test building devoid of any shading control, for a later comparison. The target, as defined previously, is the definition of a shading configuration schedule that allows to enhance the illuminance values inside the ambient allowing to guarantee the avoidance, if possible, of glare phenomena, therefore the optimization phase will start with the setting of the spreadsheet for the data management. Four shading configurations has been defined for the simulations and relate to the angle formed between the lower transom of the shading module and the façade plane, namely 0° - 30° - 60° - 90° (figure 75).

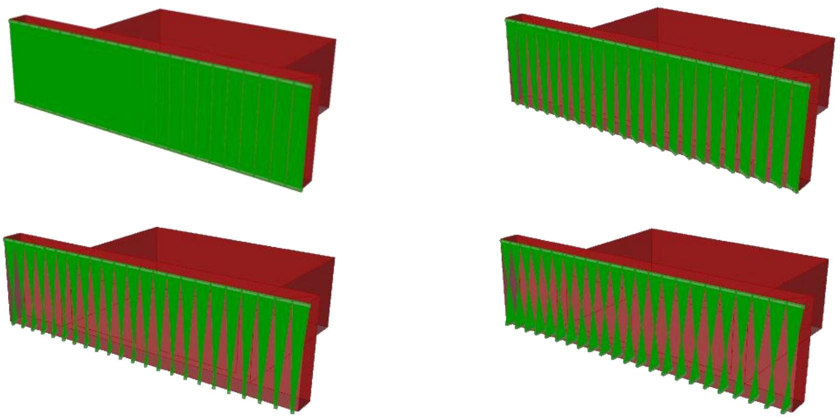


Figure 75 - Illustration of the analysed shading configurations; from upper left and going clockwise are shown 0°, 30°, 60°, 90° as rotation angles

At the end of the simulations, the daylight and energy results will be written in several files that equal the number of simulated configurations considering each orientation, which means that, for a single orientation, 10 data files should be considered for the post-process operations:

- 1 file for the daylight results of the un-shaded building;
- 1 file for the energy results of the un-shaded building;
- 4 files for the daylight results of the case study, one for each deployment stage;
- 4 files for the energy results of the case study, one for each deployment stage.

The workflow suggested now for the data post-processing (that should be performed for each orientation) consists in the collection of all the results concerning the different configurations into three spreadsheets by separating the illuminances from the DGP and the CSV results, and vice versa. Then, after this importing operations, 4 sheets will be created in a new Excel file (one for each shading configuration) collecting all the results gained with any type of simulation performed, apart from the illuminance values that will be collected in a different way: for the modelled zone,, the amount of test point created for the daylight simulations, according to a test mesh defined by a 0.5 m grid size, reaches 192 units and the file could become unstable by managing this amount of data, therefore it has been developed a subdivision of the ambient space into 4 sectors (figure 76) identified by an averaged illuminance value, accounting the specific test points. Later on, the illuminances will be evaluated in an appropriate way, along with the daylight metrics, after the definition of the optimized deployment schedule.

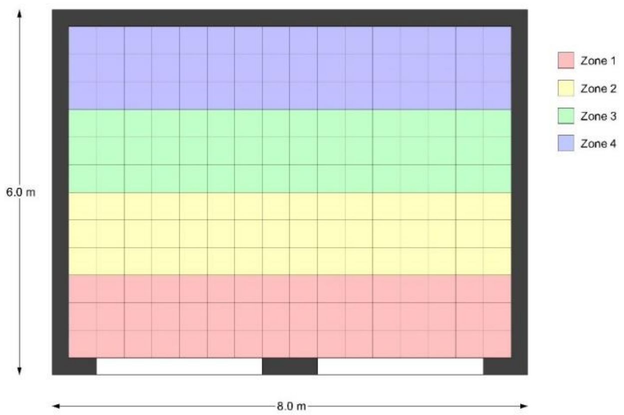


Figure 76 - Subdivision of the interior space into 4 areas according to the distance from the exterior wall, the analysis mesh is also represented; each ambient sector includes 48 test points

The data that will be imported from the CSV results file are:

- Zone Lights Electric Energy [J](Hourly)
- Zone Ideal Loads Supply Air Total Heating Energy [J](Hourly)
- Zone Ideal Loads Supply Air Total Cooling Energy [J](Hourly)

and a conversion factor will be considered in order to transform the results into kWh/m², while the other present outputs will be neglected.

The selection of the best hourly deployment state has been set in order to “choose” the configuration that provides an illuminance value on the work plane as much closer as possible to a predefined value of 500 lux and that guarantee the avoidance of glare phenomena, if possible, for each hour. The comparison will take place among the calculated differences between the averaged illuminances and a threshold value of 500 lux for each of the 4 portions of the space (figure 76): if the registered illuminance is higher than the threshold, the difference is accounted with a reduction of 50%, otherwise, for illuminances lower than 500 lux, the difference value is inherited in its absolute value and increased by 50%, allowing in this way to promote illuminances over 500 lux in comparison to lower ones in the range 0-300 lux. The defined differences for each space portion are then summed for each configuration, at each time-step, and the lowest sum of differences, representing a single deployment state, will be selected as meeting the requirement. The glare avoidance is defined by adding to the requirements that the configuration that reaches the closest illuminances to the threshold value registers also a DGPs lower than 0.4, which denotes the maximum bound for perceptible glare and, in case of no configuration meeting this requirement, the deployment state will be chosen according to the lowest DGPs. Moreover, during unoccupied hours the shading configuration will be set parallel to the façade, and in case the sunset occurs, especially in winter, the deployment state will keep the last position assumed, when natural light was still available

All the requirements descripted above have been translated through the formula:

```
=IF($F4=1;IF(AND(MIN($H4:$K4)=$H4;$H4<>3000;'0'!$L4<0.4);$H$2;IF(AND(MIN($I4:$K4)=$I4;$I
4<>3000;'30'!$L4<0.4);$I$2;IF(AND(MIN($J4:$K4)=$J4;$J4<>3000;'60'!$L4<0.4);$J$2;IF(AND($K4
<>3000;'90'!$L4<0.4);$K$2;IF('90'!$L4<0.4;$M3;IF(MIN('0'!$L4;'30'!$L4;'60'!$L4;'90'!$L4)='0'!$L4;$H$
2;IF(MIN('0'!$L4;'30'!$L4;'60'!$L4;'90'!$L4)='30'!$L4;$I$2;IF(MIN('0'!$L4;'30'!$L4;'60'!$L4;'90'!$L4)='60'!$
L4;$J$2;IF(MIN('0'!$L4;'30'!$L4;'60'!$L4;'90'!$L4)='90'!$L4;$K$2;"ERROR")))))))));"unoccupied")
```

After its definition, the selection rule is applied to the 8760-cells range and “build” the shading configuration schedule, optimized for the illuminance and glare parameters, then all the values related to the averaged illuminances, DGPs, and energy loads are reported in relation to the hourly deployment state and, on a different file, the same operation will be performed with the hourly illuminance values for each test point. The analyses of the useful illuminances for the regulation of the circadian rhythm have been developed using the averaged illuminances of each sector of the interior ambient as explained in 5.6.4. The same procedure, but simplified, has been adopted for the base case not provided with the shading system.

Chapter 6

Results and discussion

As already mentioned before, the results derived from the application of the proposed method to a case study adopting a dynamic shading system have been compared to the ones of a base case building provided with the same geometries but without a shading system, either fixed or dynamic, with the intent of validating the results accuracy. The base case is outlined by the same geometry and construction elements having unchanged Radiance and EnergyPlus material properties, then the artificial lighting control is provided by a manual on/off switch equipped with a traditional light source system (incandescent light bulbs) with an installed power of 600 W, corresponding to a lighting power density LPD = 12.5 W/m^2 against an average value of 9.1 W/m^2 (figure 20): these parameters have been set to evaluate the impact of traditional lighting systems against advanced one on both visual comfort and energy loads, and to check the correctness of both input and output data.

6.1 sDA and ASE

The combination of these two parameters should represent together a prior idea on the visual and thermal comfort conditions of the examined ambient, where the best option possible is having high sDA and low ASE: certainly, this is a complicate target to achieve since the two parameters are strongly correlated (high sDA values correlate to high ASE values), but at least it is possible to identify the boundaries that characterize the applied shading, which are a maximum sDA, achievable in the theoretical case when the maximum light permeability is allowed at all the time, and a minimum ASE, reachable in the theoretical case when the shading is continuously set to the minimum light permeability.

As expected, the application of a shading system contributes in reducing both sDA and ASE, with stronger differences for south and west oriented glazing, but a good result has been achieved for all the analyzed orientations since all the found values range in the thresholds defined by the solutions that hypothetically would offer the best performance if always adopted as static solutions, namely 90° rotation for the maximum sDA and 0° rotation for the minimum ASE (table 13).

	East		South		West	
	sDA	ASE	sDA	ASE	sDA	ASE
Base case (un-shaded building)	57.3%	38.5%	80.2%	61.5%	64.6%	62.5%
Case study	30.7%	16.7%	32.8&	21.4%	33.9%	23.4%
Theoretical best	*30.7%*	*16.7%*	*42.2%*	*37.2%*	*38.0%*	*39.6%*
Reduction against base case	*-46%*	*-57%*	*-59%*	*-65%*	*-48%*	*-63%*

Table 13 - Resulting sDA and ASE parameters of the tested solutions (un-shaded building and case study) for each orientation and related difference in percentage

Figure 77 - Comparison between the un-shaded building with the case study based on the achieved sDA and ASE for each orientation simulated

6.2 UDI levels

The useful daylight illuminance levels define the percentage of the occupied hours that meet specific thresholds for each analyzed portion of the space; given many thresholds, it is possible to consider "useful" an illuminance on the work plane when it's comprised within 100 lux and 2000 lux, which can be further subdivided into two ranges (supplementary if below 300 lux, autonomy if above 300 lux).

The obtained results look correct and illustrate the pro and cons of the optimized shading for all the orientations analyzed; the UDI autonomous, which is far preferable since it gives a greater contribution to the reduction of artificial lighting loads and the enhancement of well daylit environment, doesn't achieve valuable results, but this was expected as we previously analyzed the sDA values achieved, however the UDI supplementary and autonomous altogether show good results by reducing the exceeded illuminances (>2000 lux) in the window-area.

The method therefore seems to work in an appropriate way since the results are showing high correlations with the expected values also in this case where specific surface data are reported in the appropriate graphical way.

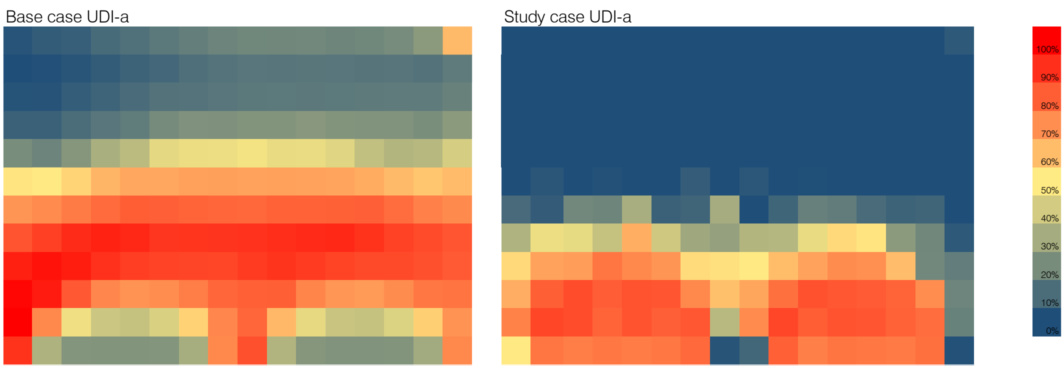


Figure 78 - Illustration of the autonomous UDI (300-2000 lux) achieved in the interior space and comparison between the un-shaded building (on the left) and the case study (on the right), for the east orientation

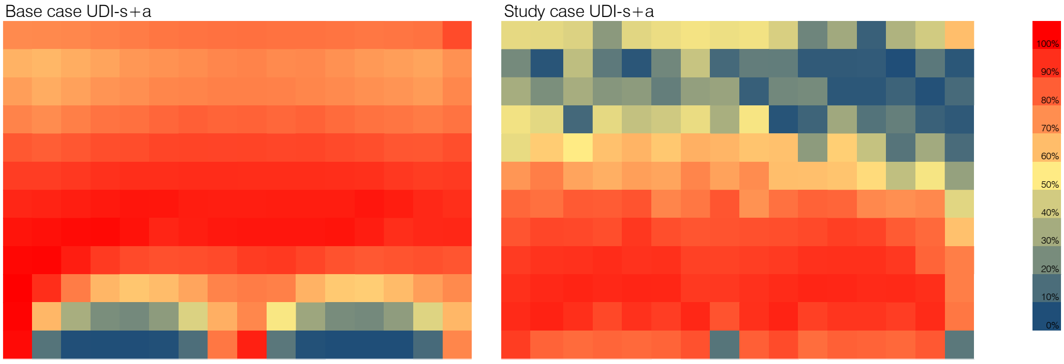


Figure 79 - Illustration of the total UDI (100-2000 lux) achieved in the interior space and comparison between the un-shaded building (on the left) and the case study (on the right), for the east orientation

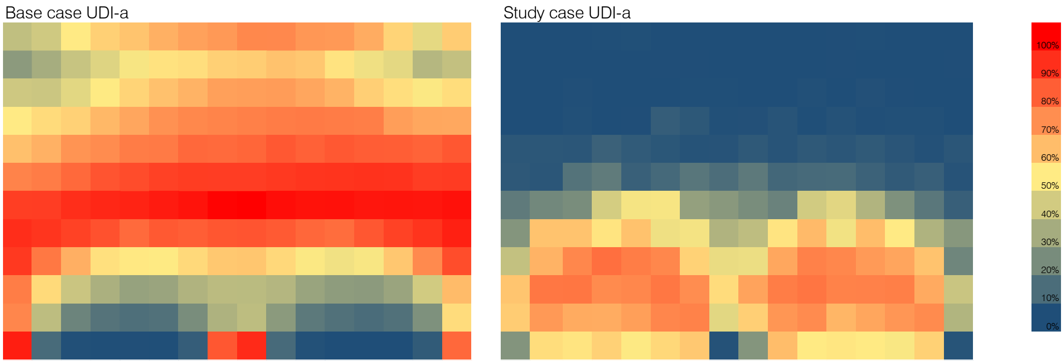


Figure 80 - Illustration of the autonomous UDI (300-2000 lux) achieved in the interior space and comparison between the un-shaded building (on the left) and the case study (on the right), for the south orientation

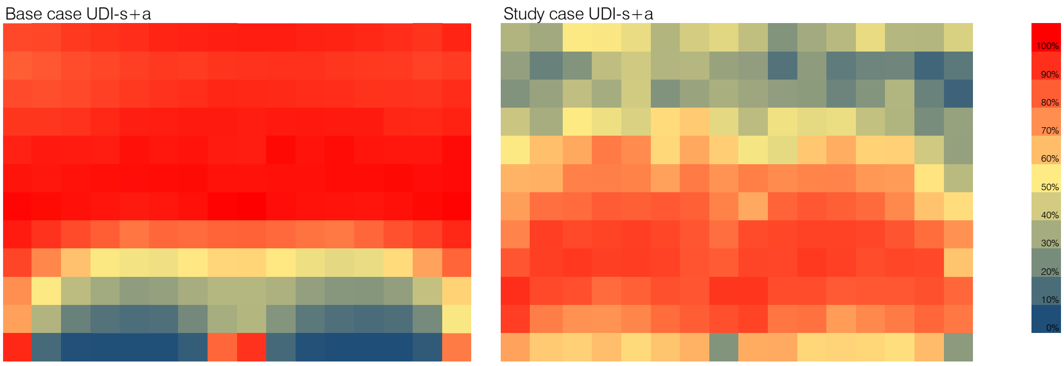


Figure 81 - Illustration of the total UDI (100-2000 lux) achieved in the interior space and comparison between the un-shaded building (on the left) and the case study (on the right), for the south orientation

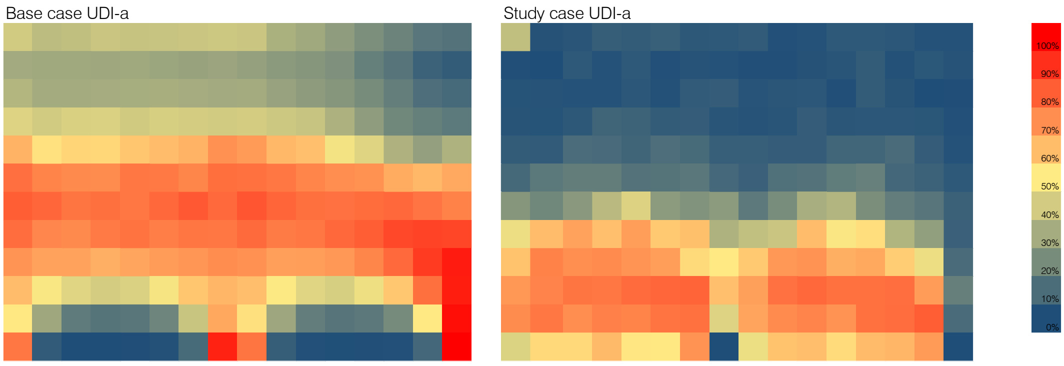


Figure 82 - Illustration of the autonomous UDI (300-2000 lux) achieved in the interior space and comparison between the un-shaded building (on the left) and the case study (on the right), for the west orientation

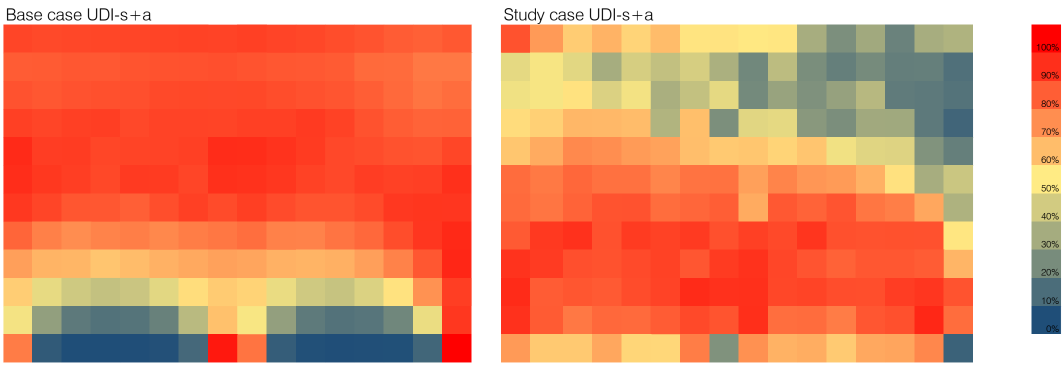


Figure 83 - Illustration of the total UDI (100-2000 lux) achieved in the interior space and comparison between the un-shaded building (on the left) and the case study (on the right), for the west orientation

6.3 DGPs values

The analyzed shading and the related configuration schedule have been set to control the illuminances on the work plane and avoid, when it's possible, the occurrence of glare phenomena: the results show again the accuracy of the formula that has been written to define the hourly configuration schedule and the whole method performed. The most of critical DGP values have been avoided (table 14), allowing to avoid glare discomfort conditions for the benefits of workers.

	East			South			West		
	Perc.	Dist.	Intol.	Perc.	Dist.	Intol.	Perc.	Dist.	Intol.
	h	h	h	h	h	h	h	h	h
Base case	131	5	0	323	283	76	124	174	266
Case study	0	0	0	0	0	0	5	2	2
Reduction	*-100%*	*-100%*	*-100%*	*-100%*	*-100%*	*-100%*	*-96%*	*-99%*	*-99%*

Table 14 - Total amount of hours when glare is registered (illustrated values refer to perceptible, disturbing and intolerable glare) and comparison between the un-shaded solution and the case study

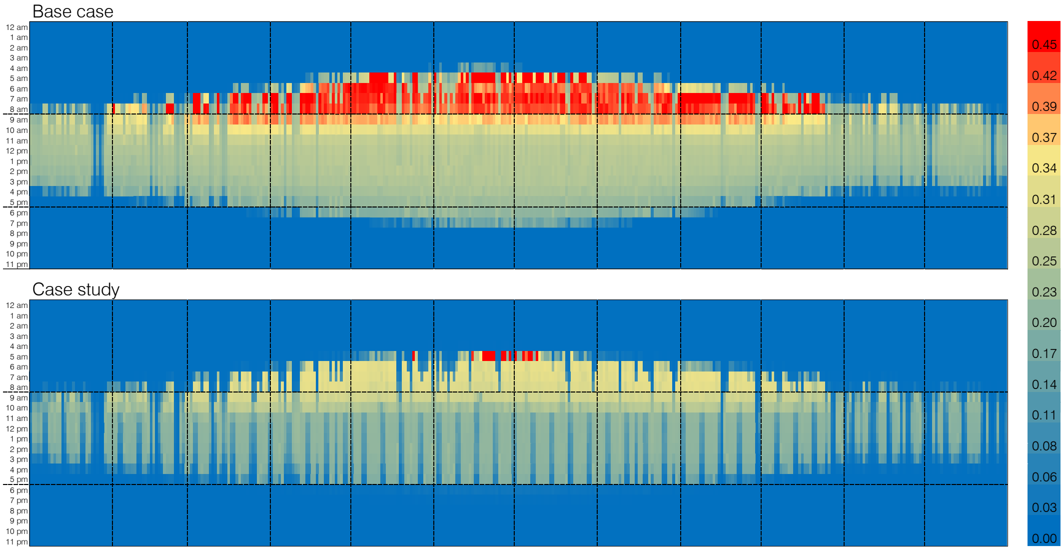


Figure 84 – Annual hourly distribution of the DGPs values and comparison between the unshaded building results with the ones of the case study, for the east orientation

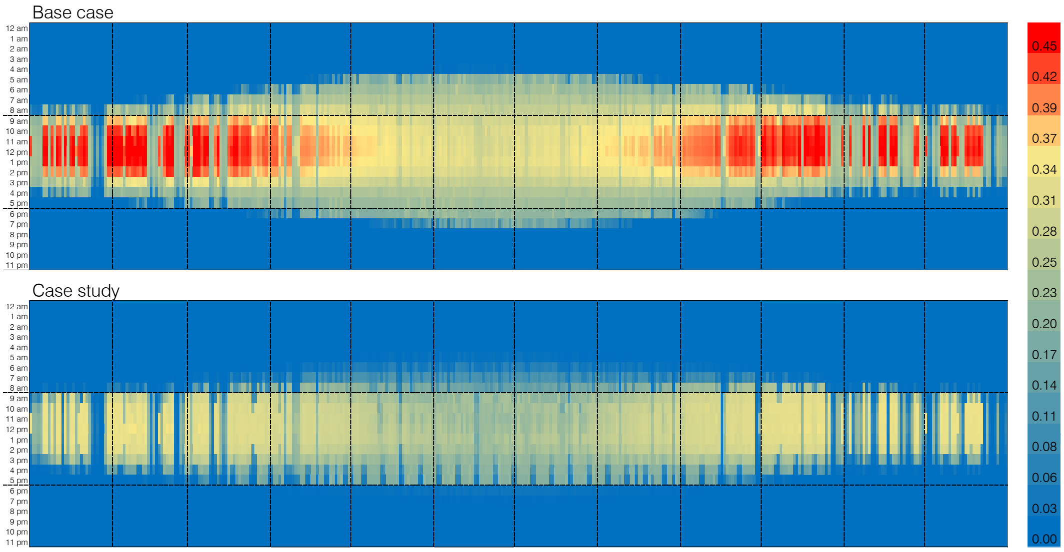


Figure 85 - Annual hourly distribution of the DGPs values and comparison between the unshaded building results with the ones of the case study, for the south orientation

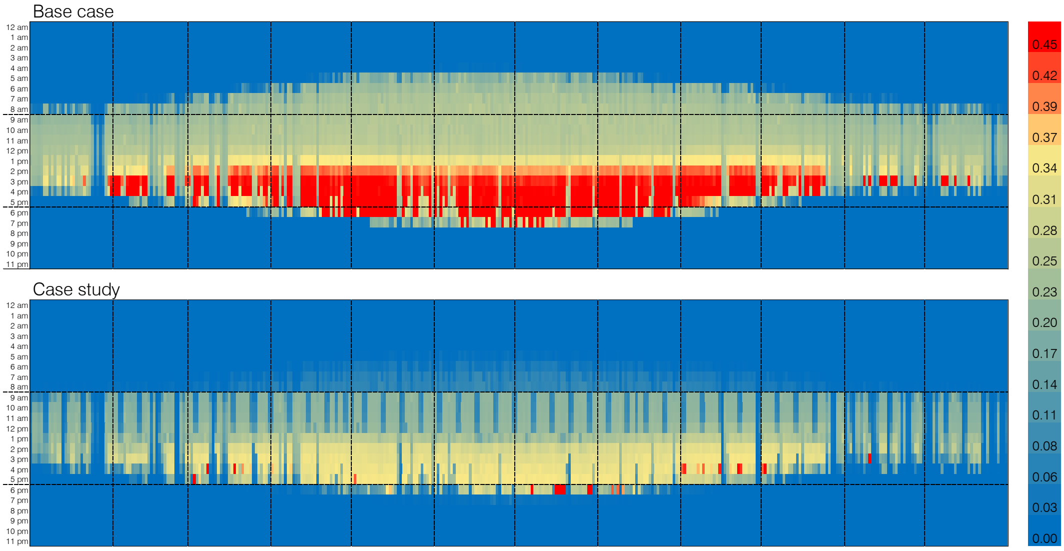


Figure 86 - Annual hourly distribution of the DGPs values and comparison between the unshaded building results with the ones of the case study, for the south orientation

6.4 Circadian rhythm regulation

As mentioned in the previous chapter, further analyses have been developed to understand the potential effects of the applied dynamic shading on the daylight quality of the interior space and the consequent effects on the circadian rhythm of the users: the interpretation of such a complex parameter has been accomplished by plotting the hourly average illuminances of each sub-zone of the interior ambient, on an annual basis, allowing to visual-check whether a minimum 180 lux are achieved during morning time (to regulate the circadian rhythm), or 226 lux for at least 4 hours straight during the day (to stimulate and not undermine the circadian rhythm, in both cases with a reasonable frequency.

The results achieved for the base case (un-shaded) are clearly the best ones and do not differ considerably according to the glazing orientations (figure 88), on the other hand the results achieved for the optimized shading system are far less promising, though they show that almost 75% of the interior space can offer acceptable daylight conditions for the regulation of the circadian rhythm. To help understanding better the graphs and their meaning, in figure 87 is reported a visual graphic that shows how each graph in the following pages correlates to a specific zone of the room.

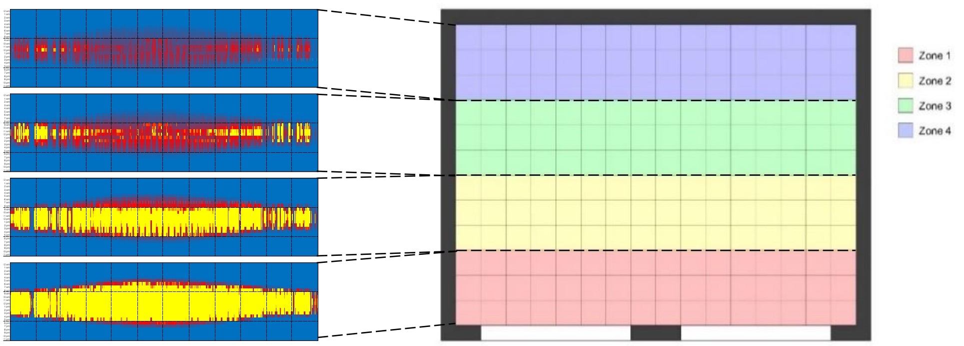


Figure 87 - Illustration of the correlation between each graph and the room zone identified before

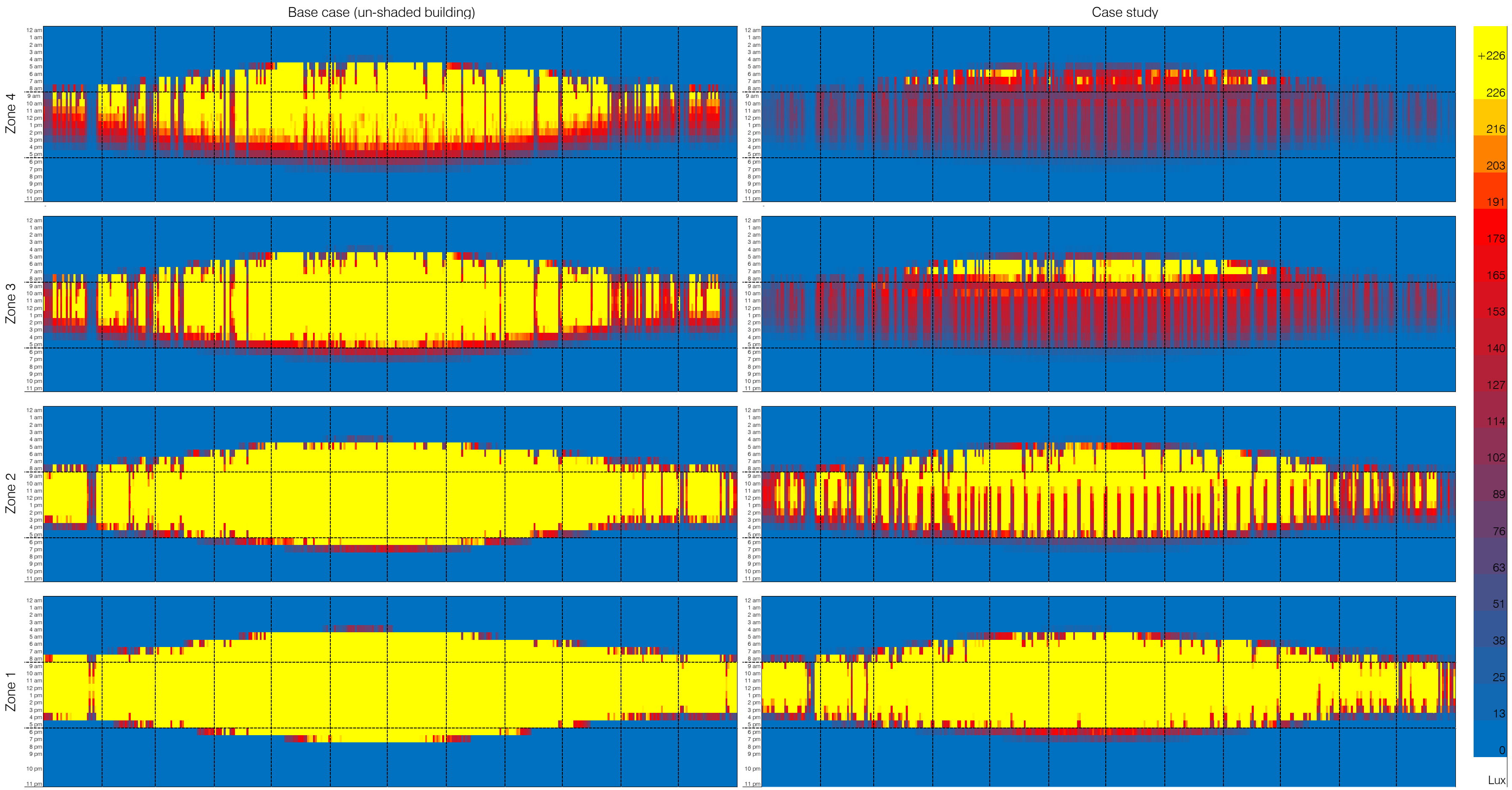


Figure 88 - Annual hourly distribution of the illuminances on the work plane that allow the regulation of the circadian rhytm for the east orientation: comparison between the four subdivion sectors of the interior ambient for the un-shaded building (on the left) and the case study (on the right)

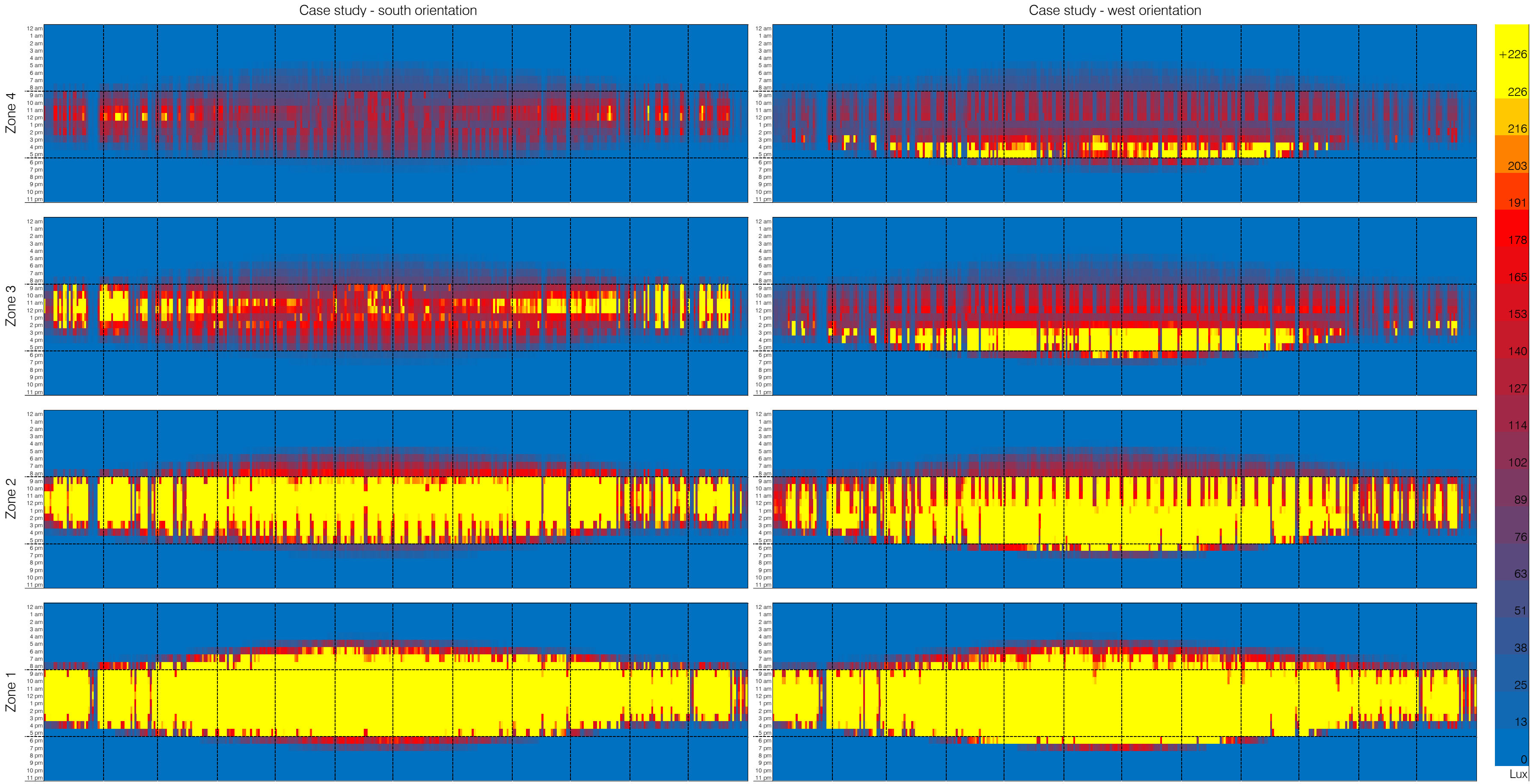


Figure 89 - Annual hourly distribution of the illuminances on the work plane that allow the regulation of the circadian rhythm for the south orientation (on the left) and west orientation (on the right)

6.5 Energy needs

The loads assessment, as previously said, has been pursued by inheriting the results related to the daylight-optimized shading system, however good results are globally achieved for the energy loads on the zone. In particular, cooling loads could be almost halved in comparison to the un-shaded solutions (figure 90), and the adoption of high-efficiency lighting systems in combination with automated controls based on occupancy, dimming and illuminance minimum thresholds, helps in sensibly decreasing the artificial lighting load even in those spaces where the sDA considerably drop, still offering sufficient illumination conditions. The heating energy loads increase as expected, because the provision of shading devices notably reduces the amount of available solar gains through the windows, hence a higher load for the HVAC will be considered.

In the next pages are illustrated more in detail the monthly trends of the loads associated to heating, cooling and artificial lighting systems, showing an already expected trend for all described the variables.

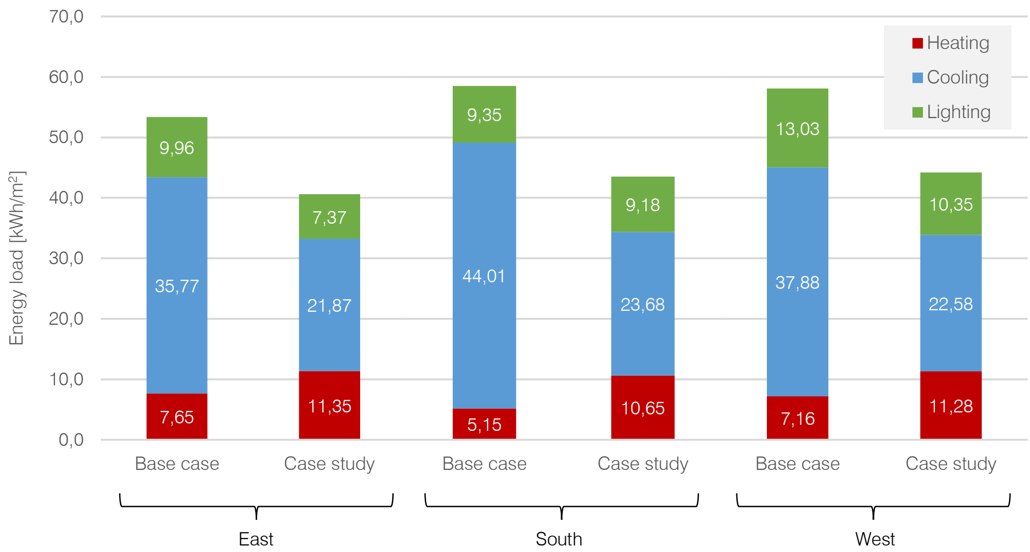


Figure 90 - Comparison between the total energy loads for all the tested orientations

According to the results found after the optimization and post-processing operation on the "new" data, it is remarked again the efficacy of the method applied to the case study since all the variables considered until now assumed the expected trend.

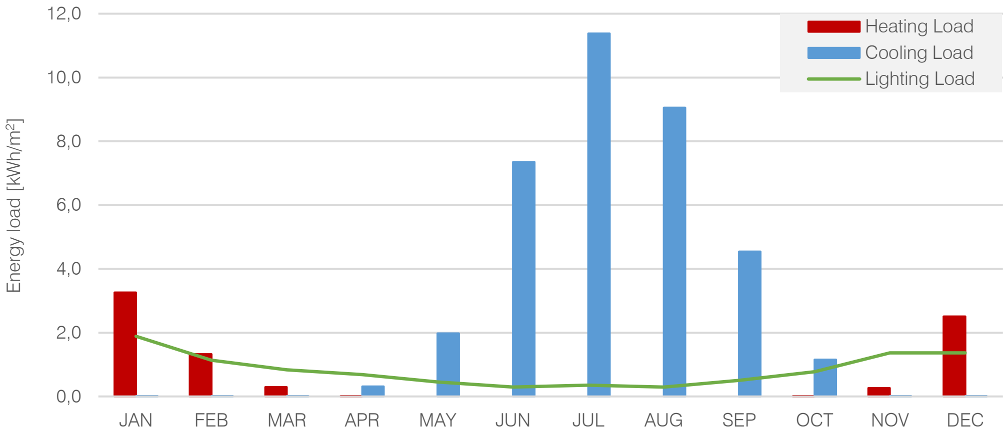


Figure 91 - Energy loads for the un-shaded building with East exposition

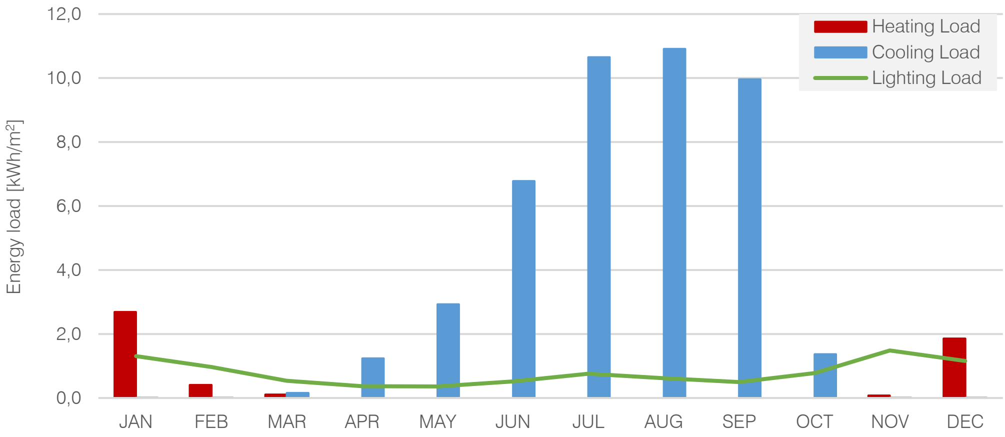


Figure 92 - Energy loads for the un-shaded building with South exposition

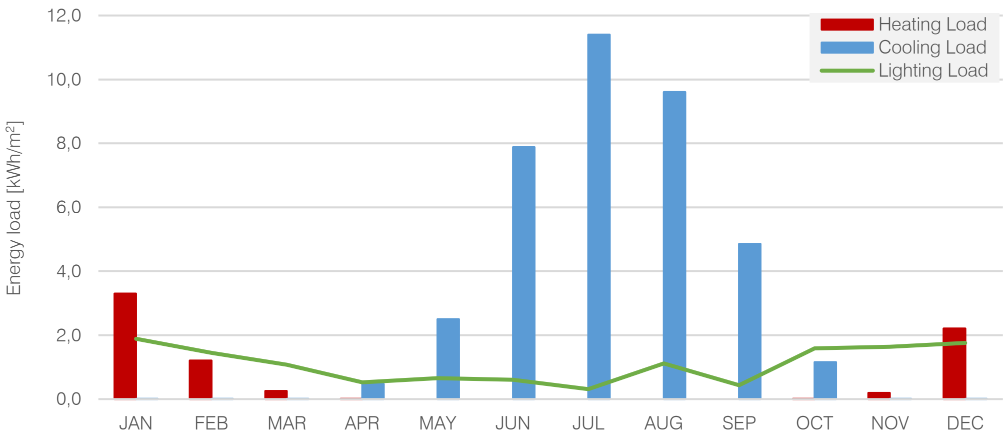


Figure 93 - Energy loads for the un-shaded building with West exposition

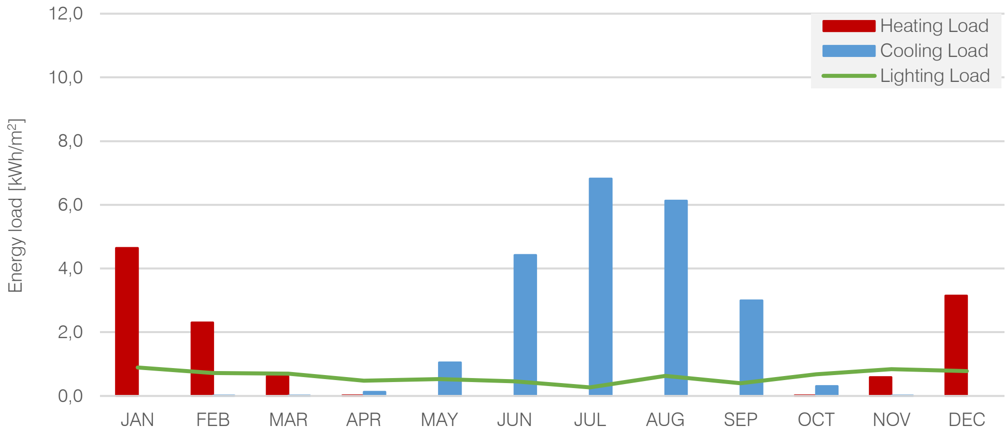


Figure 94 - Energy loads for the optimized case study with East exposition

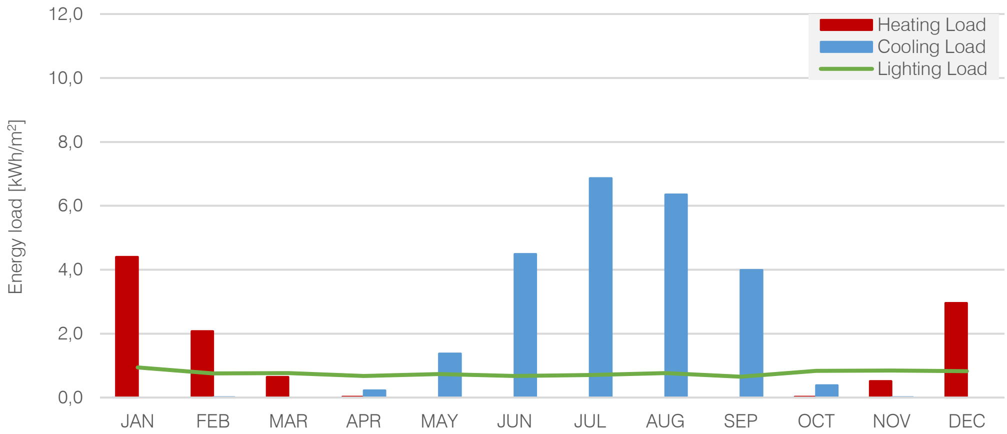


Figure 95 - Energy loads for the optimized case study with South exposition

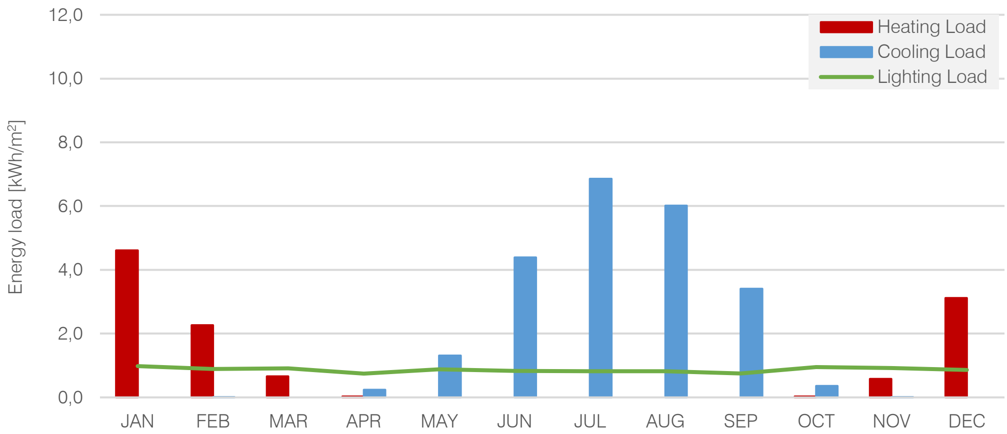


Figure 96 - Energy loads for the optimized case study with West exposition

Chapter 7

Conclusions

The work proposed here finds its basis on the relevance of daylight for our lives on a physiological, psychological and emotional way, and considering the technological development of high-performance facades under a great variety of aspects, making them more and more preferred for new commercial buildings, an evaluation method was defined to fulfill the daylight requirements in office-work places.

The workflow, starting from the definition of the necessary geometrical components in the digital environment, is used to perform daylight and energy simulations to get annual hourly results of each geometric configuration, then for the definition of an optimized schedule of the shading configuration (based on the daylight performance target) and eventually re-elaborated through post-processing operations the data associated to the optimization, returning the results under an established (but not common) graphical way of easy comprehension, right now available only for static design applications.

The suggested method was applied to a case study and another base case, similar to the previously mentioned but lacking the shading system: the results confirmed that this workflow is reliable and effective, without any notable mistake or error for both analyses, post-processing and graphical restitution of the results.

7.1 Main remarks

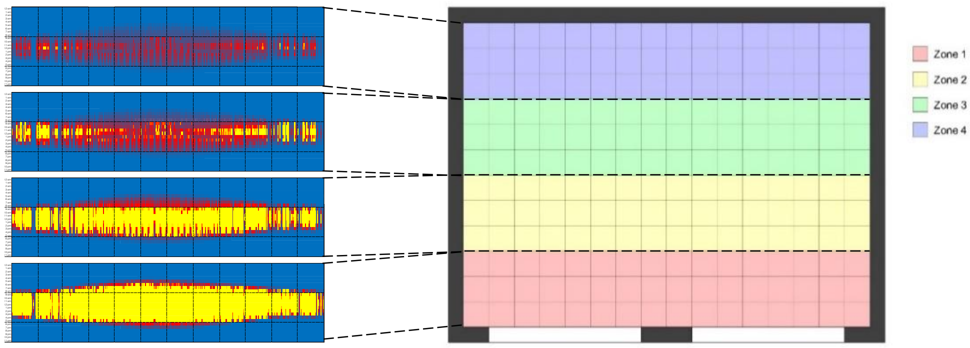
- The workflow results effective for every orientation tested, specifically because the values achieved in the daylight analyses range within the maximum and minimum thresholds expected: this is a good achievement and means that errors or mistakes have been avoided in all the phases described in chapter 5;

	East		South		West	
Daylight parameters	sDA	ASE	sDA	ASE	sDA	ASE
Base case	57.3%	38.5%	80.2%	61.5%	64.6%	62.5%
Case study	30.7%	16.7%	32.8&	21.4%	33.9%	23.4%
Theoretical best	*30.7%*	*16.7%*	*42.2%*	*37.2%*	*38.0%*	*39.6%*
Reduction against base case	*-46%*	*-57%*	*-59%*	*-65%*	*-48%*	*-63%*

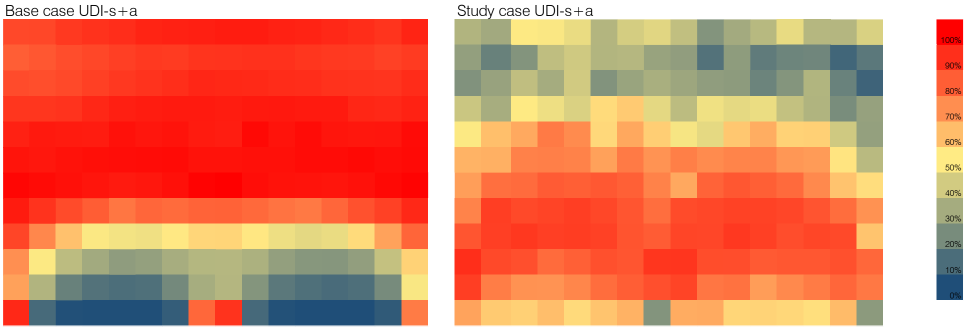
	East (kWh/m²)			South (kWh/m²)			West (kWh/m²)		
Energy loads	Heating	Cooling	Lighting	Heating	Cooling	Lighting	Heating	Cooling	Lighting
Base case	7.65	35.77	9.96	5.15	44.01	9.35	7.16	37.88	13.03
Case study	11.35	21.87	7.37	10.65	23.68	9.18	11.28	22.58	10.35
Reduction	*+48%*	*-39%*	*-26%*	*+107%*	*-46%*	*-2%*	*+58%*	*-40%*	*-21%*

- Through this application, it will be possible to analyze, during the early stage of design, the impact of a particular shading device (or kinetic envelope) on the overall performance of the building: this will allow a higher decision power and awareness to architects and engineers involved in the design process, which can study implementations or regulation of a dynamic shading device according to the achieved performance and the required parameter;

- More than one parameter can be considered for the optimization of the configuration schedule, though high attention shall be paid when writing the formulas to avoid encountering errors; for the case study, the optimization concerned both the illuminance levels on the work-plane and the avoidance, when possible, of glare phenomena, and the obtained results show a good response of the shading adopted;
- The results deriving from the analyses of certain illuminance levels on the work plane useful for the regulation of the circadian clock of the building occupants give important information about the indoor environmental quality for the non-visual system of humans, however the “splitting” of the surface area and the consideration of an averaged illuminances for each portion of the room could bring aside uncertainties related to the approximation assumed;



- The DGPs is a very useful index to estimate the potential occurrence of glare phenomena on an annual basis, though it might lead to different doubts on the accuracy of the analyses when direct sunlight “hit” the test camera / user, however the glare estimation is a complicate assessment and until now the DGP seems to correlate more with users’ perception of discomfort; for the case study, almost for every tested orientation, glare has been widely blocked, showing a good response of the adopted shading (check figures 84, 85, 86);
- The duration of both daylight and energy simulations might be very long: according to the adopted machine, actually poor Radiance settings led to 1.5 h daylight analysis for each single configuration due to the complexity of the modelled geometry of the shading devices (un-shaded building required 1.1 h considering improved settings);
- The graphical results achieved through scripting macro formulas help in shortening the post-process operations time; moreover, the graphical results achieved through this method resemble exactly the same ones available from the digital analysis tools for the investigation of static solutions, therefore no lack of information is presented and the performance can be very clear to both designers and clients.



7.2 Outlook

The suggestion to analyze the frequency of certain illuminance levels on the work plane, in specific periods of the day, that might result useful for the regulation of the circadian clock of the building occupants, can be a starting point for further implementations of this delicate topic, adding to the analyses an evaluation of the vertical illuminance instead of a horizontal one on the work-plane, which is more reliable;

The workflow might be a little complicated for *newbies*, it would be very interesting to lead investigations on the possibility to create specific components based on algorithms inside Grasshopper to shorten the procedure time.

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List of figures

List of tables