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Energy saving through the sun: Analysis of visual comfort and energy consumption in office space

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Abstract

Energy demands for heating, cooling and lighting can be dramatically prejudiced by the façade configuration, solar exposition and typology of openings trying to maximize use of natural light. Office buildings are often field of experimentation of materials and innovative components, by the way a consolidated design market promotes façade layouts strongly transparent introducing a primary need to shading and protection of the users privacy. Building Automation Systems (BAS) can reduce users' intervention on indoor condition control; on the other hand users want to be capable to fix conditions in their working space avoiding problems of visual discomfort, specifically disturbing and intolerable levels of glare. Systems to evaluate visual comfort parameters to improve consciousness in use of daylighting are fundamental in design to realize a façade which permits real energy saving during operation time.
The present study aims to analyze a single office space with three different configuration of the openings located in different orientation and position (south exposed window, north exposed window and skylight). The three cases study are evaluated on optimization of natural lighting, visual comfort, electricity consumption and heating and cooling demand and consumption. To perform these kind of calculation with the correct level of detail is crucial to make use of a appropriate tools which can estimate the value of the different parameters to assess energy and visual quality of the indoor space. It is not possible to use just one tool to collect all the information required to optimize a building in order to obtain a NZEB level of consumption. The high standards required by the new regulations need a full-range analysis and a specific knowledge of all the parameters involved. In this study are used six software for the simulation of the all needed parameters (Ecotect, Radiance, Evalglare, Daysim, Dialux, Open Studio).

Keywords: Solar heating and air-conditioning of buildings; energy performance; daylighting and glare

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1. Introduction

In Italy the consumption for electricity and primary energy for heating office buildings in different climate zones was identified by energy audits [1, 2]. The heating consumption is about 80 kWh/m^2 year. In Northern Italy the 72% of the office buildings has average specific fuel consumption about 95 kWh/m^{2}year. The average value for most of these buildings located in cold climate European areas is 100 kWh/m^2 year [3]. Energy saving can be achieved, as first by controlling the environmental energy input on the building envelope.

An average value of energy consumption for electrical equipments is about 40 kWh/m^2 year, including lighting, for standard office buildings, while 20 kWh/m^2 year is conceivable for efficient buildings, and a value of about 7 kWh/m^2 year for Net Zero Energy Buildings (NZEBs) [4].

Daylighting can strongly reduce the electric demand for artificial lighting but the use of large transparent surfaces on south/west orientation might increase the cooling energy consumption. Moreover, due to visual discomfort, the real building use might change for the user intervention. This provides discrepancies between real energy consumption and the simulation results performed during the design phase. To reach the target promoted by the EPBD directive [5] of “Nearly” Zero energy buildings for new constructions in 2018 for public buildings and in 2020 for private buildings, it is fundamental to assess the whole energy demand for the building, for air conditioning and also for electrical uses and to prevent the discomfort phenomena which can change the assumed building use.

Today, dynamic simulation of Daylight Glare Probability (DGP) can be performed by Radiance and Daysim software using enhanced simplified DGP calculation [6]. It is possible to evaluate all daylight factors to decrease energy dependency of artificial lighting in order to reduce electrical consumption. Dynamic simulation is furthermore important to verify energy performance in summer period. While in temperate climates can be performed a realistic estimation of energy performance in winter under static conditions, in summer period it is necessary to calculate the energy demand considering the variations of the parameters step by step on a hourly basis.

2. Methodology

The present work aims to analyze three different office configurations that guarantee an adequate level of visual comfort by daylighting and a reduction of energy consumption for electricity, heating and cooling loads.

The analysis is performed in four steps:

- visual comfort parameters calculation and daylighting assessment;
- identification of electrical consumption integrating daylighting;
- calculation of heating and cooling demands;
- estimation of electrical consumption considering a possible thermal system for the office space.

The tools used for the analysis are listed below and the simulation approach is shown in Fig. 1. The visual comfort parameters [7] are evaluated by modelling the office space in the software Ecotect [8] used as interface to lunch the simulation in Radiance [9], Evalglare [10] and Daysim [11]. The first software allows calculating the luminance values, the illuminance values and the daylight factor. The second one gives the data about Daylight Glare Probability (DGP), Daylight Glare Index (DGI) [12] and Unified Glare Rating (UGR) [13]. The Daysim software is used to simulate the Daylighting Autonomy (DA) and Useful Daylighting Index (UDI). Daysim allows visualizing maps of daylight autonomy and distribution of the areas in the office where it is possible to exploit daylighting at established levels.

The energy consumption (electric and thermal) is evaluated as follows. To calculate the annual electric demand for lighting the software Dialux [14] is used. The software estimates the electricity used to guarantee a standard level of illuminance in the office space considering daylighting and artificial lighting contribution. The thermal energy consumption is assessed by dynamic calculations performed by OpenStudio BEST, a Plug-in of Sketch-up running EnergyPlus 7.0 [15, 16, 17]. The climatic hourly data used for simulation is a typical meteorological year (TMY) for the reference location. The data of energy demand were implemented to energy consumption in the hypothesis of a water source heat pump (WSHP) supplying energy to the office space.

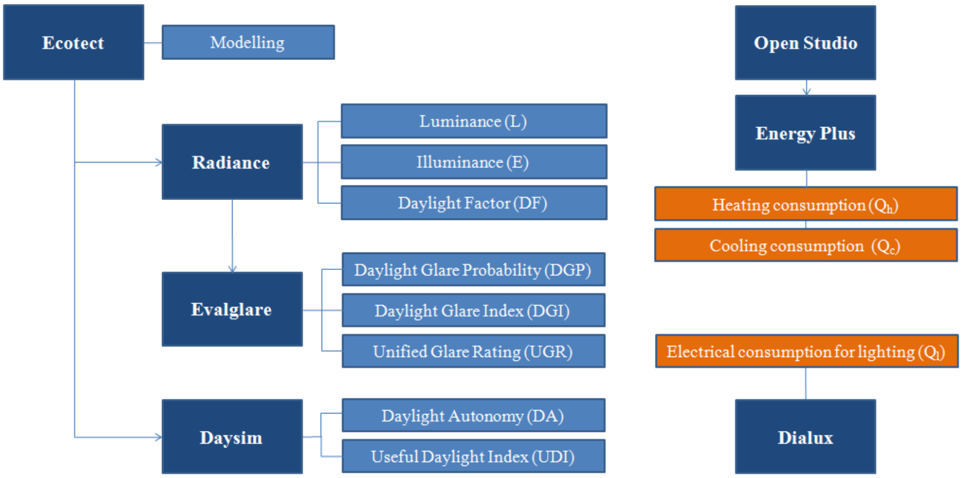


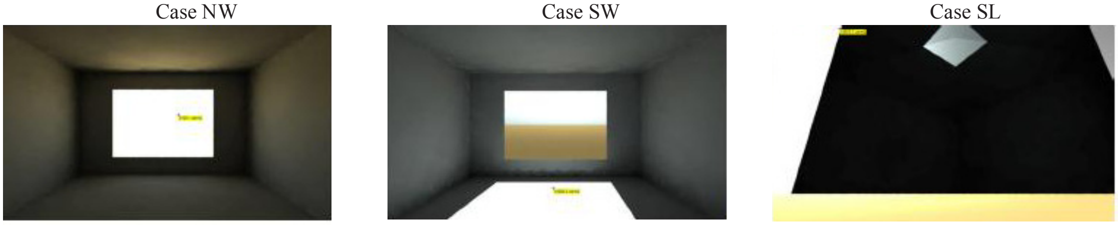
Fig.1. Simulation approach adopted in the study: parameters calculated and tools used for the analysis

The calculations are performed for a single office unit, which can be occupied by two or three people. The configurations for the single office space considered are: by a south oriented window (Case SW), by a north oriented window (Case NW) and by skylight (Case SL), as shown in Fig. 2. Note that for the complex structure of the analysis three models in the simulation software Ecotect, Open Studio and Dialux were needed. The problem of interoperability [18] between different software is not so simply to overtake and the study had to be supported by a complex of tools.

3. Simulation model and boundary conditions

The analyses have been run over a sample sidelit office space of (5x5x3) m^3 located in Milan, Italy (latitude 45.4°N – longitude 9.3°E). The transparent windows (6 m^2 for Case SW and NW and almost 2 m^2 for Case SL) have a double glazing characterized by a direct normal visual transmittance (τ_v) of 64% and a solar heat gain coefficient (SHGC) of 75%. The ceiling, walls and floor have a value of reflectance coefficient of 90%, 90% and 75% respectively. For the analyses, a target illuminance level on the work plane (height 0.85 m) of 500 lux is considered. The space is assumed as occupied on weekdays from 8 a.m. to 8 p.m.

For the thermal simulation it was assumed that the office space is surrounded on five sides by similar spaces. Thus, these five surfaces were modeled as adiabatic surfaces. In all the cases, the glazed surface has a thermal transmittance (U-value) of 2.2 W/m^2K and the exterior surface including the window has a value of 0.34 W/m^{2}K. The space is conditioned with fan coil units powered by a water source heat pump both for heating and cooling (Section 5).


Case NW

Case SW

Case SL

Fig. 2. Renders of the interior spaces for the three cases analyzed

4. Visual comfort analysis

The visual comfort analyses have been conducted during the solar analysis characteristics days, i.e. the spring equinox (March 21st), the summer and winter solstices (June 21st, December 21st). The parameters evaluated are listed in Table 1.

Table 1. Visual comfort parameters analyzed

Parameter	Symbol	Unit	Definition
Luminance	L	(cd/m^2)	Luminance [19, 20] is the luminous intensity per unit area of light traveling in a given direction.
Illuminance	E	(lux)	Illuminance [20] in a point of a surface is the ratio between the luminous flux incident on an infinitely small element of the surface that includes the point and the area of that element.
Daylight Factor	DF	(%)	Daylight factor [20, 21] is defined as the ratio between the indoor illuminance and the outdoor illuminance on a horizontal surface that sees the entire sky without obstructions; direct sunlight is excluded from both measures.
Daylight Glare Probability	DGP	(%)	Daylight glare probability [13] is based on the probability that a subject feels a disturbing glare sensation, instead on the measure or the quantification of a phenomenon. This probability is strictly related to vertical illuminance in correspondence to the observant eye.
Daylight Glare Index	DGI	(-)	Daylight Glare Index [13] is based on earlier work for luminaire-sources glare and considers large glare sources: the sky viewed through the window.
Unified Glare Rating	UGR	(-)	The Unified Glare Rating [13] is a simplification of CIE Glare Index CGI now preferred by the CIE [22].

4.1. Luminance, Illuminance and Daylight Factor simulated by Radiance

The three cases have been analyzed with Radiance to extract the levels of luminance (as false color scale), illuminance (as isolux lines) and daylight factors (as isolines). Note that the analysis of luminance and illuminance are performed during a sunny day while the daylight factor assumes only the contribution of diffuse radiation [6]. Fig. 3 shows, as example, the calculation for the equinox at 12 p.m.

As shown in Fig. 3, the most critical situation for the visual discomfort is Case SW, which has the maximum values of luminance and illuminance in the working area (more than 4000 lux, daylight factor higher than 25%). In the other two cases, a correct level of daylighting or a slightly higher values are estimated due to window dimensions (600 lux and 1000 lux very near the north window).

The analyses of these parameters, usually performed, are not enough to verify the glare problem [22]. For that reason it has been introduced the specific analysis of glare, calculating the DGP, DGI, UGR by Evalglare software. The software can elaborate fisheye images realized by Radiance running as independent tool or by other software such as Rhino/Diva [23]. In this study it is used as independent tool to calculate the parameters defined in section 4.2 by hourly step by step analysis.

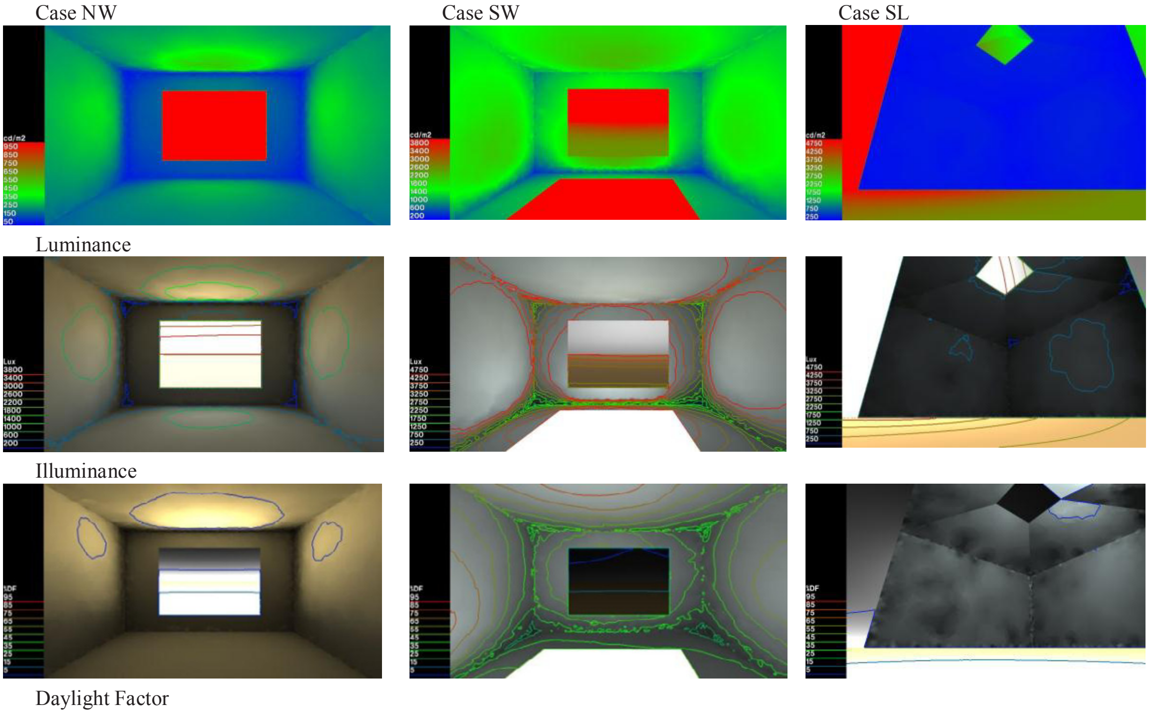
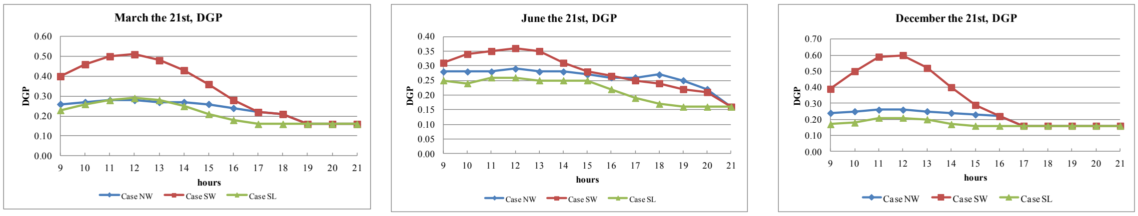


Fig. 3. Radiance simulation results: luminance, illuminance and daylight factor for March 21st

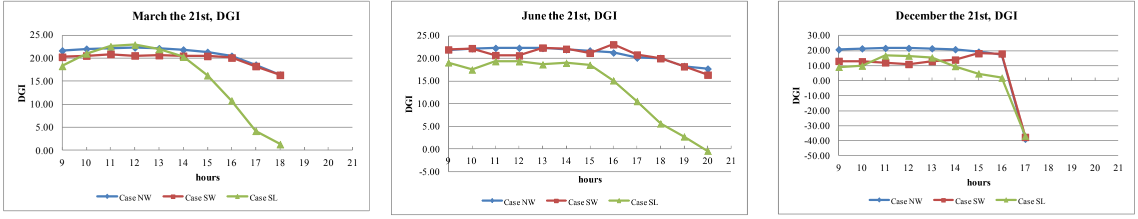
4.2. Daylight Glare Probability, Daylight Glare Index, Unified Glare Rating simulated by Evalglare

In order to evaluate the glare conditions on the working space, an analysis with Evalglare software during the three calculation days was performed. Solstices and equinox situations are reported in Fig. 4. The value of DGP which causes intolerable glare is higher than 45, for DGI is higher than 31 and for UGR is higher than 28 [22]. Is it possible to note that in March and December for the Case SW are registered values of DGP reaching 40 and 60 with critical glare effects. The DGI parameter shows for all the three situations values just below the threshold of the disturbing glare. The UGR values are in all the cases under the intolerable threshold level. In some cases disturbing glare can occur.

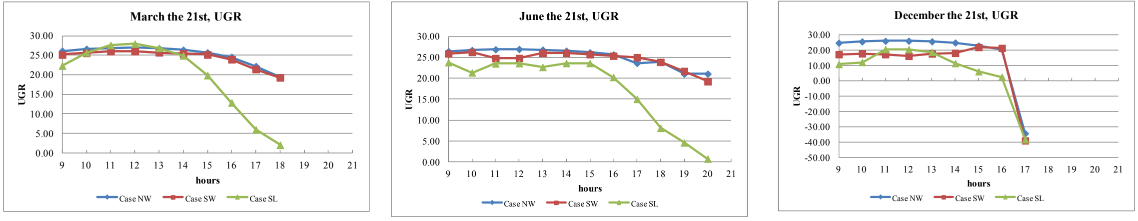
March 21st June 21st December 21st



Daylight Glare Probability (DGP)



Daylight Glare Index (DGI)



Unified Glare Rating (UGR)

Fig. 4. Evalglare simulation results: DGP, DGI and UGR, for 21st of March, June and December

4.3. Daylight Autonomy, Useful Daylight Index simulated by Daysim

The Ecotect models are exported into Daysim with the features set in Radiance. In this way it is possible to import a monitoring grid with Daylight Autonomy (DA) and Useful Daylight Index (UDI) values which can be re-imported in Ecotect software to display maps. These two parameters allow understanding the possibility to use daylighting to reduce artificial lighting complying illuminance levels. The characteristics of the parameters are listed in Table 2. The rendering parameters imported by Radiance in Daysim are listed in Table 3.

Table 2. Daylight use parameters analyzed

Parameter	Symbol	Unit	Definition
Daylight Autonomy	DA	(%)	Daylight Autonomy consists of an annual analysis to determine the fraction of the occupied time when daylight levels exceed a specified target illuminance [24].
Useful Daylight Index $UDI_{<100}$ $UDI_{100\text{-}2000}$ $UDI_{>2000}$	UDI	(%)	Useful Dayilght Index is a dynamic daylight performance measure that is also based on work plane illuminances [25]. It considers realistic sky conditions and variables in the time and defines on hour basis, absolute values of daylight illuminance. It aims to determine when daylight levels are useful for the occupant, i.e. neither too dark (<100 lux) nor too bright (>2000 lux). The upper threshold is meant to detect times when an oversupply of daylight might lead to visual discomfort. Based on the upper and lower threshold of 2000 and 100 lux, UDI results in three metrics, i.e. the percentage of the occupied times of the year when the UDI was achieved (100-2000 lux), was exceeded (>2000 lux) or fell-short (<100 lux).

Table 3. Simulation parameters for Daysim analysis

Ambient bounces	Ambient divisions	Ambient super-samples	Ambient resolution	Ambient accuracy	Limit reflection	Direct jitter
5	1000	20	300	0.1	6	0

The simulation for the office spaces assumes the daylight savings time from April 1st to October 31st. The zone is occupied from Monday to Friday from 8 a.m. to 8 p.m. with three breaks during the day (30 minutes in the morning, 1 hour at midday, and 30 minutes in the afternoon). The resulting annual occupancy hours are 1569. The minimum illuminance required for an office space is 500 lux. The office is considered without dynamic shading device system installed. The results of the hourly dynamic analysis performed by Daysim are shown in Table 4 and in Fig. 5 are reported, as example, the UDI maps.

Table 4. Results of simulation with Daysim

	Daylight Autonomy (DA) (%)	Useful Daylight Index (UDI) (%)		
		UDI<100	UDI 100-2000	UDI>2000
Case NW	73-93	8	14	78
Case SW	76-93	8	11	81
Case SL	42-67	17	50	33

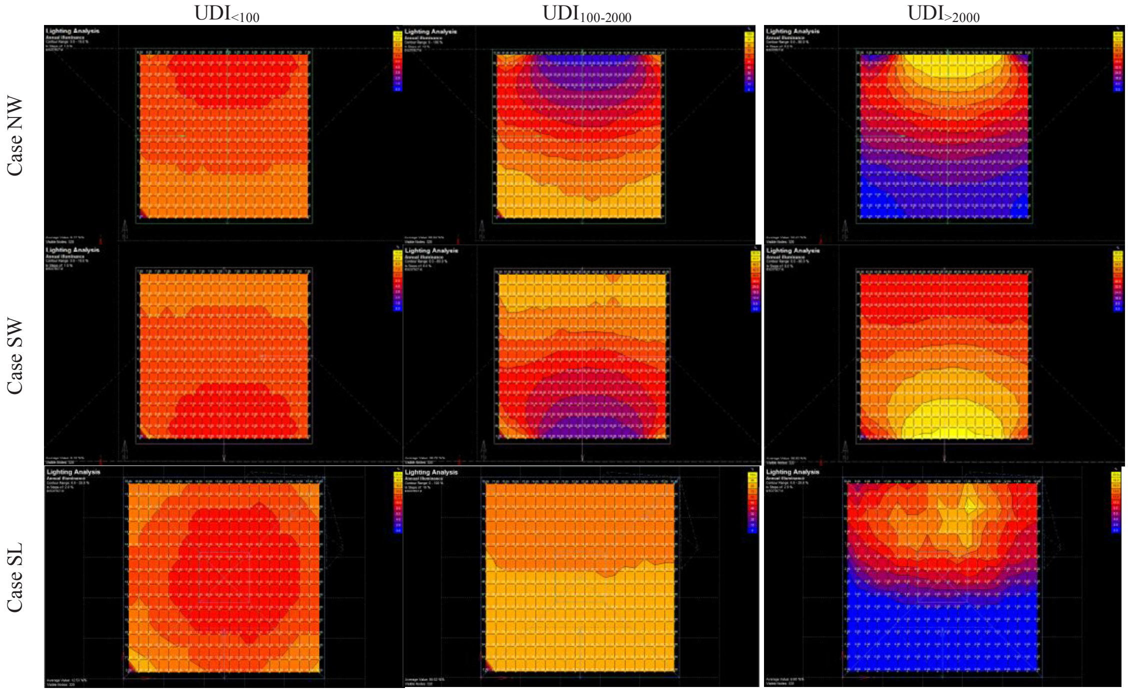


Fig. 5. Daysim simulation results: Useful Daylight Index UDI

5. Energy performance analysis

5.1. Electric consumption of the equipment simulated by Dialux

The energy consumed by electrical equipment (Q_{el}) has been calculated assuming an average power value of 15 W/m^2 and estimating a typical working week of use. It is supposed to have 5 working days in the week, where the single day is composed by 12 hours at 100% power use of electrical appliances and 12 hours at 30% of power use. Over the weekend it is assumed only 20% of active electrical equipment. This value, referred to unit volume, is equal to 21.9 kWh/year for Cases NW and SW, and 19.71 kWh/year for the Case SL.

Lighting consumption simulations have been carried out to evaluate the energy annual demand of artificial lighting. In particular, the estimation considered the integration of daylighting related to the task threshold set to 500 lux. The analyses conducted consider the natural lighting on the Daylight Factor basis, thus don't consider the direct solar radiation. The analyses have been performed in two different conditions: with an on/off control to turn on the artificial lighting when daylighting doesn't meet illuminance level requested and a dimming control to integrate the daylighting with the artificial lighting designed. The values in the one site lit office spaces are equal due to the uniformity of the diffuse solar radiation assumed but decrease in the case of the dimming control. The zenithal lighting needs the same electrical integration in both cases because artificial lighting is always needed to comply illuminance threshold requested. Results are resumed in Section 6.

5.2. Evaluation of thermal demand and consumption simulated by Open Studio BEST

Energy consumption was analyzed for the three cases (Fig. 6) with Open Studio BEST. The input parameters are shown in Table 5. The internal heat gains are estimated on the number of people, electrical appliances and lighting systems.

Table 5: Description of simulation parameters

Simulation parameter	Value
Internal gain (during winter and summer period)	
• People	0.06 person/m^2; 108 W/person presence 100% from 8 a.m. to 8 p.m.
• Illumination	10 W/m^2
• Equipment	15 W/m^2
Ventilation and infiltration rate	0.78 ach
Heating period	October 15th - April 15th
Set point from 8 a.m. to 8 p.m.	20°C and 50% Relative Humidity (RH)
Set point till 8 a.m. and from 8 p.m. to 12 p.m.	17°C and 50% % Relative Humidity RH
Cooling period	April 16 - October 14
Set point from 8 a.m. to 8 p.m.	26°C and 50% % Relative Humidity (RH)
Set point till 8 a.m. and from 8 p.m. to 12 p.m.	30°C and 50% % Relative Humidity (RH)

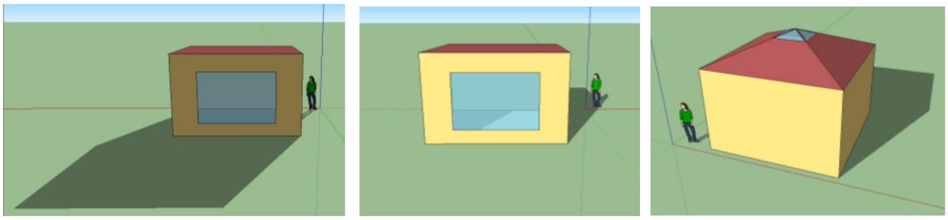


Fig. 6. Energy model of the three cases. From left (a) Case NW, (b) Case SW and (c) Case SL

It is supposed the use of a HVAC system to supply energy to the office with a water source heat pump integrated with a fan coil system providing heating in winter as well as cooling during summer period. For the calculations, the coefficient of performance (COP) for heating and energy efficiency ratio (EER) for cooling are assumed 3.6 and 4 respectively, in line with products available on the market. The energy consumption analysis assumes standard efficiency values for the auxiliary systems; the estimated overall efficiency is 89%. The results of the simulations for energy demands and energy consumption, in kWh/m^3, corresponding to winter and summer period are shown in Fig. 7.

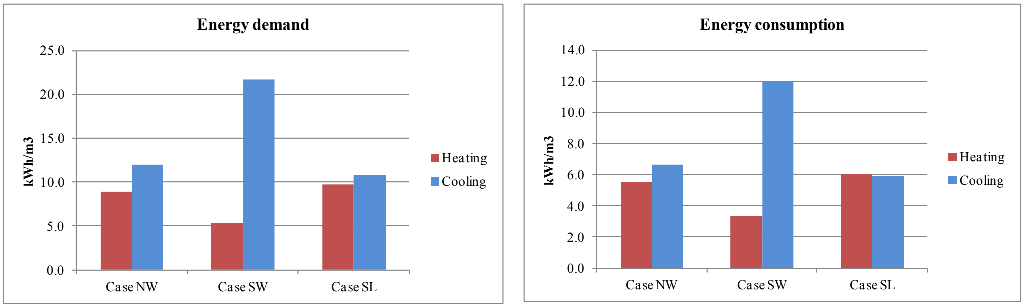


Fig. 7. Energy demands and energy consumptions, in kWh/m^3, corresponding to winter and summer period

The Case SW has the lowest heating energy demand among the three configurations, but also the highest cooling energy demand. In the Case NW and Case SL the energy in winter and summer is almost equal.

6. Results

Table 6 summarizes the values of the different parameters for the use of daylighting to reduce electrical demand and the thermal consumptions for the three configurations analyzed.

Table 6. Results of the lighting and energy analyses

	Case NW	Case SW	Case SL
Energy simulation			
Q_h, Heating consumption (kWh/m^{3}year)	5.49	3.31	6.04
Q_c, Cooling consumption (kWh/m^{3}year)	6.64	12.00	5.93
Q_{el}, Electric equipment (kWh/m^{3}year)	21.90	21.90	19.71
Q_l, Illumination without control (kWh/m^{3}year)	20.97	20.97	27.00
Illumination with control (kWh/m^{3}year)	11.52	11.52	27.00
Lighting simulation			
Daylight Factor (%)	11.31%	11.31%	4.18
UDI (%) : <100, 100-2000, >2000	8%, 14%, 78%	8%, 11%, 81%	17%, 50%, 33%
DA (%)	73% - 93%	76% - 93%	42% - 67%

7. Conclusions

The paper shows a detailed process to optimize envelope configuration for office spaces to enhance energy performance in building, visual comfort and working space quality using daylighting consciously and investigating software interoperability. It is possible to underline that considering visual comfort parameters the north window lit and the skylight lit offices present better conditions of luminance, illuminance and daylight factor, without specific problems of glare.

The distribution of daylighting potential in the indoor space is more homogeneous in skylight solution; however the level of illuminance cannot reach the comfort levels to perform visual tasks worsening electric consumption for artificial lighting. The skylight solution shows a good performance in terms of thermal consumptions, with a reduction of almost the 30% in comparison to south window case and of 1% in comparison with north window case. However, when the overall consumptions are considered, the better solution is the north window case with an energy saving of about 25% in comparison with the skylight case and of about 4% with the south window case. In the location considered and with the illuminance level required, for north side lit office space a glazing percentage of about 40% of the façade (and 20% of the floor area) can guarantee correct visual comfort parameters without strong negative effects on energy consumption. The same glazing dimensions, located in the south orientation leads to critical glare problems introducing the need of sun shading devices.

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