UNIVERSITÀ DEGLI STUDI DI PADOVA

DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

Corso di Laurea Magistrale in Ingegneria Energetica

Tesi di Laurea Magistrale

Impact of window amount and size on user perception, daylighting and energy demand in an office space.

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Questo lavoro di tesi è stato svolto presso
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ANNO ACCADEMICO 2013/2014

ABSTRACT

To reduce the energy consumption of office buildings, a strategic planning and optimization of lighting plays an important role. In fact, electric lighting is responsible of the 14% of the end-use energy consumption in EU non-residential buildings. To decrease the demand for electric lighting, daylighting has to be applied and optimized.

In general, daylighting affects positively the workers' well-being and consequently their productivity mainly because the daylighting stimulates the human circadian system and the view out enables the contact with the outside world. By modifying the window size and amount, the view out and the sun light entering the room changes. This affects the visual comfort and artificial lighting, cooling and heating demand. Shading devices are often installed to reduce direct solar radiation and to provide comfort in an office with daylighting integration, limiting glare discomfort and energy demand.

This work aims to identify the impact of different window settings in a single office, by analyzing different options with and without venetian blinds. The research is divided in two parts. Employees' satisfaction in terms of quantity of view out is analyzed with a user assessment, carried out in the daylighting laboratory of Fraunhofer ISE. Daylight penetration and heating, cooling and artificial lighting demand are calculated coupling Radiance Three-phase Method with EnergyPlus.

Before starting the comparison of the window settings, the daylighting tool Three-Phase Method is analyzed to determinate its accuracy compared to Classic Radiance, the reference for lighting tools. The results show that the Three-Phase Method is accurate enough to conduct reliable daylighting annual simulations.

In a first step, before evaluating the window settings, the Three-Phase Method is analyzed to determinate its accuracy compared to Classic Radiance, used as reference here. The results show that the Three-Phase Method is accurate enough to conduct reliable daylighting annual simulations.

The results of the study point out that employees prefer big windows. Increasing the window size, the daylight autonomy increases and the artificial lighting decreases, also if the shading strategy changes. The energy building simulations show that heating and cooling demand have opposite outcomes increasing the window size and changing the venetian blinds position. In order to optimize the total energy demand and the daylighting integration, automatically controlled blinds should be installed.

SOMMARIO

Nell'ottica di ridurre i consumi energetici di edifici non residenziali, in particolar modo edifici con uffici, gioca un ruolo importante la componente illuminazione dell'ambiente. Infatti, l'illuminazione artificiale è responsabile del 14% del consumo finale energetico per edifici non residenziali in UE. Per ridurre questa voce l'illuminazione artificiale deve essere integrata con l'illuminazione naturale.

In generale, utilizzare la luce naturale incide positivamente sul benessere dell'impiegato e conseguentemente la sua produttività, principalmente perché la luce naturale agisce positivamente sul ritmo circadiano della persona e la possibilità di guardare fuori dalla finestra garantisce un contatto con l'esterno che limita il senso di alienazione. Modificando la dimensione e il numero delle finestre cambiano la visuale esterna e la luce che entra nell'ufficio e conseguentemente il suo modo si influenzare il comfort visivo e il fabbisogno di riscaldamento, raffrescamento e illuminazione artificiale. Sistemi di ombreggiamento vengono spesso installati per ridurre la radiazione solare diretta limitando il fabbisogno energetico e l'abbagliamento e aumentando il comfort nel luogo di lavoro.

Questo lavoro si propone di individuare la miglior tipologia di finestra per un ufficio analizzando diverse misure e quantità, con e senza sistemi di ombreggiamento.

Viene analizzata la soddisfazione degli utenti in termini di quantità della visuale esterna mediante un user assessment condotto nel laboratorio di daylighting del Fraunhofer-ISE. Vengono calcolati la distribuzione dell'illuminazione naturale e il fabbisogno di riscaldamento, raffrescamento e illuminazione artificiale utilizzando Radiance Three-Phase Method e Energy Plus accoppiati.

Prima di iniziare il confronto tra le finestre, il Three-Phase Method viene analizzato per determinare l'accuratezza delle sue simulazioni comparandolo con Radiance classico, lo strumento di riferimento per le simulazioni illuminotecniche. I risultati mostrano che il Three-Phase Method è sufficientemente preciso per condurre simulazioni annuali attendibili.

I risultati dello studio evidenziano che la finestre preferite sono quelle grandi. L’analisi di daylighting mostra che aumentando l’area della finestra la daylight autonomy cresce e il fabbisogno di illuminazione artificiale cala. D’altro canto le simulazioni energetiche mostrano che il fabbisogno di riscaldamento e di raffrescamento variano al crescere della superficie vetrata e al variare la posizione delle tende veneziane. Per ottimizzare il fabbisogno energetico e l’integrazione di daylighting è preferibile installare un sistema di controllo automatico delle tende veneziane.

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1. INTRODUCTION

1.1. The importance of daylighting

Employees spend most of their working days inside offices, where physical conditions influence their well-being and, therefore, their working performance. An environment with uncomfortable thermal and visual conditions and with elements of psychological discomfort decreases the well-being and jeopardizes the health of employees. For example, an unsatisfactory lighting environment in office buildings is reported by between the 57% and the 66% of the cases according the a study by Schuster (2006). It is also pointed out that the possibility to interact with the indoor environment, as well as an adequate contact to the outside and sufficient use of daylight, enhances user comfort and satisfaction. For this reason, big windows are strongly favored in the work place. Moreover the use of daylight offers numerous alternatives to arrange the space and to improve the aesthetic of a building since light is an important design element.

Daylight is the combination of direct sunlight and diffuse sky light. Sun light is a full-spectrum light and it is the light source that most closely matches human visual response. Since the human eye is accustomed to daylight, it requests less light to perform a task than in the case of electric lighting. That offers two advantages: a more comfortable view and a lower level of light required. Another positive aspect is the color rendering. The best perception of color is possible for light that covers all the wavelengths of the visible spectrum. Additionally, no artificial light can mimic the variation in light spectrum that characterizes the daylight in different times of the day, seasons and weather conditions. To sum up, natural light stimulates physiologically the human visual system and the human circadian system, benefiting people's well-being and health (Boyce et al., 2003).

All these factors improve the living quality in an environment; however, they are not the only ones. As mentioned before, there is also a psychological component that affects the well-being of people and improves their working conditions. That is why the interaction between the person, daylight and the outside world enhances the satisfaction. A view out gives knowledge of the weather, the time of day and changing events in the outside world, and it can supply relief from feelings of claustrophobia, monotony or boredom (Collins, 1975). In support of this thesis, Ne’eman and Kopkinson maintain that occupants of windowless buildings frequently complain of deprivation and excessive enclosure, suggesting that the window is not only a source of light and fresh air but it also serves as a means of contact with the outside world. They suggest that the best size for windows, connected to the well-being of people, depends also from the size of the room and they prove that the critical minimum size of the window is in the order of one-sixteenth of the floor area (Ne’eman et al., 1970).

On the other hand, daylight might provoke visual disability or discomfort due to glare. Glare is caused by the scattering of light inside the eyes that reduces the contrast between objects. Despite the fact that glare discomfort does not impair vision, the way glare disability does distracts the employees and might lessen their reactivity in carrying out an action (Wienold, 2009). To limit glare discomfort, shading systems are installed on the windows. They provide diffuse daylight in the room and they block the sun direct light penetration.

Apart from the employee well-being, another key factor in the choice of the window type is the fact that the use of daylight or artificial light affects energy demand. According to studies reported by the European Commission, non-residential buildings are responsible for 11.4% of the total energy consumption of the European Union and, in particular, lighting is responsible of the 14% of the end-use energy consumption (Halonen et al., 2010). By integrating daylighting in buildings, electricity consumption is reduced. For a building with daylight integration, the consumption hours of artificial light is lower than for a building without, because the lights are switched off when the sunlight is sufficient for the required illumination. A possible disadvantage is that an automatic control strategy for the electric lighting and the shading system can increase installation costs.

From an energy balance point of view, both light sources introduce a heat gain into the zone. During the summer, the additional heat must be removed through a cooling process, which implies consumption of energy. On the contrary, this heat gain reduces the heating demand and therefore the energy consumption in winter. For what concerns daylighting, the direct part of sun radiation is the one that increases mainly the solar gain. An appropriate use of shading systems can reduce the solar gain and the cooling energy demand, providing an advantage in the daylighting use. Moreover, daylight integration does not increase the cost of buildings and is inexpensive to maintain. All these advantages in daylighting integration drive to study more in deep the possible use of it.

1.2. Thesis overview

This work of thesis proposes an investigation on how different size and number of windows impact employee satisfaction, energy demand and light penetration and distribution in an office.

Nine case studies are analyzed combining three different sizes and three different amounts of windows. The research is divided is two parts:

The first part analyzes employee preferences with a user assessment carried out in the daylight laboratory of Fraunhofer-ISE (Freiburg in Breisgau) that for the occasion resembles an office. Twenty-five Fraunhofer employees are asked to give their opinion on how much they are satisfied with the quantity of the view out (Mende, 2012).

The quantity of the view out (different from the quality of the view out) means how much the user can see outside and not what he/she can see. This concept has been thought to investigate what people feel in an office with a certain size and position of the windows in order to increase the well-being in the workplace. Often building designers forget the user’s point of view, although buildings are made for people who will live them.

The second part of the study analyzes the daylight distribution and the energy demand of an office in a coupled way. That means that the energy demand in terms of heating, cooling and lighting is calculated considering for each time step of the year the daylight contribution inside the room. The cases studied have installed Complex Fenestration Systems composed by a double-pane glass and external venetian blinds, which manually or automatically controlled contribute to provide visual and thermal comfort limiting the energy demand.

The analysis is carried out using two simulation tools: The Radiance-based Three-Phase Method is used for the daylighting study and EnergyPlus is used for the energy demand calculation. Both tools allow conducting simulations by implementing a Bidirectional Scattering Distribution Function BSDF dataset, a sophisticated way to represent visual and solar transmission of solar radiation through a fenestration system.

To validate the choice of these simulation tools, a preliminary analysis of the software is carried out. Radiance Three-Phase Method is compared with Classic Radiance, the reference software for lighting study, and Energy Plus is compared with Trnsys to verify the simulation setting.

1.3. Goals of the thesis

The thesis studies the effects that windows with different size and amount have in a single office. The impact is analyzed considering nine different combinations: three sizes and three amounts of windows. The analysis conducted is multidisciplinary:

- Employee view out preference. By applying a user assessment method, the first goal is to understand which type of window configuration satisfies more employees. A new approach of the problem is applied; the quantity of the view out is investigated instead of the quality of the view out, which was addressed by Mende (2012).

- Radiance-based Three Phase Method validation. The performances of the new lighting simulation tool are verified for the CFS here presented, comparing its results with the results of Classic Radiance, the reference tool for lighting simulations. Afterwards the Three Phase Method will be used in the daylighting analysis.

- Office energy demand. Heating, cooling and lighting need is analyzed with dynamic simulations, considering the contribution of daylighting. The investigation is conducted by considering a complex fenestration system (double-pane glass and external venetian blinds) and simulating three operation modes: all the year windows without blinds, all the year windows with blinds and windows with blinds controlled by the solar radiation that hits the façade.

1.4. Methodology

The thesis is divided in two parts. A user assessment highlights employees' point of view for the favorite window size and amount in a single office. Energy building dynamic simulations analyze the energy demand of the office in terms of heating, cooling and lighting, changing the window settings. The analysis is done considering different ways of daylighting integration, that means with and without shading systems and a control strategy.

The user assessment is conducted at the daylighting laboratory of the Fraunhofer Institute for Solar Energy in Freiburg im Breisgau (Germany). 25 test persons are asked to give an opinion about the quantity of the view outside the window, in other words, if they are satisfied of how much they can see of the outside environment. Different size and amount of window are under investigation. Nine window setting are projected on the window wall covered for the occasion with a white layer.

The survey is conducted in two different ways. First a single rating test allows evaluating each window setting presented one after the other. The survey points out how much employees are satisfied about the window size, amount, height and width. Then a paired comparison allows obtaining a global ranking of employees' satisfaction. All window settings are presented two by two and the test person chooses every time the favorite window setting. The data are analyzed with the test of the variance ANOVA.

The energy demand analysis is conducted by using the energy building simulation tool Energy Plus and the daylighting simulation tool Radiance Three-Phase Method.

Part of the thesis considers a preliminary study of the tools used. Radiance Three-Phase Method is compared with Classic Radiance to understand how far in terms of accuracy the Three-Phase Method results are from the results of Classic Radiance that is the state-of-the-art in lighting simulation tools. A Classic Radiance simulation is extremely time consuming, therefore, only two days are analyzed, a sunny day in summer and an overcast day in winter. The analysis is conducted both with and without blinds. The results are compared in terms of the average illuminance on the work-plane, the daylight autonomy, and the illuminance distribution. A statistical analysis is also used to compare the previous magnitudes.

On the other hand, Energy Plus simulation is compared with Trnsys to verify the simulation setting built. The goal is to obtain a reliable setting to use in the comparison of the different window cases. The results are compared in terms of heat gains and losses for 10 days in summer and in winter and for monthly average daily cycles.

Once defined the simulation setting of Energy Plus and accepted the Three-Phase Method accuracy, the single office with nine window settings is simulated. According to the weather file and the sun position of Frankfurt, for each time step of the year the daylighting penetration is calculated. With these data the energy need is calculated. All the simulations are executed with and without venetian blinds and with a vertical solar radiation control. If the sensor registers a solar radiation above 150 W/m^2 the blinds go down, if not they go up. The comparison of all the cases is conducted analyzing the heating, cooling and lighting demand and calculating the daylight autonomy.

The combination of the employees' preference, the daylight distribution inside the room and the energy demand of the office provides the guide line for window settings of single office design.

2. USER ASSESSMENT ON THE VIEW OUT SATISFACTION

2.1. Introduction

The visual comfort in the office is a branch of the workers' well-being in their work place. The Verein Deutscher Ingenieure (VDI) identifies the aspects that affect the visual well-being in the office: visual quality, clarity, brightness, glare, contrast, color rendering, and view out. (VDI 6011, 2002)

Concerning the view out, two sub factors are identified: the quality of the view out and the quantity of the view out.According to Ludlow, the quality of the view out is what people would like to see out of the window, what makes them feel good, in other words, the visual amenity function of the window. Employees prefer to see complex scenes with a balance of natural and artificial elements out of the window and they do not like static scenes (Ludlow, 1972). If on the one hand what people would like to see through a window has been recently investigated (e.g. Farley, 2001), on the other hand there has been few researches on the quantity of the view out. The quantity of view out is the magnitude of the outside scenery viewed through a window that can be seen within the human visual field (Mende, 2012). The quantity can be limited through geometric shapes in the façade level.

The quantity of view out indicates the right setting for a window in terms of size, amount, shape and arrangement for employees' satisfaction. Amount means here the number of windows. The above mentioned parameters derive from a literature study and a survey conducted at Fraunhofer ISE. A questionnaire was sent to experts in lighting research and the results of this questionnaire highlighted the four items just mentioned (Mende, 2012).

The survey was an important starting point to focus on the topic. In fact, in lighting literature, the quantity of view out in office spaces has been studied only until the `70. Ne'eman and Hopkinson (1970) found that view, distance from the view, window width, window height and visual angle affected the subjects' judgment of the acceptable size of window. They stated also that height affected less workers' satisfaction than width and that the acceptable window width was directly proportional to the distance from the window in the work place (Ne'eman et al., 1970). Keighley (1973) concluded that subjects prefer the horizontal and central windows with the window sill below the eye level. After the above mentioned studies, the academic interest in this field decreased. One of the aims of the present research is to renew the academic interest in it.

2.2. User assessment description

Within the Fraunhofer ISE research project on the quantity of the view out, a user assessment is conducted. The user assessment has the goal to determine employees' preferences about the quantity of view out, especially regarding the interaction between size and amount of windows. Size and amount are investigated before shape and arrangement because, according to the lighting experts' survey, they emerge as the most critical issues.

During the experiment the subjects are inside a room that resembled an office. In front of them they can see a white wall instead of the window wall. Nine different virtual window settings are projected on the wall, and subjects rate their satisfaction of the quantity of the view out by filling a questionnaire. The use of virtual windows comes from the fact that the assessments with real windows would not have been possible because of the need to change quickly the window settings many time for each test person.Virtual windows for this scope are eough. In a later stage (outside your scope) there will be test for the main factors of the view with real windows.

Then participants' evaluations are analyzed by means of statistical tests, to find which window setting provides the highest satisfaction score. The sample size needed is 25. The window settings are presented in a random order.

The test is divided in two sections, a single rating evaluation and a paired comparison, to study with two different methods subjects' preferences. On the one hand, in the single rating, subjects express their satisfaction with each of the nine window settings by answering questions about quantity and quality of the view out. On the other hand, in the paired comparison, 36 pairs of window settings are presented, and the subjects are required to choose the favorite one.

The two methods are different because with the single rating evaluation subjects answered freely, whilst in the paired comparison subjects are forced to make a choice between two options.

2.2.1 Setting

The test takes place in the daylight laboratory on the roof of the Fraunhofer Institute for Solar Energy Systems (ISE, Germany). The daylight laboratory (Figure 1) is a container with two rooms and two modular windows on the same wall, one for each room. The container is equipped with a rotating mechanism that permits to turn the laboratory in order to choose the direction of the sun rays that enter the room, according to the experimental condition. For the test described in the present work the sun position is not relevant, therefore the container is fixed to face north in order to reduce the temperature inside and all the windows are obscured.

Figure 1 Daylighting laboratory

The overall area of the laboratory is divided in a testing room and an observation room. The testing room (Figure 2) has an area of 17.03 m² (3.702 m x 4.60 m) and a height of 2.85 m. It is arranged to resemble a common single office. The office is furnished with a desk and a chair in the center, facing the wall with the window. The windows are covered with white plastic panels, in order to obtain a neutral surface to support the projection of the pictures of the nine different windows patterns. On the opposite wall a projector is mounted. Behind the desk there is a lamp that complements the light from the projector to provide an illuminance of 300 lux on the work plane. On the desk there is a pen to fill the questionnaire and a pointer to change the slides during the presentation. The temperature in the container is kept between 23°C and 25°C, by an air conditioner. The projector is connected with a computer in the observation room. This arrangement lets the experimenter control what is happening in the testing room. Noise is kept at a similar quality and level by using always the same equipment (computer, projector and air conditioner) for each proband.

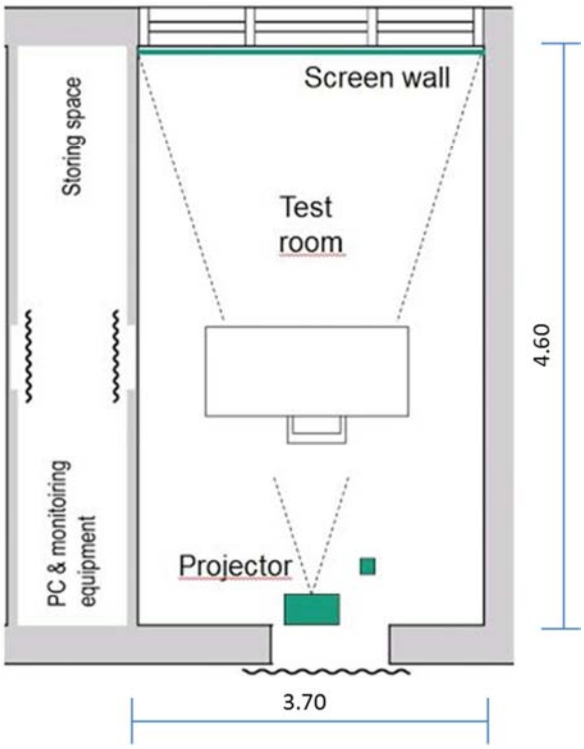

Figure 2 Test room map

2.2.2 Window

The window settings presented are nine, as they are the combination between three sizes of window (with the 10%, 25% or 40% of transparent part of the façade) and three different amounts of windows (1, 2 or 3 windows). This means that for one size, changing the number of windows, do not change the proportions between the window part and the total façade.

The view out does not change by changing the window settings. The view out presented is one of the possible views out of the daylight laboratory. It is chosen consistently with the Hester Hellinga’s DCBA scheme (Hellinga, 2012). According to this method, a view out is acceptable if includes the sky, the green and distant objects. Furthermore, the view should be wide and spacious, complex and coherent with the possibility to perceive weather, season, time of the day and human activity. Two are the view outs of the daylight laboratory that fulfill these criteria, South and Southwest directions. Southwest direction is chosen because of the better sun position.

Hereafter a code to recognize the different window settings is introduced (Figure 3). Letter L represents the large setting (40% of the façade), letter M represents the medium setting (25% of the façade), letter S represents the small setting (10% of the façade), moreover the numbers 1, 2, or 3 represent the number of the windows.

Figure 3 Nine window settings

2.2.3 Questionnaire

The questionnaire administrated is built inside the research project about view out quantity at Fraunhofer ISE (Mende, 2012).

The questionnaire is divided in three sections. In the first part, there are general questions about participant's demographic background, job, mood and feelings under certain conditions of light and view out. The second part consists of a single rating evaluation of the nine window settings. The last part consists of a paired comparison of all the window settings (36 pairs). An example of the questionnaire that is used is provided in Appendix 2. The questionnaire is in german, because the subjects are all german mother tongue. Furthermore, the questionnaire is explained in detail below.

The first part of the questionnaire contains three different answer modalities. The multiple choice format is used to know the gender of the subjects, if they are right or left handed, if they wear glasses or contact lenses, what kind of job they do, how is their work-office and if they feel sick during the experiment or have any eyes problems.

The second answer modality requires writing the percentage related to different task at work. The third one is a Visual Analogue Scale (VAS[1]). The VAS is used to quantify how much they are sensible to light brightness, how important is the view out for them, how much influential is for the subjects the glare, the view out, the perception of the weather and the sun position and how they feel at the moment of the test.

In the single rating evaluation, the same group of questions is repeated nine times, one for each window setting. The questions for each group are four. The first question assesses to what extent the subjects are satisfied when they watch out of the window. The subjects are asked to evaluate their satisfaction with respect to the size of the windows, the number of windows, the width and the height of the windows, their positions and shapes and the distance between the test person and the window. The size of the windows, the number of windows, the width and the height of the windows are the issues of interest for the user assessment described in this work. The second question is about the preference related to the quantity - and not the quality - of the view out, in particular if they want to see more or less through the windows with respect to the scene presented. In the third question the participants are asked to take a decision in

[1] A Visual Analogue Scale (VAS) is a measurement instrument that tries to measure a characteristic or attitude that is believed to range across a continuum of values and cannot easily be directly measured. Operationally a VAS is usually a horizontal line, 100 mm in length, anchored by word descriptors at each end. The subject marks on the line the point that they feel represent their perception of their current state. The VAS score is determined by measuring in millimeters from the left hand end of the line to the point that the subjects mark.

general whether they are satisfied or not with the quantity of the view out. Lastly participants are asked to choose among nine mood states how they feel when they watch out of the window. The answer mode for the first, the second and the fourth questions is again the VAS. It is worth to notice that the last question is about the quality and not the quantity of the view out and it is useful to check if the answers to the first question are conditioned to the quality of the view out.

The paired comparison requires a direct answer, asking which window setting is the favorite, in terms of quantity of view out. The same question is repeated 36 times to compare all the possible combinations.

2.3. Preliminary work

Before running the tests, some preliminary work for preparing the experimental setting is needed. The opaque plastic sheets are placed on the windows to cover the glass façade and the office furniture is set in the room. The position of all the objects in the testing room is then fixed for all the tests.

Afterwards the virtual windows to project on the wall of the testing room are adjusted for what concerns brightness and contrast. The goal is to obtain the same luminance level between all the windows projected on the wall. This is necessary to keep the same perception of the view out during the all experiment; avoiding the subjects' eyes to undergo the different luminance level (this change would cause discomfort during the test). Indeed the virtual windows have to look the most realistic as possible. A compromise is reached and an automatic script is executed to treat all the pictures in the same way.

After that, a number of presentations are created automatically by executing a script using Beamer language, the document-class of LaTeX to obtain presentations with slides. Inside the script, commands to randomize the order of the pictures are also added. With the randomization each subject sees the presentation in a different order, this avoids that the results are affected by the order. The number of presentations created is more than 25 taking in account the possible failures. The last step is the recruitment of the subjects. An appointment is fixed with each person separately.

2.4. Day of the experiment

Before the experiment begins, the experimenter asks the subject to make her/himself comfortable and to adjust the chair in her/his favorite position. The participant then receives the questionnaire instructions and in the presence of the researcher, she/he reads them. Then she/he signs the informed consent. At this point the experimenter leaves the room and the test starts. The subject looks at the slides and fills the questionnaire. After each part of the questionnaire is completed, the participant calls the researcher to receive instructions for the following part. The test normally lasts 30-40 minutes.

2.5. Data processing

In total, 26 questionnaires are administered, excluding one because of missing data. The statistical analysis is conducted with SPSS. The answers of the questionnaire are imported in SPSS by means of a dataset. Afterwards the data are sorted, eliminating the influence of random order by using two provided scripts. The script to reorder the single rating results couples the answers with the corresponding window setting and reordering the window setting according with the sequence L1, L2, L3, M1, M2, M3, S1, S2, S3. Furthermore, in order to analyze the paired comparison results, the script counts for each participant the number of times that a particular window setting is preferred and then gives the total number of times that a window setting is favored.

2.5.1. Sample

The sample is composed of 25 people (12 females), between 23 and 39 years of age (M=27.88, SD=3.70, n=25). They are all German native speakers and they work at the Fraunhofer ISE. 92% of them are right-handed. nine participants wear glasses and five contact lenses. eight participants are students, fifteen have a technical and scientific role, one have a leading role and one have another job. Furthermore, only one works alone in the office, all the others work in a shared office. The sample declares that the work is averagely divided in 60.36% VDU-work[2], 15.8% desk-work, 12.12% meeting and 11.72% other task. During the day of the experiment, six participants suffer from a mild flu, one declares eyes lacrimation and other three people have other illnesses.

2.6. Data analysis

The nine window settings are compared in two different ways, the single rating evaluation and the paired comparison. The goal is to determine which one is the favorite window setting and how is the distribution of the other window settings in a ranking of satisfaction.

The data are analyzed by means of the analysis of the variance (ANOVA). ANOVA is a statistical test for investigating data relationship. This test highlights differences among the means of different dependent variables, given a certain value of acceptable error p that has to be lower that 0.05 ($p<0.05$).

2.6.1. Single rating evaluation

The items taken into account for the single rating evaluation for this study are the first four of the first question because they are related to the evaluation of the satisfaction with the size and the amount of windows. In fact they explore users' satisfaction with the size, the number, the width and the height of the windows.

The ANOVA reveals a significant effect of the size of the window (Item 1) (Figure 4a) on the satisfaction score F (8, 216) = 33.79[3] and $p< 0.01$. The Figure 4 presents the preference order for the parameters analyzed. In the first graph the big windows (40%) are the favorite ones and especially when the settings are with one window (L1) or with 3 windows (L3). Additionally, for the other settings, the satisfaction ratings decrease.

The number of windows (Item 2) (Figure 4b) affects the satisfaction ratings as well: the one way ANOVA highlighted an F (8, 216) = 13.36, $p<0.01$. Within each size group (L,

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[2] Visual Display Unit

[3] The F ratio is the ratio of the mean square value between the groups divided by the one within the groups. The two numbers parenthetical are the degree of freedom between the groups and the degree of freedom within the groups.

M, and S) the 3 window settings are always preferred, followed by the 2 window settings, lastly the 1 window settings.

Regarding the width of the window (Item 3) (Figure 4c) the application of one way ANOVA showed again a significant effect over the satisfaction scores $F(8, 216) = 13.36$, $p < 0.01$, also in this case, as the reader can see in the graph, L setting is the favorite, followed by the M setting, and the S setting.

The ANOVA revealed a significant effect of the height of the windows (Item 4) (Figure 4d) with F (8, 216) = 28.61, $p<0.01$. The graph shows that the highest window (L1) satisfies the subjects more than the other. It indicates also that subjects are satisfied to the same extent from L2, L3 and M1 settings. Starting from M2 setting the satisfaction is decreasing.

Considering the results altogether, there is a greater satisfaction in front of a large window. The satisfaction seems to decrease with the window size. However, different ranking of satisfaction emerges, when the analysis deeply examined.

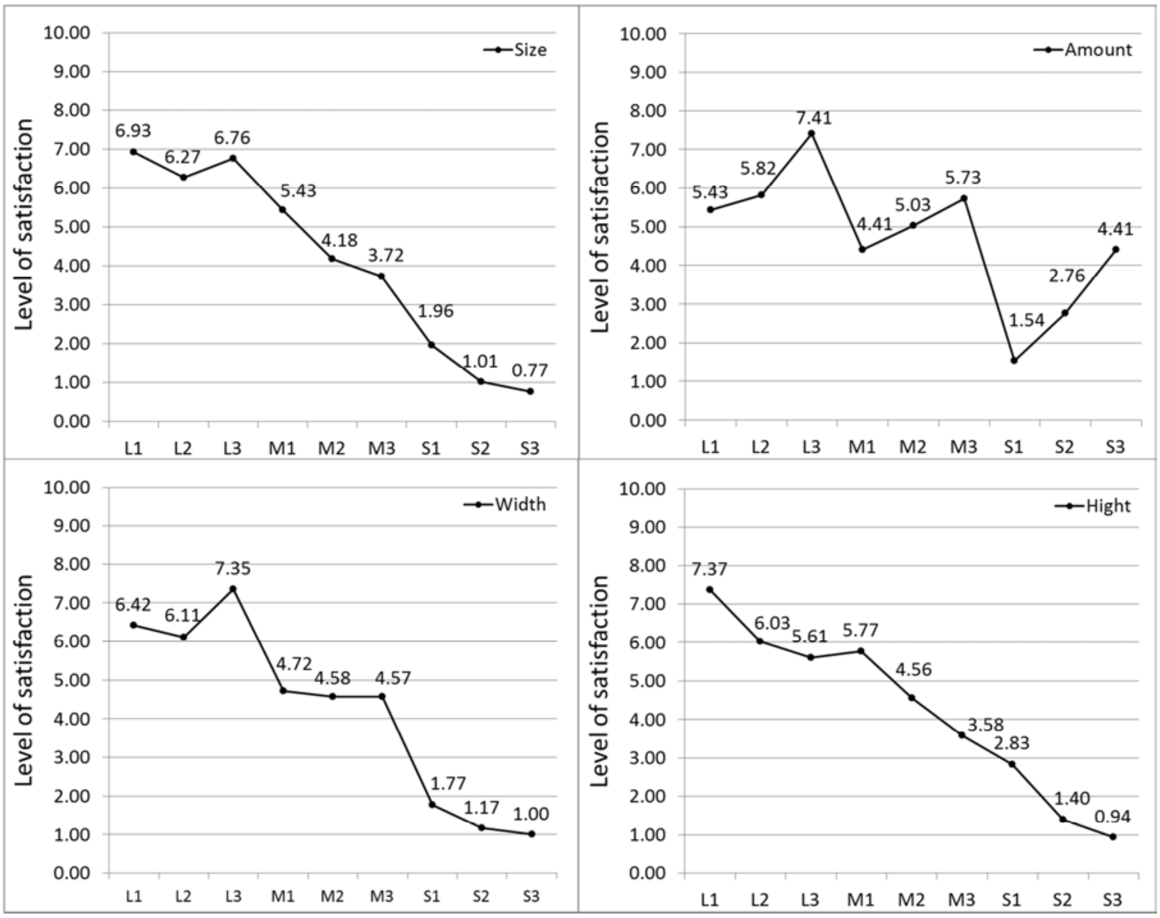

Figure 4 Single rating results: proband preferences for a) size, b) amount, c) width, d) height.

2.6.2. Paired comparison

The single rating evaluation does not provided a univocal answer among the parameters analyzed; the paired comparison is therefore the methodology that provides a global satisfaction ranking. The structure of the test is an Alternative Forced Choice (AFC): two stimuli are presented consisting of two different window settings, participants are asked to choose which one is their favorite. Forcing the participants to make a choice, they evaluate in a global way the satisfaction for the quantity of view in terms of size and amount that is the reason way a ranking is achieved.

The one way ANOVA highlights a significant effect of the global satisfaction, F (8, 216) = 30.94, $p< 0.01$. Figure 5 shows the ranking of the window settings. Overall these results are consistent with the ones of the single rating evaluation, however here it is clear that window setting L3 is the one of the most satisfying, followed by L2 and L1.

The medium window settings lead to a similar level of preference in the order M1, M2, M3, whilst the small window settings do not satisfy the subjects. The worst case is S3.

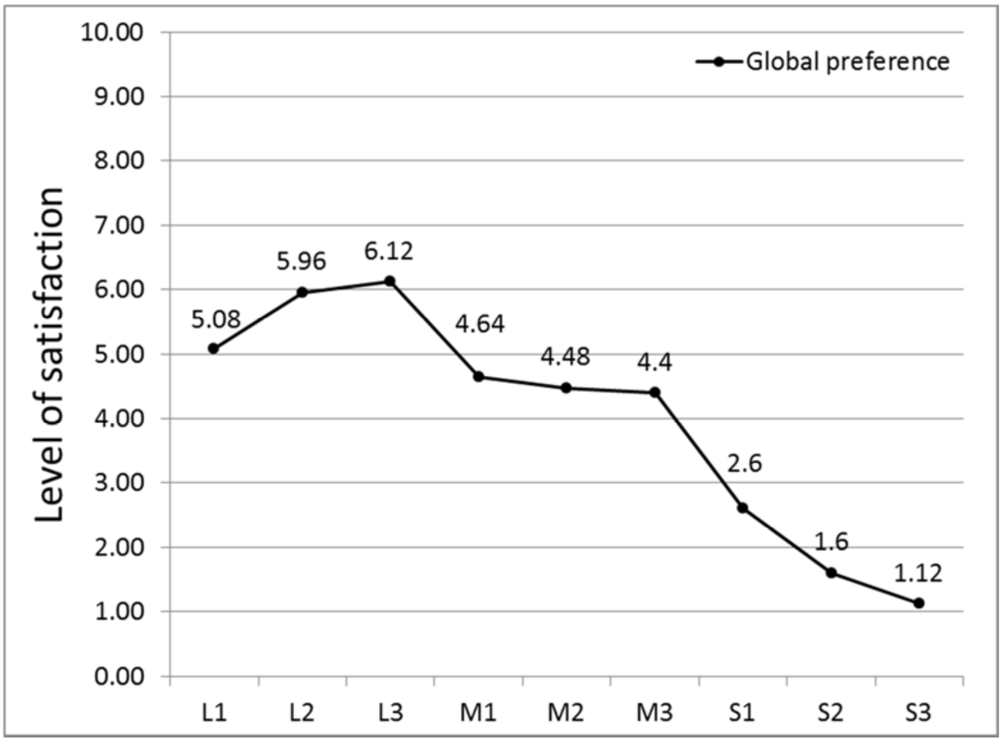

Figure 5 Paired comparison ranking of preference

2.7. Discussion

The results of the statistical analysis of the tests on users' satisfaction with the different window settings are very interesting. The first thing to notice is that, for what concern the size, all the favorite windows are the large ones (i.e. 40% of the window wall). This is consistent with Ne'eman and Hopkinson (1970) who found that a window 35% of the wall area satisfied 85% of the people.

In particular a setting with the three big windows is the participants' favorite one. At the moment, it is not yet clear if this is the favorite setting because of the 3 windows or because of the horizontal orientation of the windows. Future research will be dedicated to clarify this issue.

The medium window settings have among them nearly the same position in the general ranking in the paired comparison. To discover something more about the preference of the subjects the single rating is considered. The analysis of the size shows that the general preference is the setting with one window, which means that L/M/S 1 are favorite respect to L/M/S 2 and L/M/S 3, but looking at the number for each single size group people are more satisfy with three windows. In sum there is not a univocal preference for the medium setting. It means that according to other needs it is possible to choose one of these three settings.

Finally the small setting (i.e. 10% of the window wall) is extremely unsatisfactory. This finding is consistent with Keighley (1973a). Within the small setting, the three-window case was the least preferred.

3. EVALUATION OF THE SIMULATION TOOLS: RADIANCE THREE-PHASE METHOD AND ENERGY PLUS

After studying employees’ preferences concerning quantity of view outside a window, the thesis focuses on the daylighting and energy demand analysis. In this section, a preliminary analysis of the tools, used later to clarify the impact of window size and amount, is conducted.

The daylighting simulation tool Radiance Three-Phase Method is compared to Classic Radiance. The comparison regards one overcast day in winter and one sunny day in summer with and without blinds. It points out how much the new Radiance option, the Three-Phase Method, provides accurate results compared to the state of the art, Classic Radiance.

The energy building simulation software EnergyPlus is compared to Trnsys. One mouth in winter and one month in summer are analyzed to verify that the setting of the simulation is reliable and ready to be used in the comparison among different window settings.

3.1. Heat and light through a window

A window exchanges heat by three heat transfer mechanisms (Figure 6): conduction, convection and radiation. The conductive heat transfer carries heat through the glass panes, the frame and the walls. The convective heat transfer exchanges heat by the movement of a gas in contact with a surface. The radiative heat transfer exchanges heat between surfaces. The radiation heat transfer is composed of two types: the long-wave radiation and the short-wave radiation. The long-wave radiation heat transfer refers to the radiant heat transfer between objects at the room temperature or at an outdoor ambient temperature. Short-wave radiation heat transfer refers to the radiation from a light source. This range includes the ultraviolet, visible, and solar-infrared radiation.

There are two ways to study the solar transmission through a window. One considers the U-value, the Solar Heat Gain Coefficient and the Visible Transmittance, the other one considers the layer-by-layer heat transfer model.

Looking at the first one, the U-value determinates the heat transmitted through a window in absence of sunlight, air infiltration and moisture condensation. The heat transfer paths of a glazing unit are subdivided into center of the glass, edge of the glass and frame contribution (ASHRAE, 2009). The unit of measure is $W/(m^2 K)$. The lower the U-value, the less heat is transferred.

The Solar Heat Gain Coefficient (SHGC) represents the fractional amount of the solar energy that strikes a window that ends up warming the internal environment. A fraction of the shortwave radiation that hits a window is directly transmitted into the building. Another fraction is absorbed, heating up the layers of the window. The absorbed heat can either be conducted inside or outside of the building.

Visible Transmittance (T_{vis}) is the amount of light in the visible range of the solar spectrum that passes through a glazing material. Visible transmittance is influenced by the glazing type, the number of panes and coatings.

SHCC and T_{vis} play a role in the choice of glazing systems that maximize the visual and the thermal comfort. For example, low-emissivity (low-E) glasses select specific areas of the solar spectrum. In this way, the desirable wavelengths of energy are transmitted and the rest are reflected. A glazing material can then be designed to optimize the energy transmission in terms of solar heating and daylighting. The solar reflectance of low-E coatings can be manipulated to include specific parts of the visible and infrared spectrum. A high visible transmittance means that there is more daylight in a zone which, if designed properly, can reduce electric lighting and its associated cooling loads. Generally for a central European climate, glazing systems with low-Emissivity coating (low-E coating) and low solar heat gains are mounted. Visible light is transmitted and solar-infrared radiation is reflected. Long-wave infrared radiation is in any case reflected back in to the interior.

This choice insulates the internal environment, maintaining more easily the desired set-point temperature, and it reduces the cooling demand in summer season because the solar heat penetration is limited. For cold climates, there are glazing systems with a low-E coating and high solar heat gains. Visible light and solar-infrared radiation are transmitted. Long-wave infrared radiation is reflected back in the interior in order to keep internal temperature as constant possible (McCluney, 1996). This way of characterizing a window fails for Complex Fenestration Systems (CFS) because the complexity of the problem calls for a layer-by-layer definition.

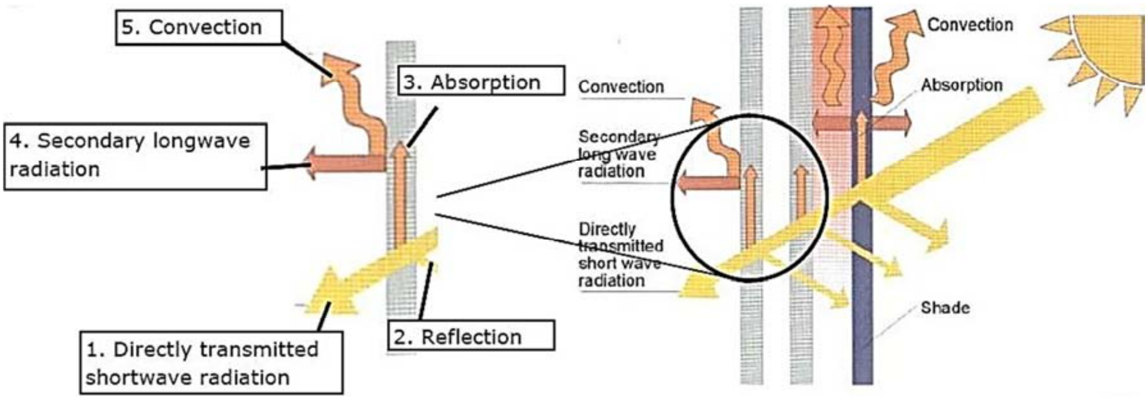

Figure 6 Heat transmission through a window[4]

CFS refer to any window technology that incorporates a non-clear (non-specular) layer that allows the scattering of the light. Examples include special glazing materials such as translucent insulating panels, solar control films, and patterned glass, and shading devices, such as venetian blinds and roller shutters. CFS have the potential to improve the thermal and visual comfort of indoor spaces as well as to save energy for lighting, cooling and heating (Laouadi et al., 2007).

At the same time, CFS need a complex model to represent its light scattering properties. The Bi-directional Scattering Distribution Function (BSDF) of a material is a standardized way to characterize its scattering properties as a function of the incoming solar radiation direction. By definition, it is calculated by the definition of each infinitesimal solid angle built following all the incoming direction of the radiation. For this the BSDF provides Lambert-emissing scattering surfaces (Apian-Bennewitz, 2010). The BSDF is composed of BRDF, used when specifically referring to reflected

[4] http://www.jamesrobertshaw.co.uk

scattering, and BTDF, used to refer to scattering transmitted through a material (Asmail, 1991).

Applied to a CFS, the BSDF is used to characterize the angularly resolved transmission and reflection of light. The BSDF method was proposed by Klems to model the solar gains through a window with CFS (Klems, 1994a, 1994b). The Klems' method calculates reflected and transmitted solar radiation for all the incident directions seen from a window point of view using bidirectional optical measurements of the CFS. In the case of windows with multiple heterogeneous parallel layers, the Klems method, starting from different BSDF for each layer, gives a BSDF for the total glazing system (McNeil et al., 2013a).

BSDF data of transparent glazing can be automatically generated from its optical properties at normal incidence by applying a model that calculates the visual and solar transmission and reflection based on the Roos model (Roos et al., 2001) and developed at Fraunhofer ISE. BSDF data of complex layers, such as shading devices, is automatically generated from the Radiance-based program genBSDF (McNeil et al., 2013b). The model can also use BSDF data generated by other means, such as Window6 (Mitchell et al., 2008), calculations or direct goniophotometer measurements (Stover, 1992).

The application of BSDF data and the Klems' method imposes a number of assumptions that require special attention. These are the following: The Klems' method assumes integrated spectral properties. The condition for this assumption to be valid is that most layers have spectrally flat optical properties, with at most one strongly selective layer. If one of the layers is selective and the other layers have an average transmission in the transmission region of the selective layer that is different from its average transmission over the full spectral region, the model fails. One solution for solar transmission is to use the visible properties of the layers after a selective, solar control layer.

The BSDF format treats spatial inhomogeneities as homogeneous. In this approximation, the directly-transmitted radiation from a venetian blind would be a uniformly-lit patch. In case of large fenestration systems with non-symmetric scattering patterns, the model introduces an error in the spatial distribution of light (not in the transmitted energy). It assumes that the whole window contributes the same to the illuminance of a certain point, when in reality the lower part of the dayligthing system might contribute more than the upper part. One solution in order to improve the calculated distribution of light is to divide the large window is two or more parts and apply the method as if each part would be a different window.

BTDF of the total window system is sufficient to solve the daylight distribution in the room. Using the BSDF to calculate the light transmission, instead of using angular dependent propriety of the glass, has the advantage that the directions of the light inside the room are described.

The thermal calculation of heat flow through the fenestration requires more information. To solve the heat transfer model, a layer by layer model is applied. The model treats layers as a simple RC network in matrix form. Temperature value for the previous time step is used as initial values for the current time step. Moreover, BSDF matrices counting the solar radiation transmitted, reflected and absorbed in each of the fenestration layers are provided. Therefore, the in-situ layer absorptance for each layer, referenced to the incident surface is needed. The absorption has to be considered as an energy source stored inside the glazing system and used in the RC network.

The radiative heat transfer is calculated with the Stephan-Boltzmann equation. The convective heat transfer is calculated by using the ISO 15099 (DOE, 2010a). The conductive heat transfer depends from the conductivity of the material and the thickness of the layers.

3.2. Description of the tools

In this section the tools are described, and their strong and weak points highlighted. The reader will know the reasons of the choice of Radiance Three-Phase Method as daylighting simulator and EnergyPlus as energy building simulator.

3.2.1. Classic Radiance and Radiance Three-Phase Method

Classic Radiance is a sophisticated lighting program. It has the capability of producing physically correct results and accurate images indistinguishable from photographs.

Radiance is based on backward ray-tracing algorithms, meaning that the rays are traced back from the sensor or view point to a light source that, in the case of daylighting, can be the sky and the sun. For each starting point of the grid inside the environment, a different ray tracing has to be processed. Radiance also takes into account the inter-reflections between objects (Jacobs, 2012). On the one hand, this is its strength because of the accuracy of its results but, on the other hand, this is also a weakness because it is a time-consuming process.

Moreover Classic Radiance does not provide a user friendly interface and its use is not straightforward especially if detailed results are requested. To help the reader an overview of the Radiance commands is presented in Appendix 1.

The Radiance Three-Phase Method (McNeil et al., 2013a) is a method to perform daylighting annual simulations of complex and dynamic fenestration systems. It is a tool developed inside Radiance environment but it uses a different approach.

In the Three-Phase Method, the flux transfer is divided in three phases, which are independently simulated. For each phase, there is a correspondent matrix of coefficients (McNeil, 2013a). Instead of simulating a specific daylight condition, the Three-Phase Method calculates normalized coefficients that connect flux input to output for each phase. The results for a specific daylight condition are calculated by multiplying the coefficient matrices with the input values. The input is represented by a vector with the sky luminance values at a specific time of the day and of the year and under certain weather conditions.

Matrix calculation can be performed very quickly and the result of the multiplications is an illuminance or irradiance vector. The illuminance or the irradiance values are calculated according to a grid of sensors arranged in the internal environment.

Writing the definition in a formula, the Three-Phase Method is:

$$i = VTDs$$

Where:
i= illuminance or irradiance values vector
V= view matrix

T= transmission matrix

D= daylight matrix

s= sky vector

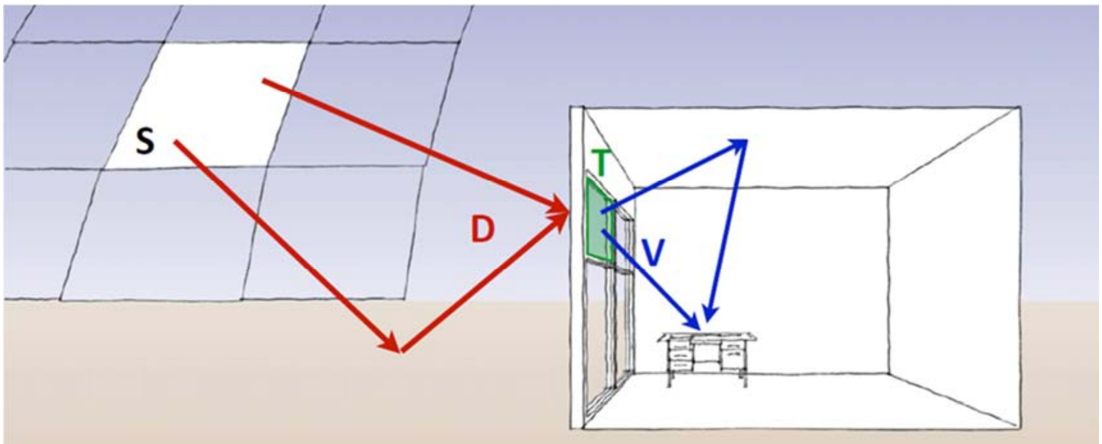

Figure 7 Three-Phase Method Matrices representation[5]

The sky is divided in patches, for each patch an average RGB radiance value is provided according to Perez (1990). The length of the sky vector changes according to the number of patches. The simulations presented in this work are executed with the Reinhart sky subdivision in 2321 patches (McNeil et al, 2013a).

The daylight matrix contains luminous flux transfer coefficients from the sky division to the window incident division.

The view matrix characterizes the relationship between light leaving a window and arriving at a point considered as a sensor inside the room (McNeil, 2013a). The transmission matrix relates incident flux directions to an outgoing flux distribution for the fenestration system. The transmission matrix is a BSDF matrix (Section 4.1).

Applied to a CFS, the BSDF is used to characterize the angularly resolved transmission and reflection of light by CFS.

There are two important advantages of using the Three-Phase Method. As already mentioned, the matrix multiplications can be really fast, enabling the user to simulate many sky conditions and fenestration transmission properties by simply changing the sky vector and the BSDF dataset. Therefore, by applying the Three-Phase Method, it is possible to perform annual daylighting simulations of CFS, which overcomes some of

[5] http://www.radiance-online.org

the limitations encountered in the dynamic daylighting program DAYSIM (Reinhart et al., 2009).

In the present study, the accuracy of Classic Radiance is used as reference to understand the accuracy of the Radiance Three-Phase Method. The later is then used for the analysis because of the need of a tool with a shorter computational time that provides at the same time a good level of daylighting simulation.

3.2.2. Energy Plus and Trnsys

EnergyPlus is an energy analysis and thermal load simulation program. It studies the performance of a building, in particular in this work of thesis it calculates the heating and the cooling demand to maintain indoor set-point temperatures. EnergyPlus is a modular, structured code, based on the most popular features and capabilities of BLAST and DOE-2.1E. It uses inputs such as the user's description of a building in terms of geometry, its physical characteristics, any associated mechanical systems and equipment in general, presence of people and their behavior, etc.

EnergyPlus calculates thermal loads of buildings by the heat balance method. The heat balance method solves energy balances on outdoor and indoor surfaces, and it solves the transient heat conduction through building construction. It is more accurate than the weighting factor methods, since it allows the variation of properties with time steps (Strand et al., 1999).

EnergyPlus was chosen as simulator for this work because of its capability to manage complex fenestration systems (from version 7.2). It provides also blind control systems and a layer-by-layer heat balance solver that allows proper assignment of the solar energy absorbed by the different fenestration layers. In fact, Energy Plus can use BSDF data to solve the heat transmission through the windows (DOE, 2010a) and for the optical representation of the fenestration system (McNeil et al., 2013b).

Another advantage of Energy Plus is that the programming language is object-oriented and eliminates the need to interconnect the various program sections. Additionally, Energy Plus is a program without a user interface and, as in the case of Radiance, inputs, outputs and weather data are given in ASCII form.

In the present study, the input data file of EnergyPlus is generated by a simulation interphase developed at Fraunhofer ISE, which collects information regarding the office position, geometry, physical proprieties of opaque surfaces, windows and external blinds and the information about occupation equipment and lighting and relative schedules. The input parameters are presented in section 4.3.

Trnsys (Klein et al., 2000) is a dynamic simulation program with a modular structure that was designed to solve complex energy system problems by breaking the problem down into a series of smaller components. The Trnsys components (referred to as "Types") may be as simple as a pipe, or as complicated as a multi-zone building model. The components are configured and assembled using a fully integrated visual interface known as the Trnsys Simulation Studio, and building input data is entered through a dedicated visual interface (TRNBuild). The simulation engine then solves the system of algebraic and differential equations that represent the whole system. In building simulations, all HVAC-system components are solved simultaneously with the building envelope thermal balance and the air network at each time step (Crowley et al., 2008).

Trnsys has been chosen because of its user-friendly interface and the possibility to implement the same weather file and artificial light input file of EnergyPlus. Simulating one case study by using to different tools allows verifying the setting of the simulations so that the results from both programs are reliable.

3.3. Description of the office

The office is simulated as a single-zone, with the same dimensions as the office recreated in the daylighting laboratory for the user assessment. The space has an internal width of 3.702 m in the east-west direction, an internal length of 4.60 m in the north-south direction and a height of 2.85 m. It represents an intermediate floor of an office building with one south-facing facade. The external wall is composed of four layers with a total thickness of 0.355 m and an overall U-value of 0.3 W/m²K. The indoor partitions are composed of three layers with a total thickness of 0.1 m and an overall U-value of 0.42 W/m²K. The ceiling and the floor have both five layers with a total thickness of 0.30 m and an overall U-value of 0.563 W/m²K. The U-values are calculated by taking into account a 0.13 m²K/W internal surface resistance and a 0.04 m²K/W external surface resistance. The indoor surface reflectances are 0.2, 0.5 and 0.7 for the floor, walls and ceiling, respectively. The properties of the different materials used are summarized in Table 1.

The windows use a double-pane glass (5.7 mm x 12.7 mm x 6 mm) with a *U*-value of 1.39 W/(m^2K), a visual transmittance (T_{vis}) of 0.744 and a SHGC of 0.576. The size of the window changes according to the cases described in Section 2.2.2. In order to simplify the daylighting simulations, the windows are provided without frame. This assumption implies an underestimation of the heat losses through windows between 15% and 30%, depending on the frame material.

The shading device consists of silver external venetian blinds. The lamellas are 80 mm width and 72 mm spaced. The surface reflectance is 0.6. This shading device spreads diffuse light in the room while limiting the direct sun penetration. To simplify the study, the lamellas do not change the angle in accordance to the sun position and the weather condition but they are fixed at 45°.

Table 1 Layer by layer wall propriety definition

External wall	Thickness	Thermal conductivity	Thermal resistance	Density	Specific heat capacity
	m	W/(mK)	m²K/W	kg/m³	J/(kgK)
External surface resistance			0.040		
Exterior finish	0.010	1.000	0.010	2500	720
Mineral wool	0.120	0.040	3.000	50	1030
Reinforced concrete	0.210	2.300	0.091	2300	1000
Interior finish	0.015	0.250	0.060	900	1050
Internal surface resistance			0.130		
U_{tot} [W/(m²K)]			0.300		

Internal wall	Thickness	Thermal conductivity	Thermal resistance	Density	Specific heat capacity
	m	W/(mK)	m²K/W	kg/m³	J/(kgK)
Internal surface resistance			0.130		
Interior finish	0.015	0.250	0.060	900	1050
Insulation	0.070	0.035	2.000	35	840
Interior finish	0.015	0.250	0.060	900	1050
Internal surface resistance			0.130		
U_{tot} (W/m²K)			0.420		

Ceiling	Thickness	Thermal conductivity	Thermal resistance	Density	Specific heat capacity
	m	W/(mK)	m²K/W	kg/m³	J/(kgK)
Internal surface resistance			0.100		
Finish	0.010	1.000	0.010	2500	720
Cement floor	0.020	0.900	0.022	1800	1100
Concrete slab	0.200	1.600	0.125	2200	1070
Insulation (2)	0.050	0.040	1.250	105	1800
Suspended ceiling	0.020	0.100	0.200	300	1700
Internal surface resistance			0.100		
U_{tot} (W/m²K)			0.553		

Floor	Thickness	Thermal conductivity	Thermal resistance	Density	Specific heat capacity
	m	W/(mK)	m²K/W	kg/m³	J/(kgK)
Internal surface resistance			0.100		
Suspended ceiling	0.020	0.100	0.200	300	1700
Insulation (2)	0.050	0.040	1.250	105	1800
Concrete slab	0.200	1.600	0.125	2200	1070
Cement floor	0.020	0.900	0.022	1800	1100
Finish	0.010	1.000	0.010	2500	720
Internal surface resistance			0.100		
U_{tot} (W/m²K)			0.553		

3.3.1. Internal parameters, heat gains and schedule

A schedule defines the presence or absence of occupants in the office. The office is fully occupied during the work time from Monday to Friday from 8 am to 6 pm. The thermostat set points (T_{set}) for the heating period are 21°C during the work time, 18°C otherwise, and 26°C and 28°C for the cooling period. In the present study, infiltration and mechanical ventilation are combined in the same parameter, 2.0 ACH during work time, 0.4 ACH otherwise. Heat gains from people are calculated according to their activity level (assuming 120 W/person, from which 65 W is sensible heat, ISO 7730). One person occupies the space during work time. Internal gains due to equipment are 50 W during the work time and 5 W for the rest of the time. The lighting is controlled by an on/off algorithm. When the illuminance due to daylight calculated at a sensor point located 2 m from the south façade and 1.2 m from the west façade is less than 300 lux, the artificial lights in the space are assumed to turn on. The installed lighting power is

14 W/m². In order to analyze the illuminance distribution in the room a grid of 6624 points (one every 5 cm for all the room area) is defined. The height of the grid is 0.8 m in accordance with the EU Directive 90/270/EEC. The internal parameters used in the simulations are in accordance with the norm DIN V 18599-10.

3.3.2. Location and weather file

The office is located in Frankfurt (50.10° N, 8.68° E). In the present study, the heating season is defined from the 1st of October to the 30th of April. The weather file for Frankfurt is obtained by using Meteonorm (Remund et al., 2007).

3.4. Comparison of the tools

Before start working with the Radiance-based Three-Phase Method and EnergyPlus respectively for the daylighting and energy need analysis, a first round of results is compared with the results of other simulation programs in order to verify the reliability of the simulations. The Three-Phase Method is compared with Classic Radiance; Energy Plus is compared with Trnsys. In order to do the comparison, the office with the window pattern L3 (three big square windows that cover 45% of the south façade) is studied, and the results are analyzed graphically and statistically to prove that they match.

Graphical analyses are done by plotting the heat gains and losses and the energy loads for certain periods of the year in time-dependent graphs and by highlighting the differences between the results from the energy building tools. On the other hand, in the daylight tool evaluation, for significant hours of the days, renderings and graph of the illuminance distributions are obtained and compared.

The statistical evaluation is conducted by using equations 1, 2, 3, and 4 to calculate the Mean Bias Error (MBE) and the Root Mean Square Error (RMSE) of the comparison. The MBE and RMSE are statistical quantities that characterize the similarity/differences between two data series. The MBE indicates the tendency of one data series to be larger or smaller than the other. The RMSE indicates how far one data series “fluctuates” around the other (Reinhart et al., 2009). Both the parameters can be calculated as absolute or relative. With the absolute results the error is directly compared with the reference, the relative results give the possibility to compare different errors.

The MBE is defined as:

$$MBE_{abs} = \frac{1}{N}\sum_{i=1}^{N} x_{test,i} - x_{ref,i} \qquad [1]$$

$$MBE_{rel} = \frac{1}{N}\sum_{i=1}^{N} \frac{x_{test,i} - x_{ref,i}}{x_{ref,i}} \qquad [2]$$

The RMSE is defined as:

$$RMSE_{abs} = \frac{1}{N}\sqrt{\sum_{i=1}^{N} (x_{test,i} - x_{ref,i})^2} \qquad [3]$$

$$RMSE_{rel} = \frac{1}{N}\sqrt{\sum_{i=1}^{N} \frac{(x_{test,i} - x_{ref,i})^2}{x_{ref,i}^2}} \qquad [4]$$

For the energy demand study, similar result help to assay that, even though the two programs solve the energy balance with different algorithms, both the simulation setting are coherent and for this reliable. For the daylighting study similar results demonstrate that the Three-Phase Method is a good alternative to Classic Radiance to carry out annual daylighting analysis.

3.5. Daylight tools comparison:

In this section, the Three-Phase Method is compared with the classic Radiance (Larson et al., 1998) for specifics days of the year.

The inability to execute annual simulation with classic Radiance requires limiting the comparison for only two typical days, a summer sunny day and a winter overcast day. This choice has been made with the same criterion of the paper that validates the Three-Phase Method (McNeil et al., 2013a). In particular, the sunny day is the 23rd of July and the overcast day is the 15th of February in Frankfurt. The comparison is conducted with two different settings, one with blinds and the other one without. That means that in total the compared cases are four.

Both tools provide a grid with the illuminance values distributed inside the room. Firstly, the average illuminance values for the points of the grid that are positioned in the center of the room are compared (Figure 8). The center of the room has been chosen because, in an office, it is usually the area to check that the minimum level of illuminance complies with the norm. In fact, it is the zone of the room where the desks are arranged whereas the bookshelves are placed next to the walls.

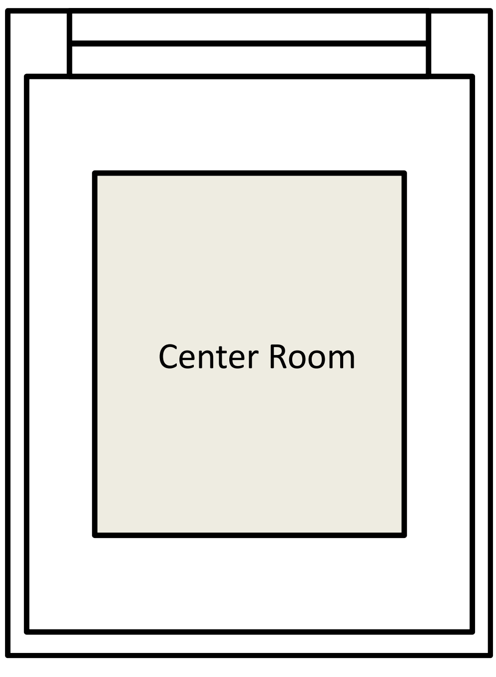

Figure 8 Central part of the room defined for the average illuminance calculation.

After identifying the area of interest[6], equation 5 is applied for each time-step and for the four case studies:

$$\sum_{i=1}^{n} \frac{i}{n} \qquad [5]$$

Where *n* is the total number of the points in the central zone of the room.

To identify the differences of the two tools, an error analysis of the average illuminance values for the considered days is done by applying the MBE and RMSE formulas described above (Equations 1-4). This type of evaluation is inspired by McNeil and Lee (2013a), where the Three-Phase Method is compared with measurements.

In the present study, reference values are those obtained from the Classic Radiance simulation, given the fact that Classic Radiance has been extensively validated. The second way to understand how different the results of the Classic Radiance and the Three-Phase Method are uses illuminance renderings of the entire room and illuminance value plots for all the depth of a central line of the room.

Firstly, the illuminance values are read as false colors in Rshow, a Radiance rendering tool together with 3D rendering file of the office (the octree file). In this way, the light distribution inside the room is visible from a top view. Rshow reads a six columns file, three to identify the position of each sensor point (x, y, z) and three to identify the color of the point (in RGB format). In order to provide some reference numbers, the illuminance values for the sensor points located along a center line from the windows to the opposite wall are also plotted.

The rendered images have different scales for the different cases in accordance with the sun penetration for a specific setting of the window (with or without blinds) and sun position, but the same scale is applied in the two different tools rendering for the same study case in order to compare them.

[6]The points of the illuminance grid that compose the center of the room are chosen with an awk command: cat illusensor.dat |tail –n+1177 |head –n+4272 |awk '{print NR, $0}' | awk '{if((NR-1)%72<24)print}'>lux_centerroom.dat

3.5.1. Analysis of the results for the daylight comparison

Looking at the graph with the average illuminance on the work-plane of the two complete days analyzed (Figure 9), the lines tent to have the same trend and in many parts there is a good overlap. That means that, even if the two programs use approaches totally different, the results cover the same range. Where the difference is registered, there is an under-prediction of illuminance by the Three-Phase Method.

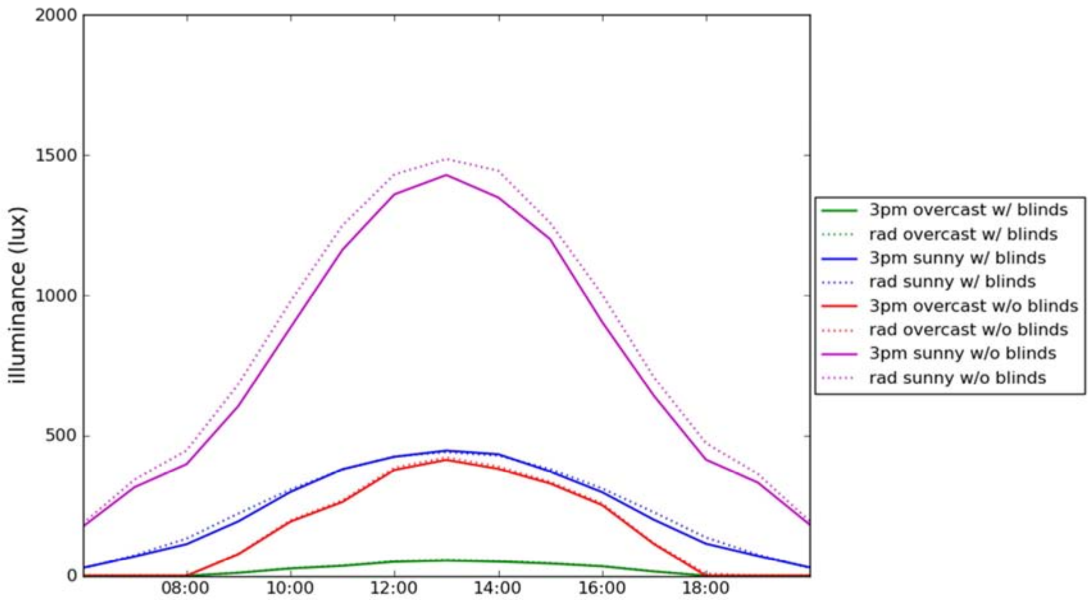

Figure 9 Comparison of the average illuminance in the central part of the room for the four analyzed cases.

Table 2 MBE and RMSE of the four analyzed cases. The reference is the average of all the time steps and all the points in work-plane grid .

Case		MBE_{abs}	$RMSE_{abs}$	MBE_{rel}	$RMSE_{rel}$	Reference
		lux	lux	-	-	lux
Sunny day summer	w/o blinds	-59.5	65.7	-0.08	0.08	757
Overcast day in winter	w/o blinds	-5.9	6.3	-0.02	0.02	266
Sunny day summer	w/ blinds	-8.1	13.7	-0.04	0.08	231
Overcast day in winter	w/ blinds	-1.4	1.6	-0.04	0.04	36

Moreover, the Table 2 shows the statistical difference between the study cases. The data is presented both as absolute and relative errors. The references for the absolute errors are the average of all the time steps and all the points in work-plane grid for each case study. The statistical analysis shows the tendency to have better results during the overcast day. In fact, for the case without blinds, a systematic error of 2% is calculated, instead 8% for the sunny day. For the cases with blinds, the error is 4% considering the overcast day instead of 8% for the sunny day.

However, the MBE and RMSE show that all the cases have an acceptable error as compared to other daylighting simulation tools. The current state-of-the-art of daylighting dynamic simulation is Daysim (Reinhart et al., 2009). Reinhart and Breton identify as satisfying those results that are in error bands of ±15% and 35% for the relative MBE and RMSE, respectively. All the studied cases are inside this range accepted from the lighting community. To understand how the differences highlighted by the statistical analysis influences the light distribution at the work-plane height, rendering pictures and light distribution graphs are provided.

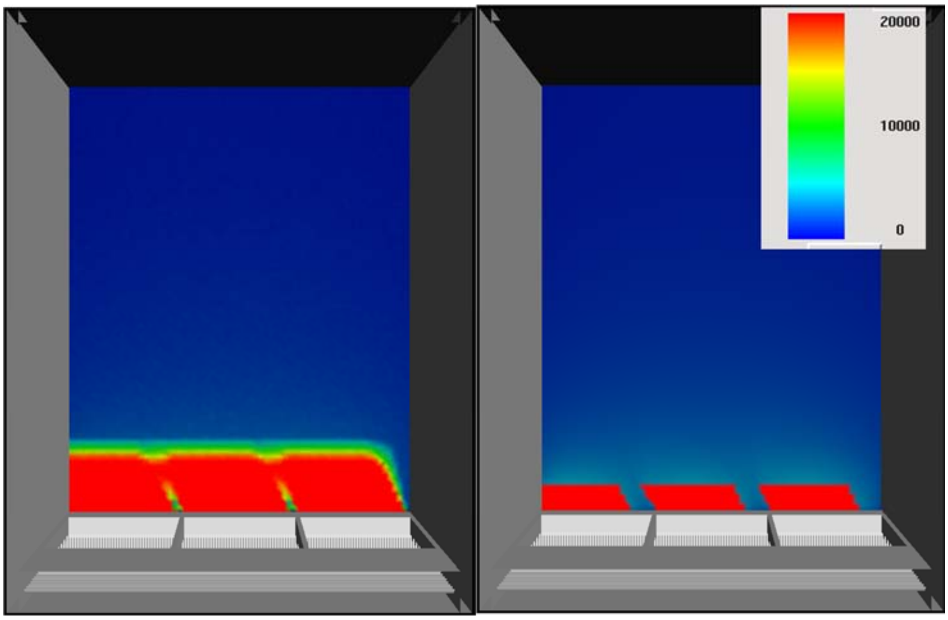

Figure 10 Illuminance rendering at the work-plane height calculated with the Three-Phase Method (a) and Classic Radiance (b) for the 23 of July at 12 am without blinds.The results are in lux.

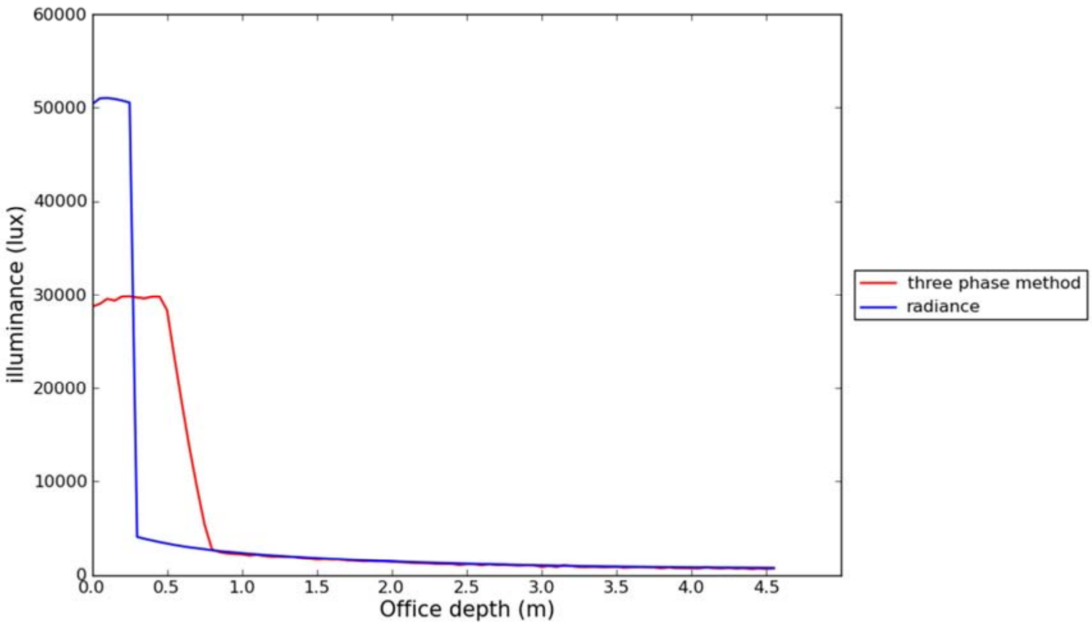

Figure 11 Illumiance plot for a central line of the room from the window wall to the opposite one for the 23 of July at 12 am without blinds.

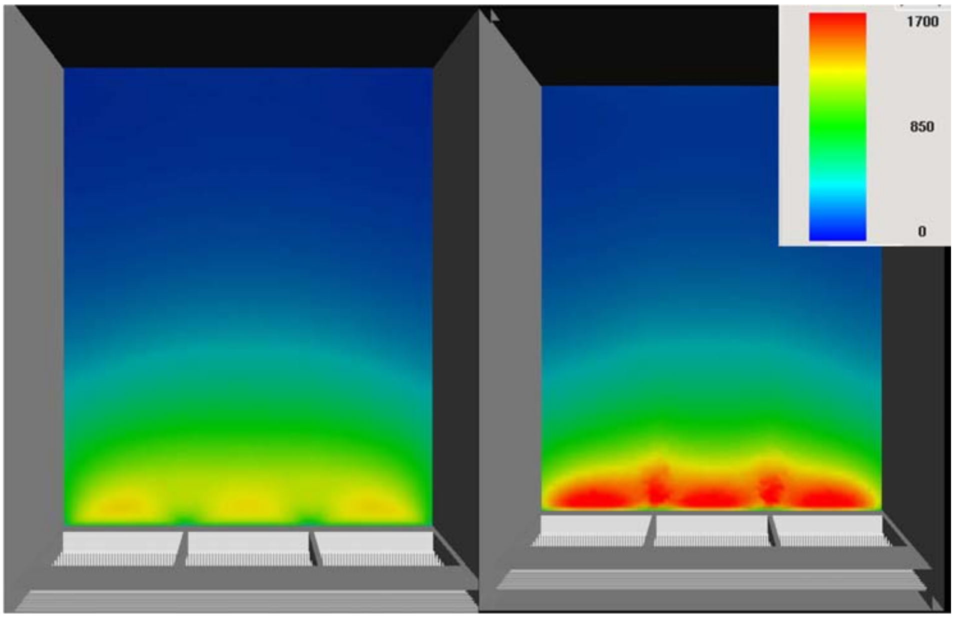

Figure 12 Illuminance rendering at the work-plane height calculated with the Three-Phase Method (a) and Classic Radiance (b) for the 15 of February at 12 am without blinds. The results are in lux.

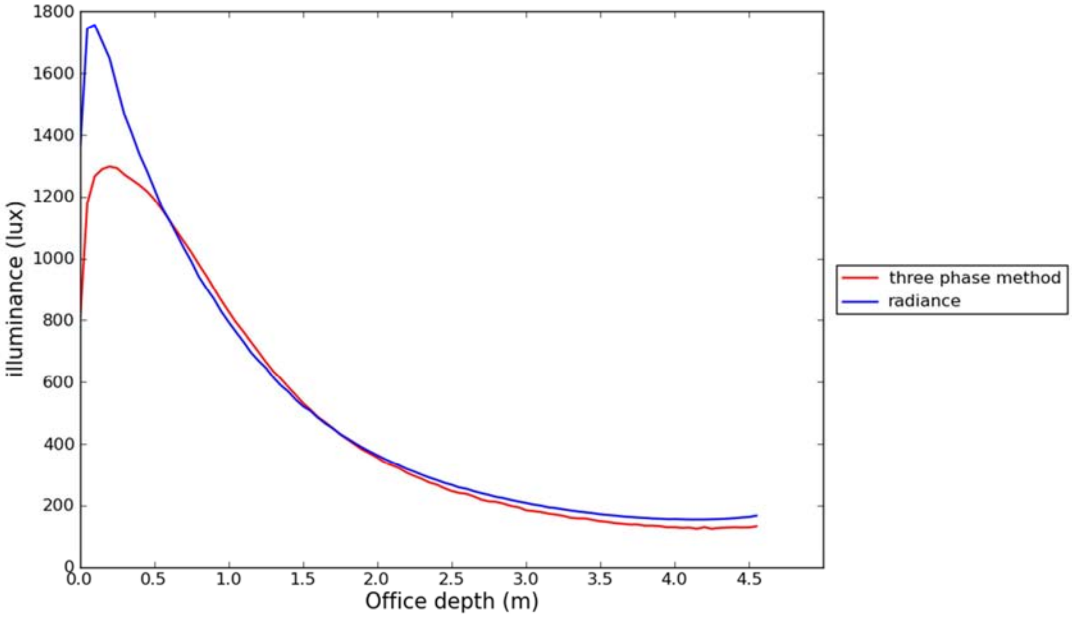

Figure 13 Illumiance plot for a central line of the room from the window wall to the opposite one for the 15 of February at 12 am without blinds.

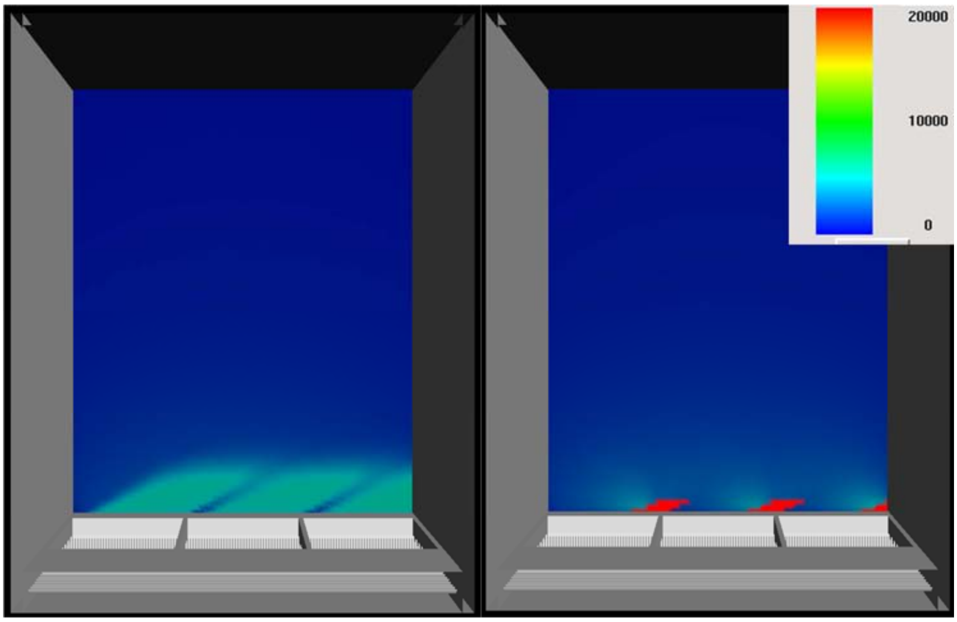

Figure 14 Illuminance rendering at the work-plane height calculated with the Three-Phase Method (a) and Classic Radiance (b) for the 23 of July at 4 pm without blinds. The results are in lux.

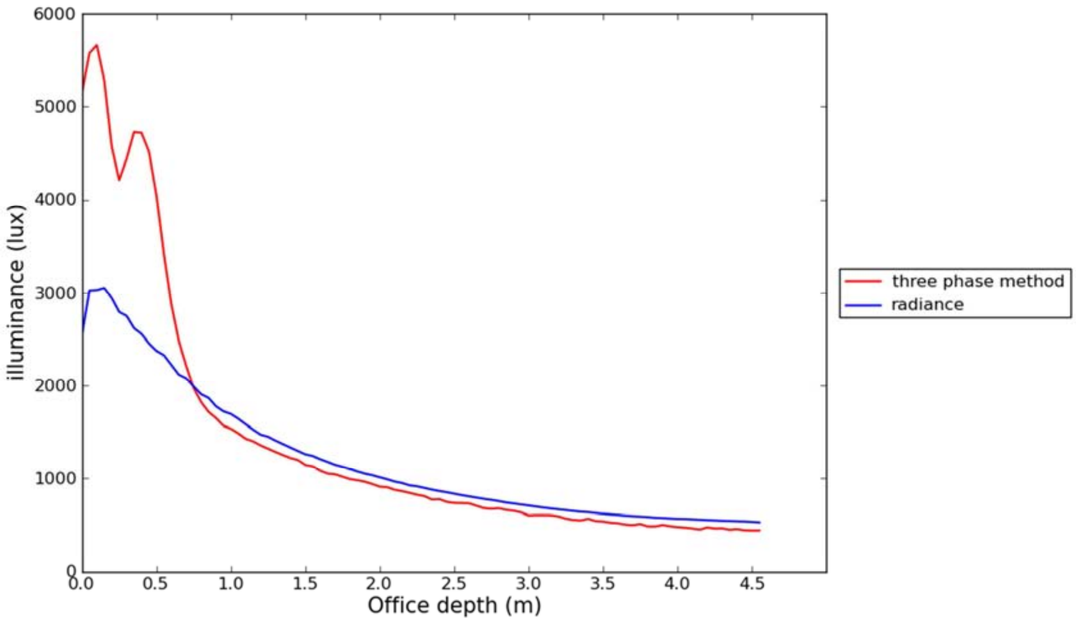

Figure 15 Illumiance plot for a central line of the room from the window wall to the opposite one for the 23 of July at 4 pm without blinds.

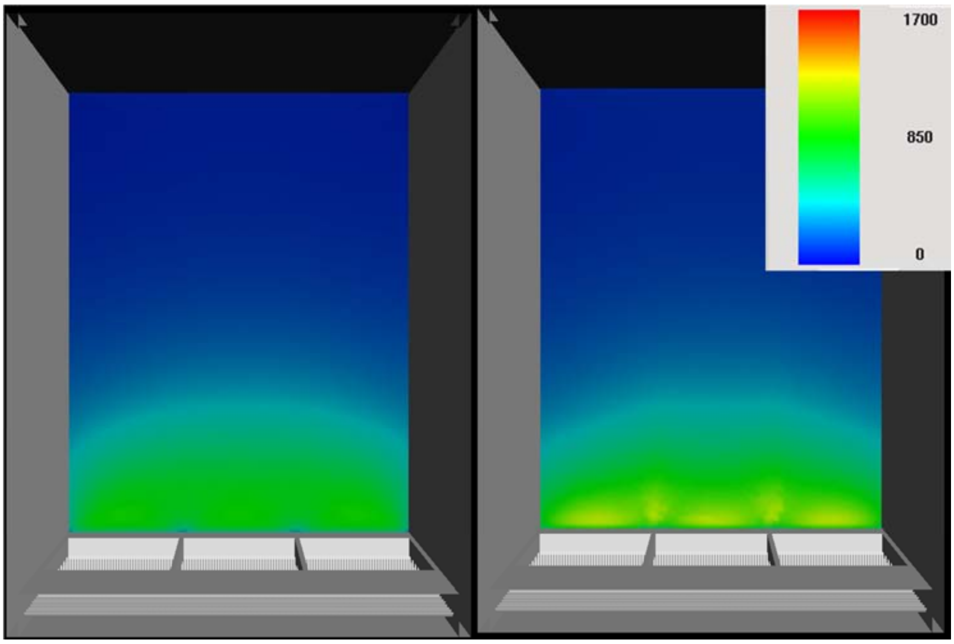

Figure 16 Illuminance rendering at the work-plane height calculated with the Three-Phase Method (a) and Classic Radiance (b) for the 15 of February at 4 pm without blinds. The results are in lux.

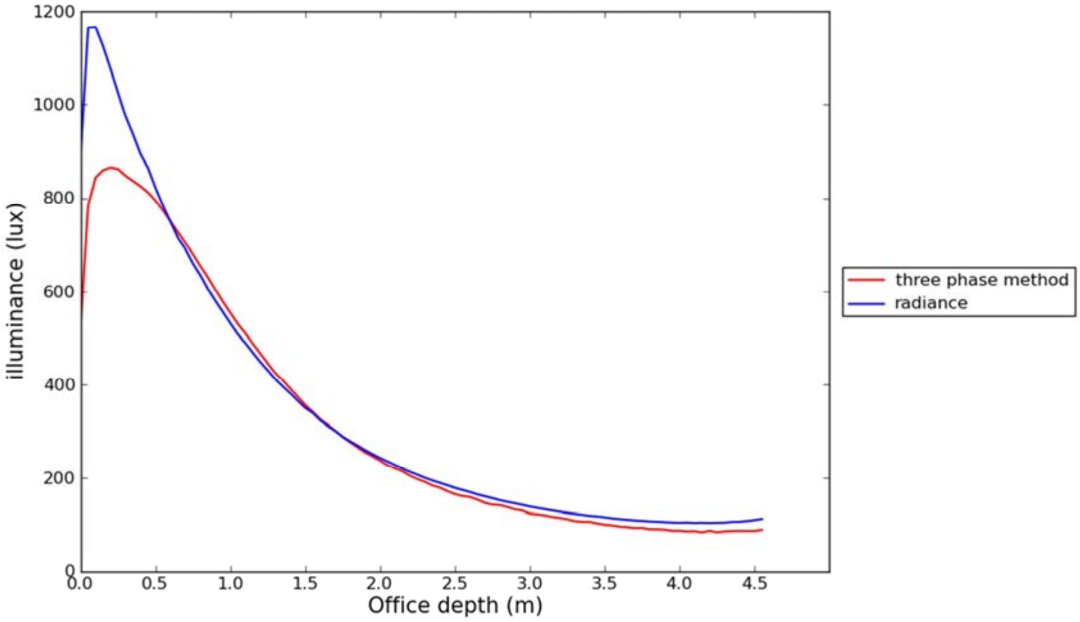

Figure 17 Illumiance plot for a central line of the room from the window wall to the opposite one for the 15 of February at 4 pm without blinds.

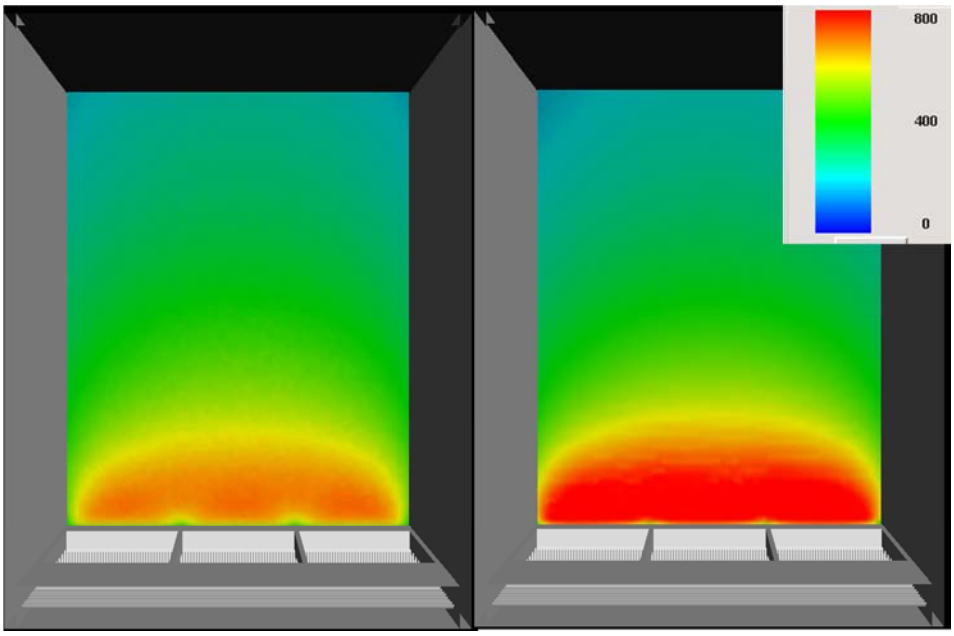

Figure 18 Illuminance rendering at the work-plane height calculated with the Three-Phase Method (a) and Classic Radiance (b) for the 23 of July at 12 am with blinds. The results are in lux.

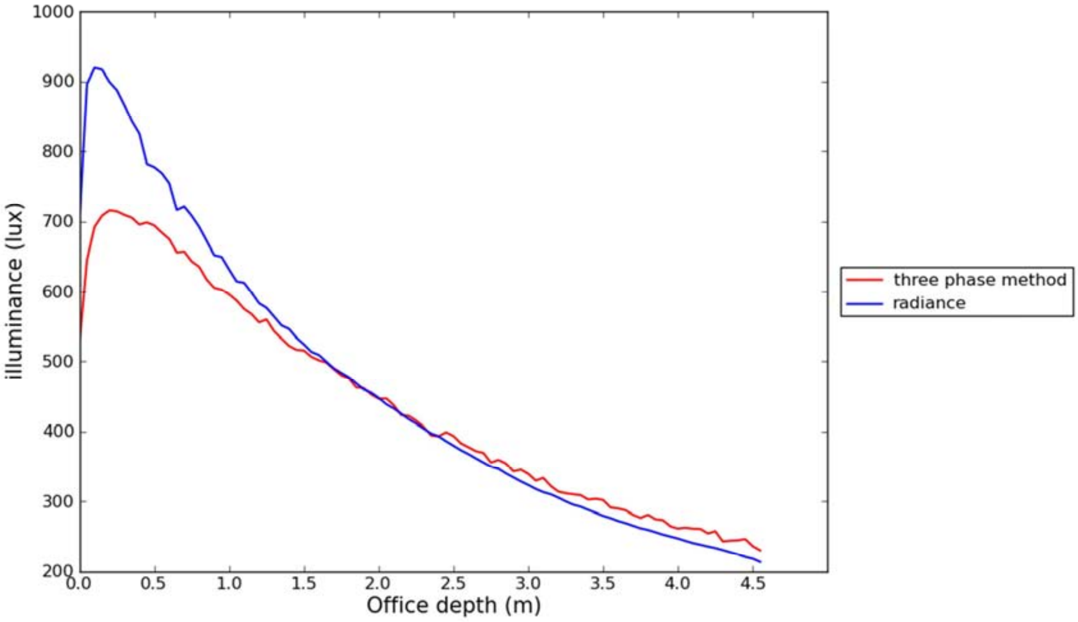

Figure 19 Illumiance plot for a central line of the room from the window wall to the opposite one for the 23 of July at 12 am with blinds.

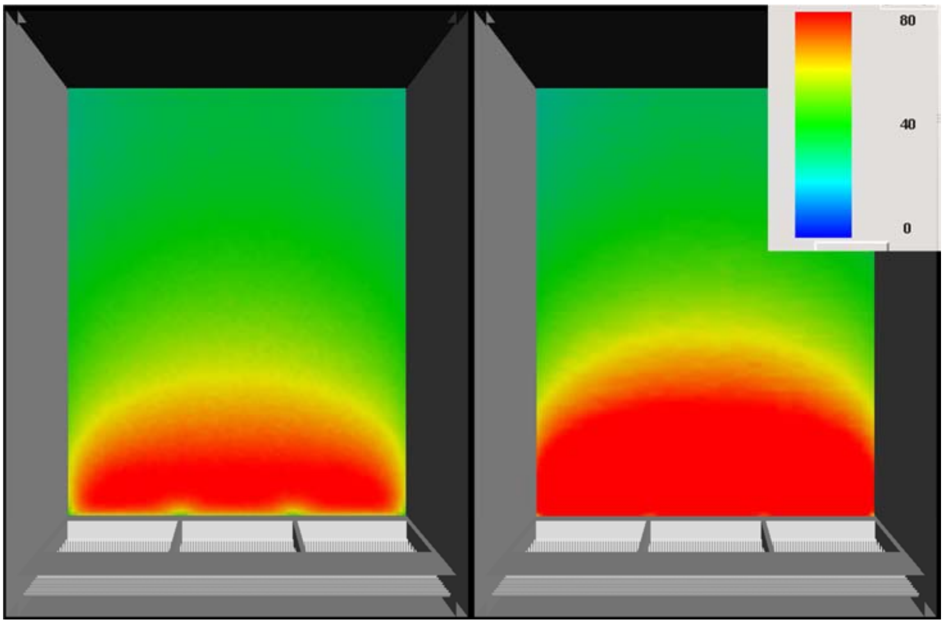

Figure 20 Illuminance rendering at the work-plane height calculated with the Three-Phase Method (a) and Classic Radiance (b) for the 15 of February at 12 am with blinds. The results are in lux.

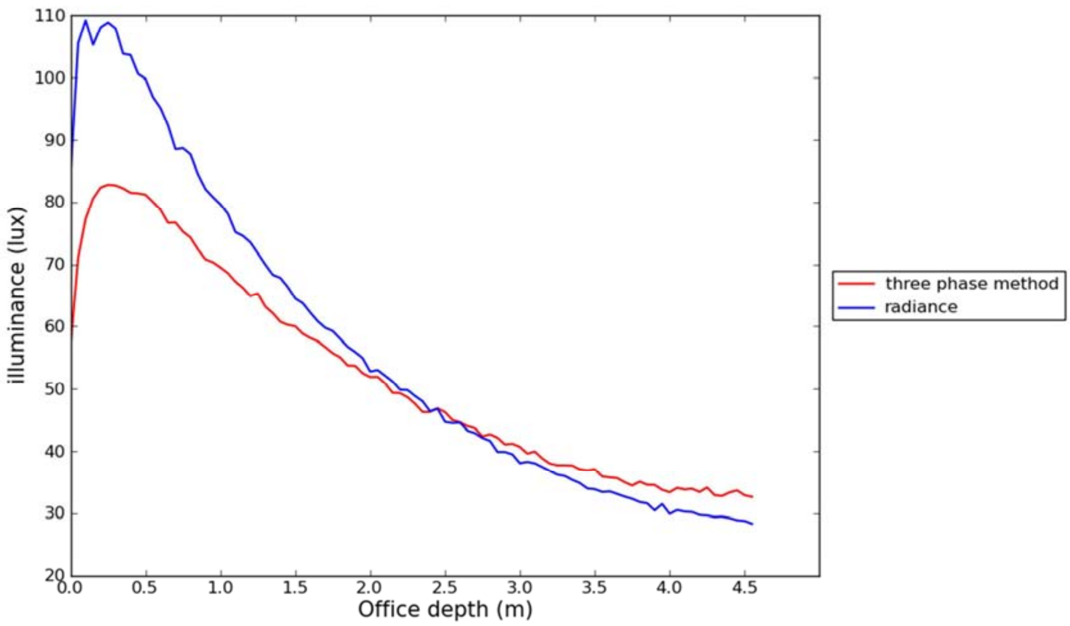

Figure 21 Illumiance plot for a central line of the room from the window wall to the opposite one for the 15 of February at 12 am with blinds.

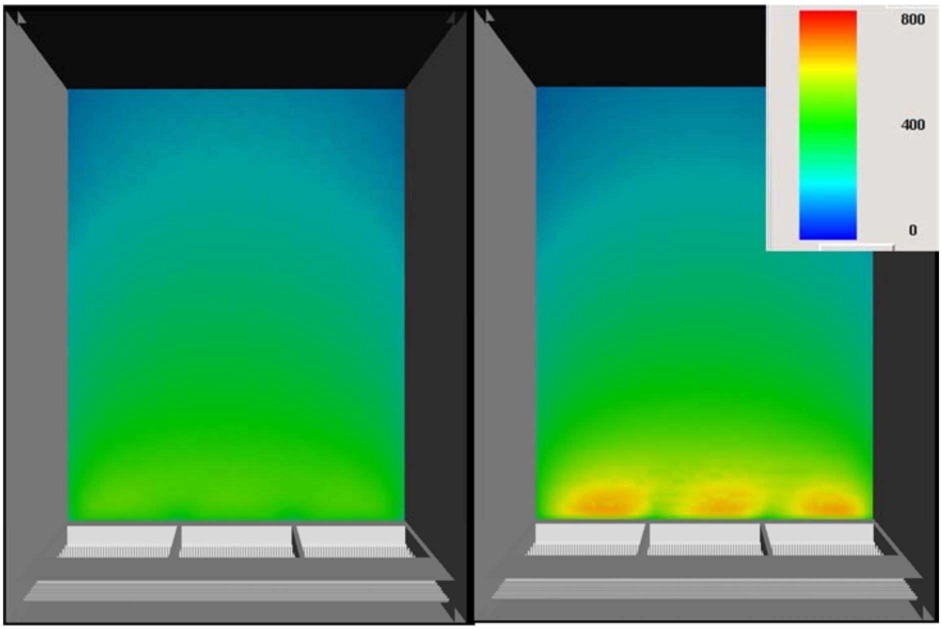

Figure 22 Illuminance rendering at the work-plane height calculated with the Three-Phase Method (a) and Classic Radiance (b) for the 23 of July at 4 pm with blinds. The results are in lux.

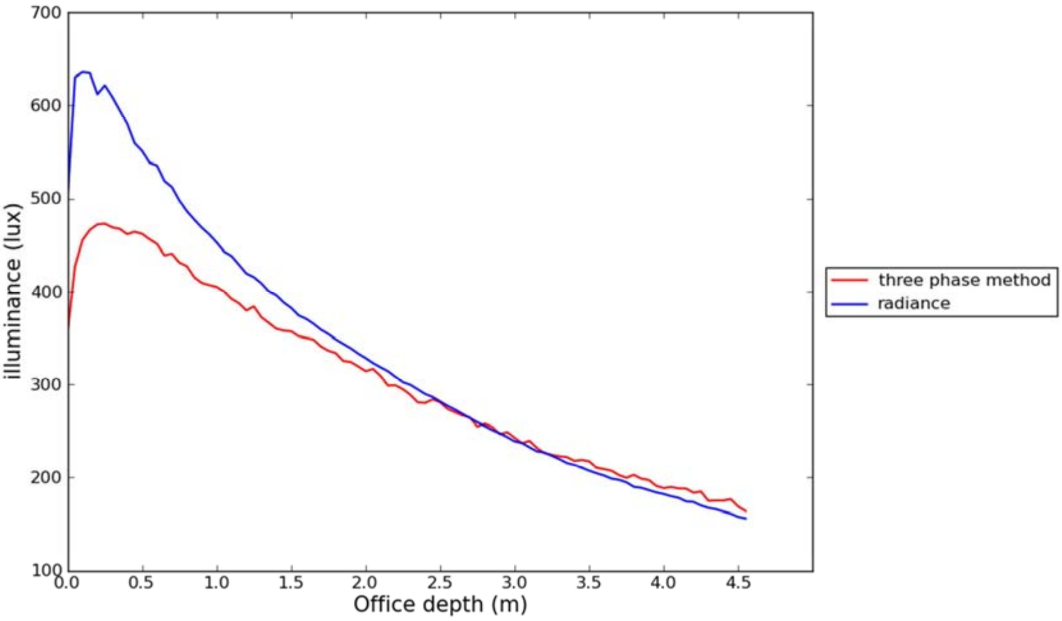

Figure 23 Illumiance plot for a central line of the room from the window wall to the opposite one for the 23 of July at 4 pm with blinds.

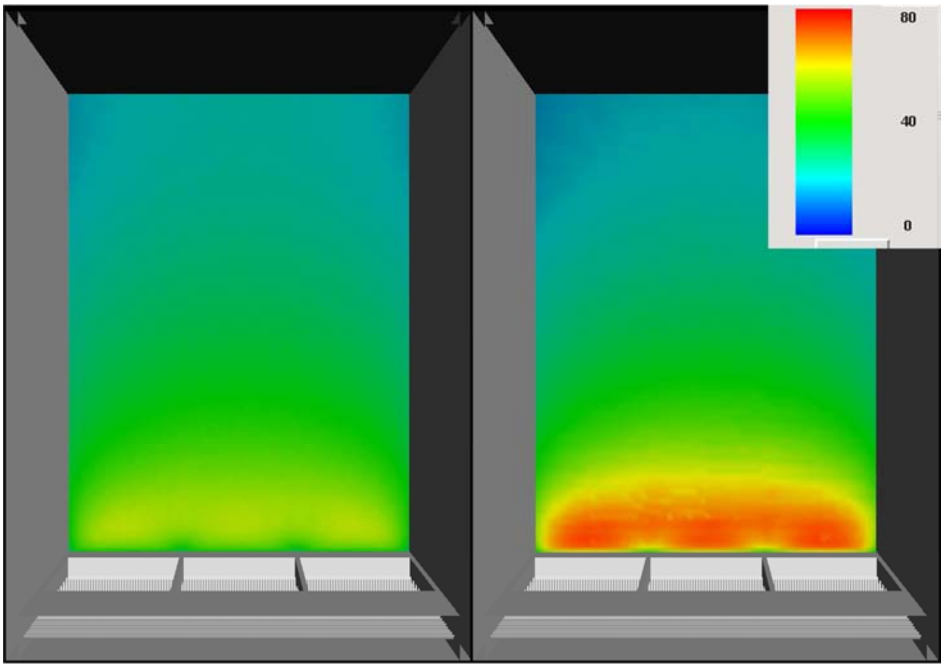

Figure 24 Illuminance rendering at the work-plane height calculated with the Three-Phase Method (a) and Classic Radiance (b) for the 15 of February at 4 pm with blinds. The results are in lux.

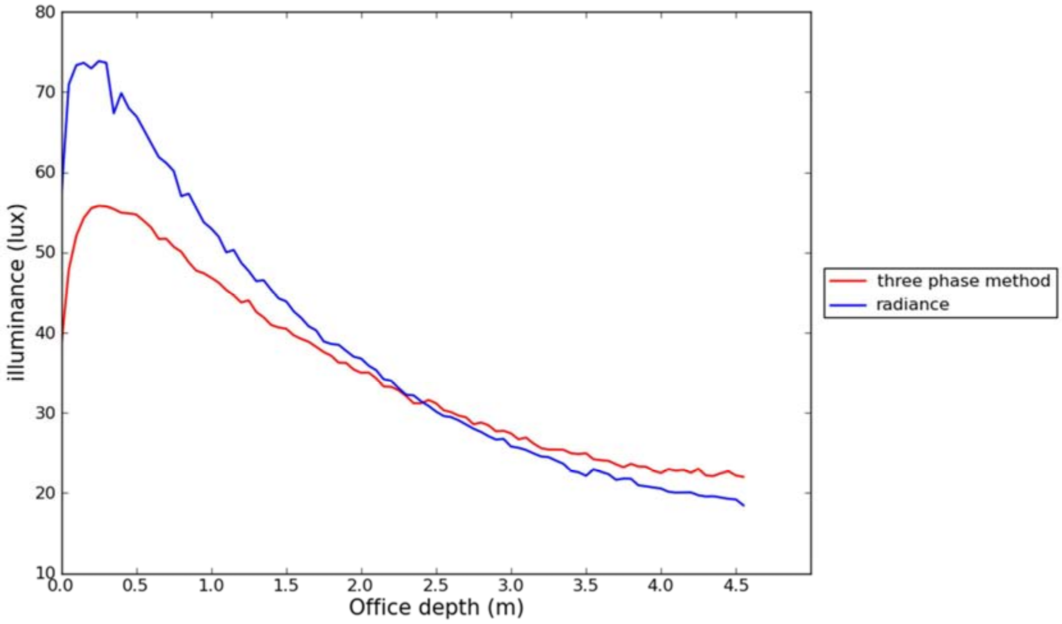

Figure 25 Illumiance plot for a central line of the room from the window wall to the opposite one for the 15 of February at 4 pm with blinds.

All the renderings show again an under prediction of the light distribution calculated by the Three-Phase Method. This is confirmed also by the graphs, the blue line runs over the red one in the first part of the room. The only graph that gives opposite results corresponds to the sunny day without blinds at 4 pm (Figure 15). This strange behavior comes from the fact that the position of the line is not suitable for this case.

The renderings show that the results of the Three-Phase Method are more scattered than those of Classic Radiance, which are more concentrated. This effect can be explained by many factors.

First the Three-Phase Method divides the sky into patches and the calculated radiation of each patch is emitted from the center of it. This assumption causes an error on the patch that in a certain time step has the sun inside its area. In fact, if the sun position is not exactly in the center of the patch, the solar radiation is distributed over the adjacent patches, in proportion with the distance between the exact sun position and the center points of the adjacent patches.

Moreover, the window is divided in 145 patches against the 2321 patches of Reinhart's sky distribution. This means that there is also a problem of resolution.

Lastly the limitation of the BSDF described in section 3.1, as the hypothesis of treating the glazing area like a homogeneous layer, can explain some inaccuracy on the results.

The problem of the mean value for each patch is clearly less relevant for the overcast days (Figures 12 and16). The sky without sun loses the strong contribution of the direct radiation on the patch emission and provides more uniform values. That is why the sunny days present larger errors.

In the configurations with blinds (Figures 18, 20, 22 and 24), the error of the patches can be explained also by considering the cut off angle of the blinds. On the one hand, Classic Radiance uses a ray tracing method so that the sun light enters the room in the right position in accordance with the angle of the shading device. In Classic Radiance simulations, the higher the number of the ray reflection considered the more accurate the results for CFS (in this case simulations consider 6 ray reflection, (Appendix 1)).

On the other hand, the Three-Phase Method, as described before, uses a weighted solar radiation distribution that cannot guaranty that the solar radiation leaves the sky in its original position. That means that there could be a sun ray that is falsely blocked by the cut-off angle of the blinds. Futher investigations would confirm it.

The Three-Phase Method underestimation influences the visual comfort analysis because it distributes differently the illuminance on the grid of sensors. However, in an office the work position is fix and to quantify the mistake committed it is enough to control the space between 1m and 3m depth. In this zone, for the cases without blinds, both for the sunny and overcast days, have similar illuminance values on the central sensor line of the office comparing Classic Radiance with the Three-Phase Method (Figures 11, 13, 15 and 17). For the cases with blinds the summer sunny day has correspondence of the two methods between the 1.5m and the 2.5m depth at 12 am and over the 2.5m depth at 4 pm; however, all the sensors measure more that 300lux so there is not a problem of visual comfort, in terms of illuminance under the required limit.

The overcast day with blinds required always the artificial lighting because the illuminance is under the 300lux. That means that, even if the two lines do not overlap, the error do not affect the total analysis. The Three-Phase Method presents another limitation that can be inferred from the noise observed in Figure 19. The bigger variation of the illuminance between adjacent points causes a problem for the sensor points for controlling the artificial light and the blinds position. In fact, if two points a few centimeters distant provide different values, for example one above and the other under the illuminance threshold, the control is not totally reliable, because in reality there is no difference between two adjacent measures.

To explain better this idea, two additional renderings (Figure 26) are shown with a smaller scale. It can be seen that the Three-Phase Method does not present a homogeneous distribution of the light.

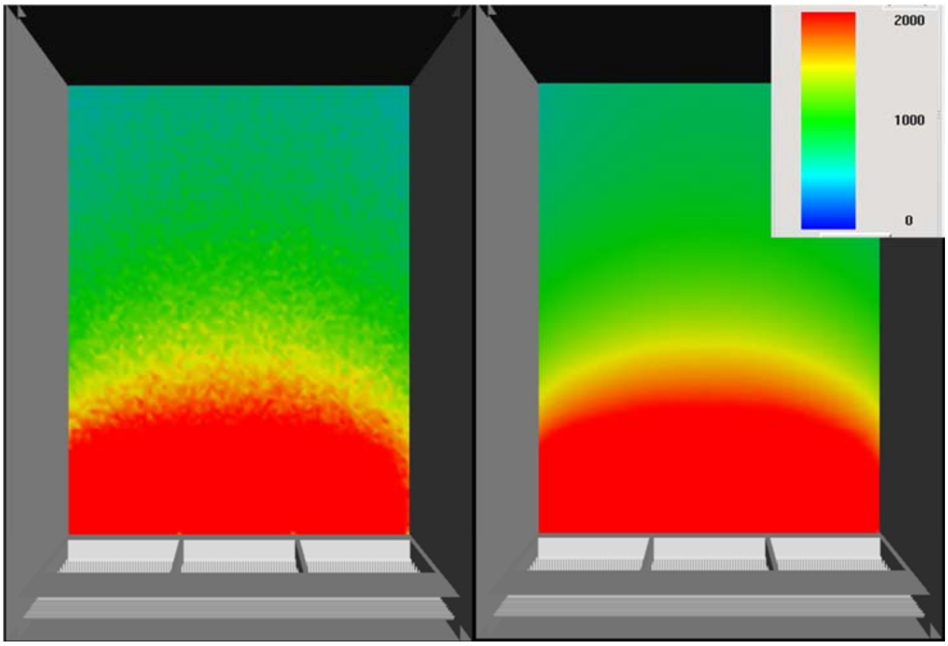

Figure 26 Illuminance rendering at the work-plane height calculated with the Three-Phase Method (a) and Classic Radiance (b) for the 23 of July at 12 am without blinds. The scale is reduced to 0-2000 lux to show the inhomogeneous distribution of the light in (a). The results are in lux.

To solve this limitation of the Three-Phase Method, it is suggested to avoid using a single control sensor by using the mean value of a certain area as control.

3.6. Energy consumption tools comparison

Even for experienced simulation engineers, setting up a model can often lead to errors. In order to increase the trust on the simulation results presented in section 4, this section compares two different building energy simulation tools that have been extensible validated: EnergyPlus and Trnsys.

For the comparison with Trnsys, some settings are modified to help interpreting the differences between the two programs. A simple natural convection algorithm is implemented as the internal surface convection algorithm. The simple convection model uses constant coefficients for different heat transfer configurations (DOE, 2010a). The same constant convection coefficients are used in Trnsys changing the default parameters.

In particular the values are:

For a vertical surface: h = 3.076 W/m² K

For a horizontal surface with reduced convection: h = 0.948 W/m² K

For a horizontal surface with enhanced convection: h = 4.040 W/m² K

In addition, the indoor air temperature is assumed constant at 23 °C instead of using the heating and cooling set point schedules presented in section 3.3. In this way the gap between the workday temperatures and the night and weekend temperatures is neglected, avoiding another cause of discrepancy between the results.

The two building energy tools were compared by plotting in graphs the results. First, ten days in winter and ten days in summer are plotted (Figures 27 and 28).

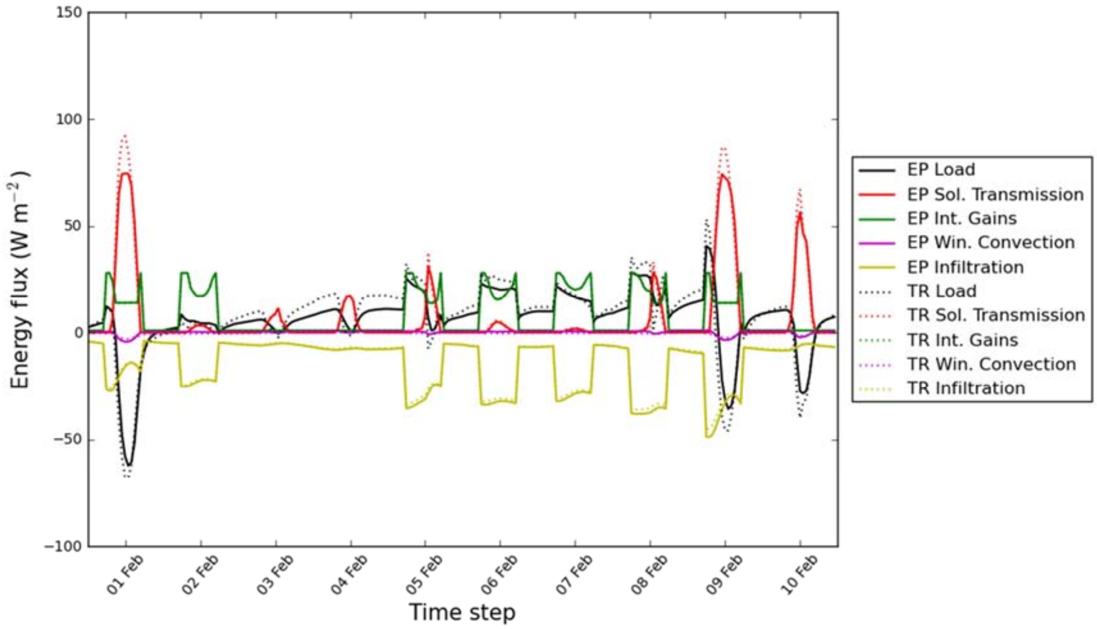

Figure 27 Heat gain comparison of EnergyPlus (EP) and Trnsys (TR) simulations for 10 days in winter.

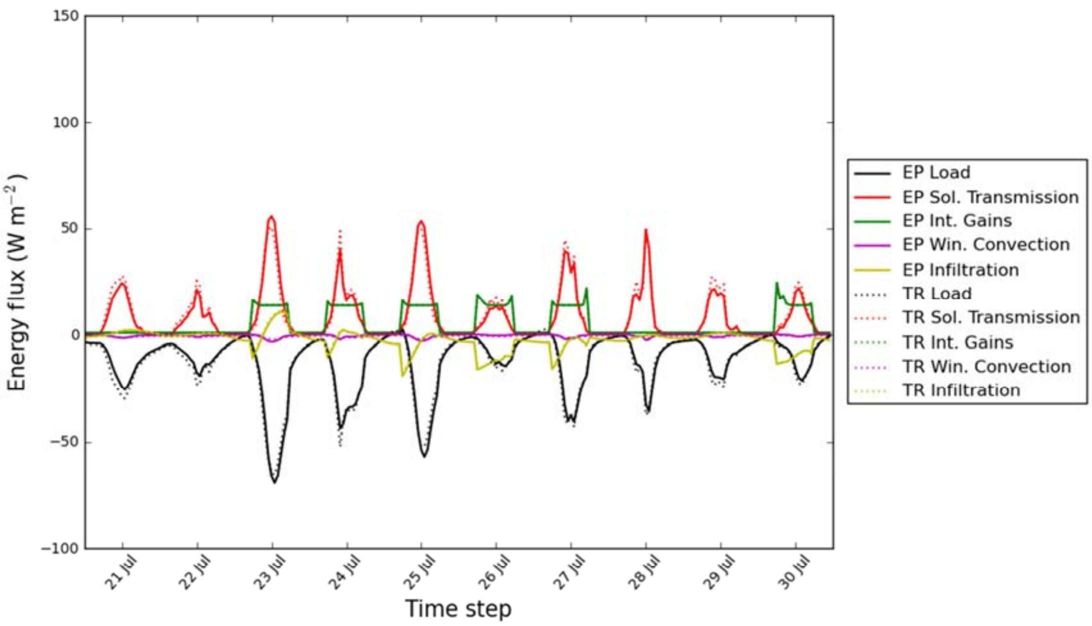

Figure 28 Heat gain comparison of EnergyPlus (EP) and Trnsys (TR) simulations for 10 days in summer.

The parameters considered are five:

Internal gain is the sum of the sensible heat provided by artificial lighting, equipment and people. Being defined by the user in both cases, the internal gain lines overlap.

The sensible heat gain from infiltration and ventilation depends on the air change per hour (ACH) and on the outside weather condition (outside temperature, wind speed, etc.). Providing the same weather file and the same ACH schedule, it can be assumed that they both affect the simulations in the same way, if indoor air temperature is kept constant.

The window interior surface convection heat gain shows the heat exchanged between the window internal surface and the internal environment. It depends on the surface temperature, indoor air temperature and the convection heat transfer coefficient. In Trnsys a glazing system built within the software Window 6 has been implemented, and the BSDF of same glazing system is used in EnergyPlus to provide the same angular dependent input. In fact, during this study, it is shown that the use of different glazing systems, even if they have a similar U-value, can change the solar radiation that enters the room affecting the simulation results. The small difference of result between the two approaches favors the use of Energy Plus and the BSDF approach because it provides more information in respect to a simple angular dependent resolution.

The window transmitted solar radiation rate affects the heat gain more in the sunny days than in the overcast days because of the direct sun contribution. It is an important parameter while studying the window impact because it varies the size of windows.

The solar radiation transmitted has the same trend in both the tools. The only parts where mismatches can be found are the picks. Here, it is hypothesized that this difference occurs due to the different algorithms implemented in the programs because, during the rest of the day, there is a good overlapping of the lines that exclude the possibility of mistakes in the model setup.

The heating and cooling load, above and under the x axis respectively shows the energy demand of the building .It is the line, sum of the other lines that evaluates the correspondence of the model setup. There is a good overlapping in summer. Observing the winter days, some differences appear during the quasi steady-state periods at night time. The trends are the same but there is a shift between them. The cause could lie in the heat transfer model.

Heating, cooling and solar transmission are the parameters that are more affected, changing the size of the windows. To investigate better their behavior, monthly average days of these are calculated, one in February (Figure 29) and the other one in July (Figure 30).

The monthly average day is created by taking the mean values for each hour of a month and creating a profile of 24 mean hourly values. This 24h-day can be taken as a reference because it is a good approximation of the month tendency. The results of the monthly average day for heating, cooling and solar transmission are given for February, and only cooling and solar transmission gains are given for July because the heating ones had irrelevant values. It is good to remind at this point that the cooling contribution in the winter graph is so relevant because the internal temperature is set at 23°C fix.

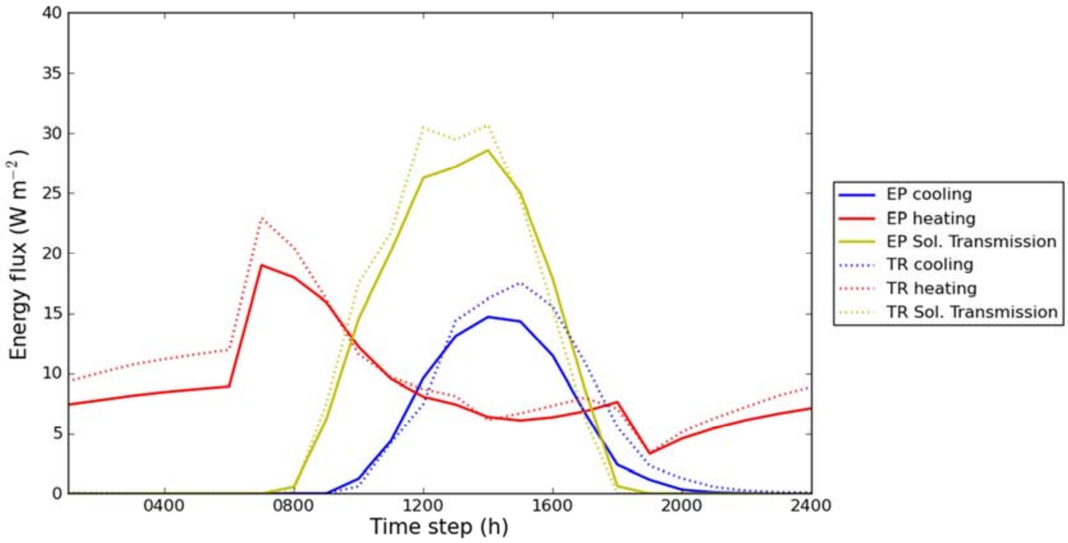

Figure 29 Monthly average day cycle of February.

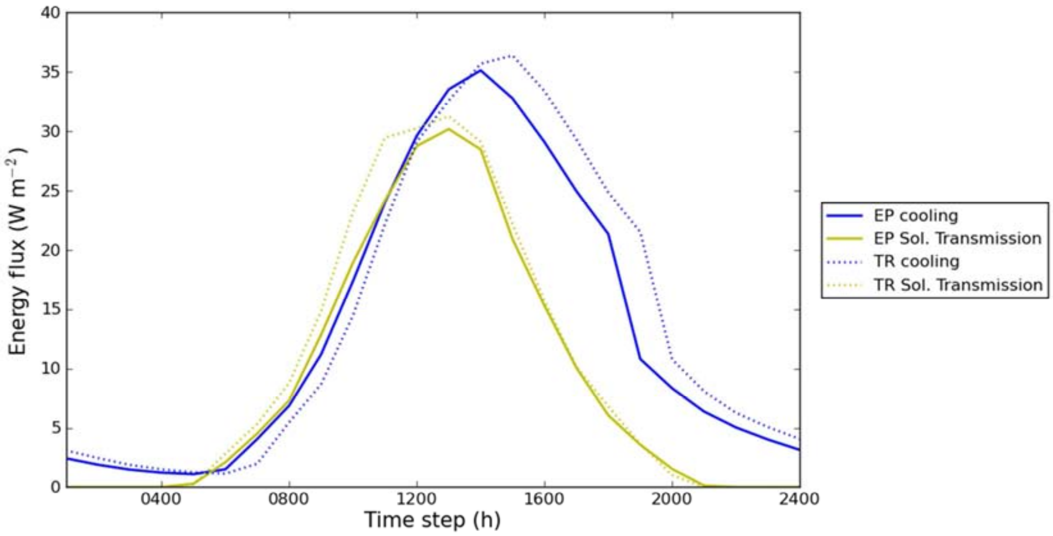

Figure 30 Monthly average day cycle of July.

The monthly average days show that the two tools provide also similar results, looking at an entire month. There is always the same trend for all the lines, apart the solar transmission picks in February. The shifts of the Trnsys results only demonstrates that the dynamic simulation are made with different programs and does not show particular reasons to think that there is a mistake in the simulation setting. To quantify the error with numbers, a statistical analysis is added.

The MBE and RMSE, as described in section 3.4, underline the error that one simulation makes towards the other. That is why one of the two programs has to be taken as reference. In the daylight analysis, it is clear that the reference program should be Classic Radiance because it is a more mature tool compared to the Three Phase Method. When looking at EnergyPlus and Trnsys there are not particular reasons why to choose one instead of the other, since they are both extensively tested programs, although EnergyPlus was preferred.

The error is calculated for six study cases, considering only the cooling in the summer month and only the heating in the winter month. Apart from the L3 window setting, which was chosen at the beginning as the case study for the comparison, another window setting is simulated (M1 setting) to verify that the second one has also a good result agreement. This is useful to double check if the simulation settings designed for the L3 window case with a step-by-step method is also reliable for other cases.

Moreover, the MBE and the RMSE between the difference of the L3 setting and M1 setting are calculated. This comparison wants to point out that dynamic simulation programs are good tools to compare case studies made with the same simulation programs but are less suitable to reproduce absolute values of building energy performance.

The statistical parameters (Table 3) require reference values for cooling and heating to understand the relevance of the error. This is taken as the maximum of the monthly average day:
Maximum monthly average day for July: 35.14 W/m²
Maximum monthly average day for February: 18.97 W/m²

Table 3 MBE and RMSE of monthly cooling demand in a summer month and monthly heating demand in a winter month between EnergyPlus and Trnsys simulation results for two window settings and the difference between the results of the window settings.

Case	Month	Time-step num.	MBE	RMSE
			W/m²	W/m²
L3 cooling	July	705	-1.0	4.0
L3 heating	February	566	-1.5	3.6
M1 cooling	July	681	-0.9	3.3
M1 heating	February	589	-0.8	3.0
L3-M1 cooling	July	705	-0.2	1.1
L3-M1 heating	February	589	-0.7	1.3

Looking at the L3 window setting the maximum value for the MBE is in February (-1.5 W/m²) and comparing it with the reference for that month (18.97 W/m²) a deviation of 7.9% between the tools is calculated. The maximum value for the RMSE is in July (4.0 W/m²) and comparing it with the reference for that month (35.14 W/m²) a deviation between the tools of 11% is calculated. Decreasing the window area results in less solar transmission. For M1 window setting both the MBE and the RMSE decrease. This can suggest that the different solar transmission calculation approach is the reason of the difference between the simulations.

As for the case of the window surface convection, it is realistic to think that EnergyPlus provides better results with CFS than Trnsys because use the BSDF for the calculation.

Lastly, the smallest errors obtained from the comparison of L3 and M1 settings shows that Energy Plus as a dynamic simulation software is a right way for comparing different window setting.

3.7. Discussion

Concluding, the comparison of the daylighting programs, Radiance Three-Phase Method and Classic Radiance, and of the building energy programs, EnergyPlus and Trnsys, shows that Radiance Three-Phase Method and EnergyPlus are suitable tools.

Three-Phase Method reduces the time to daylighting simulations, without penalizing substantially the accuracy of the results.

EnergyPlus, due to its possibility to use BSDF in the calculation, has to be preferred than Trnsys. Although there is a discrepancy between EnergyPlus and Trnsys regarding the solar transmission, the overall influence on heating/cooling for this window sizes is rather small. However, the reasons for discrepancy needs further investigations. The MBE and RMSE evaluation gives positive outcomes for all the cases studied and confirms the positive results provided by the qualitative analysis of the graphs and the renderings.

Assuming that the simulation settings are now reliable, it is possible to continue with the evaluation of the different settings windows impact.

4. IMPACT OF WINDOW POSITION AND WINDOW SIZE ON ENERGY DEMAND

4.1. Introduction

In this section nine window patterns of a single office are compared, in order to understand how window size and number affect the energy demand and the daylighting. The application of a shading system is also investigated. The analysis presents three different study settings: The first one is a case without blinds, the second one has Venetian blinds installed on the windows at a fixed position at all times and the third one implements a control strategy in order to determine the position of the blinds, according to the solar radiation that hits the facade. This approach allows to understand in which cases the office offers better visual and thermal comfort while taking into account the energy saving.

The office studied is equipped with south facing windows. The window position is selected to favor the view out. Three settings concerning the window size and three settings concerning the window number are provided. It has been decided that all the windows are square and on this assumption the distribution of the glazing area on the facade changes if the window size is maintained constant but the window number is changing. The impact of the position of the glazed surface on the façade on the cooling and on the heating demand is small and it is more relevant for the daylight distribution and consequently for the artificial lighting demand.

This happens because the daylight penetration is more effective if the glazing surface covers the upper part of the wall. That comes from the fact that daylight penetration is around three times more effective when installing a roof aperture instead of a window on the lower part of a vertical wall. The reason is that the upper part of the sky is brighter therefore; the windows facing it spread a brighter light in the room and most of all on the work plane (Fontoynont et al.,1999). Lowering the windows from the roof to the vertical wall the advantage decreases, but of course a window on the higher part of the wall is still better than one on the lower part of it. Moreover higher windows allow that the sensor points see more sky in respect to lower windows and that is another advantage pointed out. However, it is common that the window position is selected in favor of the view out, undermining the daylight penetration.

Daylighting is also affected by the shading system. The venetian blinds described in section 3.3 are installed on the windows. Venetian blinds can, in general, have either a manual or an automatic control strategy.

A manual control depends strongly on the user behavior. In fact, studies show that the user changes the blind setting only when the visual discomfort causes him/her a stressing situation. That means that the user response is delayed in respect to the moment when the blind setting needs to be changed according to the sun position and weather condition. Moreover, if during the defined work time the employee is not in the office the blinds will remain under the wrong setting because nobody is inside to feel the discomfort and modify the position. For example, in winter, leaving the blinds down reduces the solar gain and causes a higher heating demand. On the other hand, in summer, when leaving the blinds up the solar radiation heats up the room and causes a higher cooling demand.

An automatic control overcomes the disadvantages of a manual control because blinds are positioned according to measured parameters. These parameters can be, for example, the vertical solar radiation that hits the façade, the glare calculation or the internal temperature.

The blind positions used in this study are three, two extreme settings and one intermediate. In the first case the blinds are absent, in the second one the blinds are down and the lamellas are fixed in a 45° angle. The angle is selected as a good opening degree to allow incoming daylight and at the same time to block the direct radiation. The third case uses an automatic control strategy based on the vertical solar radiation. When the solar radiation that hits the facade is higher than 150 W/m^2 the blinds go down. This level is chosen because it is a suitable one in order to favor the visual comfort. The lamellas angle is again 45°.

The investigated windows are categorized by their size into big (L), medium (M) and small (S). The medium windows correspond to 25% of the wall surface. This percentage represents a common size for office windows. The large windows correspond to 40% of the wall surface. Nowadays, the architectural tendency is to increase the size of the windows, because of aesthetic reasons. The small windows correspond to 10% of the wall surface. This glazing percentage is uncommonly small for the offices, so it is reserved for other parts of the building that are rarely visited. However, this configuration is taken into account because this study wants to investigate if there is some advantage in the use of small windows (Figure 3). The three different window size (10%, 25%, 40% of the wall) combined with the three amount of windows (one, two or three windows) provide the window settings examined.

The results of the daylight distribution and the energy demand under the different window settings are presented in different ways. The total daylight autonomy provides a single value that represents the daylight behavior for the entire year. The daylight autonomy calculates the percentage of good time-steps among all the time steps considered. The investigated period is between 8.00 and 18.00, which corresponds to the work time of a day, divided in 10 time-steps. A good time-step is defined as the one having at least half of the illuminance sensor points with at least 300 lux. According to this definition, in a good time-step, no artificial lighting is required. In addition to the total daylight autonomy, office depth dependent daylight autonomy is introduced. This algorithm is useful to understand the trend of the daylighting in the room when varying window settings. Each line of the sensor grid parallel to the window wall is treated separately. For each time-step of the working time the average of the illuminance values of a line is calculated and, if this reaches 300 lux, the time-step is considered as good. The percentage of good time-steps is the value plotted in a graph that relates the daylight autonomy to the depth of the room. There is a sensor point every five centimeters (the density of the grid points increases the accuracy of the evaluation).

Both systems used to evaluate the daylight distribution take as input a Three-Phase Method output file that provides, for the 8760 time-steps of the year, the illuminance values calculated in all the sensor points distributed in the room. To investigate the heating, cooling and lighting energy demand of the office, the results for the entire year are provided in kWh/m^2. These values come from the output file of Energy Plus.

4.2. Case without blinds

The analysis of the impact of the window size and number begins with the case without blinds. Going from big window settings to small window settings, the daylight autonomy (Table 4) decreases and at the same time the artificial lighting requirement increases (Table 5). These two behaviors are connected because, by decreasing the window area, less daylight enters the room. Therefore, less light reaches the illuminance sensor point which in turn gives the input to switch on the artificial light.

Looking at the results in detail, even though the percentage difference among the window areas is constant (from S to M the window area increases of 15% as from M to L.) the daylight autonomy and the lighting demand do not change linearly. In fact, the difference is smaller when shifting from an L setting to an M one than when shifting from an M setting to an S one. For the artificial lighting the trend is reversed. From an L setting to an M setting, the percentage increases per 26% and from an M setting to an S setting per 48%. This proves that a medium sized glazing area is still enough to reach, for more than half of the year, the illuminance sufficient for the visual comfort and to moderately increase the lighting demand.

Table 4 Daylight autonomy of the settings without blinds.

L1	69.4%	M1	56.2%	S1	13.6%
L2	69.9%	M2	56.8%	S1	13.8%
L3	68.7%	M3	55.0%	S3	9.9%

The graph of the depth-dependent daylight autonomy (Figure 31) shows that, for each window size, the daylight for the single window case penetrates the office deeper than for the three windows case. On the other hand, the three window case has higher daylight autonomy value near the window wall. The two window case is an intermediate one.

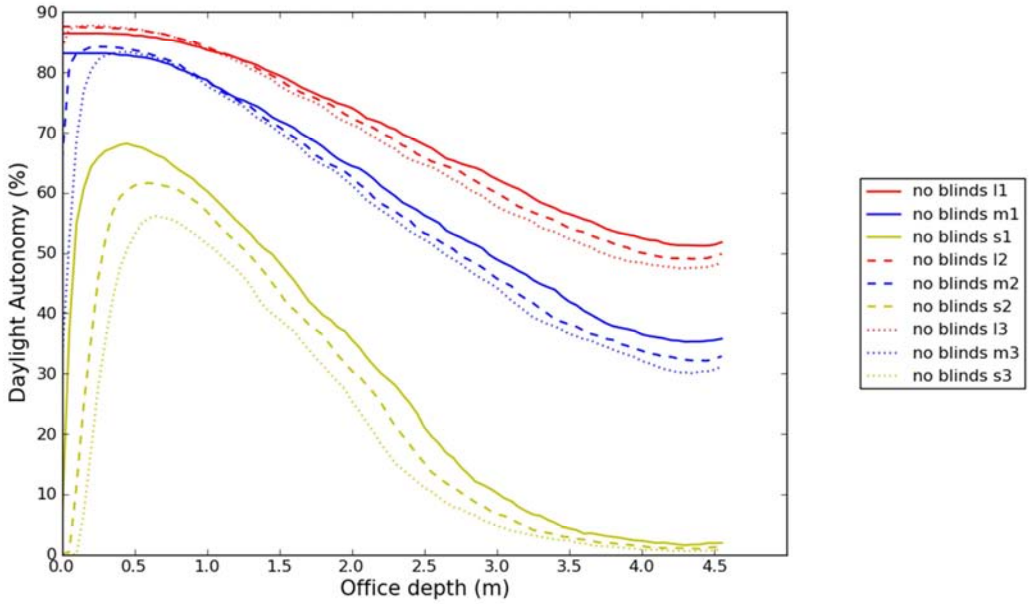

Figure 31 Daylight autonomy plot calculated for each line of the sensor grid of the settings without blinds.

The difference are relatively small, however, this behavior is explained by the fact that the window in L1, M1 and S1 settings is respectively higher than the windows in L3, M3 and S3 settings and it looks at the brighter part of the sky and the sensors see more sky. For that, the single window cases provide higher illuminance in the deeper part of the office (Figure 32). On the other hand, close to the window wall a three window setting offers an higher illuminance in the front part of the room because the glazing area is horizontally developed. However, at up to 3 m depth, the L settings and the M settings are always above the 50%, which means that there is enough sun light to fully illuminate the office. For the S settings the limit is the 1.5m depth.

Figure 32 Different height of the window in accordance with the number of windows.

Again the artificial lighting demand confirms the theory by increasing as going from one, two and three window setting, because when the daylight is brighter less artificial lighting is required.

In Table 5, the energy demand of the office relative to heating, cooling and artificial lighting is summarized. By decreasing the size of the glazing area, the heating and lighting need increases and cooling need decreases (Figure 33).

Table 5 Lighting, cooling and heating demand for the configuration without blinds.

	Lighting kWh/m²	Heating kWh/m²	Cooling kWh/m²
L1	8.47	40.34	7.86
L2	9.17	40.49	6.94
L3	9.70	40.86	6.16
M1	11.31	42.05	3.21
M2	12.64	42.15	2.77
M3	13.10	42.40	2.59
S1	21.84	42.77	1.52
S2	23.71	42.66	1.67
S3	25.27	42.74	1.95

The cooling demand could be affected from both artificial lighting heat gain and from solar gain due to the transmission through the windows. For cases without blinds the results show that the solar transmission affects more the cooling need than the artificial lighting. If it would have been the other way round, the cooling would have been incremented reducing the size.

Moreover, from L size to M size, the cooling demand decreases equally for the three amounts of windows (it decreases by around 60%) and the solar transmission affects the results in the same way. However, going from M to S size the results change with the number of windows. From M1 to S1 setting the cooling demand decreases by 53%, from M2 to S2 setting it decreases by 40%and from M3 to S3 setting it decreases by 25%. The heating demand is almost constant among the different amount of windows. The total energy demand is for all the L and M cases around 57 kWh/m² and around 68 kWh/m² for the S cases.

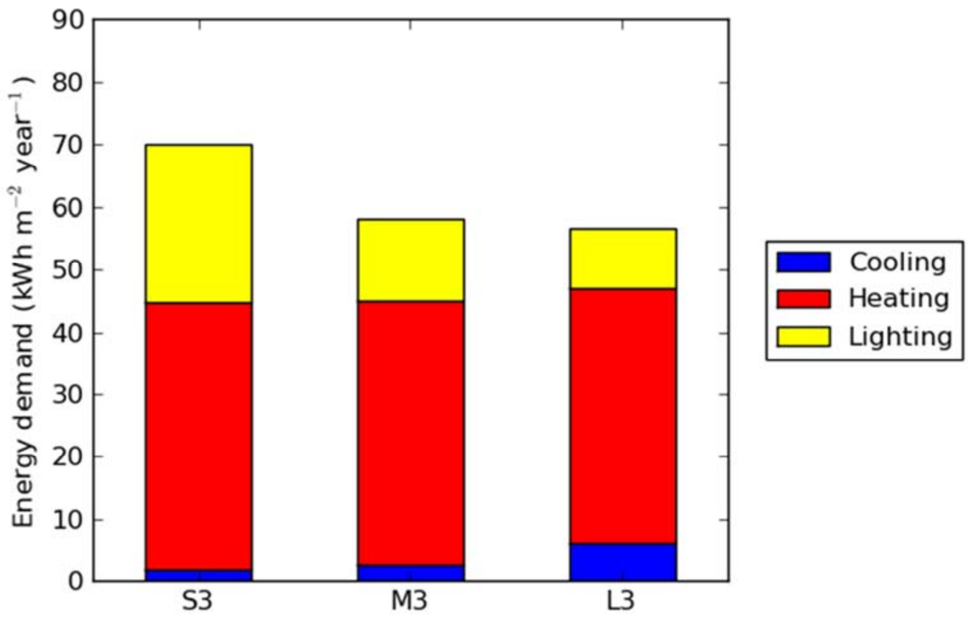

Figure 33 Total energy demand for the configuration without blinds.

4.3. Case with blinds

Looking at the cases where blinds are always present, the daylight autonomy shows that the visual comfort condition (daylight autonomy at least of 50%) is never reached with daylighting integration. In fact, with all the window settings the daylight autonomy never exceeds 50% (Table 6). Moreover, by looking at the graph of the daylight autonomy distribution (Figure 34), the highest values are slightly lower than 40% for the settings L2 and L3 and at a distance around 0.5m away from the windows. That means that it is not possible to use daylighting even in some part of the office.

On the other hand, the artificial lighting demand has high values for all the cases. Even for the big window settings with blinds, the lighting demand is at least 27 kWh/m² against 8.47 kWh/m² for the cases without blinds. The increasing trend of the artificial lighting requirement by decreasing the window area is the same than the case without blinds, and also the decreasing trend of the artificial lighting by increasing the number of windows is confirmed. However, the actual difference among the settings is smaller because the direct light is blocked by the lamellas.

Table 6 Daylight autonomy of the settings always with blinds.

L1	12.9%	M1	0.1%	S1	0.0%
L2	14.9%	M2	0.4%	S1	0.0%
L3	14.0%	M3	0.5%	S3	0.0%

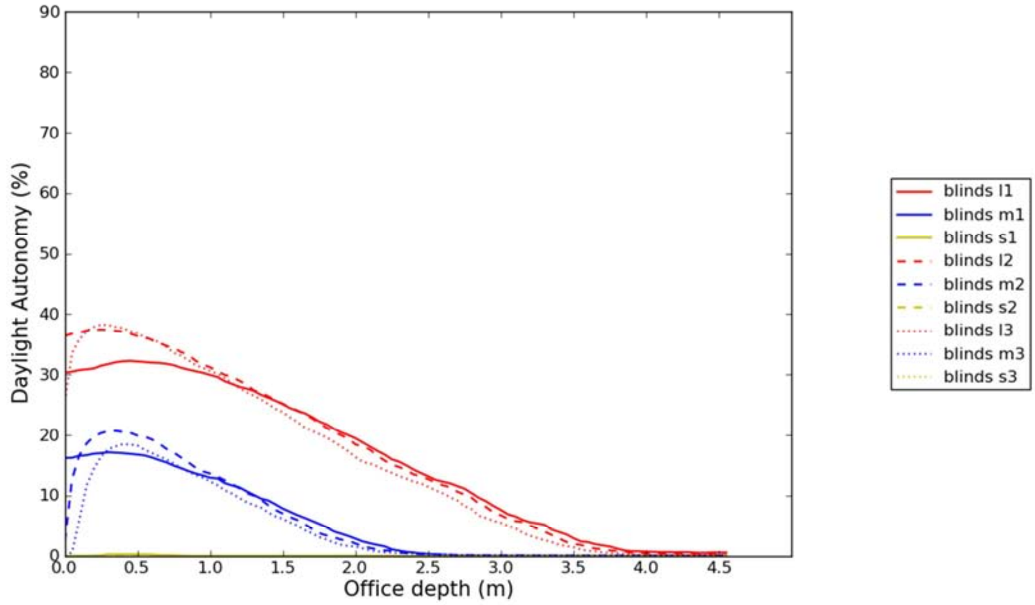

Figure 34 Daylight autonomy plot calculated for each line of the sensor grid of the settings without blinds.

The heating demand is not affected by the direct solar radiation and for this reason the heating demand trend depends only on the artificial lighting and the heat loss through the windows, and it is reversed for the cases without blinds. In fact, the heating demand has an inversely proportional behavior with respect to the artificial lighting and the heat loss; the heating decreases by decreasing the window area.

The cooling demand does not change significantly for any of the cases with blinds, it is always around 3 kWh/m². These constant values are a result of two facts: first, the absence of direct solar radiation uniforms the solar gain; second, the artificial lighting is most of the day switched on which further increases the internal gain. The small difference between the cooling demand for the different window settings makes the M setting unfavorable. That is because, the L settings allow more sunlight to enter the interior which leads to lower artificial lighting demand while the S setting allows a lower solar transmission heat exchanged through the window area, reducing the cooling need.

In general, the use of blinds for all the year requires around 80 kWh/m² of energy, which is around 10 kWh/m² more than for the S setting without blinds and around 20 kWh/m² more than the M and L cases without blinds (Figure 35). These results refer only to an office with one external wall. It means that they are also more relevant when the energy demand of an office building is calculated.

Table 7 Lighting, cooling and heating demand for the configuration with blinds.

	Lighting kWh/m²	Heating kWh/m²	Cooling kWh/m²
L1	27.52	48.32	2.63
L2	27.93	48.50	2.60
L3	29.05	48.28	2.72
M1	33.51	44.44	3.13
M2	34.51	44.25	3.20
M3	35.11	44.22	3.30
S1	36.52	41.19	2.82
S2	36.54	41.29	2.76
S3	36.54	41.37	2.73

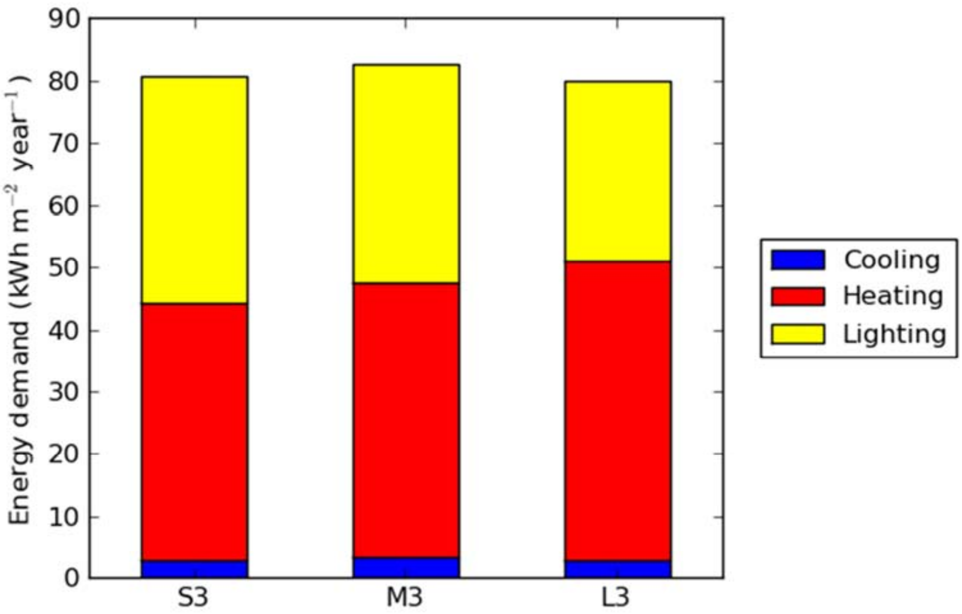

Figure 35 Total energy demand for the configuration with blinds.

Offices with their venetian blinds kept down during the whole day are a common phenomenon, even though this might mean that the artificial lighting is used at all times despite the advantages of daylighting (Figure 36). The numbers presented in this work prove that this behavior goes against energy saving.

Figure 36 Offices with blinds always kept down and artificial lighting switched on.

4.4. Case with controlled blinds

Due to the previous results a third case is studied. The installation of venetian blinds controlled based on the vertical solar radiation allows the use of daylighting when it is possible and decreases at the same time solar heat gains.

The daylighting analysis results show that, by using an automatic control system, there is an improvement over the case with fixed blinds. The daylight autonomy does not reach 50% for any of the cases but the daylight distribution shows that the big windows have over 50% daylight autonomy up to 2 m of depth from the window wall. According to these values, daylight integration is possible if the desks are positioned up to 2m away from the window wall. The medium sized windows provide daylight autonomy to only up to 1 m (Figure 37). This suggests that a suitable solution would be the installation of the artificial lighting with a partially switch-on system. In this way, when half of the room is illuminated by daylight, artificial lighting partially illuminates the half of the room away from the window wall.

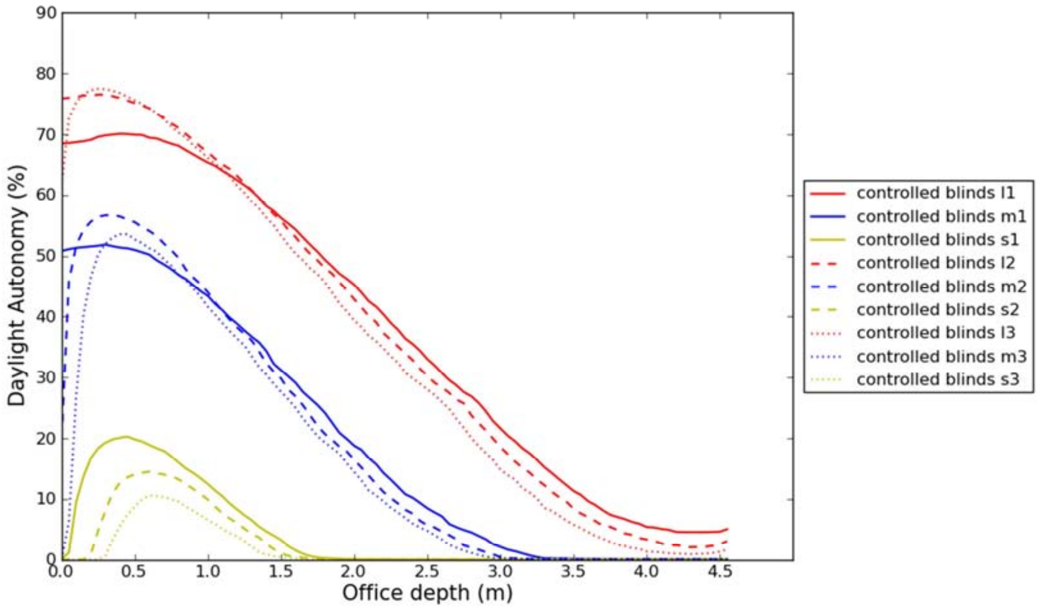

Figure 37 Daylight autonomy plot calculated for each line of the sensor grid of the settings with blinds automatically controlled.

Table 8 Daylight autonomy of the settings with blinds automatically controlled.

L1	33.0%	M1	7.4%	S1	0.0%
L2	35.3%	M2	8.2%	S1	0.0%
L3	33.2%	M3	6.3.%	S3	0.0%

The demand of artificial lighting increases when shifting from big window areas to small window ones and it decreases when shifting from the three windows to the single window case for the same reason. The heating demand decreases with the window area. That is because the artificial lighting contribution is preponderant to the solar transmission contribution. In these cases as in the cases with blinds in many hours the office lacks of the direct sun contribute. The cooling demand increases as the window size gets smaller for the same reasons.

Table 9 Lighting, cooling and heating demand for the configuration with blinds automatically controlled.

	Lighting kWh/m²	Heating kWh/m²	Cooling kWh/m²
L1	16.90	53.69	2.21
L2	18.27	55.21	1.86
L3	19.71	52.90	2.31
M1	26.00	47.85	2.58
M2	28.33	46.86	2.72
M3	29.31	46.63	2.77
S1	36.18	41.33	2.96
S2	36.50	41.33	2.91
S3	36.47	41.48	2.86

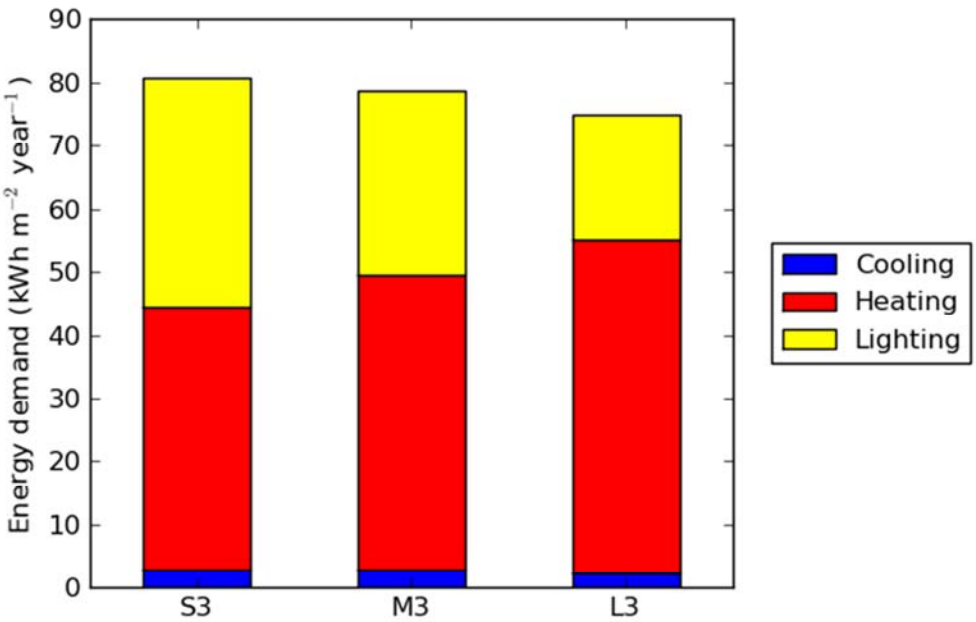

Figure 38 Total energy demand for the configuration with blind automatically controlled.

Comparing all the results, it is evident that the daylight autonomy is significantly lower in the cases where blinds are installed, from 69% without blinds to 33% with blinds for the L settings and from the 56% to the 8% for the M settings. The demand for artificial lighting varies less for the cases with blinds, from 27 kWh/m² for the M cases with blind control to 34 kWh/m² for the M cases with fixed blinds, and 36 kWh/m² for both the S cases with blinds fixed and under automatic control. This means that the control adjusts the blinds often enough to prevent the employee from direct solar radiation above the 150 W/m² and consequently the visual discomfort caused by glare. However, a more energy efficient controller could be investigated by specifically focusing on the heating, on the daylight penetration and consequently on the lighting demand.

In fact, looking at the cooling demand, it decreases for the L window settings going from the cases without blinds to the cases with blinds and to the cases with the control. In the case with no blinds installed, the solar transmission affects predominantly the cooling demand results, in the case where the installed blinds are in a fixed position at all times, the lighting demand affects it instead. By including blind control the solution is optimized and the cooling results are minimized. For the M settings, the cases with blind control result into the minimum cooling demand. This behavior is different for the S settings since, when blind control is applied, exhibit the highest cooling demand. That happens because a small glazing area always needs the artificial lighting also when the blinds are up and it increases the cooling demand in respect to the other blinds configuration. At the same time the cooling has to remove the heat gain due to the direct solar radiation. The two factors that affects the cooling demand occurs together increasing the value.

In the case of the heating demand, as mentioned above, the values with the control are the highest of the three cases. Though the control avoids glare discomfort and decreases the cooling demand, it also significantly increases the heating demand especially for the L settings (heating demand without blinds 40 kWh/m^2, with blinds 48 kWh/m^2 and with control around 53 kWh/m^2). A control that decreases the heating is recommended.

Apart from the cases simulated so far, there is one last case left to consider, the manual control managed by the employee. There are two possible scenarios. On the one hand, the employee can decide to keep the blinds closed at all times and switch on the artificial light, where the case falls under the simulations with fixed blinds as specified above. On the other hand, the employee changes the blinds position depending on her/his needs, when she/he feels discomfort. This second option cannot be simulated because it is changeable from person to person. However in this study case it is assessed as an intermediate case between the without blinds case and the blind control case. The assumption is made thinking that employees have a delay reaction compared to the automatic control and they leave the blinds up more.

The results of these scenarios are the lower heating and lighting demand compared with the automatic control but on the other hand, the cooling demand increases. Under these conditions the employee is more exposed to direct radiation and to visual discomfort.

The first scenario described, with blinds down and artificial lighting on at all times, should be avoided because it is against both energy saving and visual comfort. The second scenario does not cause completely adverse effects. However, the increase in the cooling demand, the visual discomfort and the inconvenient that the employee has to deal with the control should encourage the use of automatic control.

4.5. Discussion

The daylighting distribution and the energy demand divided in heating, cooling and lighting demand for the different options of blind position have been analyzed. The analysis shows that there are significant differences on heating, cooling and lighting demand between the cases with blinds and the cases without comparing the same window settings. This come from the fact that there are different aspects that affect the energy need and their combination gives different outcomes. These aspects can be the solar transmission and the heat loss through the windows and the daylighting penetration (Figure 40). The case with the control has intermediate results for daylighting integration and artificial lighting need, in respect to the other two shading device options. For the cooling and the heating need its position change and it can be the both the most convenient case and the lowest.

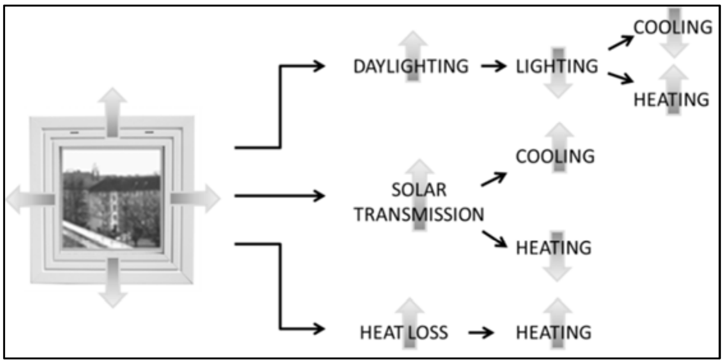

Figure 39 How daylighting, solar transmission and heat loss affect the energy demand, increasing the window area.

In the light of this it is difficult to determine the best window size and number to save energy because the answer changes in accordance to the blinds strategy applied. Moreover, if on the one hand the window size and number are fixed during the built of a building, on the other hand the shading devices used and the control provided can be easily replaced over time, obtaining a variation of the energy demand.

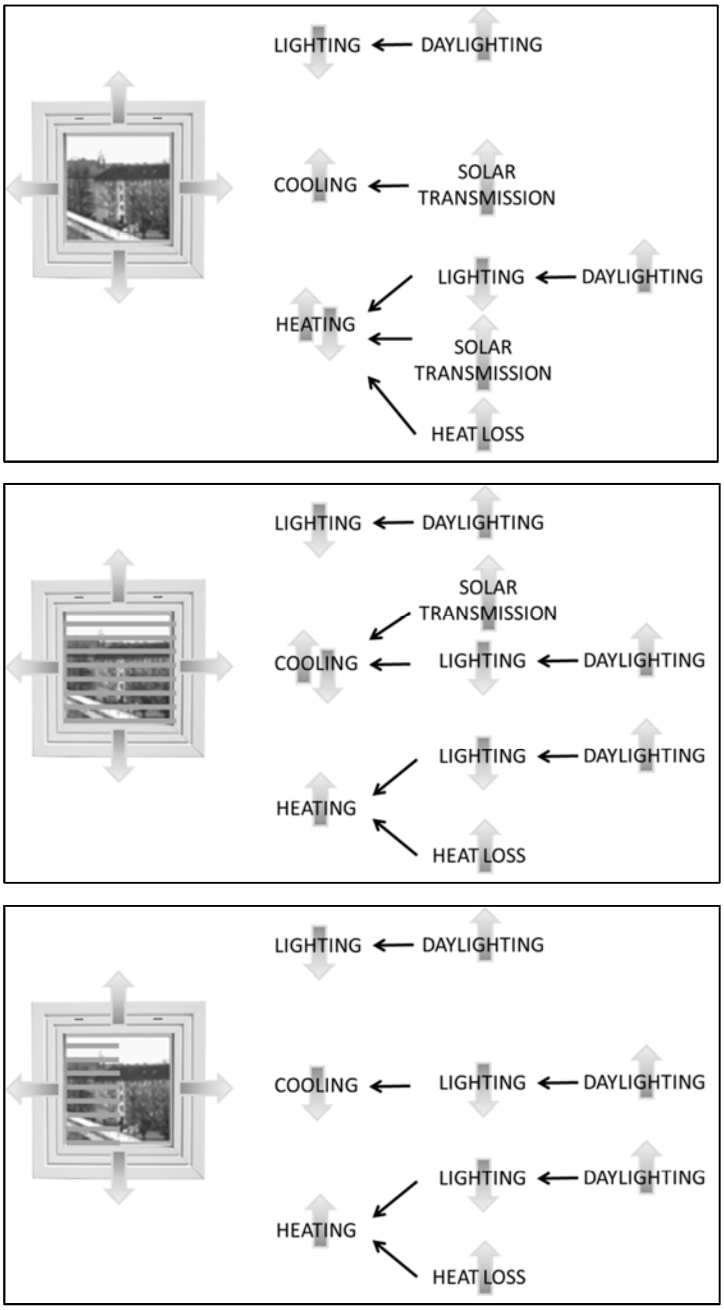

Figure 40 Heating, cooling and lighting behavior increasing the window area for the cases without blinds (a), the cases with blinds (b) and the cases with automatically controlled blinds (c). The daylighting, the solar transmission and the heat loss though the window the results.

To support this idea the comparison of the cases studied in the thesis is summarized to show how the aspects that come from the weather conditions, the shading device positions and the size of the window affect the energy demand.

The results of the simulations show that the energy demand for the without blinds options and the automatically controlled blinds options decreases, increasing the window area. Otherwise for the options always with blinds the energy demand is considerable constant. Looking at the daylight penetration, it increases for all the options increasing the size of the glazing surface. Consequently the lighting demand decreases always shifting from S to L size.

If the office has not Venetian blinds, increasing the window size, the cooling demand increases because it is more affected by the solar transmission than the by the artificial lighting. Also the heating demand is more affected by the solar transmission than by the heat loss though the windows that is why it decreases increasing the glazing area.

If the office has always the venetian blinds down, the solar transmission affects more the big windows and the artificial lighting affects more the small windows and the result is that the cooling is almost constant. On the other hand the heating increases with the glazing area, because the heat loss though the windows has a preponderant effect.

Comparing the results between the blinds position the daylighting increases shifting from a without blinds case, to a case always with blinds. The artificial lighting consequently has the opposite behavior. For a window area between the 25% and the 40% of the wall the lighting demand saved is of around 20kWh/m^2.

Looking at the window number in this work, it represents the glazing area distribution in respect to the wall. There is not a relevant difference on the energy demand changing the distribution of window area. The small difference can come from the fact that increasing the window number it increases the reveal relative to the same window area. The solar transmitted through the window is affected by the reveal width that reduces the transmission. In order to save energy the number of window does not affect the results because the energy demand depends on the heat loss or the solar transmission that pass through the glazing surface that is constant. However the distribution of the glazing surface is important for the daylight penetration and the employee well-being at the work place.

5. CONCLUSIONS

Different types of windows affect the view to the outside, the daylighting penetration and the energy demand. The thesis investigated the impact of different window settings in a single office space.

The view out is related with the well-being of the employees. It avoids the alienation at the work place because it allows the contact with the outside world. The view out favors the circadian rhythm of the person. That is why a user assessment on the quantity of view out has been carried out to determinate which window setting satisfies most the employees. The quantity of the view out is a recent research topic; the test here conducted has been the pilot test among the seven that compose the research project inside the Fraunhofer-ISE. The items here evaluated are the size and the amount of windows and the cases compared are nine. The data collected have been evaluated as significant. This means that the test procedure and the questionnaire are valid for the scope and the other tests can start.

Looking at the results of the single rating evaluation employees prefer big windows than small ones. Then, they prefer the three window settings than the one or two window settings. Summing up the outcomes three big window setting is the one that satisfies most the probands. Checking the paired comparison results the three big window setting has been confirmed as the favorite. The answers about the preference in terms of height of widow say that people prefer higher windows than the L3 setting. A suggestion can be to change the shape of the windows from square to rectangular and to install higher windows, lowering slightly the width in order to maintain fixed the size.

Before starting to define the energy demand and the daylighting through simulations, the accuracy of the daylighting tool, Radiance-based Three-Phase Method has been validated. It has been compared with Classic Radiance that is the reference for the lighting simulation. They use two different approaches to calculate the daylighting penetration in a room. The advantage of the Three-Phase Method is that it takes much less time to simulate a time step and this makes it suitable for annual simulations.

The comparison of the tools shows that the error committed by using the Three-Phase Method is relatively small and most of all it is inside the limit fixed during the comparison of Daysim and Classic Radiance. Daysim is the state of the art of daylighting annual simulation. However, an idea to improve the accuracy of the Three-Phase Method has been identified. An underestimation of the illuminance has been pointed out from the analysis. The suggestion is to increase the resolution of the patches to decrease the error.

Looking the rendering of the illuminance distribution on the work-plane, a certain inhomogeneity on the illuminance distribution has been highlighted for adjacent points of the Three-Phase Method. That is way it is suggested to change in the simulation the control to turn on the artificial lighting. Instead of using a single point on the sensor grid, the average of a small area should be preferred.

Then, the daylighting and energy building analysis have been carried out, by using the Three-Phase Method and Energy Plus coupled. The window settings simulated are nine and the simulation options are three, for a total of 27 simulations. The window settings are the same of the user assessment and the simulation options regard the shading device position.

The results show that, irrespective of the shading device position, the daylighting penetration in the office increases, increasing the window area. A consequence of this is that the artificial lighting demand decreases increasing the window area. It means that the starting point for daylighting integration is the use of big windows. For what concerns the heating and the cooling demand, increasing the window area they have not a constant behavior changing the shading device position as the artificial lighting has. In fact, the heating and the cooling demand are affected by different factors and their results depend on the more preponderant. These factors are the solar transmission and the heat loss through the windows and the artificial lighting as internal gain. Consequently the impact of window size changes by changing the shading device.

Fixed the window size, the number of windows affects in small part the energy demand. The influent factors are the daylight penetration that changes with the different distribution of the glazing surface and the solar transmission has a different behavior because of the interference of the reveal that increase with the number of windows.

As said the venetian blinds mounted have three different positions. If the blinds are up all the year the total energy demand is the lowest. However, the visual comfort cannot be guaranty because of the glare discomfort on the VDU. If the blinds are all the year down the daylighting integration cannot be optimized and the energy demand is the highest for all the sizes of window. Moreover the employees cannot have a contact with the outside world, important for the well-being and their productivity. If the blinds position is controlled by the vertical solar radiation on the façade the energy demand and the daylight penetration have intermediate results. It is the option that optimized the opposite requests: the daylighting integration and the energy saving.

However, the results show that the control closes often the blinds and the artificial lighting is often switched on. The reason is that the lamellae of the blinds in the simulation have been fixed with an angle of 45° degree, even if in the truth they can change angle of incidence, reducing the use of artificial lighting. It is suggested to improve the simulations with the automatically controlled blinds. A way can be to increase the incidence angles of the blinds available. The advantage is that more BSDF data are needed one for each angle.

Concluding big windows are preferred by employee, they favor the daylighting integration and they save energy better than small windows. The amount of windows affects the employee preference and the daylighting integration but they do not change significantly the energy demand.

Moreover, also the shading strategy has a relevant impact on the daylighting and on the energy demand. In the light of this it is important to develop energy building simulation tools that provide accurate daylighting simulation for CFS and that simulate shading device control strategy in detail. For this purpose Fraunhofer ISE is developing the simulation tool Fener (Bueno et al., 2014).

6. APPENDIX 1: CLASSIC RADIANCE COMMANDS

To validate the results obtained with the Radiance-based Three-Phase Method, Classic Radiance is chosen because it is a tool extensively validated, both the tools lacks of an user-friendly interface. The Three-Phase Method provides a tutorial and following it the simulations here conducted have been executed. Classic Radiance, on the other hand, allows more freedom during the simulation setting. For this reason the commands, that have been used to execute the simulations, are described below.

To generate the virtual environment three elements are required, a geometry file, a material file and a light source file. For what concerns the first two, they are not built manually for each case, but rather they are taken directly among the outputs of the script that couples the Three Phase Method and EnergyPlus. Webport.rad is for the geometry and webport.mat describes the materials. In fact, reading the input of the config.dat with the size of the office and the characteristic of walls and windows materials, the script creates automatically radiance format files to utilize executing the Three-Phase Method. The format of these files is the same as that for classic Radiance.

The third file includes the light source and in this specific circumstance it is a daylight source. The source is reproduced by using Gendaylit, one of the tools of Radiance. Gendaylit produces a Radiance scene description based on an angular distribution of the daylight sources (direct+diffuse) for the given atmospheric conditions (direct and diffuse component of the solar radiation), date and local standard time using Perez models. The default outputs are the radiance of the sun (direct) and the sky (diffuse) integrated over the visible spectral range (380-780 nm) (McNeil, 2013b).

The command in the specific is the following, considering the 23 of July at 12 a.m. in Frankfurt (8.68° E and 50.10° N) with a direct-normal-irradiance of 938 W/m² and a diffuse-horizontal-irradiance of 96 W/m².

```
gendaylit 7 23 12 -a 50.10 -o -8.68 -m -15 -W 938 96 > sky_frankfurt_7_23_12.rad
```

where –a indicates the latitude (+ for north), -o the longitude (- for east) and –m the site standard meridian to calculate the solar time (- for east).

When the three files are available the scene needs to be compiled in an octree, and in this way they are gathered together. The propose of an octree is to speed up the calculation by only considering the objects that lay within the path of the ray. The command to use is oconv (Jacobs, 2012). To execute oconv the name of the file with the light source, the name of the file with the materials and the name with the file with the geometry are specified.

oconv -f sky_frankfurt_7_23_12.rad outside.rad webport_simple_U148_roos.mat webport_simple_U148.rad > scene_frankfurt_7_23_12_l3win.oct

where -f is an option that produces a frozen octree containing all the scene information.

Rtrace traces rays from the standard input through the RADIANCE scene given by octree and sends the results to the standard output. Input for each ray is xorg, yorg, zorg, xdir, ydir, zdir that state the positions and the directions of the rays. The input file is a file made again by the script, that determinates the positions and the directions of 6624 illuminance sensors. The grid of sensors is created by the config.dat and it is called photocells_6000.pts. To calculate the illuminance instead of the irradiance the command rcalc is used with the formula: '$1=47.4*$1+120*$2+11.6*$3'

cat photocells_6000.pts |rtrace -h -I -n 20 -ab 5 -ad 16000 -ar 256 -as 8000 -aa 0.1 scene_frankfurt_7_23_12_l3win.oct | rcalc -e '$1=47.4*$1+120*$2+11.6*$3' > illum_frankfurt_7_23_12_l3win_6000_roos.dat

where:

-I Boolean switch to compute irradiance rather than radiance, with the input origin and direction interpreted instead as measurement point and orientation.

-n number of processes execute in parallel

-ab This is the maximum number of diffuse bounces computed by the indirect calculation. A value of zero implies no indirect calculation.

-ar This number will determine the maximum density of ambient values used in interpolation.

-aa This value will approximately equal the error from indirect illuminance interpolation. A value of zero implies no interpolation.
-as N Set the number of ambient super-samples to N. Super-samples are applied only to the ambient divisions which show a significant change.

Through these three steps a grid of illuminance values is calculated.

Furthermore to have a rendering of the results rshow is used. The tool shows how the scene looks and it has also the possibility to read a file with a grid for points to see the distribution of the parameter chosen with a false color picture. To visualize the illuminance distribution picture a file compatible with rshow requests is created with the programming language awk. The command written below displays that rshow asks a file with six columns, the first three taken from the sensors file say the exact position of each point inside the room and the second three, taken from the illuminance results file, attribute the right color for each point, according to the illuminance scale indicated.

paste photocells_6000.pts illum_frankfurt_7_23_12_l3win_6000_roos.dat |awk '{print $1,$2,$3,$7,$7,$7}' > illufile_rshow_23_7_12_l3_6000_radiance_roos.dat

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