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MODELING AND EXPERIMENTAL RESULTS IN DAYLIGHTING ANALYSIS TO IMPROVE VISUAL COMFORT AND TO REDUCE ENERGY DEMAND IN BUILDINGS

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Alla mia famiglia

Sommario

Se, da un lato, la crisi energetica impone la costruzione di edifici efficienti (responsabili di circa il 40% del consumo totale di energia), dall'altro è comunque richiesto un buon livello di comfort. Certe volte queste due esigenze (comfort e risparmio energetico) sono tra loro contrastanti. Una migliore qualità dell'ambiente interno (IEQ) può rappresentare un extra-costo presto ripagato in termini di benessere degli occupanti e questo dimostra come sia possibile progettare un edificio in cui siano raggiunti gli obiettivi del risparmio energetico e dell'elevata qualità dell'ambiente costruito .

La luce influisce non solo sulla visione, ma anche sui cosiddetti effetti non-visivi: molti studi hanno dimostrato come sia possibile ottenere un incremento della produttività, della performance e del benessere in generale se la luce naturale viene sfruttata come principale sorgente di luce. Inoltre, considerando il problema del cambiamento climatico e del riscaldamento globale, l'ottimizzazione della luce naturale all'interno degli edifici non è soltanto una questione riguardante il miglioramento del benessere delle persone, ma è un requisito necessario per la costruzione di edifici sostenibili. Il consumo energetico, dovuto all'illuminazione artificiale, rappresenta una discreta parte del consumo totale di un edificio, per cui l'orientamento, le dimensioni, la forma delle aperture vetrate necessitano di una particolare attenzione nella fase progettuale, ai fini di un aumento della penetrazione della luce diurna.

La vista è, tra i cinque sensi, uno tra i più rilevanti, soprattutto in ambienti lavorativi, per cui questo studio si è orientato principalmente ad edifici scolastici e del terziario.

I due principali lavori oggetto di questa tesi riguardano la comparazione tra il monitoraggio e il calcolo, tramite modelli di simulazione, dei profili di illuminamento in un edificio per uffici e l'analisi della qualità percepita, mediante un approccio sia oggettivo che soggettivo, all'interno di due scuole elementari.

Per quanto concerne la prima tematica, è stato scelto un edificio oggetto di un intervento di pellicolatura esterna, visti i problemi connessi ad elevati consumi dell'impianto di raffrescamento (spesso anche insufficiente a garantire un livello accettabile di comfort termico) e all'abbagliamento sui monitor dei computer. Questo

lavoro ha permesso di valutare quali siano le problematiche connesse alle simulazioni illuminotecniche nel momento in cui l'oggetto dell'analisi è un edificio effettivamente esistente. Le semplificazioni spesso adottate nei modelli di calcolo, ma soprattutto la componente umana (ovvero l'interazione delle persone con l'ambiente in cui vivono) generalmente trascurata, hanno richiesto un'analisi particolarmente accurata. Le strategie adottate nel caso in esame hanno portato ad una soddisfacente corrispondenza dei risultati in condizioni di cielo coperto, viceversa, in presenza di elevata radiazione diretta, tale corrispondenza non è sempre stata rispettata. Si è resa inoltre necessaria la validazione dei sensori utilizzati nella campagna di misura, attraverso la comparazione, in un ambiente controllato (un'aula del Dipartimento di Fisica Tecnica), con uno strumento di nota affidabilità (capitolo 5.3.1).

La disponibilità di luce naturale in un ambiente è stata descritta tramite un parametro di performance dinamico (UDI): a partire dai profili di illuminamento annuale calcolati con il software DAYSIM, combinando uno specifico profilo di occupazione, gli indici UDI sono stati calcolati supponendo dei nuovi intervalli di illuminamenti, dal momento che il valore centrale di UDI ($UDI_{100-2000}$), attualmente calcolato da DAYSIM, comprende un troppo elevato *range* di illuminamenti. Questi nuovi indici UDI sono stati calcolati per l'edificio per uffici analizzato, considerando la facciata prima e dopo l'intervento di pellicolatura esterna. Per un ufficio orientato a sud-est, in inverno, la presenza della pellicola determina valori insufficienti di illuminamento (UDI_{100}) il doppio delle volte rispetto a quelli ottenibili con il solo vetro. Una facciata puramente vetrata, però, determina problemi di abbagliamento, per cui è necessaria una schermatura: il fatto di avere, come in questo caso, una tenda abbassata porta ad avere dei livelli di illuminamento simili a quelli ottenibili con la sola pellicola applicata al vetro, senza però richiedere alcuna schermatura. In estate, in condizioni di vetro con pellicola applicata, un buon livello di comfort visivo è accettabile per almeno l'80% , anche con la tenda alzata, mentre, in presenza del solo vetro, la tenda è quasi sempre necessaria, impedendo così la vista verso l'esterno, ritenuta una delle principali esigenze da parte dei lavoratori.

Diversi altri intervalli di UDI si sono espressamente calcolati per gli edifici scolastici, considerando due diversi profili di occupazione: con o senza rientro pomeridiano. Questi parametri si sono calcolati per ciascun mese dell'anno scolastico 2008/2009 e per due classi, una orientata a Sud e una ad Ovest, di una scuola media di Santa Lucia di Piave. I valori di UDI ottenuti in base ai due diversi profili di occupazione sono risultati significativamente differenti solo per l'orientamento ovest e questo rappresenta un'ulteriore conferma di quanto influisca il profilo di occupazione (oltre che l'orientamento dell'edificio stesso) nell'analisi dei consumi energetici.

Infine, il lavoro svolto nelle due scuole elementari ha riguardato l'indagine sperimentale sulla qualità dell'ambiente costruito. I fabbricati coinvolti sono stati due scuole elementari, una situata a Ceggia (VE) e una a Noventa di Piave (VE). La scuola di Noventa è di tipo tradizionale, mentre quella di Ceggia è caratterizzata da una pianta circolare e, per quanto riguarda la parte impiantistica, da un pavimento radiante e da un sistema di ventilazione meccanica. L'analisi si è svolta su due fronti: monitoraggio dei

principali parametri ambientali e valutazione, mediante questionario, del livello di comfort percepito da parte dei bambini. Essendo le due scuole diverse per tipologia, scelte architettoniche e impiantistiche, lo scopo della ricerca è stato quello di valutare se la concezione degli spazi di un edificio, nonché l'aspetto tecnologico, potesse influire sul livello di benessere riscontrato. La collaborazione con un professore di "Psicologia della percezione" si è resa necessaria nella formulazione delle domande, in modo che esse potessero, da un lato, essere comprensibili da parte dei bambini e, dall'altro, che mirassero ad ottenere le risposte necessarie per la successiva analisi. L'elaborazione delle risposte, infine, è stata effettuata mediante un software per statistica non parametrica (NPC Test). Non è stata riscontrata alcuna differenza significativa nella comparazione tra le due scuole, tuttavia la maggior parte delle bambine ha espresso giudizi più positivi nei confronti della scuola più "moderna" (Ceggia). L'analisi statistica delle risposte date al questionario è stata infatti svolta anche scegliendo due variabili di stratificazione, il sesso e l'età, dal momento che non si sono individuate interessanti differenze considerando assieme tutti gli alunni di ciascuna scuola. Questi test aggiuntivi hanno mostrato come bambini e bambine siano diversi già nella giovane età: le femmine sono risultate più attente alle condizioni ambientali rispetto ai maschi; inoltre, le loro risposte si sono rivelate diverse in base all'età, alla scuola e persino alla classe di appartenenza.

Abstract

If the energy crisis requires efficient buildings (responsible of about the 40% of the total energy consumption), on the other hand a good comfort level is anyway requested; this means that sometimes comfort and energy savings are in conflict. A better indoor environmental quality (IEQ) may represent an extra-cost that can be soon recovered in terms of well-being and this demonstrates that IEQ and energy saving can be met together.

Light has both visual and non-visual effects: many studies have demonstrated that if daylight is the primary source of lighting, there is a great improvement in productivity, performance and well-being in general. Moreover, facing the problem of world climate change and global warming, the optimization of daylight in buildings is not only a question of improving people’s well-being, but it is also part of a sustainable design strategy. Energy consumption due to electric light represents a great part of the overall demand of buildings, therefore the orientation, the size and the shape of fenestration systems must be carefully designed, in order to improve daylight availability.

Vision is the most important of all the five senses, especially at work, therefore the present study has been addressed to commercial and educational buildings.

The two main studies that will be presented in this thesis involve the comparison between measured and calculated illuminance profiles in an office building and the IEQ analysis, by means of an objective and a subjective approach, in two Italian Primary Schools. The first one deals with a full-glazed office building in which window films have been externally applied, since occupants complain about overheating, comfort and glare problems. In overcast sky condition, the measured and the calculated illuminance profiles are similar for the two offices, while, in sunny days, there are some significant differences: this is due to the extreme variability of sky luminance, especially in such conditions and due to the sensor used to record data which has resulted to have a different behaviour according to both inside and outside conditions (chapter 5.3.1).

Daylight availability of a space has been described by means of the UDI dynamic daylight performance metric: from annual illuminance profiles calculated with DAYSIM,

combining a specific occupancy schedule, UDI indexes have been calculated supposing some new illuminance ranges, because the default central UDI index ($UDI_{100-2000}$) includes a wide range of illuminances.

Considering the analysis of the office building, the UDI values have been calculated for both glazed and film coated façade. For an office South-East oriented, in winter, the presence of film determines insufficient lighting levels (UDI_{100}) which happen twice with respect to having glass alone. Glass alone cannot limit the occurrence of glare, thus the shading has to be closed; this fact leads to lighting levels similar to the ones obtained by the application of films. In summer visual comfort can be guaranteed for at least the 80% of the time in film coated façade, even with the curtains down, while, in glazed façade condition, the shading is required most of the time: in this condition (glazed façade with shading down) occupants lose the view with the outside which has been demonstrated to be one of the main sources of dissatisfaction.

Some other ranges have been expressly created for educational buildings, considering two different kinds of occupancy schedules, with and without after school. These parameters have been calculated for each month of the academic year 2008/2009 and for two classrooms, one facing South and one facing West, of a Secondary School located in Santa Lucia di Piave. The obtained UDI values are significantly different only for West orientation, comparing the two analysed occupancy schedules and this confirms again how important the occupancy schedule (and also building orientation) is in energy consumption analysis.

Finally, an analysis, administrating a survey during a monitoring campaign, of indoor environmental quality has been carried out in two primary schools aiming at verifying if the building type, in terms of both architectural and technological choices, can influence children satisfaction and well-being. Two educational buildings have been compared, one traditional and one characterized by a circular plant ad by indoor environmental quality systems, such as radiant floor and mechanical ventilation. The survey has been created in cooperation with a Professor of Perception Psychology, in order to reach the purpose desired and to make the questions as much comprehensible and unambiguous as possible. The statistical analysis has been performed with NPC Test. No significant differences have been noticed in schools' comparison, even though the more “modern” school (Ceggia) has obtained more positive opinions than the more traditional one (Noventa) especially by girls. The statistical analysis has been in fact carried out also choosing two stratification variables, the gender and the age, because no remarkable differences have been found considering all the children of the same school together. These additional tests have revealed how boys and girls are different, even from the childhood: girls seem to pay more attention about environmental condition than boys and, moreover, their answers differ depending on age, school and even classroom.

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Chapter 1

Introduction

Light is perhaps the element with the greatest influence over the atmosphere of a place; a good lighting quality intensifies the poetic and emotional impact of a project. Architecture can be perceived only with light, which enables us to appreciate the diverse qualities of a space (size, texture, geometric shape, colour). Natural light has always played an important role in the history of architecture. Sunlight, with its continuous variations, over days and even seasons, in terms of luminous flux and colour, changes the environment perception, creating dynamic spaces. The way in which a ray hits an object changes the perception of the object itself, revealing different effects, from dramatic to grotesque ones. In Romanesque, Gothic and Baroque architecture, buildings were designed to be able to manipulate and control the qualities of daylight in order to enhance the shapes of the interior space of buildings and achieve the desired ambience.

The aim of a lighting project cannot be only to guarantee safety and sufficient levels of light to carry out any given activity. A lighting designer has to think about of all the so-called non visual effects of light which are related to psychological aspects. This argument will be developed in Chapter 2.

Sunlight is the most economical and also the most beneficial aspect for health and well-being, nevertheless, an excess of natural light can cause annoyance and it may not provide the right kind of illumination needed to carry out certain activities. A good lighting project has to improve, on a hand, daylight availability and, on the other hand, to avoid undesirable effects, visual discomfort and glare. However, darkness and shadows have to be considered as well as light, because both are necessary for the balance and well-being of people. About that, the Swiss architect Peter Zumthor has asked “How much light does man need and how much darkness?”.

Windows are one of the most fundamental components in a building: they establish a relationship between the occupant and the outside and they are probably the most important element of a space, since they provide natural light, possible ventilation and external view, which has been demonstrated to be one of the main workers requirement for their office. One of the main workers' dissatisfactions is, in fact, the lack of view out. It is difficult to know if the problem concerns the need of daylight or just the need of the contact with the outside. The reason is that, if glare appears, blinds are taken down, but they are left in down position for days and even months, even when blinds are no more necessary. Therefore blind automation can be a good solution to control solar radiation and to optimize daylight in buildings.

In a world concerned with climate change and global warming, the optimization of daylight in buildings is not only a question of improving people's well-being, but it is also part of a sustainable design strategy. Energy consumption due to electric light represents a great part of the overall demand of buildings, therefore the orientation, the size and the shape of fenestration systems must be carefully designed, in order to improve daylight availability. This will be presented in Chapter 4.

Moreover, many times it happens that in energy evaluations, designers do not take into account occupant behaviour and this leads to unrealistic results. In fact, the way in which the users interact with the building, in particular with electric lighting and with shading devices, influences energy consumption prediction, therefore simulation software, like DAYSIM which employs the user behaviour model called Lightswitch, can be useful to quantify the potential energy savings due to building automation systems combined with occupant behaviour (Chapter 3).

Nowadays simulation tools are used to predict daylight availability and it is interesting to make a comparison between measured and calculated lighting parameters, such as illuminance or luminance. This topic is deeply analysed in Chapter 5.

Finally it must be remembered that the measurements of all indoor environmental parameters have to be related to people' perception, therefore it would be advisable to analyse IEQ (Indoor Environmental Quality), comparing recorded indoor parameters with the answers given to a survey. This work has been experienced in two educational buildings and several interesting conclusions have been carried out in Chapter 6.

Chapter 2

Productivity and energy in commercial and educational buildings

The use of artificial light is debated due to the contribution to energy reduction in buildings consumption, comfort and productivity. The importance of daylight in buildings is therefore nowadays of particular interest, in terms of visual comfort and well-being. People live most of their time indoor, therefore it is necessary to create a comfortable environment to prevent disease, lack of motivation and sometimes even sickness. Many studies have demonstrated that, if daylight is the primary source of lighting, there is a great improvement in productivity, performance and well-being in general.

This chapter would like to be a sort of review on the factors which contribute to enhance visual comfort, especially in office buildings, where vision is the most important of all the five senses.

2.1. Introduction

Humans, from the origins, have always lived in daylight conditions, since the sun was the only known lighting source. For that reason, some researchers have stated that all physiological processes can develop in the right way only under daylight (Wurtman, 1975).

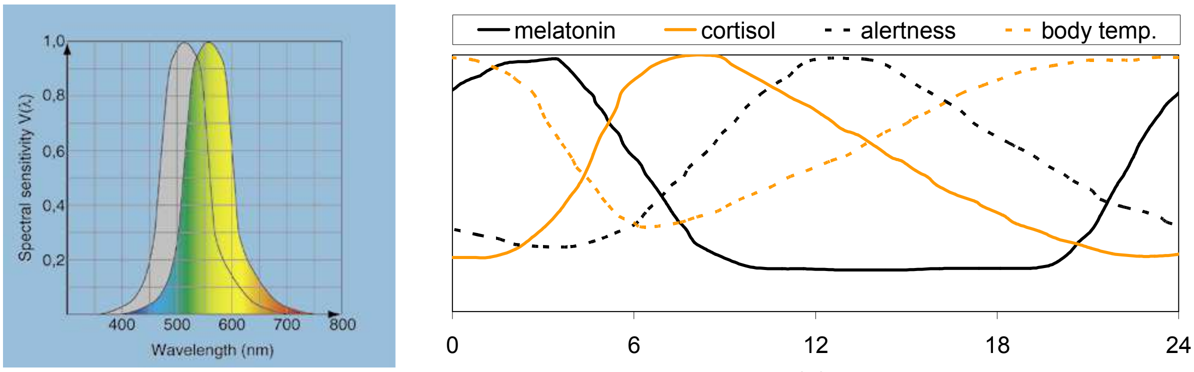
For fifty years, people have been affected by the so-called three screens syndrome: cinema, television and computer. In all these three situations, people are forced to stay in indoor environments. This new condition leads to a considerable adaptation and the research is addressed to recreate the original human environment, to reach comfort and well-being, because light has an important role, since it impacts human health and performance by enabling performance of visual tasks, by controlling the body's circadian system, by affecting mood and perception and by facilitating the direct absorption for critical chemical reactions within the body.

The aim of this work is to demonstrate, by means of a literature study about the state of knowledge and test experiments, that there is a strict link between lighting quality and people productivity and well-being. The goal is to awaken public opinion to the importance to reach a high lighting quality, especially in office buildings, to improve performance and satisfaction at work. This review could also provide an input to revise current lighting Standards and to guide future research.

2.2. Definition of light

Light is defined as the part of the band of electromagnetic radiation to which the eye is sensitive; this part of the spectrum extends from 380 nm to 780 nm. The response of the human visual system is not the same at all wavelengths, so it is necessary to adopt other quantities, derived from radiometric ones, to quantify light. Two types of visual cell are involved in the visual process: cones and rods. The 120 million rods are highly sensitive to brightness, but relatively insensitive to colour. They are most active in scotopic vision (night vision), in low luminance condition. The maximum spectral sensitivity lies in the blue-green region at 507nm (Figure 2.1).

The about 7 million cones are the more sensitive receptors for colour. They are most active in photopic vision (day vision), in high luminance conditions, with the maximum spectral sensitivity at 555 nm. There are three types of cones, one sensible to red, one to green and one to blue. The eye can adjust to higher or lower levels of luminance and the state of adaptation affects visual performance: a higher level of lighting improve visual performance and minimized visual errors.



(a) (b)

Figure 2.1 - Curve of relative spectral sensitivity in photopic and scotopic vision (a); typical daily rhythms (b)

The perception and identification of an object depends on four minimum requirements: luminance, contrast, size and time. To see an object in detail it is necessary that there is a difference between its brightness and the brightness of the immediate surroundings.

2.3. Daylight

The sources of daylight are the sky vault, that provides the diffuse radiation, and the sun, that provides the direct one, which is strictly connected to glare problem. There is also another source, which derives from the reflections of the outside environments (ground and other buildings).

Daylight is the preferred lighting source: it is energy-efficient, flicker-free, dynamic and it has a spectrum that ensures excellent colour rendering. However, a good combination of daylight and artificial light has to be reached, since daylight cannot be the only source, because of its continuous variability, according to weather, the time of day and year and because its intensity decreases as the distance from windows increases. Natural light has positive effects on human beings and these effects can be distinguished in two types: direct and indirect. The direct effects are caused by chemical change in tissues due to the energy of the absorbed light, while the indirect ones are the regulation of the basic biological functions and the production of hormones, connected to light exposure. The regulation of circadian rhythms, seasonal cycles and neuroendocrine responses in many species, including humans, is due to light stimuli (Klein et al., 1991; Wehr, 1991). Circadian rhythms are changing patterns that run over a period of approximately 24 hours, trying to establish an internal replication of external night and day: these rhythms are associated with body temperature, alertness and the secretion of hormones, such as melatonin and cortisol (Figure 2.1).

Melatonin is known as the “sleep hormone”: it drops in the morning, reducing sleepiness and it rises when it becomes dark. Cortisol is the “stress hormone”: its level increases in the morning, falling to a minimum at midnight.

Shift work may cause a shift of the biological clock that may result in extreme sleepiness, in lack of concentration, increasing the risk of accidents. Manipulation of the circadian system, by means of different lighting conditions, can make people work at times when one would normally be sleeping; this statement is at the basis of the concept of the dynamic lighting. Some researchers have argued that all the physiological processes should function optimally when exposed to daylight, since daylight has been the sole source of illumination for most of the period of humans’ evolution (Thorington et al., 1971). According to this hypothesis, electric lighting should be as similar as possible to daylight.

John Ott (1973; 1982) was the pioneer of full spectrum light: initial interest in Full Spectrum Fluorescent Lamps (FSFL) began with observations of plants’ growing under different lamp types. FSFLs emit light that is supposed to be similar to daylight over the visible range and some in the ultraviolet-A region of short-wavelength, high energy radiation. However, FSFL cannot be like daylight, because of the colour temperature (daylight varies in colour temperature from 5000 K to 10000 K, according to sky conditions, season and time of the day), the illuminance that they provide, and the polarisation of daylight.

2.4. Visual comfort

Good lighting is the result of the proper combination of three aspects: visual comfort, visual performance and visual ambience. Visual comfort is due to colour rendering and to a harmonious brightness distribution, visual performance refers to the lighting level and glare limitation, while visual ambience is connected to the effect of modelling, to light colour and to the direction of light.

Visual comfort can be defined if visual discomfort does not occur (Boyce, 2003). Visual discomfort is a feature of subjective and individual manner, due to many people expectations. It depends on the context: the same light can be acceptable in one application, but not in another (i.e. flicker light in an office or in a dance club). Visual discomfort involves the whole environment, not only the task area, which is related to visual performance.

The visual environment can have a negative influence in the act of vision. A difficult visual task leads to headaches and fatigue, as well as if the visual size is small. An under and over stimulation occurs when there is no or little information to be extracted, or when many repetitive informations are present. If in the surrounding area there are bright, moving or flickering objects that can easily be detected, they can become sources of stressful distraction. If the visual environment is not the result of balanced luminances due to differences in reflectance of the surfaces and to the illuminance distribution on those surfaces, then a perceptual confusion occurs.

Lighting Standards specify a minimum illuminance uniformity, measured as the ratio between lower and higher illuminance. A complete uniformity must not be reached , because it is the variation in luminances that makes seeing possible.

Another important aspect of lighting is the direction of light and modelling, since they help to define the visual ambience. Shadows can cause visual discomfort, but without shadows we see objects only as two-dimensional images. A room characterized by diffuse lighting and no shadows gives a monotonous impression.

Fluorescent light is the typical lighting installed in office buildings. One of the main problems that may occur with such installation is flicker. The use of high-frequency control gear has been demonstrated to reduce headaches and eyestrain.

2.4.1. Glare

Vos (1999) considers eight types of glare, four of which do not occur frequently. They are flash blindness, in which an extremely bright light source causes a complete bleaching of retinal photo pigment, paralyzing glare, that occurs with an unexpected light, distracting glare, produced by the lighting condition in the peripheral visual field, and glare that leads to retinal damage, due to the exposure to bright light.

The saturation glare is the result of the exposure to a high luminance for over long time, while the adaptation glare occurs when the visual system is exposed to a sudden increase of luminance.

The two most common glare types are the disability and the discomfort glare.

Disability glare directly affects the visual system, disabiliting it; the discomfort glare is difficult to characterize, since it does not impair vision, but it produces discomfort, which is a concept that involves many different aspects. Glare sensation is directly proportional to the luminance of the glare source (L_s) and to the solid angle subtended at the eye by the glare source (ω), while it is indirectly proportional to the deviation of the glare source from the line of sight (*p*)and to luminance of the background (L_b). There are many methods to calculate the discomfort glare: in 1995 the CIE has adopted the UGR formula, proposed by Sorensen [13].

$$UGR = 8\log_{10}(0.25 / L_b)\Sigma(L_s^2 \cdot \omega / p^2) \qquad (1)$$

This index ranges in value from 10 to 30. The UGR can be calculated only if ω ranges from 0.0003 sr to 0.1 sr.

Veiling reflections from specular surfaces can cause reflected glare: these reflections change the luminance contrast of the task and they cause the same kind of disturbance as direct glare, reducing the contrasts needed for trouble-free vision. This problem can occur, depending on the surface kind and on the geometry between the observer, the surface and any sources of high luminances. To quantify the magnitude of veiling reflections, the contrast rendering factor (CRF) is used. The CRF is determined by the ratio of the luminance contrast of the object under the lighting of interest to the luminance contrast of the object under completely diffuse lighting. For a normal office work, a minimum CRF of 0.7 is assumed to be enough.

2.5. Light and Standards

There are poor recommendations for office lighting, the most important of which is the horizontal illuminance on the working plane, while also the vertical illuminance should be evaluated, in order to know the amount of light entering the eye. These recommendations are based only on visual criteria, but they do not take into account that light controls the human biological clock.

The reference Standard to lighting requirements for indoor workplaces is the EN 12464-1. This standard specifies the minimum illuminance level, the UGR value and the colour rendering index for many different tasks.

In 2003, the Light and Health committee of the Dutch Lighting Society (NSVV) has considered the non-visual effect of light, recommending vertical illuminance on the order of 1000-1500lux. These values are not demanded during the all day, but they can be achieved in particular times of the day. It is preferable to increase the lighting level in the morning and during the “post-lunch dip”, to contrast tiredness.

2.6. Light and work

Lighting quality can be measured in terms of how much an installation meets the objectives and the constraints set by the client and the designer (Boyce, 2003).This is not a technical definition and there is no mention to numbers as it could be expected: the reason is that the perception of lighting quality is influenced by many physical and psychological processes.

Especially in an office space, it is necessary to establish a hierarchy of luminances, in which it is suggested that the working area has the highest luminance, to avoid distraction and fatigue. Boyce (1979) has found that the most preferred form is to provide a uniform illuminance in a surrounding area of about 1 m^2 and lower illuminances outside that area, since having high illuminances immediately outside the working area resulted in distraction and irritation. Another problem concerns the desk surface reflectance, relative to the reflectance of the task materials. Many studies analysed this aspect: Touw (1951) found that the preferred luminance ratio (desk/paper) was 0.4. Wibon and Carlsson (1987) studied the effects due to a repeated movement from a low luminance surface to a higher one, as it happens when watching a computer monitor and a piece of paper. The results showed a marked increasing in eye discomfort for a luminance ratio greater than about 15:1.

Daylight availability is one of the main important requirements, especially for office buildings. In fact, one of the main sources of dissatisfaction in offices is the lack of the physical connection with the outside: the contact with the natural environment is important because it brings dynamism to the indoor and a sense of relax for people. Artificial light is static, while natural one changes all over the day and year, providing many different scenarios which can enhance productivity and attention. For this reason, the concept of dynamic light has been recently introduced, in order to model, as far as possible, the variable lighting conditions that occur outdoor. The question is if daylight is requested for natural illumination or for view out. Many studies have been developed in windowless spaces, aiming to define how important is the view out. Heerwagen and Orians (1986) observed that in small windowless offices there are more natural illustrations on the walls than in offices with windows. It would be argued that the view out is more important than natural light, but many times it happens that, when the blinds are pulled down to avoid glare, people leave the blinds down for days, months or even years (Rea, 1984).

For a conventional office building, about the 95% of all costs is represented by the salaries, therefore any action devoted to increase individual comfort is a greater cost that can be sooner recovered, thanks to the reduction of sickness and absenteeism. Vision is the most important of all the five senses, especially at work, hence a good lighting quality is strictly connected to people's comfort and consequently to performance, even if it is impossible to find an objective law to describe the relationship between light and productivity, as many other factors are involved (Figure 2.2).

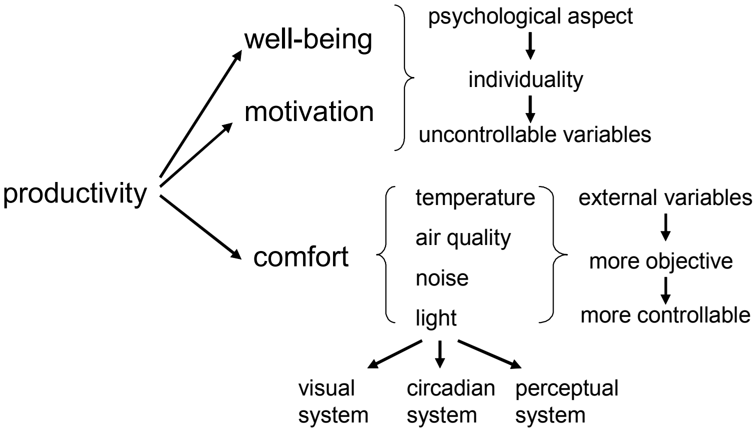


Figure 2.2 - Productivity related to people and indoor environment

The use of daylight as a primary source in buildings can reduce energy demand, in terms of electricity consumption, but construction and maintenance costs of glazing surfaces are higher than opaque walls. Moreover, a large use of glazing surfaces can cause glare and overheating, if shading device is not sufficient. The benefits of daylight in terms of human performance, workplace productivity, human health and, eventually, the financial return on investment of daylight in buildings has been analysed (Boyce, 2003).

The disruption of the biological clock, due to a poor exposition to sunlight, can cause many problems, both physiologic and psychologic. Especially at high latitudes, during the dark season (from November to February), a large part of the population is affected by excessive fatigue or even depression, due to the decrease in the number of daylight hours. These symptoms can lead to a serious disorder, the so-called Seasonal Affective Disorder (SAD). This disorder can be alleviated by means of exposure to bright light or, in the most serious cases, by light therapy (Küller, 2002).

Since the fertility is low and people retire late the working force is growing old and visual performance is affected by age. In fact, the need for light increases as a function of age, due to the deterioration of the transmittance of the eyes lenses with age (Edwards et al., 2002). Lighting for older people should be designed more carefully than ordinary office lighting, due to the particular requirements especially in visual acuity and in glare (Boyce, 2003).

2.7. Literature review

This work has been carried out, looking for the results of test and experiments about the interaction between people and light. The research started with literature, concerning daylight, productivity, visual comfort and lighting quality in offices. The book “Human factors in lighting” written by Boyce has been very useful, since it is a sort of collection of the main results and reflections over several years of studying about these items. This book also provides an exhaustive bibliography, which has been very helpful to enlarge the research.

2.7.1. Tests and experiments

Many tests and experiments have been carried out, with the purpose to create comfortable environments for workers, preventing disease, sickness, dissatisfaction, accidents and to understand in which way light can influence productivity and well-being in general.

Begemann et al. (1994) studied a long-term behaviour/response of people working in cell-offices, equipped with different experimental lighting systems. They found that most people prefer a variable lighting level which follows the daylight cycle instead of a static one. The results also show that indoor lighting standards levels are lower than preferred ones, which correspond to levels where biological stimulation can occur: therefore a poor lighting quality can cause sleep problems, lack of performance or even depression.

Fluorescent light is the typical lighting installed in office buildings. One of the main problems that may occur with such installation is flicker. Küller and Laike (1998) studied the impact of the non-visible flicker from fluorescent tubes on subjective well-being, performance and physiological arousal. The experiment has been carried out inside a laboratory office, comparing the effects of fluorescent light powered by the conventional and high-frequency ballasts on 37 healthy males and females. The affective state of the participants was tested twice, in terms of activation (awake/sleepy), orientation (interested/bored), evaluation (happy/sad), control (confident/hesitating) and other subjective ratings. Performance was tested by a numerical proof-reading test and it was measured in terms of speed and accuracy. Küller and Laike's results show that people with high critical flicker fusion frequency (the frequency at which even for 100% contrast the subject sees no fluctuation) responded with an increase in speed and a decrease in accuracy. In general, light powered by conventional ballasts resulted less pleasant than light powered by high-frequency ballasts, but no relevant effects were found in terms of visual comfort, headache, stress and fatigue. The lack of effects on headache and eye-strain in this experiment can probably be justified by the insufficient exposure time of only three hours.

Nogouchi and Sakaguchi (1999) tried to verify Kruithof's research (Kruithof, 1941), investigating how illuminance and colour temperature in illumination affects the autonomic nervous system and central nervous system, in terms of lowering physiological activity. Kruithof studied the interactive effects of colour temperature and illuminance to establish which combination defines a comfortable and pleasant lighting condition.

The experiment has been performed on 8 healthy male subjects in four different conditions obtained by the combination of two levels of colour temperature (3000 K and 5000 K) and two levels of illuminance (30 lux and 150 lux). The index of autonomic nervous system has been the heart rate variability (HRV) and the index of the central nervous system has been the alpha attenuation coefficient (AAC) and the mean frequency of EEG. The AAC is defined as the ratio of mean total alpha power (frequency range of 8-12 Hz) recorded with eyes closed and open. An increase in AAC indicates a higher alertness level. Nogouchi and Sakaguchi found that low colour temperature light determines a lowering of central nervous activity.

S.L. McColl and J.A. Veicht (2001) analysed critically the direct effects of FSFL through skin absorption and indirect effects on hormonal and neural processes. Whillock (1988) stated that people, under interior conventional fluorescent lighting condition, receive only about 5% of the UVR dose received from daylight exposure over the year at 50°-60°latitude. The question is whether FSFL are more efficacious than other lamps for supplying this need. One of the most important effects due to light exposition is the metabolism of vitamin D, essential to calcium metabolism and to the maintenance of bones and teeth. Hathaway et al. (1992) analysed the effects of FSFL in schools, measuring them in terms of likelihood of developing dental caries.

All the experiments aiming to support the superiority of FSFL over other lighting sources have not shown evident dramatic effects on behaviour, visibility, academic performance, fatigue in office workers, hyperactivity in children and in health in general. For example, Hathaway’s experiments (1992) are influenced by many uncontrolled external variables, such as nutrition, tooth-brushing, fluoride treatments, etc., that make the outcome unreliable.

Tanabe and Nishihara (2004) developed some new methods to evaluate the factors affecting productivity, involving fatigue and not only task performance. They state that in experiments, generally carried out for a short time period, people are highly motivated and this fact leads to conflicting and not significant results. To evaluate the feeling of fatigue, subjects had to evaluate their symptoms, belonging to three different categories (this evaluation method is used in the fields of science and of labour and ergonomics in Japan): drowsiness and dullness (I), difficulty in concentration (II) and projection of physical disintegration (III). Yoshitake (1973) suggested three types of fatigue, depending on the rate of complaints among the three categories above-mentioned: general pattern of fatigue (if I> III > II), typical pattern of fatigue for mental work and overnight duty (if I> II > III) and typical pattern for physical work (if III> I > II). Sixteen college-age males have been involved to perform two different tasks, an addition of three-digit numbers on paper and reading aloud, under two different lighting conditions, 800 lux and 3 lux. Physical fatigue and the degree of mental effort required to perform the task were measured by voice analysis (Shiomi, 1999) and cerebral blood oxygenation changes, the last one by means of near infrared spectroscopy (NIRS). The results in terms of evaluation of fatigue by human voices show an increasing fatigue after performing tasks at 3 lux. This result has been validated even with the evaluation by near infrared spectroscopy which has shown an increasing in haemoglobin concentration in the brain under 3 lux, despite the one under 800 lux. Moreover, the performance of addition task did not show significant differences under the two lighting conditions, but, after performing the task, the rate of complaints increased. The condition of 800 lux caused a general pattern of fatigue, while the 3 lux one a typical pattern of fatigue for mental work and overnight duty. The conclusion is that, even if it seems that performance is not affected by illuminance level, a low lighting level increases mental fatigue and therefore performance.

Ariës (2005) analysed the lighting conditions in ten office buildings in the Netherlands, by means of questionnaires and of lighting measurements at workstations. The purpose of this study was to characterize these offices with regards to current lighting standards and non-visual effects and to find solutions for a so-called “healthy lighting”, which satisfied both visual and non-visual demands. Many parameters that could be related to the vertical illuminance level have been taken into account: these parameters are reported in Table 2.1, which shows some recommendations, based on literature and on Ariës results from the short-term measurements in real offices and the long-term measurements in laboratory offices.

Table 2.1 - Ariës’ recommendations for a “healthy lighting”

Building orientation	It has no influence on the amount of vertical illuminance. Diffuse daylight through a vertical window determines a higher vertical illuminance than direct daylight. More openings do not always mean higher vertical illuminances. East, South and West orientations require shading devices.
Obstructions	Surrounding buildings are permanent obstructions that reduce daylight penetration substantially. Vegetation can be considered as a shading device only in summer.
Daylight opening	A window in the upper part of the façade increases the penetration of daylight in the deeper part of a room and it contributes to enhance vertical illuminances.
Office type	It has no significant effect on the vertical illuminance, but people prefer a window position.
Interior	Lighting measurement should be done in furnished rooms, since surface reflections contribute to enhance or reduce the illuminance. Specular reflections can cause glare. Using different colours is more preferable for users and it can increase interest.
Position of the work station	A window-facing position is more effective for a high daylight illuminance at the eye, even in the deeper part of a room
Daylight control devices	They should be effective, adjustable and user-friendly. In multi-occupied offices, individual control is often disliked, since it can bring into conflict with other occupants. People are dissatisfied with permanently closed blind, but they often leave the blinds down: an automatic system which open the blinds in the evening would be useful.
Electric lighting	The highest vertical illuminance values can be obtained with a perpendicular view and with a little distance (0.5 m) from an upper luminaire.
Fatigue	It decreases with high levels of vertical illuminance, determining more alertness.
Sleep quality	Higher levels of vertical illuminance increase the level of sleep quality
Physical health	Its correlation with the vertical illuminance is not significant.
Other human parameters	Gender, age, eye correction, season sensitivity, chronotype and light sensitivity have no significant influence in the relationship between vertical illuminance and the parameters fatigue and sleep quality.

The amount of light falling on the retina has been measured in "*Troland*" units with a tailor-made measuring instrument called RED (Retinal Exposure Detector). *Troland* values are related to illuminance at the retina (Nilsson, 1983). In 90% of the cases, visual lighting criteria are satisfied, but not non-visual criteria. According to literature and standards, 1000-1500 lux are the required vertical illuminance for biological stimulation: Ariës measured these values only in 20% of the examined buildings.

Boyce et al. (2006) tried different lighting conditions, in order to evaluate the effects on office worker performance, health and well-being. They experienced direct and indirect lighting and the possibility to have an individual lighting control and they found that a direct/indirect system is more comfortable than a fully direct one and that an individual control increases motivation and vigilance over the day.

2.8. Conclusion

All the experiments are related to a specific group of people, therefore maybe the analysis on other people could reach different results. An acceptable lighting condition can change from one person to another and the same lighting condition can be suitable depending on the context (i.e. flicker light in an office or in a dance club). In laboratory experiments, people are usually highly motivated and they probably would ignore any discomfort. Analysing human factors in lighting, Boyce states that there is no doubt that motivation can affect task performance, but motivation is not only related to lighting conditions, but to many other factors. Moreover, even if lighting requirements are reached, visual comfort is linked to people's expectations and these expectations can change over time.

The reference standard for lighting requirements in indoor workplaces is the EN 12464-1. This standard gives some recommendations, for many different tasks, based only on visual criteria (minimum illuminance level, UGR value and colour rendering index), omitting to mention also the vertical illuminance, which should be evaluated, in order to know the amount of light entering the eye. Moreover, there is no reference to the possibility to increase lighting quality and productivity by means for example of personalised lighting control, dynamic light and indirect light and there is a poor investigation on colour appearance, colour rendering and daylight. It would be necessary to underline the importance of a high lighting quality, to persuade the employers to invest in new technology and in the optimization of daylight, demonstrating them that the over cost will be justified by the amount of productivity and the reduction of absenteeism and dissatisfaction.

It would be interesting to develop the concept of the interaction between people and light, especially by means of test and experiments, trying to find an objective law, which is rather impossible, due to the fact that vision is a subjective feature, connected to many psychological and physiological aspects. It would be easier to define which lighting conditions allow disease, annoyance, irritation, etc. As this literature study shows, once visual discomfort is avoided, the creation of a stimulating environment must be perceived, especially in office buildings, where workers, living in a pleasant condition, would feel and perform better (Baron, 1994). For this reason, field tests would be carried out in offices and classrooms, in order to evaluate the effective visual conditions in workplaces.

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Chapter 3

Daylight simulation tools: RADIANCE and DAYSIM

Lighting simulation tools are essential to evaluate the luminous environment in terms of lighting availability and quality inside of buildings. The RADIANCE tool introduced in this Chapter is one of the most advanced daylighting/lighting tools available today and it has been fully validated. It provides both illuminance/luminance values and renderings. The RADIANCE-based DAYSIM tool predicts annual illuminance profiles, due to daylight only. Based on these profiles, DAYSIM calculates electrical energy consumption for lighting, considering many different combinations of user behaviours and shading and lighting control strategies. Dynamic daylight performance metrics, which are useful for sustainable building design, are also supplied.

3.1. RADIANCE simulation tool

RADIANCE is a free ray-tracing software for lighting simulation and rendering. It is a computer software package developed by the Lighting Systems Research group at Lawrence Berkeley Laboratory under the direction of Greg Ward (Ward, 1992). It is a research tool for accurately calculating and predicting the visible radiation in a space by using the backward ray-tracing algorithm. Rays of light backwards to the sources are traced from a measurement point (usually a viewpoint). The lighting calculation can be divided into three main parts :
direct component: light arriving at a surface directly from light sources or via one or more perfectly specular transfers from other surfaces.
specular indirect component: light arriving at a surface from other surfaces and being reflected off or transmitted through in a directional manner.
diffuse indirect component: light arriving at a surface and being reflected or transmitted with no directional preference.
The program requires three dimensional (3D) geometric models as input, to generate spectral radiance values in the form of photo realistic images. The package though is more than just a photo-realistic renderer; it calculates also luminance/illuminance (radiance/irradiance) in all desired points of the scene.
A detailed description of RADIANCE simulation tool could be easily found in the internet sites and in the publications suggested in the References, though a general introduction is given in this chapter.

3.1.1. RADIANCE programs

The main RADIANCE programs are:

- *oconv*: it compiles the scene materials and geometry into a binary model
- *rtrace*: it is the core of the program: it traces rays through a model and it calculates radiance or irradiance at a given point
- *rvu* (or *rview*): it is the interactive rendering program and it is very useful to check the model and to set the desired view
- *rpict*: it generates accurate renderings.

3.1.2. Material file

The material determines how light will interact with the geometric surface. In the material file the description of the optical properties of the materials surfaces is specified. RADIANCE offers four classes of materials:

- Normal materials: *plastic*, *metal*, *trans* and *mirror*
- Lights: *spotlight*, *light, illum* and *glow*
- Dielectric materials: *dielectric*, *interface* and *glass*

- *BRDF* materials: materials with Bidirectional Reflectance Distribution Functions.

The material "*plastic*", which can be used for many building materials, is characterized by the fact that the colour of the material does not affect the specular reflections. It is defined by means of five numbers, which correspond to the red, green and blue reflectance values, the specularity and the roughness.
The "glass" material only produce one reflected ray and one transmitted ray through a single thin surface, therefore internal reflection are avoided. The "glass" type has a standard refractive index of 1.52 and it is defined by the visual transmission in RGB. It is important to remember that RADIANCE uses transmissivity (i.e. the percent of light not absorbed in one traversal) to define "*glass*", while glass manufacturers give transmittance, which is the percentage of light transmitted including inter-reflection.
The syntax and definition for the other materials can be found in the RADIANCE Reference Manual or in the internet sites suggested in the References.

3.1.3. Geometry file

RADIANCE uses a right handed coordinate system: the z vector or axis points up, the x vector or axis points East and the y North. A 3D CAD model could be imported through a conversion program. Many different geometry types can be directly generated in RADIANCE: *polygon*, *bubble*, *cone*, *cup*, *cylinder*, *tube*, *ring*, *sphere*, *source*, *istance* and *mesh*.

3.1.4. Sensor point file

The sensor point file contains the list of the position of the sensors in which the illuminance/luminance (or irradiance/radiance) are calculated. Each sensor is defined by 6 numbers: its geometrical position (x, y and z) and its direction.
An example of a sensor point in horizontal position is the following:

1.5 2 1.7 0 0 1

The sensor is located at (1.5; 2; 1.7) and it faces the zenith.

3.1.5. Simulation parameters

A set of parameters needs to be defined before the simulation starts. These parameters represent the most important part of the overall simulation, because they define its accuracy. They are grouped in different set, as, for example, in ambient options (which begin with the letter "*a*"), concerning the indirect calculation and in direct calculation ones, concerning the direct calculation.
The main important ambient parameters are:

- *ab*: ambient bounces
- *ad*: ambient divisions
- *as*: ambient super samples
- *ar*: ambient resolution
- *aa*: ambient accuracy

The main important direct parameters are:

- *dj*: direct jitter
- *ds*: direct sampling

The meaning of these options is explained in RADIANCE Manual Pages

3.2. DAYSIM simulation tool

The presented studies have been carried out with the RADIANCE-based software DAYSIM. The model DAYSIM can predict the energy requirement for artificial lighting and indoor illuminance profiles under all appearing sky conditions throughout the year – the so-called “All weather sky model” (Perez et al., 1993). These profiles are based on a weather climate file and they can be coupled with a stochastic user behaviour model, to predict some daylight performance indicators, such as daylight autonomy, annual light exposure and lighting energy use for different lighting and shading control strategies. The energy requirement for artificial lighting depends on the user behaviour and on the control strategies for lighting and shading systems which will be explained afterwards.

In order to calculate annual illuminance profiles, thousands of RADIANCE simulations could be run for all sky conditions of the year, but a single RADIANCE simulation can take several hours to complete, therefore an hourly simulation could not be realistically performed. To perform such hourly simulations, DAYSIM couples RADIANCE algorithm with a daylight coefficient approach., originally proposed by Tregenza (Tregenza, Waters, 1983). The celestial hemisphere is divided into different sky patches (145, according to Tregenza division) and the contribution to the total illuminance in a given point in a building (*x*) is calculated for each sky patch. The daylight coefficient (Figure 3.1) is defined as:

$$DC_{\alpha}(x) = \frac{E_{\alpha}(x)}{L_{\alpha}\Delta S_{\alpha}}$$

where:

S_{α} is the sky element

ΔS_{α} is the angular size of S_{α}

$E_\alpha(x)$ is the illuminance at x due to S_α
L_α is the luminance of S_α

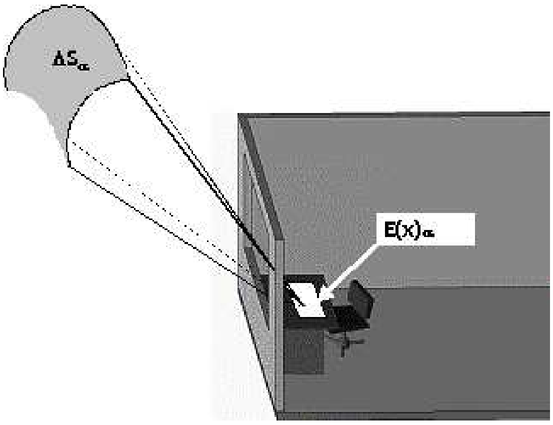

Figure 3.1 - Daylight coefficients (DAYSIM Tutorial)

Once all daylight coefficients, for a given point, relative to all sky patched, have been calculated, the illuminance or luminance at a point can be quickly calculated for any possible sky condition , combining these coefficients with sky luminous distribution. The format that DAYSIM uses for daylight coefficient is explained in Appendix B of DAYSIM tutorial. The sky model used by DAYSIM is the Perez sky, the model for “all weather sky”. The definition of this sky model can be found in the Reference section (Perez et al., 1990 and 1993).
As for RADIANCE section, a general introduction of DAYSIM is given in this chapter.
The inputs needed by the program are: the climate file, the geometry of the room, the material of the surfaces’ room and the position of the sensors.

3.2.1. Climate file

The weather file is a file imported from the DOE (US Department of Energy): this climate file contains a series of hourly direct and diffuse irradiances, which can be converted into a time series of down to five minutes direct and diffuse irradiances, using a stochastic autocorrelation model (a modified version of the Skartveit-Olseth model).
Due to short-term dynamics of daylight, a one hour time step of irradiance data can lead to unrealistic results. The quantification of simulation errors in the prediction of the annual daylight availability depending on irradiance step data is investigated in Walkenhorst et al., 2002.
From the EPW climate file, DAYSIM will then create a file, with *.wea* extension, which contains annual direct normal (or horizontal) irradiance and diffuse horizontal irradiance data of the building site.

3.2.2. Geometry, material and sensor files

Three types of building files are allowed: a 3DStudio file, a RADIANCE *.rif* file or one or several RADIANCE source files (*.rad, *.mat, *.sky). The surface material description and the sensor point file correspond to the ones explained in the RADIANCE tool section.

3.2.3. Shading device model

DAYSIM allows three modes to model shading devices:

- *static shading devices*: no shading device is provided or the building has a fixed shading, like a light shelf
- *dynamic shading device (simple)*: a generic venetian blind which blocks all direct sunlight and transmits 25% of all diffuse daylight is directly created by DAYSIM
- *dynamic shading device (advanced)*: the user has to insert the geometry and material description of the building shading. It is required to explicit two RADIANCE files, one with the geometry of the blinds up configuration and the other one with the blinds down

The first mode gives only one set of annual illuminance profiles, while, for the other two, DAYSIM will calculate two sets of illuminances, one for the blinds up and one for the blinds fully down. The difference between them consists on the level of design stage (strictly connection to simulation time, which is more than double for the advanced one): the first one can be considered an early design stage, while the second one (*dynamic advanced*) refers to a more detailed simulation, because the effective shading device is simulated.

3.2.4. Daylight analysis

After the ray-tracing run is finished, two daylight coefficient files (**.dc*) and two annual illuminance profiles (*.ill), one for blinds up and one for blinds down, are created in the "*res*" subdirectory of the DAYSIM project. Then the tool allows to carry out an in-depth analysis of the annual daylight availability (in terms of dynamic daylight performance metrics) and electric lighting energy use in the investigated offices. Some informations are then needed:, like, for example, the typical hours of occupancy (i.e. arrival time, departure time, lunch and intermediate breaks, daylight savings time).

The user behaviour implemented in DAYSIM is based on a model, called Lightswitch (Reinhart, 2004), which is the result of some studies in buildings throughout the Western world. These behaviour models mimic how users interact with personal controls (light switches, blinds, window opening). Three different user behaviours are considered, for both lighting and blind control: passive, active and mix. A passive user is defined as a “user who keeps the electric lighting on throughout the working day and keeps the blinds partly closed throughout the year to avoid direct sunlight”. An active user is a “user who operates the electric lighting in relation to ambient daylight conditions, open the blinds in the morning and partly closes them during the day to avoid direct sunlight”. The mixed user behaviour is the mix of both active and passive behaviours. For each different user, different lighting control strategies can be considered.

3.2.5. Lighting control systems

When using a switch off occupancy sensor, the light can only be activated manually, while the switch off can be either manual or automatic (with a delay time of five minutes) when the occupancy sensor is installed; in this case the consumption of a standby power is 3 W when the light is switched on. An on/off occupancy sensor is permanently in standby mode (electric power of 3 W) and it activates the lighting whenever occupancy is detected.

The controlled dimmed lighting system photo sensor consists of a photocell (standby power of 2 W) which dims the activated light until the total work plane illuminance reaches the illuminance threshold (500 lux). At a minimum lighting output of 1% the system consumes 15% of its full electric power. The lighting is activated by a manual switch on/off near the door. The combination dimmed lighting and energy-efficient occupancy sensor has a standby power of 5 W.

It must be noticed that the standby power has to be divided for the surface dimension of the analysed room, otherwise it will be summed to the installed lighting power.

3.2.6. Dynamic daylight performance metrics

Some daylight indexes have been proposed as alternatives to the daylight factor metric to evaluate the performance of buildings (Reinhart, Mardaljevic et al., 2006). DAYSIM calculates two set of these parameters, one for a passive and one for an active user.

The dynamic daylight performance metrics are the followings:

- *Daylight Autonomy* (DA): in a particular point of a building, it is defined as the fraction of the occupied times per year when daylight is sufficient to guarantee the required illuminance level. This metric consider all sky conditions throughout the year, while the daylight factor refers only to the overcast one. It also depends on the occupancy hours, the status of the blinds during the year and the required illuminance; it does not take into account the installed electric lighting power and lighting control, so it cannot be considered a parameter to evaluate energy savings.
- *Continuous Daylight Autonomy* (DA_{cont}): it is a quite recent metric that considers the fact that many office occupants work under the minimum

illuminance required by the Standards. This index, in fact, attributes a credit even when daylight ensures an illuminance level under the required one.

- *Maximum Daylight Autonomy* (DA_{max}): it indicates, in percentage, if, during occupied hours, direct sunlight occurs or excessive daylight conditions are present.
- *Useful Daylight Illuminances* (UDI): it gives informations about how “bright” is an environment and if the daylight levels exceed the required and the actual useful ones. This metric is divided in three indexes, UDI<100, UDI100-2000 and UDI>2000, depending on the illuminance threshold considered (< 100 lux, 100-2000 lux and > 2000 lux). If there is a high percentage of UDI<100 , the ambient would result too dark, while if UDI>2000 is high it would result too bright and then glare would occur.
- *Annual Daylight Exposure*: it is measured in lux hours per year and it is defined as the cumulative amount of visible light incident on a point of interest over the course of a year.

3.2.7. DAYSIM limits

DAYSIM is an interesting tool which gives the possibilities to researchers to predict daylight availability of a space, illuminance distribution and to evaluate different lighting and shading controls with the aim at reducing energy demand for lighting. Despite that it has some limits which have to be taken into account. These limits are the followings:

- Electric lighting contribution is not considered. Moreover, carrying out the energy analysis, only the installed lighting power is requested, but the number of luminaries, nor their position, are not specified.
- Glare prediction refers only to daylight.
- All the lighting and the energy analysis refer to commercial buildings, therefore it cannot be used for other building types.
- The occupancy schedule cannot be modified, according to the effective one.
- It is not possible to simulate coloured surfaces, but only grey-scales materials.

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Internet sites:
www.radiance-online.org
radsite.lbl.gov/radiance
http://luminance.londonmet.ac.uk.learnix/

Chapter 4

Preliminary analysis

In this Chapter some preliminary lighting analysis are shown. All the simulations have been carried out for an ideal office and four an existing educational building.

Natural light is irreplaceable because it is a full-spectrum light, it changes during the day and it is different every day of the year. A variable illumination throughout the day, in terms of intensity and colour temperature, creates dynamic indoor environments that are more pleasant for people. Daylight needs to be controlled, especially in office buildings, to avoid discomfort glare and high luminance reflections on display screens, to provide a good lighting level even in the deeper part of a room and to reduce cooling loads. To improve the lighting quality, visual comfort and to minimize lighting, heating and cooling loads, advanced daylighting systems (such as BMS, Building Management Systems) and external shadings should be used. The aim of the study described in this Chapter is to optimize the availability of glare-free daylight in commercial and educational buildings, in order to create spaces of high visual quality, where the energy demand for artificial lighting (and cooling) can be reduced by means of control strategies and shading devices.

4.1. Office building

An ideal office, equipped with different shading devices, has been supposed at different latitudes, with the aim at analysing daylight distribution and electric energy requirements for lighting.
The objectives of this study are:

- to evaluate the impact of these external shading devices, both fixed and movable, on the illuminance levels inside the investigated room and on their associated energy savings;
- to evaluate the lighting energy savings from daylighting with some types of lighting control systems;
- to evaluate which shading device is to be preferred, according to latitude;
- to evaluate the office energy efficiency and sustainability by means of some dynamic daylight metrics.

The lighting simulation has been carried out with the software DAYSIM, developed by the National Research Council of Canada and by the Fraunhofer Institute for Solar Energy Systems and the software Radiance, developed by Greg Ward and by the Lighting System Research group of the Lawrence Berkeley Laboratory.

4.1.1. Case study

The same single office (Figure 4.1), facing south, has been analysed in five different latitudes: Stockholm (59°65' N), Venice (45°50' N), El Cairo (30°13' N), Bombay (19°12' N) and Colombo (6°82' N).
It is a box-shaped room, 3.5 m wide, 7 m long and 3 m high. No external obstructions and no internal furnishing have been considered.

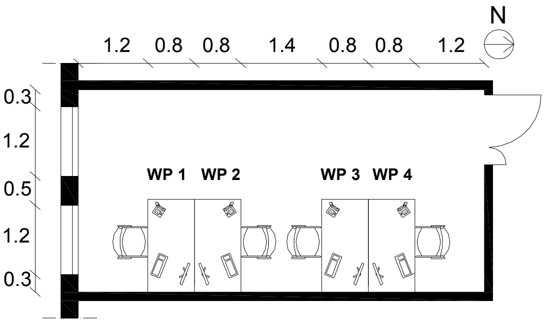


Figure 4.1 - Office plant with the position of the four work planes

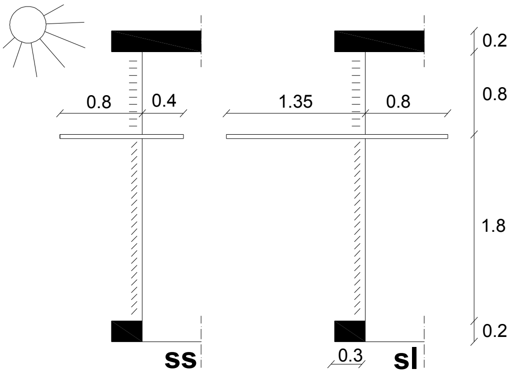


Figure 4.2 - Office sections: light shelf short (ss) and light shelf long (sl)

The façade has two glazing surfaces of 1.2 x 2.6 m^2 (Figure 4.3).

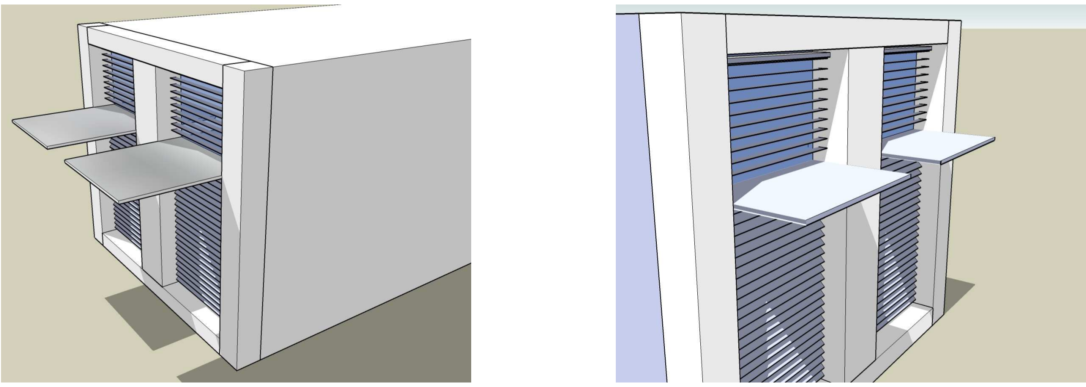


Figure 4.3 - Office perspective

The shading system consists of a fixed light shelf, both internal and external, with a reflective upper surface, and two movable external venetian blinds, with the slats 0.08 m wide. The reflective light shelf is designed to shade and redirect light to deep areas of the room interior. Two different dimensions of both internal (0.4 m and 0.8 m) and external (0.8 m and 1.35 m) light shelf have been supposed (Figure 4.2), depending on the solar altitude of each location considered during the year.

Venetian blinds are the typical shading system which occurs in buildings: they protect against glare and redirect daylight, they may obstruct, absorb, reflect and/or transmit solar radiation (both diffuse and direct) to indoors, depending on the position of the sun, their location (internal or external), slat angle and slat surface reflectance characteristics.

4.1.2. Occupancy

The office is supposed to be occupied by four persons (Figure 4.1). Occupancy profiles are generated by the program. The following assumptions have been considered:

- arrival time: 9:00;
- departure time: 18:00;
- the work place is occupied from Monday to Friday;
- the lunch break occurs at noon and two 15 minutes breaks are scheduled around 10:00 and 15:00.

4.1.3. Simulation

Assumption for calculations have been done according to the Standard EN 12464-1 and the Standard EN 15193. The simulation time step was five minutes. It is supposed to know the position of the work places (Figure 4.1) and the height of the working area is fixed at 0.75 m. The illuminances and all the dynamic parameters have been calculated on a 0.5 x 0.5 m grid over the whole office and on a 0.2 x 0.2 m grid over each work-station. The maintained illuminance in the work plane is fixed at 500 lux. The installed lighting power density load is assumed to be 15 W/m^2, which corresponds to the benchmark value for a typical office room of one star quality class (EN 15193, Annex F).

The optical properties of each building element, supposed monochrome, are reported in Table 4.1.

Table 4.1 - Optical properties of building elements

Building element	Material description
ceiling	80% diffuse reflection
floor	30% diffuse reflection
wall	60% diffuse reflection
glass	76% visual transmittance
blind	50% diffuse reflection
light shelf	upper side: 80% RGB reflection, 80% specularity lower side: 80% diffuse reflection

Non-default DAYSIM-RADIANCE simulation parameters are listed in Table 2.

Table 4.2 - Simulation parameters

ambient bounces	ambient divisions	ambient accuracy	ambient resolution	direct threshold	direct sampling
7	1500	0.1	300	0	0

The DAYSIM dynamic advanced shading device model has been chosen, because, by means of this model, it is possible to simulate a specific shading device. In this case, two RADIANCE files are required to be explicated, one with the geometry of the blinds up configuration and the other one with the blinds down. DAYSIM will then calculate two sets of illuminances, one for the blinds up and one for the blinds fully down. In this work, the advanced model has been applied, for all the five latitudes, in the two façade configurations (Figure 4.2), trying many slat angle in the “blinds down” geometry file, in order to reach a good compromise of daylight distribution for all the four work-stations.

4.1.4. Results

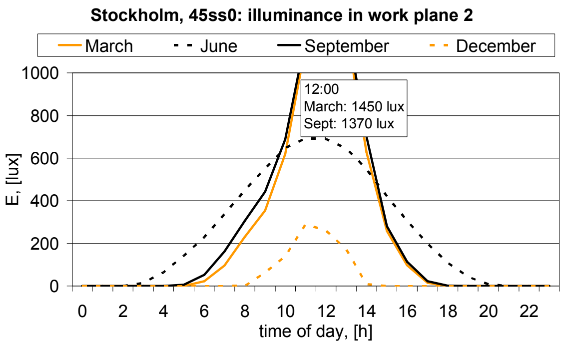
Annual illuminance profiles

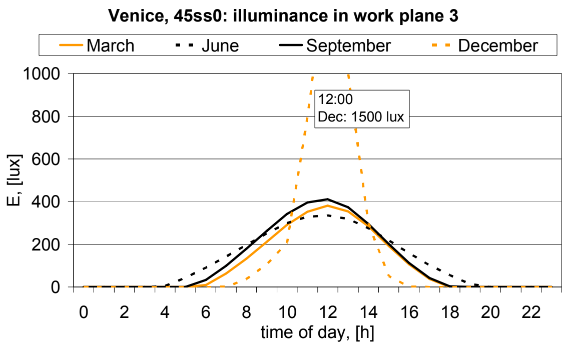
The simulations of the annual illuminance profile have been carried out with DAYSIM, for each latitude, in the two façade configurations, with the blinds slats at different angles, as explained in the table below (Table 4.3).

Table 4.3 - Description of the façade configurations

up	no shading device, neither fixed nor movable
int_ss	internal light shelf, 0.4 m wide
int_sl	internal light shelf, 0.8 m wide
ext_ss	external light shelf, 0.8 m wide
ext_sl	external light shelf, 1.35 m wide
ss	internal light shelf, 0.4 m wide and external light shelf, 0.8 m wide
sl	internal light shelf, 0.8 m wide and external light shelf, 1.35 m wide
45	movable blind, in the lower part of the façade, with slats at 45°
45ss	internal light shelf, 0.4 m wide and external light shelf, 0.8 m wide movable blind, in the lower part of the façade, with the slats at 45°
45sl	internal light shelf, 0.8 m wide and external light shelf, 1.35 m wide movable blind in the lower part of the façade with the slats at 45°
45_0	movable blind, in the lower part of the façade, with the slats at 45° movable blind in the upper part of the façade, with the slats at 0°
45ss0	internal light shelf, 0.4 m wide and external light shelf, 0.8 m wide movable blind, in the lower part of the façade, with the slats at 45° movable blind in the upper part of the façade, with the slats at 0°
45sl0	internal light shelf, 0.8 m wide and external light shelf, 1.35 m wide movable blind, in the lower part of the façade, with the slats at 45° movable blind in the upper part of the façade, with the slats at 0°
45ss30	internal light shelf, 0.4 m wide and external light shelf, 0.8 m wide movable blind, in the lower part of the façade, with the slats at 45° movable blind in the upper part of the façade, with the slats at 30°
45sl30	internal light shelf, 0.8 m wide and external light shelf, 1.35 m wide movable blind, in the lower part of the façade, with the slats at 45° movable blind in the upper part of the façade, with the slats at 30°

The following graphs (Figure 4.4) show the monthly illuminance profiles for the façade with the shorter light shelf (Stockholm and Venice) and the longer one (El Cairo, Bombay and Colombo). These values have been obtained by the average of the simulated illuminance values of each month of the year. These profiles, reported in four representative months of the year (March, June, September and December), refer to the "shading down" condition, with the venetian blinds fully down, with the lower blind with the slats at 45° and the upper one at 0°, which turns to be the more efficient for all the work-stations.





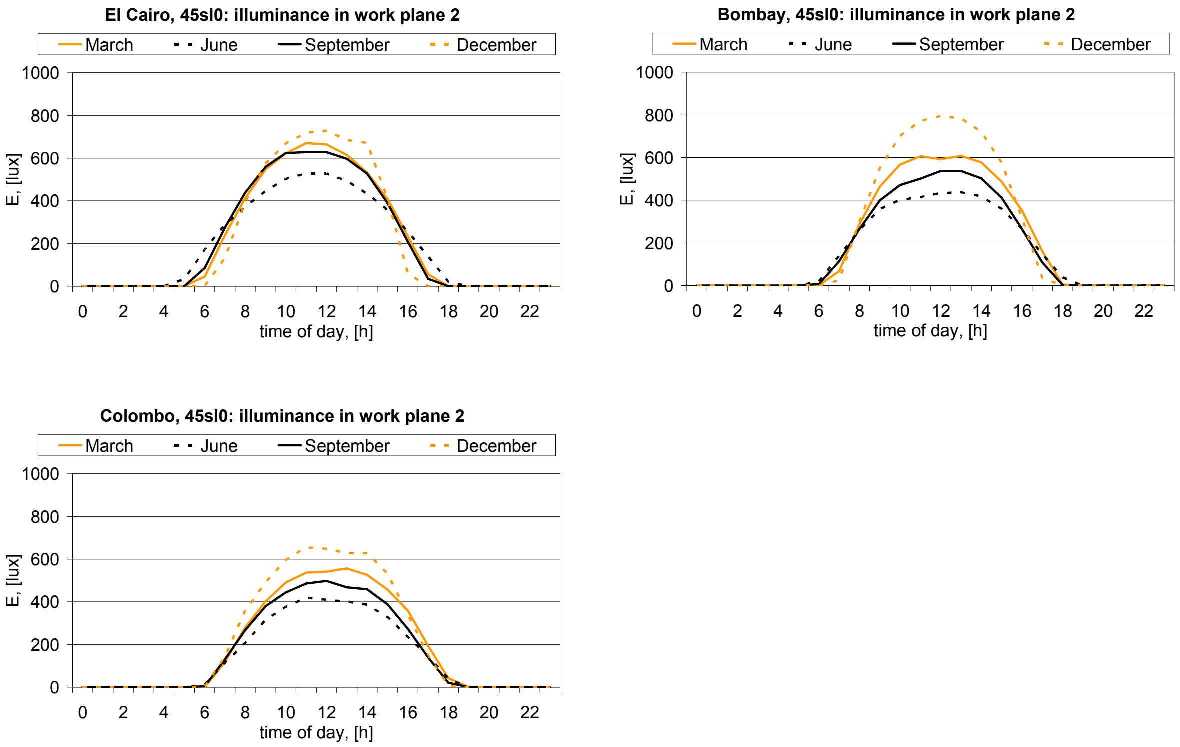


Figure 4.4 - Average illuminance profiles in March, June, September and December

In Stockholm, daylight need to be controlled, especially at midday, in spring and autumn, when the sun is low on the horizon and light, directly entering in the room, determines unacceptable high values of illuminance and therefore luminances and glare. In this case, it is necessary to keep the blinds with a greater slat angle. In Venice, the same problem occurs in winter.

In the other three sites, these configurations provide an efficient daylight control and illuminance distribution.

Illuminance over the work planes

The simulations in particular sky conditions and time of day and year have been performed with RADIANCE. Different façade configurations have been simulated (Table 4.3), in order to determine the effect of each device separately, compared to the case with no shading provided (“*up*”).

The graphs in Figure 4.5 show the main important results obtained in a sunny day (standard CIE clear sky) of 21st December, at noon, when there is a low solar altitude. In all the sites considered, in this particular sky condition and time, the illuminances are higher than the required ones.

For Stockholm, due to the fact that December does not show significant results, the illuminance values in a sunny day of March are also reported, the month in which the annual illuminance profile (Figure 4.4) reveals a peak of illuminance. In fact, in March, the illuminance, in work plane 1 is controlled only if there is a long light shelf

(“*sl*”) or a combination of light shelf and blinds (“*45ss0*” or “*45ss30*”). In the work plane 2, it is also necessary to keep the upper blind with the slats at 30°.
For an office in Venice, the illuminance in work plane 3 is over 10000 lux in every façade configuration, except the one with the light shelf and the blinds with the slats at 45° and at 30°, the lower and the upper one respectively. For work planes 1 and 2, only a blind with the slats at 45° can control the illuminance level.
The case of El Cairo reveals that the longer light shelf (“*int_sl*”, “*sl*”) is sufficient to control illuminance in work planes 1 and 2.
Finally, for an office located in Bombay, the work plane 1 reaches an acceptable illuminance level only with the longer light shelf.

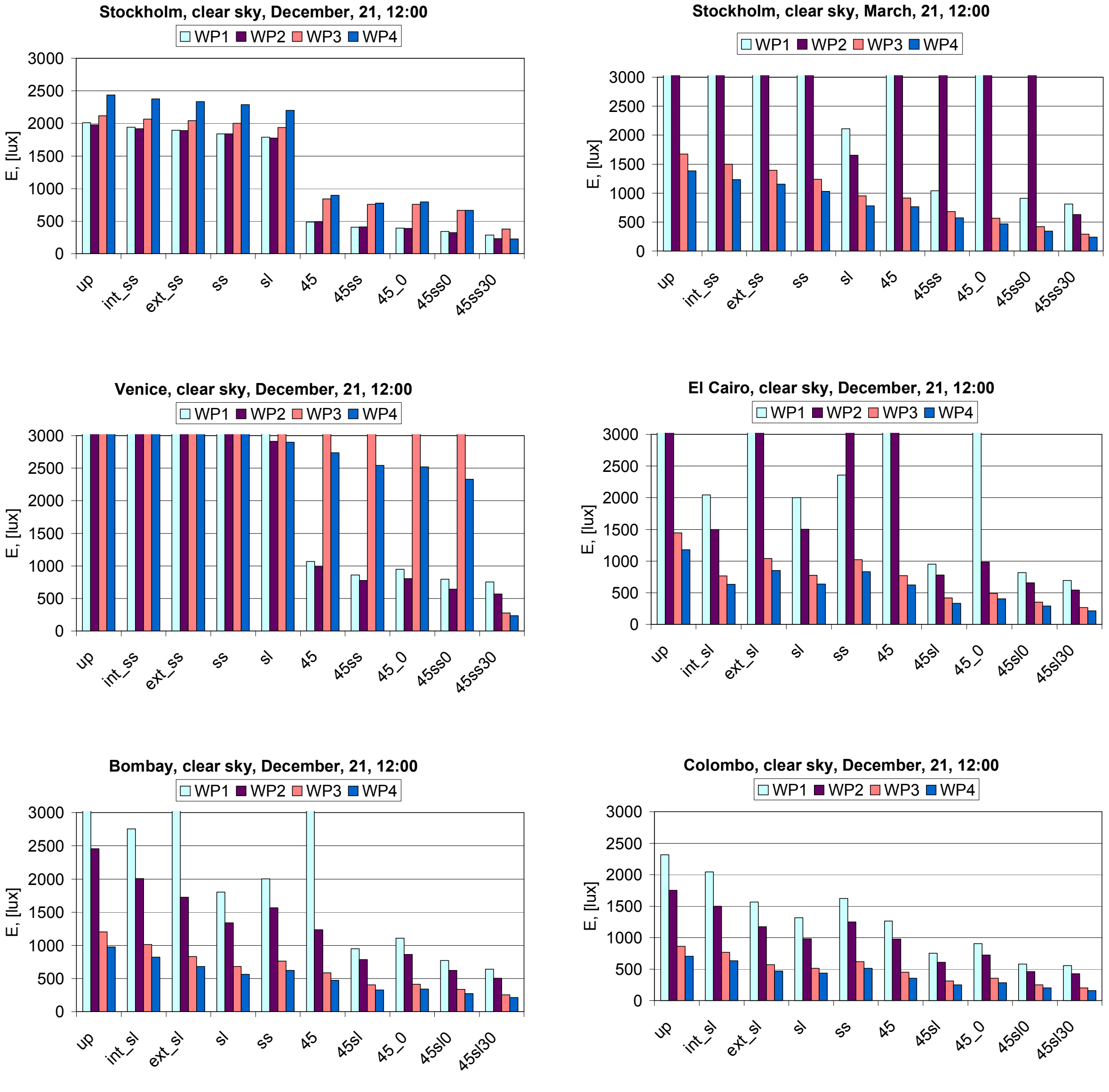


Figure 4.5 - Illuminance over the work planes

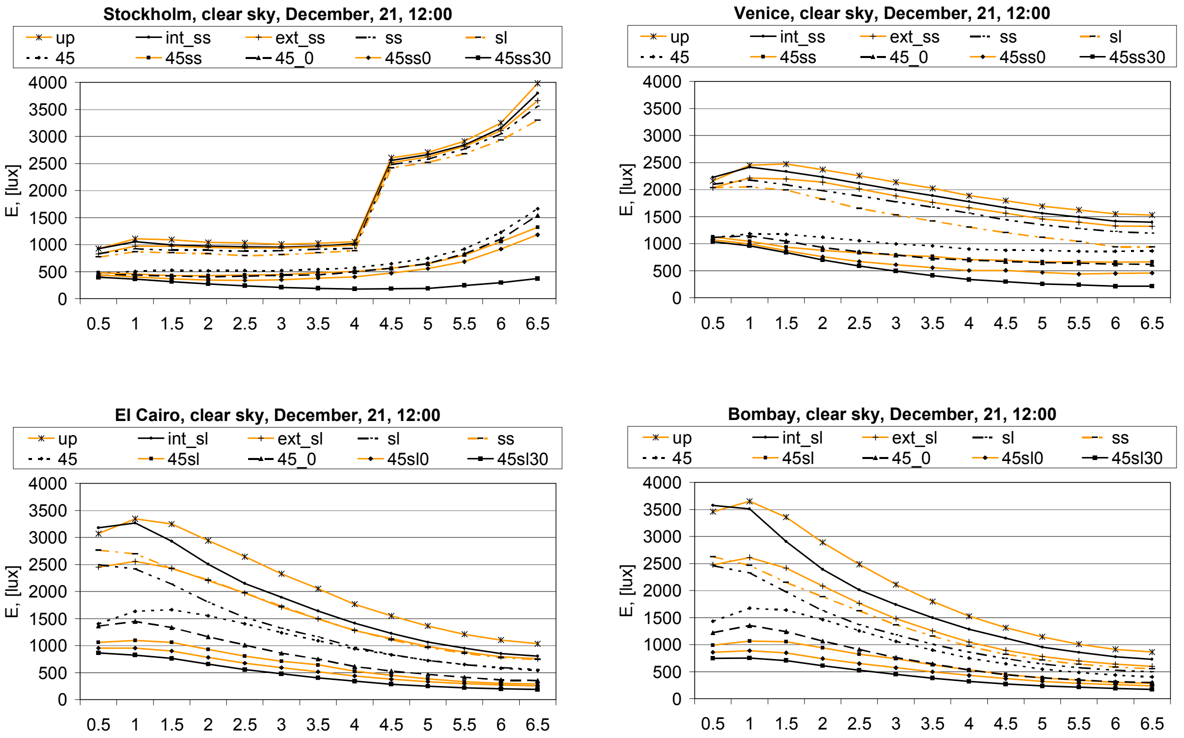
For Stockholm and Venice, in December, the effect of the longer light shelf is the same of the shorter one, while in a sunny day of March the longer one provides a better shading in the area close to the window. However, the annual profile reveals that the shorter light shelf performs better all over the year.

In general, an internal light shelf reduces daylight penetration in the first part of the room, increasing illuminance uniformity, while an external light shelf controls the thermal load.

The simulations in overcast conditions are not reported, since they do not show significant results.

Illuminance values along the central axis

For the different façade configurations explained in Table 3, the predicted illuminance values along the central axis at work plane level (0.75 m) have been simulated and they are shown in Figure 4.6. For each site, the sky condition is the standard clear CIE and time is 21st December, at noon.



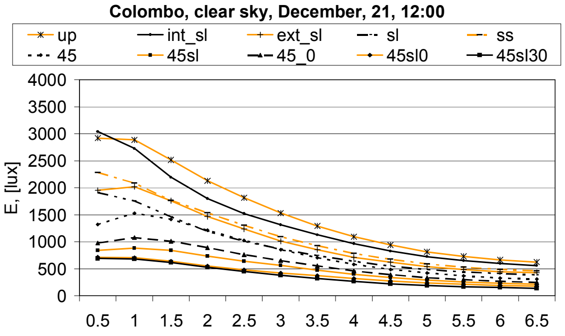


Figure 4.6 - Illuminance along the office central axis

In Stockholm, the higher illuminance values are in the deep part of the office, because of very low solar altitude. In Venice, and in the other three locations, it is possible to reduce the high illuminance values close to the windows only by means of blinds.

Daylight Factor (DF)

The daylight factor measures the amount of daylight in buildings in a specific sky condition – the overcast one- which is the worst sky condition. In an office, a DF_{med} of 2% is required.

The Figure 4.7 reports the DF over the work planes. The Standard EN 15193 classifies the daylight penetration as a function of the DF: if 1%≤DF<2%, it is considered weak, if 2%≤DF<3%, medium, if DF≥3% strong. A DF of less than 1% is irrelevant. In this case, a medium daylight penetration is reached only with the blinds up.

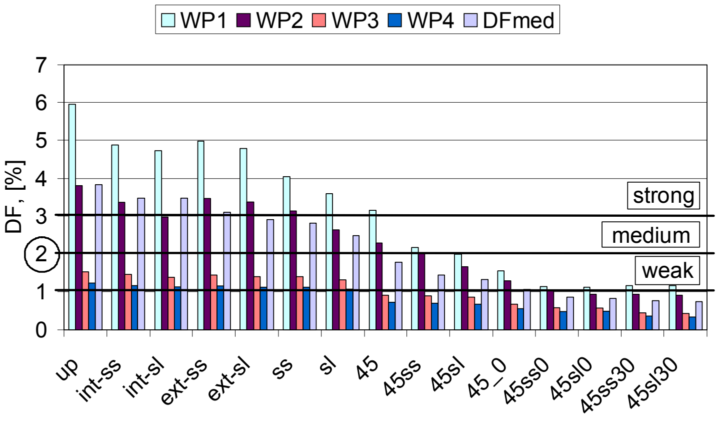


Figure 4.7 - Daylight Factor calculated in the four work planes

This parameter takes into account the building geometry, the external obstructions and the material properties. It is a factor that gives information about the quantity and not about the quality of light inside a building. It does not take into account the building orientation, the time of day, the season, the site, the weather conditions, the variable sky conditions, etc. Despite of that, all the Standards refer to the daylight factor as a performance metric for daylighting. In this work, some dynamic daylight performance metrics, which consider the climate of the building site and the occupational profile of the building, have been calculated with the software DAYSIM.

Dynamic daylight performance metrics

Some daylight indexes have been proposed as alternatives to the daylight factor metric to evaluate the performance of buildings (Reinhart, Mardaljevic et al., 2006). In Table 4.4 these metrics are reported for each work-station, comparing the difference between a passive and an active user who operates the blind manually and an automated shading control.

Table 4.4 - Dynamic daylight performance metrics

	Shade control	**Passive Manual**				**Active Manual**				**Automated**			
	WP positions	WP1	WP2	WP3	WP4	WP1	WP2	WP3	WP4	WP1	WP2	WP3	WP4
Stockholm	DA, [%]	40	35	9	4	53	49	25	19	64	60	35	26
	DA_{cont}, [%]	60	57	42	36	70	67	54	48	76	74	61	55
	DA_{max}, [%]	0	0	0	0	0	0	0	0	1	0	0	0
	$UDI_{<100}$, [%]	28	29	36	40	20	21	28	31	16	18	25	27
	$UDI_{100-2000}$, [%]	72	70	64	60	71	73	71	68	68	74	75	73
	$UDI_{>2000}$, [%]	0	1	1	0	10	5	1	0	16	8	1	0
Venice	DA, [%]	41	34	5	2	67	62	38	27	77	72	43	30
	DA_{cont}, [%]	68	65	45	36	82	79	66	59	88	85	71	64
	DA_{max}, [%]	0	0	0	0	0	0	0	0	0	0	0	0
	$UDI_{<100}$, [%]	16	18	25	30	8	9	16	20	6	7	13	15
	$UDI_{100-2000}$, [%]	84	82	73	70	76	86	82	80	75	86	86	84
	$UDI_{>2000}$, [%]	0	0	1	0	16	5	1	0	19	7	1	0
El Cairo	DA, [%]	67	48	2	0	90	87	56	39	94	91	63	46
	DA_{cont}, [%]	88	83	54	45	94	93	84	78	97	96	87	82
	DA_{max}, [%]	0	0	0	0	0	0	0	0	0	0	0	0
	$UDI_{<100}$, [%]	4	4	7	9	3	4	5	6	1	2	3	4
	$UDI_{100-2000}$, [%]	96	96	93	91	81	94	95	94	77	93	97	96
	$UDI_{>2000}$, [%]	0	0	0	0	16	2	0	0	22	6	0	0
Bombay	DA, [%]	58	40	1	0	95	91	56	39	96	93	59	42
	DA_{cont}, [%]	88	81	53	43	99	97	87	80	99	98	89	82
	DA_{max}, [%]	0	0	0	0	0	0	0	0	0	0	0	0
	$UDI_{<100}$, [%]	1	1	3	6	0	0	1	1	0	0	0	1
	$UDI_{100-2000}$, [%]	99	99	97	94	81	97	99	99	79	97	100	99
	$UDI_{>2000}$, [%]	0	0	0	0	19	3	0	0	21	3	0	0
Colombo	DA, [%]	53	32	0	0	97	94	60	41	98	95	61	41
	DA_{cont}, [%]	86	79	50	41	99	98	90	83	100	99	90	84
	DA_{max}, [%]	0	0	0	0	0	0	0	0	0	0	0	0
	$UDI_{<100}$, [%]	0	1	3	6	0	0	0	1	0	0	0	0
	$UDI_{100-2000}$, [%]	100	99	97	94	82	98	100	99	82	98	100	100
	$UDI_{>2000}$, [%]	0	0	0	0	18	2	0	0	18	2	0	0

An automated shading control can efficiently improve Daylight Autonomy only in Stockholm and in Venice, while in the other three sites an active user can reach almost the same results.

The DA cont index attributes a credit even when daylight ensures an illuminance level under the required one. In the analysed building, for the two work planes in the back of the office, the DA_{cont} value is twice the DA for the active manual and for the automated shade control while, for the passive manual, it is even higher (i.e. from 0% to 50%).

The Maximum Daylight Autonomy (DA_{max}) indicates, in percentage, if, during occupied hours, direct sunlight occurs or excessive daylight conditions are present. In this case, this value is every time 0%, except for WP1 in Stockholm.

From Table 4.4, it can be deduced that, for lower latitudes, the “useful daylight” lies almost all around the range of 100-2000 lux, while, for Stockholm, the UDI100-2000 is around the 70%.

Electrical energy consumption for artificial lighting

The different lighting and blind control strategies analysed, combined with the user behaviour, are summarised in Table 4.5.

Table 4.5 - User behaviour and control strategies analysed

User beviour type		Lighting control	Blind control	Symbol
lighting	blind			
passive	passive	manual switch on-off	man	PM
active	active	manual switch on-off	man	AM
mix	mix	manual switch on-off	man	MM
active	active	automatic switch-off	autom	ASF
mix	mix	automatic switch-off	autom	MSF
mix	mix	dimmer	autom	MD
active	active	dimmer	autom	AD
passive	passive	autom switch off and dimmer	autom	PSFD
active	active	autom switch off and dimmer	autom	ASFD
mix	mix	autom switch off and dimmer	autom	MSFD
mix	mix	autom switch on/off and dimmer	autom	MSNFD

The electrical energy demand for artificial lighting is represented in Figure 4.8. The user behaviour is very important: only if the user interacts with the building a significant reduction is possible to be reached. For example, the combination passive user with the most performant BMS (SFD), compared to the one with an active or a mixed user, confirms this statement.

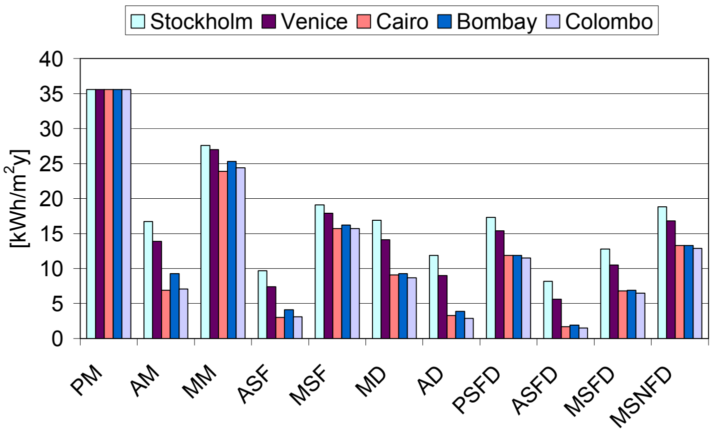


Figure 4.8 - Energy requirement for artificial lighting, for the five investigated places, considering users' behaviour and different control strategies

The combination passive user and manual control has the same energy consumption in all the latitudes, because it is supposed that the occupants leave the blinds fully down all the time.

The reduction of energy consumption by means of BMS systems are listed in Table 4.6.

Table 4.6 - Electric energy reduction, depending on user behaviour and control strategies

	S-45ss0	V-45ss0	CA-45sl0	B-45sl0	C-45sl0
PM--AM [%]	53	61	81	74	80
PM--MM [%]	22	24	33	29	31
PM--PSFD [%]	51	57	67	67	68
AM--ASF [%]	42	47	57	56	56
AM--AD [%]	29	35	52	58	59
AM--ASFD [%]	51	60	75	80	79
MM--MSF [%]	31	34	34	36	36
MM--MD [%]	39	48	62	63	64
MM--MSFD [%]	54	61	72	73	73
MM--MSNFD [%]	32	38	44	47	47
MSFD--ASFD [%]	36	47	75	72	77
PSFD--ASFD [%]	53	64	86	84	87

4.1.5. Conclusion

This work shows that daylighting systems are necessary to control visual environment, because they provide solar shading, protection from glare and redirection of light. Each latitude needs different shading devices: in high latitudes (Stockholm), cloudy skies are predominant and the exterior illuminance on winter days at noon is often even less than 5000 lux, while a realistic horizontal illuminance for a bright overcast sky is about 10000 lux. In these latitudes light shelves are not sufficient, while for low latitudes they can correctly control visual comfort in indoors.

On the other hand, daylighting systems can reduce peak demand especially during summer peak periods, when there is a good daylight availability: if no shading device is provided, solar heat gains can increase the cooling load. The optimization of the use of BMS system, integrated with daylight, can save energy, both for artificial lighting and cooling demand: they can reduce electric power for artificial lighting from 31% to 73%, supposing a mixed user behaviour, depending on control strategies and site latitude.

The evaluation of sustainable buildings cannot be drawn without considering how the occupant behaves and interact with the environment, in terms of shading and lighting control. In many office buildings it happens that people work with the light switched on, leaving the blinds down, even when there is no possibility of glare appearance (Rea, 1984). Simulations carried out in this work, confirm that the combination “passive user” and “manual control” is responsible of a non efficient building. For that reason an automated lighting and shading control system should be provided.

The actual Standards evaluate the amount of daylight entering a space by means of the daylight factor, a parameter that is just a “quantitative” information, not sufficient to evaluate the “quality” of light (i.e. a complete glazed building would reach a very high DF, but it would have many problems, in terms of thermal comfort and energy consumption). The software DAYSIM is very useful, since it includes a behaviour occupancy model and it can help the designer to analyse and compare critically the impact of different shading devices and control strategies, by means of some dynamic daylighting metrics.

Finally, the concept of visual comfort depends on people and a lighting condition can be acceptable for a person but not for another. The Standards try to give some suggestions with the purpose to create a acceptable and safe environment, but they miss many aspects (i.e. people preferences and behaviour, etc).

It would have been interesting to compare these simulation results by directly measuring the illuminance values in a real office room, asking the occupants, by means of questionnaires, how they feel in those conditions, which shading they prefer and how and if they operate the lighting and shading systems.

4.2. Analysis of lighting quality and energy savings in an Italian Secondary School

Schools are of primary importance for energy consumption as well as for comfort requirements. In the last years, international research has been addressed to educational buildings, since children cannot interact with the environment and they do passively accept indoor conditions. Usually, the energy in schools is reported as electrical and fuel consumptions, which can be monthly based on lectures or seasonal values. The question is how much energy is due to heating, hot water and, concerning electrical energy, how much is due to lighting, pumps and, in case, cooling.

In this work 1.5 years operation of an Italian Secondary School has been monitored via wi-fi instruments for checking electrical consumptions as well as energy need of the building. Electrical measurements have been carried out for the whole period, while energy need of the building has been monitored for the second year.

In this study only the electrical consumption and lighting conditions, by means of simulations and measurements taken with the wi-fi sensors, are reported. The simulations have been carried out with the software DAYSIM, which gives the electrical energy consumption for lighting, depending on occupancy, shading devices and lighting control strategies, showing which improvements on lighting and electrical energy demand can be obtained. The classrooms face to South and West, so the two different classroom orientations have been compared, in order to underline the importance of orientation in daylighting availability.

In each classroom of the ground floor there is a sensor, put in the wall close to the blackboard, which measures air temperature, humidity and illuminance. The measurements have been recorded from October 2008 to March 2009 (after 12th March a problem of connection occurred). Due to sensors position, only vertical illuminance has been measured.

Finally, in May 2009 the luminaries of two classrooms have been replaced; the new ones can dim the luminous flux according to measured indoor lighting conditions, hence a significant energy saving is obtained. Moreover the new luminaries, compared to the old ones, improve illuminance and lighting quality, therefore it would be advisable the replacement of all the old luminaries.

4.2.1. Case study

The analysed Secondary School “Beato fra Claudio” is located in Santa Lucia di Piave, a little town around Treviso, in the North East of Italy. The surroundings are a quiet rural area with a great panorama (Figure 4.9).

(a) (b)

Figure 4.9 - Secondary School perspective (a); school panorama (b)

The school is composed by two buildings: one includes the classrooms and the administration and the other one the gym.

The school has been built in 1986, it has two floors and it is made of brick and concrete. The entrance and the administration offices are East oriented, while the classrooms and the laboratories are West and South oriented (Figure 4.10). The gym has one floor and the changing rooms are North oriented. Last year there were 207 children, 30 teachers and 11 administrators.

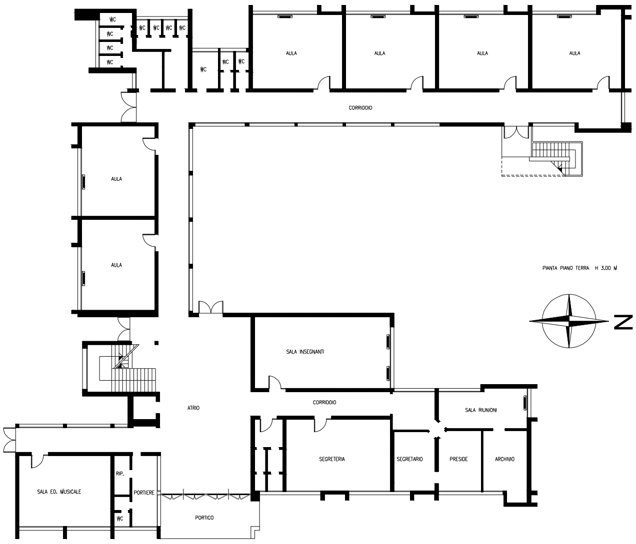


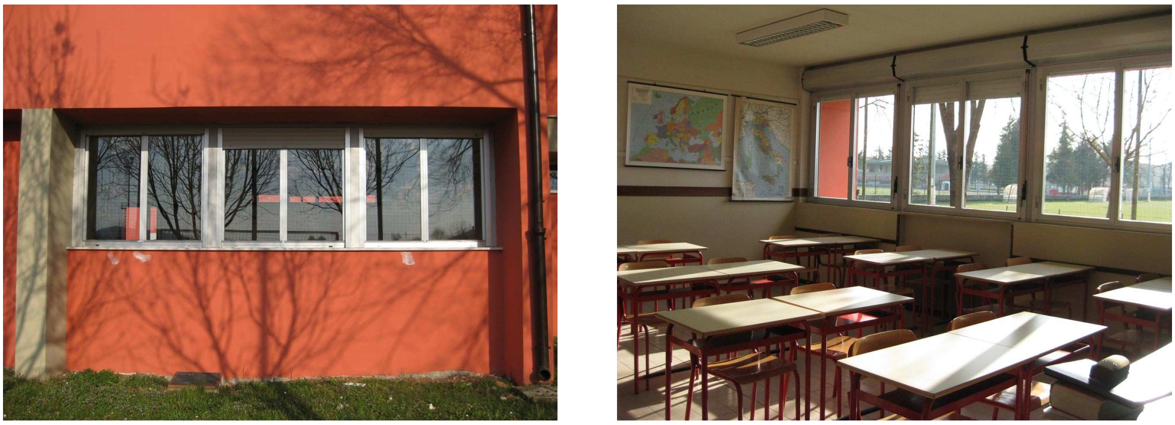
Figure 4.10 – School plant (ground floor)

In all the classrooms, the direction in which the students usually face the teacher is parallel to the perimeter wall. All the classrooms are rectangular with one wall bordering the building perimeter. The internal wall facing the perimeter wall is partly glazed above the regular door height (2.3 m) and it separates the classroom from an aisle or circulation area (Figure 4.11).

(a) (b)

Figure 4.11 – (a) Classroom; (b) aisle

The school is open from 7:30 to 18:30 and class is from Monday to Saturday, from 8:00 to 13:00 or from Monday to Friday, from 8:00 to 16:00. On Tuesday and on Thursday, from 14:00 to 17:00 there are some laboratories.



(a) (b)

Figure 4.12 – Shading devices: external view (a); internal view (b)

Considering lighting and shading systems, the classrooms have fluorescent lamps, rolling shutters and internal venetian blinds (Figure 4.12).

4.2.2. Measurements

The school is monitored in terms of electric energy consumption and of indoor environmental conditions, the latter by means of wireless sensors (4Noks) which record air temperature, relative humidity and illuminance (Figure 4.13). These sensors face South, therefore they are positioned beside the blackboard or beside the door, depending on classroom orientation.

The system is composed by wireless sensors, the gateway and some repeaters. The sensors, with a low consumption battery (2-3 years of length), send data, with a specific measurement step, to the gateway. The repeaters extend the signal in the school. The measurements are not registered in a data-logger or in computer located in the school, but they are directly transmitted to the ASCOTLC data-centre, where, by means of an open-source software called Mango, they are recorded and elaborated (Figure 4.14). This software can provide reports and graphs representing indoor parameters during a specific day or month. This technology is low-cost and efficient because it is possible to download internal measurements just from internet connection. The data transmission follows the standard Zigbee, based on the standard IEEE 802.15.4 (Wireless Personal Area Networks, WPAN), a technology that works under radio frequency, at 2.4 GHz, with a distance of no more than 100m. The sensors and the repeaters have been offered by Carel SPA. Electric energy consumption has been monitored since January 2008, while gas only since autumn 2008.

Figure 4.13 – Wireless sensor

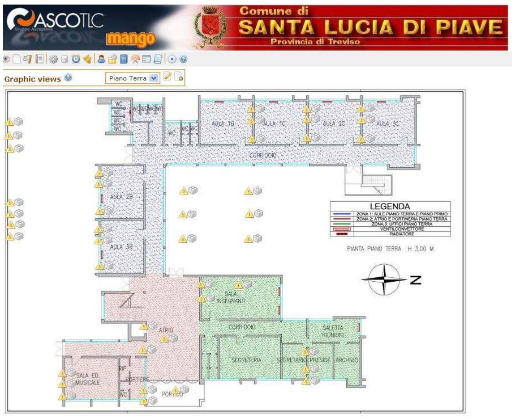


Figure 4.14 – Internet connection to school recorded data

4.2.3. Simulations

Based on the classroom geometry (Figure 4.15), daylight simulations were carried out for South and West orientation. The annual illuminance profiles in five points over each desk (Figure 4.17) have been calculated with DAYSIM.

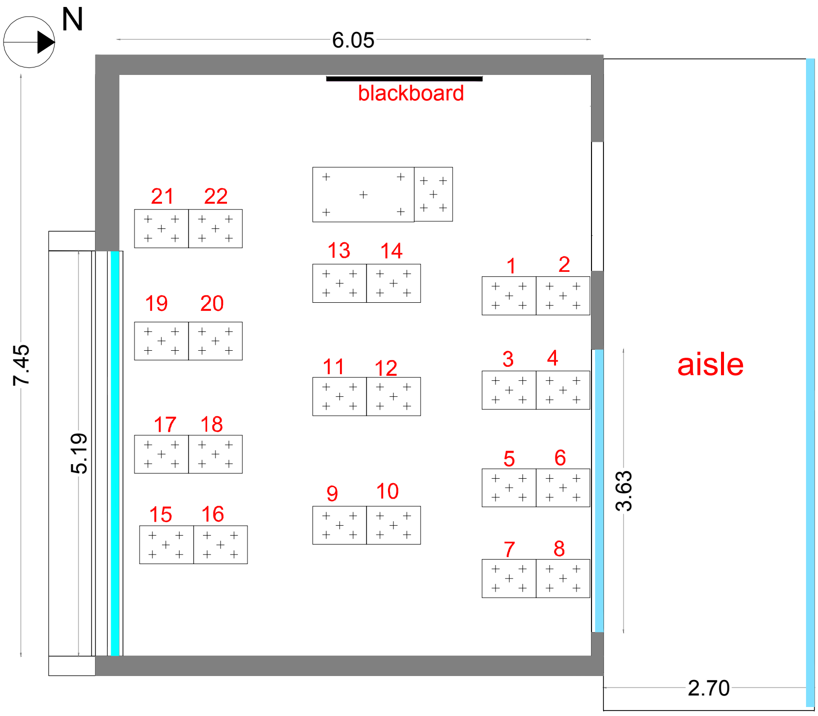
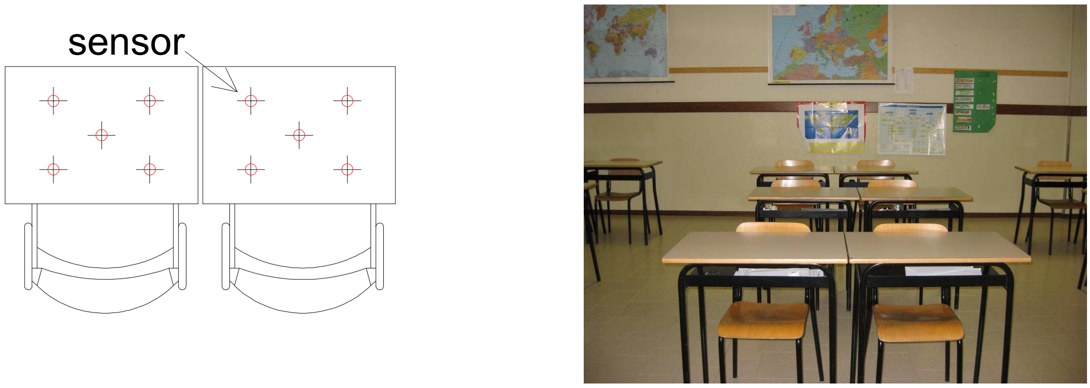


Figure 4.15 – Classroom South oriented plant

Some quick RADIANCE renderings of the South oriented classroom are reported in Figure 4.16. The scene refers to 21st March, 12:00 and the sky is supposed overcast.

Figure 4.16 – Quick RADIANCE renderings (21st March, 12:00, overcast sky)

The climate file used to start the DAYSIM simulation is a recreated EPW file, bringing the effective solar radiation of the academic year 2008/2009 (i.e. the months from September to December refer to year 2008, while the months from January to August refer to year 2009) provided by the ARPAV (local Environmental Agency) station located in Conegliano, a town near the analysed building. The available solar global hourly horizontal radiation has been then split into the normal beam and the horizontal diffuse radiation and finally a five minutes time step has been chosen to run the simulations.



(a) (b)

Figure 4.17 – Sensors position (a); classroom layout (b)

The classrooms have been modelled as empty rooms, to reduce calculation time, but the effective desks positions have been considered and reported in the sensor point file.

The aisle is part of the classroom scene because it contributes to provide daylight to the interior. The internal blinds have the slats 0.02 m long and the blinds down condition corresponds to the slats with a tilt angle of 45°.

The surface materials are described in the table below (Table 4.7).

Table 4.7 – Classroom material description

Building element	**Material description**
blackboard	plastic (2% diffuse reflection)
blind	plastic (50% diffuse reflection)
ceiling	plastic (70% diffuse reflection)
door	plastic (30% diffuse reflection)
floor	plastic (50% diffuse reflection)
frame	metal (24% RGB reflection, 30% specularity, 20% roughness)
glass	glass (83% visual transmittance)
ground	plastic (20% diffuse reflection)
wall	plastic (60% diffuse reflection)
window sill	plastic (50% diffuse reflection)

No external obstruction has been considered because the school is surrounded by a green area. The ground has been modelled as a disk with a radius of 30 m.

The non default DAYSIM simulation parameters are reported in Table 4.8.

Table 4.8 - DAYSIM simulation parameters

ambient bounces	ambient divisions	ambient accuracy	ambient resolution	direct threshold	direct sampling
7	1500	0.1	300	0	0

4.2.4. Comparison between old and new luminaries

In May 2009 the luminaries of two classrooms have been replaced (Figure 4.18); the new ones are equipped with a high frequency regulator and a lux sensor, in order to dim the luminous flux according to measure indoor lighting conditions. The maximum luminous flux has been set in blinds down shading condition.


(a) (b)

Figure 4.18 – Lighting appearance with the old luminaries (a) and with the new ones (b).

The horizontal illuminance on the desks, before and after luminaries replacement, has been measured with a lux meter, with a great improvement in lighting quality and in illuminance values (Figure 4.19). The desks numbers are reported in Figure 4.15.
From the graph in Figure 4.19 it can be noticed that the illuminance over the desks provided by the old luminaries was under 300 lux (which is the minimum illuminance required by the Standard UNI 10840), while, with the new ones, the illuminance is over 400 lux for almost all the desks. Moreover, the lighting appearance of the classrooms is become more pleasant (Figure 4.18).

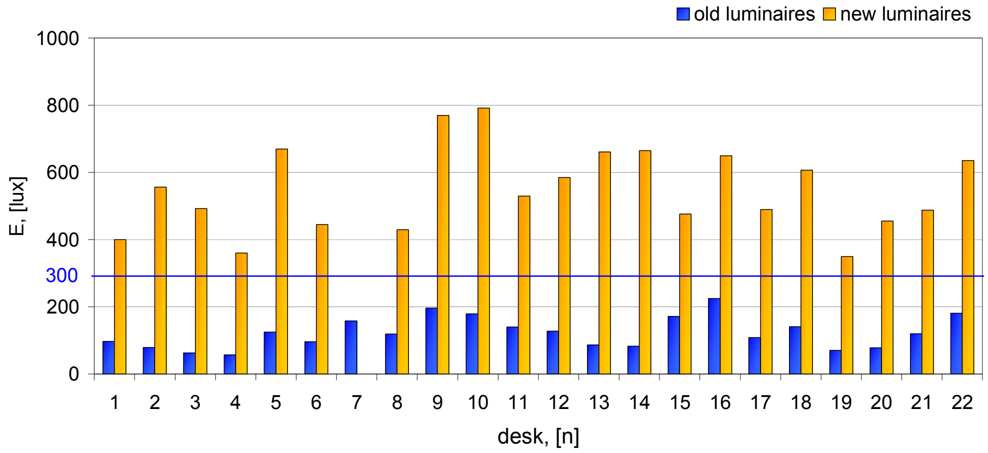


Figure 4.19 – Measured illuminnace over the desks before and after luminaires replacement

4.2.5. Recorded illuminance values

The following figures show the vertical illuminance profiles recorded in January 2009, with a time step of three minutes. The sensor is put along the wall close to the door for South orientation and beside the blackboard for West orientation, therefore the sensor faces South in both cases.

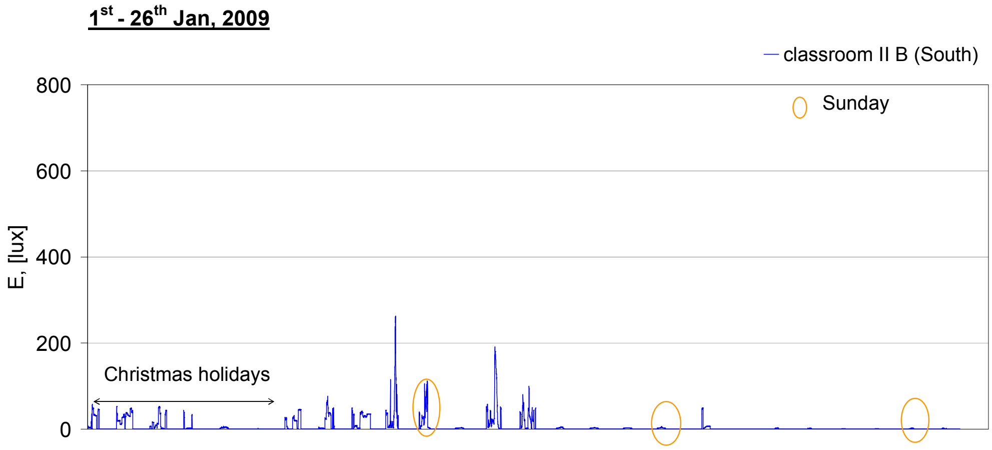


Figure 4.20 – Vertical illuminance recorded in January 2009, in one classroom facing South (classroom II B)

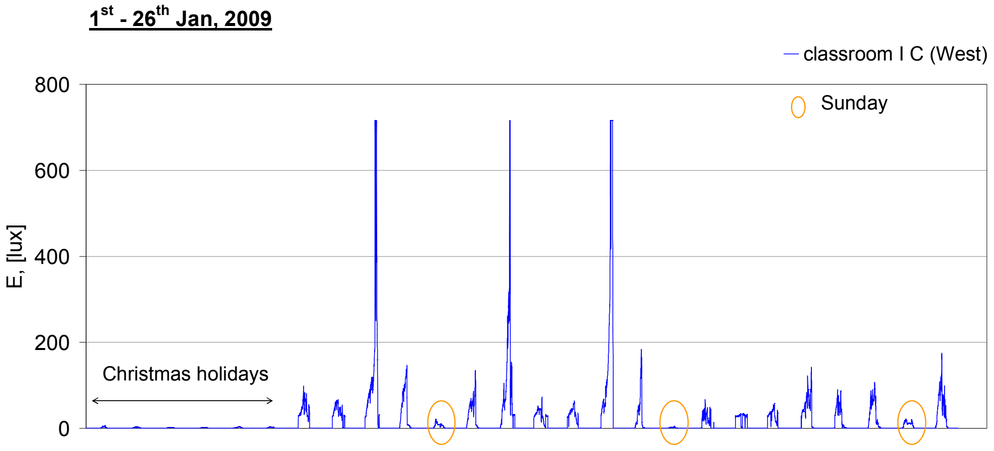


Figure 4.21 – Vertical illuminance recorded in January 2009, in one classroom facing West (I C)

It can be noticed that in general the illuminance values are higher in West condition than in South one, but this does not occur from 1st to 6th of January, when nobody was at school because of Christmas holidays. Considering electric light contribution to the overall recorded illuminances, this can be explained because the sensor put near the blackboard is more influenced by electric light than the one located near the door. Moreover, in West orientation, especially in winter, the need to switch on the light to improve lighting level is higher than in the South one.

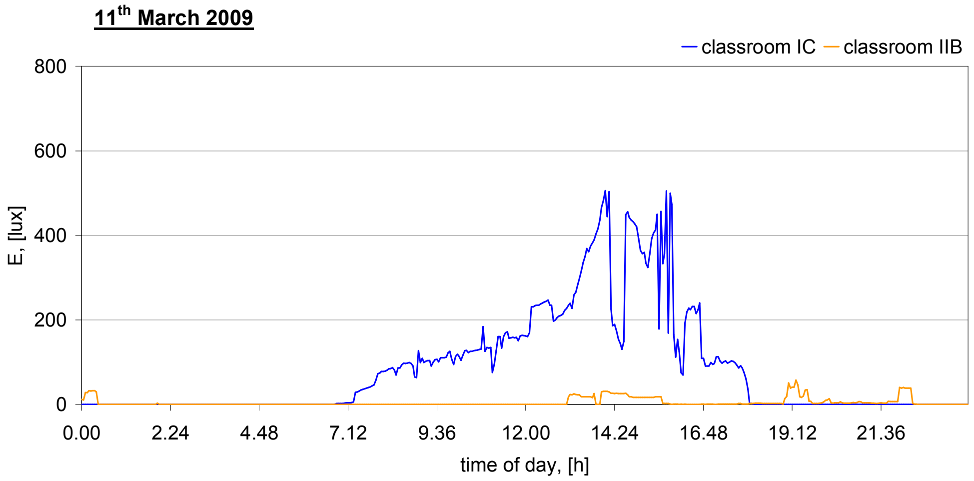


Figure 4.22 – Vertical illuminance recorded in 11th March 2009, in one classroom facing South (III B) and in one facing West (I C)

4.2.6. Comparison between electrical energy consumption and available solar radiation

The electrical energy consumption of the school has been compared to the available solar radiation, in order to analyse if an increase in solar radiation corresponds to an electrical energy reduction. It must be taken into account that the recorded energy consumption includes not only electric lighting, but also the energy required by the heat pumps and other electrical facilities (i.e. computers, photocopier, etc.).

The graph in Figure 4.23 refers to February 2009: the Sundays (e.g. 8th February) can be easily identified because of low electrical consumption.

Considering for example Tuesday 10th, compared to Tuesday 24th, it can be noticed that an increase in available solar radiation corresponds to a lower electrical energy demand. This does not happen every time: in fact, considering Tuesday 24th and Thursday 26th, the available solar radiation is the same, but the energy consumption is twice for the 26th.

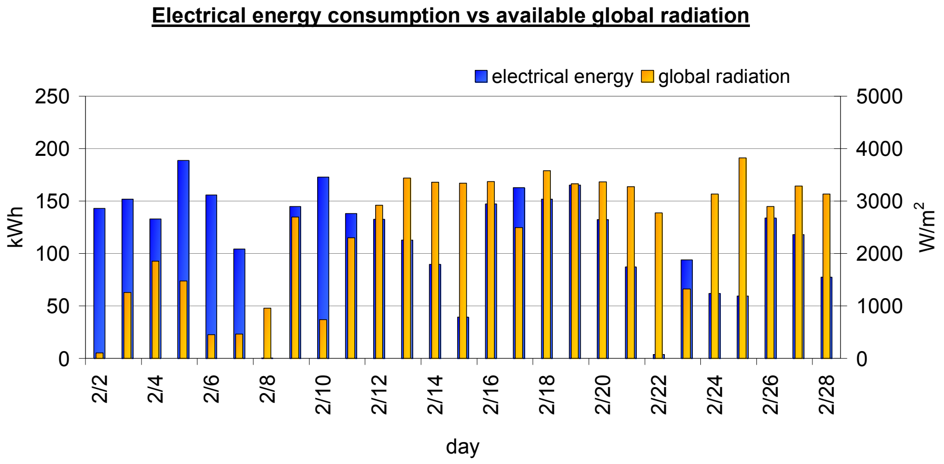

Electrical energy consumption vs available global radiation

Figure 4.23 – Comparison between electrical energy consumption and available solar radiation (February 2009)

In conclusion, occupants do not care about daylight availability and they switch on the light even if the required lighting level can be obtained by daylight alone. Moreover often, in schools, all the lights in the classrooms are turned on in the morning and a possible resetting of the electric lighting can take place only in break time. The electric energy saving can be therefore obtained only with a lux sensor and dimmable luminaries in order to dim the luminous flux according to available daylighting levels.

4.2.7. Comparison between measured and calculated illuminance values

The illuminance over the desks in daylight condition has been measured with a lux meter (Minolta CL200). The Figure 4.24 shows the comparison between the measured values with the simulated ones. These values refer to 11th March 2009, a sunny day, it was 16:00 and the classroom faces West.

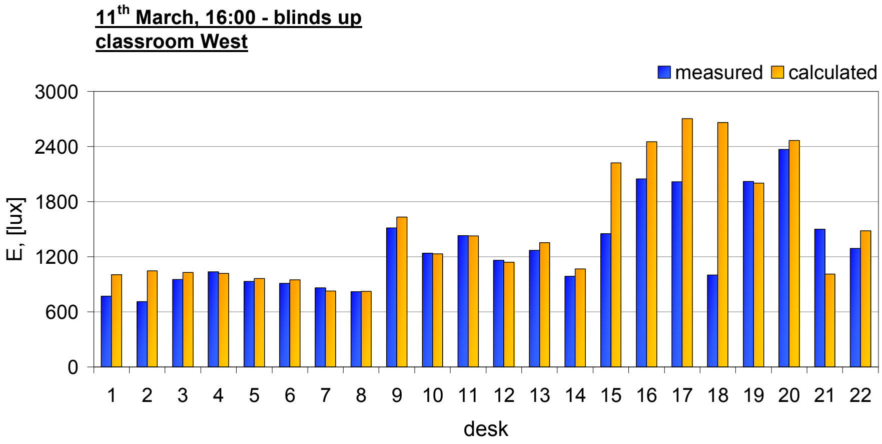


Figure 4.24 – Comparison between measured and calculated illuminance values

From Figure 4.24 it can be noticed that the calculated illuminances correspond to the measured ones, except for the ones related to the desks close to the windows.

4.2.8. Analysis of daylight availability by means of UDI dynamic performance metric

The annual illuminance profiles calculated with DAYSIM have been used to calculated some UDI indexes. As already explained in chapter 3, this dynamic index predicts if the available daylight can be useful for occupants or can be responsible of glare occurrence. DAYSIM gives three possible UDI ranges (UDI<100, 100<UDI<2000 and UDI>2000): the medium one (100<UDI<2000) includes a n extremely high range of values, therefore it would be advisable to split this range in two or more intervals. Moreover, the occupancy schedule used by DAYSIM is referred to an office building, therefore it cannot be applied to this kind of buildings. Some UDI indexes have been then calculated for the two analysed classrooms, even if the classrooms have been added as a second building type to Lightswitch Wizard, (Reinhart, 2004), in this work UDI indexes have been calculated with a specific spreadsheet macro, in order to leave the possibility to change the input required (e.g. the occupancy profile).

In this specific case, two different occupancy schedule are considered:

- Without after school: class starts, from Monday to Saturday, at 8:00 in the morning and it finishes at 13:00
- With after school: class starts, from Monday to Friday, at 8:00 and it finishes at 16:00

The lunch break occurs from 13:00 to 14:00 and holidays and not only Sundays are taken into account. From the two set of annual illuminance profiles (one with the shading up and one with the shading down) six UDI indexes have been calculated, for both the occupancy schedules (i.e. with and without after school):

- UDI<100: a high percentage of this value means that the electric light is necessary to reach sufficient lighting levels
- 100<UDI<300: this percentage is useful if the luminaries are dimmable, because it is possible to save energy due to an available free lighting level
- 300<UDI<500: this range corresponds to the one required by the Standards
- 500<UDI<1000: this range indicates a great daylight availability
- 1000>UDI<2000: this range is related to a very bright environment,
- UDI>2000: illuminance over 2000lux can lead to glare occurrence

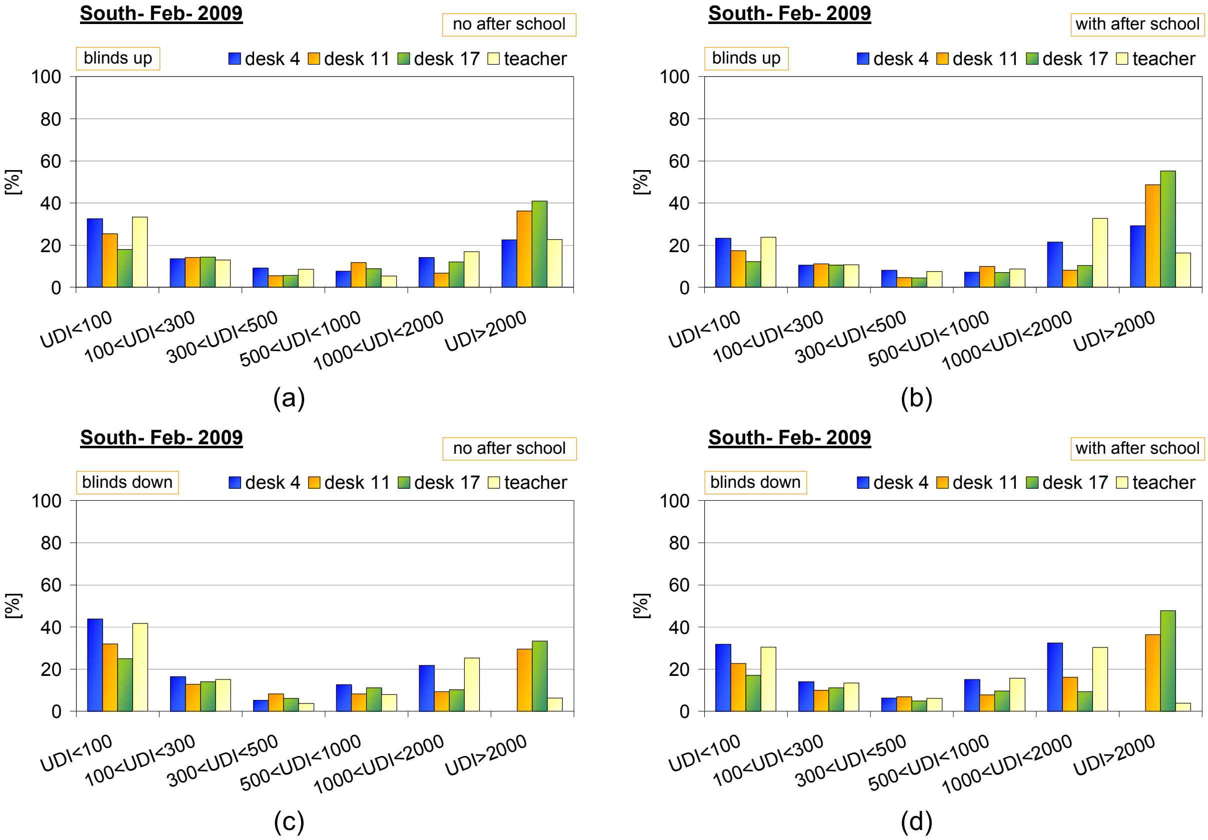
The bar charts from Figure 4.25 to Figure 4.32 show these six ranges of UDI values that have been monthly calculated for four specific desks positions (Figure 4.17):

- Desk 4: it represents the desks farthest from the window
- Desk 11: it is representative of the desks in the middle of the classroom
- Desk 17: it represents the desks closer to the windows
- Teacher’s desk: usually the teacher decides on the settings of the electric lighting system to asses the visual environment in the classroom, therefore he can decide to switch on the light if the illuminance over his desk is insufficient.

The calculated annual illuminance profile refers to the academic year 2008/2009 therefore the occupancy schedule is referred to that year. The UDI indexes are reported for four representative months of the academic year: February 2009, May 2009, October 2008 and December 2008. The “blinds down” condition corresponds to the blinds with the slats at 45°.

Classrooms South oriented

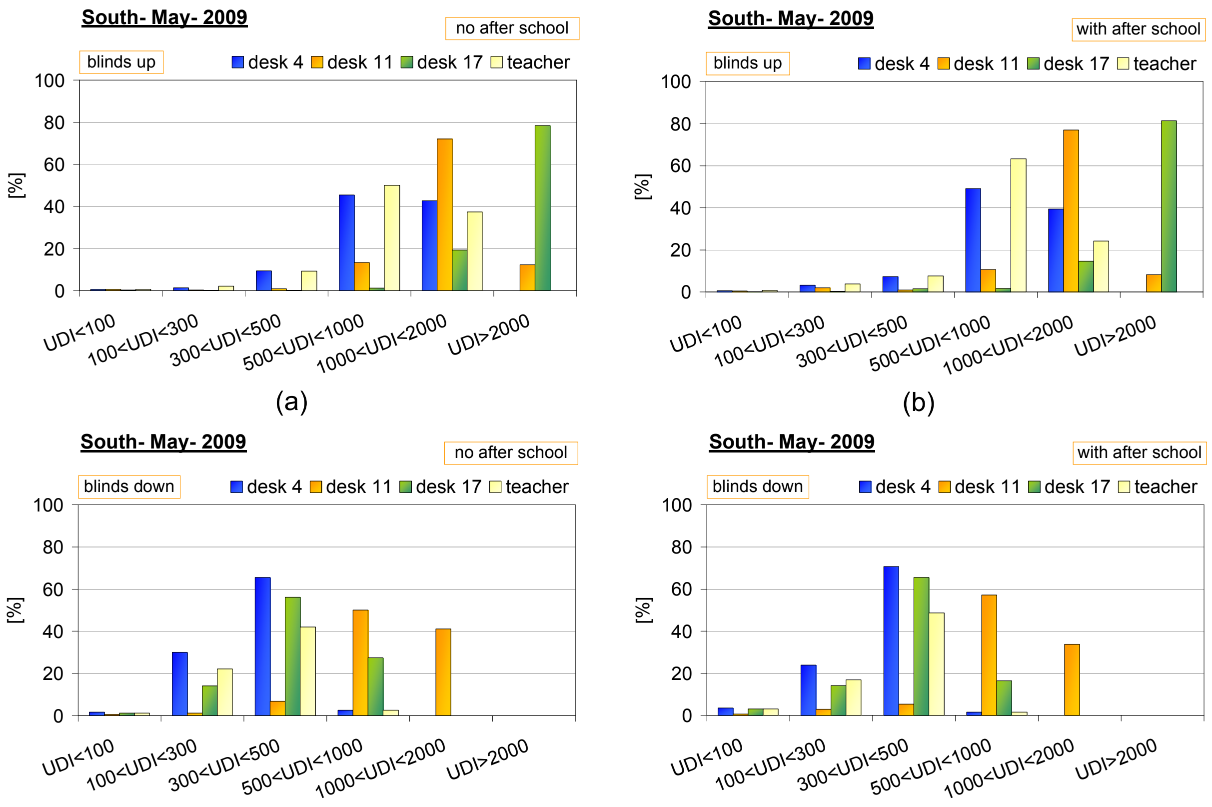
The UDI values for a representative classroom facing South are reported from Figure 4.25 to Figure 4.28.



(a) (b) (c) (d)

Figure 4.25 – Calculated UDI values in February 2009. South orientation. Blinds up, with (a) and without (b) after school; blinds down with (c) and without (d) after school

In February (Figure 4.25) UDI_{2000} values can reach very high levels (over 50%) in the desks close to the windows (desk seventeen) or in the middle of the classroom (desk eleven) and even if the blinds are down this percentage is only 10% less. This means that the blinds need to be fully closed, due to low solar altitude. In the desks far from the windows (i.e. desk 4) over the 30% of the month there is insufficient lighting levels even if the blinds are fully up: this percentage becomes around the 45% if the blinds are closed (and this condition is necessary 40% of the month, otherwise glare would appear). No significant differences can be noticed between the two occupancy schedules, even though the one with after school has more available daylight.

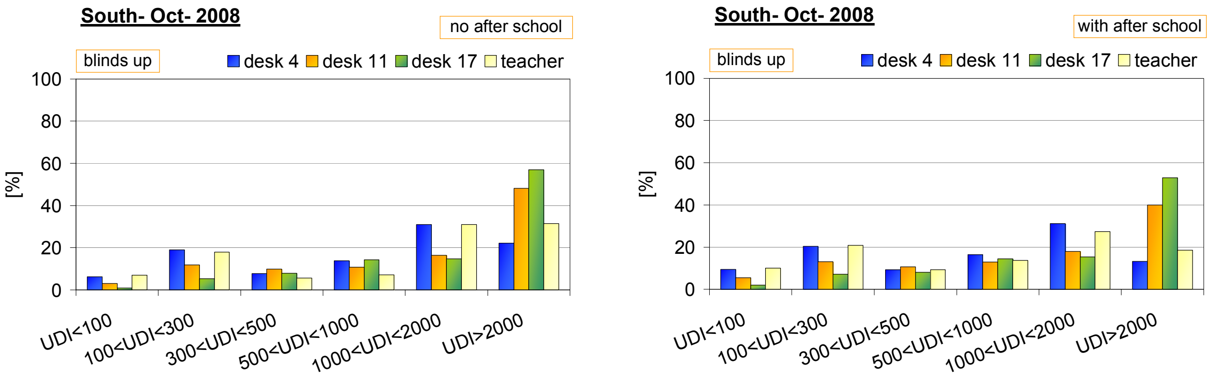


(a) (b)

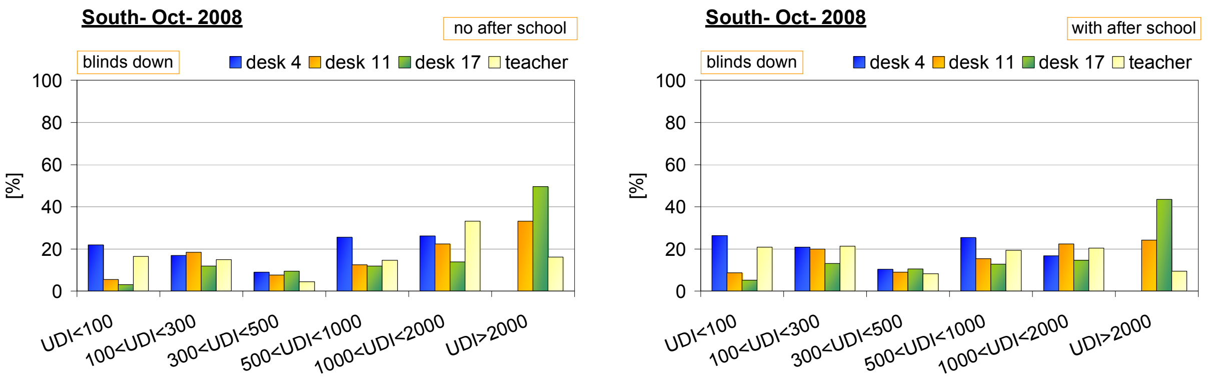
(c) (d)

Figure 4.26 – Calculated UDI values in May 2009 . South orientation. Blinds up, with (a) and without (b) after school;, blinds down with (c) and without (d) after school

In May, glare would appear the 80% of the time in the desks close to the windows if the blinds are retracted, therefore the blinds will be frequently closed. In blinds down condition there are not illuminance values over 2000 lux and for the 70% of the time no electric light is needed (in the desks far from the windows, the $UDI_{100-300}$ is around the 30%).



(a) (b)

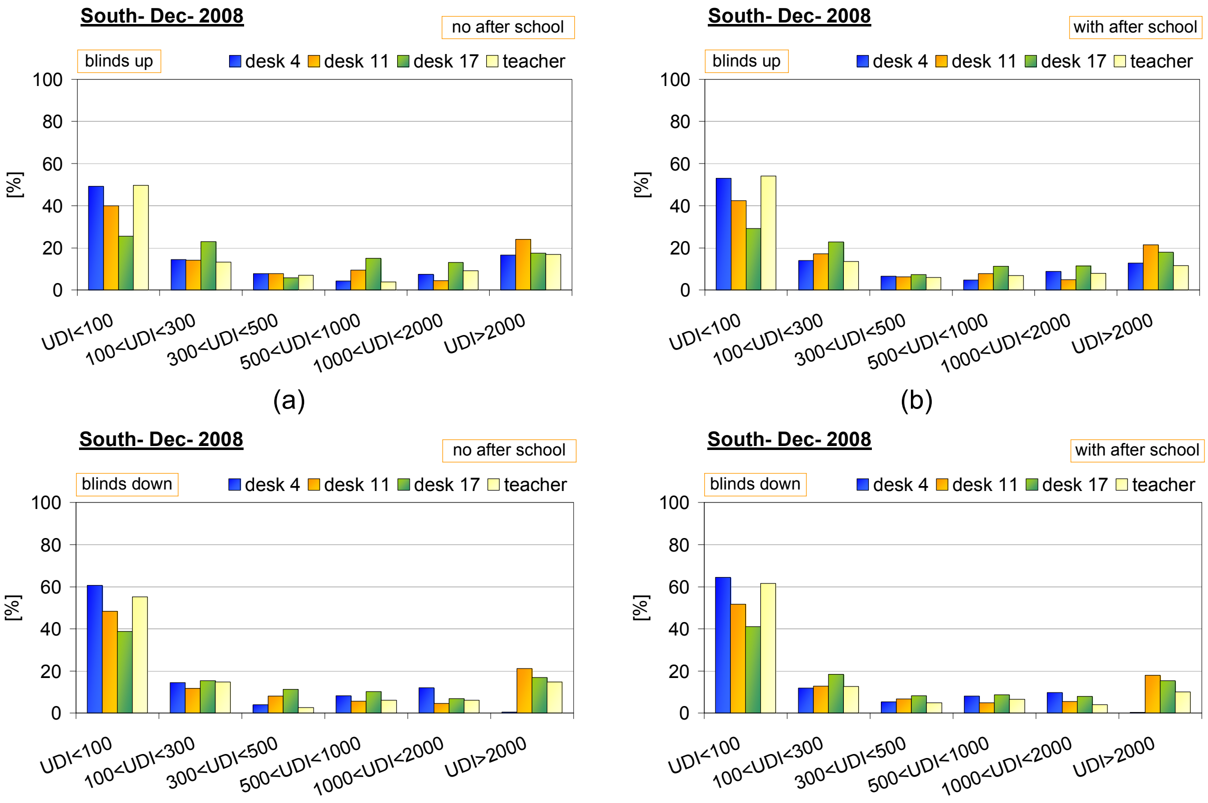


(c)

(d)

Figure 4.27 – Calculated UDI values in October 2008. South orientation. Blinds up, with (a) and without (b) after school;, blinds down with (c) and without (d) after school

In October there are the same problems, concerning glare appearance, that occur in February, but there is a low percentage of UDI_{100}, therefore there will be a lower electrical energy consumption for lighting.



(a)

(b)

(c)

(d)

Figure 4.28 – Calculated UDI values in December 2008. South orientation. Blinds up, with (a) and without (b) after school;, blinds down with (c) and without (d) after school

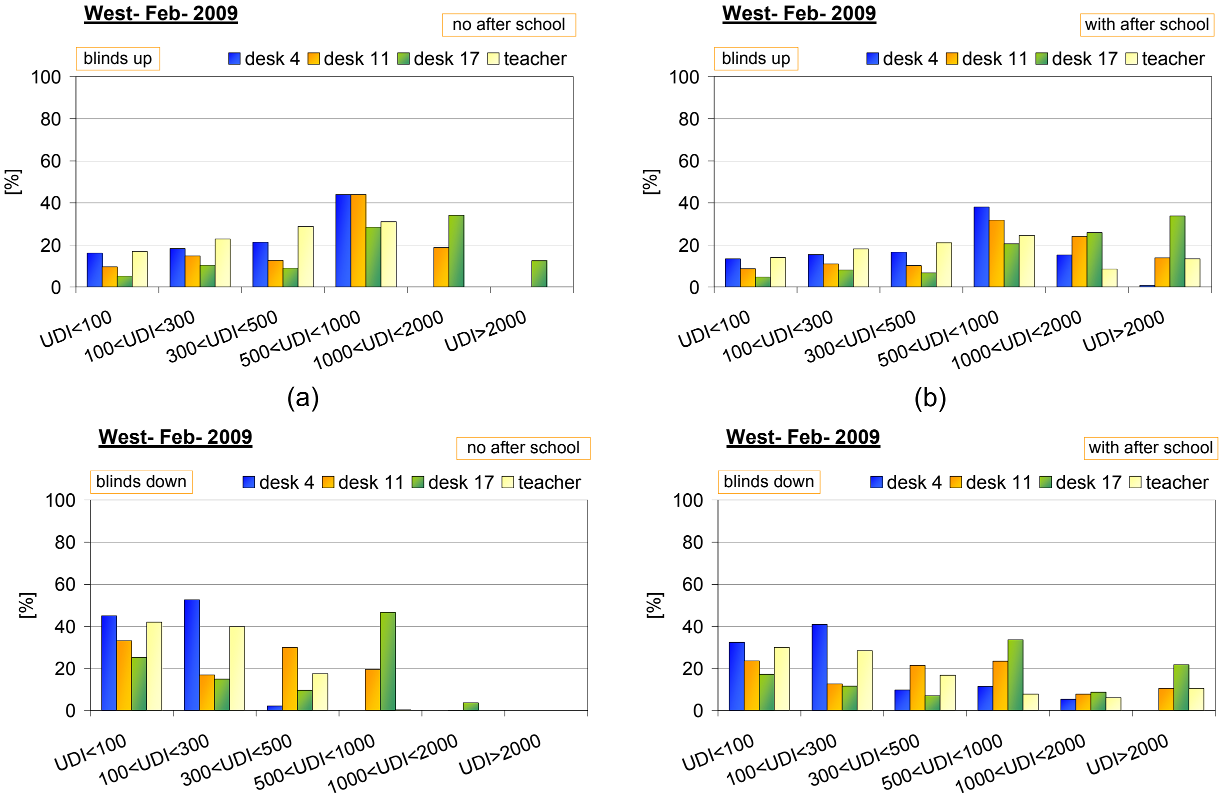
Finally, in December, UDI_{100} values are more than 50% in “blinds up” condition and more than 60% with the blinds down. Moreover, glare would appear for almost the 15% of the time in all the analysed desks in “blinds up” condition and even in “blinds down” one for the desk close to the windows and in the middle of the classroom.

Like for all the analysed months no significant differences can be appreciated between the two occupancy schedules, because of South orientation.

Classroom facing West

The same UDI values are presented from Figure 4.29 to Figure 4.32 for West orientation.

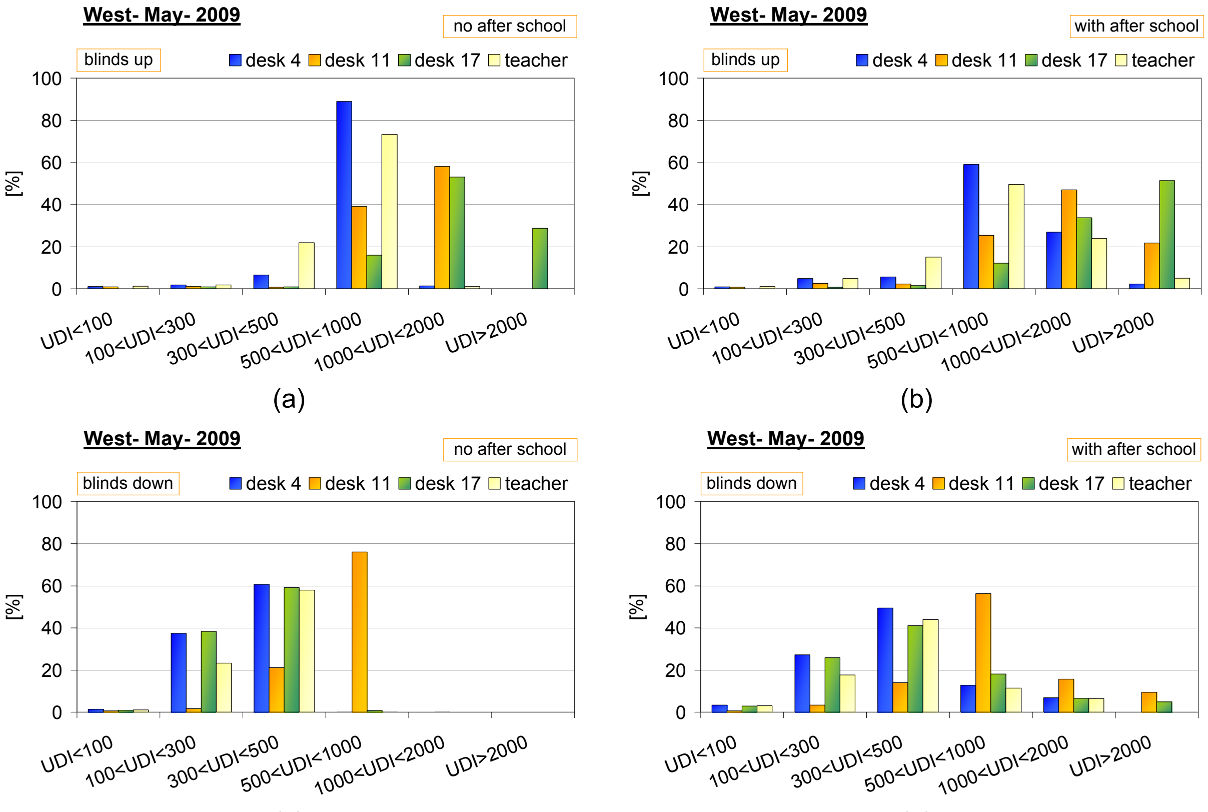
In February only the desks close to the windows can perceive glare for the 15% of the time in “no after school” condition, while all the classroom, except the desks far from the windows, is characterized by UDI_{2000} values (around 15%). Even with the blinds down glare is not avoided, for the same problem explained for South orientation, but the UDI2000 values are 20% at most, while, for the West one, they are around 60%.



(a) (b) (c) (d)

Figure 4.29 – Calculated UDI values in February 2009. West orientation. Blinds up, with (a) and without (b) after school;, blinds down with (c) and without (d) after school

Despite of what happens in classrooms facing South, the UDI values considering the “*with after school*” schedule, are higher than the ones in “*no after school*” one, except in winter, when there is a low solar radiation available in the afternoon. This difference becomes significantly high in May (Figure 4.30) , where all the analysed desks present a percentage of UDI_{2000}, considering the pupils' occupancy even in the afternoon.

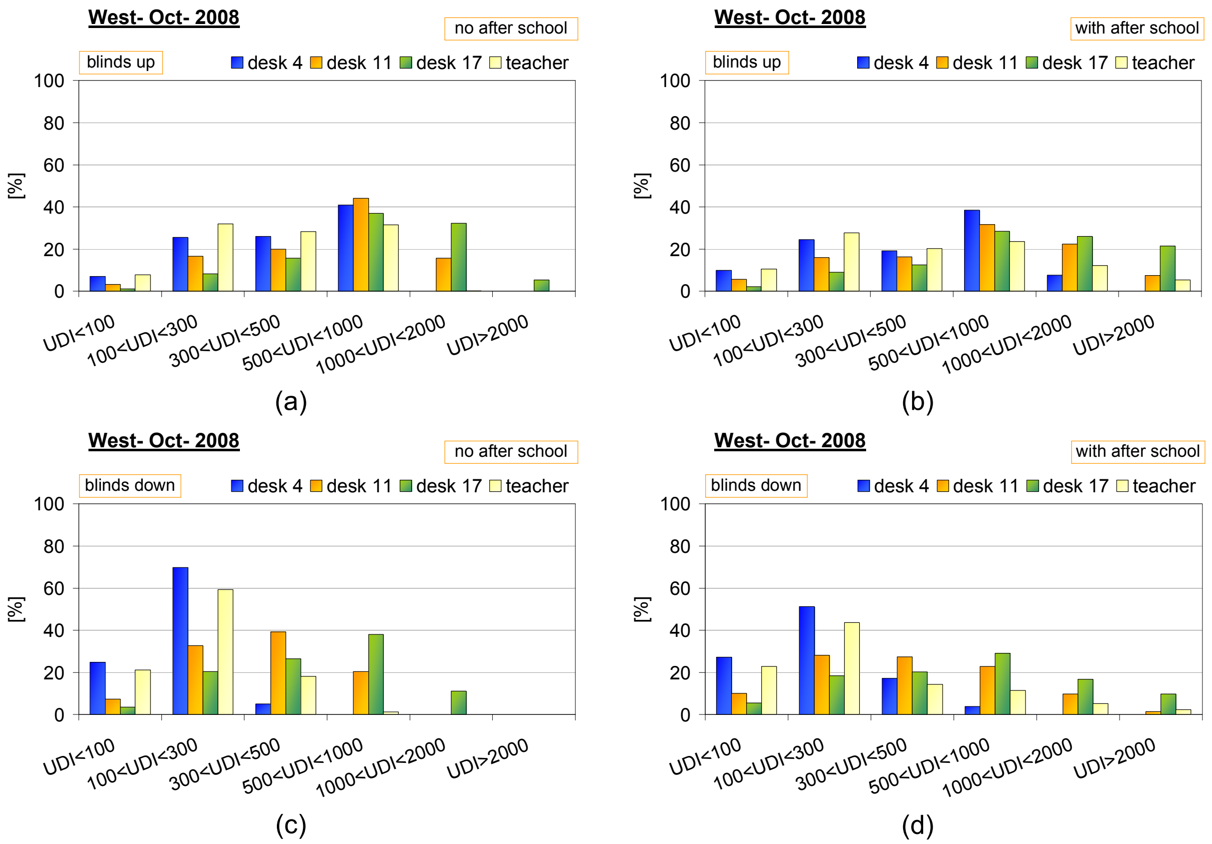


(a) (b)

(c) (d)

Figure 4.30 – Calculated UDI values in May 2009. West orientation. Blinds up, with (a) and without (b) after school;, blinds down with (c) and without (d) after school

In October (Figure 4.31) all the classroom can be autonomous in terms of lighting for almost the 60% of the month (considering both UDI $_{300\text{-}500}$ and $UDI_{500\text{-}1000}$. Glare would appear for the desks close to the windows for the 20% of the time with the blind retracted, while, in "*blinds down*" condition this problem is noticed only in this part of the classroom and it is reduced to 10%.

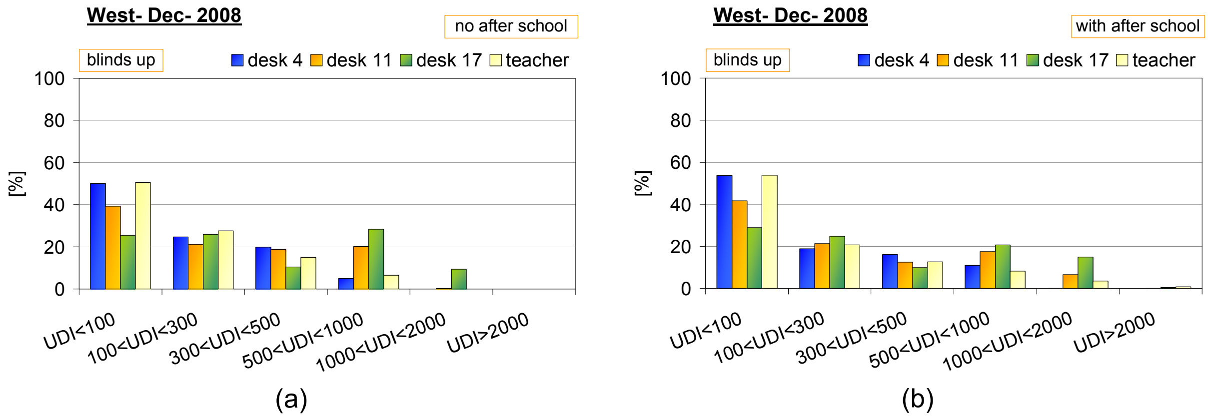


(a) (b)

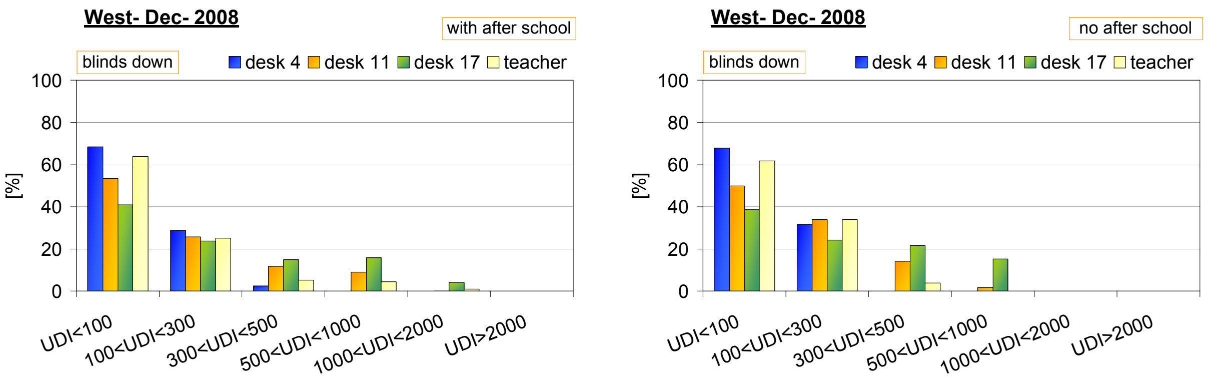
(c) (d)

Figure 4.31 – Calculated UDI values in October 2008. West orientation. Blinds up, with (a) and without (b) after school;, blinds down with (c) and without (d) after school

Finally, in December, the light will be switched on most of the time due to low lighting levels (more than 70% of the time, considering both UDI100 and UDI100-300). No glare appearance would be perceived in any part of the classroom, for both "*blinds up*" and "*blinds down*" conditions.



(a) (b)



(c) (d)

Figure 4.32 – Calculated UDI values in December 2008. West orientation. Blinds up, with (a) and without (b) after school;, blinds down with (c) and without (d) after school

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Chapter 5

Simulation versus monitoring campaign in an office building

In Chapter 4, some preliminary lighting analysis carry out with the software DAYSIM have been shown: those case studies are useful to understand assumptions and possible results of the software. Many simulations of theoretical offices have been considered, taking into account different orientations, different glazing transmittances and different shading devices (such as venetian blinds, light-shelves, curtains). The purpose was to see how daylight penetration changes according to shading type and condition (up or down) for calculating illuminance and luminance values. Some dynamic performance metrics have been also calculated to know, for example, how much a building could be considered autonomous for lighting (daylight autonomy) and the range of annual illuminance values (UDI) to determine when daylight levels are suitable for the occupant or when the environment appears too dark (<100 lux) or too bright (> 2000 lux) and glare would appear. Finally different lighting and blind strategies (i.e. switch off sensor, dimmer, etc.) and human behaviour (passive, mixed and active) have been combined to find the solution which lowers more electrical energy. The present chapter goes a step further: it describes the problems (i.e. the model construction the surfaces characterisation and the occupant behaviour) that occur when an existing building, instead of an ideal one, has to be simulated.

5.1. Simulations versus monitoring campaign

The problems to face when making a comparison between simulations and a measurement campaign involve many different aspects:

- the optical properties of the offices surfaces cannot be supposed, but they should be measured;
- the available EPW climate files do not correspond to the period in which the measurements have been carried out, so any comparison can be drawn out;
- the setting of the blinds and the time when the luminaries are switched on or off are not usually known;
- the human behaviour is unpredictable.

All these aspects will be analysed in the following work.

5.2. Case study

The analysed office building is an eight floor tower located in the industrial area of Padua. Climatic conditions are characterized by hot and humid summers and short but cold winters. The building has over than 1000 m^2 of glazed area which covers all the orientations except the North one.

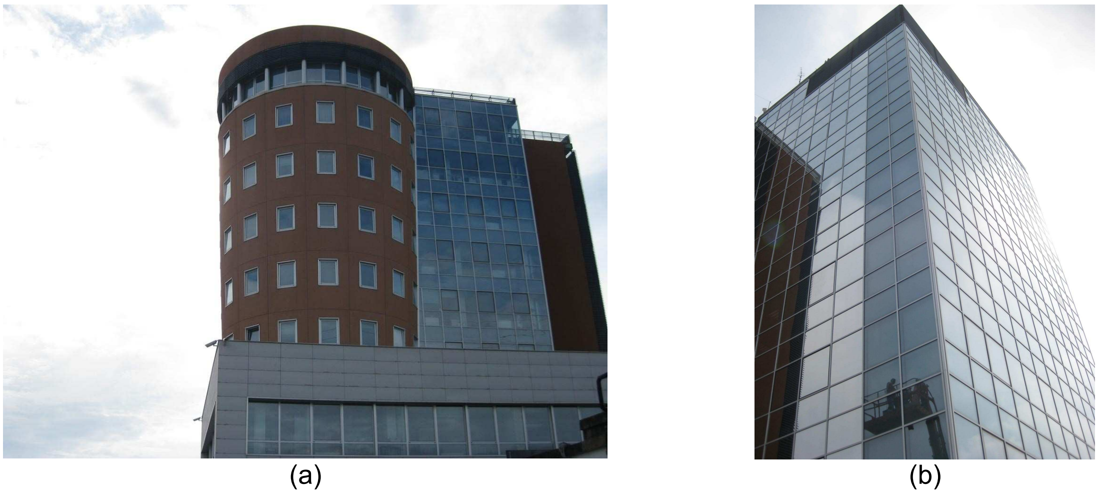

(a) (b)

Figure 5.1 - Tower exterior before (a) and after (b) retrofitting

About the 80% of this façade has been externally covered by a reflective film (Figure 5.1) because occupants complained about overheating, comfort and glare problems. Façade characteristics before and after intervention are reported in Table 5.1.

Table 5.1 – Façade characteristics

Pre-intervention glass;	U = 1.2 W/(m^2 K); g = 0.41; VT = 59.3
Post-retrofit glass;	U = 1.2 W/(m^2 K) ; g = 0.12; VT = 13.6

5.3. Measuring campaign

All the tower, except the offices facing North, has been monitored in terms of air temperature, humidity and illuminance. The measuring campaign has been running since May 2009: 12 sensors (Figure 5.2), which measure relative humidity and air temperature, have been located in each level of the Tower. From July some other sensors (Figure 5.3) are recording not only the same microclimatic parameters, but also illuminance value over some offices work planes. From 18th November the lighting analysis has involved only two rooms, one double office located at the 4th floor and a single office located at the 6th floor. One illuminance value cannot describe the lighting availability of a space; therefore two or three sensors have been put over the work plane and one for each vertical wall, at eye level, in order to measure vertical illuminance.

Figure 5.2 – TyniTag sensor

Figure 5.3 – HOBO U12 sensor

5.3.1. HOBO sensors

The sensor used to measure illuminance is the HOBO U12. It is a wireless sensor which records also air temperature and relative humidity with different time steps.

The illuminance measurements recorded by the HOBO sensor have been compared to the ones recorded by another lux-meter, the Minolta CL200 (Figure 5.4).

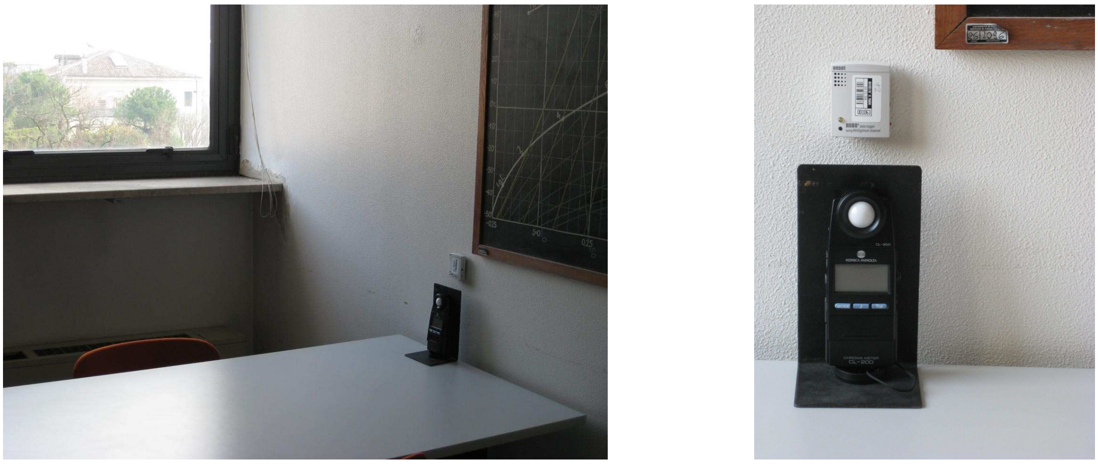
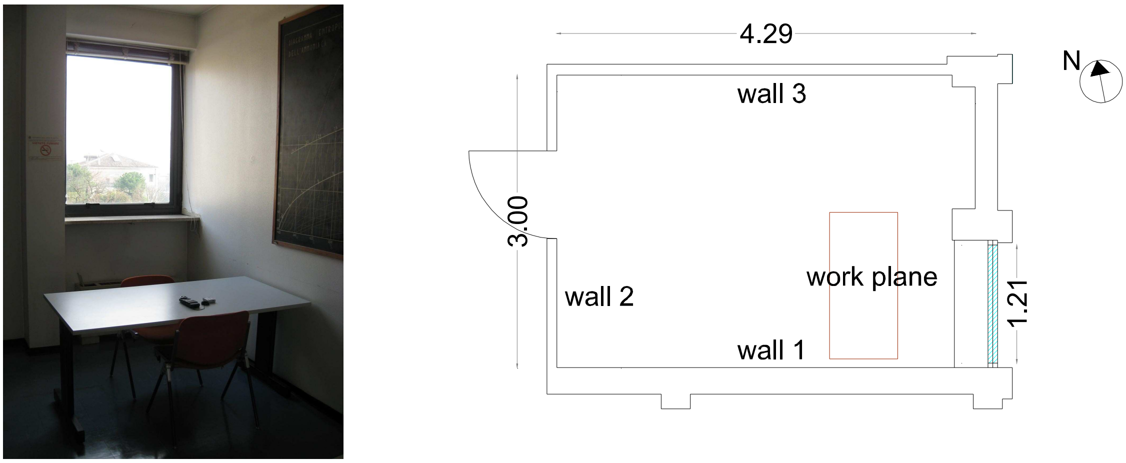


Figure 5.4 – Comparison between Minolta CL200 and HOBO instruments

The comparison took place from the end of November 2009, in an office, equipped as a test-room, of the Department of Applied Physics of Padua (Figure 5.5).



(a) (b)

Figure 5.5 – Test room (a); test room plant (b)

The room has only one window, South-East oriented, and no significant obstructions are present.

The measurements took place changing many different parameters:

- position of the sensor: horizontal (at work plane level) and vertical (in three perimeter walls)
- time of day
- sky condition (overcast, intermediate and clear)
- lighting condition (daylight only, electric light only and the combination of them)

Some of the more interesting results are shown in the Figures below.

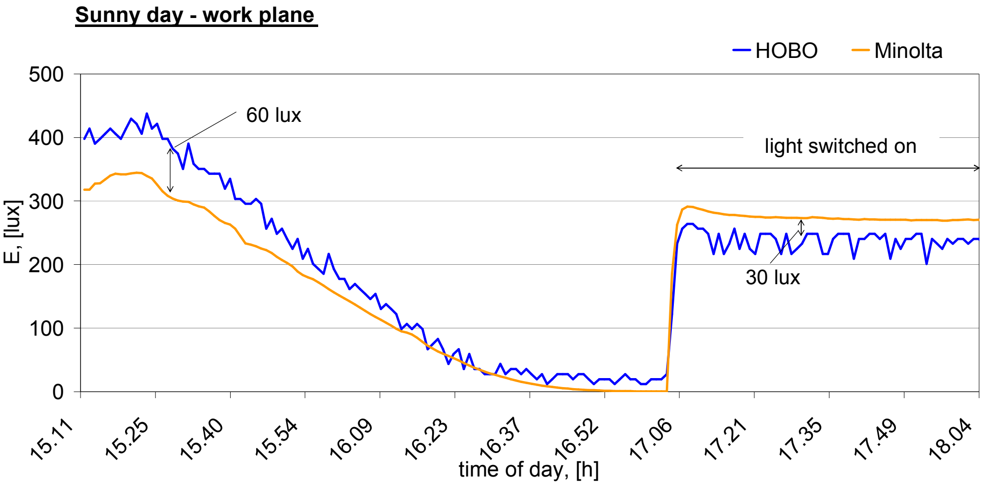


Figure 5.6 - Comparison between HOBO and Minolta recorded illuminance values over the work plane (Figure 5.5) in 1st December 2009 (sunny day)

The HOBO recorded illuminances over the work plane are almost the same than the ones recorded by the Minolta. In daylight conditions, the HOBO ones are 60 lux higher at most, while if electric light is switched on, Minolta illuminances are about 30 lux higher.

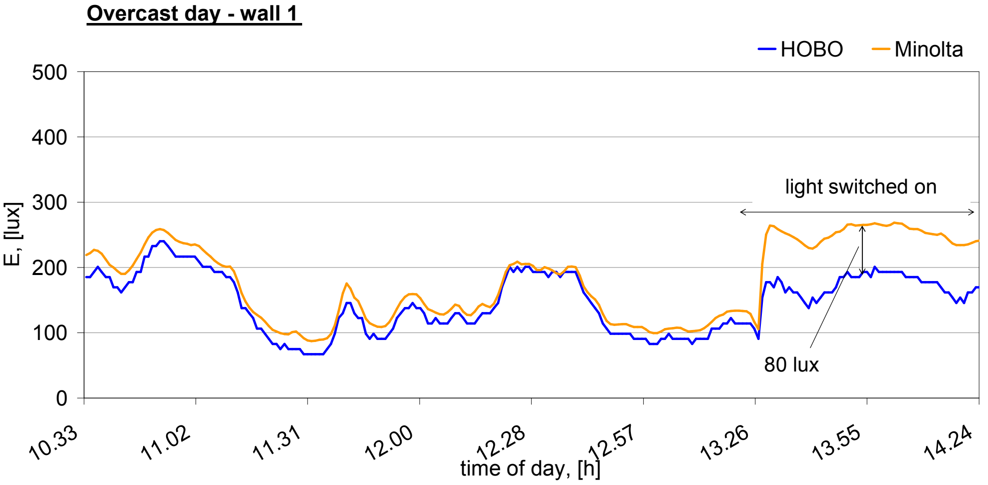


Figure 5.7 - Comparison between HOBO and Minolta recorded illuminance values in wall 1 (Figure 5.5) in 30th November 2009 (overcast day)

The illuminances recorded in wall 1 (Figure 5.7) are almost the same in overcast sky condition and with light switched off. If lighting is on Minolta registers about 80 lux more.

The following graphs show the comparison between the two instruments in sunny sky condition, since no significant differences have been found in overcast days.

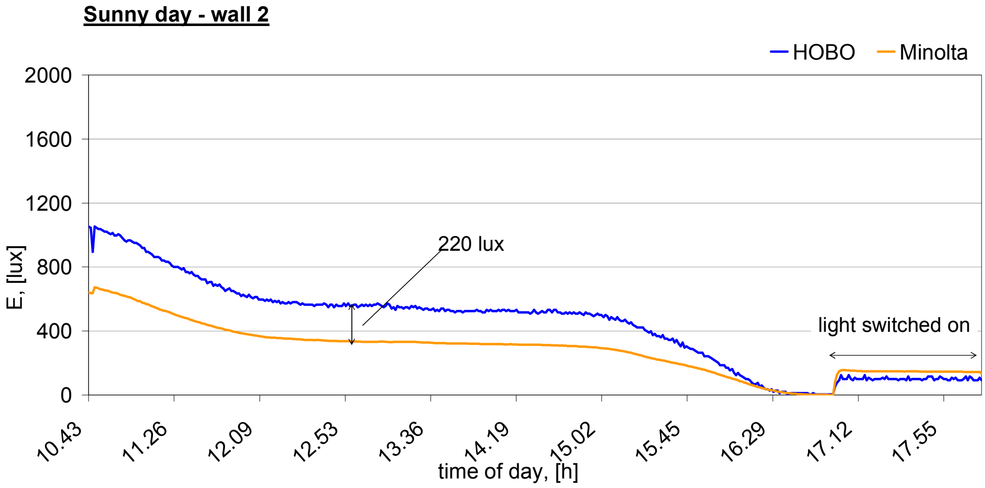


Figure 5.8 - Comparison between HOBO and Minolta recorded illuminance values in wall 2 (see Fig. 4.7) in 9th December 2009 (sunny day)

In a winter sunny day and in daylight conditions, HOBO sensor measures about 200 lux more than the Minolta in the wall in front of the window (wall 2), while, if the light is on, Minolta lux meter records 50 lux more.

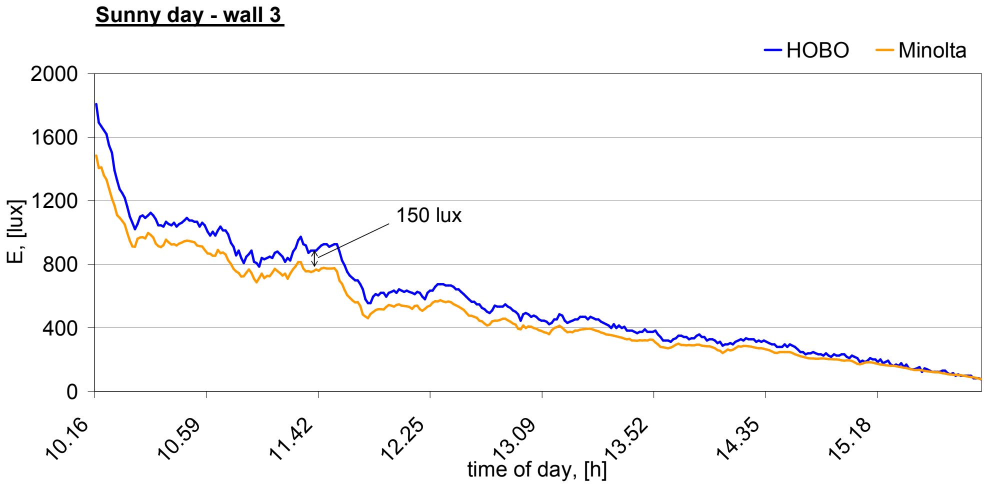


Figure 5.9 - Comparison between HOBO and Minolta recorded illuminance values in wall 3 (Figure 5.5) in 3rd December 2009 (sunny day)

The difference between illuminance values measured in wall 3 is around 150 lux, but when the illuminance is under 200 lux no significant difference can be appreciated (Figure 5.9).

If the sensor is hit by direct radiation (Figure 5.10), differences between the two instruments can be very high (even 13000 lux).

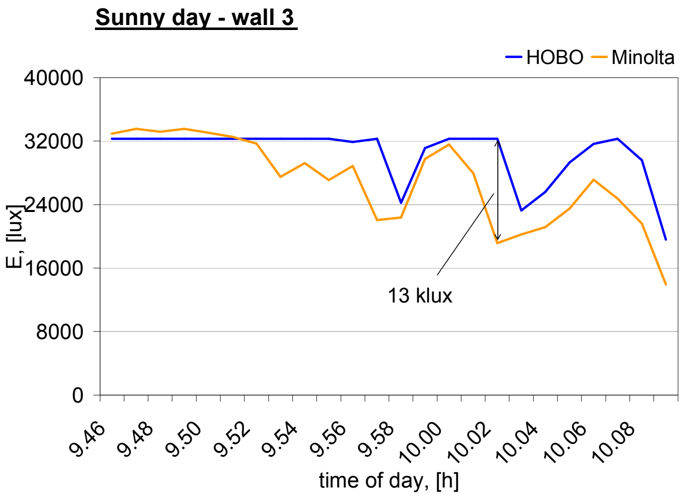


Figure 5.10 - Comparison between HOBO and Minolta recorded illuminance values with direct beam radiation hitting the sensor. Wall 3 (Figure 5.5) in 3rd December 2009 (sunny day).

From the graphs above, some conclusions can be carried out:

- the illuminance profiles recorded by the Minolta sensor are more homogeneous then HOBO ones;
- the behaviour of the two illuminance sensors is different according to lighting conditions: in daylight conditions, HOBO values are higher than the Minolta ones; if electric light is switched on, Minolta has higher values than HOBO;
- for low lighting levels (under 200 lux), the two instruments measure almost the same values, while the difference becomes significant as the lighting level increases;
- in horizontal position, no significant differences can be appreciated.

5.4. Building model construction

The analysed offices have been modelled according to real dimensions, paying attention to windows' frames, in order to define the ratio between the opening and the glazed area, and to the furniture (table, bookshelves), which has been geometrically simplified, to reduce calculation time.

5.4.1. Double office

The office located in the 4th floor, characterized by full glazed façade South-East oriented, has been simulated as a box shaped office (Figure 5.11), positioned at its effective height (14.6 m). It is equipped with grey roller blinds, manually operated. Six sensors have been positioned in the double office: two over the work plane (H9 and H10), one in vertical position beside the computer (H7) and three (H5, H8 and H11) at eye level, along the perimeter walls (Figure 5.12).

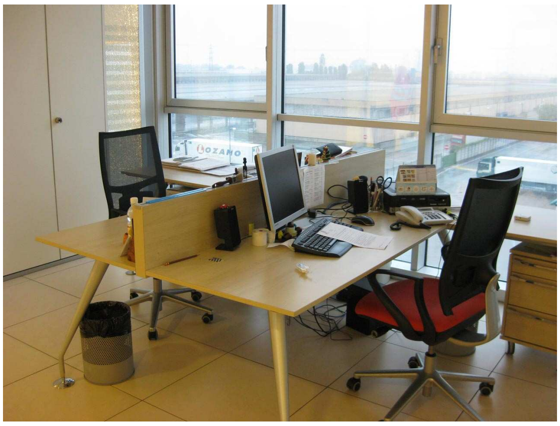


Figure 5.11 – Double office

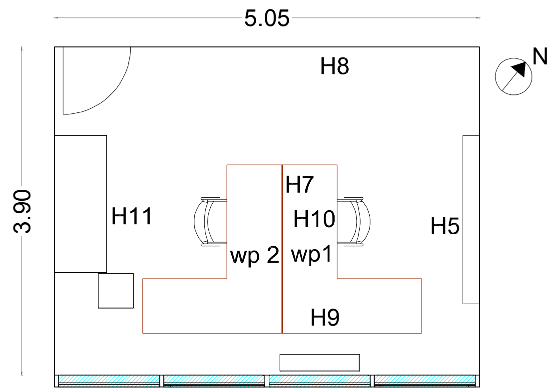


Figure 5.12 – Double office: sensors position

The partition walls are made of glass, therefore the model takes into account also the 2 side offices and the aisle (Figure 5.13). The ground has been modelled as a disk with a radius of 60 m.

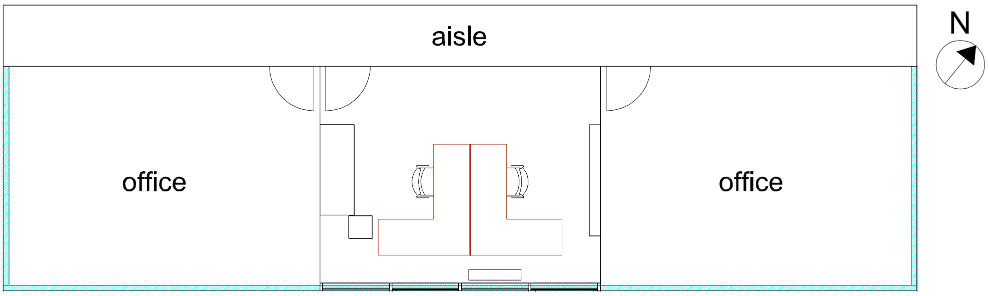


Figure 5.13 - Double office: scene used for lighting simulation

Single office

The office located in the 6th floor (Figure 5.14) has been simulated as a box shaped office, positioned at its effective height (21.6 m). It has two full glazed façades, one North-East and one South-East oriented and it is equipped with grey roller blinds, manually operated. In the single office five sensors, three over the work plane (H3, H4 and H5) and two along the perimeter walls (H1 and H2) are still recording illuminance (Figure 5.15). The ground has been modelled as a disk with a radius of 60 m.

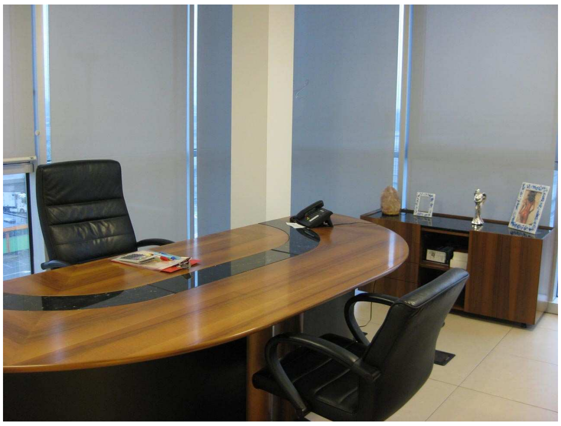


Figure 5.14 - Single office

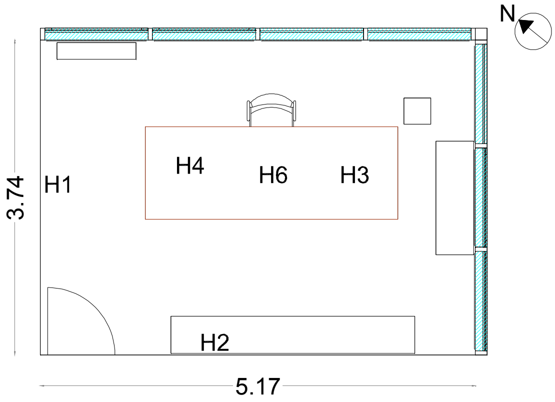


Figure 5.15 - Single office: sensors position

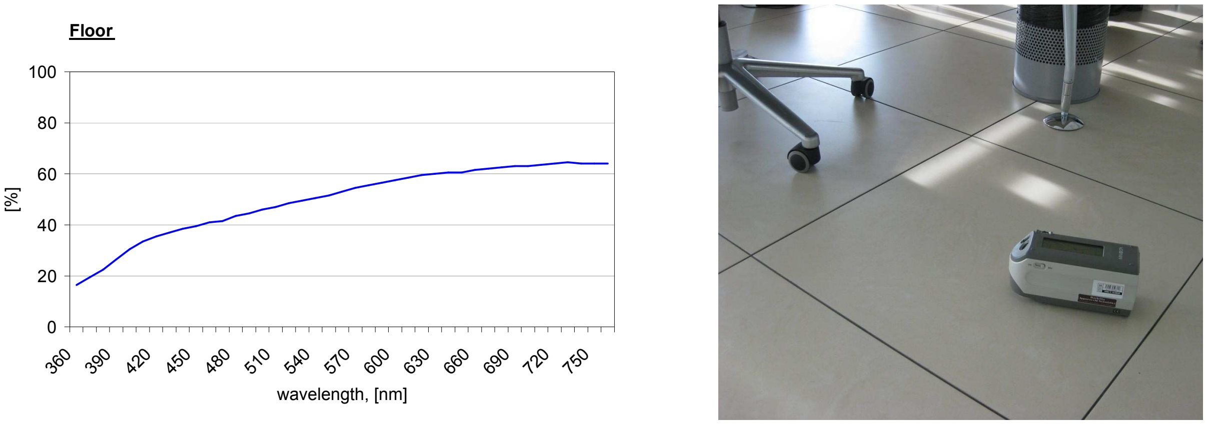
5.5. Material description

Some preliminary simulations have been carried out supposing materials reflectance, but later all the surfaces of the two analysed offices have been characterized, by a portable spectrophotometer (Figure 5.16).

Figure 5.16 - Spectrophotometer used for surface characterization (Minolta CM2600)

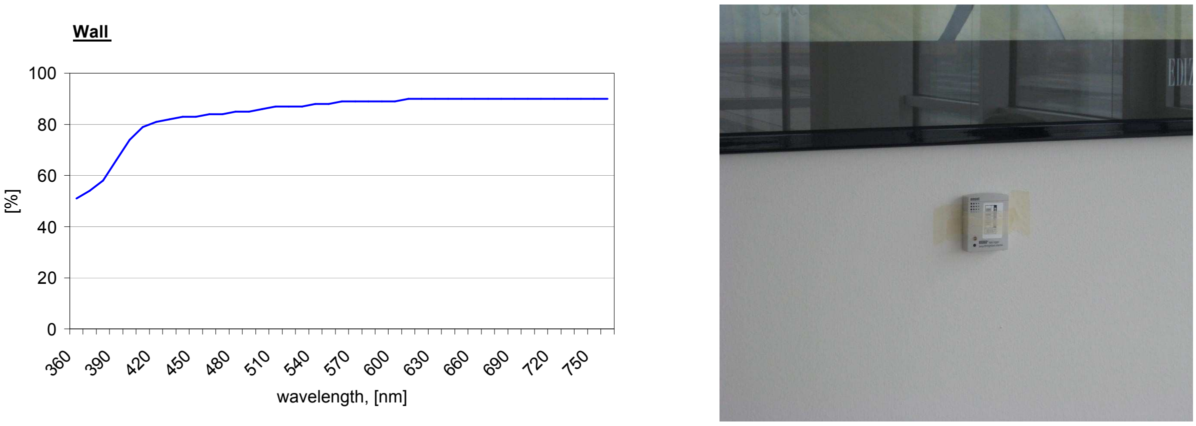
5.5.1. Surfaces characteristics

The graphs below show the surfaces reflection with a 10 nm step of the visible spectrum, from 360 nm to 760 nm.



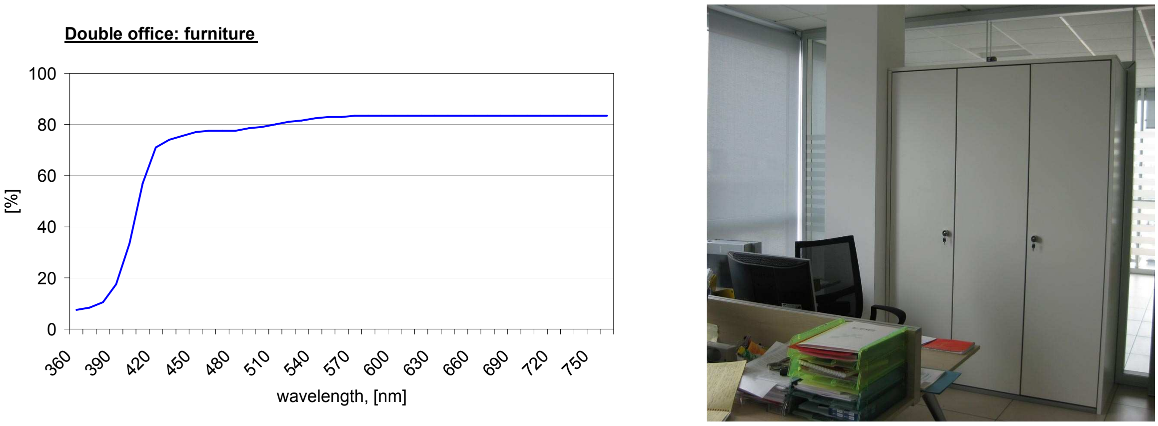
(a) (b)

Figure 5.17 - Measured floor surface reflection for both the offices (a); office floor (b)



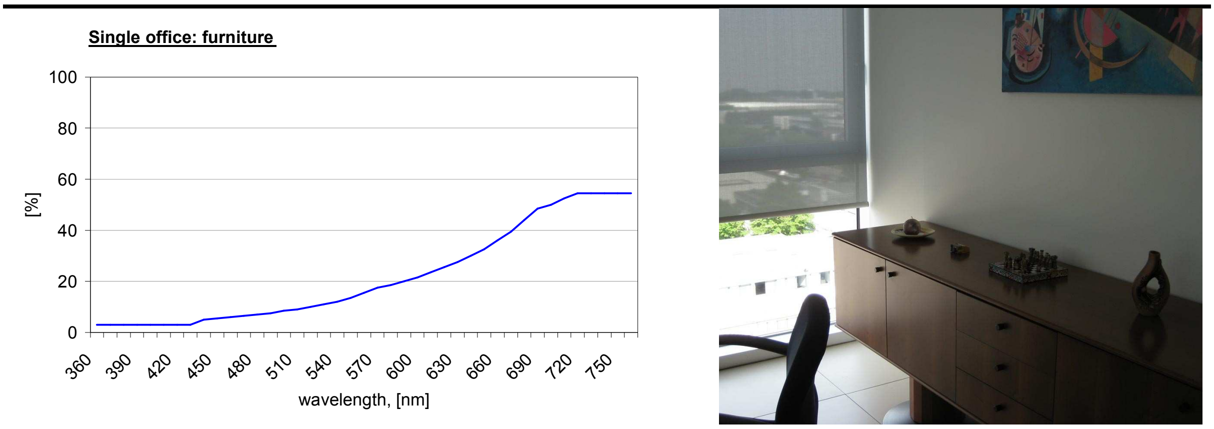
(a) (b)

Figure 5.18 - Measured reflection of the single office partition wall (a); single office wall (b)



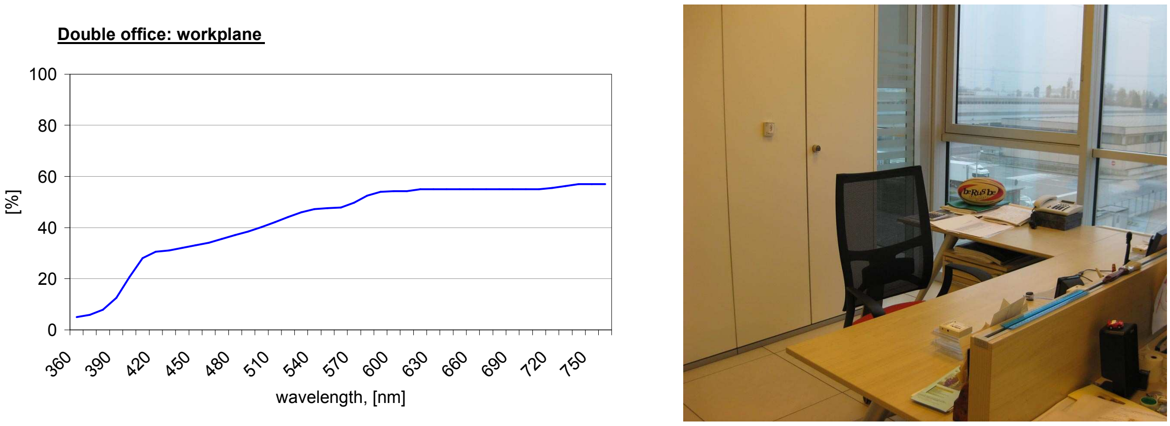
(a) (b)

Figure 5.19 - Measured double office furniture reflection (a); double office furniture (b)



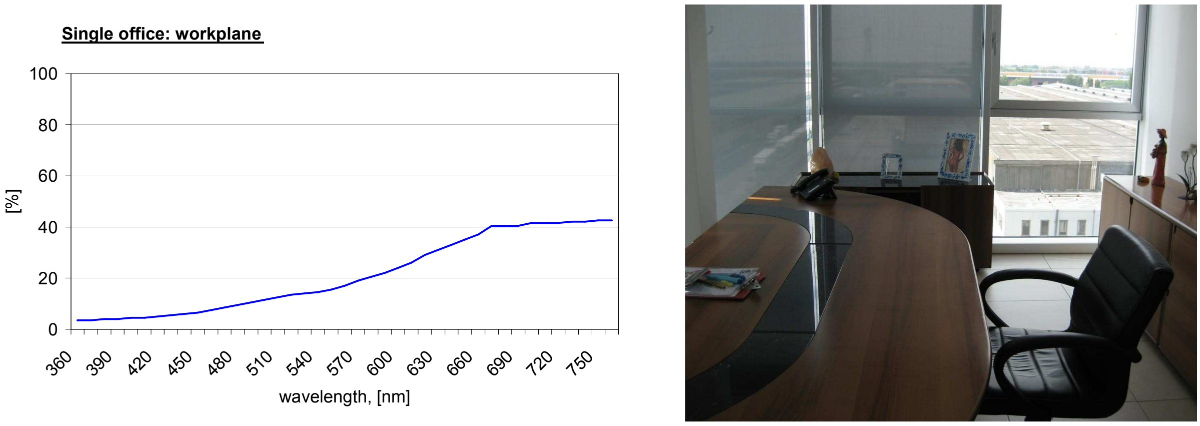
(a) (b)

Figure 5.20 - Measured single office furniture reflection (a); single office furniture (b)



(a) (b)

Figure 5.21 - Measured double office work plane reflection (a); double office work plane (b)



(a) (b)

Figure 5.22 - Measured single office work-plane reflection (a); single office work plane (b)

5.5.2. Roller blinds

The visual transmittance of the roller blind (Figure 5.23) was not available, therefore it has been calculated by the ratio between illuminance recorded with the curtain up and down. Vertical and horizontal illuminance have been measured with the lux meter in front of the window, at a distance of 1.5 m.

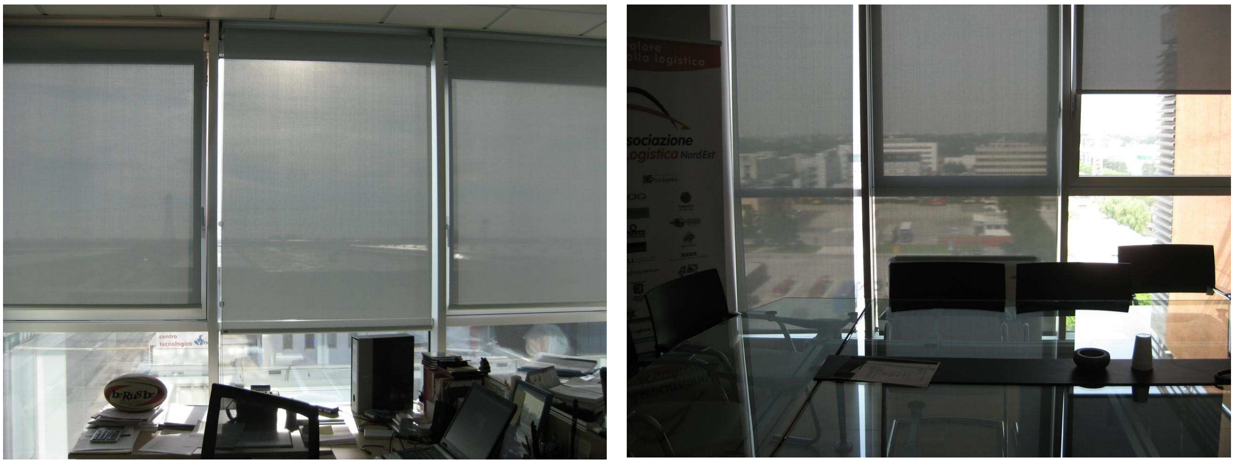


Figure 5.23 - Office roller blinds

The "*trans*" material has been used to model the blinds. This is defined by seven numbers which indicates:

- *RGB reflectance* ("*0 0 0*" corresponds to a full absorbing black surface, while "*1 1 1*" to a white surface which does not absorb anything)
- *Specularity*: The fraction of incident light that is immediately reflected ("*0*" corresponds to a matt surface; values greater than 0.1 are unrealistic)
- *Roughness* ("*0*" corresponds to a perfectly smooth surface, "*1*" would be a very rough surface)
- *Transmissivity*: the fraction of penetrating light that travels all the way through the material ("*0*" means opaque, "1" transparent)
- *Transmissive Specularity*: the fraction of transmitted light that is not diffusely scattered ("*0*" means diffuse, "*1*" clear)

The material description is the following:

```
#roller blinds
void trans curtain_mat   0   0   7   0.66   0.66   0.66   0   0   0.24242   0.2
```

5.5.3. Glazed and film coated façade

Glazing characteristics were available, so the lighting transmittance (59%) has been used to model glazing surfaces for RADIANCE and DAYSIM simulations. The material description of the glazed façade is:

```
#glazed_façade
void glass glazed_façade   0   0   3   0.646   0.646   0.646
```

The film coated façade has been modelled using the “*trans*” material, taking into account the combination of both glass and film characteristics. The film has a visible lighting transmittance of 18%, an external visible light reflection of 63% and the internal of 60%. The material description of the film coated façade is:

```
#external_glazed_façade
void trans film_mat   0   0   7   0.3562   0.3562   0.3562   0   0   0.2981   0.5
```

5.5.4. RADIANCE material description of the scene

The RADIANCE material description of the two offices (Table 5.2 and Table 5.3) is the result of some approximations made from measurements taken with the spectrophotometer. All materials, except the frame, the roller blinds and the glazed facade and partition wall, are supposed “plastic”, as they behave appreciatively as lambertian diffusers.

Table 5.2 – Double office material description

Building element	**Material description**
ceiling	plastic (75% diffuse reflection)
floor	plastic (50% diffuse reflection)
frame	metal (24% RGB reflection, 30% specularity, 20% roughness)
furniture	plastic (80% diffuse reflection)
glazed partition wall	glass (78% visual transmittance)
ground	plastic (20% diffuse reflection)
wall	plastic (80% diffuse reflection)
work plane	plastic (40% diffuse reflection)

Table 5.3 – Single office material description

Building element	**Material description**
ceiling	plastic (75% diffuse reflection)
chairs	plastic (4% diffuse reflection)
door	plastic (16% diffuse reflection)
floor	plastic (50% diffuse reflection)
frame	metal (24% RGB reflection, 30% specularity, 20% roughness)
furniture	plastic (20% diffuse reflection)
ground	plastic (20% diffuse reflection)
wall	plastic (85% diffuse reflection)
work plane	plastic (20% diffuse reflection)

5.6. Climate file

The climate file used is the EPW recalculated by means of the hourly horizontal global radiation values recorded by the ARPAV (Local Environmental Agency) station located in Legnaro, a town near the analysed tower site. The global radiation has been then split into the normal beam and the horizontal diffuse radiation: this operation can lead to unrealistic values of direct normal beam radiation, especially in winter when there is a low solar altitude.

The hourly radiation values have been finally converted into a time series of five minutes, using a stochastic autocorrelation model which is implemented in DAYSIM.

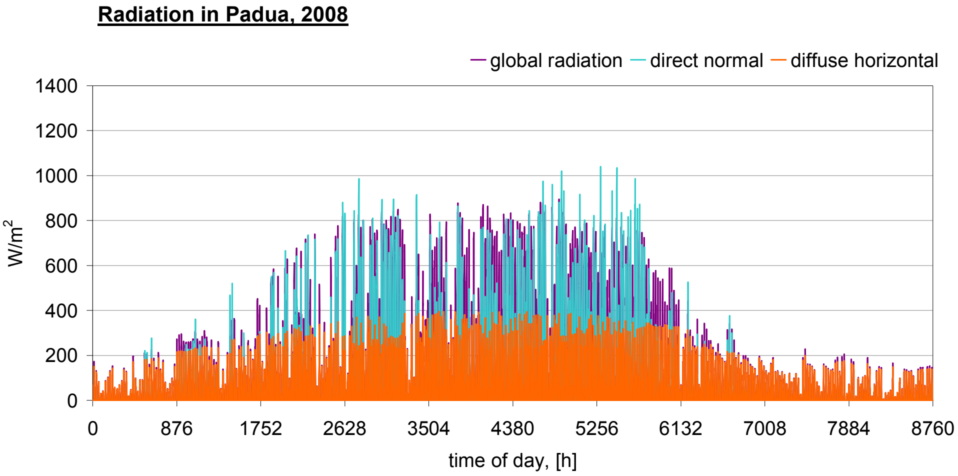


Figure 5.24 - Global, direct normal beam and diffuse horizontal radiation, referring to Legnaro (Padua), for year 2008

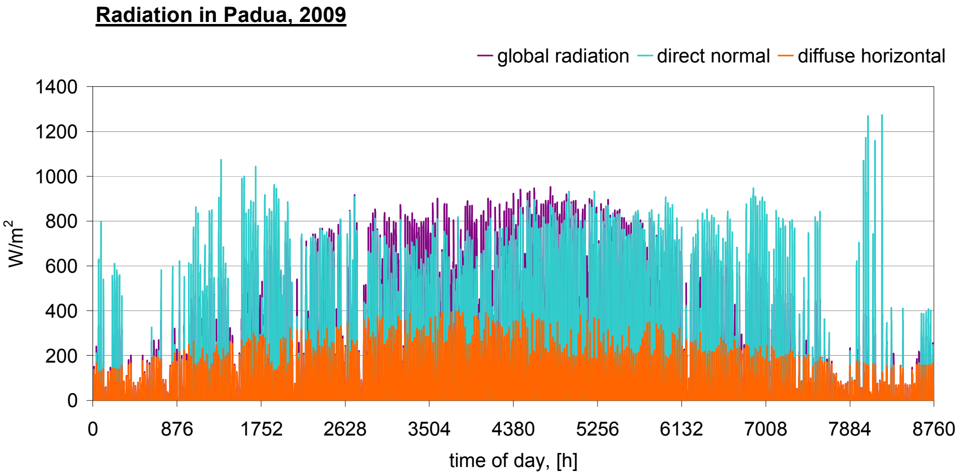


Figure 5.25 - Global, direct normal beam and diffuse horizontal radiation, referring to Legnaro (Padua), for year 2009

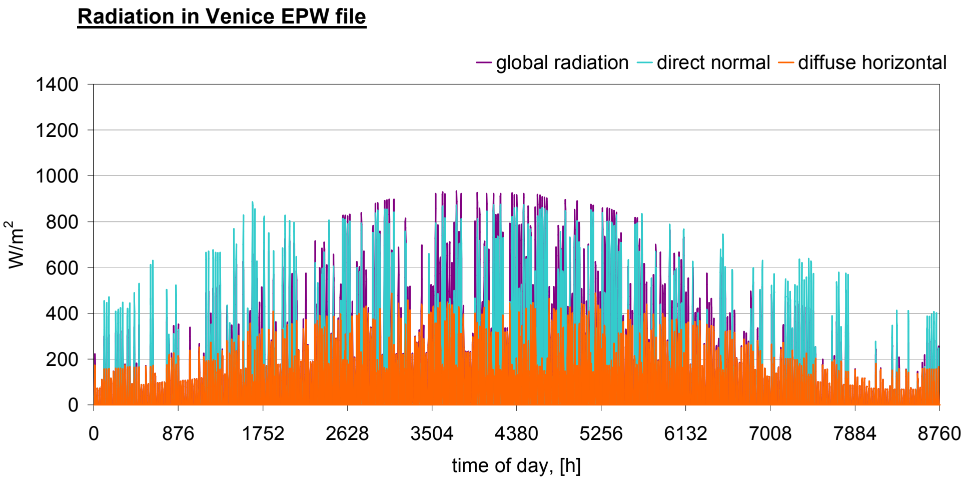


Figure 5.26 - Global, direct normal beam and diffuse horizontal radiation, in the EPW of Venice

From the above Figures, it can be noticed how different is the available EPW file from the effective climate profile, therefore using the standard EPW file for this study would lead to unrealistic results.

5.7. Shading and lighting

In this study two different offices has been chosen to draw out a comparison between measured and simulated illuminances.

The most important difference between the two offices is the occupancy: the double office is most of the time occupied, while the single one is rarely occupied. The single office could be therefore considered as a sort of test room: the curtains are always up and the electric light is often switched off. In the double office , instead, the lighting (switched on or off) and the curtains setting (up or down) were not known. Looking at the great gap (which is always the same) between two subsequent illuminance values recorded by the sensors it was easy to understand when electric lighting was switched on. This “gap value” has been then subtracted to the one measured by the HOBO sensor to have the one due to daylight only. This operation is necessary since in DAYSIM only daylight is considered as lighting source, while electric lighting is taken into account only for energy evaluation. For curtain setting, occupants were asked to leave them up on Fridays, in order to be sure that the blinds were up during Saturday and Sunday, when nobody works. During weekdays, in fact, occupants complain lighting discomfort in sunny days, therefore they use to change blind setting according to sky condition.

5.8. Human behaviour

Probably the bigger source of quantify energy benefits is that daylighting methods fail to assume how shading and lighting devices are used by building occupants. “Lightswitch Wizard” which is implemented in DAYSIM offers a comparative, reliable and fast analysis of the annual amount of daylight in offices, as well as the lighting energy performance of automated lighting and shading controls compared to standard on/off switches and manual blind control (Reinhart, 2004). This model predicts the electric energy demand in offices for manually and automatically controlled lighting and blind systems. It is based on behaviour patterns of how office occupants use their blinds and electric lighting. The required inputs to have a prediction of annual electric energy demands and the status of the blinds throughout the year are annual profiles of user occupancy and work plane illuminances.

5.9. DAYSIM simulations

DAYSIM simulations have been carried out importing a 3DStudio file exported from AutoCad. The material file and the climatic file have been modified according to chapter 5.5.

5.9.1. Sensor point file

The illuminances have been calculated in the same position of the sensors, making an average of five values for horizontal position and of nine for vertical ones, every 0.05 m). The Figure 5.27 is an example of the grid used to calculate horizontal illuminance over the work plane.

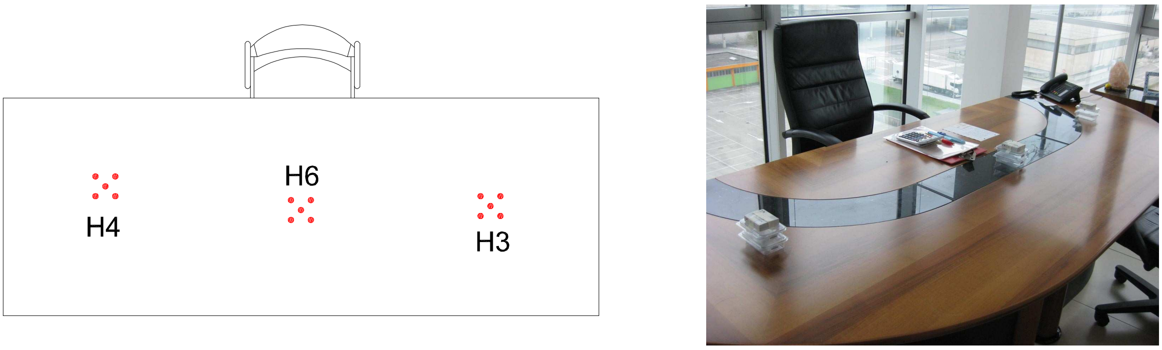


Figure 5.27 - Sensor points in DAYSIM simulations: horizontal illuminance over the work plane (single office)

5.9.2. Simulation parameters

Non default DAYSIM-RADIANCE simulation parameters are listed in Table 5.4 - DAYSIM simulation parameters.

Table 5.4 - DAYSIM simulation parameters

ambient bounces	ambient divisions	ambient sampling	ambient resolution	ambient accuracy
6	2048	1024	512	0.05

The DAYSIM dynamic advanced shading device model has been chosen, therefore two sets of annual illuminance profiles have been calculated.

5.9.3. Daylight analysis

Occupancy

The single office is occupied by one person, while the double office by two persons. Occupancy profiles are generated by the program. The following assumptions have been considered:

- arrival time: 8:00;
- departure time: 18:00;
- the work place is occupied from Monday to Friday;
- the lunch break occurs at noon and two 15 minutes breaks are scheduled around 10:00 and 15:00.

User requirements and user behaviour

The maintained illuminance level in the work plane is fixed at 500 lux, according to the Standard EN 12464-1.

All the three available user behaviour have been considered, for both lighting and blind use: active, passive and mix of both.

Lighting and shading control systems

The effective installed lighting power density load is 15 W/m^2, which corresponds to the benchmark value for a typical office room of one star quality class (EN 15193, Annex F).

Any kind of lighting and blind control is provided in the analysed office, so only manual control has to be considered; nevertheless many different blind and lighting controls, in combination with different user behaviour, have been examined to evaluate possible energy savings due to BMS. The list of all these combinations is reported in Table 5.5.

Table 5.5 - User behaviour and control strategies analysed

user behaviour		lighting control	shading control	symbol
lighting	shading			
passive	passive	manual	manual	PM
mix	mix	manual	manual	MM
active	active	manual	manual	AM
passive	passive	switch off occupancy sensor	manual	PMSWF
mix	mix	switch off occupancy sensor	manual	MMSWF
mix	mix	switch off occupancy sensor	automated	MASWF
passive	passive	dimmer	manual	PMD
mix	mix	dimmer	manual	MMD
mix	mix	dimmer	automated	MAD
passive	passive	switch off occupancy sensor and dimmer	manual	PMSWFD
passive	passive	switch off occupancy sensor and dimmer	automated	PASWFD
mix	mix	switch off occupancy sensor and dimmer	manual	MMSWFD
mix	mix	switch off occupancy sensor and dimmer	automated	MASWFD
active	active	switch off occupancy sensor and dimmer	automated	AASWFD

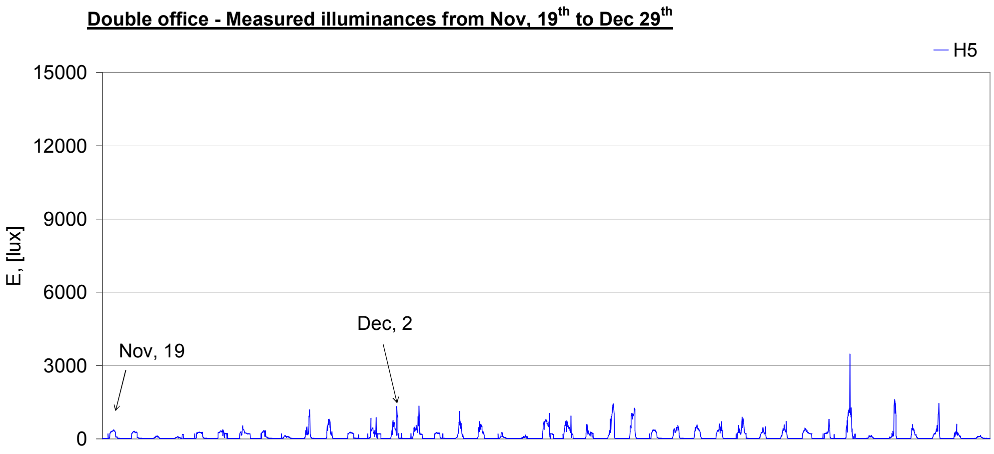
5.10. Recorded illuminance values from 19th November to 29th December 2009

The following graphs (Figure 5.28 and Figure 5.29) show the recorded illuminance values, due to both natural and electric light, from 19th November to 29th December, in all the eleven sensors put in the two offices.

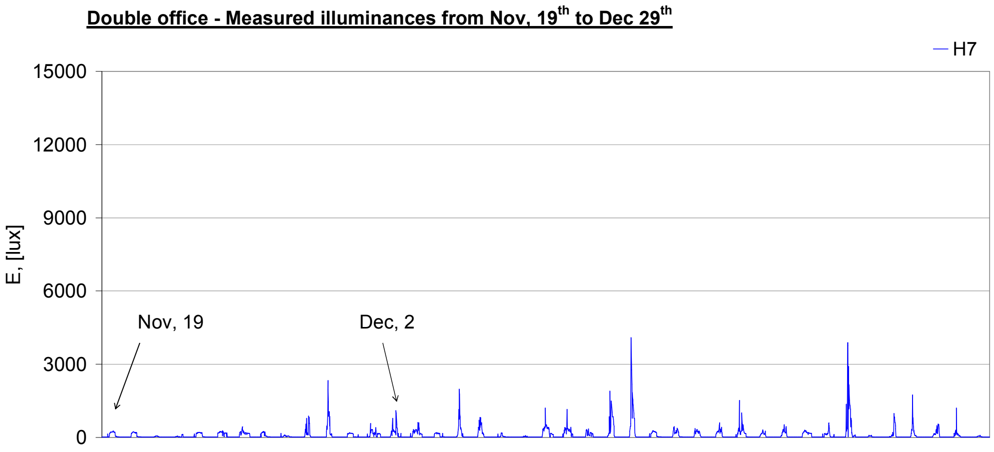
Double office

Sensor H9 and H10 are over the work plane: their illuminance profiles are similar, but the first one has higher values because it is close to the window.

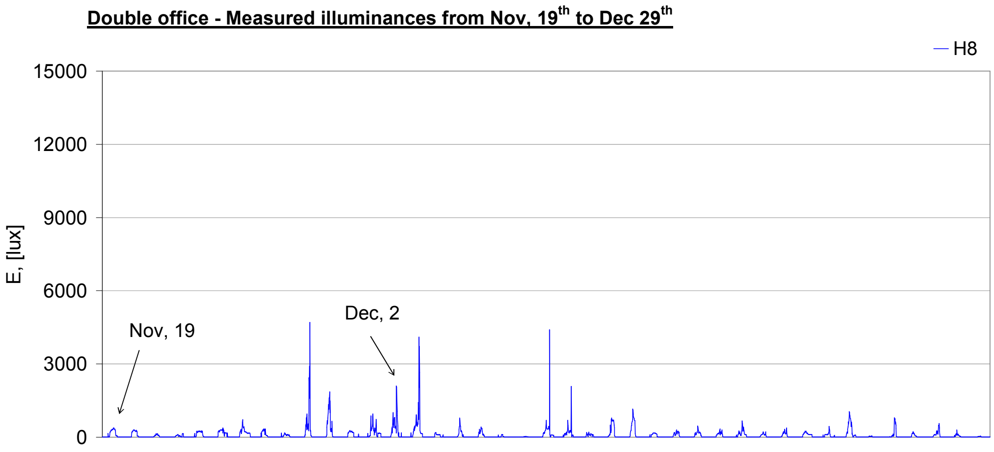
It can be noticed that illuminances over the work plane (sensor H10, which is the most representative) are most of the time around 500 lux, except during weekdays, or in the afternoon, when often nobody is working. This means that occupant use lighting and shading properly, in order to improve visual comfort. Sensor H7 is oriented as the sensor H11, though recorded vertical illuminances are very different, because the first one is attached to one storage cabinet, while the other one near the computer (Figure 5.28), therefore all the objects over the work plane affect the measurements.


Double office - Measured illuminances from Nov, 19th to Dec 29th
H5
15000
12000
9000
6000
3000
0
E, [lux]
Nov, 19
Dec, 2

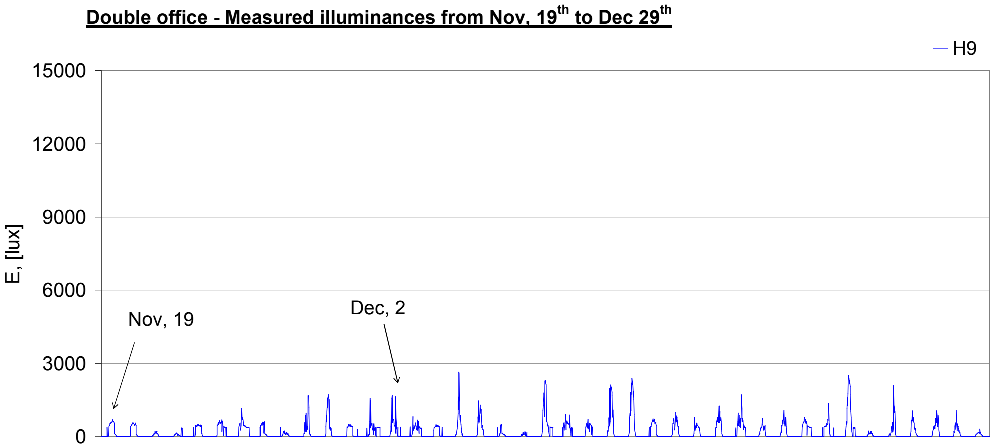
(a)


Double office - Measured illuminances from Nov, 19th to Dec 29th
H7
15000
12000
9000
6000
3000
0
E, [lux]
Nov, 19
Dec, 2

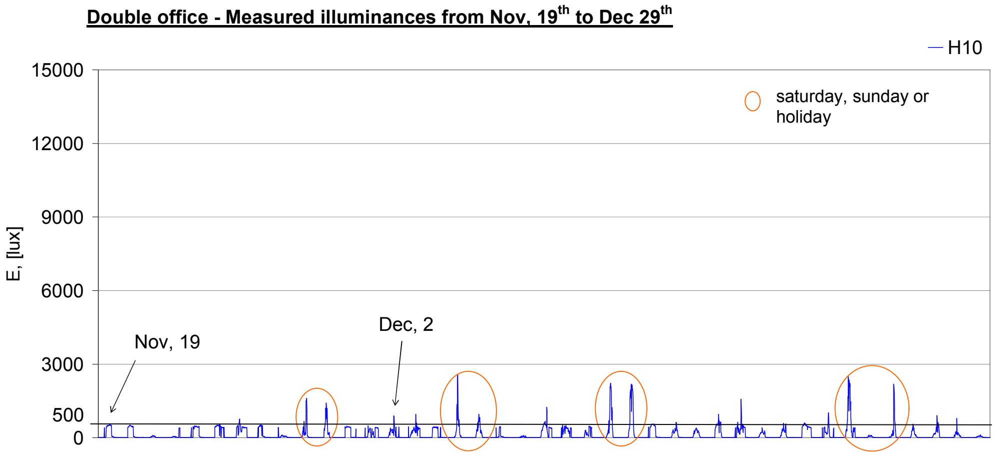
(b)


Double office - Measured illuminances from Nov, 19th to Dec 29th
H8
15000
12000
9000
6000
3000
0
E, [lux]
Nov, 19
Dec, 2

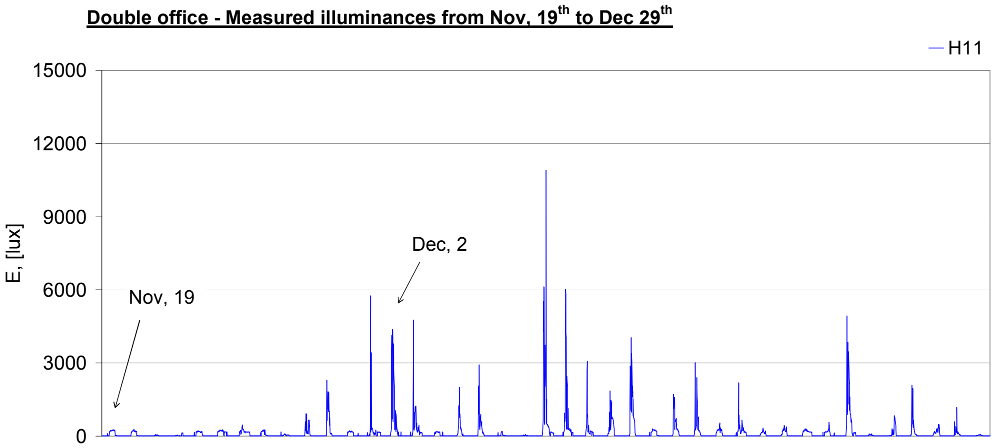
(c)



(d)



(e)



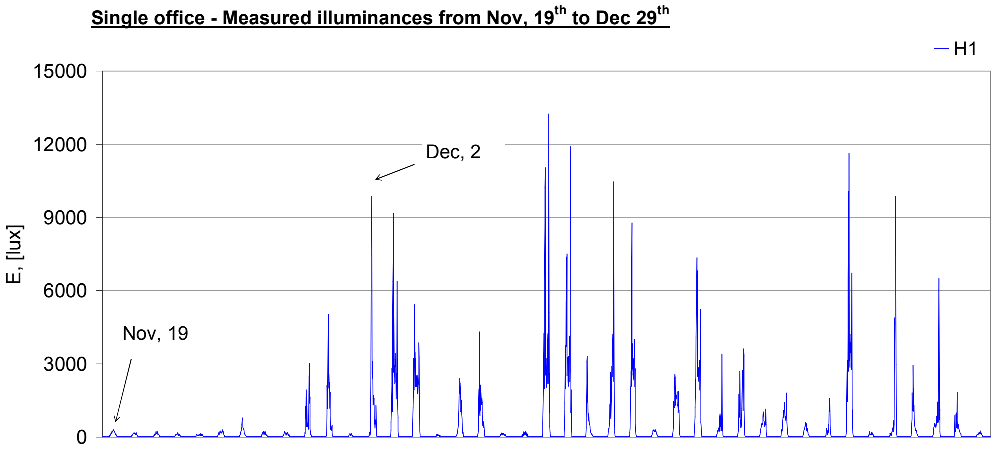
(f)

Figure 5.28 - Recorded illuminance values in each sensor of the double office (H5 (a), H7 (b), H8 (c), H9 (d), H10 (e) and H11 (f)) from 19th November to 29th December (year 2009)

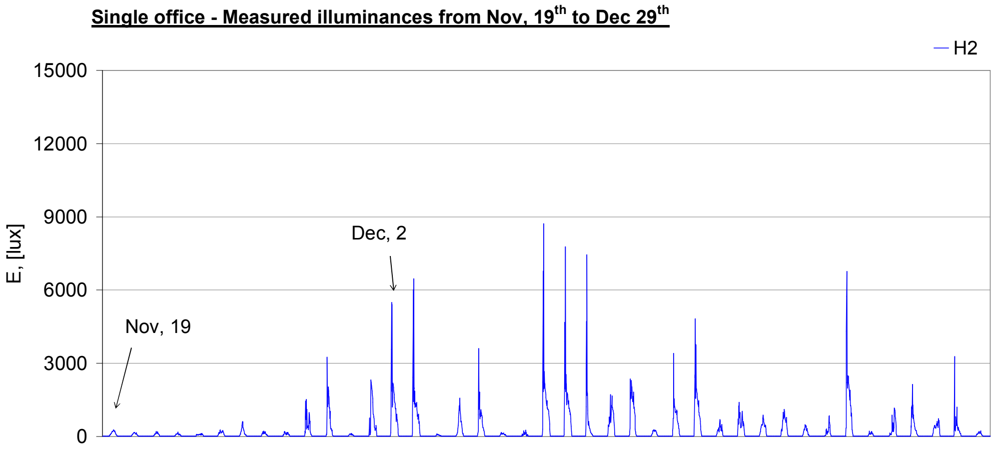
Single office

The illuminances recorded in the single office are higher than the ones in the double office, because it has two full glazed façades and, due to the fact that it is rarely occupied, the roller blinds are most of the time retracted.

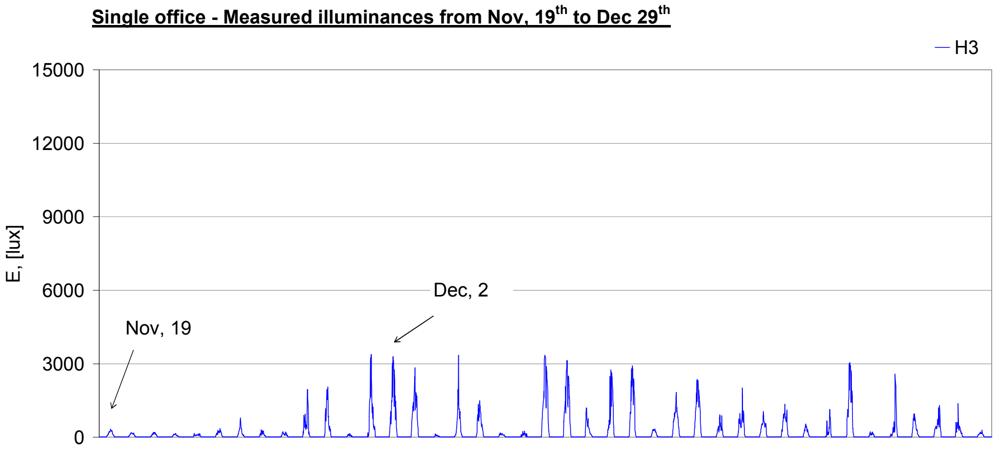
The illuminances recorded by the sensor H1 are higher than the ones in H2, because the first one is South-East oriented, while the second one faces North-East. The three illuminance profiles measured by the sensors H3, H4 and H6 are very similar, because the sensors are over the work plane and their distance from the windows is the same (Figure 5.29).



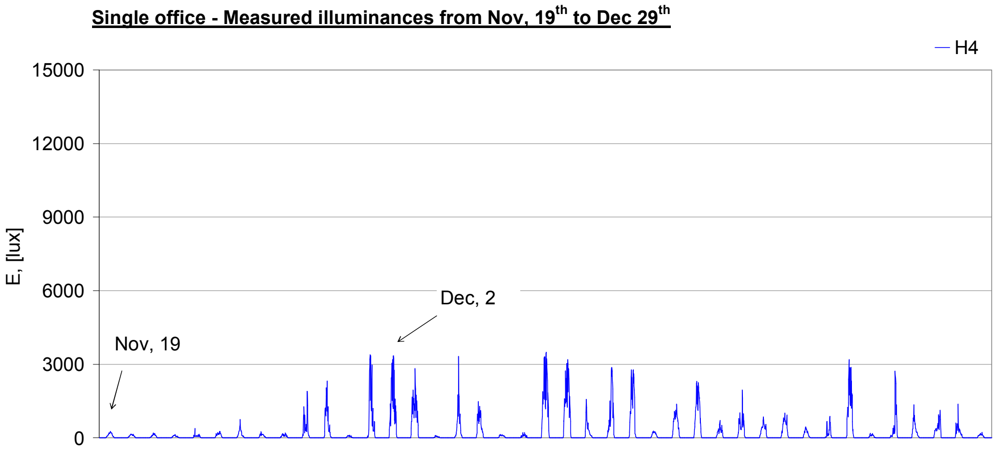
(a)



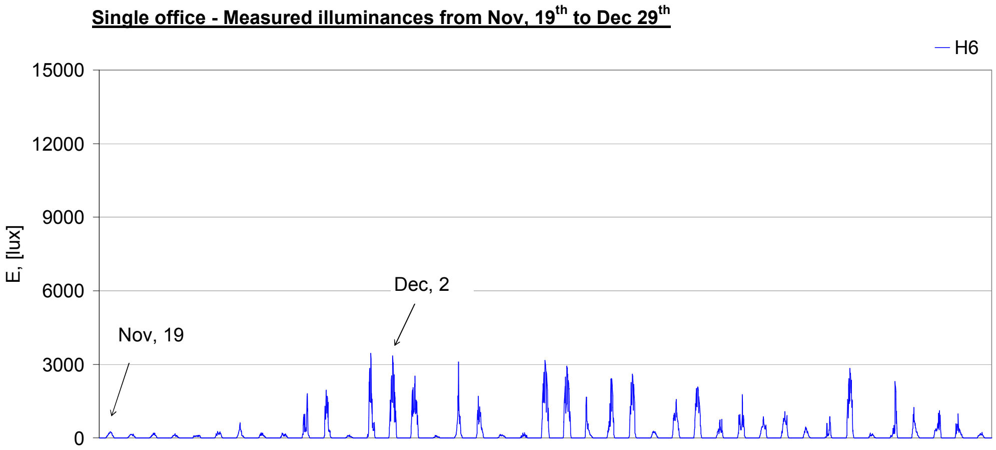
(b)



(c)



(d)



(e)

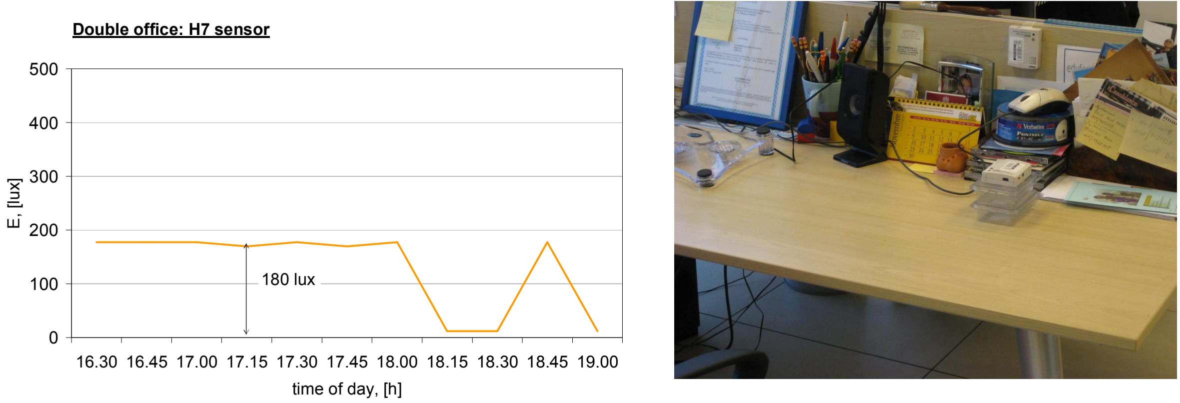
Figure 5.29 - Recorded illuminance values in each sensor of the single office (H1 (a), H2 (b), H3 (c), H4 (d) and H6 (e)) from 19th November to 29th December (year 2009)

5.11. Comparison between measured and calculated illuminances

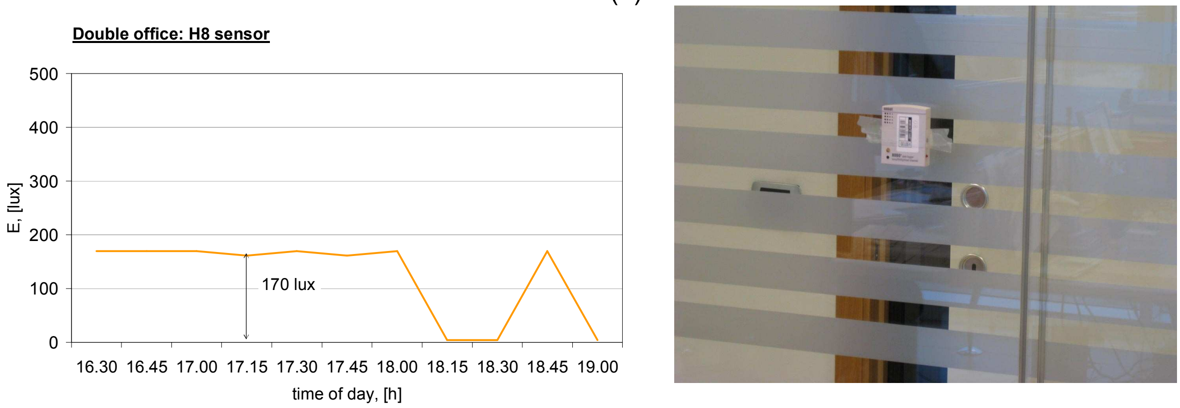
The illuminance values calculated with DAYSIM have been compared to the ones measured by the HOBO sensors.

Illuminance due to electric lighting has been obtained by recorded illuminance values in a typical winter afternoon, when daylight was no more available (from 16:30). Figure 5.30 reports these values which have been subtracted to the measured ones, so a comparison with calculated illuminance profiles, due to daylight only, could be carried out.

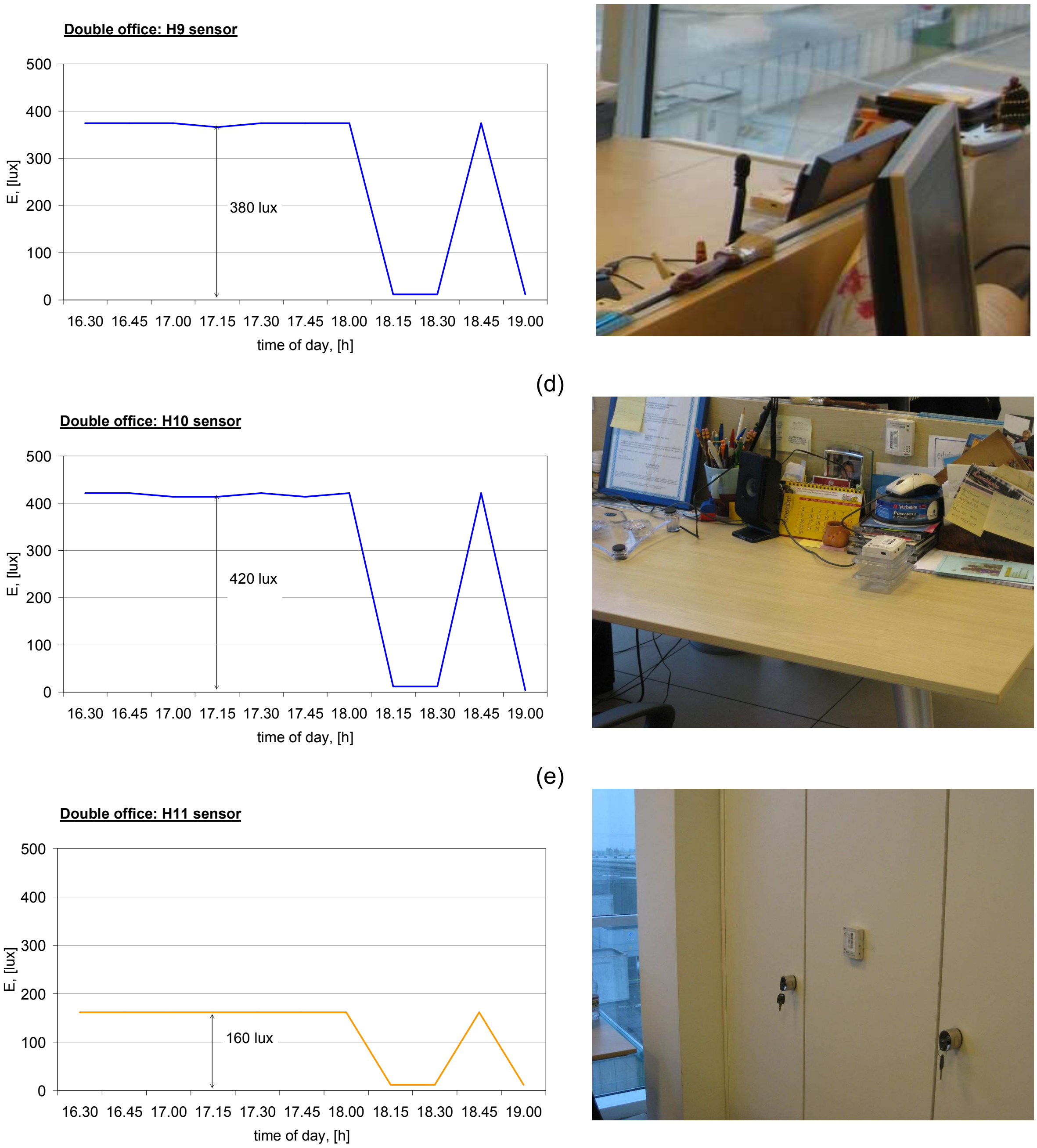
(a)



(b)



(c)



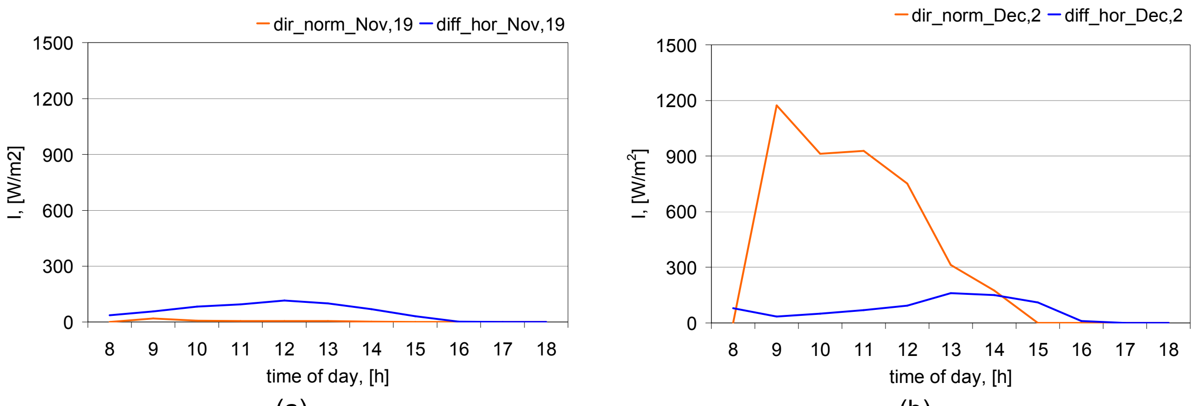
(f)

Figure 5.30 - Double office: Illuminance due to electric lighting in sensor H5 (a), H7 (b), H8 (c), H9 (d), H10 (e) and H11 (f)

Two days have been chosen to show the relationship between the two sets of illuminance values (calculated and measured): 19th November, which was an overcast day, and 2nd December, a sunny day.

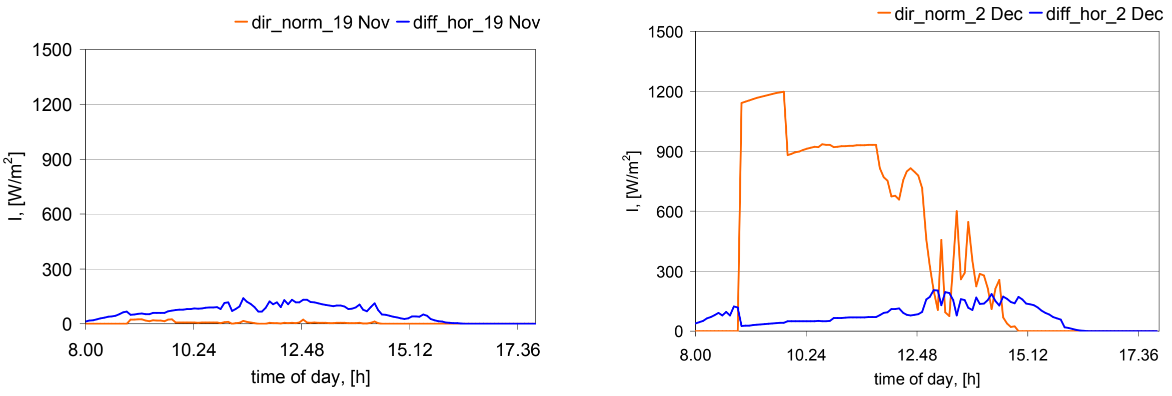
Available solar radiation in the analysed days

The available solar radiation in 19th November and in 2nd December is reported in Figure 5.31 and in Figure 5.32, in terms of direct normal beam and diffuse horizontal radiation, considering both an hour and five minutes time steps.



(a) (b)

Figure 5.31 - Direct normal beam and diffuse horizontal radiation in 19th November (a) and in 2nd December (b), considering one hour time step



(a) (b)

Figure 5.32 - Direct normal beam and diffuse horizontal radiation in 19th November (a) and in 2nd December (b), considering five minutes time step

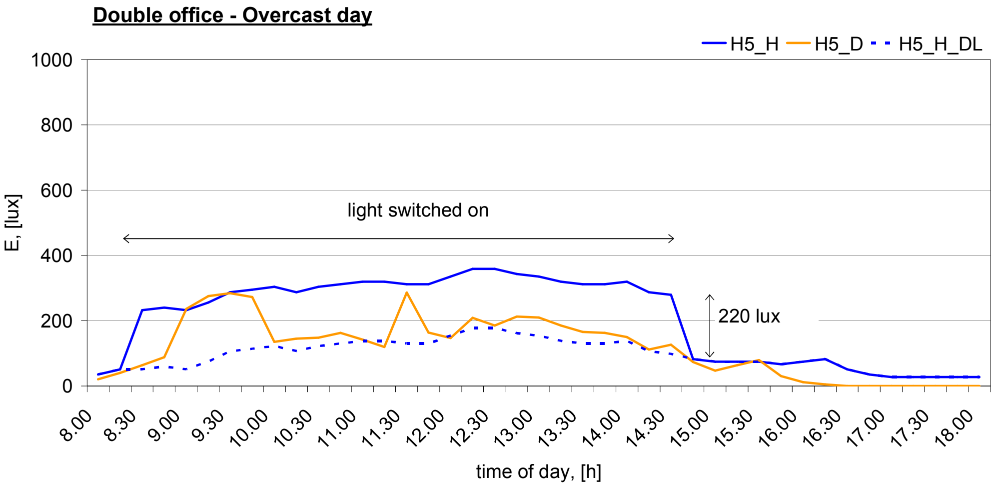
Double office

The graphs in Figure 5.33 show the illuminance profiles in the double office, in each of the six sensors (Figure 5.12), in an overcast day (19th November). From illuminance gaps, it can be deduced that the light was switched on from 8:30 to 15:00. The illuminances produced by the lamps (Figure 5.30) have been then subtracted to the measured ones, to obtain the illuminance due to daylight only and finally they have been compared to the ones calculated with DAYSIM.

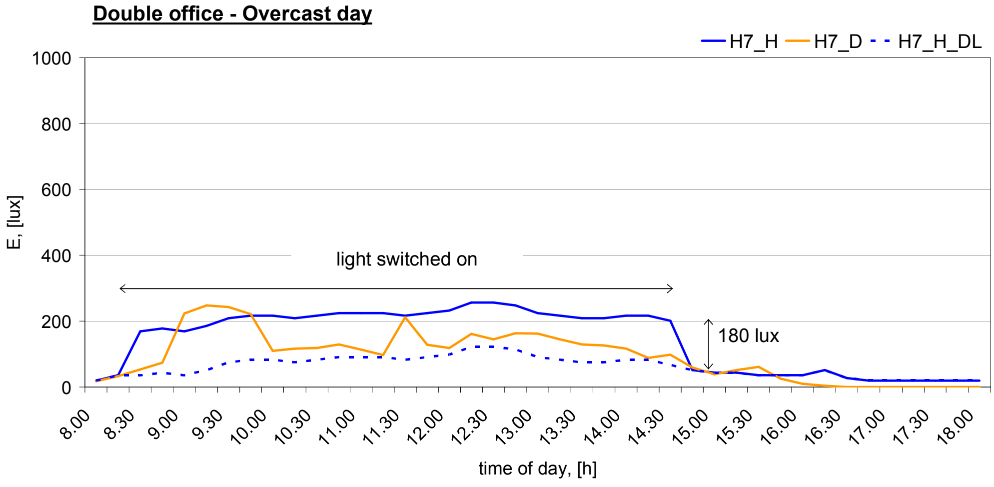
The illuminance profiles in Figure 5.33 ((d) and (e)) refer to the two sensors positioned over the work-plane, while the other ones are relative to vertical illuminance. The graphs legend is reported in Table 5.6.

Table 5.6 – Legend for Figures from Figure 5.33 to Figure 5.36

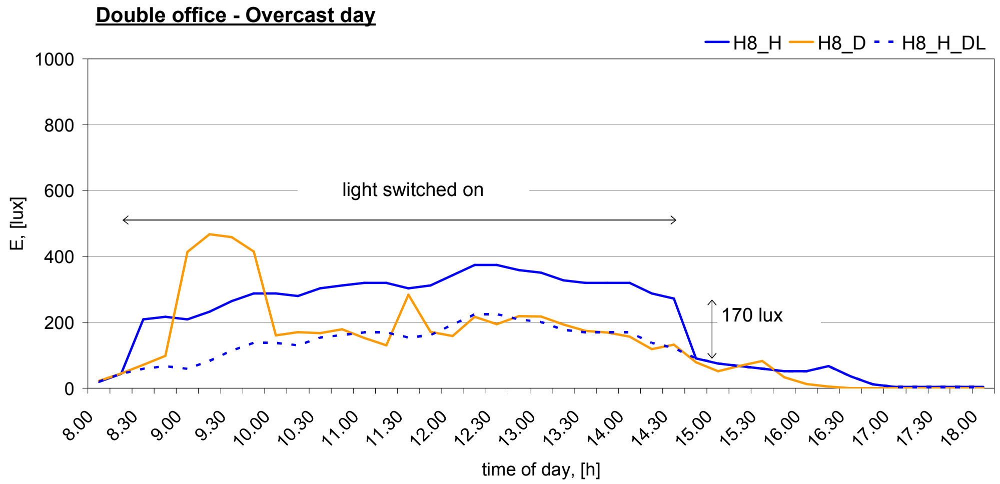
H *sensor number* _H	measured illuminance
H *sensor number* _D	calculated illuminance with blinds up
H *sensor number* _D_down	calculated illuminance with blinds down
H *sensor number* _H_DL	measured illuminance in daylight condition



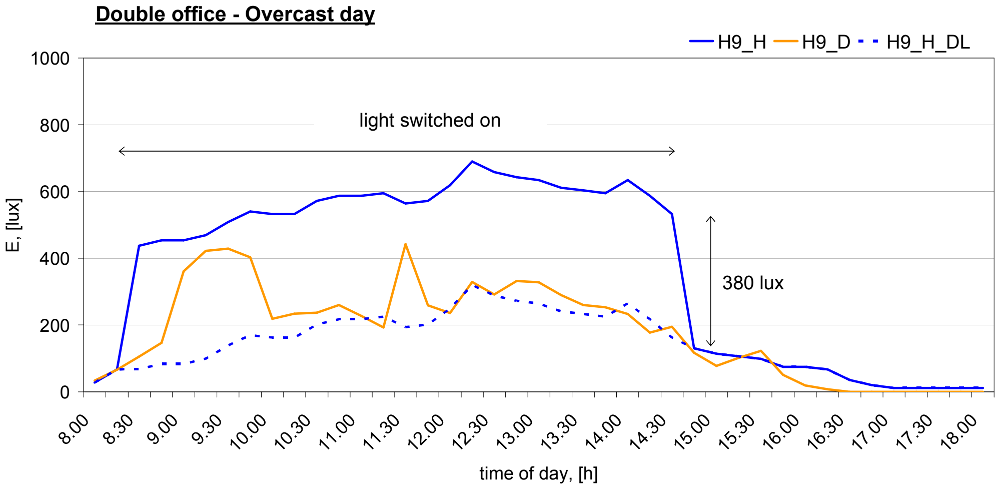
(a)



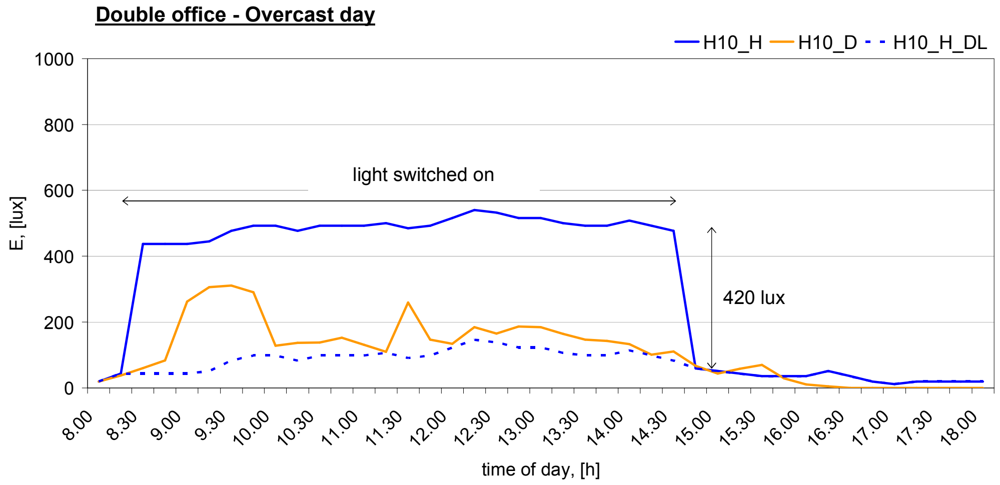
(b)


Double office - Overcast day
H8_H
H8_D
H8_H_DL
1000
800
600
400
200
0
E, [lux]
light switched on
170 lux
8.00
8.30
9.00
9.30
10.00
10.30
11.00
11.30
12.00
12.30
13.00
13.30
14.00
14.30
15.00
15.30
16.00
16.30
17.00
17.30
18.00
time of day, [h]

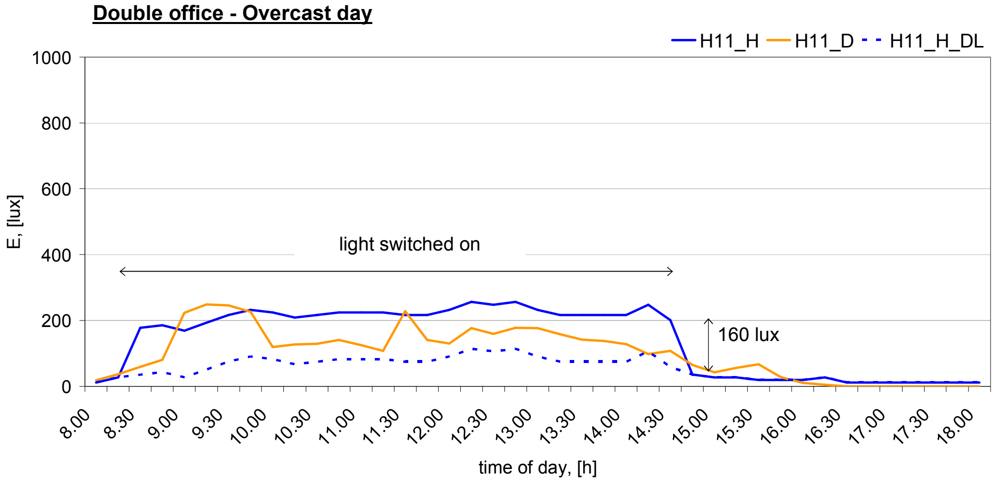
(c)


Double office - Overcast day
H9_H
H9_D
H9_H_DL
1000
800
600
400
200
0
E, [lux]
light switched on
380 lux
8.00
8.30
9.00
9.30
10.00
10.30
11.00
11.30
12.00
12.30
13.00
13.30
14.00
14.30
15.00
15.30
16.00
16.30
17.00
17.30
18.00
time of day, [h]

(d)


Double office - Overcast day
H10_H
H10_D
H10_H_DL
1000
800
600
400
200
0
E, [lux]
light switched on
420 lux
8.00
8.30
9.00
9.30
10.00
10.30
11.00
11.30
12.00
12.30
13.00
13.30
14.00
14.30
15.00
15.30
16.00
16.30
17.00
17.30
18.00
time of day, [h]

(e)

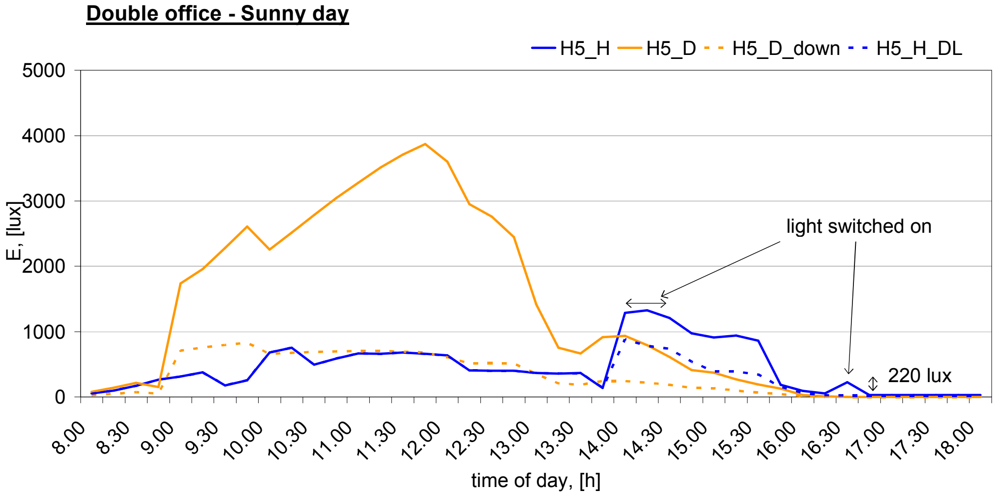


(f)

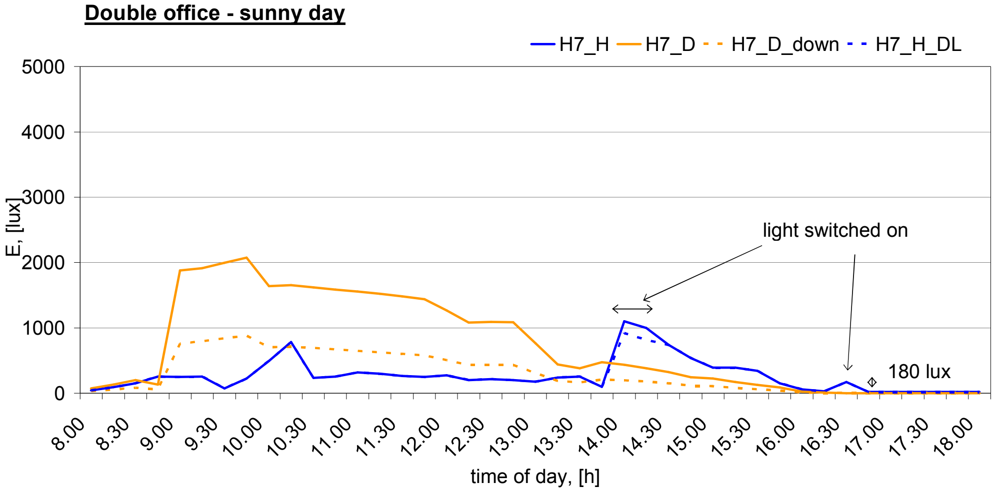
Figure 5.33 - Double office: illuminance values in sensor H5 (a), H7 (b), H8 (c), H9 (d), H10 (e) and H11 (f). 19th November 2009, overcast day, film coated façade

It can be noticed that the two profiles are similar except for one hour in the morning (from 9:00 to 10:00). This is due to the fact that, splitting the global irradiance, the direct normal radiation becomes very high because of the low solar altitude.

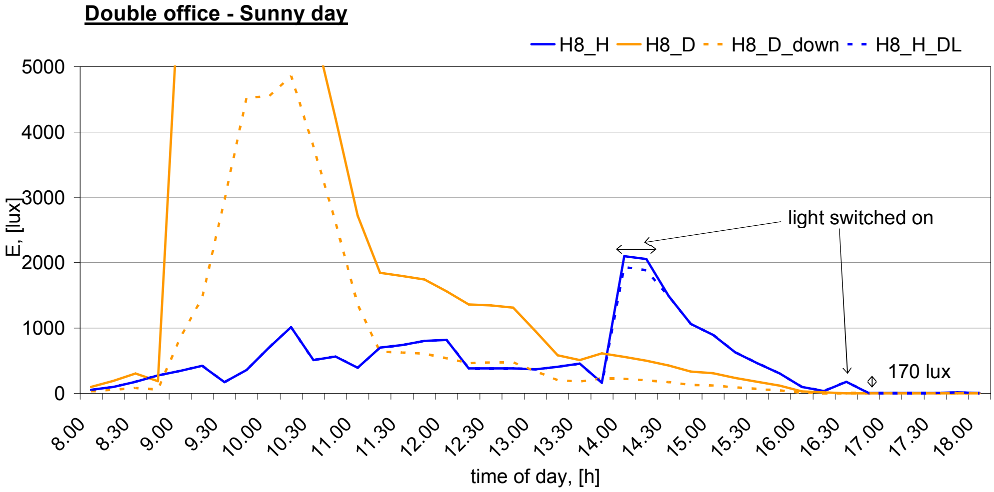
The following graphs (Figure 5.34) refer to 2nd December 2009, which was a sunny day.



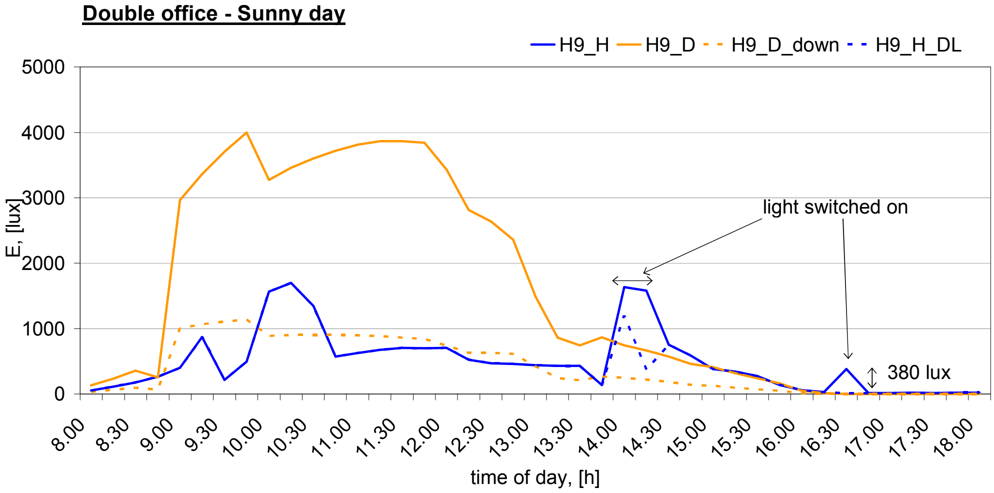
(a)


Double office - sunny day
H7_H
H7_D
H7_D_down
H7_H_DL
E, [lux]
5000
4000
3000
2000
1000
0
light switched on
180 lux
8.00
8.30
9.00
9.30
10.00
10.30
11.00
11.30
12.00
12.30
13.00
13.30
14.00
14.30
15.00
15.30
16.00
16.30
17.00
17.30
18.00
time of day, [h]

(b)


Double office - Sunny day
H8_H
H8_D
H8_D_down
H8_H_DL
E, [lux]
5000
4000
3000
2000
1000
0
light switched on
170 lux
8.00
8.30
9.00
9.30
10.00
10.30
11.00
11.30
12.00
12.30
13.00
13.30
14.00
14.30
15.00
15.30
16.00
16.30
17.00
17.30
18.00
time of day, [h]

(c)


Double office - Sunny day
H9_H
H9_D
H9_D_down
H9_H_DL
E, [lux]
5000
4000
3000
2000
1000
0
light switched on
380 lux
8.00
8.30
9.00
9.30
10.00
10.30
11.00
11.30
12.00
12.30
13.00
13.30
14.00
14.30
15.00
15.30
16.00
16.30
17.00
17.30
18.00
time of day, [h]

(d)

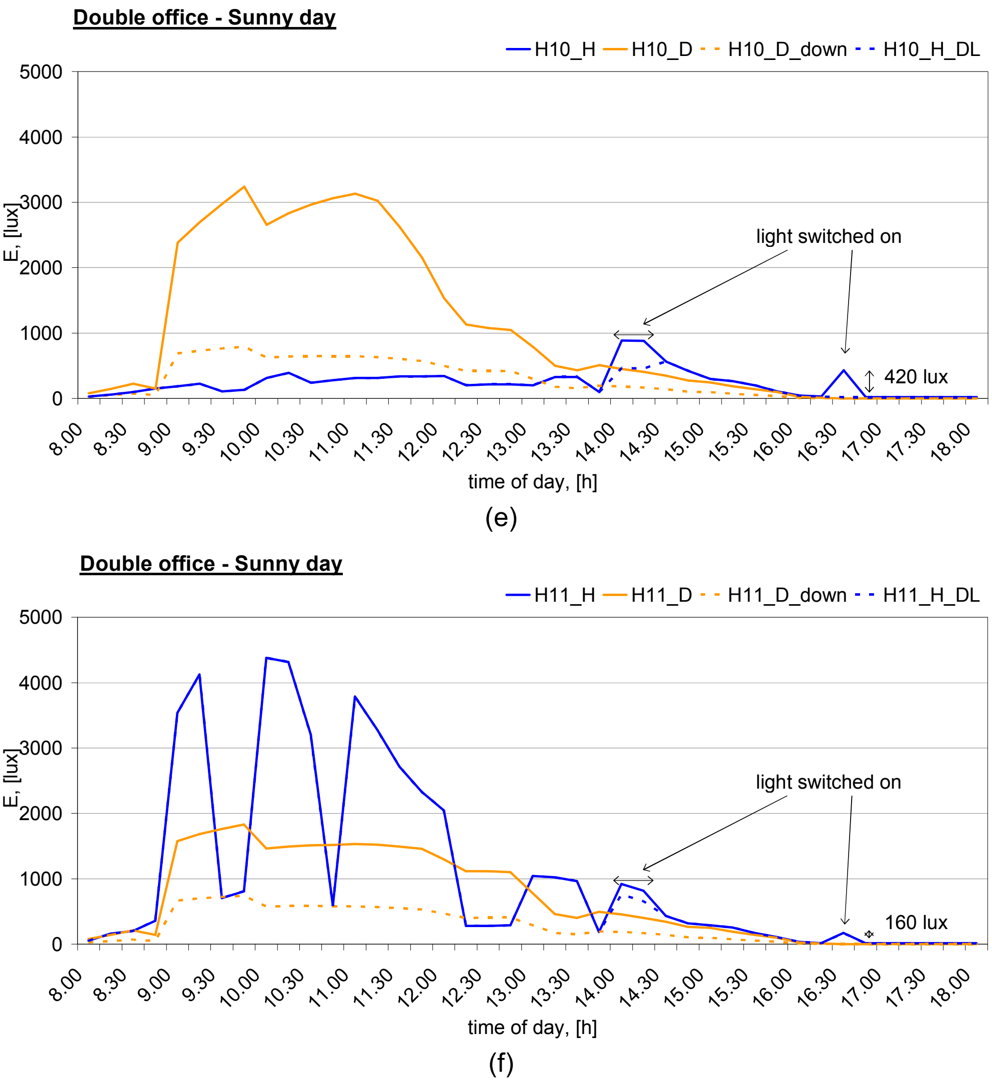
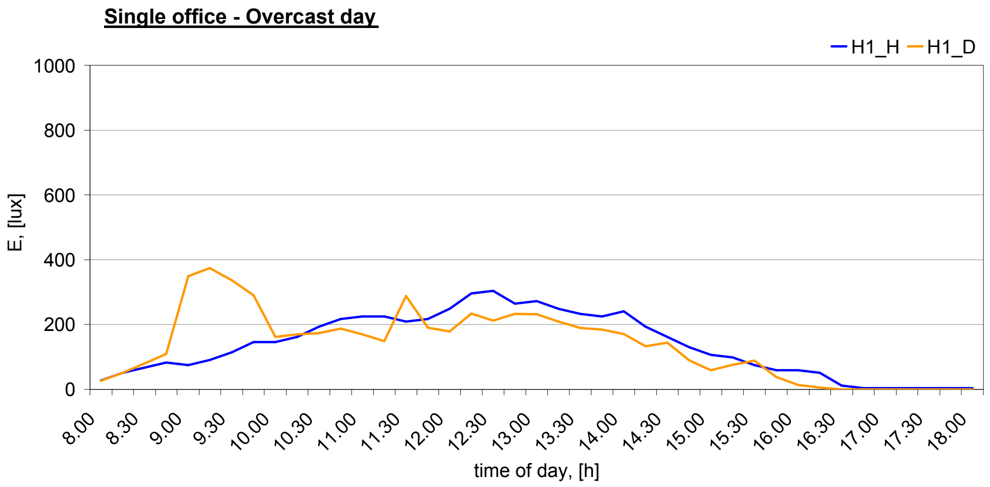


Figure 5.34 - Double office: illuminance values in sensor H5 (a), H7 (b), H8 (c), H9 (d), H10 (e) and H11 (f). 2nd December 2009, sunny day, film coated façade

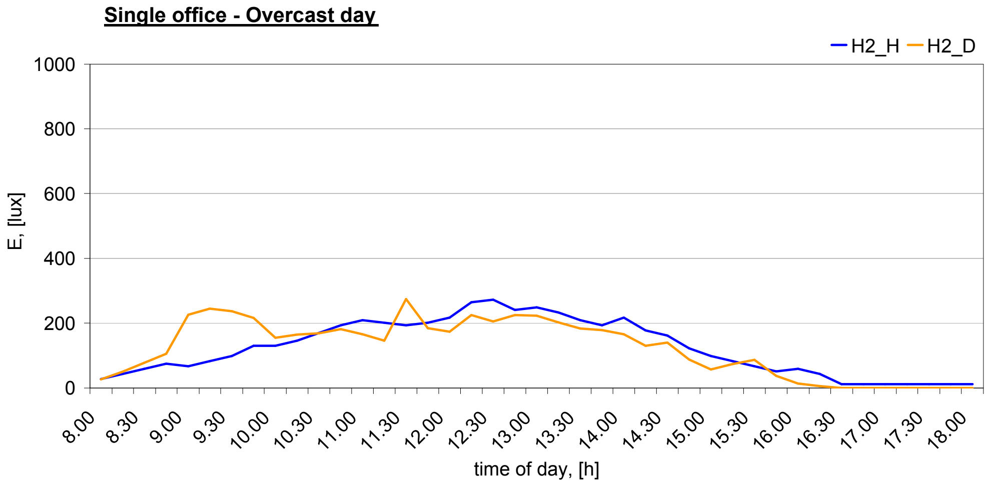
For 2nd December DAYSIM has predicted that the curtains would be down, due to high illuminance values. The occupants in the double office stated that they actually kept the shading down that day, because of visual discomfort: this demonstrates that human behaviour predictions of DAYSIM correspond (in this case, at least) to the effective real ones.

Single office

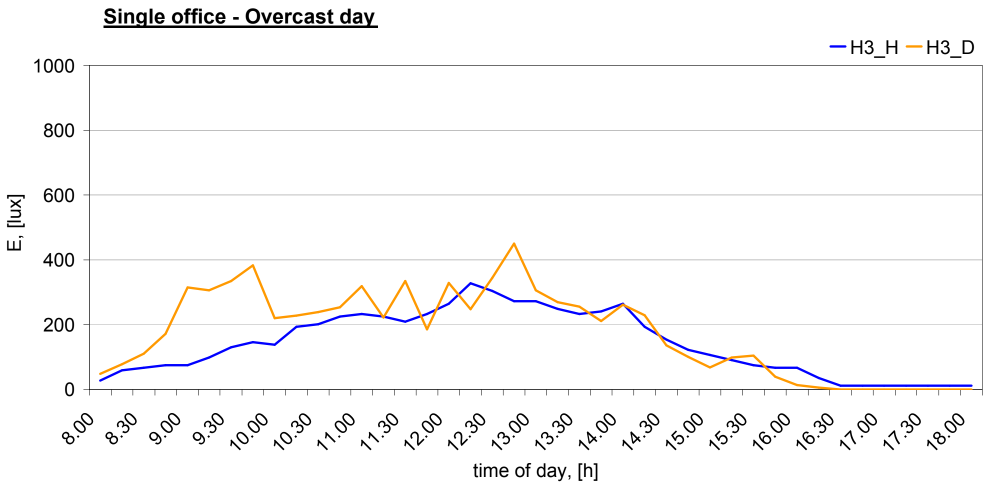
The following graphs (Figure 5.35) refer to the single office. In both the analysed days the office was unoccupied, the shadings were always up and the light switched off, therefore no human interaction, nor electric lighting have influenced illuminance measurements.


Single office - Overcast day
H1_H
H1_D
E, [lux]
1000
800
600
400
200
0
8.00
8.30
9.00
9.30
10.00
10.30
11.00
11.30
12.00
12.30
13.00
13.30
14.00
14.30
15.00
15.30
16.00
16.30
17.00
17.30
18.00
time of day, [h]

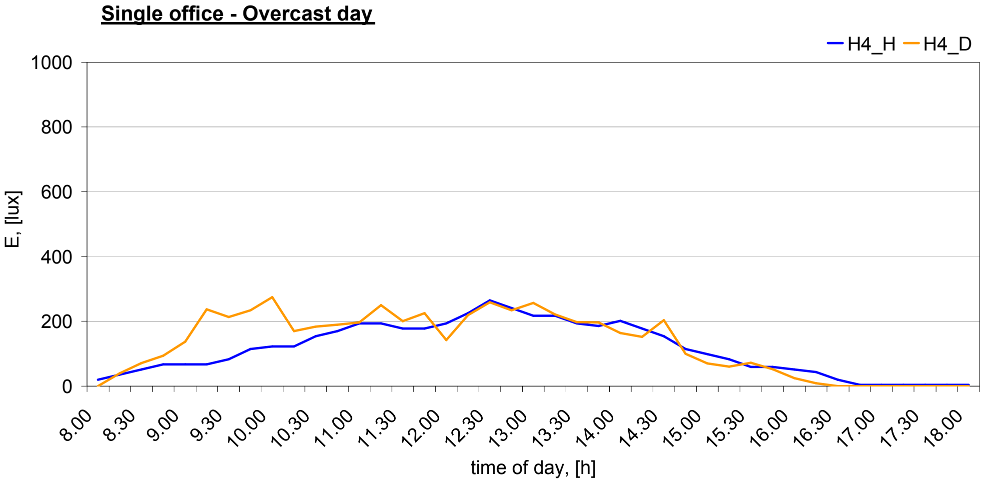
(a)


Single office - Overcast day
H2_H
H2_D
E, [lux]
1000
800
600
400
200
0
8.00
8.30
9.00
9.30
10.00
10.30
11.00
11.30
12.00
12.30
13.00
13.30
14.00
14.30
15.00
15.30
16.00
16.30
17.00
17.30
18.00
time of day, [h]

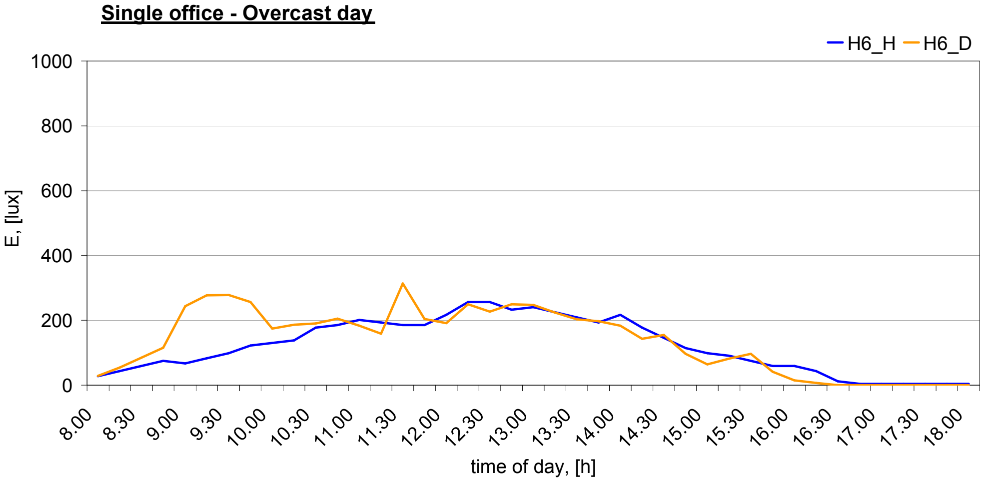
(b)


Single office - Overcast day
H3_H
H3_D
E, [lux]
1000
800
600
400
200
0
8.00
8.30
9.00
9.30
10.00
10.30
11.00
11.30
12.00
12.30
13.00
13.30
14.00
14.30
15.00
15.30
16.00
16.30
17.00
17.30
18.00
time of day, [h]

(c)



(d)

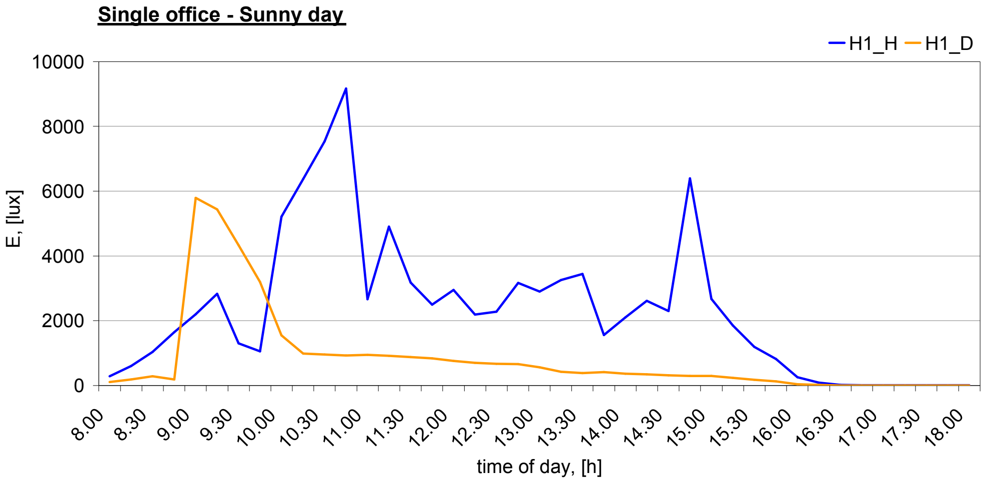


(e)

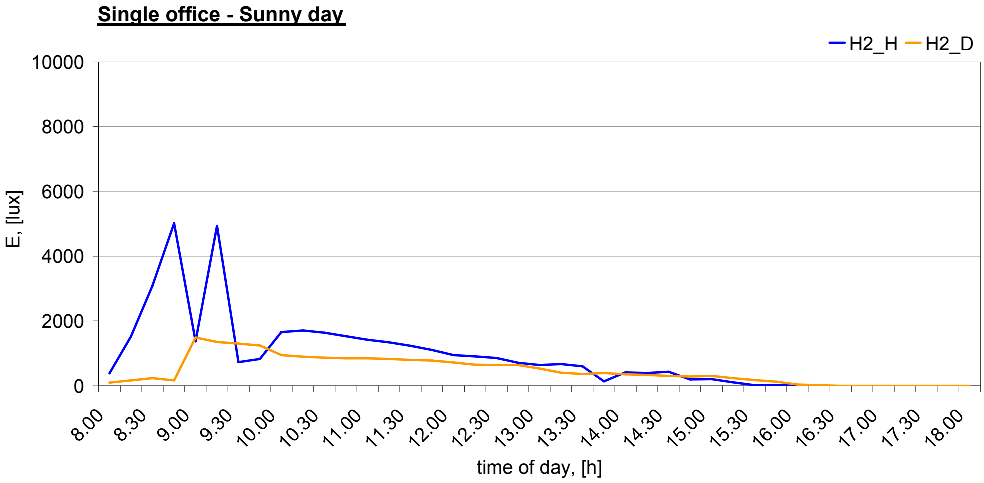
Figure 5.35 - Single office: illuminance values in sensor H1 (a), H2 (b), H3 (c), H4 (d) and H6 (e). 19th November 2009, overcast day, film coated façade

In the overcast day (Figure 5.35) the measured illuminance profiles correspond to the ones calculated by DAYSYM, both for horizontal and vertical sensors, although there is the same problem that occurs for the double office (higher calculated illuminances from 9:00 to 10:00).

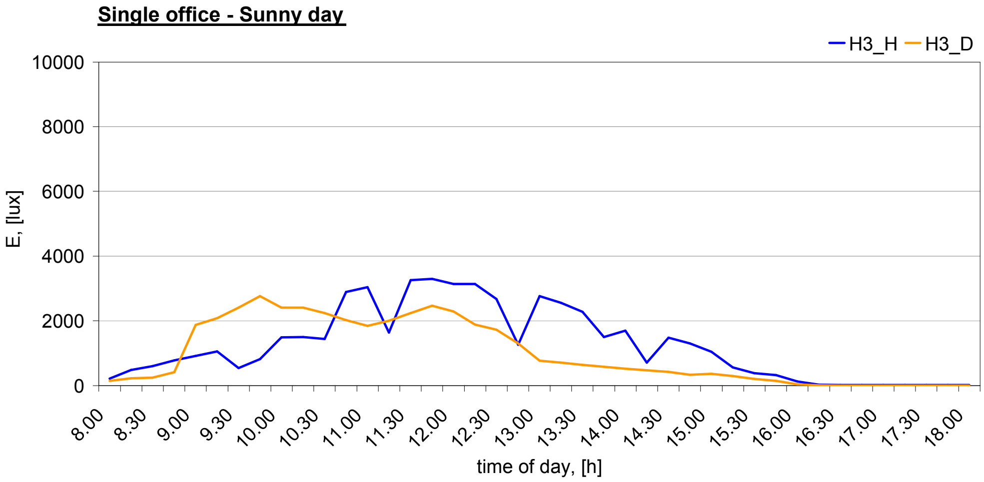
The following graphs (Figure 5.36) refer to illuminance profiles recorded in 2nd December, in each of the five sensors positioned in the single office.


Single office - Sunny day
H1_H
H1_D
E, [lux]
10000
8000
6000
4000
2000
0
8.00
8.30
9.00
9.30
10.00
10.30
11.00
11.30
12.00
12.30
13.00
13.30
14.00
14.30
15.00
15.30
16.00
16.30
17.00
17.30
18.00
time of day, [h]

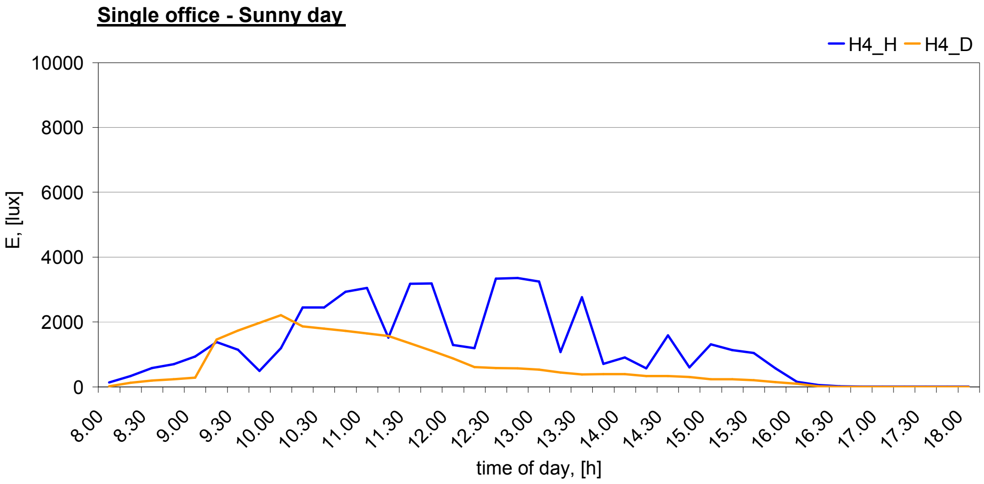
(a)


Single office - Sunny day
H2_H
H2_D
E, [lux]
10000
8000
6000
4000
2000
0
8.00
8.30
9.00
9.30
10.00
10.30
11.00
11.30
12.00
12.30
13.00
13.30
14.00
14.30
15.00
15.30
16.00
16.30
17.00
17.30
18.00
time of day, [h]

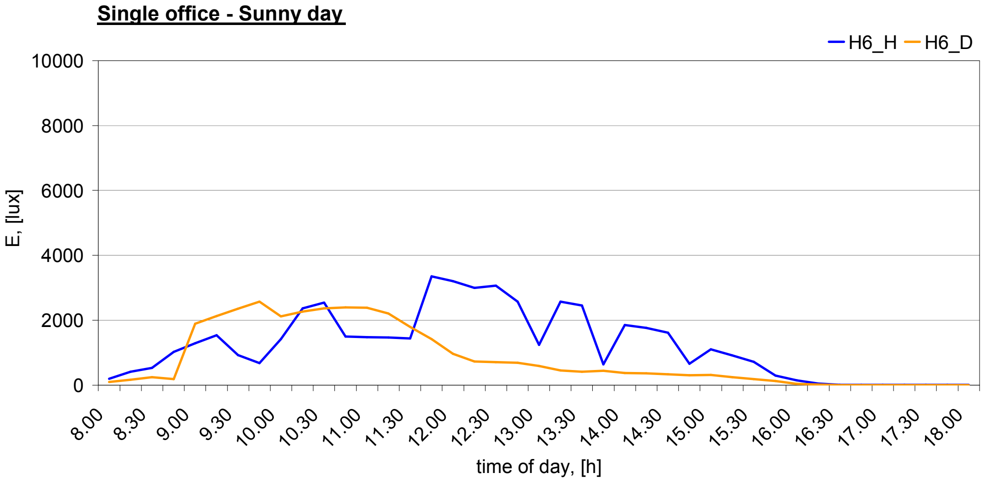
(b)


Single office - Sunny day
H3_H
H3_D
E, [lux]
10000
8000
6000
4000
2000
0
8.00
8.30
9.00
9.30
10.00
10.30
11.00
11.30
12.00
12.30
13.00
13.30
14.00
14.30
15.00
15.30
16.00
16.30
17.00
17.30
18.00
time of day, [h]

(c)



(d)



(e)

Figure 5.36 - Single office: illuminance values in sensor H1 (a), H2 (b), H3 (c), H4 (d) and H6 (e). 2nd December 2009, sunny day, film coated façade

In clear sky condition, the two sets of values are very different, since the recorded values result even ten times higher than the calculated ones (see sensor H1). This is probably explained by the fact that solar radiation hit directly the sensor: in fact, this problem occur in sensor H2 in the first hours of the morning (the sensor is North-East oriented), while, in sensor H1, which faces South-East, from 11:00 to all the afternoon. The same problem, but with lower differences (due to horizontal position instead of vertical one), happens in work plane sensors (H3, H4 and H6).

5.12. Calculated illuminance: comparison between glazed and film coated façade

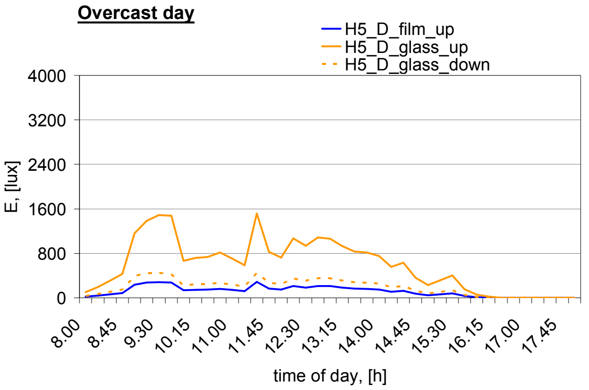
Even though a comparison between measured and calculated illuminance profiles, before and after film application, was not possible, some other simulations have been performed to analyse how lighting distribution would have been resulted if no film would have been provided.

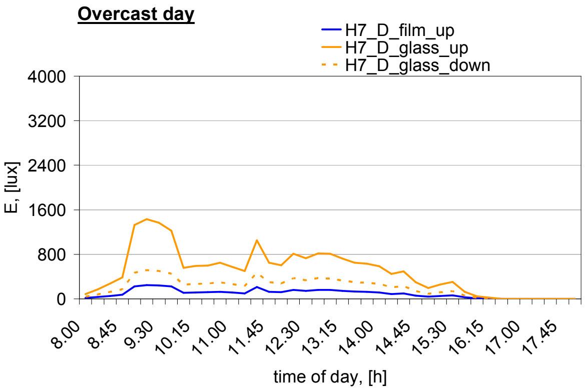
Double office

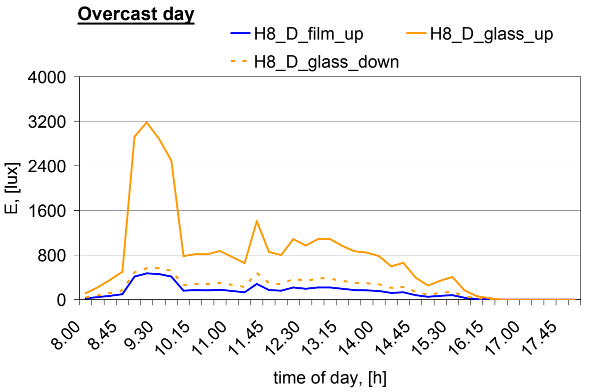
The following figures compare illuminance profiles inside the double office, considering glazed and film coated façade, in an overcast day (19th November) and in a sunny day (2nd December). The graphs legend is reported in Table 5.7.

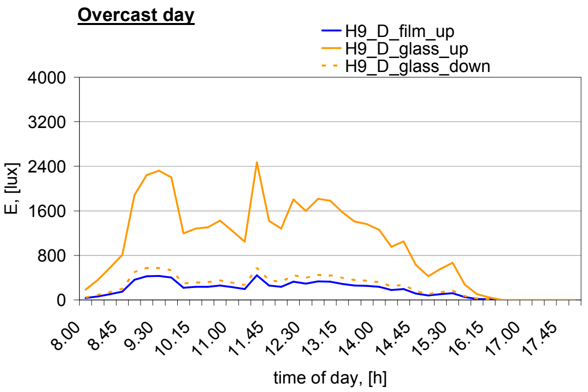
Table 5.7 – Graphs legend for figures from Figure 5.37 to Figure 5.40

H *sensor number* _D_film_up	film coated façade condition, with blinds up
H *sensor number* _D_film_down	film coated façade condition, with blinds down
H *sensor number* _D_glass_up	glazed façade condition, with blinds up
H *sensor number* _D_glass_down	glazed façade condition, with blinds down









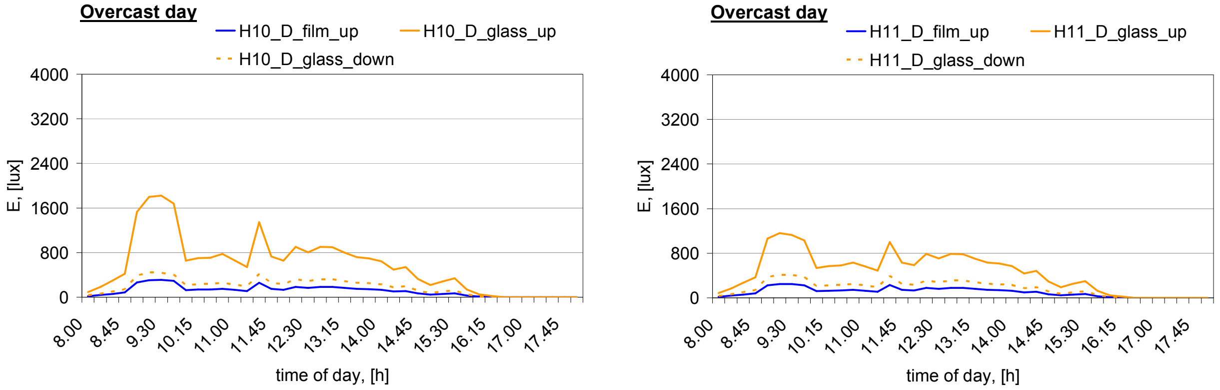
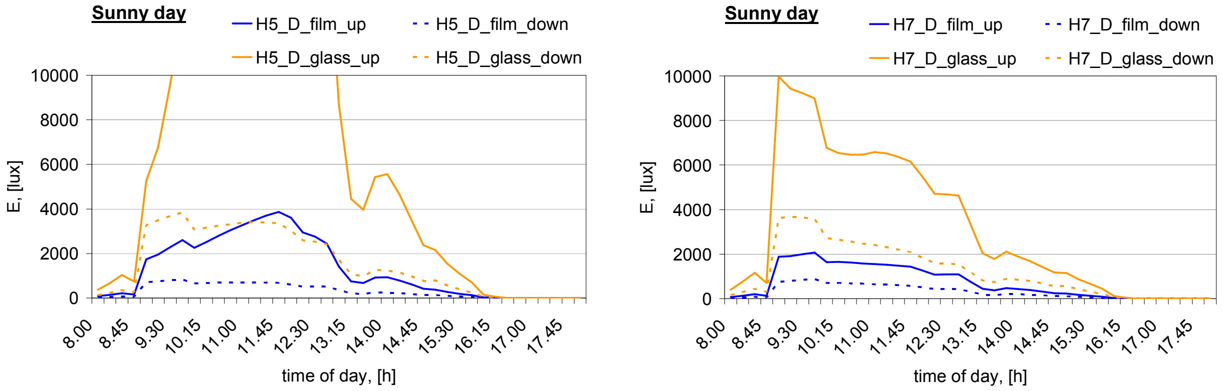


Figure 5.37 - Double office: comparison between calculated illuminances in glazed and in film coated façade condition. 19th November 2009, overcast day

In overcast conditions (Figure 5.37), the glazed façade can be responsible of high illuminance values, therefore the shading could be necessary. The need to keep the blinds down even in overcast conditions corresponds to the effective office assessment before film application, because occupants complained about glare. Moreover, keeping the blind always down means the loss of the view out and the contact between people and the outside, which is one of the most worker's complaints. If a film coating is provided, the same illuminance profiles, obtained in glazed façade condition with a shading, could be obtained and no shading is requested. On the other hand, electric lighting will be probably switched on because of low illuminance levels over the work plane.



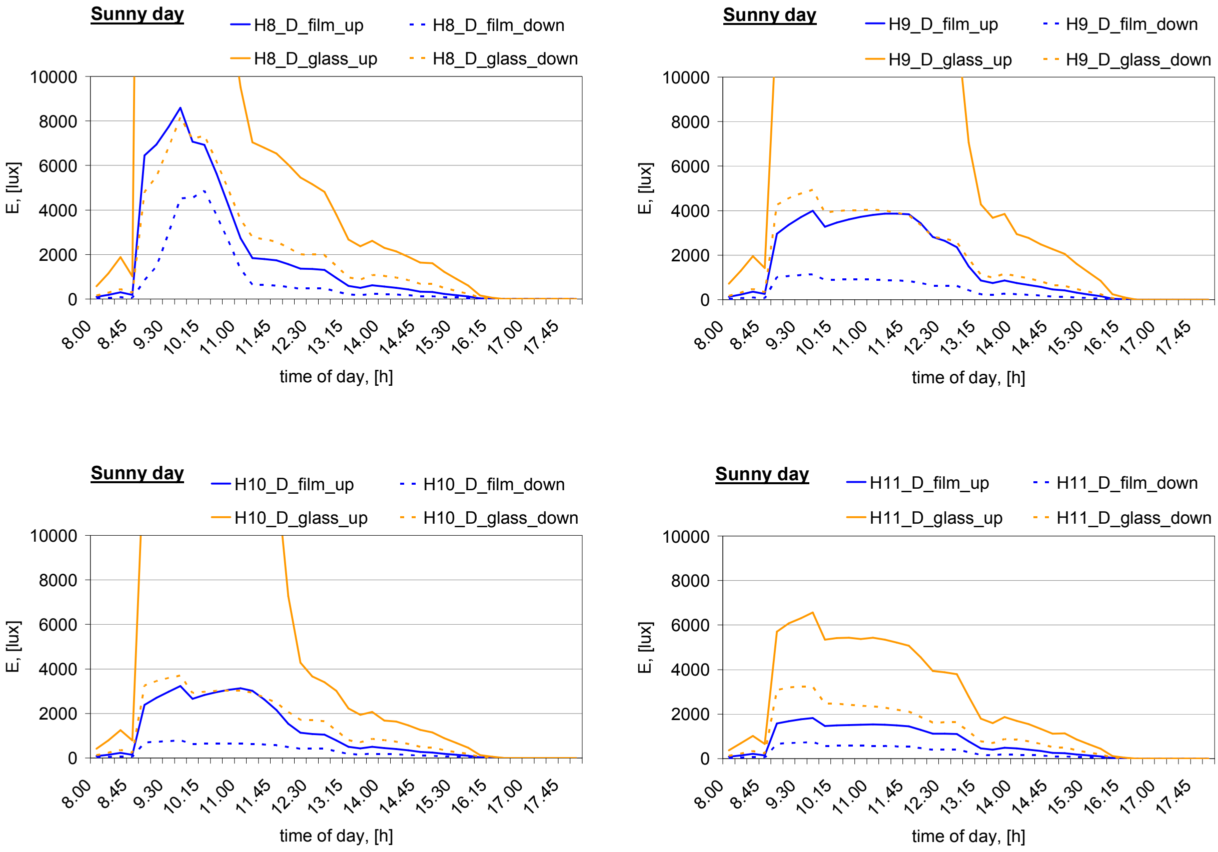


Figure 5.38 - Double office: comparison between calculated illuminances in glazed and in film coated façade condition. 2nd December 2009, sunny day

Considering the glazed façade, in clear sky condition (Figure 5.38) there is a great probability of visual discomfort, even if the rolling blinds are closed. In fact, in this case, illuminances are higher than in film-coated façade condition with the blinds retracted. Moreover, in sunny days, occupants would keep the blinds down, because the film coating is not sufficient to prevent glare. Only in film coating and blinds down condition, an acceptable lighting environment could be obtained and glare could be avoided.

Single office

The same conclusions carried out for the double office can be applied in the single office, if the following graphs are considered (Figure 5.39 and Figure 5.40).

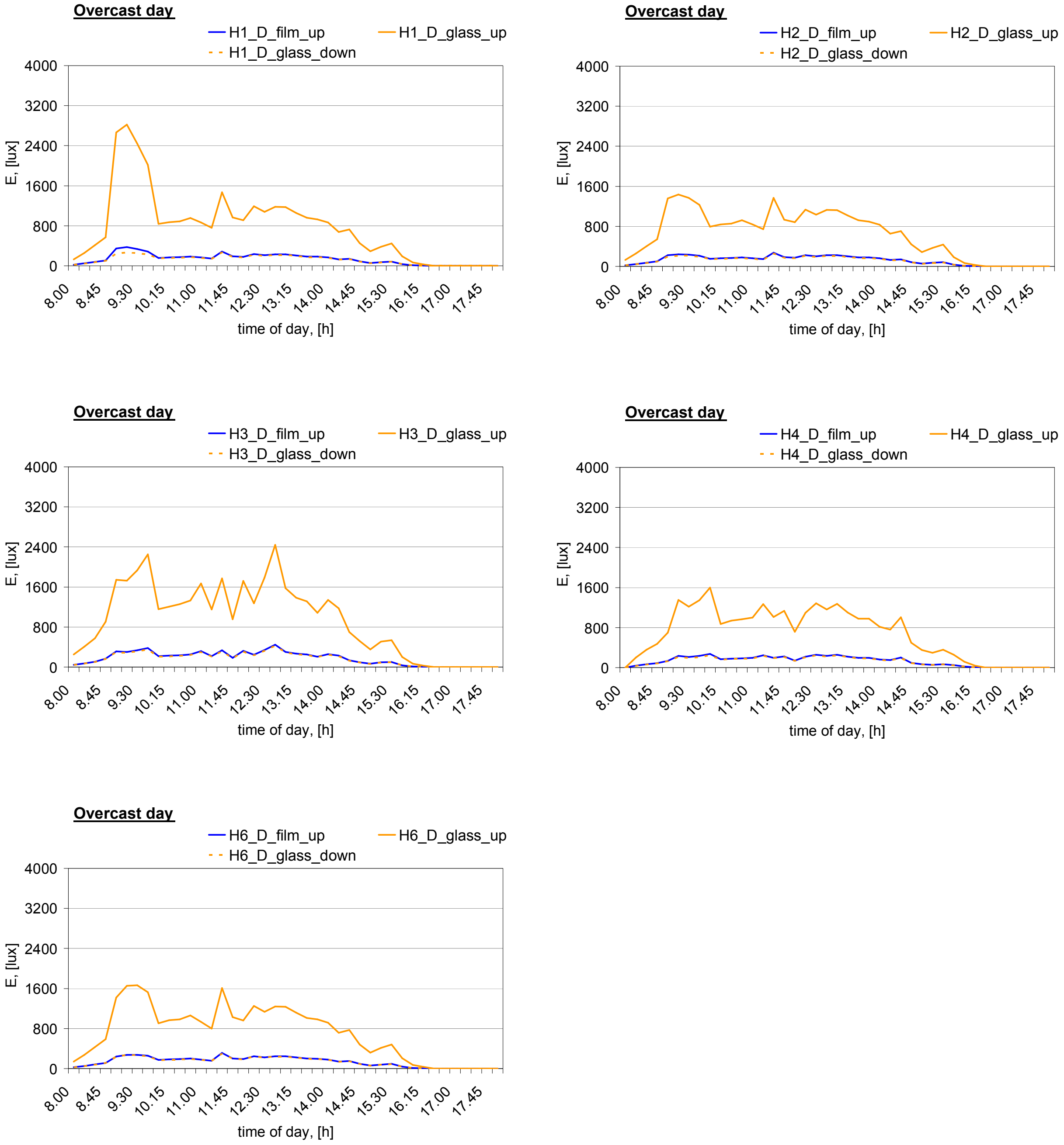


Figure 5.39 - Single office: comparison between calculated illuminances in glazed and film coated façade condition. 19th November 2009, overcast day

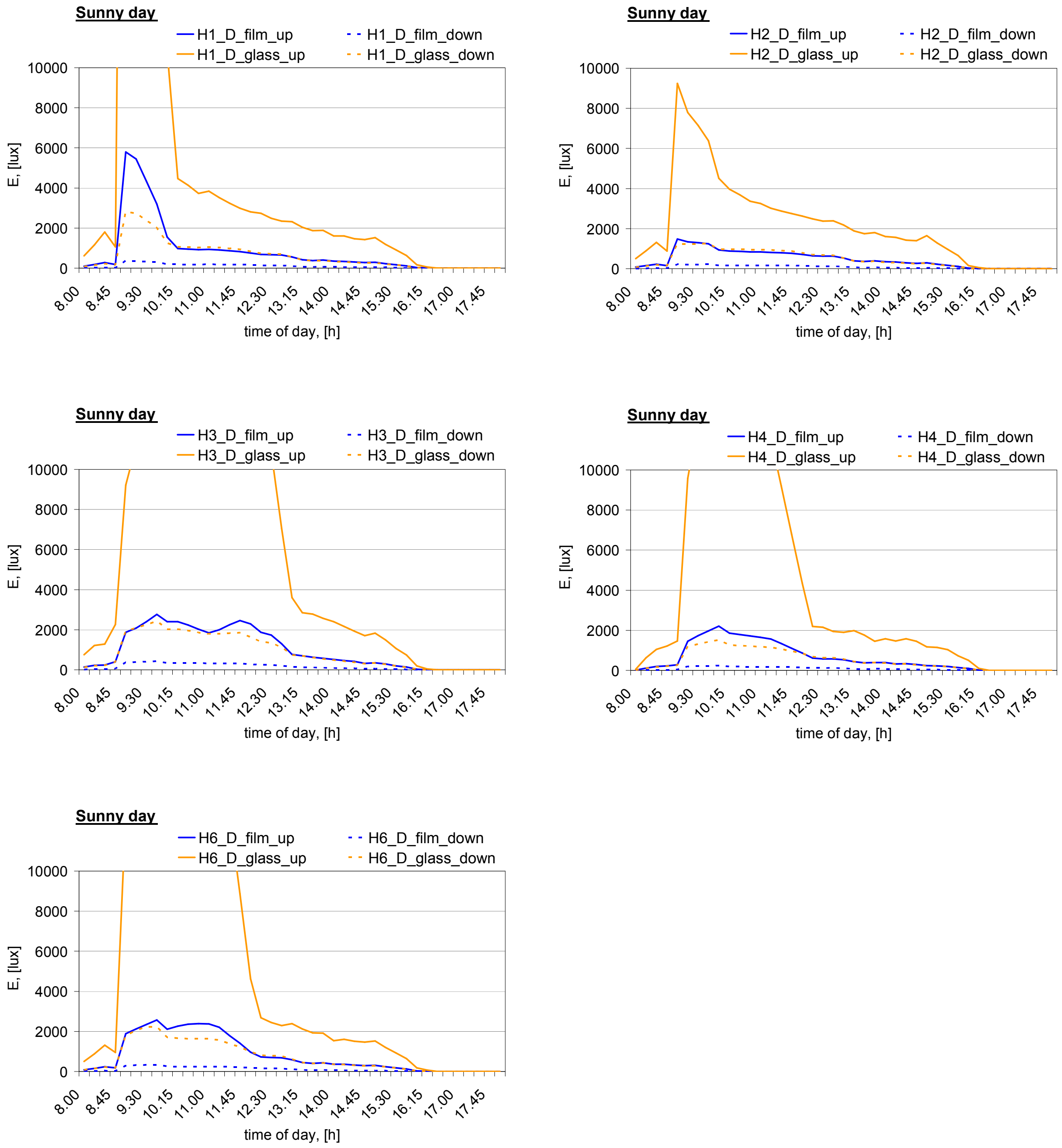


Figure 5.40 - Single office: comparison between calculated illuminances in glazed and film coated façade condition. 2nd December 2009, sunny day

5.13. Electric energy consumption for lighting

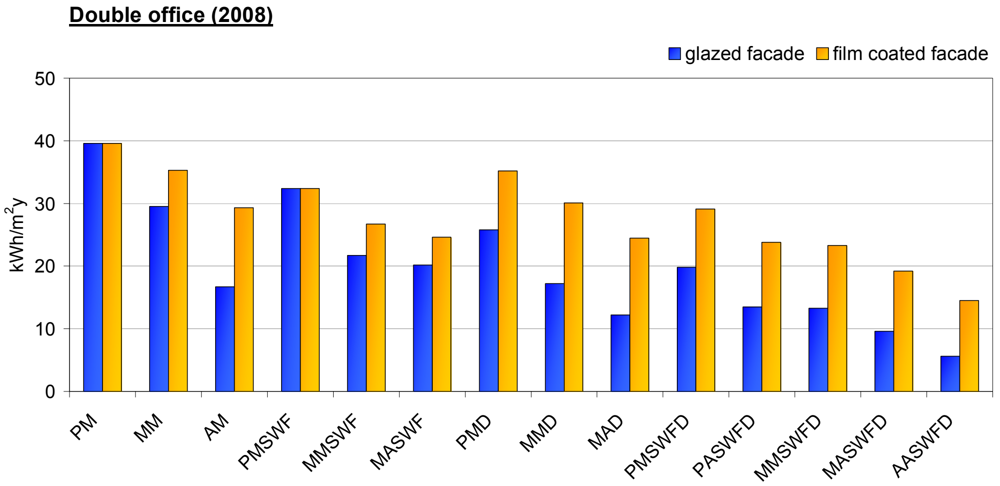
The electric energy demand, referred to the different lighting and blind control strategies, combined with the three user behaviours, listed in Table 5.5, has been calculated, considering both glazed and film coated façade, for both the year 2008 and 2009. The year 2008 has been taken into account because the overall energy evaluation, briefly reported in section 5.15, refers to that year. Moreover, the available effective electric energy consumption is relative to 2008.

In all the offices of the tower no lighting nor shading automatic control are provided, therefore only manual control (PM, MM and AM) should be considered; nevertheless some combinations of user behaviour and automatic controls have been supposed in order to evaluate which ones can lead to significant energy savings.

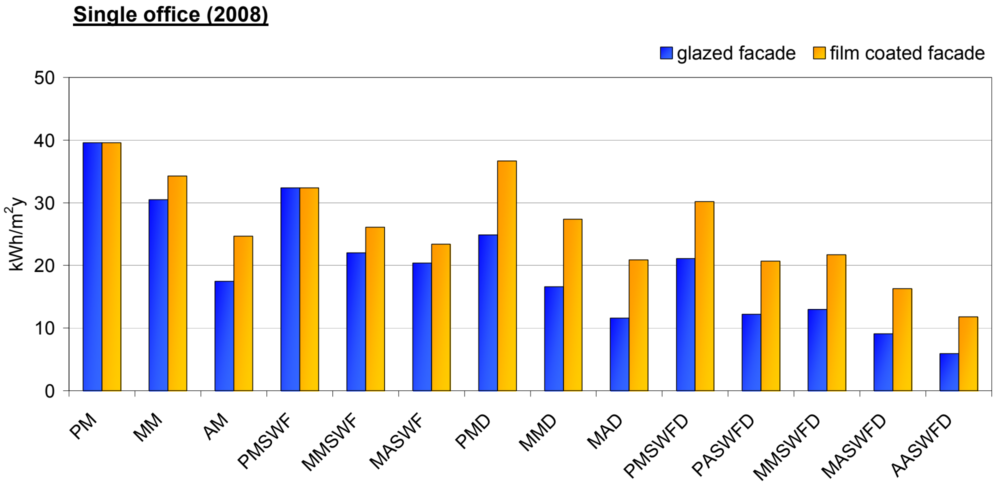
The graphs related to year 2008 are reported in Figure 5.41, while the ones to year 2009 in Figure 5.42.

The energy consumption referred to the combination passive user and manual control (PM) is the same in all the four cases (considering both façade conditions and reference years), because the model considers that the light is switched on for all occupancy hours. The same happens even if there is a switch off occupancy sensor, because the occupancy profile is the same.

Comparing the energy requirement for lighting in 2008, for the double office , a film coated façade requests at least 22% more energy with a switch off occupancy sensor, 36% with a dimmer system and 47% (and even the double and a half for an active user) with the combination of them, instead of a glazed façade. In 2009 a film coated façade needs at least 11% more energy with a switch off occupancy sensor, 75% with a dimmer system and 64% (and even the double for an active user) with the combination of them instead of a glazed façade.



(a)

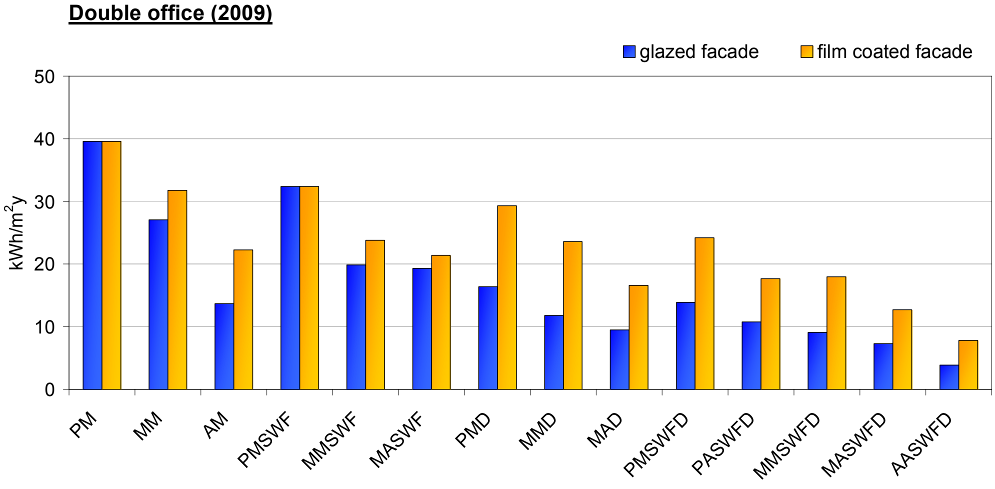


(b)

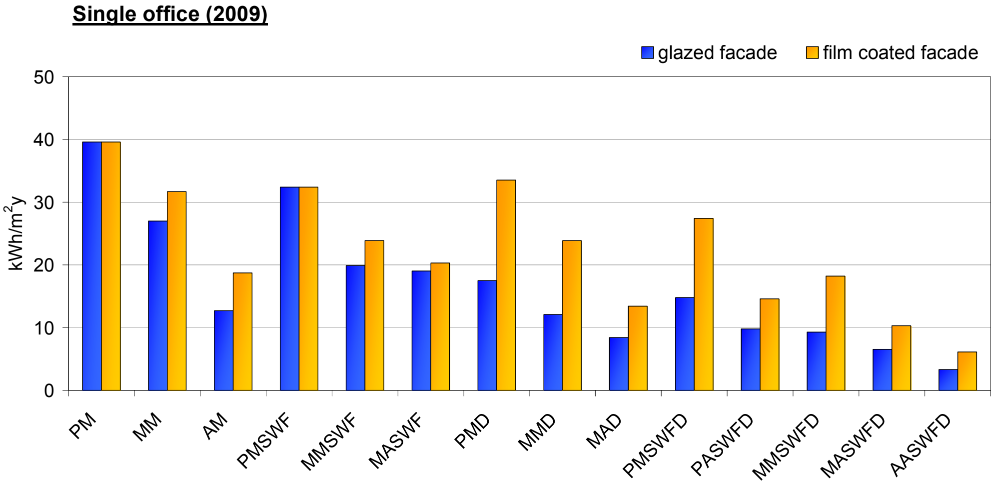
Figure 5.41 - Double office (a) and single office (b): electric energy consumption depending on user behaviour and lighting/shading control (year 2008)

For the single office, in 2008, a film coated façade requests at least 15% more energy with a switch off occupancy sensor, 47% with a dimmer system and 43% (and even the double for an active user) with the combination of them instead of a glazed façade. In 2009 a film coated façade needs at least 7% more energy with a switch off occupancy sensor, 60% with a dimmer system and 49% (and even 85% for an active user) with the combination of them instead of a glazed facade.

Considering manual control, no significant energy increase is found if the offices are occupied by a mix user (for the double office the increase is around 18%, while for the single one, it is around 15%), while if an active user is assumed, the increase is around 70% for the double office and around 45% for the single one.



(a)



(b)

Figure 5.42 - Double office and single office: electric energy consumption depending on user behaviour and lighting/shading control (year 2009)

In general, electric energy consumption for lighting is higher for year 2008 than for year 2009, in both offices. Considering the double office in glazed façade condition, in 2009 there is at most an 8% of energy reduction with a switch off occupancy sensor, a 36% with a dimmer system and a 30% with the combination of dimmer and switch off occupancy systems. For manual control, the energy saving is 18% for an active user, while 8% for a mix of both users. In film façade condition, the energy saving is at most 16% higher with a switch off occupancy sensor, 32% with a dimmer system and 37% (and even 46% for an active user) with the combination of these two systems. For manual control, the energy saving is 14% for an active user and 10% for a mix of both users.

For the single office, in glazed façade condition, there is at most 10% of reduction providing a switch off occupancy sensor, while, considering the presence of a dimming system alone, or in combination with a switch off occupancy sensor, the energy reduction becomes the 30% (and even 44% for an active user). For manual control, the energy saving is 27% for an active user and 12% for a mix of both users. Finally, in film coated façade condition, the energy saving is at most 13% providing a switch off occupancy sensor, 36% (and even 48% for an active user) with a dimmer system and with the combination of them. For manual control, the energy saving is 24% for an active user and 8% for a mix of both users.

The comparison between the two analysed years, demonstrates that the energy savings obtained by BMS depend also on weather condition (i.e. available solar radiation).

The bar charts in Figure 5.43 show how the user behaviour can influence energy consumption in manual control condition. The mix of both users and the active user are compared against the passive one (MM vs PM and AM vs MM); moreover, the mix of both users are compared against the active one.

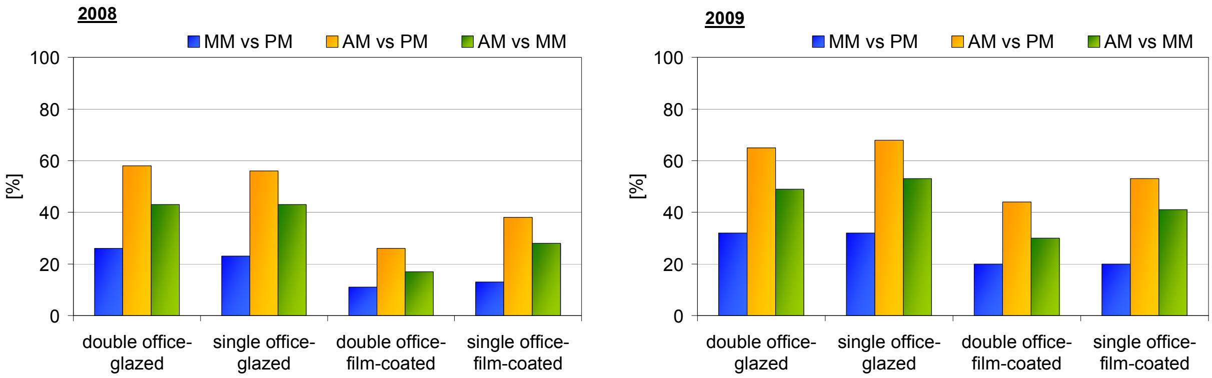


Figure 5.43 - Electric energy savings for lighting, depending on user behaviour (year 2008 and 2009)

For example, for the single office, in 2009, an active user behaviour, compared to a passive one, can reduce energy consumption of 68% in glazed façade condition and of 53%, if the film coated is provided.

In conclusion, the occupant behaviour has a great influence in energy reduction for lighting, even if any kind of automation is supplied, therefore it is important to make people aware of possible energy reduction depending on how they operate both lighting and shading systems. Moreover, BMS can sensibly reduce electrical energy requirements for lighting, so they should be taken into account in building design.

5.14. Dynamic daylight performance metrics

Dynamic daylight performance metrics have been calculated with DAYSIM, considering both façade configurations for the two offices.

The difference between a passive and an active user, who operates the blind manually, against an automated shading control has been evaluated; in Table 5.9 daylight performance metrics are reported for the two work-stations (Figure 5.12) of the double office and in Table 5.11 for the single one.

Table 5.8 – Legend for Table 5.9

wp1-G-08	glazed façade, year 2008, workplane 1
wp2-G-08	film coated façade, year 2008, workplane 2
wp1-F-08	film coated façade, year 2008, workplane 1
wp2-F-08	film coated façade, year 2008, workplane 2
wp1-G-09	glazed façade, year 2009, workplane 1
wp2-G-09	glazed façade, year 2009, workplane 2
wp1-F-09	film coated façade, year 2009, workplane 1
wp2-F-09	film coated façade, year 2009, workplane 2

Table 5.9 - Dynamic daylight performance for the double office

	wp1-G-08	wp2-G-08	wp1-F-08	wp2-F-08	wp1-G-09	wp2-G-09	wp1-F-09	wp2-F-09
DA$_{act}$	71	71	19	23	83	83	47	49
DA $_{pass}$	36	35	2	2	67	66	17	16
DA$_{con, act}$	82	82	46	49	89	89	70	71
DA$_{con, pass}$	61	59	20	21	78	78	46	46
DA$_{max, act}$	2	2	0	0	3	3	1	1
DA$_{max, pass}$	0	0	0	0	1	1	0	0
UDI $_{act}$<100	11	11	33	31	8	8	17	16
UDI$_{pass}$<100	21	23	65	65	13	14	33	33
UDI$_{act}$100-2000	64	65	66	68	51	52	77	77
UDI$_{pass}$100-2000	74	73	35	35	67	68	67	67
UDI$_{act}$>2000	25	24	1	1	42	40	6	7
UDI$_{pass}$>2000	4	4	0	0	20	18	0	0
annual light exposure [luxh]	5553155	5589362	1277840	1473337	7834906	7712743	2780215	2994813

Table 5.10 – Legend for Table 5.11

G-08	glazed façade, year 2008
F-08	film coated façade, year 2008
G-09	glazed façade, year 2009
F-09	film coated façade, year 2009

Table 5.11 - Dynamic daylight performance for the single office

	G-08	F-08	G-09	F-09
DA$_{act}$	71	23	84	54
DA $_{pass}$	21	0	53	1
DA$_{con, act}$	81	50	90	73
DA$_{con, pass}$	48	11	72	25
DA$_{max, act}$	2	0	5	0
DA$_{max, pass}$	0	0	0	0
UDI $_{act}$<100	14	29	7	15
UDI$_{pass}$<100	30	82	16	51
UDI$_{act}$100-2000	57	71	45	80
UDI$_{pass}$100-2000	70	18	81	49
UDI$_{act}$>2000	30	0	48	4
UDI$_{pass}$>2000	0	0	3	0
annual light exposure [luxh]	5951725	1234770	8852547	2636885

The Useful Daylight Illuminances (UDI) is one of the main interesting parameters, since it aims at determining when daylight levels can guarantee a sufficient lighting level or when glare can occur.

DAYSIM gives only three UDI parameters and its default range $UDI_{100-2000}$ considers an extremely high illuminance range. For this reason, another set of UDI has been suggested, considering six illuminance ranges, instead of three, that are:

- UDI< 100 (UDI_{100}): already calculated by DAYSIM, it indicates when electric lighting is necessary because of very low levels of daylight.
- 100<UDI<300 ($UDI_{100-300}$): this range has been chosen because illumination preferences vary between individuals (Jennings et al., 1999; Reinhart and Voss, 2003) and sometimes it happens that people work in such illuminance conditions.
- 300<UDI<500 ($UDI_{300-500}$): this range can be compared to the Continuous Daylight Autonomy (DA_{con}) parameter, because it takes into account that, even if illuminance is under the required 500 lux, electric lighting could not be necessary.
- 500<UDI<1000 ($UDI_{500-1000}$): this range is meant to detect when there is a great daylight availability and a proper visual comfort
- 1000<UDI<2000 ($UDI_{1000-2000}$): if illuminance levels belong to this range the environment looks bright, but glare could not occur.
- UDI>2000 (UDI_{2000}): already calculated by DAYSIM, it indicates when glare (and also overheating) can occur.

These UDI have been set and calculated by means of a spreadsheet macro. The input required are: illuminance profiles and occupancy schedule. The occupancy schedule can be directly chosen by the designer, considering the actual occupancy of the analysed building or making predictions, according to different building occupancy. The possibility to change the occupancy schedule allow to calculate these parameters for any kind of buildings, not only commercial ones. Moreover, these new UDI indexes can be calculated even for each month of the year, to know how daylight availability changes during the year. Finally, if the same room is occupied by many people (open-spaces, classrooms, etc.), the designer can choose to consider one or more work planes at the same time, to predict daylight distributions in different part of the same environment.

In the analysed case, UDI values have been obtained from the following occupancy schedule:

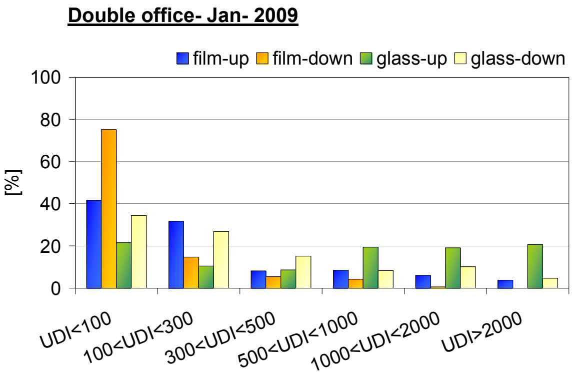
- arrival time: 9:00;
- departure time: 18:00;
- the work place is occupied from Monday to Friday;
- the lunch break occurs from 13:00 to 14:00;
- two fifteen minutes breaks are scheduled from 10:30 to 10:45 in the morning and from 16:00 to 16:15 in the afternoon;
- holidays and vacation days (Easter, Christmas, all Italian public holydays and the second week of August) have been considered (DAYSIM does not consider them).

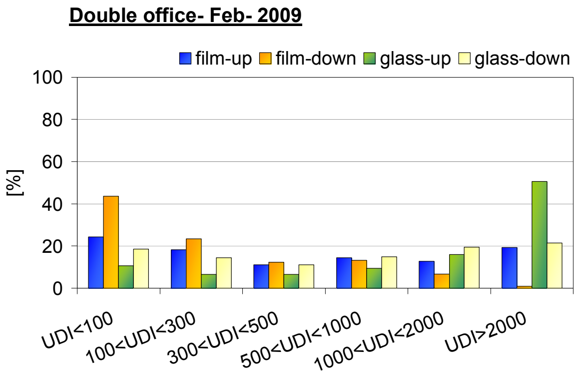
The illuminance profiles refer to year 2009, therefore the annual occupancy schedule has been calculated for the year 2009. Two set of monthly UDI have been estimated: one for the shading up and one for the shading down condition, since two set of illuminance profiles are available by means of DAYSIM simulations. The graphs legend for Figure 5.44 and Figure 5.45 is reported in Table 5.12.

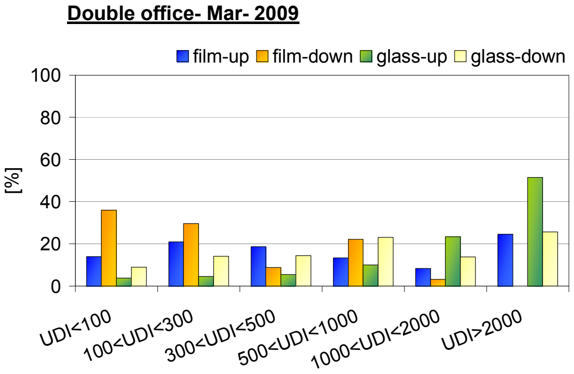
Table 5.12 – Legend for graphs in Figure 5.44 and in Figure 5.45

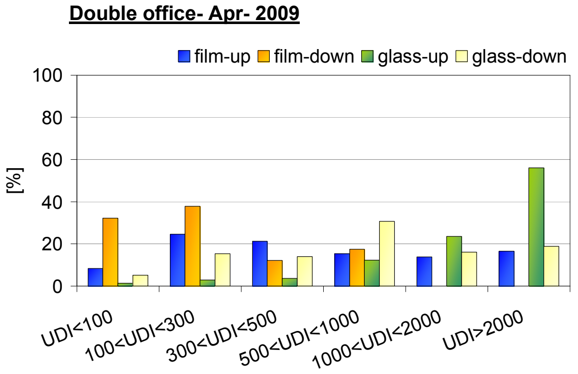
film_up	film coated façade condition, with blinds up
film_down	film coated façade condition, with blinds down
glass_up	glazed façade condition, with blinds up
glass_down	glazed façade condition, with blinds down

The UDI values calculated for the double office (Figure 5.44) refer to work plane 1 (Figure 5.12). The bar charts compare illuminance ranges, for each month of the year 2009, obtained in glazed façade condition and in the film coated one. Moreover, the setting of the shading device (i.e. the curtains) is taken into account.









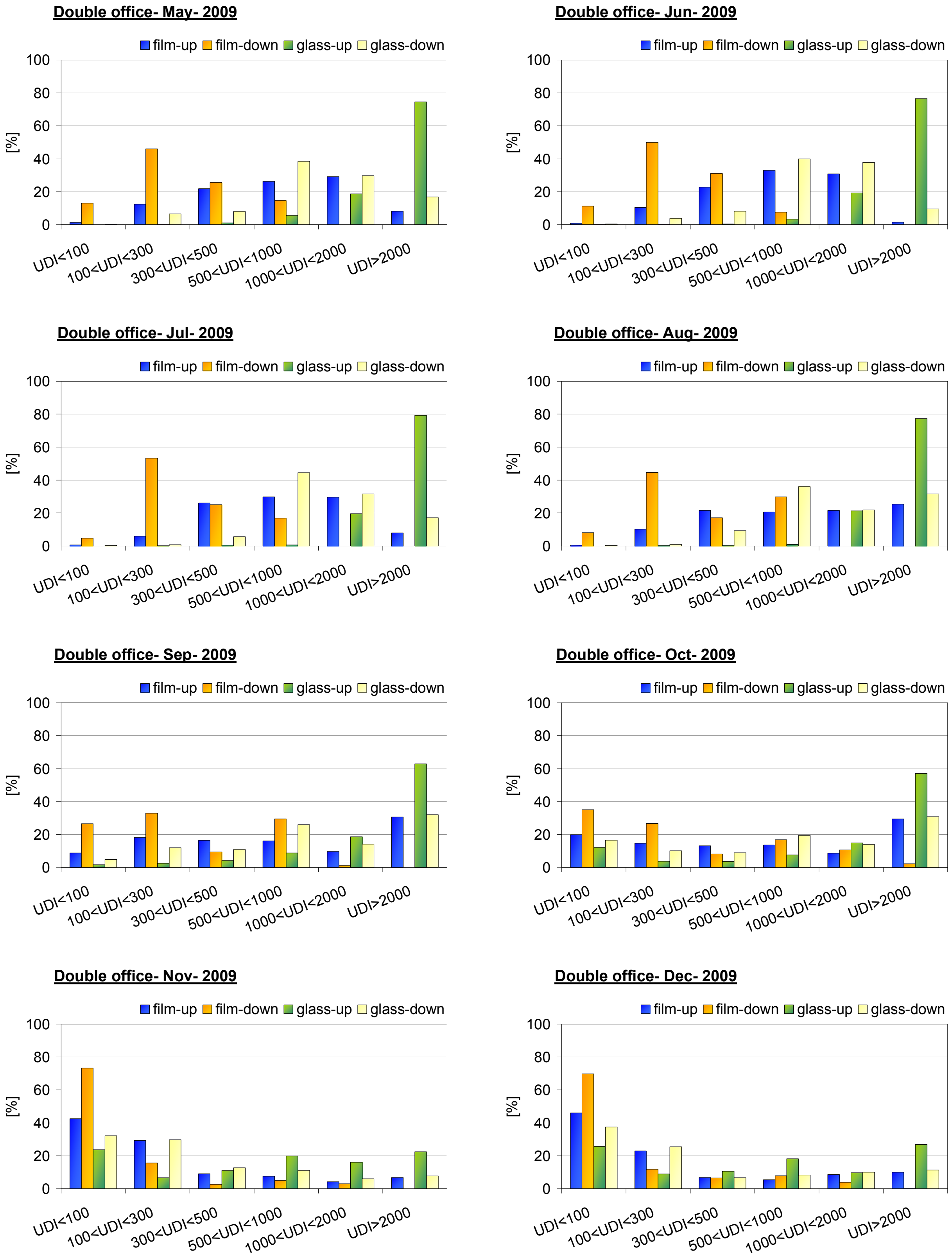
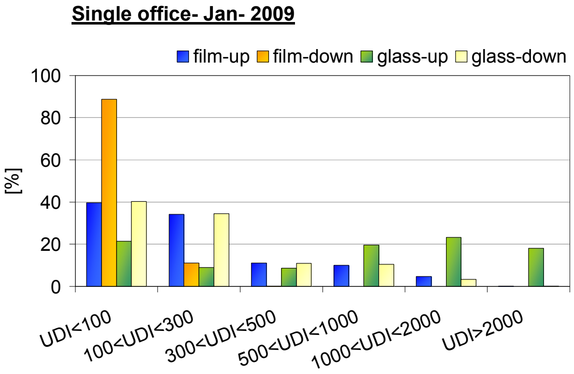
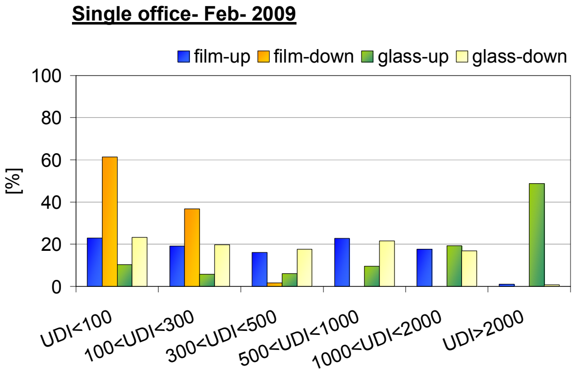
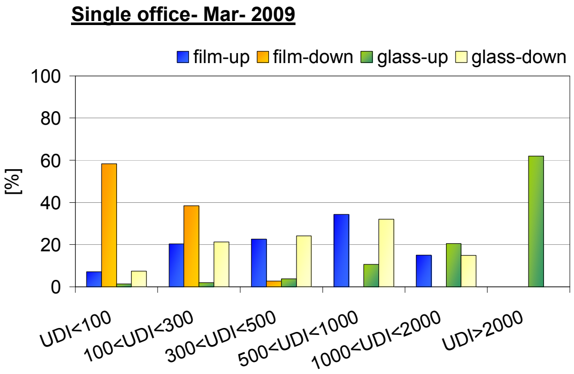


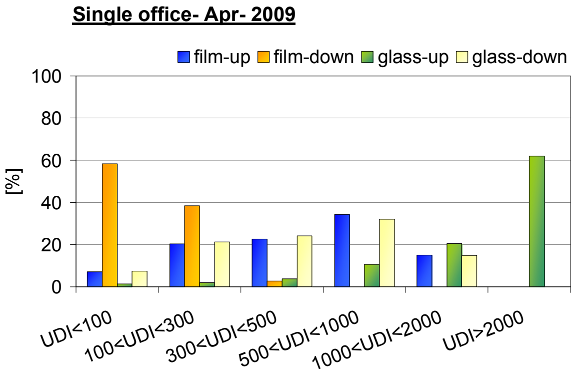
Figure 5.44 - Double office: UDI, calculated for each month of year 2009, considering both the shading up and fully down

It can be noticed that in glazed façade condition, for an office South-East oriented, glare would occur every month of the year, even with the curtains fully closed: the UDI_{2000} is, in blinds up condition, at least 20% and it reaches the maximum percentage in June (80%), while, with the curtains down, it is at least 5% and it is 35% at most from August to October. In film-coated façade condition, no glare problems would occur leaving the curtain down, while, if the curtain is retracted, glare could occur at most for the 30% of the month in September and in October. This means that the glazed façade does not guarantee an acceptable visual comfort, while the application of window films can be a solution to this problem. In winter, the presence of film determines insufficient lighting levels, which happen twice with respect to having glass alone. Glass alone cannot limit the occurrence of glare, thus the shading has to be closed; this fact leads to lighting levels similar to the ones obtained by the application of films. In summer, visual comfort can be guaranteed for at least the 80% of the time in film coated façade even with the curtains down, while, in glazed façade condition, the shading is required most of the time: in this condition (glazed façade with shading down) occupants lose the view to the outside, which has been demonstrated to be one of the main sources of dissatisfaction.


Single office- Jan- 2009


Single office- Feb- 2009


Single office- Mar- 2009


Single office- Apr- 2009

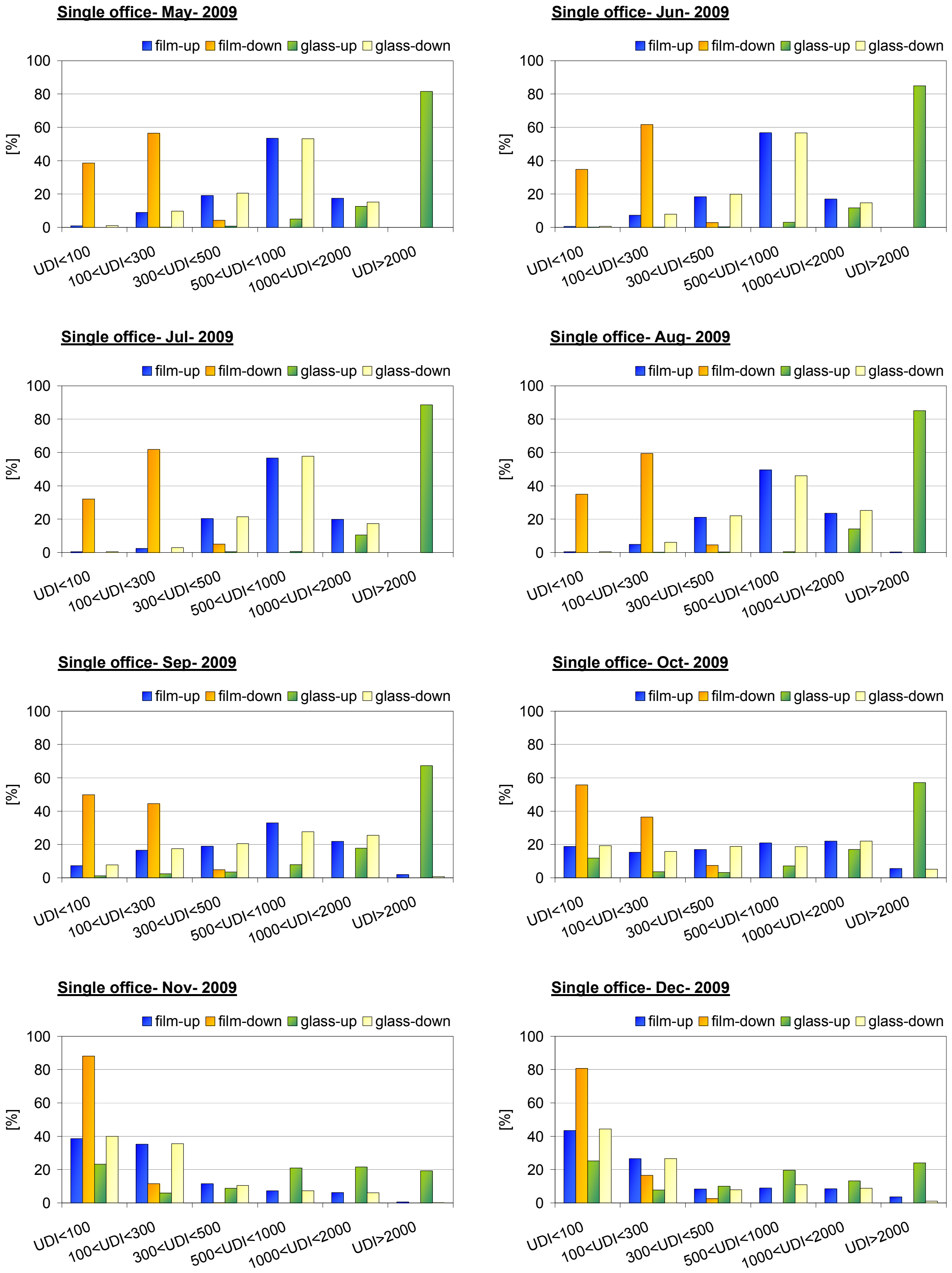


Figure 5.45 - Single office: UDI, calculated for each month of year 2009, considering both the shading up and fully down

The Figure 5.45 shows the monthly UDI values calculated in the work plane of the single office (Figure 5.15), North-East oriented, considering both glazed and film coated façade condition. It can be noticed that UDI_{2000} values in "*glass-up*" condition are higher than in the double office work plane (e.g. in July it is 90%), therefore the curtain would be left down most of time in summer, avoiding the possibility to have a view out. In any time of the year, the "*film-up*" condition would determine visual discomfort, even though sometimes the office would result bright ($UDI_{1000\text{-}2000}$ is at most 25% in August). Moreover, in summer, the "*film-up*" condition guarantees the required illuminance ($UDI_{500\text{-}1000}$) values for the 60% of the time, while, in winter, the presence of film determines insufficient lighting levels twice the time than having glass alone, as it happens in the double office.

5.15. Energy model

A thermal model of the analyzed building has also been developed. For the calculation of internal loads to be considered, the thermal model has taken advantage of the results predicted by the lighting model about electric usages for lightning. Measured and predicted energy needs have been compared with reference to 2008 conditions, and it has been found that thermal model predictions align with measured energy use data. Then, it has been assumed that 2008 represents the base case adopted for the comparison. The lighting model and the thermal model have been coupled to simulate 2008 weather conditions, supposing films were applied to glazed surfaces. Finally, the resulting energy needs have been compared to the base case energy requirements, thus enabling the verification of the energy conservation potential of window films.

The analyzed building has been modelled using the computer program TRNSYS (Klein et al., 2002). The analyzed building has been divided into nineteen thermal zones. Data from construction documents have been used to develop the simulation model. Data include building geometry and construction details. Construction thermal properties used in the simulation are listed in Table 5.1 and in Table 5.13. Each zone has been characterized in terms of use patterns. Each zone is given different set point temperatures, occupancy period and HVAC operation basing on the data collected by means of occupants surveys and walk through inspections.

Table 5.13 – Envelope characteristics

External wall	U = 0.54 W/(m^{2}K)
Internal wall (stairwells)	U = 2.36 W/(m^{2}K)
Internal partition	U = 1.82 W/(m^{2}K)
Attic	U = 1.43 W/(m^{2}K)
Roof	U = 0.68 W/(m^{2}K)

Internal loads have been calculated as being the result of the sum between a component related to office equipment (such as computers, copiers and printers) and a component related to artificial lightning. The latter (Q_{el}) has been calculated as follows (ASHRAE, 2005):

$$Q_{el} = W \times F_{ul}$$

where W is the total light wattage (obtained from the ratings of all lamps installed) and F_{ul} is the ratio of wattage in use to total installed power. The component related to office equipment has been calculated making reference to the occupancy patterns of single offices.

DAYSIM has been applied to predict the ratio of wattage in use to the total installed power for lights to enable the evaluation of internal gains to be used in the thermal analysis for 2008 analysis (Table 5.14). The mean between the results referencing to the two offices assumed as being representative of the different usage patterns recognized in the analyzed building has been implemented in thermal model.

Table 5.14 - Calculated ratio of the wattage in use due to electric lighting to the total installed power with reference to 2008 conditions (pre-intervention status)

Month	F_{ul}	Month	F_{ul}
Jan	0.42	Jul	0.08
Feb	0.41	Aug	0.17
Mar	0.28	Sep	0.23
Apr	0.22	Oct	0.39
May	0.09	Nov	0.44
Jun	0.08	Dec	0.46

It has been assumed that the reported values for lights usage are common to all the zones of the thermal model. Calculated internal loads have been implemented into the thermal analysis and 2008 conditions have been simulated. The total calculated energy need resulted in being 285 MWh, while the total measured energy was 293 MWh. The discrepancy is about 3%. The comparison between measured and calculated energy needs, taking into account each single floor of the analyzed building, is presented in Figure 5.46.

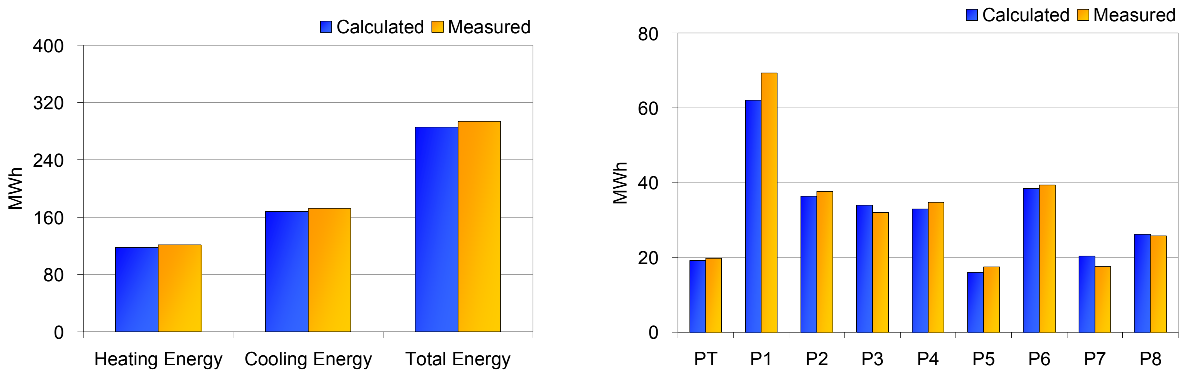


Figure 5.46 - Measured and calculated annual energy needs

DAYSIM has then been applied to predict the ratio of wattage in use to the total light installed power assuming that films were applied to the East, South and West façade. 2008 weather conditions still apply. Results are presented in Table 5.15.

Table 5.15 - Calculated ratio of the wattage in use due to electric lighting to the total installed power with reference to 2008 conditions. It has been assumed that films were applied to glazed surfaces

Month	F_{ul}	Month	F_{ul}
Jan	0.51	Jul	0.34
Feb	0.37	Aug	0.36
Mar	0.41	Sep	0.35
Apr	0.38	Oct	0.49
May	0.39	Nov	0.48
Jun	0.28	Dec	0.44

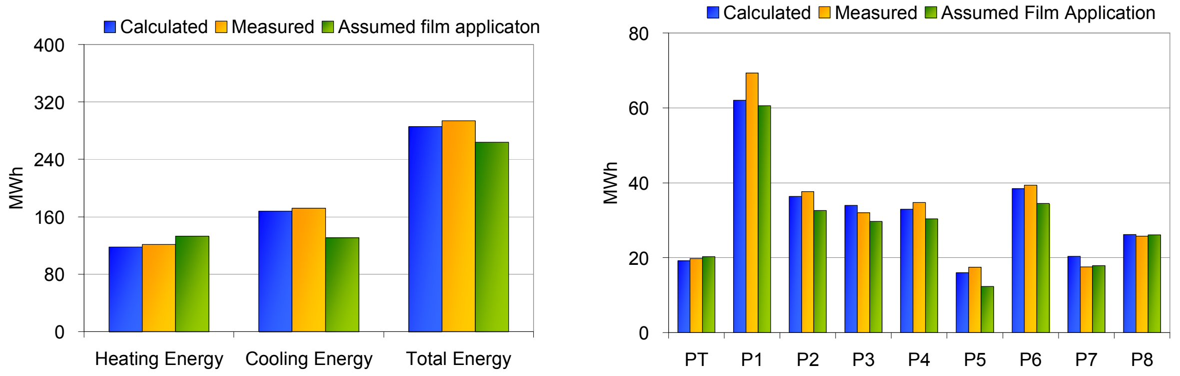


Figure 5.47 - The saving potential consequent of the application of window films compared to 2008 actual energy needs

The resulting energy need is 264 MWh, about 10% less than the total measured value. The comparison referred to each single floor is presented in Figure 5.47. It is interesting to see how the reduction in the solar heat gain coefficient due to the application of films resulted in a higher heating demand. Nevertheless, the raise in the heating demand is lower than the reduction in the cooling needs.

5.16. Simulations with RADIANCE

DAYSIM does not produce rendering scenes, therefore some RADIANCE simulations (by using "*rpict*", which is one of the main tools of the program) have been run to show how the two offices look like in the two analysed days. The simulated hour is midday and the two analysed days are 19th November 2009 (overcast day) and 2nd December 2009 (sunny day).

The CIE overcast sky model has been chosen for 19th November, considering the effective value of diffuse and direct horizontal radiation (using the options *–B* and *–R*, respectively). The following command line calls the tool "*gensky*" which generate a sky:

```
!gensky   11   19   12   -a 45.25   -o   -11.52   -m   -15   -B 96   -R 2   –c
```

"*Gensky*" produces a RADIANCE scene description for the CIE Standard Sky distribution: it is possible to specify month, day and time or solar altitude and azimuth (RADIANCE command manual). "*Gensky*" supports many different options; In this case, the specified options are:

- month day and hour (11, 19, 12)
- latitude (-*a*), longitude (-*o*), time zone (-*m*): 45.25 , -11.25 and -*15* (Padua)
- horizontal diffuse irradiance (-*B*): 96
- horizontal direct irradiance (-*R*): 2
- sky distribution: -c which correspond to the standard CIE overcast sky

The CIE clear sky model (option "-*s*") has been chosen for 2nd December, considering the effective value of diffuse and direct horizontal radiation (using the options "*–B"* and "*–R"*, respectively). The "*gensky*"command line is the following:

```
!gensky 12  2  12  -a 45.25  -o  -11.52  -m -15  -B 68  -R 309  -s
```

The sky description used in both the days is the following:

```
skyfunc glow skyglow   0   0   4   1   1   1   0

skyglow source sky   0   0   4   0   0   1   180
```

The first part is the material description of the sky, using the material type "*glow*", which is used for surfaces that are self-luminous, but limited in their effect. It is defined by four numbers which correspond to the RGB radiance value (W/(m^2 sr)) and a maximum radius for shadow testing. The second part corresponds to the geometrical sky description ("*source*"). A *"source"* is not really a surface, but a solid angle. It is used to specify light sources that are very distant (like the sky). The "*source"* is described by four numbers, which correspond to the direction to the centre of the source and the number of degrees subtended by its disk.

The ground description used in both the two days is the following:

skyfunc glow groundglow 0 0 4 1 1 1 0

groundglow source ground 0 0 4 0 0 -1 180

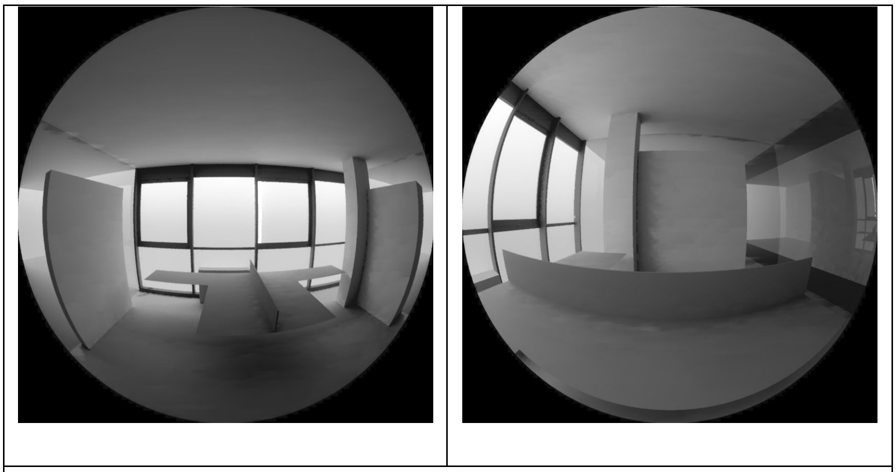
Some of RADIANCE simulation parameters used for the simulations are reported in Table 5.16.

Table 5.16 – Simulations parameters used for RADIANCE simulations

ambient bounces	**ambient divisions**	**ambient sampling**	**ambient resolution**	**ambient accuracy**
5	1024	512	256	0.1

Renderings

Figures below are rendering images of the two offices in the specified time of day.



(a)

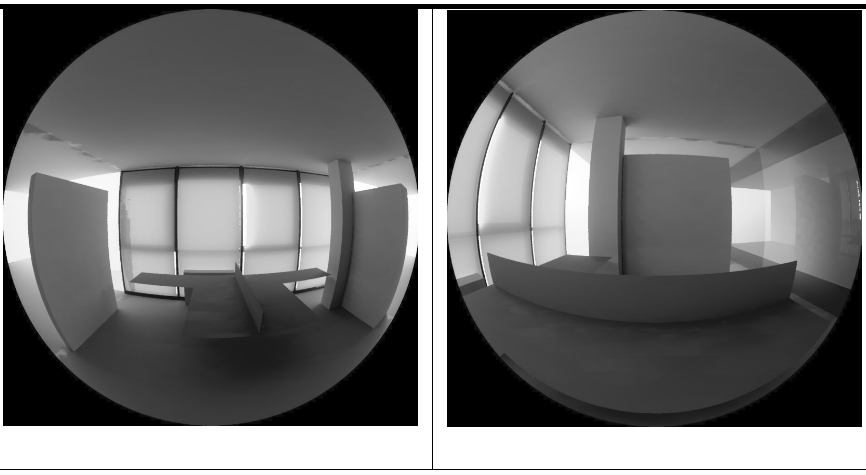
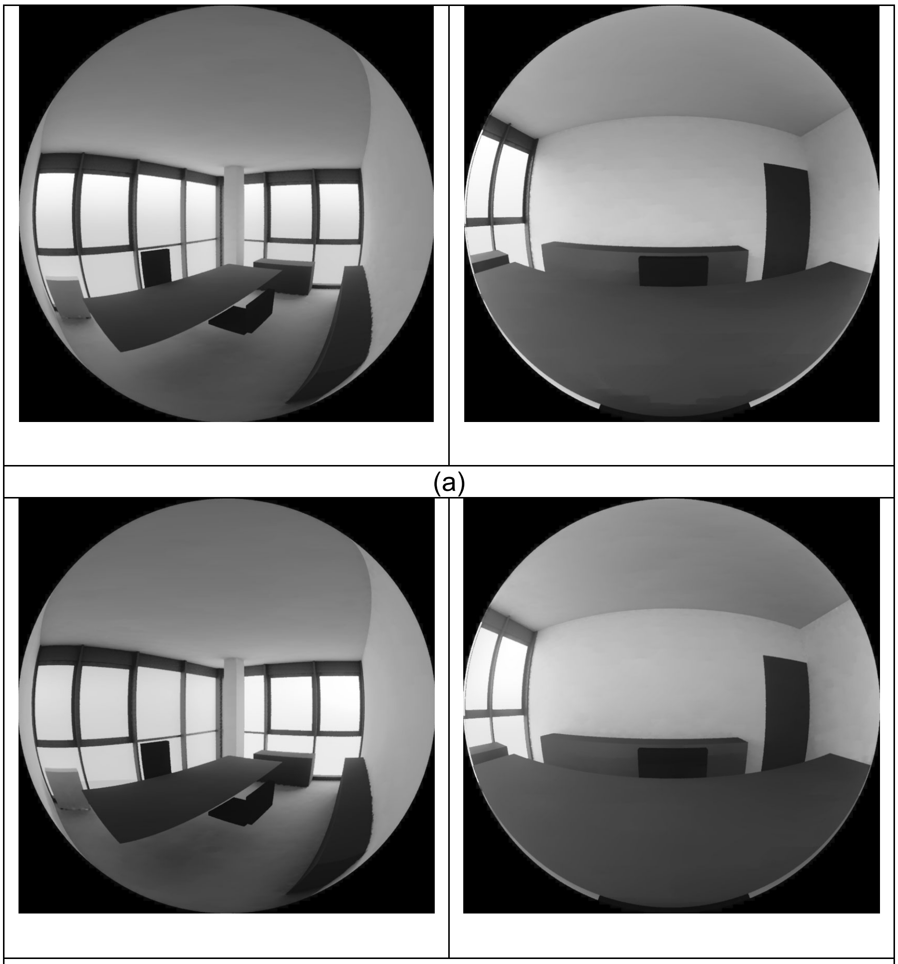

(b)

Figure 5.48 - Double office with film coated façade: renderings in overcast sky condition, with roller blinds up (a) and in clear one, with roller blinds down (b)

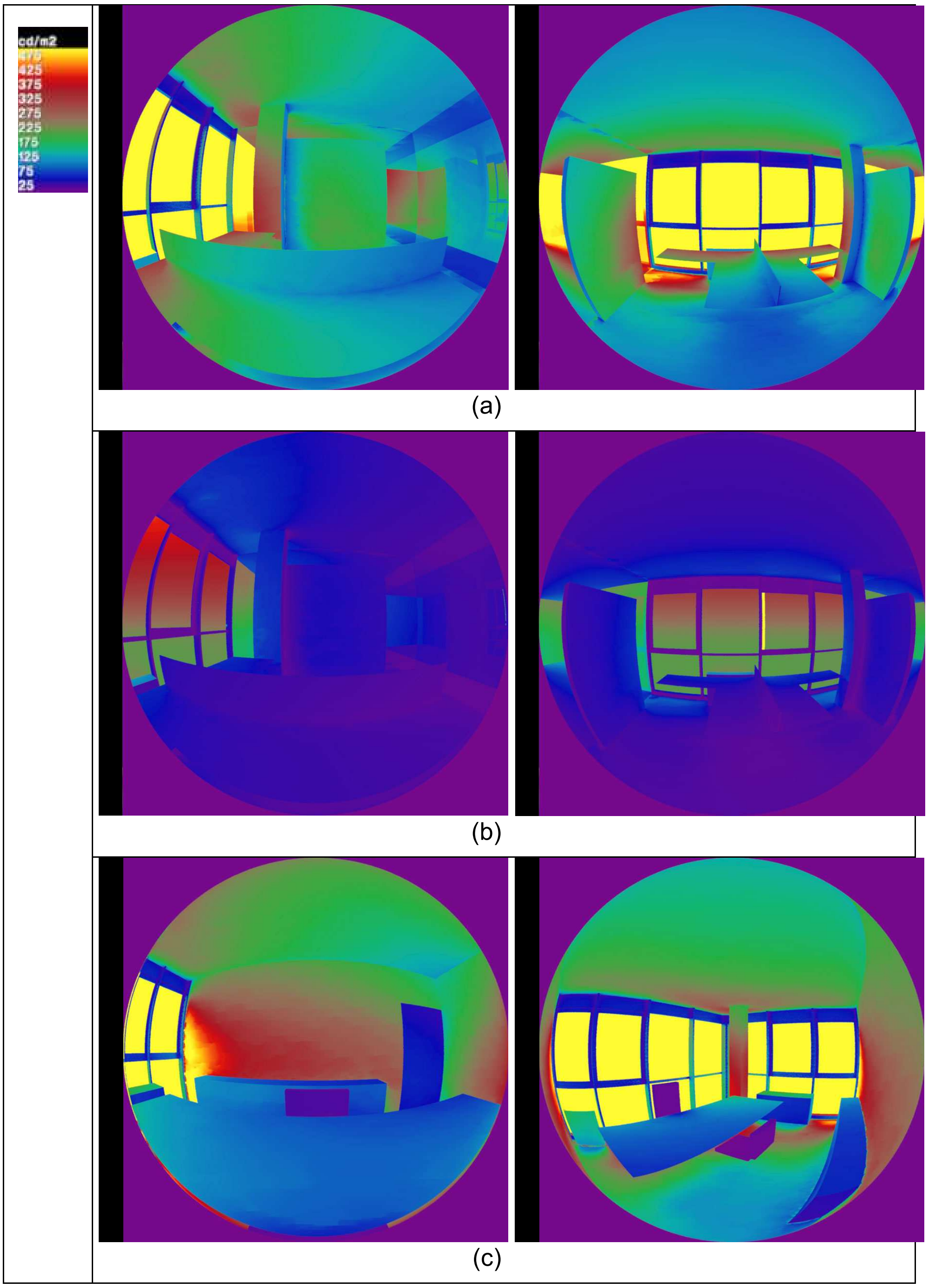

(a)

(b)

Figure 5.49 – Single office with film coated façade: renderings in overcast sky condition (a) and in clear one (b), both with roller blinds up

Luminance distribution

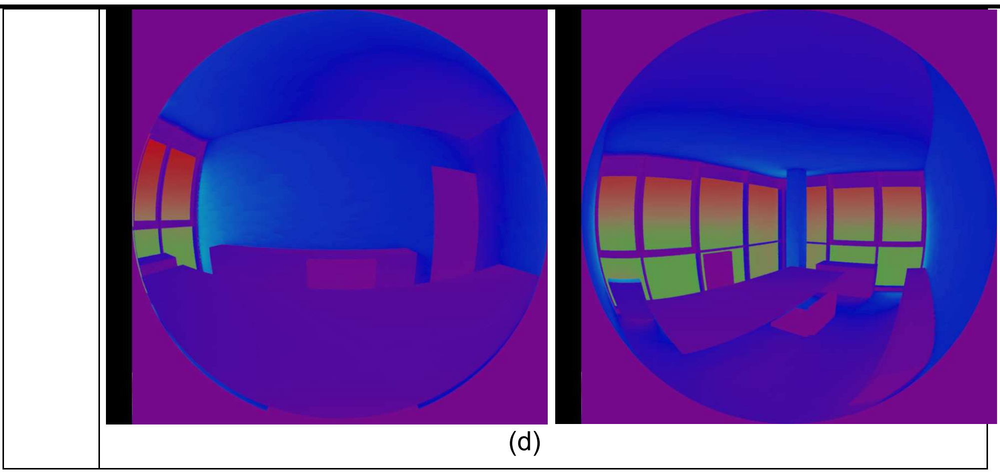
The following set of figures represents some false colour images that show the luminance distribution of the offices, considering both glazed and film-coated façade conditions. Figure 5.50 is referred to 19th November 12:00; the sky description is the CIE overcast sky. The luminance distribution, supposing a glazed façade ((a) and (c)) is compared to the one obtained if a film coated would have been provided ((b) and (d)).



(a)

(b)

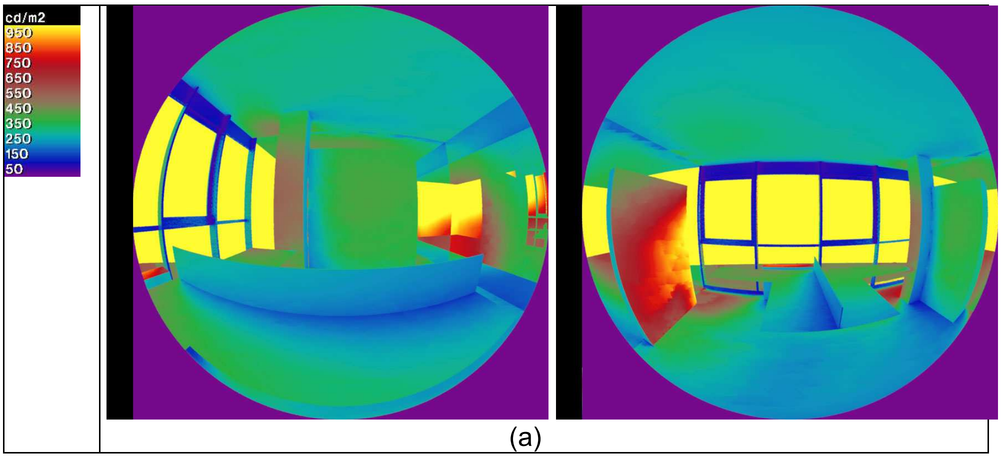
(c)



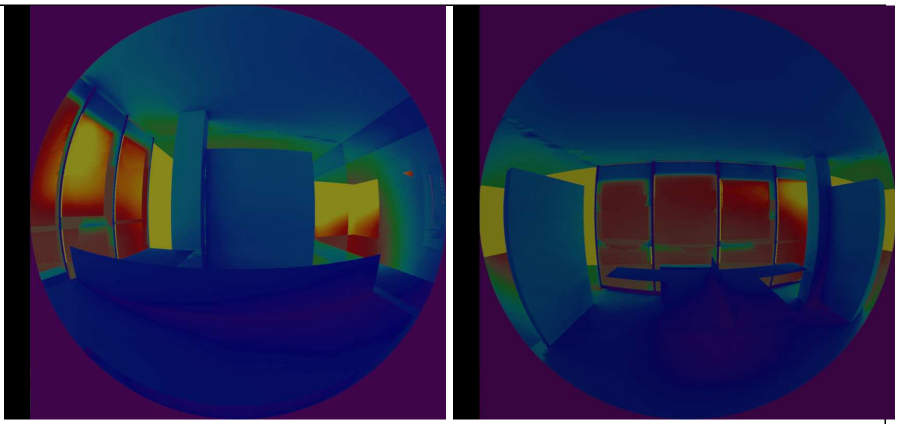
(d)

Figure 5.50 - Double office. False colour images which map luminance distribution: 19th November 12:00 (overcast sky), with glazed façade (a) and with film coated façade (b); Single office. False colour images which map luminance distribution: 19th November 12:00 (overcast sky), with glazed façade (c) and with film coated façade (d)

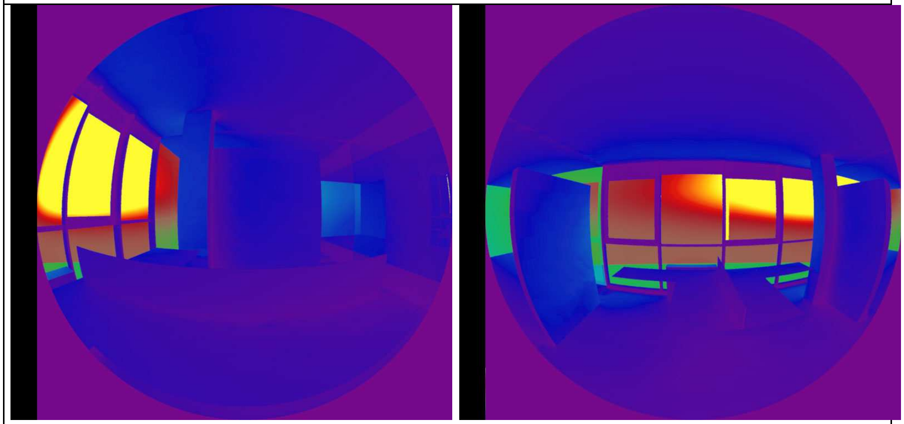
Figure 5.51 is referred to 2nd December 12:00; the sky description is the CIE clear sky. The luminance distribution, supposing a glazed façade ((a), (b) and (e)), is compared to the one obtained if a film coated would have been provided ((c), (d) and (f)). Figures (b) and (d) show the luminance distribution in the double office with the curtains down.



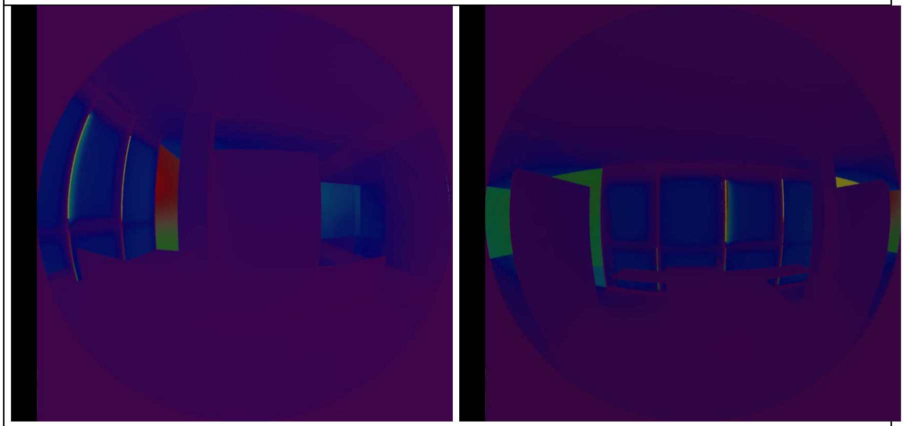
(a)



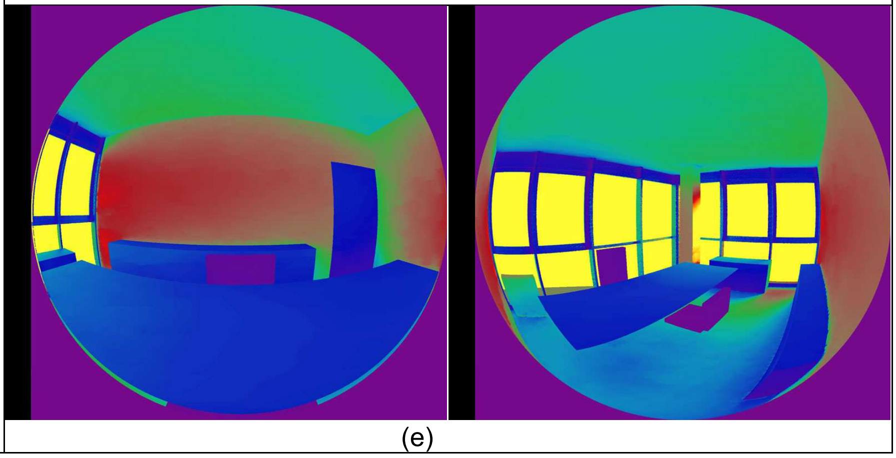
(b)



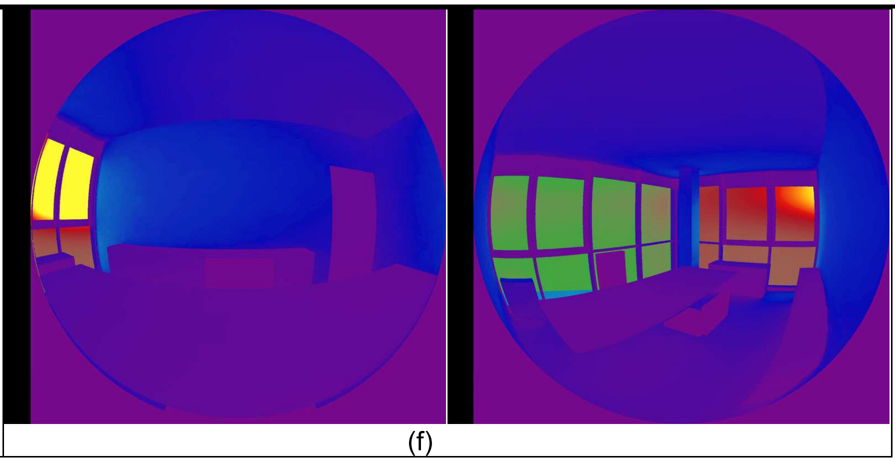
(c)



(d)



(e)

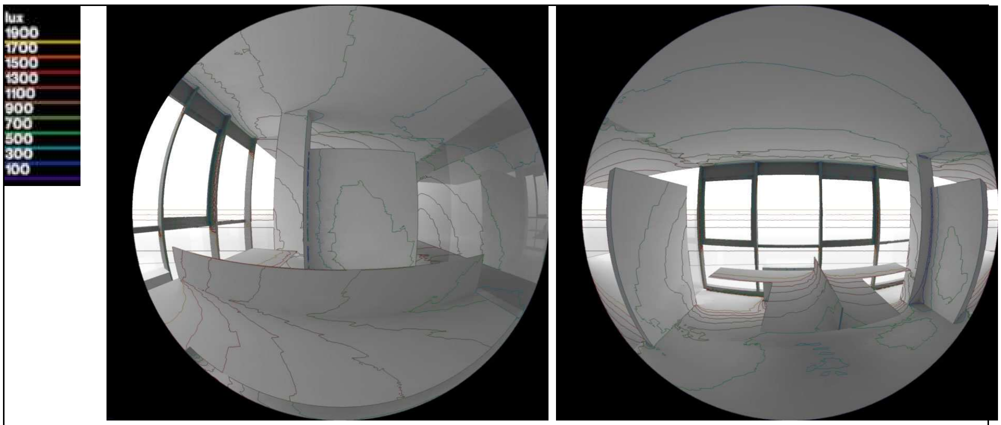


(f)

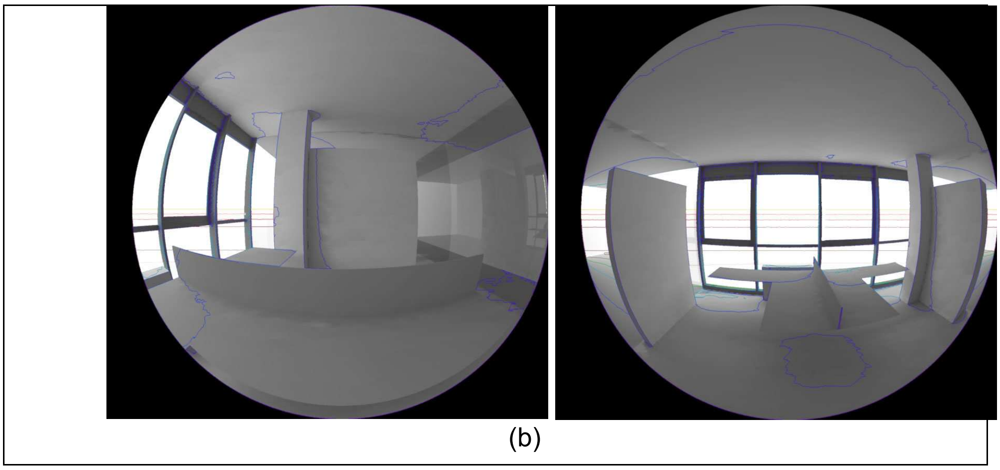
Figure 5.51 –Double office. False colour images which map luminance distribution: 2nd December 12:00 (clear sky), with glazed façade and blinds up (a) and with blinds down (b); with film coated façade and blinds up (c) and with blinds down (d). Single office, blinds up. False colour contour lines of illuminance: 2nd December 12:00 (clear sky), with glazed façade (e) and with film coated façade (f)

Illuminance distribution

The following figures show the false colour contour lines of the illuminance which have been overlaid onto a background image, considering both glazed and film-coated façade conditions. Figure 5.50 (double office) and Figure 5.53 (single office) are referred to 19th November 12:00; the sky description is the CIE overcast sky. The illuminance distribution, supposing a glazed façade (a) is compared to the one obtained if a film coated would have been provided (b).

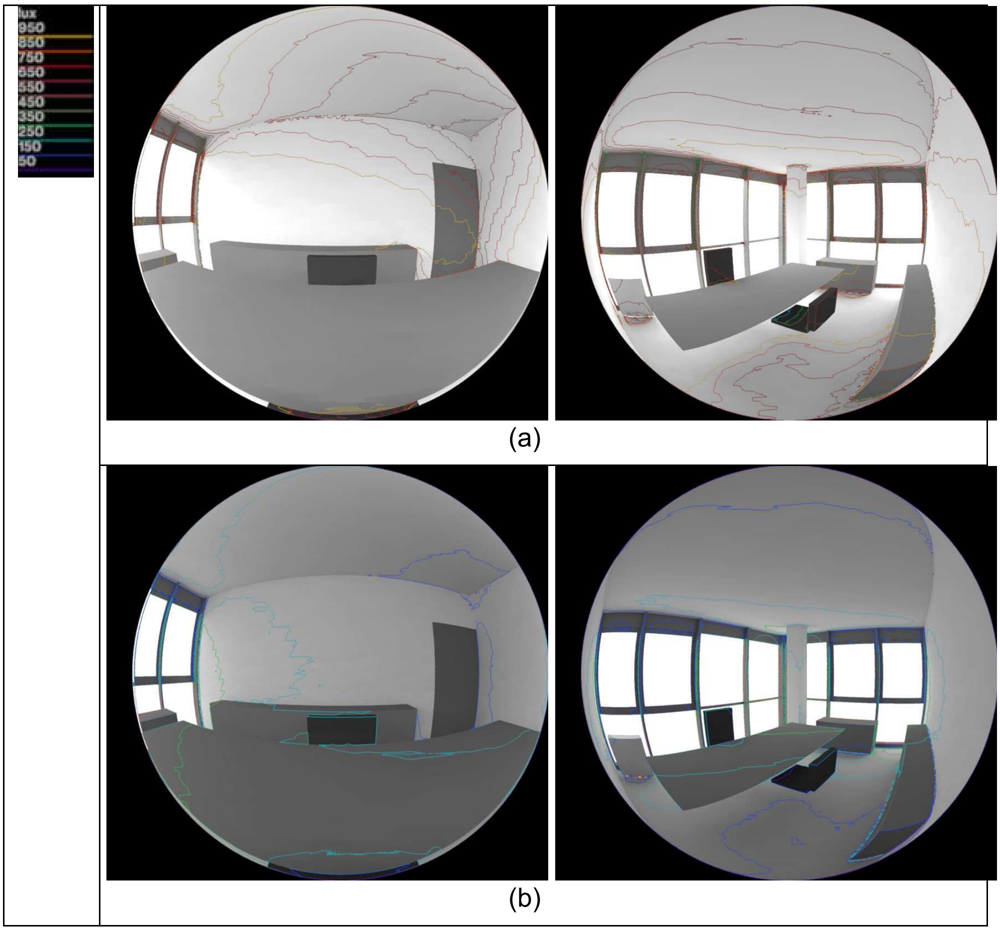


(a)



(b)

Figure 5.52 – Double office. False colour contour lines of illuminance: 19th November 12:00 (overcast sky), with glazed façade (a) and with film coated façade (b)

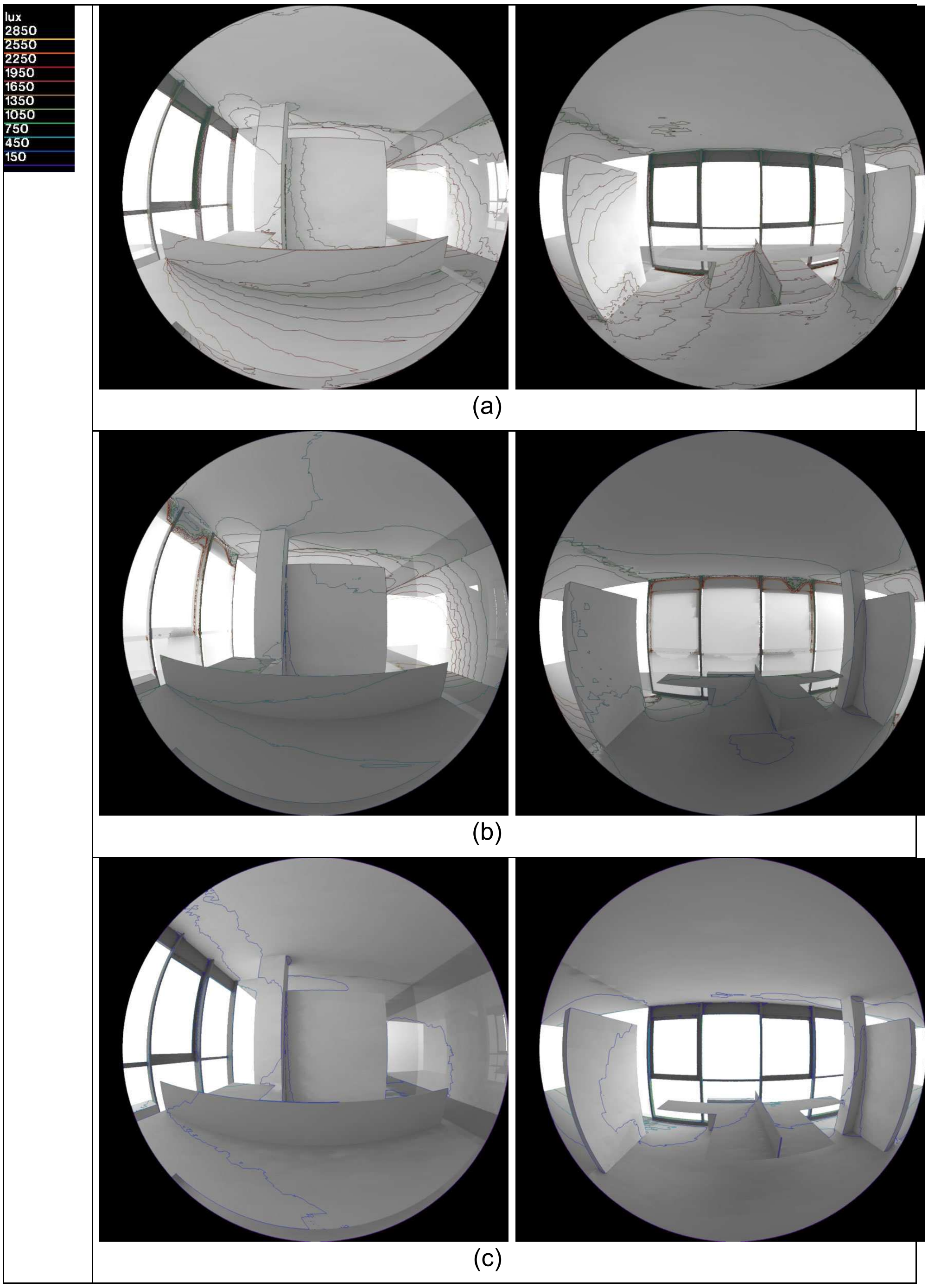


(a)

(b)

Figure 5.53 - Single office. False colour contour lines of illuminance: 19th November 12:00 (overcast sky), with glazed façade (a) and with film coated façade (b)

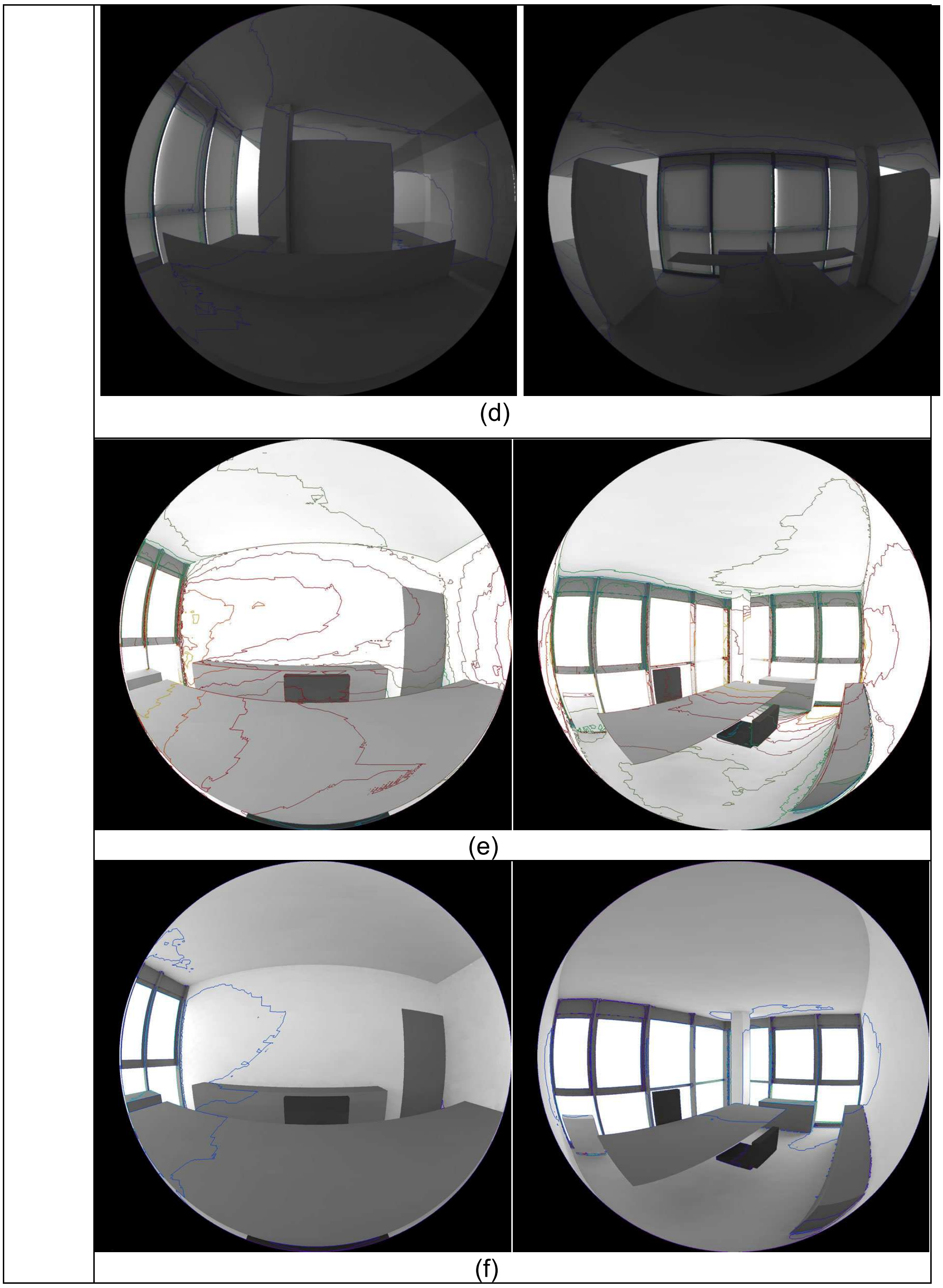
Figure 5.51 is referred to 2nd December 12:00; the sky description is the CIE clear sky. The illuminance distribution, supposing a glazed façade ((a), (b) and (e)) is compared to the one obtained if a film coated would have been provided ((c), (d) and (f)). Figures (b) and (d) shows the illuminance distribution in the double office with the curtains down.



(a)

(b)

(c)



(d)

(e)

(f)

Figure 5.54 –Double office. False colour contour lines of illuminance: 2nd December 12:00 (clear sky), with glazed façade and blinds up (a) and with blinds down (b); with film coated façade and blinds up (c) and with blinds down (d). Single office, blinds up. False colour contour lines of illuminance: 2nd December 12:00 (clear sky), with glazed façade (e) and with film coated façade (f)

5.17. HDR images

High Dynamic Range (HDR) photography technique is nowadays considered a recent approach in the evaluation of luminance values. It consists in taking multiple exposure photographs of static scenes with a common digital camera to capture all possible luminance variation within the scene. All the photographs taken are then fused into only one picture, which captures a much extended dynamic range of luminances. The theory and application of such images are described in (Axel Jacobs, 2007), while the evaluation of HDR photography as a luminance mapping technique is presented in (Inanici, Galvin, 2004; Inanici, 2005 and Inanici, 2006).

During film coating installation, some multiple exposure photographs of different offices of the Tower have been taken with CANON EOS 5D camera and fisheye lens. These pictures have been then fused into an HDR image by using Photosphere software and converted into false-colour images, in order to evaluate luminance distribution. Moreover, the pixel values in the HDR photographs have been compared to luminance values measured in the same time with a Minolta LS100 luminance meter. The pictures have been taken in 15th July, during film coating application and they are not referred to the analysed offices.

The Figure 5.55 shows two HDR images of two different offices of the analysed tower. The film coating is going to be applied on the South-East façade and, from Figure 5.56 and Figure 5.57, it can be easily noticed how indoor luminance values change according to glazing characteristics.

(a) (b)

Figure 5.55 – HDR images of two offices during film coating application

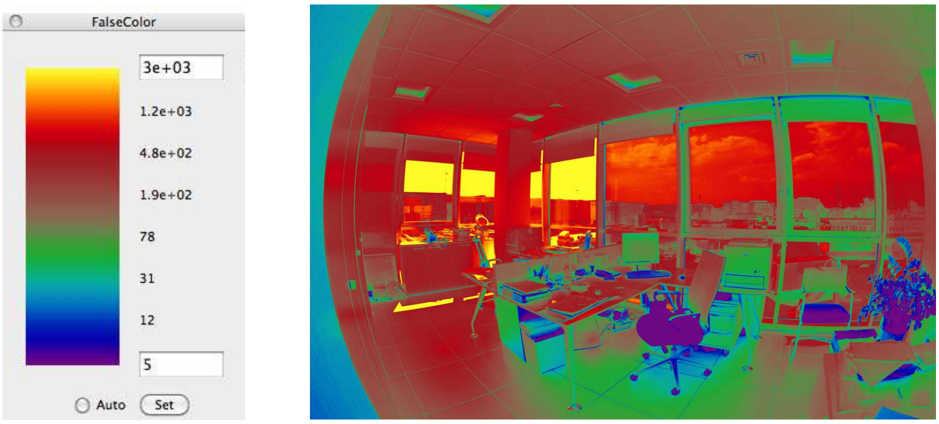


Figure 5.56 - False colour image which maps the luminance distribution of the office (a) in Figure 5.55

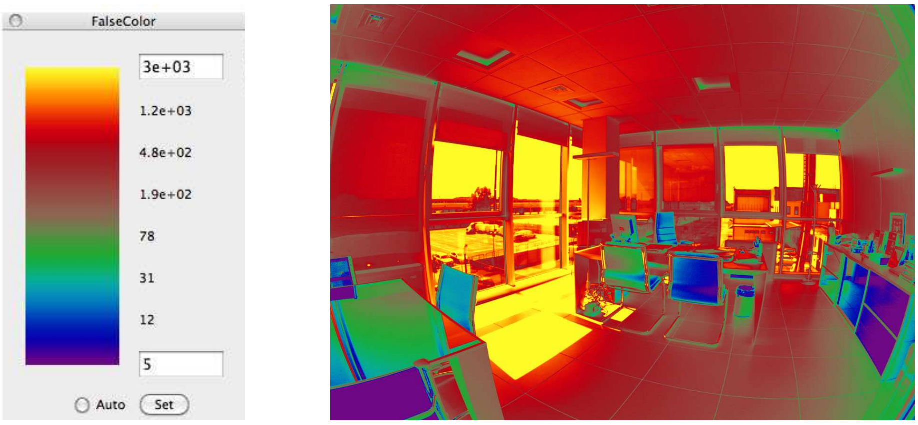


Figure 5.57 - False colour image which maps the luminance distribution of the office (b) in Figure 5.55

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Chapter 6

IEQ analysis in Primary Schools

Comfort inside buildings is a purpose that designers and committees have to reach, in order to guarantee a good level of wellbeing in indoor. People spend a lot of their time indoor, therefore comfort is an important goal to reach. Moreover, children need to live in good conditions, due to the fact that they are growing. Many studies have demonstrated that most of children diseases are caused by poor indoor conditions. For that reason the internal conditions of two Primary Schools have been measured. Moreover, children and teachers have been asked to answer to a questionnaire, in order to know how they feel in their school, if they are satisfied of indoor conditions and how (and if) they interact with the school environment.

6.1. Case study

The IEQ analysis has been performed in two Primary Schools near Venice. These schools have been selected because they differ in terms of space arrangement and of architectural and technological choices. The objective of this study was in fact to see if the building type can influence well-being and perceived indoor quality.

6.1.1. “Collodi” Primary School, Ceggia (Venice)

The “Collodi” Primary School is located in a quite and recent residential area of Ceggia (Figure 6.1), a little town near Venice, where the traffic is so rare that it cannot be considered a source of noise. The school has been built from 2003 to 2004; its main characteristic is its circular shape which creates a sort of central *atrium*, two levels high, around which all the classrooms are faced. This space becomes a sort of meeting point, where children have break and can play. This *atrium* is lightened by the aisle windows and by a skylight on the top of it (Figure 6.4).

Educational building: “Collodi” Primary school	Dimensions:
Address: via Folegot, n.57, Ceggia ,Venice	
Building year: 2003/2004	Area: 3790 m2
	Maximum height:7.70 m
	Floors: 2
	Volume : 11370 m3
	Morphology
	classrooms facing a central circular *atrium*

Figure 6.1 – School panorama

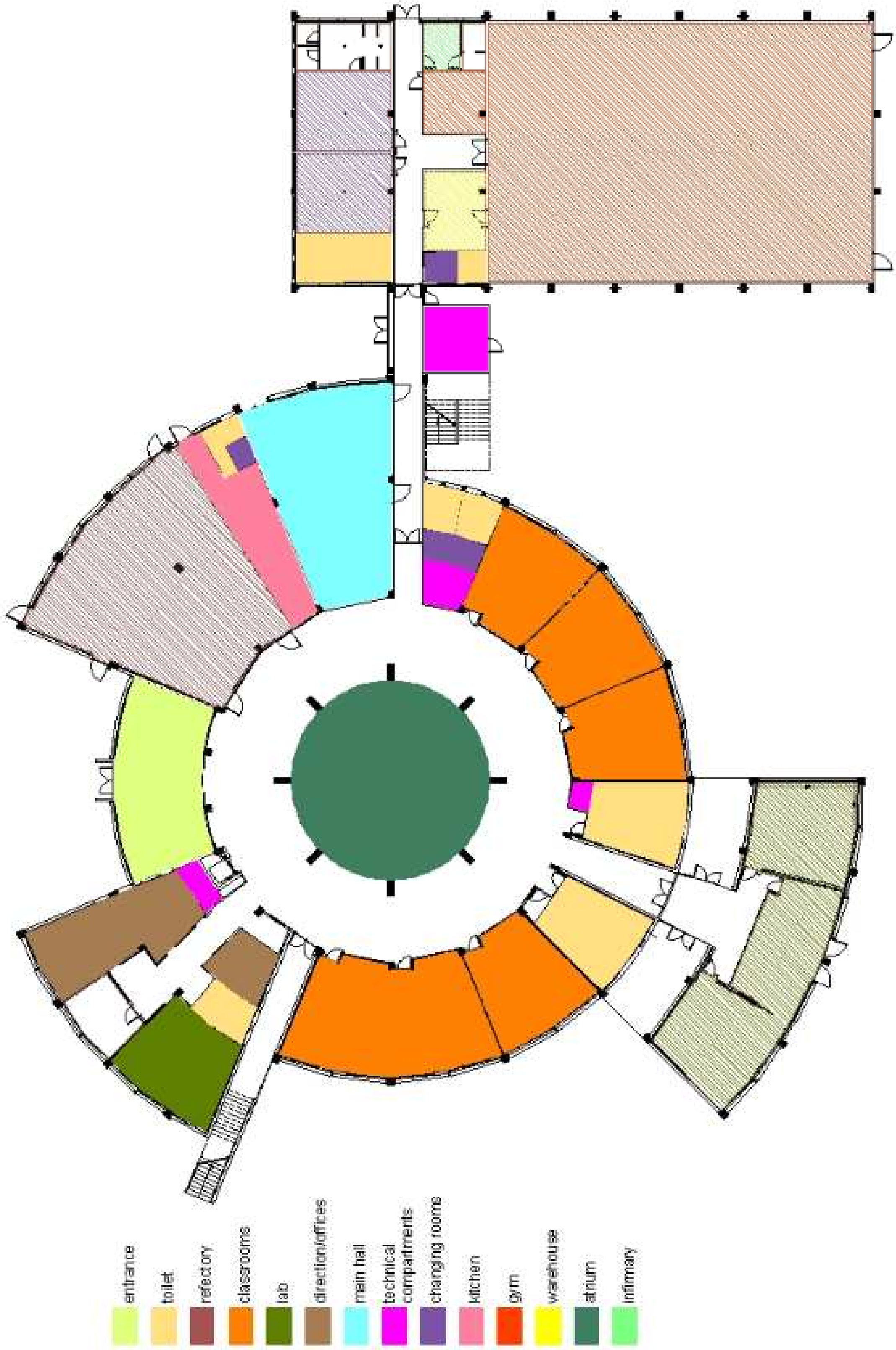


Figure 6.2 – Ceggia school plant (ground floor)

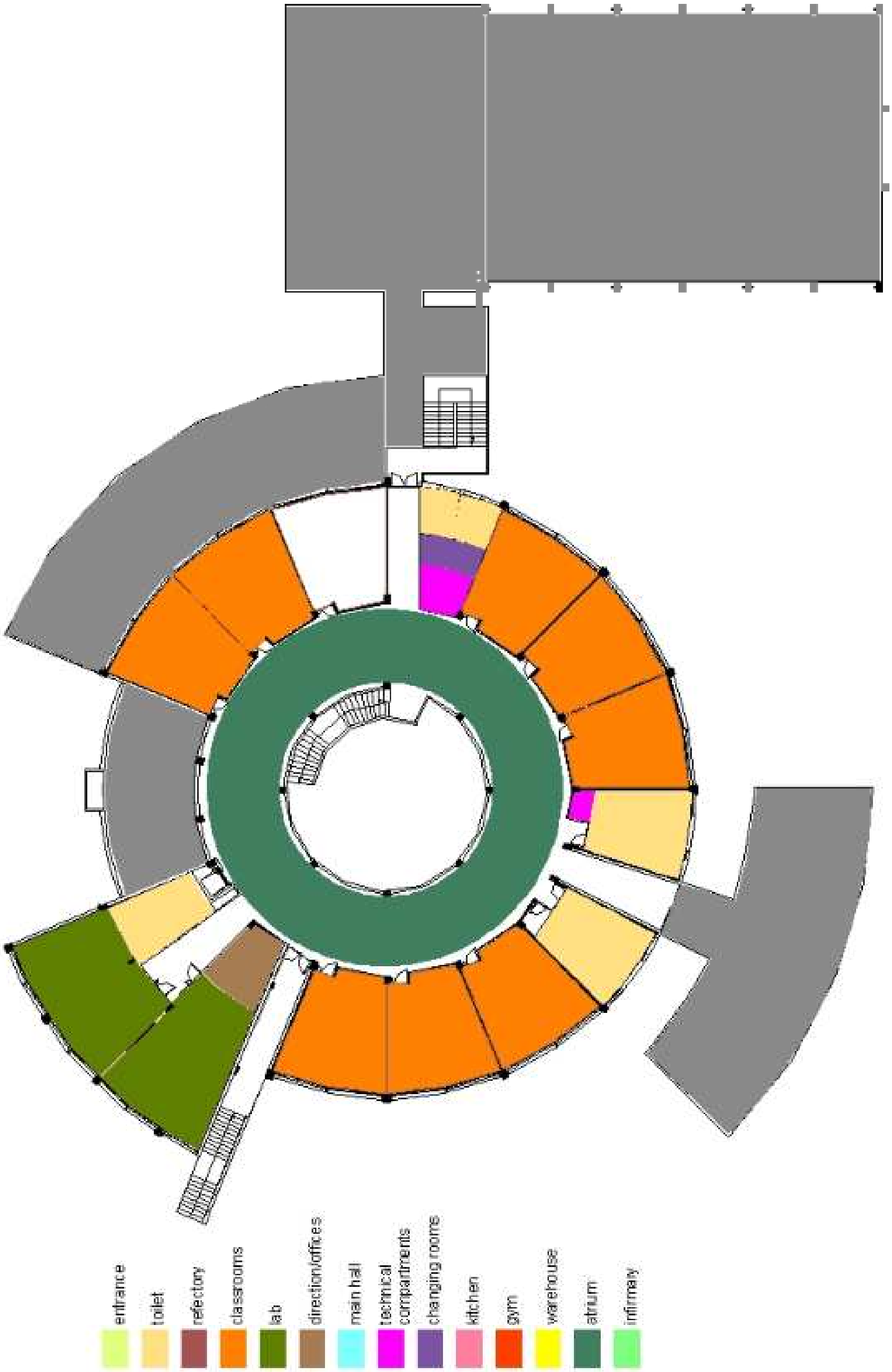


Figure 6.3 – Ceggia school plant (first floor)


(a) (b)

Figure 6.4 – School exterior (a); the atrium (b)

In the ground floor there are six classrooms, an auditorium, the gym, the refectory and some other spaces in which some different activities, such as artistic and music laboratories, take place in the afternoon (Figure 6.2). All the fifteen classroom have the same area of about 50 m^2. The blackboard is positioned in front of the windows which are shaded by an external *brise-soleil*, manually controlled. Each classroom differs for wall and door painting and the desks arrangement changes according to school activities (Figure 6.5).

Figure 6.5 – Different desks arrangements

The school is equipped with an embedded water based floor radiant system, a mechanical ventilation system which operates during occupancy time and it has PV solar collectors roof mounted. Finally, the lighting system consists of fluorescent lamps which can be dimmed according to daylight conditions.

6.1.2. “G. Noventa” Primary School, Noventa di Piave (Venice)

The Primary School “G. Noventa” is located in Noventa di Piave, a town near Venice, along a street that is close to a traffic road (Figure 6.6). The school has been built in 1962; the library and the refectory have been recently added. It is a traditional educational building, with most of the twenty-two classrooms South-East oriented and facing the aisle. The school has no particular details for considering new trend in the architecture of Primary Schools.

Educational building: Primary school ‘G.Noventa’	Dimensions:
Address: via Noventa, n 1, Noventa di Piave ,Venice	
Building year: 1962 2003-2006 : extension (refectory construction)	Area: 3320 m 2
	Maximum height: 8.70m
	Floors: 2
	Volume:12044m3
	Morphology:
	Geometrical configuration: classrooms facing the aisle

Figure 6.6 - School panorama

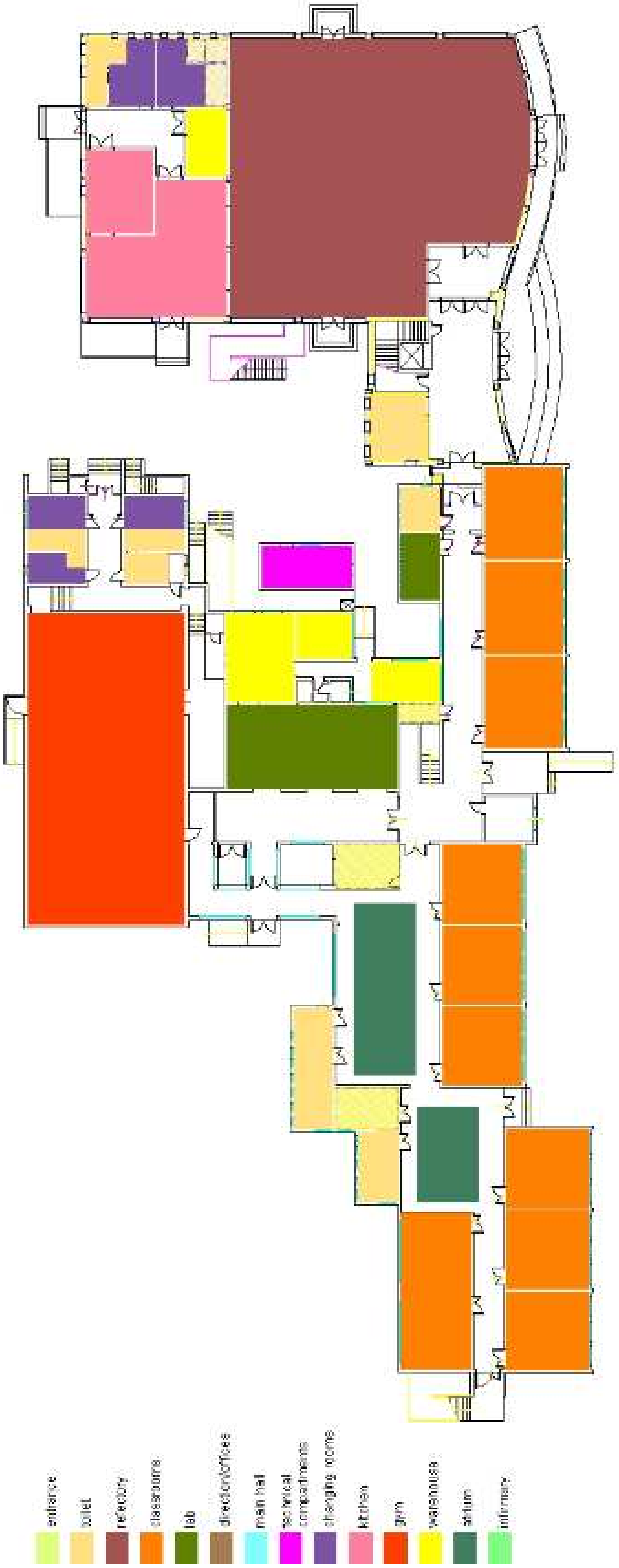


Figure 6.7 – Noventa school plant (Ground floor)

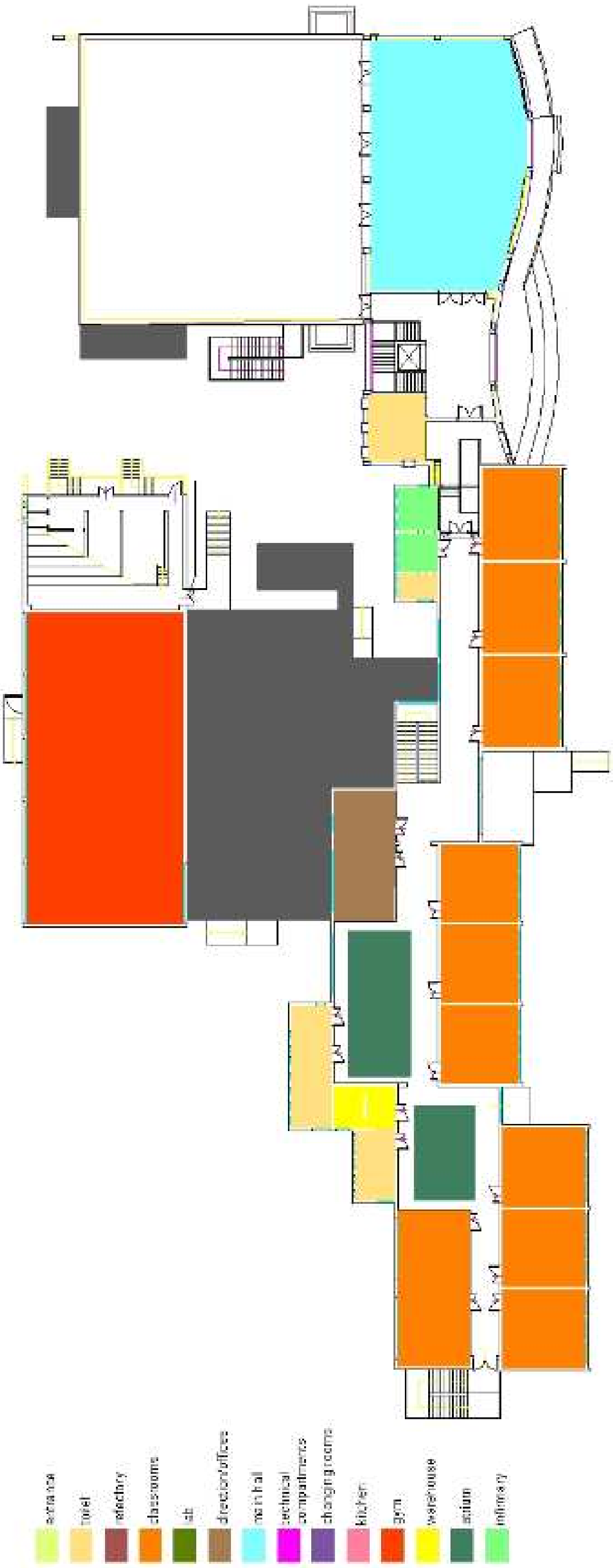


Figure 6.8 – Noventa school plant (first floor)


(a) (b)

Figure 6.9 – School exterior (a); the aisle (b)

Some of the classrooms are rectangular, with an area of 42 m^2, and some others have a square shape, with an area of 36 m^2. The available shading devices are curtains and rolling shutters.


(a) (b)

Figure 6.10 – Shadings

The desks arrangement is different according to teaching activities, even though usually the direction in which the students face the teacher is parallel to the perimeter wall.

The building is made of bricks and concrete; it has a traditional heating system and no mechanical ventilation system is provided.

Figure 6.11 – Desk arrangement

6.2. The survey construction

The subjective approach of this study consists of administrating a questionnaire to the pupils during their class. The survey structure that will be further presented is the result of all the careful considerations made in cooperation with a Professor of “Perception Psychology”, about how to build a survey on perception of school environment.

The steps to follow in a survey design can be summarized in:

- Establish the goals of the project: What do you want to learn?
- Determine your sample: Who will you interview?
- Choose interviewing methodology: How will you interview?
- Create a questionnaire: What will you ask?
- Pre-test the questionnaire, if practical: Test the questions
- Conduct interviews and enter data: Ask the questions
- Analyze the data: Produce the reports

The first step in any survey is deciding what an interviewer want to learn. The goals of the project determine to whom the survey will be addressed and what kind of questions will be asked. If the goals are unclear, the results will probably be unclear. The goal of the presented survey is to know if the building type (in this case, the school) can influence well-being, satisfaction and indoor environmental quality.

In general, the aim of a question is to obtain as more informations as possible and it is not wise to ask something that will be not useful for the analysis. Surveys addressed to children have to be as much comprehensible as possible. It is important to remember that children use to call things in another way than the one of adults. The need to give a name to things arises from the need to communicate them; there is hence a strict link between words and communication, so if, for example, the presence of glare is perceived as a problem a person will give a name to it. It is important to use a language as close as possible to the one used by the interviewed. The survey has been thought and written for Italian pupils, therefore the English translation provided in this thesis would be misunderstood if administrated to English pupils. Moreover the same thing can be differently called even in the same country: for example, the word "*tapparelle*" (which means "rolling shutters") has been chosen instead of "*persiane*", which can result incomprehensible for someone. The corresponding English word "*rolling shutters*" can be unknown for English children.

The overriding consideration in a questionnaire design is to make sure that the questions can accurately tell what the interviewer wants to learn. The way a question is asked can influence the interviewee's answer. It is very important to make sure that the wording does not favour one answer choice over another.

In this survey emotionally charged words or leading questions, that point towards a certain answer, are avoided. Moreover technical terms, like air quality, acoustic quality, illuminance and even temperature are avoided because of the uncertainty that children know what they mean.

Considering whom the study is addressed, cartoon pictures were added to make the survey look attractive by children. The way in which the questions are asked is easy and the questions on the same topic are grouped together, to make the questionnaire easier to answer.

The survey is composed by 38 questions (41 for the school sited in Noventa di Piave, because it has two different types of shading devices). The early questions concern general informations, in order to make pupils at ease and to encourage them to continue the survey. Only five questions are open, while the others are based on rating scale, agreement scale or multiple choices. Pupils are forced to give an answer that is clearly positive or negative, to avoid the possibility to choose a neutral option that would result in an unusable information. This can be criticized, since it may happen that a person could leave a question blank, if a middle answer is not allowed. However, in this case there have been only some few blank answers.

Some questions have been changed, according to psychologist and teachers observations: the reason was to make the questions as much comprehensible and unambiguous as possible.

In general, a survey investigates the indoor environmental quality of a space in terms of "level of people satisfaction", for example asking:

"How satisfied are you with the thermal comfort/air quality/noise level/visual comfort of your ...?"

In the present survey, the word "*satisfaction*" is never mentioned and this kinds of questions have been simplified like:

"Do you like your school/classroom/ etc....?"

The question concerning the visual comfort over desk :

Can you see well over your desk when you read and write?

In its first wording, it did not include “*when you read and write*”, but just the fact to see well over the desk. This specification has been added in order to help pupils to understand the meaning of the question.
The questions referred to the importance assigned to perceived comfort in different fields (i.e. acoustic, visual, thermal, etc) are sometimes asked in the following way:

“Do you think it is important to have a good level of visual comfort?”

In this specific case, the same question is worded like:

“Are you bored/ are you annoyed if …?”

The word “*importance*” implies a judgement which can be carried out only taking into account many different aspects of the same topic. A child of ten years old is not probably able to make this sort of conjecture.
The question concerning classroom cleanness was worded like:

“Do you think that your school is clean?”

It has been then modified like:

“At school do you like to see waste paper over the floor?”

This question should be better worded putting “*at school*” at the end of the question, because, leaving “*at school*” in the beginning, the notion “*do you like*” is strictly connected to the place “*school*” (i.e. when you are at school …, unlike when you are at home…), therefore the cleanness concept is related only to the school environment.
Some concepts have been simplified in order to make them more comprehensible: “*glare*” has been translated in “*blinding lights*” and “*school accessibility*” has been investigated asking “*Do you think it is easy to move around in your school?”.* Finally, for the questions concerning pupils’ and teachers’ interaction between the environment (i.e. window opening, shading operating, etc.) the suggested answers have been arranged with the teachers, to give all the proper possible and realistic choices.
Sometimes it can be helpful, to reduce habituation, mainly to level-of-agreement questions, to change the “*positive*” answer. This means to word some questions so that a “*positive*” answer (i.e. “*yes*”) means agreement (e.g., *“Do you like blinding*

lights in your classroom?") and others so that a "*positive*" answer means disagreement (e.g., *"Are you annoyed if your classroom smells bad?").* This technique forces the respondent to think more about each question. One negative aspect of this technique is that the interviewer may have to modify some of the data after the results are entered, because having the higher levels of agreement always mean a positive (or negative) answer makes the analysis much easier. However, the few minutes of this extra work may be a worthwhile price to pay to get more accurate data.

6.3. The proposed survey

The survey is divided into questions which investigate not only indoor environmental quality, but also children satisfaction about school, furniture, their behaviour when a discomfort occurs and classroom habits in terms of window opening and blind position.

The survey involves many different aspects that can be grouped as follows:

- general informations (age, gender, etc.);
- children satisfaction towards many different aspects (e.g. school, school mates, furniture, etc.);
- questions concerning IEQ (thermal, acoustic and visual comfort and indoor air quality);
- frequency of discomfort (e.g. "*how often does your classroom smell bad* ")
- importance given to a discomfort (e.g. "are you annoyed when your classroom smells bad?");
- children behaviour when a discomfort occurs (e.g. "*What do you do when your classroom smells bad?*";
- possibility of individual microclimatic control in the environment (e.g. "*Does your teacher open the blinds during break time* ").

A keyword has been chosen to summarize each question and, for statistical evaluation, the answers have been translated in numbers. The questions with the relative keyword and the answers codifying are reported in the following pages.

1) How old are you? AGE
2) Are you a boy or a girl? GENDER
3) What are you wearing now? DRESS
4) Do you like your classroom? CLASSROOM
5) Do you like your desk? DESK
6) In which desk are you sitting now? POSITION
7) Do you change your desk during the year? DISPLACEMENT

8) If you can choose your favourite desk, where do you would be sit? FAVOURITE DESK
9) Do you like your school mates? SCHOOL MATES
10) Do you like the desks arrangement in your classroom? ARRANGEMENT
11) At school do you like to see waste paper over the floor? CLEANNESS
12) Do you feel good sitting in your chair? CHAIR
13) How do you feel like today? WELLBEING
14) If you do not feel good, what is wrong? (open question)
15) How do you feel now? TEMPERATURE
16) How often does your classroom smell bad? SMELL-1
17) Are you annoyed if your classroom smells bad? SMELL-2
18) If your classroom smells bad what do you do? SMELL-3
19) Can you hear your teacher well? HEAR-1
20) If you cannot hear well your teacher speaking, what do you do? HEAR-2
21) How often is there noise in you classroom? NOISE-1
22) What kind of noise is it? NOISE-2 (this is an open questions)
23) Are you bored from the noise in your classroom? NOISE-3
24) Can you see the blackboard well? (SEE BLACKBOARD-1)
25) If you cannot see the blackboard well, what do you do? (SEE BLACKBOARD-2)
26) Can you see well over your desk when you read and write? (SEE DESK-1)
27) If you cannot see well over your desk, what do you do? (SEE DESK-2)
28) Are there in your classroom blinding lights that annoy you? (LIGHT-1)
29) Do you like blinding lights in your classroom? (LIGHT-2)
30) Do you feel air drafts in your classroom? (AIR DRAFT-1)
31) Do you like to feel air drafts in your classroom? (AIR-DRAFT-2)
32) Do you feel well at school? SATISFACTION
33) Why? (open question)
34) Do you think it is easy to move around in your school? ACCESSIBILITY
35) Who can open the windows? WINDOW-1
36) Does your teacher open the windows during break time? WINDOW-2
37) Does your teacher open the windows during lessons? WINDOW-3
38) Who can open or close the blind? BLIND-1
38bis) Who can close the curtains? (only for Noventa school)
39) Does your teacher open the blinds during lesson? BLIND-2
39bis) Does your teacher open the curtains during lesson? (only for Noventa school)
40) When does your teacher open the blinds? BLIND-3
40bis) When does your teacher open the curtains? (only for Noventa school)
41) Did you like to answer to that survey?

The provided answers and the relative codifying are:

Question 2: “Are you a boy or a girl?” GENDER
Boy = 0
Girl = 1

Question 3: “What are you wearing now?” DRESS
Lightweight = 0
Warm clothes = 1

Questions: 4, 5, 9, 10, 11, 12, 17, 19, 23, 24, 26, 29, 31, 32, 34, 41

a) Yes = 3
b) Enough = 2
c) A little = 1
d) No = 0

Questions: 16, 21, 28, 30, 36, 37, 39

a) Often = 3
b) Sometimes = 1.5
c) Never = 0

Questions 6, 7 (POSITION and FAVOURITE DESK)

a) Near the window = 0
b) Near the blackboard = 1
c) In the first line = 2
d) In the last line = 3
e) Near your favourite school mate = 4
f) In the middle of your classroom = 5
g) Near the teacher desk = 6

Question 7: “Do you change your desk during the year?” DISPLACEMENT
No = 0
Yes = 1

Question 13: “How do you feel like today?” WELLBEING

a) Well = 2
b) Not very well = 1
c) Bad = 0

Question 15: “How do you feel now?” TEMPERATURE

a) I’m very cold = 0
b) I’m a little cold = 1
c) I feel good = 2
d) I’m a bit hot = 3
e) I’m very hot = 4

Question 18: “If your classroom smells bad what do you do?” SMELL-3

a) I tell it to the teacher = 0
b) I hold my nose = 1
c) I ask the teacher to open the window = 2
d) Nothing = 3

Question 20: “If you cannot hear well your teacher speaking, what do you do?” HEAR-2

a) I ask the teacher to close the door, if it is open = 0
b) I ask the teacher to speak up = 1
c) I tell my school mate to shut up = 2
d) Nothing = 3

Question 22: “What kind of noise is it?” NOISE-2
The answers to this open question have been divided in three groups:

a) Internal noise = 0
b) External noise = 1
c) Both internal and external noise = 2

Question 25: “If you cannot see the blackboard well, what do you do?” (SEE BLACKBOARD-2)

a) I ask the teacher to write bigger = 0
b) I ask the teacher to switch on the light = 1
c) I ask the teacher to open the blinds = 2
d) I ask to the school mate in front of me to move = 3
e) I move = 4
f) Nothing = 5

Question 27: “If you cannot see well over your desk, what do you do?” (SEE DESK-2)

a) I ask the teacher to switch on the light = 0
b) I ask the teacher to open the blinds = 1
c) I move my desk = 2
d) Nothing = 3

Question 33 : “Why (you do not feel good now?)?”
The answers to this open question have been divided in three groups:

a) Personal matter (i.e. friendship) = 0
b) Reason connected to school building = 1
c) The above reasons together = 2

Question 35, 38: “Who can open the windows/ close the blind?” WINDOW-1, BLIND-1

a) The teacher only = 0
b) Also the pupils = 1

Question 40: “When your teacher open the blinds? BLIND-3”

a) When there is poor light = 0
b) When a pupil asks it = 1
c) When a pupil is sleeping = 2

Initially, only one answer was admitted, but pupils demanded the possibility to multiple choices for the questions number 6, 8, 18, 20, 25, 27 and 40. For these particular questions, another codifying has been created, for all the combinations obtained. The multiple choice will be no more admitted because it turned out to be a problem during statistical elaboration. Moreover, to carry out statistical tests with the software used (NPC Test), there must be almost three identical answers to the same question and, considering all the combinations obtained, some questions could not be analysed. This happened, for example, with the question concerning the pupils' position throughout the classroom: the answers to this question would have been interesting to understand if a relationship between position and perceived IEQ could be found.

6.4. Measurements

The indoor thermal environment in the two Primary Schools was analysed only once. It was not possible to perform the measurements in the same date, because there was no time to investigate all the classrooms (six in one school and five in the other) in the same day.
The measured indoor parameters are:

- Air temperature
- Plan radiant temperatures
- Mean air velocity and standard deviation of air velocity
- Relative air humidity
- Co_2 concentration
- Illuminance over the desks

The measurements of the first four indoor parameters listed above have been performed with the Indoor Climatic Analyser Brüel&Kjær (Figure 6.12), positioned in the centre of each classroom. The parameters have been measured at a height of 0.6 m above the floor, according to the Standard ISO 7726 for seated persons, for the whole classrooms (CEN, 2001). Through these data, the thermal comfort Fanger's indices, the predicted mean vote (PMV) and the predicted percentage of dissatisfied people (PPD), were calculated, the actual people clothing and metabolic rate being known.


(a) (b)

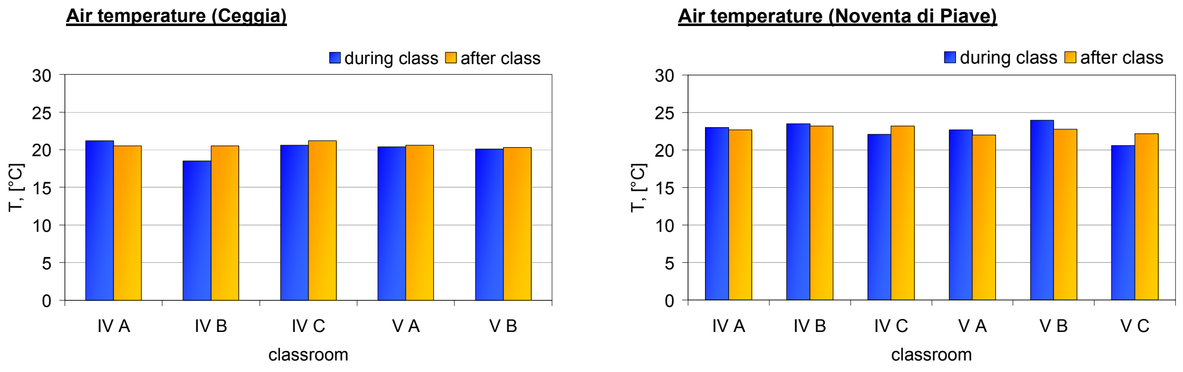
Figure 6.12 – Measurements recorded with the Indoor Climatic Analyser Brüel&Kjær in Ceggia school (a) and in Noventa one (b)

Moreover, the colour temperature and the chromaticity have been measured, but they are not reported in this work. The CO_2 concentration was measured with the IAQ monitor AirBoxx (which records also air temperature and relative humidity), while the chromaticity, colour temperature and illuminance were recorded by the Minolta CL 200 lux meter (Figure 6.13).


(a) (b)

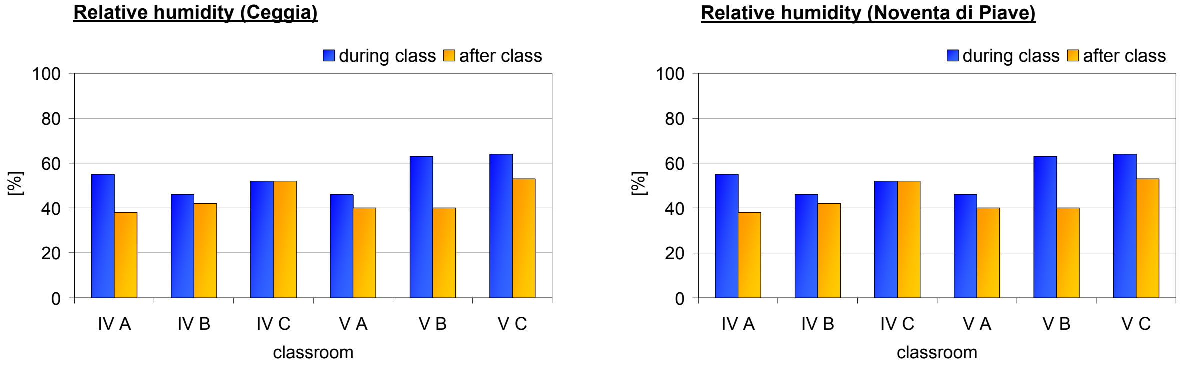
Figure 6.13 – AirBoxx (a) and Minolta CL200 (b)

Only the air temperature, the relative humidity and CO_2 concentration have been recorded when the pupils filled the survey, while all the other parameters have been measured immediately after (during the break, the lunch or when the children had gym). It was in fact very difficult to take measurements during class, due to children curiosity and to lack of space.



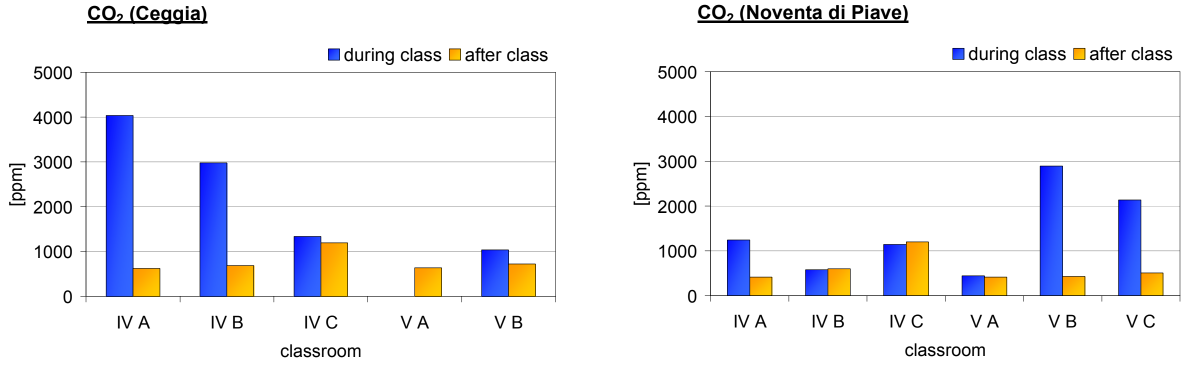
(a) (b)

Figure 6.14 – Recorded air temperature during and after class in Ceggia school (a) and in Noventa school (b)



(a) (b)

Figure 6.15 – Recorded relative humidity during and after class in Ceggia school (a) and in Noventa school (b)



(a) (b)

Figure 6.16 – Recorded CO_2 concentration during and after class in Ceggia school (a) and in Noventa school (b)

Indoor environmental parameters (air temperature, relative humidity and CO_2 concentration), recording during and after class in the two educational buildings, are reported from Figure 6.14 to Figure 6.16. From Figure 6.16 it can be noticed that sometimes CO_2 values are extremely high and this means that there was a poor indoor air quality. In Ceggia school mechanical ventilation was not running and the windows were often closed, while in Noventa school the windows were opened, except in classrooms V B and V C.

6.4.1. Ceggia Primary School

The measurements and the survey in “Collodi” Primary School have been performed in 29th April 2009. The school is not equipped with a mechanical cooling system: neither the radiant floor, nor the mechanical ventilation system were operating, so the classrooms were in free-running conditions: only natural ventilation was used to control the temperature. In most of the classrooms the *brise-soleil* were in horizontal position and the lighting was switched off.

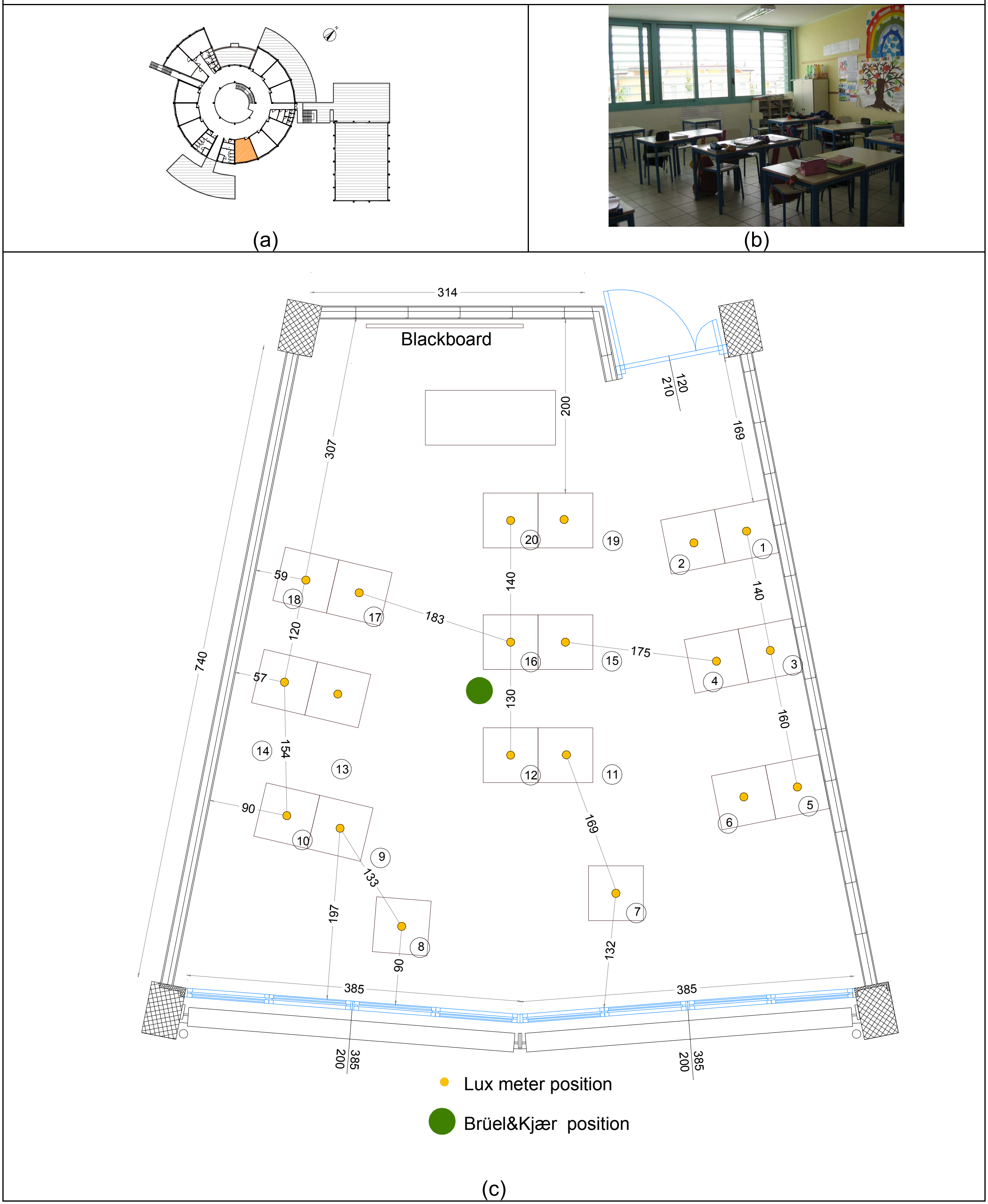
The recorded data were elaborated in order to calculate, according to ISO 7730, Fanger’s thermal comfort indices (PMV and PPD). The metabolic rate was fixed at 1.2 met (sedentary activity) and the actual people clothing were obtained by the questionnaire (0.7 clo).

For each of the five investigated classrooms all the recorded environmental parameters are reported in the following pages.

Considering classrooms’ lighting levels, in both survey administration condition and with the electric light switched on and the *brise-soleil* closed, illuminance values in all the desks were over 300 lux, that is the minimum level required by the Standard (UNI 10840).

Classroom IV A

Classroom IV A



(a) (b) (c)

Figure 6.17 - Classroom IV A (Ceggia): key plant (a); photo (b); desks layout and position of the Indoor Climatic Analyser Brüel&Kjær and of the Minolta luxmeter (c)

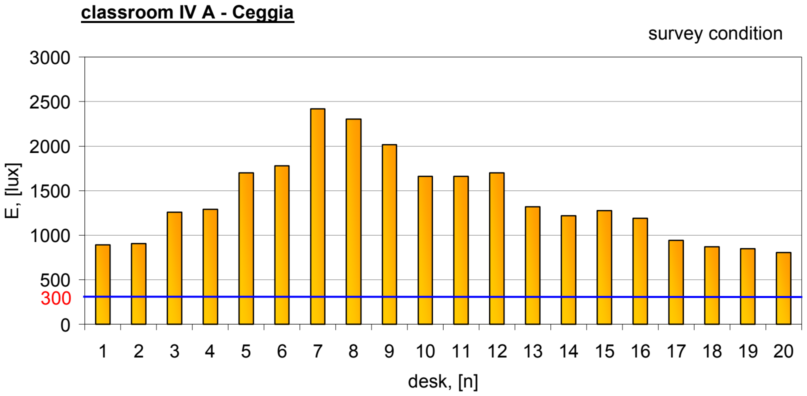


Figure 6.18 - Classroom IV A (Ceggia). Measured illuminance over the desks in survey administration conditions (lights switched off and brise-soleil in horizontal position)

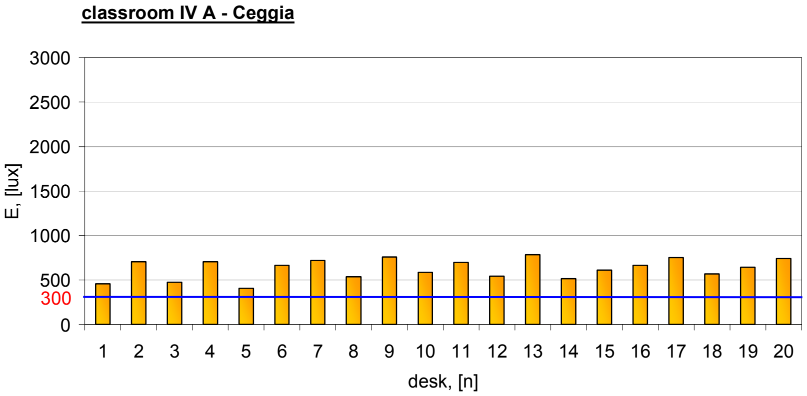


Figure 6.19 - Classroom IV A (Ceggia). Measured illuminance over the desks with lights switched on and brise-soleil closed

Table 6.1 - Classroom IV A Indoor micro-climatic parameters from which PMV and PPD indexes have been calculated

Ceggia, IVA	Date	4/29
Pupils		20
Time of survey administration (during class)		12:15
Time of measurements (after class)		13.25
Metabolic rate (met)		1.2
Clothing insulation (clo)		0.70
Indoor microclimatic parameters during class:		
Air temperature (°C)		21.2
Relative humidity (%)		74
CO_2 (ppm)		4035

Operative temperature (°C)	**21.2**
PMV	**-0.5**
PPD (%)	**10.2**

Indoor microclimatic parameters after class:	
Air temperature (°C)	20.5
Mean radiant temperature (°C)	21.9
Air speed (m/s)	0.08
Relative humidity (%)	58
CO_2 (ppm)	623
Plane radiant temperature (°C)	
wall	22.4
wall	20.8
window	23.1
wall	21.3
ceiling	22
floor	21.7

Classroom IV B

Classroom IV B

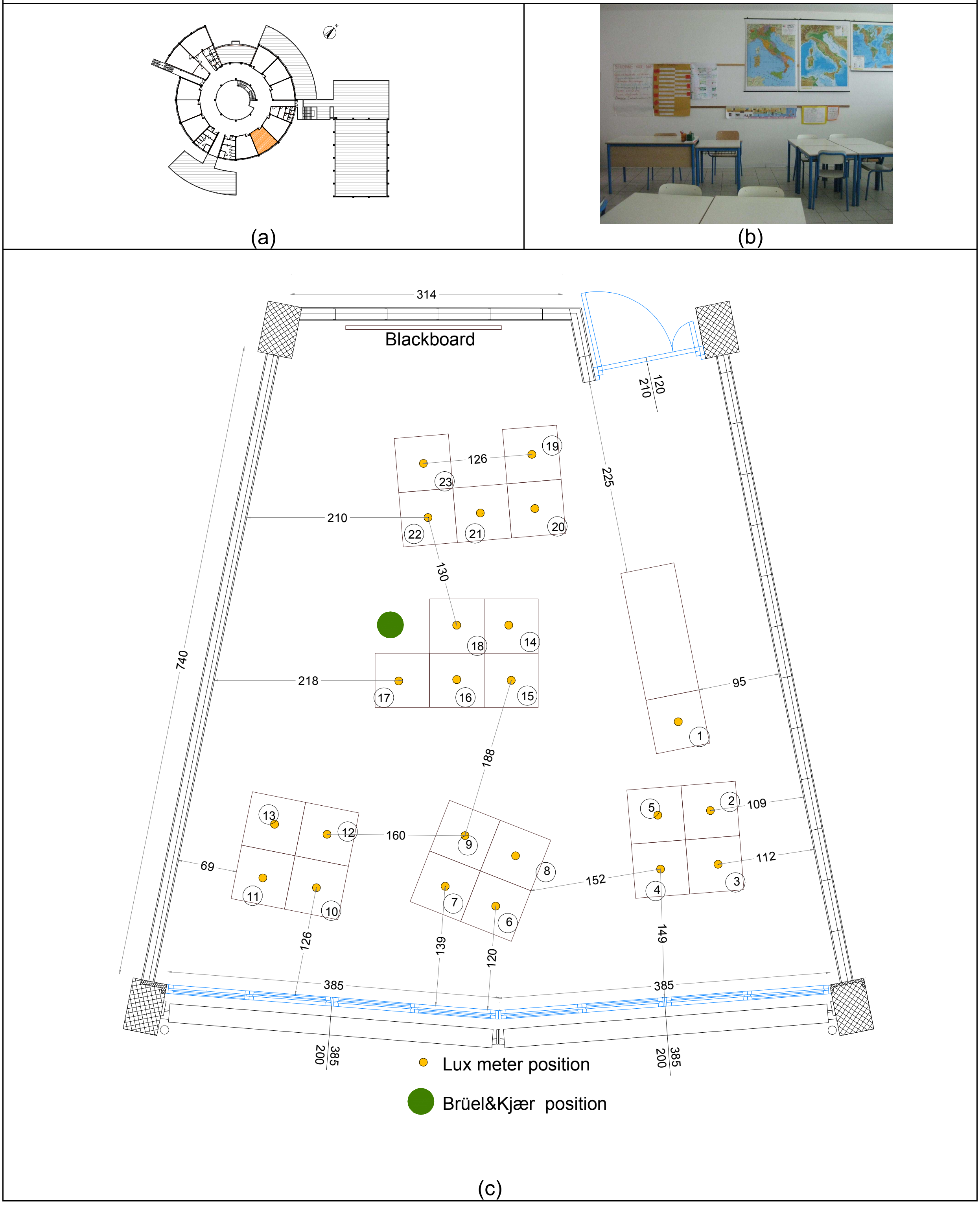


Figure 6.20 - Classroom IV B (Ceggia): key plant (a); photo (b); desks layout and position of the Indoor Climatic Analyser Brüel&Kjær and of the Minolta luxmeter (c)

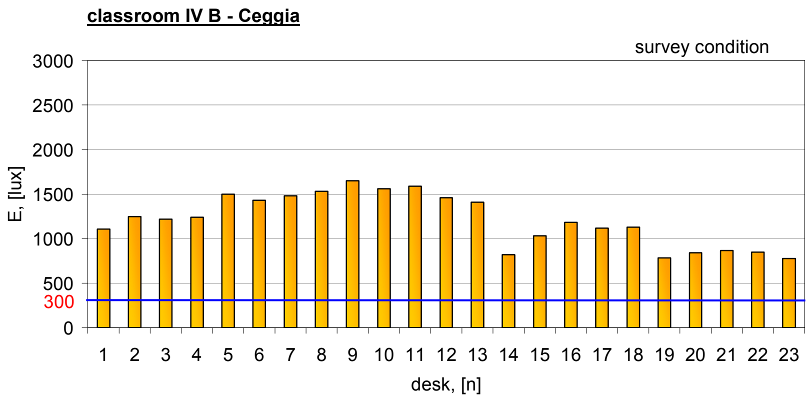


Figure 6.21 - Classroom IV B (Ceggia). Measured illuminance over the desks in survey administration conditions (lights switched off and brise-soleil in horizontal position)

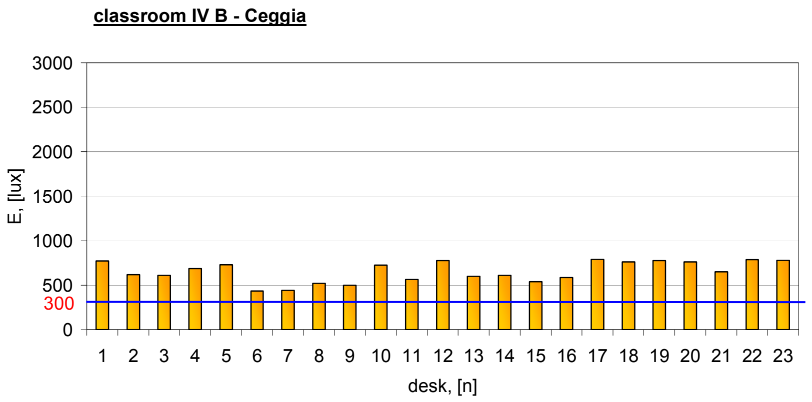


Figure 6.22 - Classroom IV B (Ceggia). Measured illuminance over the desks with lights switched on and brise-soleil closed

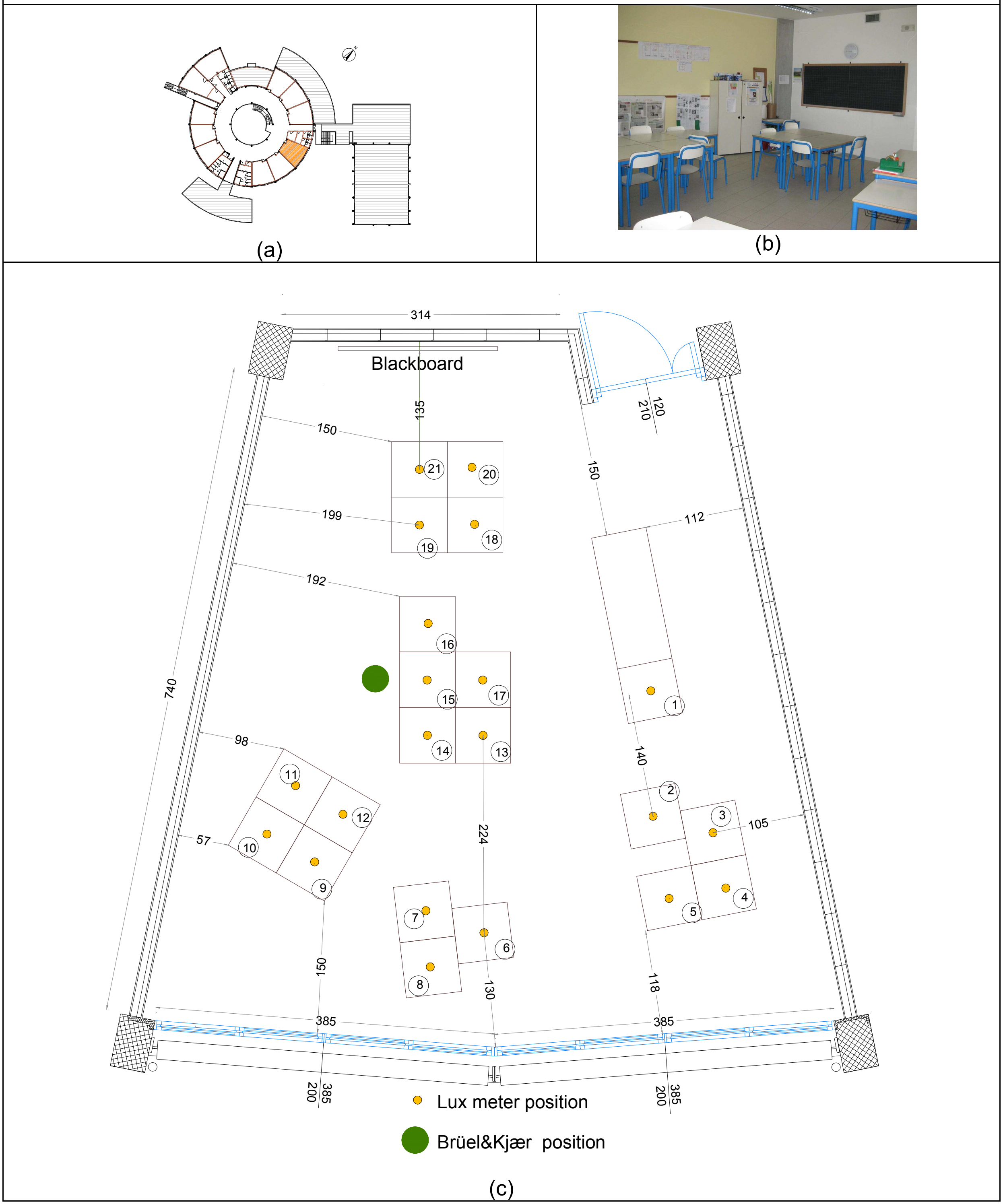
Table 6.2 – Classroom IV B. Indoor micro-climatic parameters from which PMV and PPD indexes have been calculated

Ceggia, IVB	Date	4/29
Pupils (present: 21)		23
Time of survey administration (during class)		9:45
Time of measurements (after class)		12.10
Metabolic rate (met)		1.2
Clothing insulation (clo)		0.70
Indoor microclimatic parameters during class:		
Air temperature (°C)		18.5
Relative humidity (%)		76
CO_2 (ppm)		2953

Operative temperature (°C)	**20.85**
PMV	**-0.6**
PPD (%)	**12.5**

Indoor microclimatic parameters after class:	
Air temperature (°C)	20.5
Mean radiant temperature (°C)	21.2
Air speed (m/s)	0.03
Relative humidity (%)	56
CO_2 (ppm)	689
Plane radiant temperature (°C)	
wall	21.6
wall	20.2
window	22.6
wall	20.6
ceiling	21.3
floor	21.1

Classroom IV C


(a)

(b)

(c)

Figure 6.23 - Classroom IV C (Ceggia): key plant (a); photo (b); desks layout and position of the Indoor Climatic Analyser Brüel&Kjær and of the Minolta luxmeter (c)

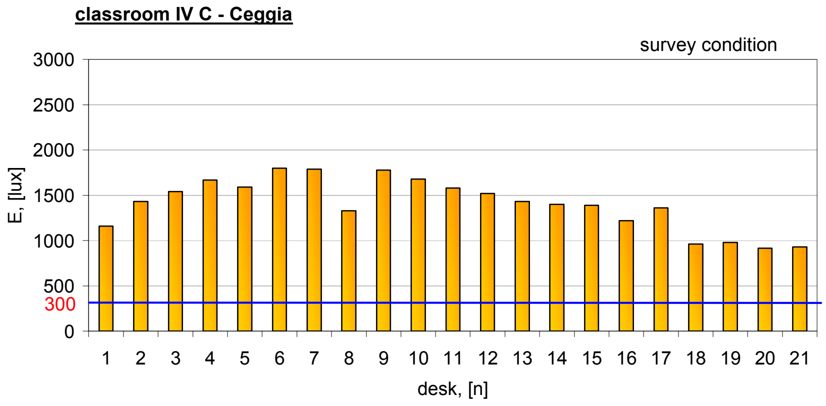


Figure 6.24 - Classroom IV C (Ceggia). Measured illuminance over the desks in survey administration conditions (lights switched off and brise-soleil in horizontal position)

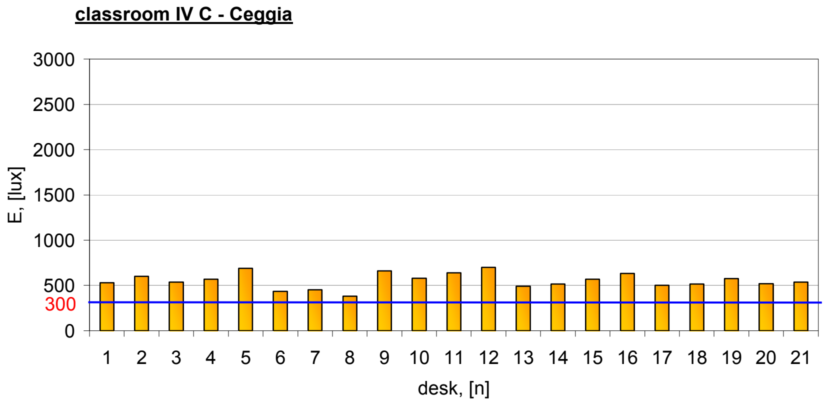


Figure 6.25 - Classroom IV C (Ceggia). Measured illuminance over the desks with lights switched on and brise-soleil closed

Table 6.3 – Classroom IV C Indoor micro-climatic parameters from which PMV and PPD indexes have been calculated

Ceggia, IVC Date	4/29
Pupils	21
Time of survey administration (during class)	14:30
Time of measurements (after class)	14.55
Metabolic rate (met)	1.2
Clothing insulation (clo)	0.70
Indoor microclimatic parameters during class:	
Air temperature (°C)	20.6
Relative humidity (%)	60
CO_2 (ppm)	1340

Operative temperature (°C)	**21.75**
PMV	**-0.4**
PPD (%)	**8.3**

Indoor microclimatic parameters after class:	
Air temperature (°C)	21.2
Mean radiant temperature (°C)	22.3
Air speed (m/s)	0.07
Relative humidity (%)	61
CO_2 (ppm)	1197
Plane radiant temperature (°C)	
wall	22.8
wall	21.3
window	23.8
wall	21.8
ceiling	21.9
floor	21.9

Classroom V A

Figure 6.26 - Classroom V A (Ceggia): key plant (a); photo (b); desks layout and position of the Indoor Climatic Analyser Brüel&Kjær and of the Minolta luxmeter (c)

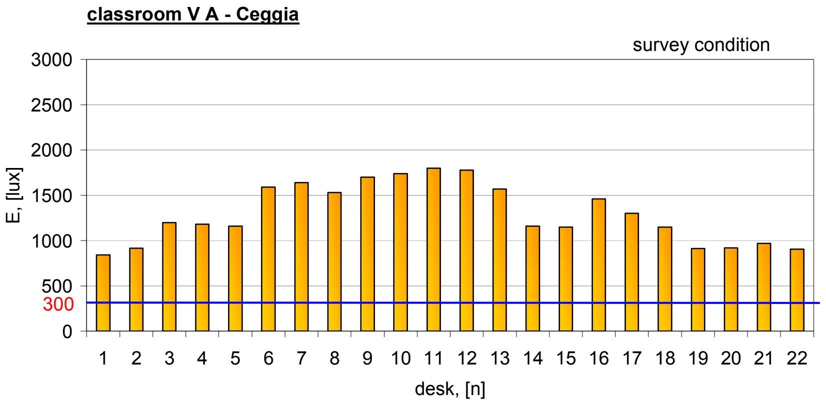


Figure 6.27 - Classroom V A (Ceggia). Measured illuminance over the desks in survey administration conditions (lights switched off and brise-soleil in horizontal position).

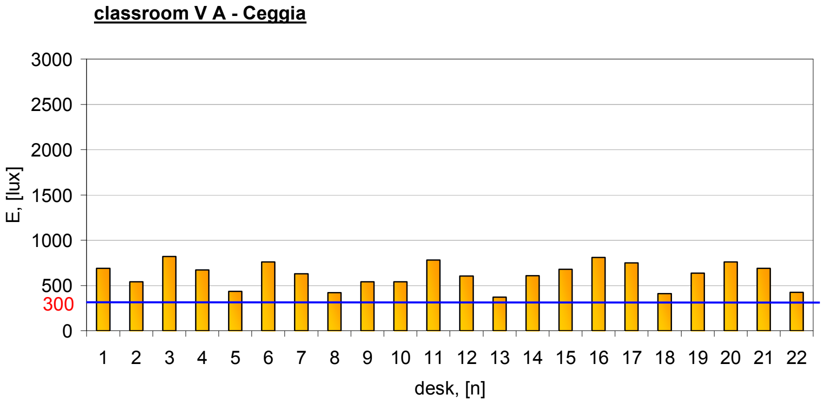


Figure 6.28 - Classroom V A (Ceggia). Measured illuminance over the desks with lights switched on and brise-soleil closed

Table 6.4 – Classroom V A Indoor micro-climatic parameters from which PMV and PPD indexes have been calculated

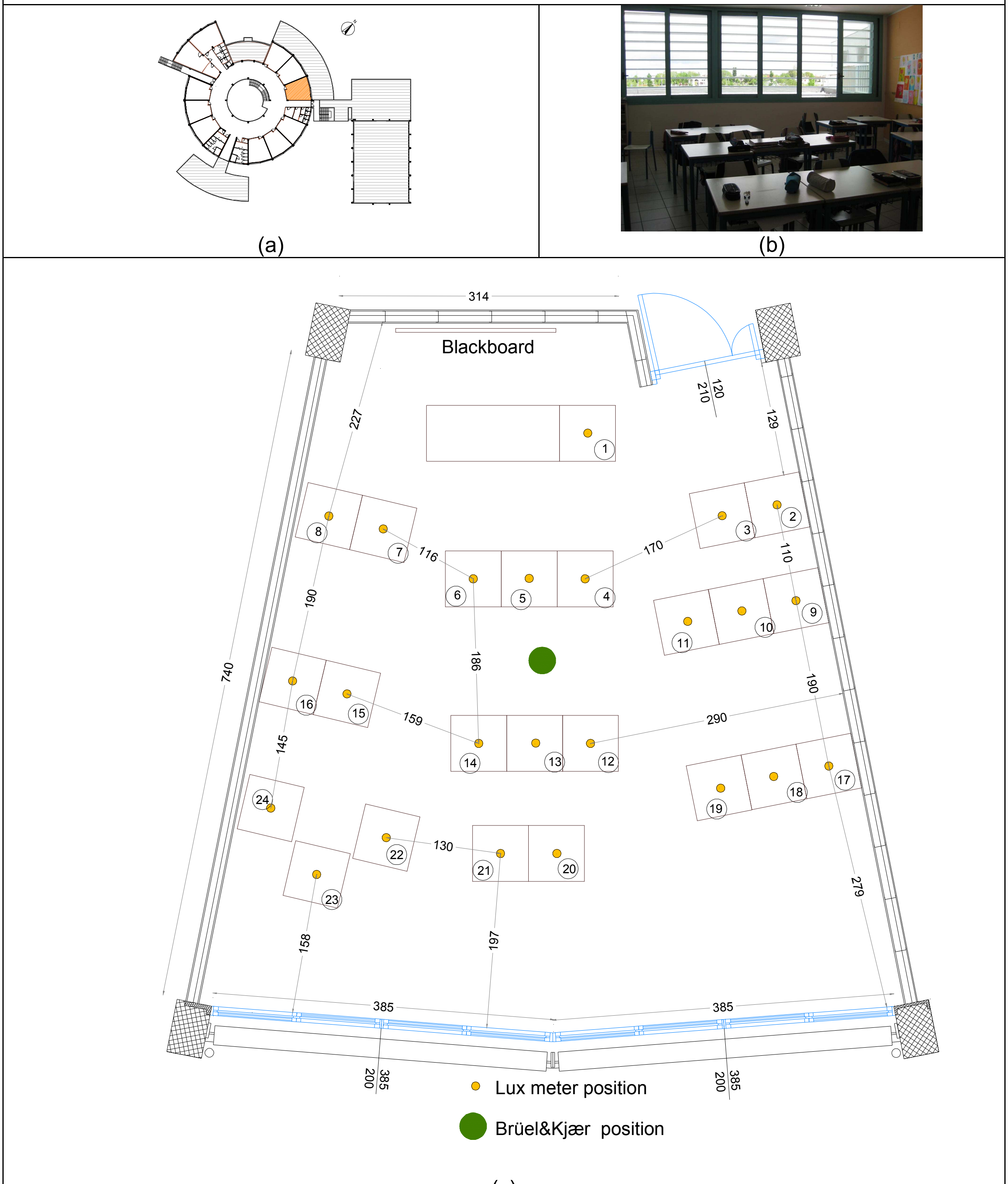
Ceggia, VA Date	4/29
Pupils	22
Time of survey administration (during class)	-
Time of measurements (after class)	13.50
Metabolic rate (met)	1.2
Clothing insulation (clo)	0.70
Indoor microclimatic parameters during class:	
Air temperature (°C)	-
Relative humidity (%)	-
CO_2 (ppm)	-

Operative temperature (°C)	**21.35**
PMV	**-0.5**
PPD (%)	**10.2**

Indoor microclimatic parameters after class:	
Air temperature (°C)	20.6
Mean radiant temperature (°C)	22.1
Air speed (m/s)	0.08
Relative humidity (%)	58
CO_2 (ppm)	640
Plane radiant temperature (°C)	
wall	22.5
wall	20.8
window	22.9
wall	21.4
ceiling	21.8
floor	22.9

Classroom V B

Classroom V B



(a) (b)

(c)

Figure 6.29 - Classroom V B (Ceggia): key plant (a); photo (b); desks layout and position of the Indoor Climatic Analyser Brüel&Kjær and of the Minolta luxmeter (c)

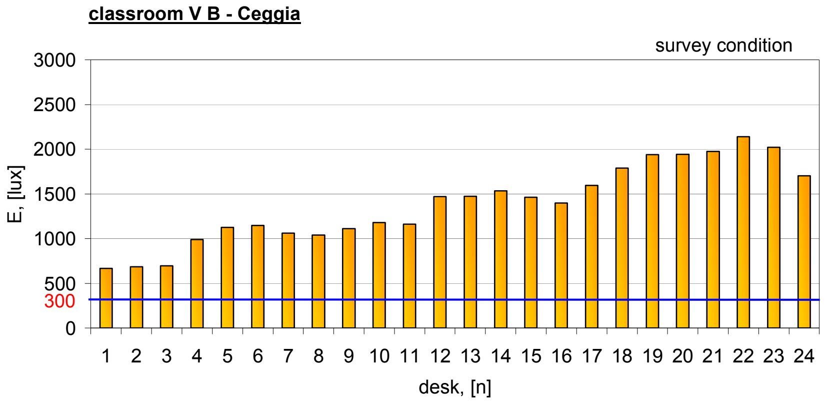


Figure 6.30 - Classroom V B (Ceggia). Measured illuminance over the desks in survey administration conditions (lights switched off and brise-soleil in horizontal position)

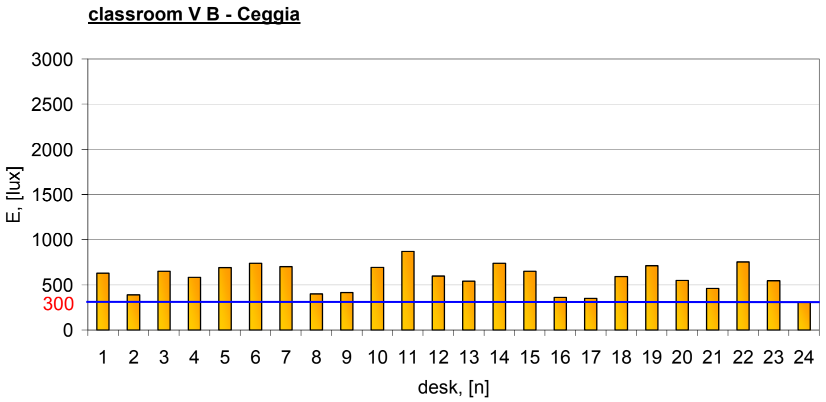


Figure 6.31 - Classroom V B (Ceggia). Measured illuminance over the desks with lights switched on and brise-soleil closed.

Table 6.5 – Classroom V B Indoor micro-climatic parameters from which PMV and PPD indexes have been calculated

Ceggia, VB	Date	4/29
Pupils (21 present)		23
Time of survey administration (during class)		10:50
Time of measurements (after class)		11.15
Metabolic rate (met)		1.2
Clothing insulation (clo)		0.70
Indoor microclimatic parameters during class:		
Air temperature (°C)		20.1
Relative humidity (%)		64
CO_2 (ppm)		1041

Operative temperature (°C)	**20.85**
PMV	**-0.6**
PPD (%)	**12.5**

Indoor microclimatic parameters after class:	
Air temperature (°C)	20.3
Mean radiant temperature (°C)	21.4
Air speed (m/s)	0.09
Relative humidity (%)	65
CO_2 (ppm)	724
Plane radiant temperature (°C)	
wall	22.4
wall	21.1
window	21.8
wall	20.9
ceiling	21.8
floor	20.2

6.4.2. Noventa di Piave Primary School

The measurements and the survey in the "G. Noventa" Primary School have been performed in 4th May 2009, therefore the radiators were not operating. The school is not equipped with a mechanical cooling system, therefore the classrooms were in free-running conditions: only natural ventilation was used to control the indoor temperature. In some classrooms the windows were opened to maintain an acceptable level of both thermal and indoor air quality. Moreover, some curtains and roller blinds were closed to assess lighting conditions.

The recorded data were elaborated in order to calculate, according to ISO 7730, Fanger's thermal comfort indices (PMV and PPD). The metabolic rate was fixed at 1.2 met (sedentary activity) and the actual people clothing were obtained from the questionnaire (0.7 clo).

For each of the six investigated classrooms all the recorded environmental parameters are reported in the following pages.

Considering classrooms' lighting levels, in survey administration condition many desks in all the classrooms had illuminance values under 300 lux, that is the minimum level required by the Standard (UNI 10840). Moreover, even with the electric light switched on and the shading devices closed, illuminance values were lower than 300 lux, therefore school luminaries should be replaced.

Classroom IV A

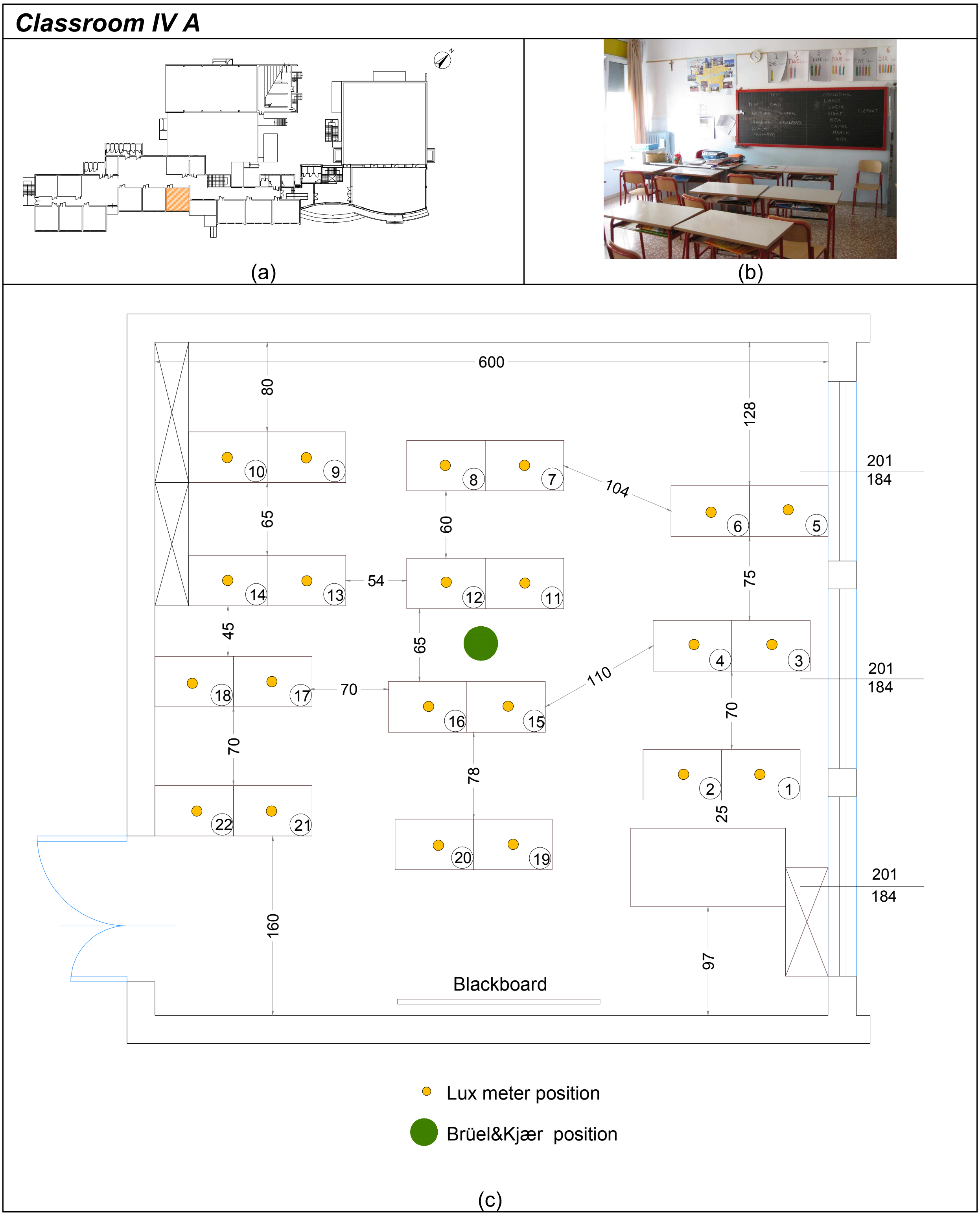


Figure 6.32 - Classroom IV A (Noventa di Piave): key plant (a); photo (b); desks layout and position of the Indoor Climatic Analyser Brüel&Kjær and of the Minolta luxmeter (c)

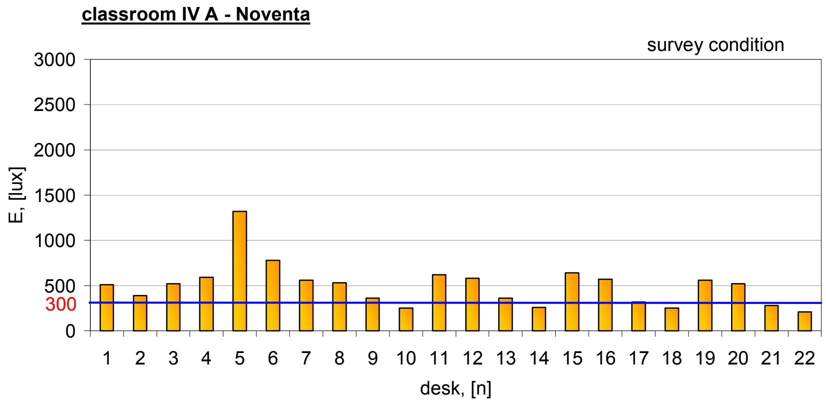


Figure 6.33 - Classroom IV A (Noventa di Piave). Measured illuminance over the desks in survey administration conditions (lights switched on, half closed curtains and rolling shutters)

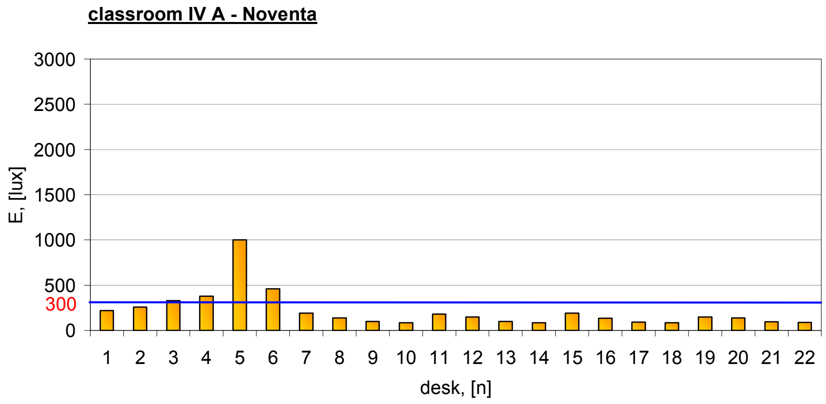


Figure 6.34 - Classroom IV A (Noventa di Piave). Measured illuminance over the desks in survey administration condition, but with lights switched off

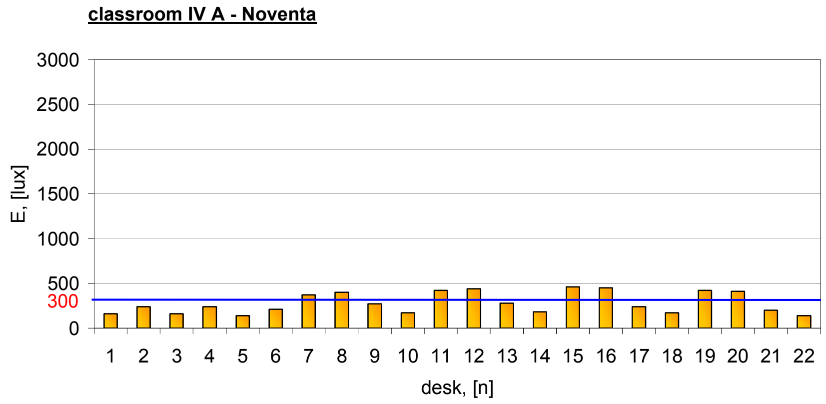


Figure 6.35 - Classroom IV A (Noventa di Piave). Measured illuminance over the desks with lights switched on and rolling shutters down

Table 6.6 – Classroom IV A Indoor micro-climatic parameters from which PMV and PPD indexes have been calculated

Noventa, IV A Date	5/4
Pupils	21
Time of survey administration (during class)	14:30
Time of measurements (after class)	17.35
Metabolic rate (met)	1.2
Clothing insulation (clo)	0.70
Indoor microclimatic parameters during class:	
Air temperature (°C)	23.2
Relative humidity (%)	55
CO_2 (ppm)	1245

Operative temperature (°C)	**23.15**
PMV	**-0.1**
PPD (%)	**5.2**

Indoor microclimatic parameters after class:	
Air temperature (°C)	22.7
Mean radiant temperature (°C)	23.6
Air speed (m/s)	0.05
Relative humidity (%)	38
CO_2 (ppm)	415
Plane radiant temperature (°C)	
wall	-
wall	-
window	23.8
wall	23.3
ceiling	24.3
floor	23

Classroom IV B

Classroom IV B

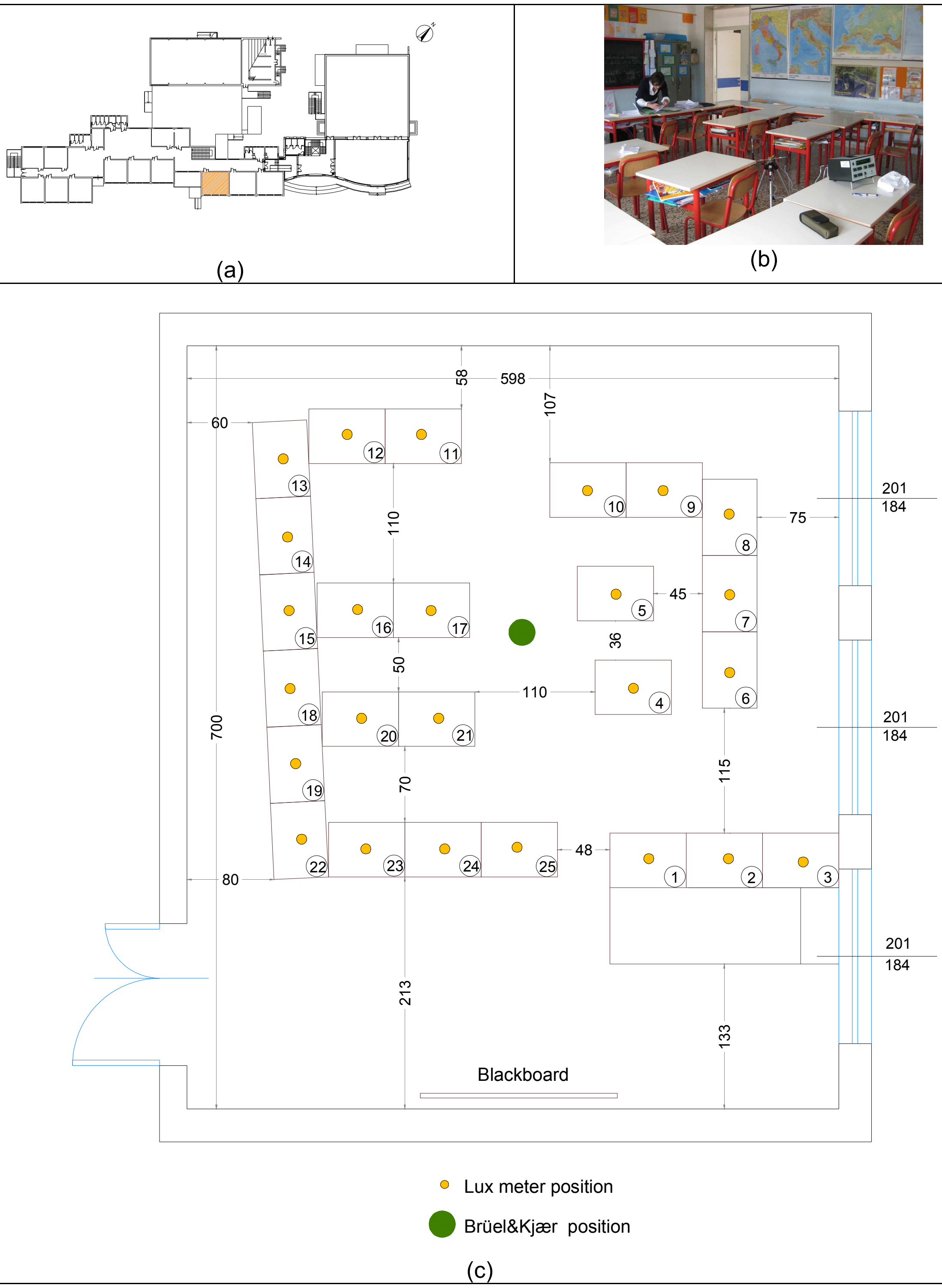


Figure 6.36 - Classroom IV B (Noventa di Piave): key plant (a); photo (b); desks layout and position of the Indoor Climatic Analyser Brüel&Kjær and of the Minolta luxmeter (c)

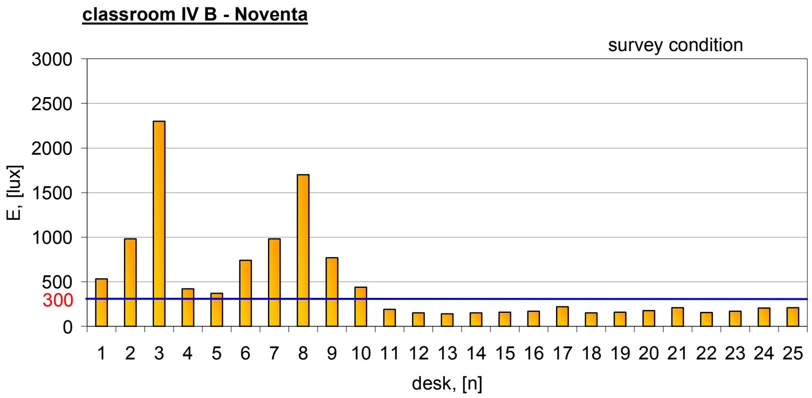


Figure 6.37 - Classroom IV B (Noventa di Piave). Measured illuminance over the desks in survey administration conditions (lights switched, curtains opened and half closed rolling shutters).

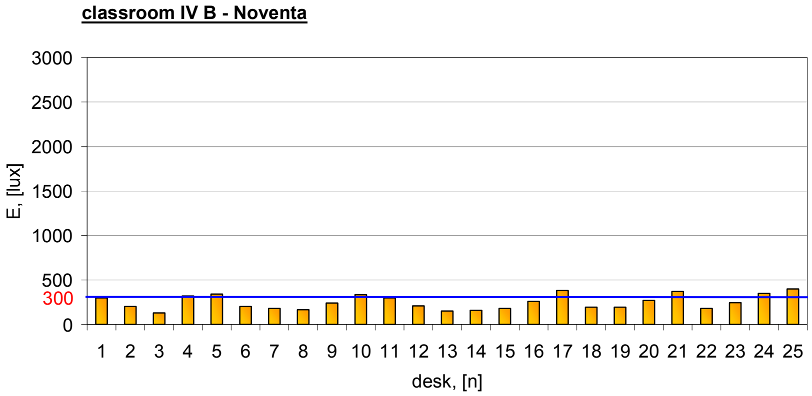


Figure 6.38 - Classroom IV B (Noventa di Piave). Measured illuminance over the desks with lights switched on and rolling shutters closed

Table 6.7 – Classroom IV B Indoor micro-climatic parameters from which PMV and PPD indexes have been calculated

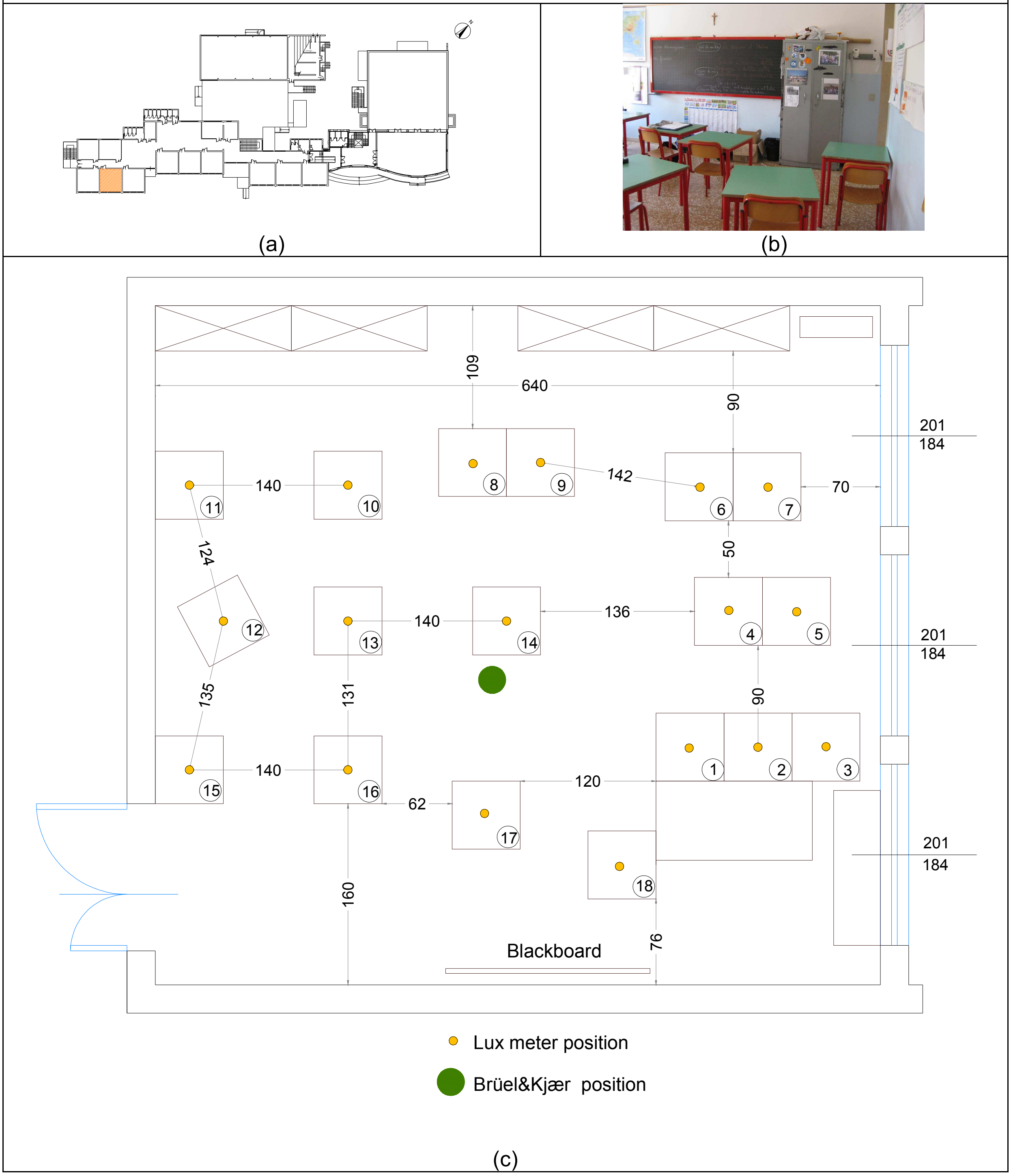
Noventa, IV B	Date	5/4
Pupils (23 present)		25
Time of survey administration (during class)		14:55
Time of measurements (after class)		17.15
Metabolic rate (met)		1.2
Clothing insulation (clo)		0.70
Indoor microclimatic parameters during class:		
Air temperature (°C)		23.5
Relative humidity (%)		46
CO_2 (ppm)		579

Operative temperature (°C)	**23.3**
PMV	**-0.1**
PPD (%)	**5.2**

Indoor microclimatic parameters after class:	
Air temperature (°C)	23.2
Mean radiant temperature (°C)	23.4
Air speed (m/s)	0.11
Relative humidity (%)	42
CO_2 (ppm)	602
Plane radiant temperature (°C)	
wall	-
wall	-
window	23.8
wall	22.9
ceiling	23.9
floor	23

Classroom IV C

Classroom IV C



(a)

(b)

(c)

Figure 6.39 - Classroom IV C (Noventa di Piave): key plant (a); photo (b); desks layout and position of the Indoor Climatic Analyser Brüel&Kjær and of the Minolta luxmeter (c)

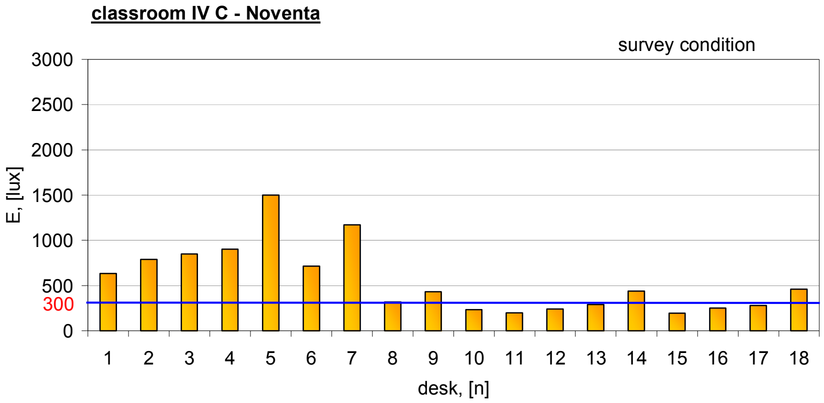


Figure 6.40 - Classroom IV C (Noventa di Piave). Measured illuminance over the desks in survey administration conditions (lights switched off, half closed curtains and rolling shutters)

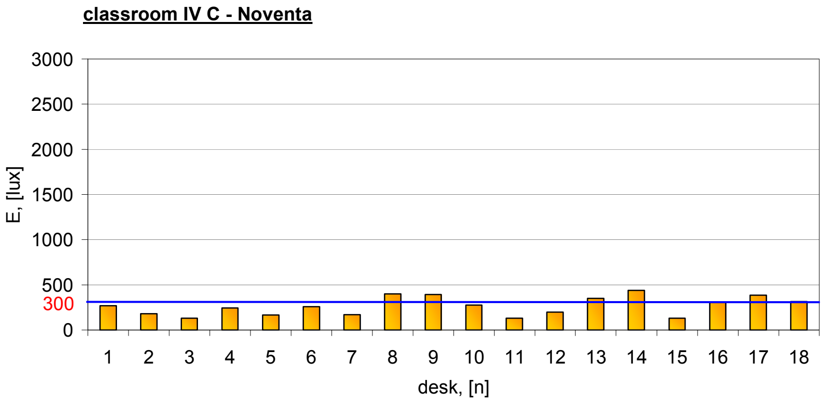


Figure 6.41 - Classroom IV C (Noventa di Piave). Measured illuminance over the desks with lights switched on and rolling shutters closed

Table 6.8 – Classroom IV C Indoor micro-climatic parameters from which PMV and PPD indexes have been calculated

Noventa, IV C	Date	5/4
Pupils (16 present)		18
Time of survey administration (during class)		12:35
Time of measurements (after class)		13.00
Metabolic rate (met)		1.2
Clothing insulation (clo)		0.70
Indoor microclimatic parameters during class:		
Air temperature (°C)		22.1
Relative humidity (%)		52
CO_2 (ppm)		1143

Operative temperature (°C)	**23.2**
PMV	**0**
PPD (%)	**5**

Indoor microclimatic parameters after class:	
Air temperature (°C)	23.2
Mean radiant temperature (°C)	23.2
Air speed (m/s)	0.07
Relative humidity (%)	52
CO_2 (ppm)	1200
Plane radiant temperature (°C)	
wall	-
wall	-
window	24.3
wall	22.7
ceiling	23.5
floor	22.3

Classroom V A

Classroom V A

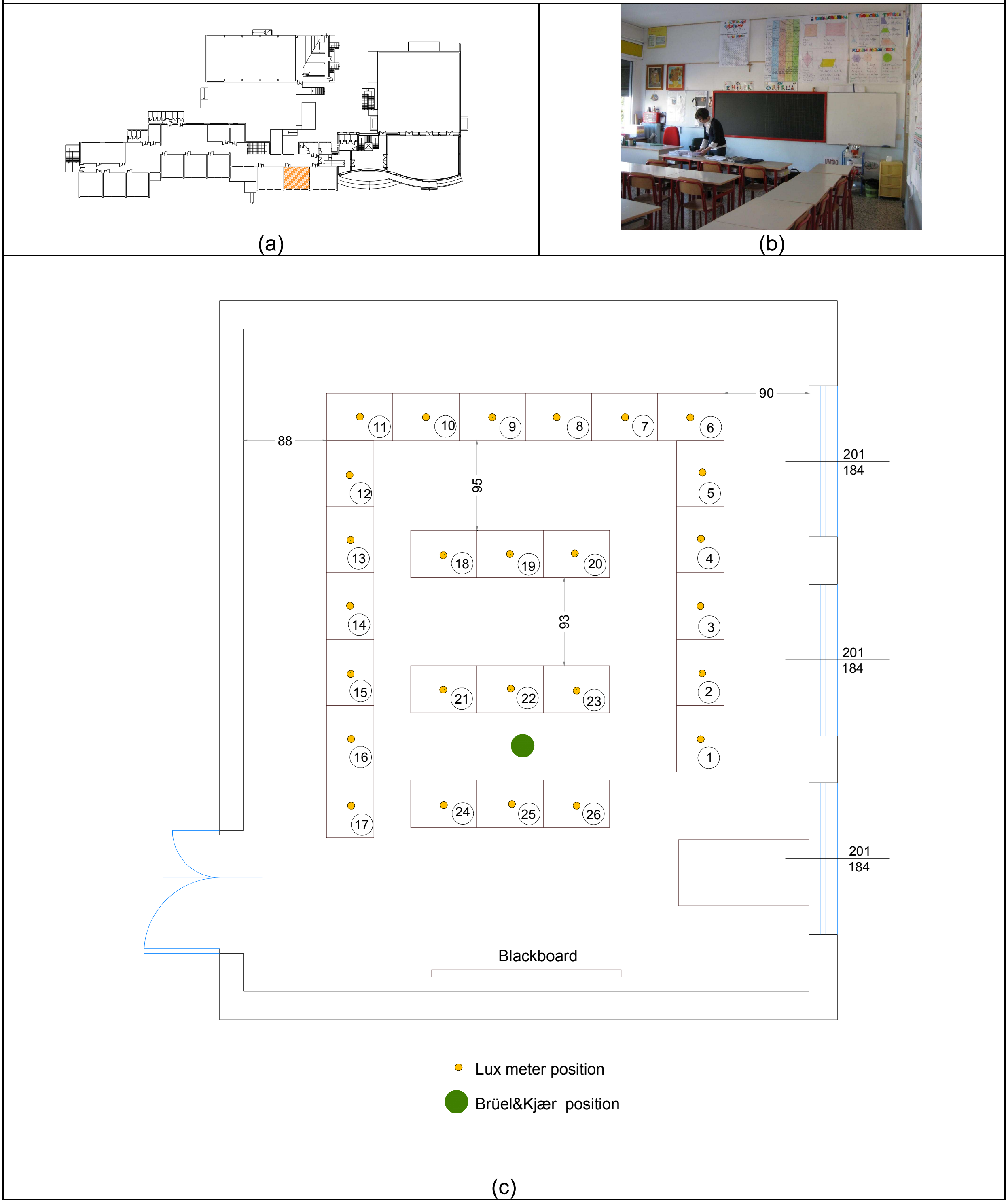

(a)
(b)
(c)

Figure 6.42 - Classroom V A (Noventa di Piave): key plant (a); photo (b); desks layout and position of the Indoor Climatic Analyser Brüel&Kjær and of the Minolta luxmeter (c)

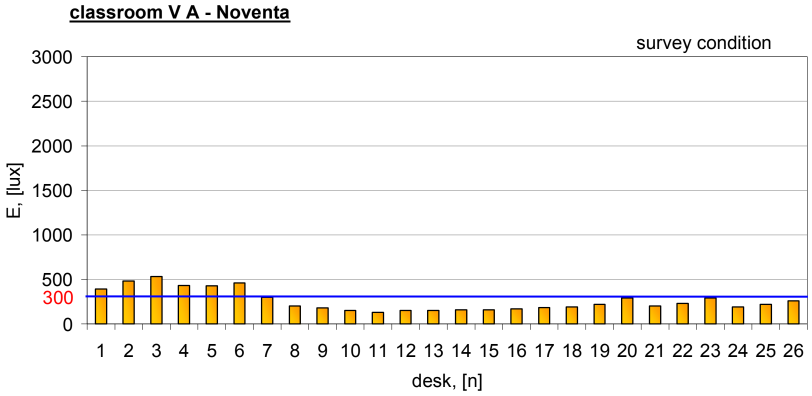


Figure 6.43 - Classroom V A (Noventa di Piave). Measured illuminance over the desks in survey administration conditions (lights switched off, curtains opened and half closed rolling shutters)

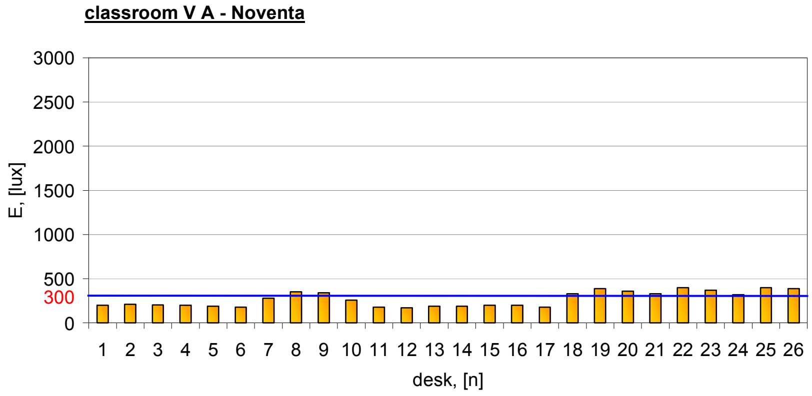


Figure 6.44 - Classroom V A (Noventa di Piave). Measured illuminance over the desks with lights switched on and rolling shutters closed

Table 6.9 – Classroom V A Indoor micro-climatic parameters from which PMV and PPD indexes have been calculated

Noventa, V A	Date	5/4
Pupils (24 present)		26
Time of survey administration (during class)		15:20
Time of measurements (after class)		18.05
Metabolic rate (met)		1.2
Clothing insulation (clo)		0.70
Indoor microclimatic parameters during class:		
Air temperature (°C)		22.7
Relative humidity (%)		46
CO_2 (ppm)		445

Operative temperature (°C)		**22.6**
PMV		**-0.3**
PPD (%)		**6.9**

Indoor microclimatic parameters after class:	
Air temperature (°C)	22.0
Mean radiant temperature (°C)	23.2
Air speed (m/s)	0.11
Relative humidity (%)	40
CO_2 (ppm)	415
Plane radiant temperature (°C)	
wall	-
wall	-
window	23.5
wall	22.9
ceiling	23.5
floor	22.7

Classroom V B

Classroom V B

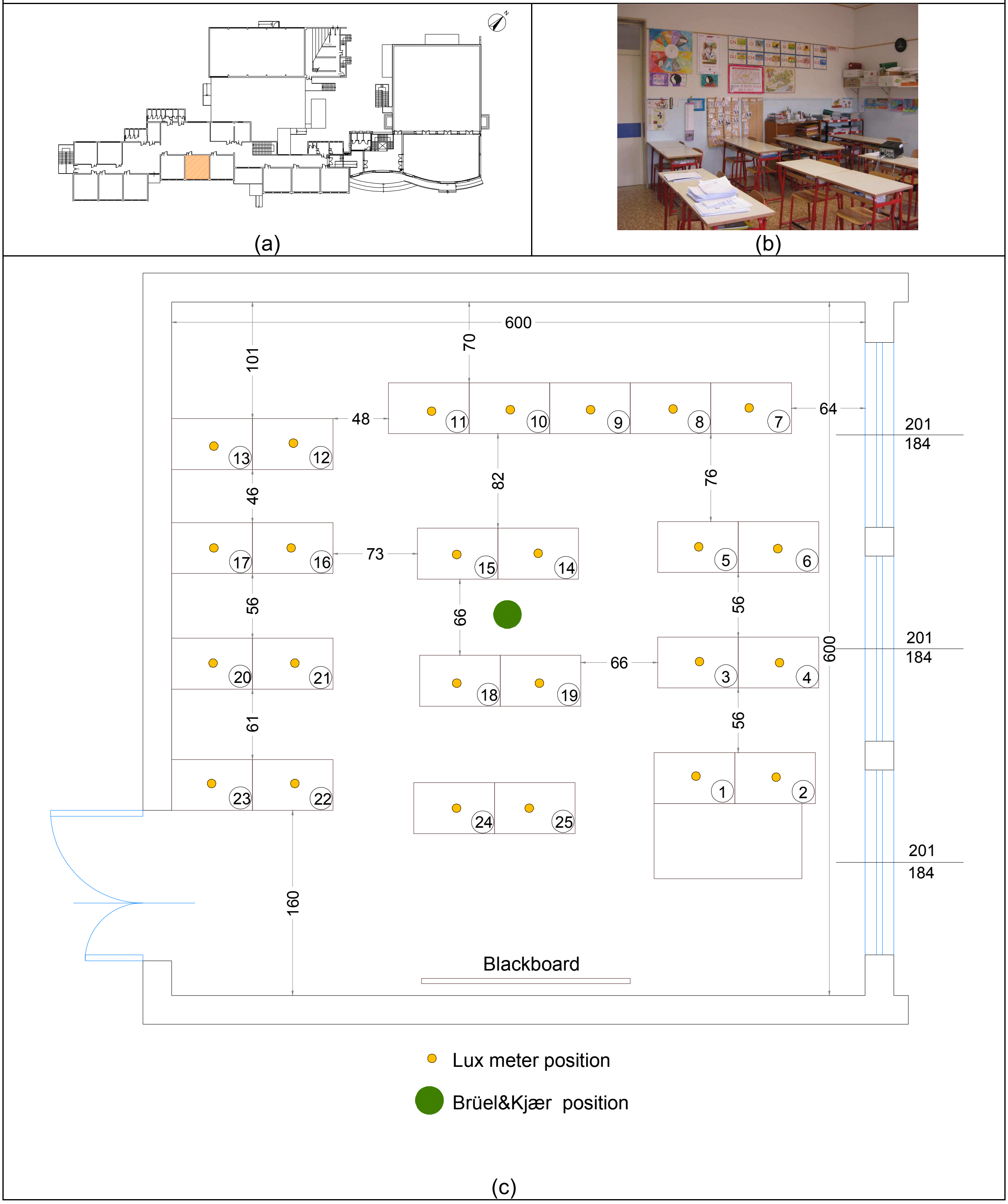


Figure 6.45 - Classroom V B (Noventa di Piave): key plant (a); photo (b); desks layout and position of the Indoor Climatic Analyser Brüel&Kjær and of the Minolta luxmeter (c)

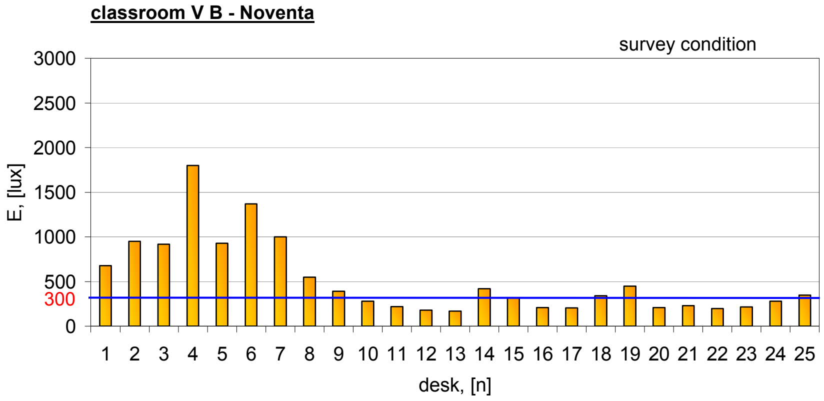


Figure 6.46 - Classroom V B (Noventa di Piave). Measured illuminance over the desks in survey administration conditions (lights switched off, curtains opened and two of the three rolling shutters closed)

Table 6.10 – Classroom V B Indoor micro-climatic parameters from which PMV and PPD indexes have been calculated

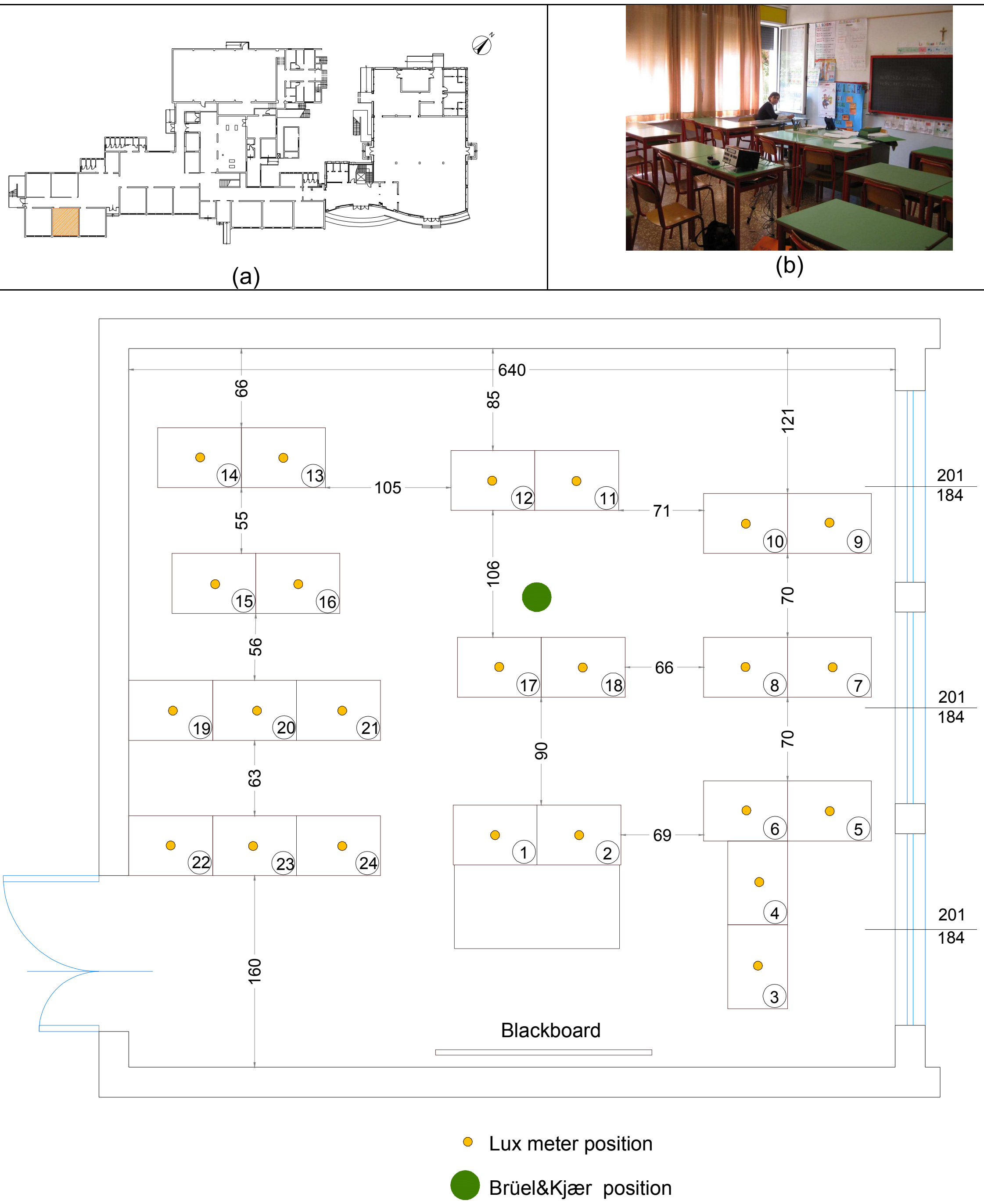
Noventa, V B	Date	5/4
Pupils (24 present)		25
Time of survey administration (during class)		15:45
Time of measurements (after class)		17.15
Metabolic rate (met)		1.2
Clothing insulation (clo)		0.70
Indoor microclimatic parameters during class:		
Air temperature (°C)		24.0
Relative humidity (%)		63
CO_2 (ppm)		2891

Operative temperature (°C)		**23.25**
PMV		**-0.1**
PPD (%)		**5.2**

Indoor microclimatic parameters after class:	
Air temperature (°C)	22.8
Mean radiant temperature (°C)	23.7
Air speed (m/s)	0.03
Relative humidity (%)	40
CO_2 (ppm)	432
Plane radiant temperature (°C)	
wall	-
wall	-
window	24.6
wall	23.1
ceiling	24
floor	23.1

Classroom V C

Classroom V C



(a)

(b)

(c)

Figure 6.47 - Classroom V C (Noventa di Piave): key plant (a); photo (b); desks layout and position of the Indoor Climatic Analyser Brüel&Kjær and of the Minolta luxmeter (c)

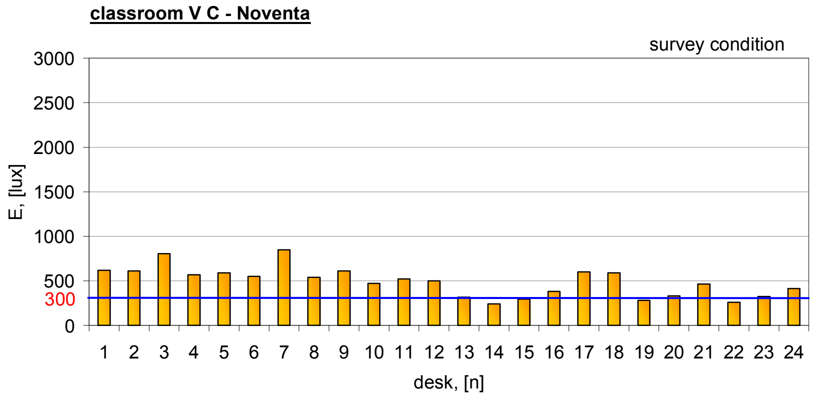


Figure 6.48 - Classroom V C (Noventa di Piave). Measured illuminance over the desks in survey administration conditions (lights switched on, curtains opened and half closed rolling shutters)

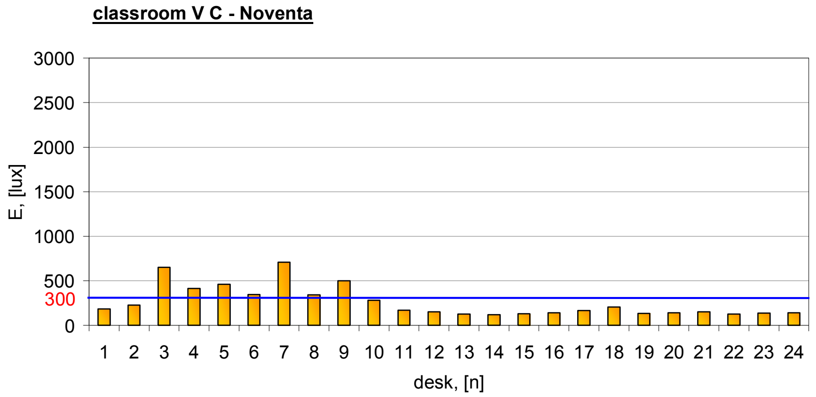


Figure 6.49 - Classroom V C (Noventa di Piave). Measured illuminance over the desks with lights switched off, curtains closed and half closed rolling shutters

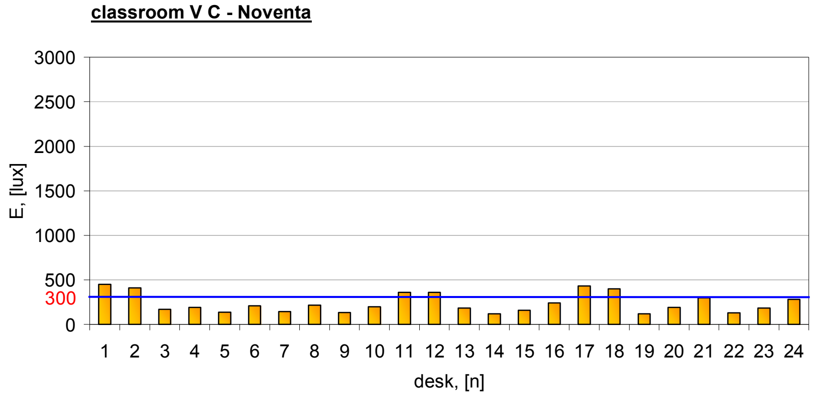


Figure 6.50 - Classroom V C (Noventa di Piave). Measured illuminance over the desks with lights switched on and rolling shutters down

Table 6.11 – Classroom V C Indoor micro-climatic parameters from which PMV and PPD indexes have been calculated

Noventa, V C	Date	5/4
Pupils (22 present)		24
Time of survey administration (during class)		12:00
Time of measurements (after class)		13.50
Metabolic rate (met)		1.2
Clothing insulation (clo)		0.70
Indoor microclimatic parameters during class:		
Air temperature (°C)		20.9
Relative humidity (%)		63
CO_2 (ppm)		2135

Operative temperature (°C)		**22.3**
PMV		**-0.2**
PPD (%)		**5.8**

Indoor microclimatic parameters after class:	
Air temperature (°C)	22.2
Mean radiant temperature (°C)	22.4
Air speed (m/s)	0.05
Relative humidity (%)	53
CO_2 (ppm)	510
Plane radiant temperature (°C)	
wall	-
wall	-
window	23.3
wall	21.5
ceiling	23.5
floor	21.1

6.5. Statistical results

The answers given to the survey have been elaborated with NPC Test (NPC Test User Guide; Pesarin, 2001) for permutation test and non parametric statistic. This software has been used to analyse the main differences between the two educational buildings and between classrooms of the same school. The data sheet requested by the program must have the statistical units (the pupils) along the row and each answer along the column, therefore all the informations related to each pupil are included in a single row. The potential difference between the answers has been measured in terms of p-value: if the p-value is below 0.05, it means that there is a significant difference. Moreover, the closer the p-value to 0, the more significant the difference.

Finally, it must be reminded that not all the children have answered to all the survey and the percentage of answers reported in the following graphs refers to all the investigated pupils, not only to the ones who have expressed their preferences.

6.5.1. Difference between the two primary schools

The difference between the schools has no led to significant results: only two questions had different answers (Figure 6.51).

The pupils answer that there is a good lighting quality, because they can see well both the blackboard (more than the 70% of the answers is "*yes*") and the desk (more than the 90%).

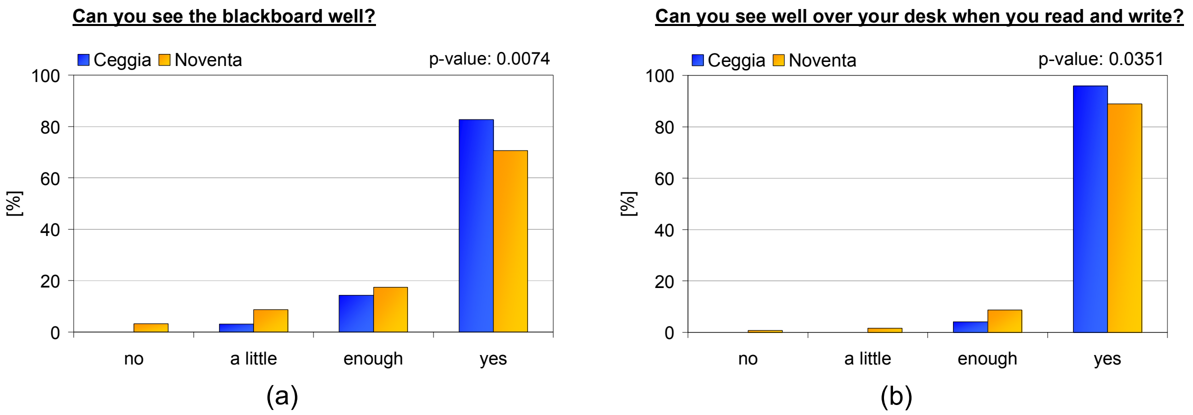


Figure 6.51 - Visual quality: blackboard (a); desk (b)

Even though only the two questions in Figure 6.51 have led to significant differences between the two schools, it is interesting to report what the pupils have answered to the questions concerning IEQ. For example, considering acoustics, it could be noticed, from Figure 6.52, that the Noventa school is considered more noisy than the Ceggia one. This can be explained watching the bar chart in Figure 6.53 where the higher percentage of the answer "*external*" confirms the fact that Noventa school is characterized by the traffic noise caused by the near main road.

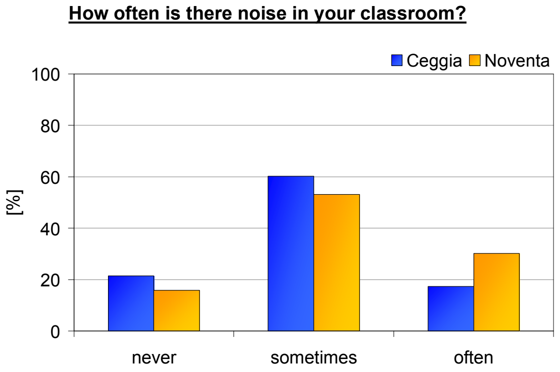


Figure 6.52 – Noise frequency

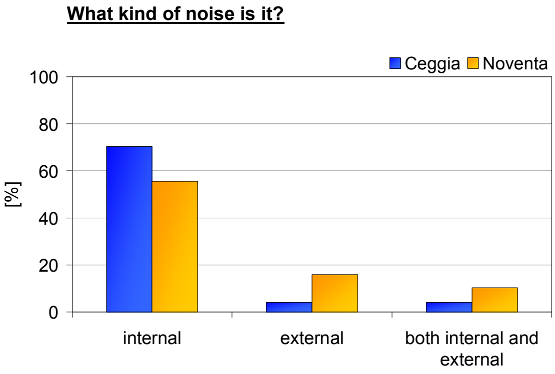


Figure 6.53 - Noise sources

No significant problems of speech intelligibility are present in both the schools (Figure 6.54).

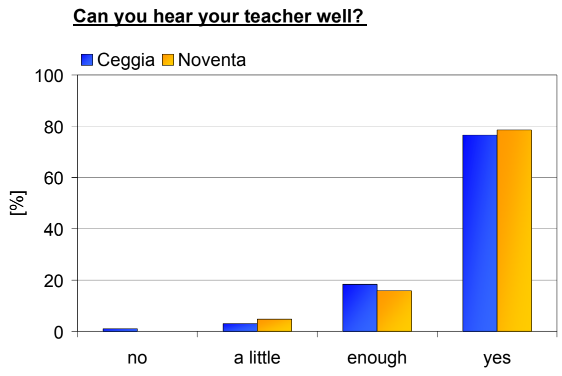


Figure 6.54 - Speech intelligibility

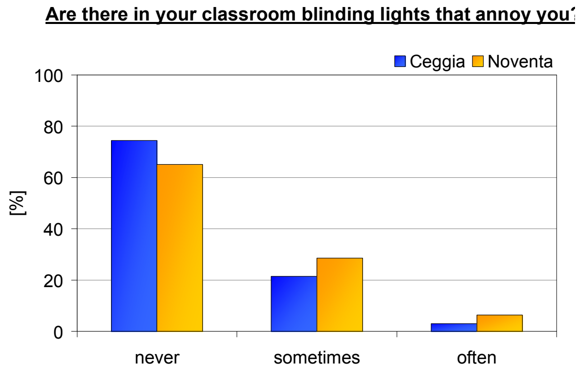


Figure 6.55 – Glare appearance

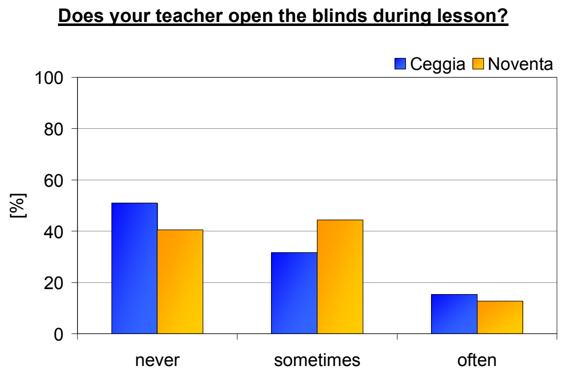


Figure 6.56 - Frequency of blind opening

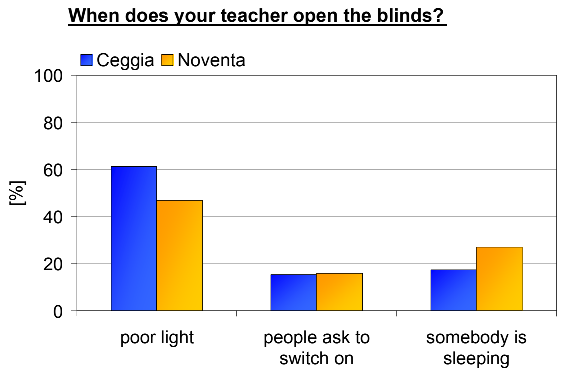


Figure 6.57 - Blind opening

The visual quality of the two schools, in terms of glare appearance (Figure 6.55), is good, in fact more than the 60% of the pupils is not annoyed by blinding lights. In Ceggia school, a great percentage of children states that glare does not frequently occur. This can be explained by the provided shading systems: in Noventa school the rolling shutters could not be frequently closed (45% of children answered "*sometimes*") otherwise no view out is available and the curtain could not be sufficient to prevent high lighting levels. On the contrary, the external venetian blind in Ceggia school can, on one hand, control daylight and, on the other, allow a view out. Finally most of the children state that the blinds are opened when there is a low lighting level.

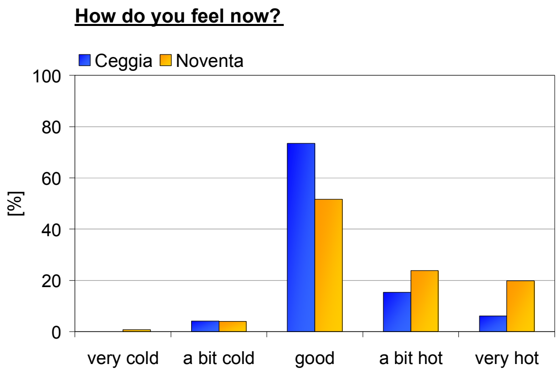


Figure 6.58 – Perceived temperature

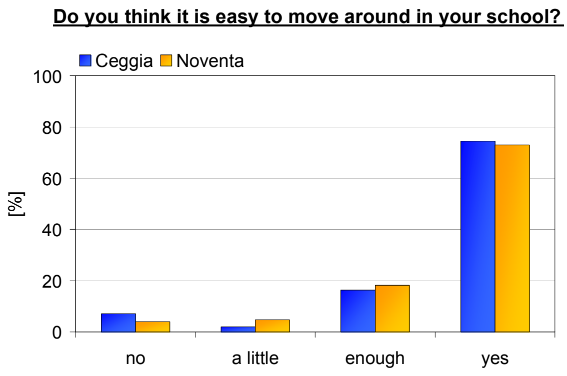


Figure 6.59 - School accessibility

The answers given to the question concerning how pupils feel in terms of perceived temperature (Figure 6.58) is in agreement with the recorded operative temperature in the classrooms. In fact, in Noventa school, the temperature was around 22-23°C, while in the Ceggia school 20-21°C. It cannot be assumed that this is due to building construction, because measurements have been recorded in two different days (29th April for Ceggia and 4th May for Noventa) and in free running period (no heating nor cooling).

More than the 70% in both schools affirmed that it is easy to move around the school (Figure 6.59), so no problems connected to accessibility have been found, even though it is not certain if the pupils have really understood the question.

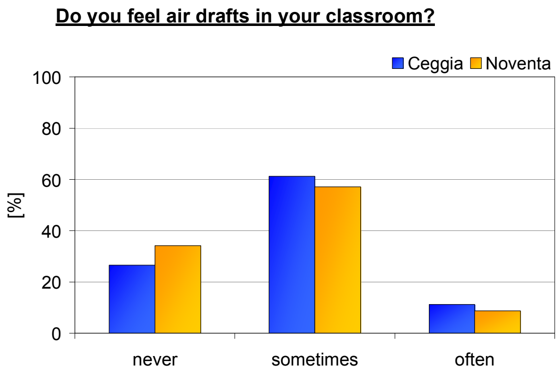


Figure 6.60 – Frequency of air drafts

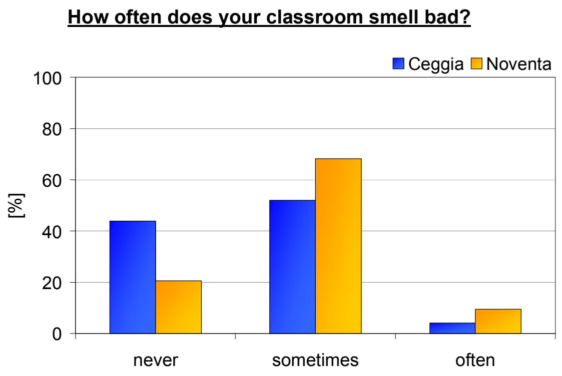


Figure 6.61 - Indoor air quality

The fact that in Ceggia school there is a greater percentage of pupils saying that the classroom rarely smells bad can be a consequence of the presence of mechanical ventilation (and this can also explain the higher frequency of air drafts (Figure 6.60)), even though the system did not work when the survey has been administrated, or simply by the fact that the school is surrounded only by houses and public parks (no traffic).

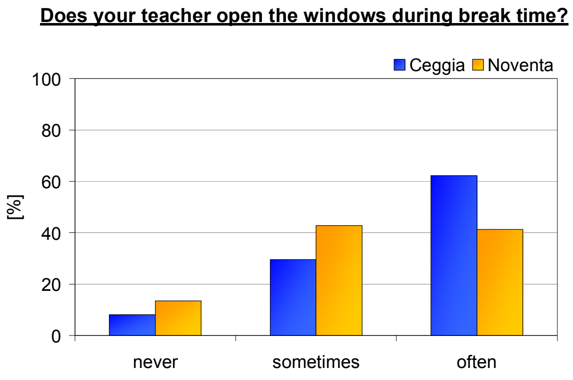


Figure 6.62 - Windows opening in break time

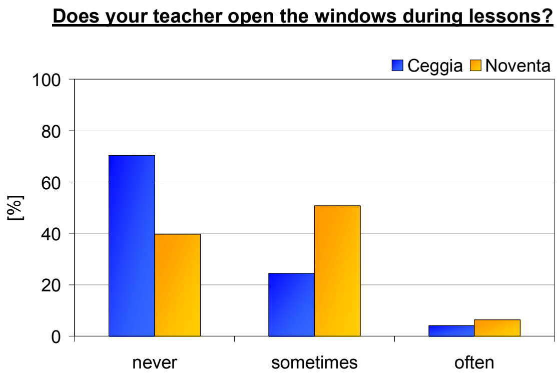
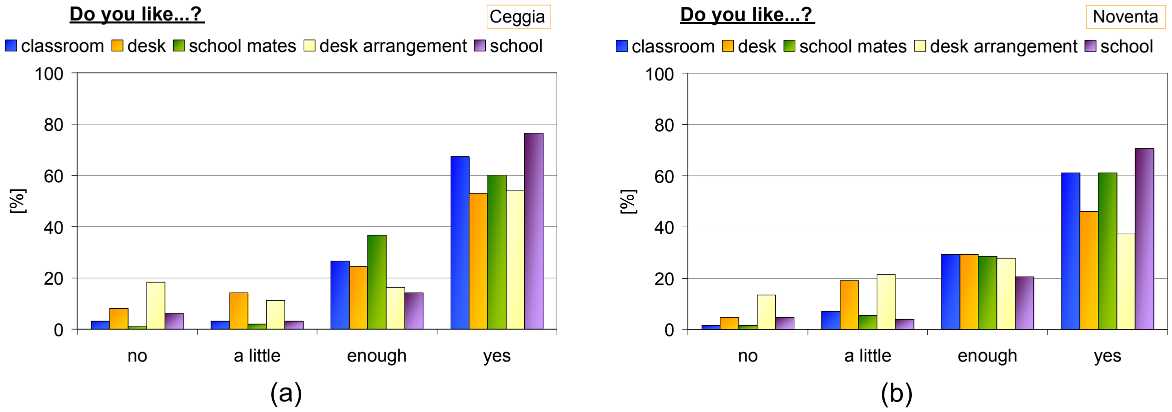


Figure 6.63 - Windows opening during lessons

The bar charts in Figure 6.62 and in Figure 6.63 confirm that typically in educational buildings windows are opened only in break time, even though it would be necessary, if no ventilation system is provided, to open the windows also during class, because CO_2 levels can be very high (Figure 6.16).

The pupils' satisfaction, regarding the classroom, the desk, the school mates, the desk arrangement and the school, is summarized in the graphs below (Figure 6.64). In general, all these aspects are considered satisfactory in both the school. The desk and the desk arrangement are the most criticized items.



(a) (b)

Figure 6.64 – Pupils' satisfaction: Ceggia school (a); Noventa school (b)

The main sources of pupils' dissatisfactions are the bad smells and the blinding lights, while the air drafts are not considered so important for a comfortable environment (Figure 6.65).

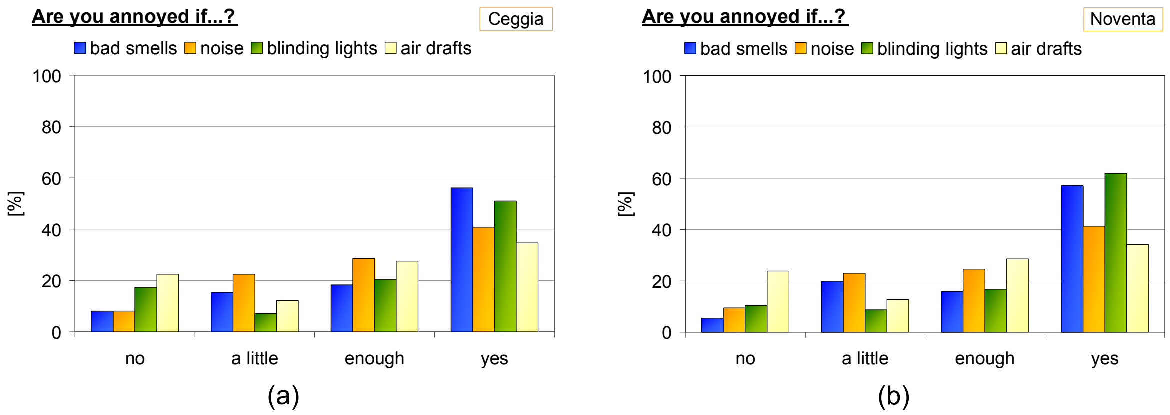


Figure 6.65 – Pupils' annoyance sources: Ceggia school (a); Noventa school (b)

Finally, the bar charts relative to pupils' reactions when a discomfort is perceived are reported from Figure 6.66 to Figure 6.68. It can be noticed that children behaviour towards such problems is almost the same in both schools and it is probably the expected one.

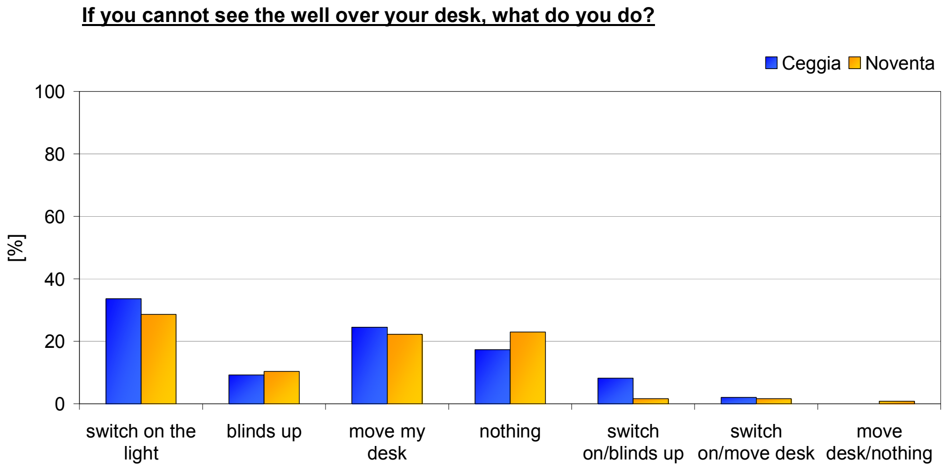


Figure 6.66 – Pupils' reaction to a poor visual quality over the desk

When pupils cannot see well over the desk, they ask to turn on the light or they move their desk (Figure 6.66. About the 20% of them is not interested in this problem and it has answered "*nothing*".

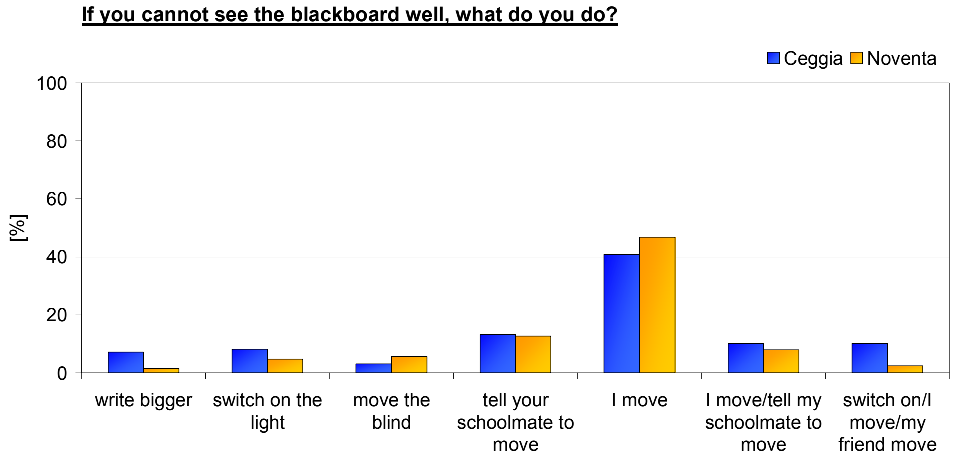


Figure 6.67 – Pupils' reaction when they do not see well the blackboard

The poor visibility of the blackboard (Figure 6.67) is not solved asking to switch on the light, as it happens for the poor visibility over the desks (Figure 6.66). This can be explained because no specific luminaries pointed to the blackboard are provided. Moreover, the fact that the most of them answered "*I move*" means that they probably associate the poor visibility of the blackboard to desk position or to the presence of a school mate in front of them.

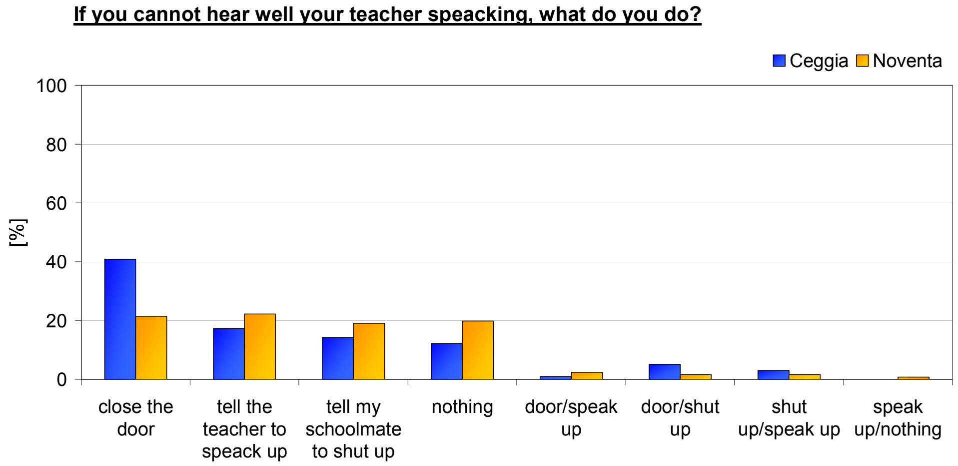


Figure 6.68 – Pupils' reactions when there is a poor speech intelligibility

When there is a problem concerning speech intelligibility, the 40% of pupils of Ceggia school answer that they ask to close the door, while for Noventa pupils each of the possible answer has the same percentage (Figure 6.68).

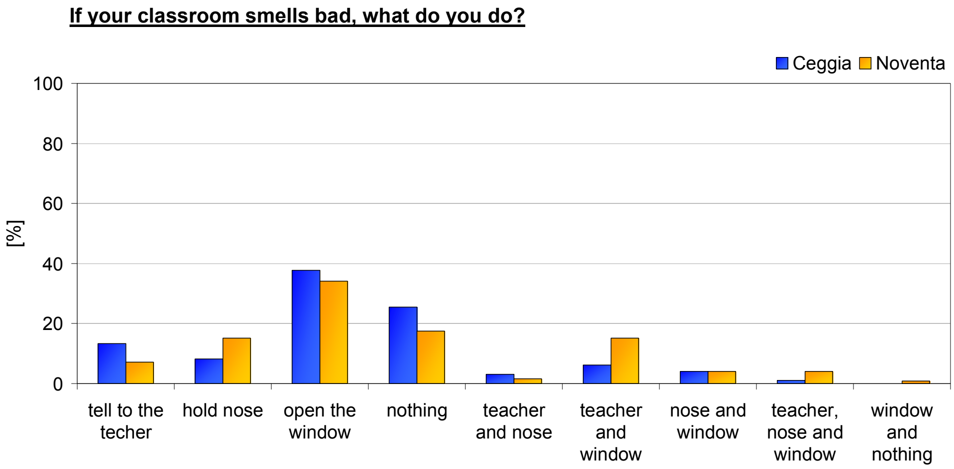


Figure 6.69 – Pupils' reaction to poor air quality

In case of poor indoor air quality, almost the 30% of the pupils of both schools asks the teacher to open the window (Figure 6.69). As for the desk visibility, a great percentage of pupils does not consider that the poor air quality is a problem to work out.

6.5.2. Further statistical analysis

The comparison between the two schools have not led to significant results, therefore other tests have been carried out selecting two stratification variables: the gender and the age. The significant differences, measured in terms of p-value, are reported in each of the following bar charts.

Classrooms V

In classrooms V, the boys differ for four aspects, while the girls only for two. The main difference is about the question concerning school satisfaction (Figure 6.73): the boys of Noventa schools feel good at school (around 80%), while the 25% of remaining children said that they do not like their school. Moreover, the 90% of Noventa boys states that there are no problems of speech intelligibility (Figure 6.70), while the boys of the other school affirmed that they sometimes have such problem (the 35% have answered "*enough*").

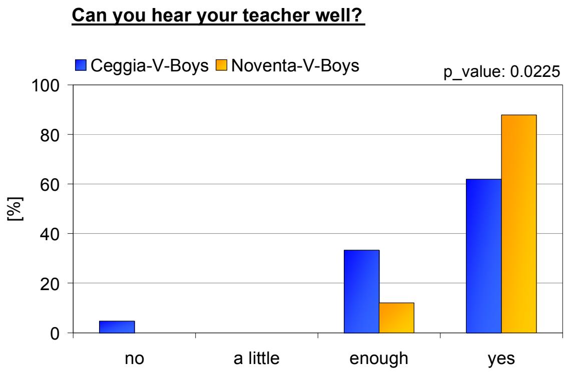


Figure 6.70 – Difference in speech intelligibility between boys of classrooms V (p-value: 0.0225)

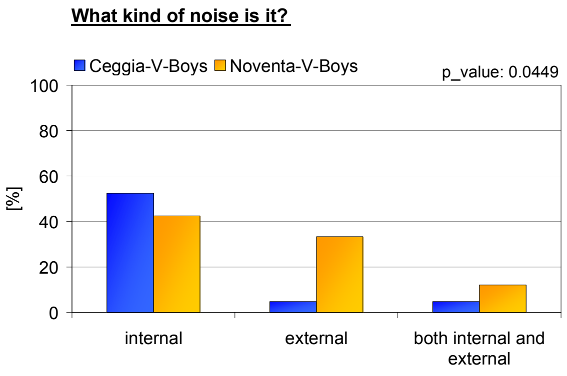


Figure 6.71 - Difference in identifying noise sources between boys of classrooms V (p-value: 0.0449)

Considering desk arrangement (Figure 6.72), the same percentage of pupils (40%) stated that they do not like it (Ceggia school) and that they like it (Noventa school). Finally, the difference in the answer concerning the noise sources can be explained by the effective difference in school location, as already discussed for Figure 6.53.

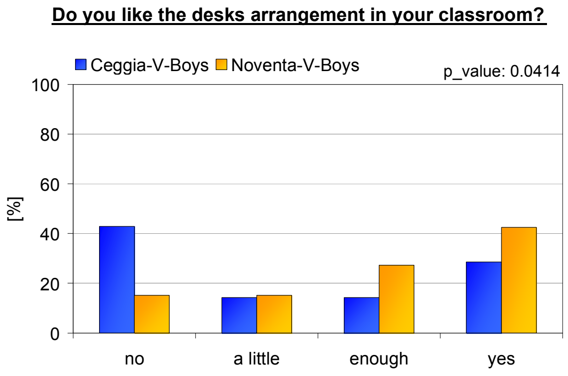


Figure 6.72 – Difference in satisfaction of desk arrangement between boys of classrooms V (p-value: 0.0414)

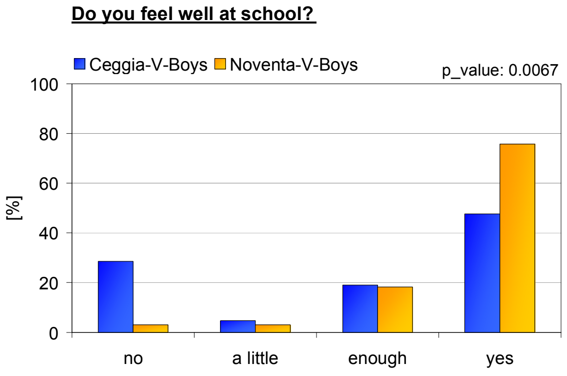


Figure 6.73 - Difference in school satisfaction between boys of classrooms V (p-value: 0.0067)

Almost the same percentage of girls stated that sometimes it happens that there is a poor air quality in the classroom, but, considering Noventa school, the same percentage (15%) of girls has answered “*never*” and “*often*”, while all the remaining percentage of Ceggia school girls answered “*never*”. Considering glare appearance (Figure 6.75), the 90% of Ceggia girls does not perceive visual problems inside the classroom, while the 40% of the Noventa ones notices this discomfort. In conclusion, the school of Ceggia is preferred by the girls than the Noventa one, in terms of both visual and indoor air quality.

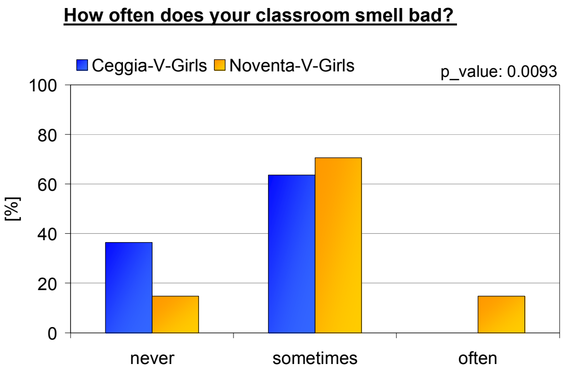


Figure 6.74 – Difference in frequency of poor air quality between girls of classrooms V (p-value: 0.0093)

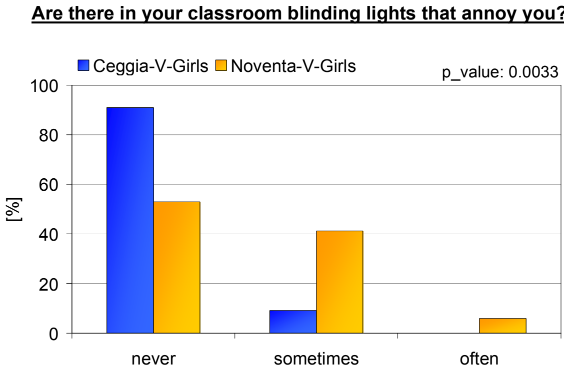
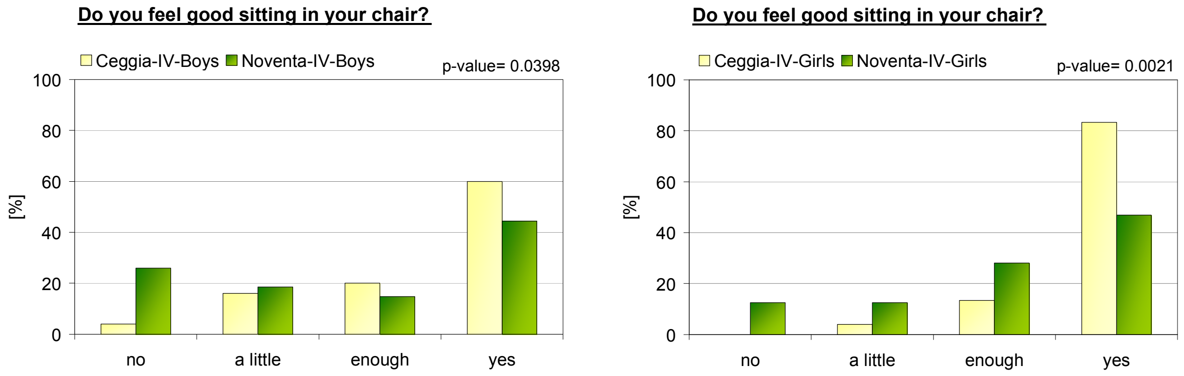


Figure 6.75 - Difference in glare appearance between girls of classrooms V (p-value: 0.0033)

Classrooms IV

Both boys and girls of the classrooms IV of the two schools have given different answers considering chair comfort (Figure 6.76), school satisfaction and blackboard visibility.



(a) (b)

Figure 6.76 - Difference in chair comfort between boys of classrooms IV (p-value: 0.0398) (a); between girls of classrooms IV (p-value: 0.0021) (b)

The chairs in both schools are more or less the same, but the pupils prefer the ones in Ceggia school (e.g. the girls who stated that they feel good sitting in their chair are the double in Ceggia than in Noventa, while for the boys, the difference is only 20%). In Ceggia school, more than the 90% of girls and the 80% of boys is satisfied by the school, while only the 60% of both is satisfied of Noventa school (Figure 6.77).

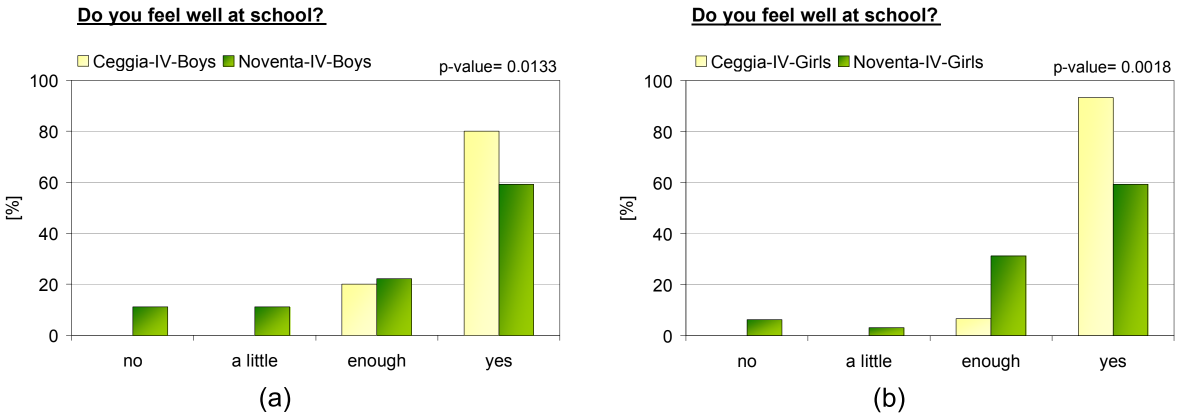


Figure 6.77 - Difference in school satisfaction between boys of classrooms IV (p-value: 0.0133) (a); between girls of classrooms IV (p-value: 0.0018) (b)

Considering blackboard visibility (Figure 6.78), both boys and girls of Ceggia school have not this problem, while both boys and girls of the other school notice sometimes this problem.

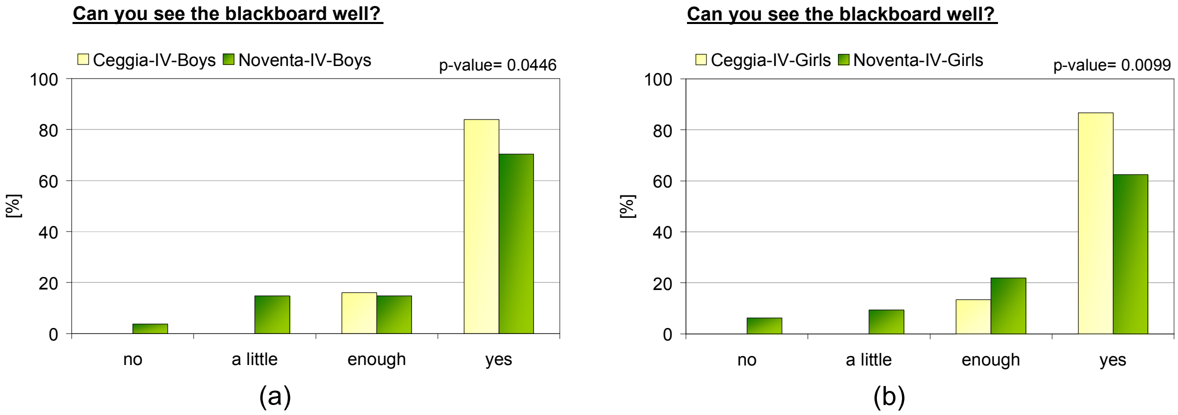


Figure 6.78 - Difference in blackboard visibility between boys of classrooms IV (p-value: 0.0446) (a); between girls of classrooms IV (p-value: 0.0099) (b)

The girls of classroom IV differ by four other aspects:

- Satisfaction about desks arrangement (Figure 6.79): the 70% of Ceggia school likes it, while the 20% of the other school is not satisfied.
- School accessibility (Figure 6.80): more than the 80% of Ceggia school thinks that it is easy to move around the school, while in the other school the percentage of girls who gave a positive answer is 70%.
- Desk visibility (Figure 6.81): all the girls of Ceggia school agree that they can see well over the desk, while in the other school this percentage is 80%.
- Perceive temperature (Figure 6.82): over the 90% of Ceggia school felt good, while, in the other school, the 30% felt hot and the 20% very hot. It must be

remembered that the survey was not administrated in the same day and the operative temperatures in the two schools were different.

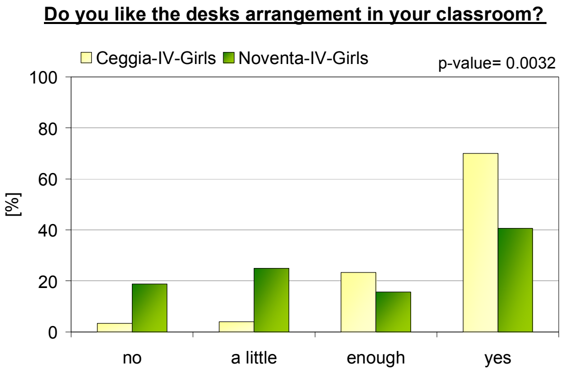


Figure 6.79 - Difference in satisfaction about desk arrangement between girls of classrooms IV (p-value: 0.0032)

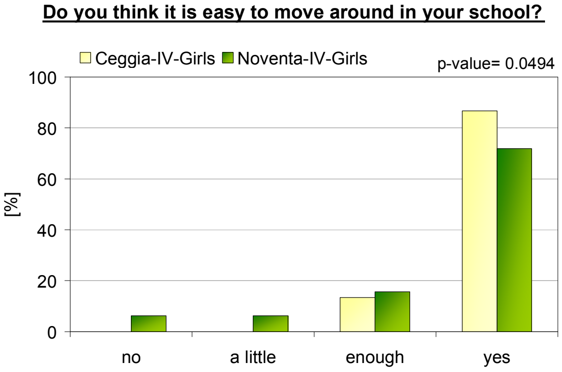


Figure 6.80 - Difference in school accessibility between girls of classrooms IV (p-value: 0.0494)

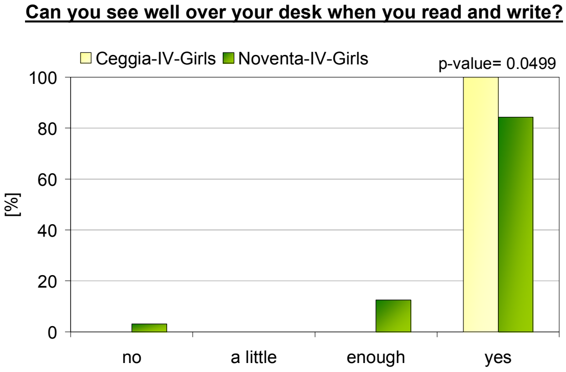


Figure 6.81 - Difference in desk visibility between girls of classrooms IV (p-value: 0.0499)

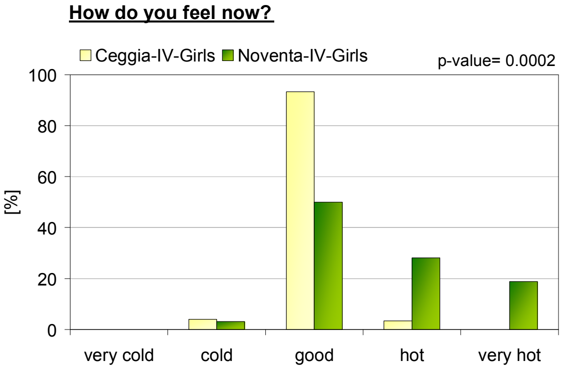


Figure 6.82 - Difference in perceived temperature between girls of classrooms IV (p-value: 0.0002)

6.6. Conclusion

No significant differences have been noticed in schools' comparison, even though the more "modern" school (Ceggia) has obtained more positive opinions than the more traditional one (Noventa), especially by girls. The statistical analysis has been in fact carried out also choosing two stratification variables, the gender and the age, because no remarkable differences have been found considering all the children of the same school together. These additional tests have revealed how boys and girls are different, even from the childhood: girls seem to pay more attention about environmental condition than boys and, moreover, their answers differ depending on age, school and even classroom. Considering perceived comfort, women are in fact more sensible than men, therefore girls should be more representative than boys.

In order to carry out a more interesting analysis, the same pupils should have had the possibility to study in both the schools, therefore a more useful and realistic comparison could have been performed. In fact, children have only experienced only one of the two schools, then it cannot be stated that one school is more comfortable than the other.

No questions concerning the switch on off frequency has been asked and the survey should be revised in that way. In fact, the electric lighting is most of the time turned on early in the morning and it is never switched off, even though the available natural light can guarantee a good lighting level.

6.7. References

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Chapter 7

Conclusion

People spend large amount of their time indoors and, without proper light, they may have physiological and psychological problems, which in some cases can cause sickness. Many studies have demonstrated that if daylight is the primary source of lighting, there is a great improvement in productivity, performance and well-being in general. Natural light, in fact, has both direct and indirect effects on human beings: the direct effects are caused by chemical change in tissues due to the energy of the absorbed light, while the indirect ones concern the regulation of the basic biological functions and the production of hormones, connected to light exposure. Therefore, to improve well-being, satisfaction and productivity, especially in offices and educational buildings, it is very important to design indoor spaces with specific attention to people's comfort. This topic has been discussed in Chapter 2.

Daylight constantly varies throughout the day and year, so an ideal assessment of daylight availability and quality should consider this transient character, but this would result in an unrealistically time-consuming task. Therefore it is recommended to choose some extreme and average conditions, for example an overcast and a clear day of the solstices and equinoxes, and simulate some few working hours of them. In this kind of sky conditions, some RADIANCE simulations have been performed for two different office spaces, showing how they appear in terms of illuminance and luminance distribution (Chapter 5). As an alternative to this kind of approach, the Perez sky, used by DAYSIM, can be used: this model calculates the sky luminous distribution for a given sky condition from date, time, site and direct and diffuse irradiance values. The actual irradiation data have been used to run DAYSIM simulations shown in Chapters 4 and 5: the first ones refer to two classrooms, one South and one West oriented, of an Italian Secondary School, while the other ones to two existing office rooms, one South and one North-East oriented. The available EPW climatic files can be used only to make predictions for and ideal building, but the actual climate data have to be applied if a comparison between measured and calculated indoor parameters, such as air temperature, relative humidity and illuminance, would be carried out.

Solar shading devices are often used in buildings to reduce overheating, to control glare from windows and to provide privacy. Daylight control is very important, especially in office buildings because of its relationship with occupants' satisfaction and performance. On the other hand, lighting and blind control systems can reduce energy demand for electric lighting, which can contribute to the development of sustainable buildings. In this thesis different kinds of such devices have been analysed, in terms of daylight control, depending on latitude and building orientation: light shelves and venetian blinds in Chapter 4 and curtains and film coating in Chapter 5.

The comparison between measured and calculated illuminance profiles in real buildings has been carried out for an office building located in Padua, even though some preliminary analyses have been carried out also in an educational building (Chapter 4). In overcast sky condition, the measured and the calculated illuminance profiles are similar for the two offices, while, in sunny days, there are some significant differences: this is due to the extreme variability of sky luminance, especially in such conditions, and to the sensor used to record data, which has resulted to have a different behaviour according to both inside and outside conditions (chapter 5.3.1).

The problems that occur making a comparison between simulations and measuring campaigns have been deeply analysed in Chapter 5. To avoid some of these problems the following aspects should be known:

- The optical properties of the surfaces
- The effective irradiation data
- The setting of the blinds and the time when the luminaries are switched on or off

One of the main sources of uncertainty is the human behaviour: the Lightswitch Wizard is a model that provides a validated occupancy schedule and behaviour, but the actual human behaviour is unpredictable. In the lighting analysis of the office building it was necessary to ask occupants to leave the curtains up every Friday, if not it was impossible to know the blind setting and then to compare the calculated illuminances with the measured ones. Moreover, the graph in Figure 4.23 demonstrates that a greater solar radiation availability does not correspond to an electrical energy reduction and this means that people do not change the lighting setting, according to weather conditions. Anyway, building automation systems would be advisable for sustainable buildings.

Daylight availability of a space has been described by means of the UDI dynamic daylight performance metric: from annual illuminance profiles calculated with DAYSIM, combining a specific occupancy schedule, UDI indexes have been calculated supposing some new illuminance ranges. Considering occupancy time over an year, UDI indexes obtained with DAYSIM for a specific work plane consider in fact only three illuminance ranges (chapter 3.2.6). The default central UDI index ($UDI_{100-2000}$) includes a wide range of illuminances, therefore it has been split in four parts, in order to understand if daylight alone can be sufficient to carry out working activities or if electric light is necessary, but with a dimmed luminous flux.

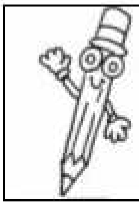
Considering the analysis of the office building, the UDI values have been calculated for both glazed and film coated façade. In summer, visual comfort can be guaranteed for at least the 80% of the time in film coated façade, even with the curtains down, while, in glazed façade condition, the shading is required most of the time, avoiding any possible view to the outside, which has been demonstrated to be one of the most sources of dissatisfaction. In winter, the presence of film determines insufficient lighting levels, which happen twice with respect to having glass alone.

Some other ranges have been expressly created for educational buildings, by considering two different kinds of occupancy schedules, with and without after class. These parameters have been calculated for each month of the academic year 2008/2009 and for two classrooms, one facing South and one facing West. The obtained UDI values are significantly different only for West orientation, comparing the two analysed occupancy schedules and this confirms again how important is the occupancy schedule in energy consumption analysis.

Finally, an analysis of indoor environmental quality has been performed in two Primary Schools aiming at verifying if the building type, in terms of both architectural and technological choices, can influence children satisfaction and well-being. Two educational buildings have been compared, one traditional and one characterized by a circular plant ad by innovative schemes and systems for improving indoor environment, such as radiant floor and mechanical ventilation. No significant differences have been noticed in schools comparison, even though the more “modern” school is preferred by girls. The statistical analysis has been in fact carried out also by choosing two stratification variables, the gender and the age, because no remarkable differences have been found considering all the children of the same school together. These additional tests have revealed how boys and girls are different even from the childhood: girls seem to pay more attention about environmental condition than boys and, moreover, their answers differ depending on age, school and even classroom.

Appendix

The survey



Alcune domande per capire come ti trovi nella tua scuola…

Quanti anni hai?	…………………………….
Sei maschio o femmina?	

In questo momento come sei vestito?

………
…….

Ti piace la tua aula?

- ☐ sì
- ☐ abbastanza
- ☐ poco
- ☐ no

Ti piace il tuo banco?

- ☐ sì
- ☐ abbastanza
- ☐ poco
- ☐ no

In che banco sei seduto adesso?

- ☐ vicino alla finestra
- ☐ vicino alla lavagna
- ☐ in prima fila
- ☐ in ultima fila
- ☐ vicino al tuo compagno preferito
- ☐ in mezzo all'aula
- ☐ vicino alla cattedra

Cambi posto durante l'anno?

- ☐ sì
- ☐ no

Se potessi scegliere il tuo banco preferito, dove ti piacerebbe sederti?

- ☐ vicino alla finestra
- ☐ vicino alla lavagna
- ☐ in prima fila
- ☐ in ultima fila
- ☐ vicino al tuo compagno preferito
- ☐ in mezzo all'aula
- ☐ vicino alla cattedra

Ti trovi bene con i tuoi compagni?

- ☐ sì
- ☐ abbastanza
- ☐ poco
- ☐ no

Ti piace come sono disposti i banchi nella tua aula?

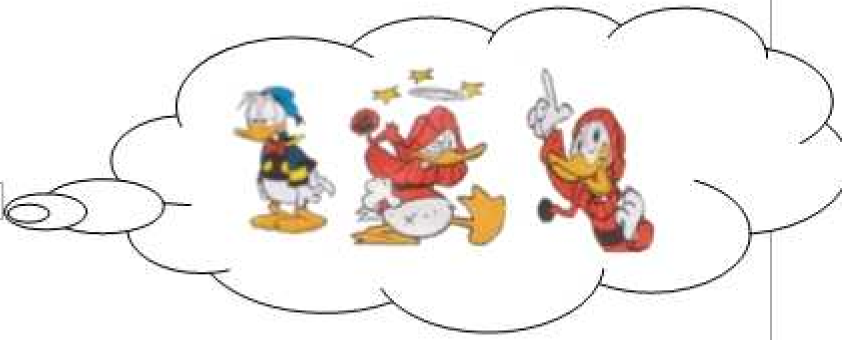
☐ sì
☐ abbastanza
☐ poco
☐ no

A scuola ti piace vedere carte per terra?

☐ sì
☐ abbastanza
☐ poco
☐ no

Stai comodo sulla tua sedia?

☐ sì
☐ abbastanza
☐ poco
☐ no



Come ti senti oggi?

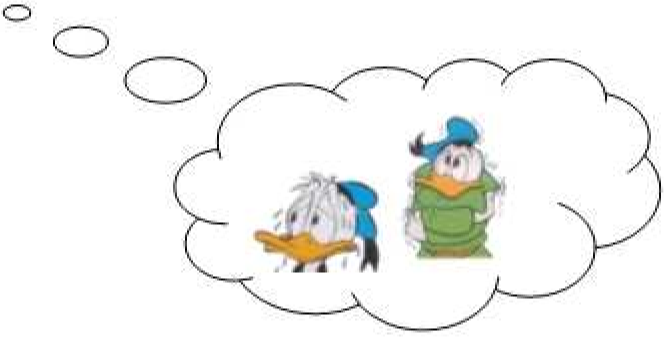
☐ bene
☐ non tanto bene
☐ male

Se adesso non ti senti bene, cosa ti senti?

……
……

Come stai adesso?

☐ ho tanto freddo
☐ ho un po' freddo
☐ sto bene
☐ ho un po' caldo
☐ ho tanto caldo



Quanto spesso senti cattivi odori in classe?

- ☐ spesso
- ☐ qualche volta
- ☐ mai

Ti dà fastidio sentire cattivi odori in aula?

- ☐ sì
- ☐ abbastanza
- ☐ poco
- ☐ no

Se senti cattivi odori cosa fai?

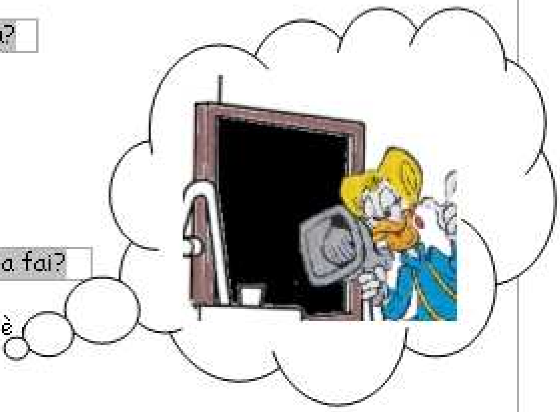
- ☐ lo dico alla maestra
- ☐ mi tappo il naso
- ☐ chiedo di aprire la finestra
- ☐ niente

Riesci a sentire bene la maestra che spiega?

- ☐ sì
- ☐ abbastanza
- ☐ poco
- ☐ no

Se non riesci a sentire bene la maestra,cosa fai?

- ☐ dico alla maestra di chiudere la porta, se è
- ☐ dico alla maestra di parlare più forte
- ☐ dico al mio vicino di banco di stare zitto
- ☐ niente



Ti capita di sentire rumori fastidiosi in classe?

- ☐ spesso
- ☐ qualche volta
- ☐ mai

Che tipo di rumori fastidiosi sono?

………
………

Ti dà fastidio sentire rumore in classe?

☐ sì
☐ abbastanza
☐ poco
☐ no

Riesci a vedere bene la lavagna?

☐ sì
☐ abbastanza
☐ poco
☐ no

Se non riesci a vedere bene la lavagna ,cosa fai?

☐ dico alla maestra di scrivere più grande
☐ dico alla maestra di accendere la luce
☐ dico alla maestra di alzare le tapparelle
☐ dico al mio compagno che mi sta di fronte di spostarsi
☐ mi sposto
☐ niente

Riesci a vedere bene sul tuo banco quando leggi e scrivi?

☐ sì
☐ abbastanza
☐ poco
☐ no

Se non riesci a vedere bene sul banco cosa fai?

☐ dico alla maestra di accendere la luce
☐ dico alla maestra di alzare le tapparelle
☐ sposto un po' il mio banco
☐ niente

Nella tua classe ci sono luci troppo forti che ti danno fastidio?

☐ spesso
☐ qualche volta
☐ mai

Ti piace che ci siano delle luci forti nella tua classe?

☐ sì
☐ abbastanza
☐ poco
☐ no

Ti capita di sentire fastidiose correnti d'aria in classe?

☐ spesso
☐ qualche volta
☐ mai

Ti piace sentire delle correnti d'aria in classe?

☐ sì
☐ abbastanza
☐ poco
☐ no

Ti trovi bene nella tua scuola?
☐ sì
☐ abbastanza
☐ poco
☐ no

Perché?

………..
………..

Ti è facile muoverti nella tua scuola?

☐ sì
☐ abbastanza
☐ poco
☐ no

Chi può aprire le finestre?

☐ solo la maestra
☐ anche gli alunni

La maestra apre mai le finestre durante l'intervallo?

☐ spesso
☐ qualche volta
☐ mai

La maestra apre mai le finestre mentre spiega?

☐ quasi mai
☐ qualche volta
☐ spesso

Chi può alzare o abbassare le tapparelle?

☐ solo la maestra
☐ anche gli alunni

Chi può tirare le tende?

☐ solo la maestra
☐ anche gli alunni

La maestra alza mai le tapparelle mentre spiega?

☐ spesso
☐ qualche volta
☐ mai

La maestra tira mai le tende mentre spiega?

☐ spesso
☐ qualche volta
☐ mai

Quando la maestra alza le tapparelle?

☐ quando c'è poca luce
☐ quando qualche alunno lo chiede
☐ quando c'è qualcuno che si addormenta

Quando la maestra tira le tende?

☐ quando c'è poca luce
☐ quando qualche alunno lo chiede
☐ quando c'è qualcuno che si addormenta

Ti è piaciuto rispondere a queste domande?

☐ sì
☐ abbastanza
☐ poco
☐ no