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Daylighting design for energy saving in a building global energy simulation context

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Abstract

A study on the impact that different daylighting solutions have on the global energy demand of a space is presented. The methodology relies on dynamic simulations carried out with Daysim and EnergyPlus used in synergy to perform a parametric study to assess the indoor daylighting conditions and the energy performance of rooms with different architectural features: room depth, window size, external obstruction angle and glazing visible transmittance. Furthermore, different lighting and shading control strategies were tested. The results of the study demonstrated that optimizing daylight can lead to a reduction of up to 30% in the global energy demand for a building.

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Keywords:

1. Introduction

A key factor to substantially reduce the energy consumption for electric lighting relies on a more widespread exploitation of daylight, coupled with the use of the most energy efficient lighting technologies, such as LEDs or lighting controls. At the same time daylight harvesting in indoor spaces can influence the global energy performance of a building also in terms of heating and cooling loads. In fact the internal gains from lighting can be affected by the solar radiation that enters through the openings and by the load emitted by electric lighting systems. The challenge is to find the best trade-off between cooling, heating and lighting energies which can only be achieved through an integrated approach which combines daylight and thermal analyses.

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Some recent studies demonstrated that a design strategy based on daylight optimization can be a reliable method to improve the global energy performance of a space [1-2-3].

In order to accurately predict daylight levels within a building space, daylight has to be studied according to its dynamic behaviour over a period of time. In this context, the 'Climate-Based Daylight Modelling (CBDM)' approach can be used [4]. Following this approach several daylight dynamic performance metrics have been proposed over the last ten years, the so-called climate-based daylight metrics (Daylight Autonomy, Continuous Daylight Autonomy, Maximum Daylight Autonomy, Useful Daylight Illuminance and Annual Light Exposure) [5-6-7-8]. Recently the Illuminating Engineering Society of North America, IESNA [9] proposed to assess the indoor daylighting performance through two new metrics: the spatial Daylight Autonomy (sDA), which assesses the sufficiency of annual illuminance in an interior work environment, and the Annual Sunlight Exposure (ASE), which expresses the annual glare potential risk. In more detail, sDA is defined as the percent of an analyzed area that meets a minimum daylight illuminance level of 300 lx for 50% of the operating hours per year ($sDA_{300/50\%}$). Two target levels have been established to assess the luminous performance of a space: a space can be rated as "neutral" when $sDA_{300/50\%}$ meets or exceeds 55% and "favorably" daylit when $sDA_{300/50\%}$ meets or exceeds 75%,. A space with $sDA_{300/50\%}$ below 55% is considered as an insufficiently daylit space.

Furthermore the increasing awareness of the potential benefits of daylight has resulted in an increased need for objective information and data on the impact that different design solutions, in terms of architectural features, can have on the daylighting condition within a space and on the related energy demand for lighting, heating and cooling.

In this context, the study presented in the paper had two main goals:

- analyzing the effect of multiple design solutions on energy requirements for electric lighting, associated with the use of efficient lighting control systems.
- assessing the influence of energy demand for electric lighting on the global energy performance.

Results related to the amount of daylight available in a space (in terms of spatial Daylight Autonomy) and annual energy demand for lighting, heating and cooling are presented to highlight the substantial influence of a proper daylighting design approach on the global energy performance.

2. Methodology

The method is based on a parametric study to assess through simulations how the daylight availability and the consequent energy demand for lighting, heating and cooling vary as the building/room architectural characteristics vary. Simulations were performed using a 2-step procedure: 1) in step 1, Daysim 3.1 [10] was used to calculate the annual illuminance profile of each space configuration as well as the corresponding annual electric lighting demand. Illuminance data were then elaborated to calculate the spatial Daylight Autonomy values. Among the simulation output, Daysim provides a Comma Separated Value (CSV) file which contains hourly schedules of the status of all lighting and shading groups of the simulated room; 2) in step 2, CSV files from Daysim were used as input in EnergyPlus [11]. The parametric analysis in EnergyPlus was conducted using jEPlus (www.jEplus.org), a graphical interface which allows setting alternative values for each parameter and simultaneously running multiple simulations calling EnergyPlus.

As final output, annual energy demands for lighting, heating and cooling were calculated and converted into primary energy data for every room configuration.

Some considerations were then drawn comparing $sDA_{300/50\%}$ and primary energy demand results.

2.1. Definition of the model

A single office room was used as 'case study' and analyses were carried out changing its characteristics in terms of site, orientation, Room Depth (RD), window area (expressed in terms of Window-to-Wall ratio, WWR), external obstructions (γ) and visible glazing transmittance of the window system (τ_{vis}). All the design variables are summarized in Table 1. Results presented in the paper refer to a sub-dataset highlighted with a grey background.

The room width and height were kept constant at 12 m and 3 m, respectively. The effect of an automated venetian blind with a diffuse transmittance of 25% (when in closed position) was considered in the simulations to dynamically control glare and overheating.

Table 1. Design variables used in the overall parametric study.

Site	Orientation	Room Depth (RD) [m]	Window-to-Wall Ratio (WWR) [-]	Obstruction angle (γ) [°]	Glazing visible transmittance (τ_{vis}) [%]
Turin (45.1°N)	South	4.5	0.2		35
Catania (37.5 °N)	North		0.3	15	50
Berlin (52.5 °N)	West	7.5	0.4	30	70
			0.5	45	90
		10.5	0.6	60	
		12		75	

2.2. Simulation input parameters

The room was modeled with walls and window frames, floor and ceiling with a diffuse reflectance of 50%, 30% and 70%, respectively. The daylight illuminances were calculated according to a 50 cm * 50 cm calculation grid over the whole working plane (minus a peripheral stripe of 50 cm all along the walls) set at a distance of 80 cm above the floor.

The target task illuminance was set to 500 lx, according to typical office visual tasks requirements [12]. The analysis was carried out considering a lighting power density of 12 W/m^2.

The shading control strategy is based on the algorithm implemented in Daysim, which assumes the presence of active and/or passive users. Active users open the blinds in the morning and partly close them to avoid visual discomfort when direct sunlight above 50 W/m^2 is incident on the work plane calculation greed points. Passive users keep the blinds lowered throughout the year [10]. The strategy adopted during the simulations refers to mixed behaviour, i.e. both types of users were assumed to equally influence the blind control.

Two different electric lighting control systems were simulated in Daysim: a manual on-off switch and a daylight responsive dimming system. The manual on-off switch is based on the Lightswitch algorithm [10]. We referred to a user who partially do not turn electric lights on if there's sufficient daylight on the work plane. The daylight responsive dimming system takes advantage of the daylight availability over the working plane and reduces, proportionally, the electric light use by dimming the luminaire light output.

The Radiance simulation parameters were set as follows: ab = 6; ad = 1000; as = 20; ar = 300; aa = 0.05; the simulations were run using the climate files of the considered locations with a time-step of 5 minutes.

The space was assumed with only one wall exposed to the outdoor environment. Accordingly, interior walls, floor and ceiling were modeled as adiabatic. The wall and the window facing the outdoor environment were modeled with a thermal transmittance of 0.25 W/m^{2}K and 1.6 W/m^{2}K, respectively. The Solar Heat Gain Coefficient of the glazing was set equal to 0.67.

The number of people and the air change rate were set according to the Italian Standard UNI EN 10339:1995 [13], assuming to 0.12 people/m^2 and 11 l/s· person respectively . Internal loads (people and equipment) were set according to the Italian Technical Standard UNI TS 11300-1:2008 [14], assumed 70W/person and 3W/ m^2, respectively. Winter and summer setpoint temperatures were set based on the Italian Standard UNI EN 15251:2008 [15] equal to as 21°C and 26°C during occupancy hours, respectively.

3. Results

A synthesis of the results that were obtained through the integrated approach is presented in this section, with reference to the sub-dataset of configurations highlighted in Table 1.

Results are divided in two different subsections. The first subsection refers to the simulations conducted in Daysim and presents a comparison between $sDA_{300/50\%}$ and energy demand for electric lighting (Q_{EL}) values. The second subsection refers to the simulations conducted in EnergyPlus using the jEPlus interface analyzing the overall energy performance of each room configuration compared with $sDA_{300/50\%}$ values.

In order to correctly sum energies consumed for lighting (Q_{EL}), heating (Q_H) and cooling (Q_C), the primary energy equivalent demand ($E_{P,glob}$) was calculated:

$$E_{P,glob} == \frac{Q_H}{\eta_H} + \left(\frac{Q_C}{EER} \cdot \eta_{el} \right) Q_{el}\ {}_{el} \qquad (1)$$

where η_H is the mean thermal energy generation efficiency, EER is the Energy Efficiency Ratio of a "reference" air-to-air chiller and η_{el} is the mean National electricity generation efficiency. For the present study the following values were assumed: $\eta_H = 0.85$; EER = 3; $\eta_{el} = 2.17$.

3.1. Daylight and energy demand for electric lighting evaluation

The parametric analysis in Daysim generated results about the influence of different architectural features on daylight availability ($sDA_{300/50\%}$) and, consequently, on the energy demand for electric lighting (Q_{EL}). In this section, results obtained for a manual on-off switch and a daylight responsive dimming system are shown in comparison with a "base-case" which consists in the "worst" situation, with lights turned on during the whole working hours.

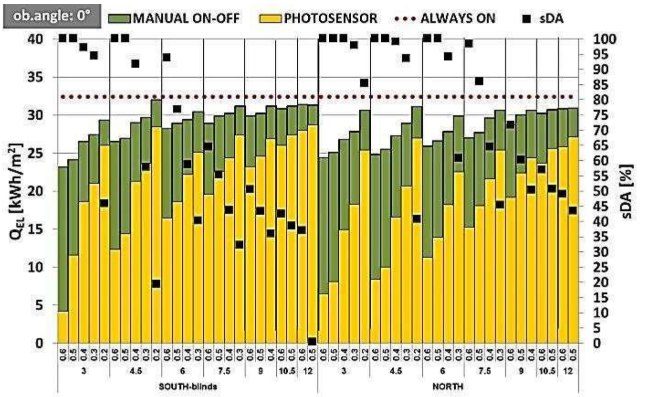

Fig. 1. Q_{EL} and sDA values for configurations with γ=0° (South and North-facing rooms)

Figure 1 shows the results for room configurations without external obstructions (γ=0°). It could be noted that $sDA_{300/50\%}$ values are on average lower for South-facing than for North-facing rooms (sDA_m=60.8% vs. 78%, respectively). This is due to the presence of the movable shading device. As a consequence, the mean Q_{EL}, even in presence of a daylight responsive dimming system, is higher for South-facing than North-facing rooms ($Q_{EL,m}$= 21.7 vs. 18.8 kWh/m$^{2}\cdot$ a, respectively). RD and WWR also showed a substantial influence: a progressive increase in RD and a decrease in WWR result in a decrease in $sDA_{300/50\%}$ values and an increase in the energy demand.

The sDA performance criteria suggested by IESNA was then used as a reference to relate the acceptability of daylight amount in a space to the consequent Q_{EL}. The entire database of results was divided according to these criteria, as explained in Figure 2a. For each performance class and for each type of lighting control (manual and daylight responsive), the mean Q_{EL} was calculated (Figure 2b). It could be noted that increasing daylight results in a decrease of energy demand for electric lighting: passing from cases with $sDA_{300/50\%}$<55% to cases with $sDA_{300/50\%}$≥75% results in a mean Q_{EL} reduction of -14% and -45% (in presence of a manual on-off switch and a daylight responsive dimming system, respectively).

Figures 2b shows the percentage decrease of the mean Q_{EL} values with respect to the "base case". As one might expect, the higher the daylight availability ($sDA_{300/50\%}$≥75%) the higher the reduction in the energy demand for electric lighting in presence of a daylight responsive dimming system. This was observed for both orientations: the mean percentage difference with respect to the "base case" reaches -48% for South orientation and -52% for North orientation. Values of $sDA_{300/50\%}$ below 55% result in a lower reduction in $Q_{EL,m}$ values, even in the presence of a daylight responsive dimming system (-7% for South orientation, -11% for North orientation).

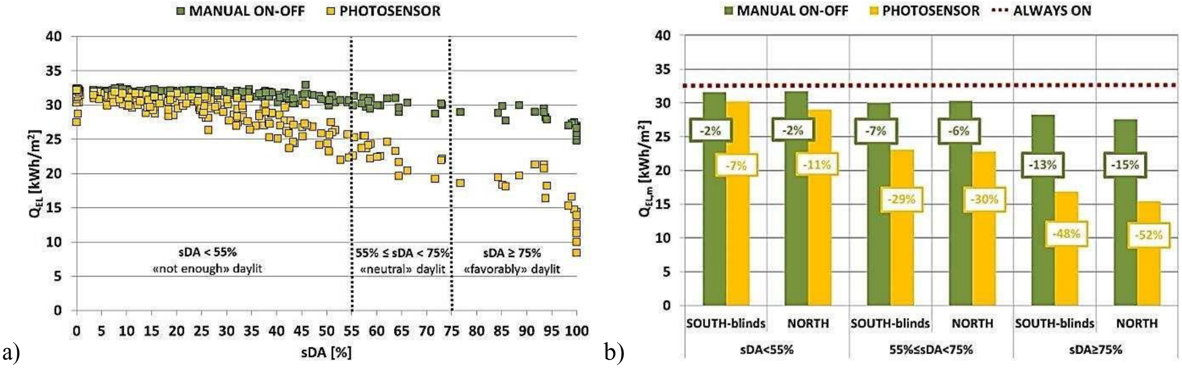

Fig. 2. Overall database of Q_{EL} and sDA results (a); Mean annual Q_{EL} for each $sDA_{300/50\%}$ performance class (b)

3.2. Overall energy performance evaluation

This section focuses on how a design strategy based on the optimization of daylighting can influence the global energy demand of a room. In this study a daylighting optimization corresponds to an increase in the $sDA_{300/50\%}$ and to the use of a daylight responsive lighting control system.

Figure 3a shows the entire database of results divided according to $sDA_{300/50\%}$ criteria and the relation between $sDA_{300/50\%}$ and $E_{p,glob}$ for all simulated case studies. The higher the amount of daylight available in a space the lower the global primary energy demand, in particular in presence of a daylight responsive dimming system. Furthermore the mean global primary energy demand ($E_{P,glob,m}$) was calculated for each performance class of $sDA_{300/50\%}$: for cases with $sDA_{300/50\%}$ <55% and $sDA_{300/50\%}$ ≥75% $E_{P,glob,m}$ is 112.4 kWh/m² and 87.6 kWh/m² respectively, with a mean energy saving, increasing the daylight availability, of 24%.

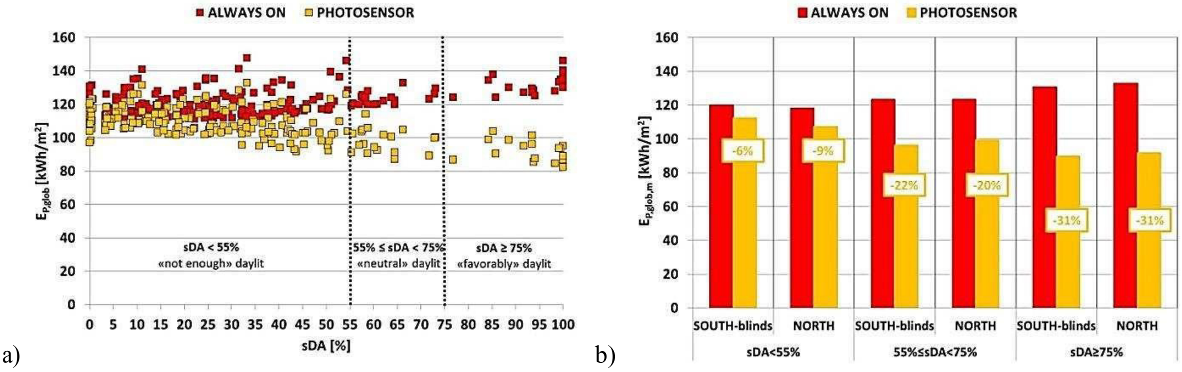

Fig. 3. Overall database of $E_{P,glob}$ and sDA results (a); Mean annual $E_{P,glob}$ for each $sDA_{300/50\%}$ performance class (b)

Figures 3b shows the results in terms of percentage difference between $E_{P,glob,m}$ values with a daylight responsive dimming system and the $E_{P,glob,m}$ for the "base-case" control system (light always turned on). For both South and North-facing rooms, the maximum mean reduction in the global primary energy equivalent demand (-31%) can be reached for "favorably" daylit cases, i.e. cases with $sDA_{300/50\%}$ ≥75%. In spaces with a non-sufficient level of daylight ($sDA_{300/50\%}$ <55%) the mean global primary energy demand is higher and the reduction that could be obtained in presence of a daylight responsive dimming system doesn't exceed -9%.

4. Discussion and conclusions

Results related to the amount of daylight available in a space (in terms of spatial Daylight Autonomy) and annual energy demand for lighting, heating and cooling were presented to highlight the substantial influence of the daylight harvesting on the global energy performance. The methodology was based on the use of both Daysim and EnergyPlus which were employed in synergy for a parametric study to assess the lighting and energy performance of rooms with different architectural features.

The analysis conducted in Daysim demonstrated, initially, that the daylight amount within a space is strongly influenced by its architectural features: a progressive increase in Room Depth and a decrease in Window-to-Wall Ratio result in a decrease in $sDA_{300/50\%}$ values and an increase in the energy demand for electric lighting.

Furthermore a substantial reduction in the energy demand for electric lighting for "favorably" daylit cases ($sDA_{300/50\%} \geq 75\%$) has been proved, in particular in presence of a daylight responsive dimming system compared to a "base-case" in which lights are always turned on (up to -48% for South orientation and -52% for North orientation).

A design strategy based on the optimization of daylight also has a meaningful influence on the global energy demand of a space. Increasing the daylight amount results in a reduction of the global primary energy demand, in particular in presence of a daylight responsive dimming system: the saving in terms of global primary energy demand ($E_{P,glob,m}$) when increasing the $sDA_{300/50\%}$ from less than 55% to more than 75% is, on average, 24%. Furthermore, average savings of 31% can be achieved in spaces with high daylight availability ($sDA_{300/50\%} \geq 75\%$) when a daylight responsive control system is considered instead of a "worst case", with lights always turned on.

However it has to be highlighted that these results were obtained using specific input data. For instance the space was assumed with only one wall exposed to the outdoor environment, considering a central position of a common office within a building. Results might be different if a corner office was considered. A second input data that can have a massive influence on the energy performance of a space is represented by the type of shading and its control strategy. In this study the shading control strategy is based on the algorithm implemented in Daysim and it's based on the control of the direct solar radiation on the workplane.

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