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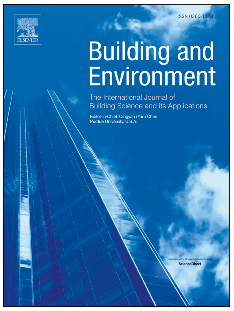

Impact of daylighting on total energy use in offices of varying architectural features in Italy: Results from a parametric study

Anna Pellegrino, Silvia Cammarano, Valerio Loverso, Vincenzo Corsrado

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Abstract

The growing attention towards the optimization of the overall performance of a building, in terms of both indoor environmental quality and energy consumption, has brought about the need to carry out analyses, which consider the interactions of all affecting parameters. In particular, thermal and daylighting analysis should be carried out in synergy to ensure the best performance in both domains. Within this framework, the paper presents a study on daylighting and energy behavior of rooms with different architectural features. The study has been conceived to account for a broad range of possible configurations of office buildings in the climate site of Turin (Northern Italy), and has been performed through numerical simulations carried out with Daysim and EnergyPlus. The results outline the daylighting performance (in terms of spatial Daylight Autonomy (sDA)) and the energy demand for lighting, heating and cooling and demonstrate that optimizing daylighting can lead to a reduction of the total energy demand of an office.

1. Introduction

Daylight is a feature of many buildings and it is highly regarded by people who, generally, prefer to live and work in spaces where daylight is available and a view to the outside, through windows and rooflights, is accessible. The potential positive impact of daylight on people's visual performance, comfort, and well-being has been extensively investigated from the past to the present days and fundamental reviews on the topic have been carried out by various authors [1,2]. Results demonstrate that daylighting in buildings, and especially in work places, is desired by most users and a proper use of daylight contributes to occupants' performance and well-being. Furthermore the effects of light on people's health (effects beyond vision), has been object of investigation during the last fifteen years. Health effects depend, among the other factors, on people's exposure to light and on its spectrum, and daylight is recognised to be the most energy-efficient means to deliver a proper light exposure [3].

In addition to that, and taking into account the broader issue of sustainability, from environmental quality to energy issues, daylight is an important resource to improve the energy efficiency of buildings. The planned use of natural light can become a cost-effective strategy to reduce energy consumption, mainly by minimizing the use of electric lighting, but also because of its influence on the heating and cooling loads of a building.

Electric lighting is estimated to account for a significant part of the overall energy demand of buildings (15 - 20% of the total building electricity consumption) [4,5] and the potential of daylight exploitation to reduce electricity consumption associated with lighting requirements has been demonstrated in several past and recent studies, as reported also in some literature reviews [6,7]. Maximizing indoor daylight availability by means of a proper design of spaces, openings and shadings or by the use of appropriate daylighting systems is the first approach to achieve the goal of energy conservation related to lighting [8,9,10,11,12,13]. Reinhart [10] investigated the influence of various design variables on daylight availability in over 1000 open-plan office settings with different external shading contexts, glazing types, façade orientations, ceiling designs and partition arrangements, located in five different climatic sites. One of the outcomes was the influence of glazing visible transmittance on the energy consumption for lighting: the reduction of transmittance from 75% to 35%

increased the energy consumption for lighting of about 20%. Krarti et al. [11] carried out a parametric study where different building geometries, window sizes, glazing types and geographical areas were considered. The results showed the increasing trend of energy saving when increasing daylighting, but also demonstrated that little additional reduction can be achieved increasing the Window to Floor Ratio above 0.5 in buildings with glazing visible transmittance above 0.5. Similar results were found by Dubois and Flodberg [12], that presented a study on daylight utilization in perimeter office rooms at high latitudes and investigated, through annual lighting simulations, how the continuous daylight autonomy was influenced by various room features, such as the Glazing-to-Wall Ratio (GWR), glazing visible transmittance, inner surfaces reflectance, orientation and latitude. The variation in the daylight autonomy as a function of the window to wall ratio, space sizes, external obstruction and orientation was also studied by Cammarano et al. [13], for office rooms located in the North of Italy.

Further improvements, in terms of energy savings for lighting, can be obtained by optimizing the use of electric lighting and/or shading system through daylight responsive control systems. Several simulation and field studies have demonstrated the broad range of energy saving that could be achieved, depending on the building features, by adopting daylight responsive control strategies [10,14,15,16,17,18,19,20,21]. The simulation study carried out by Reinhart [10] demonstrated that the electric lighting energy savings, with an ideally commissioned lighting control system, vary between 25% and 60%, depending on the daylighting due to the combination of the design variables. Results in the same range were also obtained in field studies. Li and Lam [14] monitored the energy consumption of a lighting plant with daylight responsive dimming system in a daylit corridor at the City University of Hong Kong. Their results demonstrated that using a daylight responsive control system determined a 65% reduction in the electricity use compared to an on-off system operating 12 hours a day. Lower savings were estimated for a group of offices with occupancy and daylighting dimming control that was monitored, for a whole year, at the Politecnico di Torino by Aghemo et al. [21]. The measured energy consumptions were compared to the ones calculated for manual on/off control, obtaining saving of 17%.

Besides, in a recent literature review about energy-efficient retrofit of lighting in buildings, Dubois et al. [22] reported that, according to many authors, simulation studies as well as field monitoring, lighting controls based on the integration of daylighting and electric lighting could result in significant lighting savings, ranging from 30% to 77%.

Daylight exploitation in buildings also affects the heating and cooling consumption, with positive or negative implications, depending on many aspects, such as the climate of the site, the architectural and occupational features of the building, the characteristics of the shading systems and of the building services. Several studies were carried out to evaluate the impact of windows size, glazing properties, shading systems, blinds control systems, etc., on the daylighting performance and the thermal energy consumptions [23,24,25,26,27,28,29].

Ghisi and Tinker [24] presented a methodology to predict the potential for energy savings due to daylighting using an 'Ideal Window Area' concept, i.e. a window area which allows a balance between solar thermal load and daylight supply to be obtained. This methodology was developed using ten differently sized and five differently shaped rooms considering two climatic conditions.

More recently, Shen and Tzempelikos [25] carried out an integrated daylighting and thermal simulation analysis for private office rooms, varying the windows and shading properties, for different climates and orientations. Among the results they pointed out that façade with window to wall ratio (WWR) between 30% and 50% can result in lower total energy consumption (with automated shading) than smaller or larger windows. Similar results were also found in a recent study carried out by Goia [26] on office buildings. The aim of the study was to search for the optimal WWR, in terms of daylighting performance and thermal energy consumption, in different European climates. The results showed that most of the optimal WWR values are included in a relatively narrow range (0.30 < WWR < 0.45). Exceptions were found for offices facing South, for which the optimal glazed area can be as high as 0.60 in very cold climates and as low as 0.20 in very warm climates.

Further studies, focused on the impact of different automatic shading control strategies, were carried out by Tzempelikos and Shen [27], to investigate their impact on daylighting, thermal loads and energy consumption in private offices. Similarly, Shen et al. [28] evaluated and compared the total energy consumption (lighting, heating and cooling) obtained with different daylight responsive control strategies applied to shading and electric lighting systems. The comparison was between independent and integrated controls. With the former, the blind and lighting control systems independently regulate the indoor lighting conditions while the integrated controls operate as one system, by sharing the control information (including occupancy information and HVAC state), to keep the required lighting levels. The study was carried out through simulation and demonstrated that, for total lighting, heating and cooling energy performance, integrated controls achieve the lowest total energy, but with different partial performance depending on the local climate, type of shading, etc.

Hegazy et al. [29] assessed the daylighting and energy performance of an office room with different window to wall ratios and shading systems in hot climate regions. The absence of a shading system produced, as expected, the highest daylight autonomies and total energy consumption, while an optimised combination of WWR and type of shading allowed achieving high daylighting with low lighting consumption and acceptable cooling demand.

The review of the recent literature demonstrates that to optimize the total energy performance of buildings the design solutions need to consider all affecting factors: the daylight analysis should be carried out in synergy with the thermal and the energy simulation so that the resulting project can achieve a suitable balance between these domains.

Even though a number of researches were conducted to study the impact of daylighting on the performance of a building, many aspects still have to be addressed to provide building design practitioners, lighting engineers, product manufacturers and building owners with a comprehensive reference on this subject.

The studies carried out in the past were often based on simplified daylight metrics, such as the daylight factor, [24], in other cases the settings explored were oversimplified, or the experimental or simulation analysis were referred to a specific space or, at least to a limited number of space configurations or building features.

Within this framework, the objective of the study presented in this paper is to estimate, through a parametric study based on dynamic, climate based annual simulations, the influence of daylighting on the energy demand for a large number of space configurations and combination of building features. In particular, the energy results and potential savings are correlated to different classes of daylighting performance, which were defined based on the spatial Daylight Autonomy (sDA).

The analysis was initially focused on the correlation between the indoor daylighting conditions and the electricity demand for lighting and secondly on the relationship between the indoor daylighting conditions and the total energy demand (lighting plus heating and cooling).

2. Methodology

The study is grounded on a database that was built with the results of a parametric study carried out, through numerical simulation, to evaluate the daylighting conditions and the electric lighting energy demand for rooms with different architectural features.

The parametric study, conceived in previous researches and still in development, accounted for the main factors that influence the indoor daylighting and the energy demand for a room with unilateral fenestration. The variables considered in the comprehensive study were: the geographic location and the local climate; the room orientation; the room geometry in terms of room depth (RD); the window sizes (expressed as window to wall ratio - WWR); the optical properties of the glass (τ_{vis}); the external obstruction from nearby buildings of different height (obstruction angle - γ); and the presence of a blind. Furthermore, different lighting requirements (average illuminance on the working plane) and lighting control systems were considered to estimate the lighting energy demand for different types of spaces and control strategies. The combination of the variables adopted in the comprehensive parametric study determined a sample of 828 cases. The annual climate based daylight simulations were carried out with Daysim 3.1 and the details on the dependent and independent variables and on the calculation assumptions are described in previously published papers [30,13].

Within this research, a subset of the cases considered in the previous comprehensive study were assumed, results elaborated and new simulations carried out to evaluate: 1) how daylighting varies as a function of the architectural features; 2) the amount of the energy savings for electric lighting as a function of the daylighting and the type of lighting control system; and finally, 3) how the total energy demand (lighting, heating and cooling) varies as a function of the environmental daylighting and the corresponding savings. The overall number of cases used for this study is 570.

The metric used in this study for the daylighting analysis is the Spatial Daylight Autonomy ($sDA_{300,50\%}$). This metric was proposed in 2012 by the Illuminating Engineering Society of North America (IESNA) to assess the sufficiency of annual daylighting in an interior work environment [31]. In more detail, $sDA_{300,50\%}$ is defined as the percent of an analysed area that meets a minimum daylight illuminance level of 300 lx for at least the 50% of the operating hours. In the IESNA document, some reference values are also defined: a space can be rated as acceptably daylit when $sDA_{300,50\%}$ meets or exceeds 55% but is below 75%, favorably daylit when $sDA_{300,50\%}$ meets or exceeds 75% and insufficiently daylit when $sDA_{300,50\%}$ is below 55% [31]. It is interesting to point out that this metric, conceived to assess daylighting preferences, was defined assuming an illuminance threshold of 300 lx independently of the illuminance requirement typically specified for the room usage (for instances, 500 lx for offices).

It is also worth noting that this metric has been adopted in the rating system of the ‘LEED Reference Guide for Building Design and Construction’ [32] among the options that can be used to evaluate the daylighting condition in order to get the credit concerned with the quantity of daylight.

No specific metrics were used to evaluate the glare probability because, for South-facing rooms, the use of a blind was assumed, whenever an irradiance of 50 W/m^2 hitting any point of the working plane is detected.

The annual Energy Performance for Lighting (EP_L), also called LENI (Lighting Energy Numeric Indicator) in the European standard EN 15193:2007 [33], was calculated to estimate the energy savings from electric lighting, while the annual total energy demand was determined by summing the equivalent primary energy demand for lighting ($E_{P,L}$), heating ($E_{P,H}$) and cooling ($E_{P,C}$).

In the following sub-sections, the simulation approach and the features of the models used for this research are described.

2.1 The simulation approach

Simulations were performed using a 2-step process. In step 1, Daysim 3.1 was used to calculate the annual illuminance profile of each space configuration and the annual electric lighting energy demand (LENI) for different lighting controls, user behaviours, lighting requirements and characteristics of the lighting system. Annual illuminance profiles were determined considering a time step of 5 minutes on an horizontal work plane whose extent was set so as to cover the whole room area minus a 50 cm deep strip all along the room perimeter. The sensor points were positioned according to a grid across the work plane, with a spacing of 30 cm. Afterwards, to calculate the $sDA_{500,50\%}$, the annual illuminance data, obtained from the Daysim simulations, were processed with a specifically developed Matlab routine.

In step 2 of the simulation process, the assumptions made for the lighting analysis were coupled with the thermal analysis, in order to evaluate the total energy demand of each space configuration and the influence of the daylighting design on internal loads,. Among the simulation results, Daysim provides a Comma Separated Value (CSV) file, which contains hourly schedules of the status of all lighting and shading groups within the model. The CSV files generated by Daysim were directly used as input for the energy simulation carried out in EnergyPlus. The parametric analysis in EnergyPlus was conducted using jEPlus [34], a graphical interface that allows setting alternative values for all the parameters and simultaneously running multiple simulations calling EnergyPlus.

As final output of the 2-step process, the annual energy demands for lighting, heating and cooling were calculated and converted into primary energy data for every room configuration.

The overall simulation methodology is explained in Figure 1.

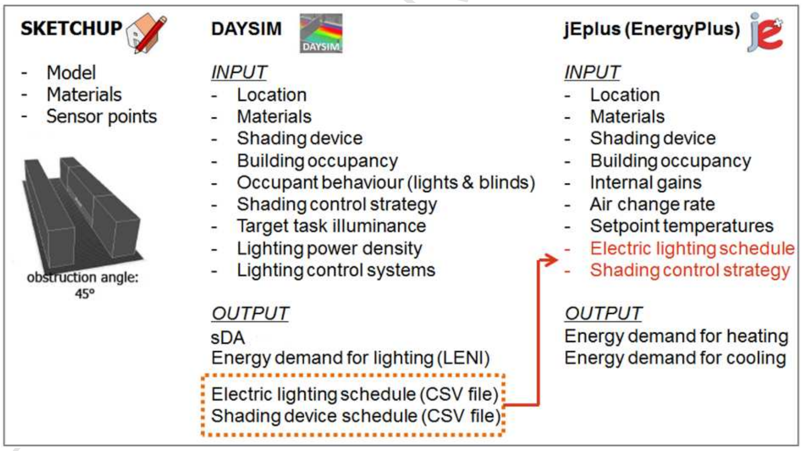


Figure 1 - Overall simulation methodology.

2.2 The model configurations

The study was carried out for several configurations of a target room with unilateral fenestration. The lighting requirement, assumed for the calculation of the lighting energy demand, was 500 lux, therefore the simulated rooms can be regarded as representative of different types of offices: single, multiple or open plan offices, depending on the RD. The model configurations considered in this study refer to a single location and climate site (Torino, Northern Italy). External nearby buildings were modelled to reproduce different obstruction angles, and two orientations (North and South) were considered. The RD and the WWR are the other features, which were varied, while, the room width and height as well as the optical properties of opaque and transparent surfaces were kept constant. It is worth stressing that a number of parameters were kept constant or varied in a limited range. In some cases, the values assumed represent the most common condition for typical office buildings (this is the case, for instance, of the glazing visible transmittance or the reflectance of opaque surfaces). In other cases, because the range that was assumed for the variable corresponds to extreme behaviours in terms of energy performance of a building (North and South orientations, consistently with has been pointed out in some studies, such as [12,30]). Furthermore, a single climate condition was assumed (Torino – latitude 45° N – HDD 2617) as it was considered representative of large areas in the North of Italy and, in more general terms, of regions with subtropical climates.

In Table 1, the values of the variable and fixed parameters assumed in this study for the calculation of the daylighting conditions and the electric lighting energy demand are reported. It is important to stress that the illuminance over the work plane was set equal to 500 lx in accordance to the lighting requirements for offices that are reported into Italian and international standards. [35]. The target illuminance of 500 lux was adopted in this study to calculate the energy demand of the lighting systems, that are usually designed and regulated in compliance with these standards. This threshold value differs from the one used to calculate the sDA (300 lx), which is a metric conceived to determine when a space is perceived as sufficiently daylit.

Table 1 – Variable and fixed parameters assumed in the parametric study for the lighting simulations.

	Site Features	
Fixed parameters	Location	Torino (Italy); latitude 45°N
Variable parameters	External Obstruction (obstr. angle γ)	0°- 15°- 30°- 45°- 60°- 75°
	Rooms Features	
Fixed Parameters	Room width	12 m
	Room height	3 m
	Window-head-height	2.7 m
	Walls reflectance	50%
	Ceiling reflectance	70%
	Floor reflectance	30%
	Glazing visible transmittance	70%
Variable parameters	Rooms orientation	South - North
	Room depth (RD)	4.5 m - 6 m – 7.5 m – 9 m – 10.5 m – 12 m
	Window to Wall Ratio (WWR)	0.2 – 0,3 – 0.4 – 0.5 – 0.6
	Lighting system features	
Fixed parameters	Lighting Power Density	12 W/m^2
	Stand-by power for automated controls	0.12 W/m^2
Variable parameters	Lighting control system	Manual on/off (MAN) - Daylight responsive dimming (DR)
	Type of space and use	
Fixed parameters	Type of space	office
	Lighting requirement (Mean illuminance)	500 lux
	Operating time	Monday through Friday; 8:30 a.m. – 6:30 p.m.
	Users behavior	Mixed (50% active; 50% passive)

The effect of a shading system, consisting of a Venetian blind with a diffuse transmittance of 25% (when in the closed position), was considered in the simulations of the South oriented rooms so as to account for the need for reducing glare and overheating phenomena over the work plane. The algorithm implemented in Daysim 3.1 assumes that the blind is automatically pulled down whenever an irradiance of 50 W/m^2 hitting any point of the working plane is detected [36]. Furthermore, the rooms were supposed to be occupied by users with a mixed active and passive behavior: active users operate the electric lighting in relation to ambient daylight conditions, while passive users keep the electric lighting on throughout the work day. Both types of users were assumed to equally influence the lighting control.

For the thermal simulations, it was assumed that the space has only one wall that is exposed to the outdoor environment. As a consequence the interior walls, the floor and the ceiling were modelled as adiabatic elements.

The wall and the window facing the outdoor environment were modelled with a thermal transmittance of 0.25 W/m^2K and 1.6 W/m^2K, respectively. The glazing Solar Heat Gain Coefficient was set equal to 0.67.

The occupancy index and air change rate were set according to the Italian Standard UNI 10339:1995 [37] while internal loads (people and equipment) were set according to the Italian Technical Standard UNI TS 11300-1:2014 [38]. Winter and summer set point temperatures were defined on the basis of the European Standard EN 15251:2007 [39].

The input parameters used in the study for the thermal analysis are summarized in Table 2.

HVAC systems were modelled considering an ideal air load simplification. This assumption permits to assess the theoretical thermal loads needed to achieve the thermal balance at any time step of the simulation.

As regards the building technical systems, the heating system is modelled through a predefined value of the global energy efficiency (η_H), while the cooling system through a predefined value of the energy efficiency ratio (EER).

Table 2 - Thermal input parameters.

Parameter	Definition	Source
U-value wall	0.25 W/m^2K	values assumed in North Italian best practice design
U-value window	1.6 W/m^2K	
Solar transmittance (τ_{sol}), glazing	0.60	
SHGC (g)	0.67	
Solar transmittance (τ_{sol}), shading	0.25	Daysim
Shading control	Active if $I_{direct, workplane}$ >50 W/m^2	Daysim (Lightswitch)
Occupancy hours	Monday through Friday 8:30 a.m. - 6:30 p.m.	
Occupancy density	0.12 $people/m^2$	UNI 10339
People heat gains	70 W/person	UNI TS 11300-1
Air change rate	11 l/s·person	UNI 10339
Equipment heat gains	3 W/m^2	UNI TS 11300-1
Lighting power density (LPD)	12 W/m^2	
Lighting management systems (LMS)	Manual on-off (MAN) Daylight responsive (DR)	
Winter set point temperature	21 ℃ (7:00 a.m. - 9:00 p.m.) 18 ℃ (9:00 p.m. - 7:00 a.m.)	EN 15251
Summer set point temperature	26 ℃ (7:00 a.m. - 9:00 p.m.) 28 ℃ (9:00 p.m. - 7:00 a.m.)	

3. Results

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

The results are divided in three different sections. The first and second sections refer to the simulations conducted with Daysim and report a synthesis of the daylighting results in terms of $sDA_{300/,50\%}$ values and of the corresponding annual energy demand for electric lighting, in terms of LENI values, respectively.

The third section refers to the simulations conducted in EnergyPlus using the jEPlus interface and reports the results that were obtained in terms of lighting, heating, cooling and total energy demand for the different room configurations. The results are presented with respect to the daylight amount in the space.

As regards the total energy demand, in order to consistently sum lighting (Q_L), heating (Q_H) and cooling (Q_C) contributions, the primary energy has been considered and calculated as follows:

$$E_{P,glob} = \frac{Q_H}{\eta_H} + \left(\frac{Q_C}{EER} \cdot f_{\mathrm{P},el}\right) + Q_L \cdot f_{\mathrm{P},el}$$

where η_H is the mean heating system global efficiency, EER is the Energy Efficiency Ratio of a 'reference' air-to-air chiller and $f_{P,el}$ is the primary energy factor of the National electricity grid. For the present study, the following values were assumed: $\eta_H = 0.85$; EER = 3; $f_{P,el} = 2.17$. The value of η_H derives from,a widely accepted practice, while the values of EER and $f_{P,el}$ derive from the Italian legislation.

3.1. Daylighting results

The parametric analysis conducted in Daysim generated results about the internal daylighting conditions, and, as a consequence, about the energy demand for electric lighting based on the lighting requirement, lighting power density and control systems that were assumed.

The first phase of the analysis was focused on the influence that different orientations and architectural features have on the internal daylight amount and spatial distribution, expressed according to the $sDA_{300,50\%}$ performance classes. Results are shown using a graphical tool, which was specifically developed to represent the great number of daylighting results obtained from the parametric study.

The graphs are designed in order to account for all the variables influencing the daylighting performance: Room Depth, RD (along the x-axis), obstruction angle, γ, (along the y-axis) and Window-to-Wall Ratio, WWR, from 0.6 to 0.2 (represented by a number of partially overlapping circles for each room depth and obstruction angle). The diameter of the circles is proportional to the absolute value of the represented metric. Two separated graphs are reported to account for the different room orientations (South and North). A detailed description of the graphical tool and of its possible applications were presented in previous papers [13,40,41].

For this study, the tool was used to point out which combinations of room features allow a certain daylighting performance class to be achieved. Consistently with the $sDA_{300,50\%}$ limits proposed by IESNA [31], three classes of performance were adopted:

- Insufficiently daylit spaces, when $sDA_{300/,50\%}$ is below 55%;
- Acceptably daylit spaces, when $sDA_{300,50\%}$ is equal or above 55% and below 75%;
- Favourably daylit spaces, when $sDA_{300,50\%}$ is equal or above 75%.

The results for South and North-facing rooms are shown in Figure 2, and Figure 3, respectively.

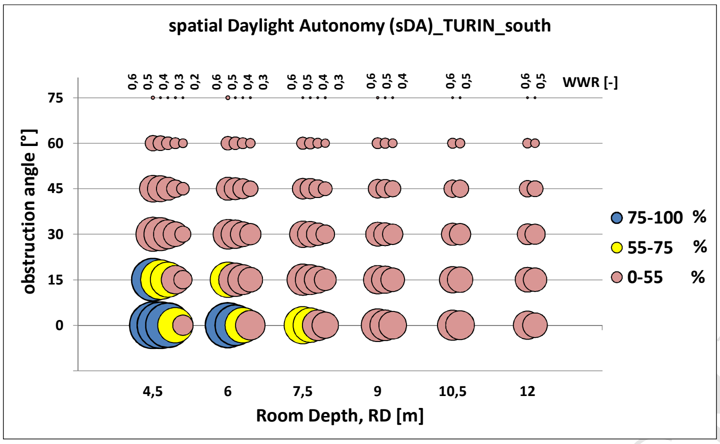


Figure 2 – sDA$_{300,50\%}$ results for the room configurations facing South (with blind)

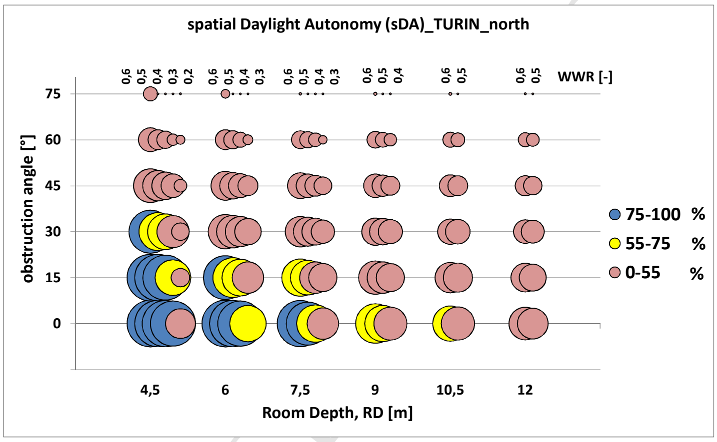


Figure 3 - sDA$_{300,50\%}$ results for the room configurations facing North

Looking at the graphs it is possible to detect directly the different daylighting performance that was obtained for South and North-facing rooms. For South-facing rooms, the adoption of the blind, associated with the assumption of mixed active and passive occupant behaviour, determine lower values of spatial Daylight Autonomy for almost all the room configurations that were simulated. The sDA of North-facing rooms exceeds the one of the corresponding South-facing rooms of about 10% on average, with a maximum difference of 36% (Figure 4).

Furthermore, from the graphs of Figure 2 and 3 it can be observed that the increase in the obstruction angle is the factor that mainly affects the value of spatial Daylight Autonomy. Obstruction angles higher than 45° determine an insufficient daylight condition for all room configurations, for both North and South orientations (Figure 2 and Figure 3).

Taking into account the South facing rooms (Figure 2), an insufficient daylighting condition (sDA$_{300,50\%}$<55%) always occurs for rooms with the following architectural characteristics:

- high depths (RD ≥ 9 m);
- medium and high obstruction angle (γ ≥ 30°);

- medium deep rooms (7.5 m), low obstruction angles (γ between 0° and 15°) and small Window-to-Wall Ratios (WWR < 0.4).

On the other hand, ‘favourably’ daylit spaces ($sDA_{300,50\%}$≥75%) are rooms with the following architectural features:

- limited depths (RD ≤ 6 m) without external obstruction (γ = 0°) and WWR>0.4; it is worth stressing that this result appears in line with some rules-of-thumbs available in literature, which suggest to limit the room depth to no more than 2-2.5 times the window-head-height (in the presence and in the absence of a shading device, respectively) [42,43]: applying this rule to the room configurations used in the present study would yield a limiting RD of 5.4 m or of 6.75, respectively, which means that a RD of 6 m is between these two values
- room depth of 4.5 m, medium obstruction angle (γ = 15°) and high Window-to-Wall Ratios (WWR = 0.6).

For North facing rooms (Figure 3), insufficient daylighting conditions were found for:

- obstruction angles above 45°;
- obstruction angle above 30° and room depth equal or greater than 6 m;
- room depths greater than 10.5 m.

Favourable daylighting conditions (sDA ≥ 75%) were found for model configurations with room depths up to 7.5 m and obstruction angles up to 30°, with WWR over 0,5, when RD or γ rise, or with WWR down to 0.3 for little depth and unobstructed rooms.

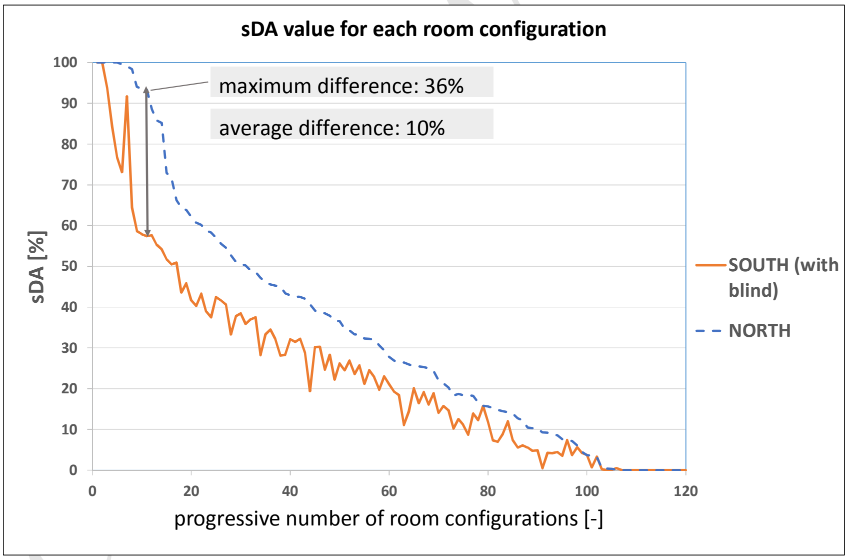


Figure 4. $sDA_{300,50\%}$ for South and North oriented rooms (overall set of 570 room configurations)

3.2. Energy demand for electric lighting

For what concerns the energy demand for lighting, in the graph of Figure 5, the LENI values obtained for the overall set of model configurations are plotted versus the sDA variation and the type of lighting control system. The graph highlights the potential of daylight responsive dimming systems (DR) in reducing the energy demand with respect to manual control (MAN): in the presence of a manual on/off switch, the LENI values are always between 25 kWh/(m^{2}a) and 32.9 kWh/(m^{2}a), even when daylighting is high (sDA$_{300,50\%}$≥75%). In the presence of a daylight responsive dimming system the range of LENI values is wider, with a minimum and a maximum value of 4.20 kWh/(m^{2}a) and 32.3 kWh/(m^{2}a) respectively.

The reduction of the energy demand from MAN to DR lighting control was calculated for the whole set of room configurations. The energy savings with DR dimming system are encompassed between almost 0% for very scarcely daylit spaces to 66% for rooms with very high daylighting (rooms with $\gamma = 0°$, WWR = 0.6, RD = 4.5 m, North oriented and with sDA$_{300,50\%}$ = 100%). Considering the overall set of simulated cases, the average energy saving with automatic DR dimming system is equal to 7,5% for South oriented rooms and 14% for North oriented rooms. The low average savings are a consequence of the large number of room configurations with insufficient daylighting included in the study (84% of the overall database has a SDA$_{300,50\%}$ <55%).

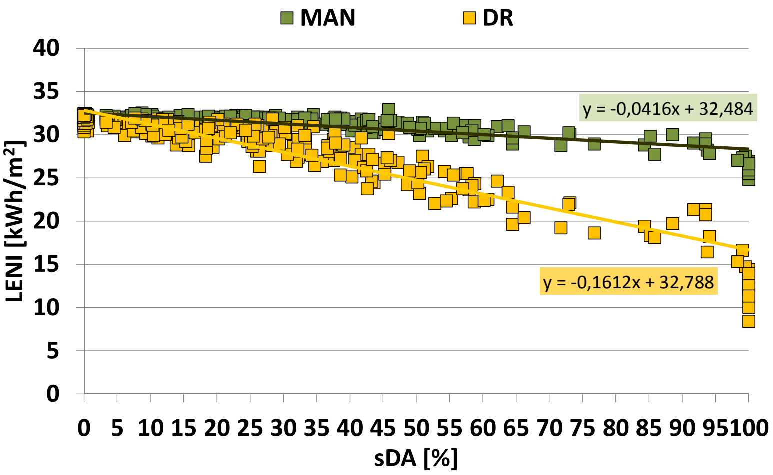


Figure 5 - Overall database of LENI results depending on the sDA results.

In order to compare, with a more effective approach, the electric lighting energy performance with the indoor daylighting, the entire database of results was divided according to sDA performance classes and considering the two types of lighting control systems. For each performance class and type of lighting control, the minimum, maximum and mean value of LENI were calculated. The results are presented in Table 3.

Table 3 – LENI values and standard deviation for each sDA performance class and for the two lighting controls.

	LENI [kWh/m^{2}a]					
	sDA$_{300,50\%}$< 55%		**55% ≤ sDA$_{300,50\%}$< 75%**		**sDA$_{300,50\%}$ ≥ 75%**	
	MAN	**DR**	**MAN**	**DR**	**MAN**	**DR**
Mean	31.72	29.72	30.14	22.86	27.66	16.08
Max.	32.90	32.30	31.30	25.50	29.99	21.30
Min.	29.90	22.00	28.70	19.20	24.80	8.40
Stand. Dev.	0.45	2.18	0.71	1.86	1.46	3.81

As one might expect, increasing the daylighting performance, which means moving from a lower to an upper sDA class, results in a decrease in the energy demand for electric lighting both with manual on/off and DR dimming control. Obviously, the reduction in the energy demand are more substantial with DR control.

Figure 7 shows the mean LENI value for each sDA class and the mean energy saving that can be achieved, for both manual and DR control, moving from lower to upper sDA performance classes. With a manual control, a mean demand reduction of 5% can be achieved moving from insufficiently daylit spaces to acceptably daylit spaces, while the mean saving is 13% if an increase the sDA of two classes is performed, from insufficiently daylit spaces to favourably daylit spaces. For the same changes of class, the mean saving, with DR control system, is equal to 23% and 46%, respectively.

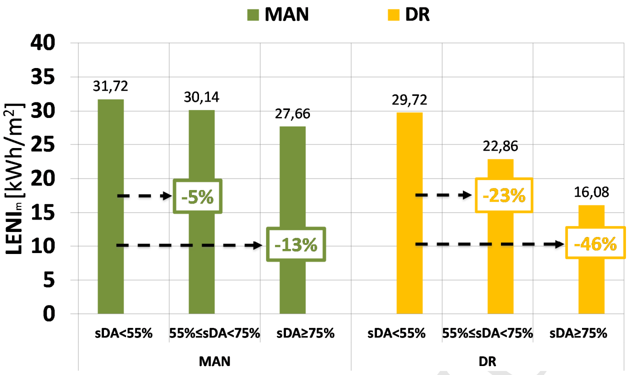


Figure 7 - Mean LENI values and percentage differences for every sDA performance class.

On the other hand, Figure 8 shows the mean energy saving that can be achieved, within a daylighting performance class, if a DR lighting control is used instead of a manual on/off control. In this case the results highlight that the use of a DR control system becomes really effective (average energy reduction higher than 40%) in rooms with sDA>75%, and, in any case, useful (average energy reduction of 24%) in rooms acceptably daylit (55% ≤ sDA < 75%).

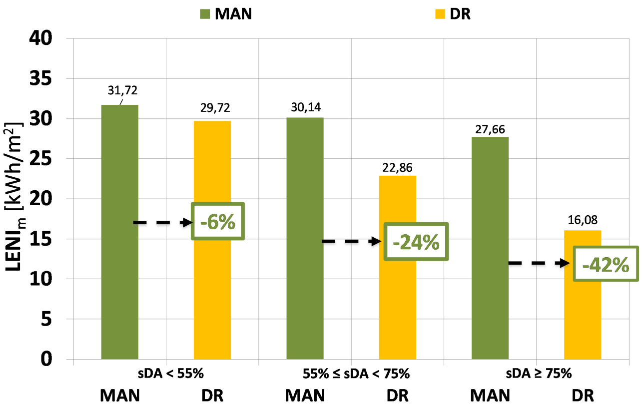


Figure 8 - Mean LENI values and percentage differences for type of control system.

In conclusion, the energy savings that can be obtained combining the effect of increasing daylighting (moving to higher sDA classes) and introducing a daylight responsive control system ranges between 29% and 74% with a mean value of 49%. These values were calculated from the LENI reported in Table 3, comparing the cases with $sDA_{300,50\%}$<55% and MAN lighting control with the cases with $sDA_{300,50\%}$≥ 75% and DR lighting control: minimum (29.90 kWh/m^{2}a) vs. maximum (21.30 kWh/m^{2}a), maximum (32.90 kWh/m^{2}a) vs. minimum (8.40 kWh/m^{2}a), average (31.72 kWh/m^{2}a) vs. average (16.08 kWh/m^{2}a) respectively.

3.3. Daylight availability and overall energy performance evaluation

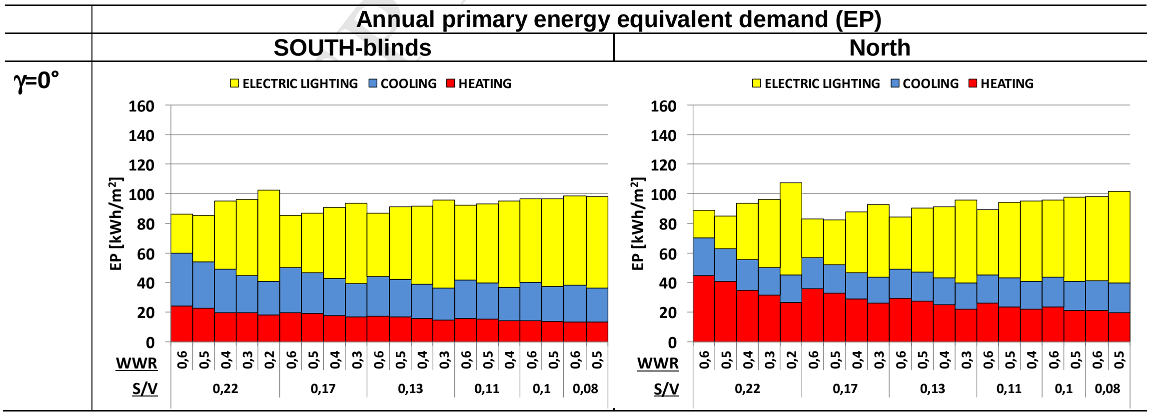
The parametric analysis conducted in EnergyPlus using the jEplus interface allows the total energy performance of a room with multiple design options to be studied.

This section focuses on how a design strategy based on the optimization of daylight can influence the total energy demand of a room (EP_{tot}). As explained in the previous paragraph, an optimized daylight exploitation corresponds to an increase in the $sDA_{300,50\%}$ and to the use of a daylight responsive lighting control system. For this reason, this second part of the study will only focus on the results that were obtained for cases with a daylight responsive dimming system (DR) in order to analyse the influence of increasing daylight on the total energy demand of the room.

The results shown in Figure 9, which are expressed in terms of primary energy, with a conversion factor for electric energy of 2.17, refer to North and South-facing rooms located in Turin with a glazing visible transmittance of 70% and external obstruction angles of 0°, 30° and 60°. In the graphs, the Room Depth was shown on the x-axis in terms of S/V ratio (surface that is exposed to the outdoor environment to the heated space volume ratio).

Among the different energy services, the electric lighting represents the main contribution to the total primary energy demand counting as heating and cooling added together in the rooms with a low sDA.

As far as the effect of the orientation is concerned, the South-facing rooms without external obstruction (γ=0°) reveal a lower heating demand mainly because of the benefit of the direct solar radiation coming into the space, but at the same time a higher lighting and cooling demand than North-facing rooms. Increasing the obstruction angle results in an increase in the lighting and heating energy demand for South-facing rooms and in a decrease in the cooling energy demand, mainly because of the lack of direct solar radiation, which is blocked by the external obstructions.



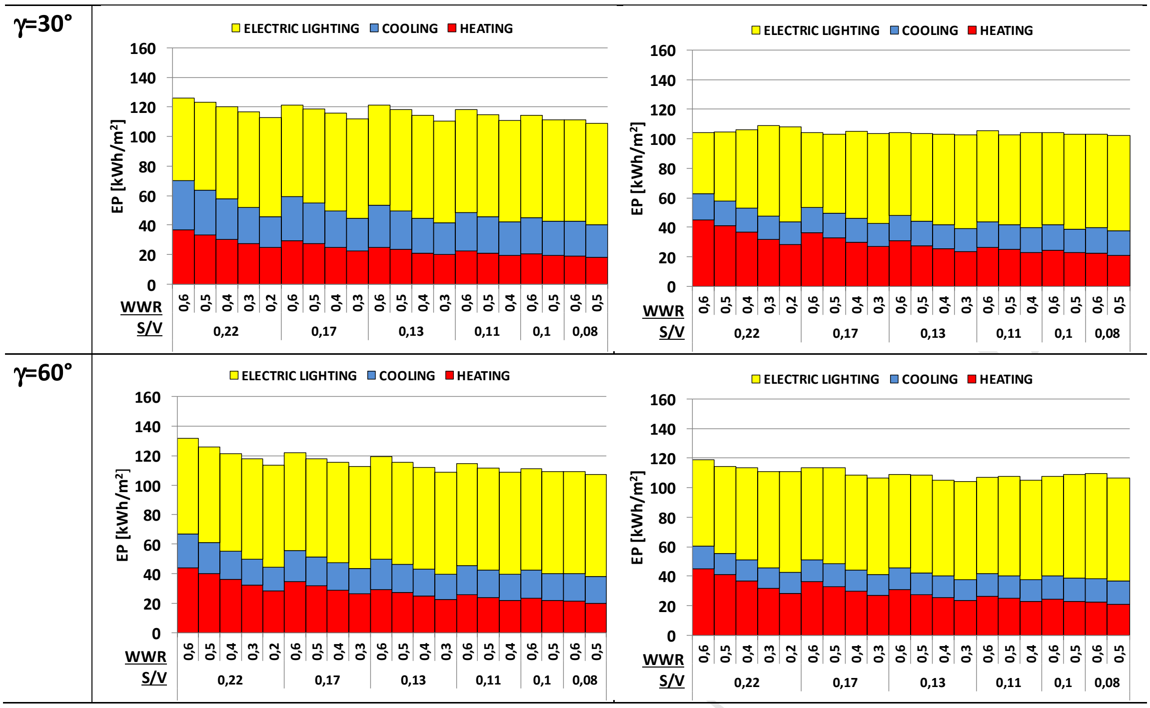


Figure 9 - Annual primary energy demand (EP) for lighting, heating and cooling for South and North-facing room configurations with γ=0°, 30° and 60°.

As regards the total energy demand variation, the most influencing factor is the external obstruction angle: on the South-facing rooms an increase of γ from 0° to 30° causes an increase in the total energy which is around 20%. Therefore the negative effects of a reduction in daylighting and in the solar gains in winter prevail over the positive effect of reduction in solar gains in summer. This also depends on the higher efficiency of the cooling system in comparison with the heating system and with the lighting system.

In order to analyse the influence of increasing the daylighting level, a comparison between $sDA_{300,50\%}$ and primary energy demand for lighting, heating and cooling values was carried out and shown in Figure 10. The entire database of results was divided according to the spatial Daylight Autonomy classes.

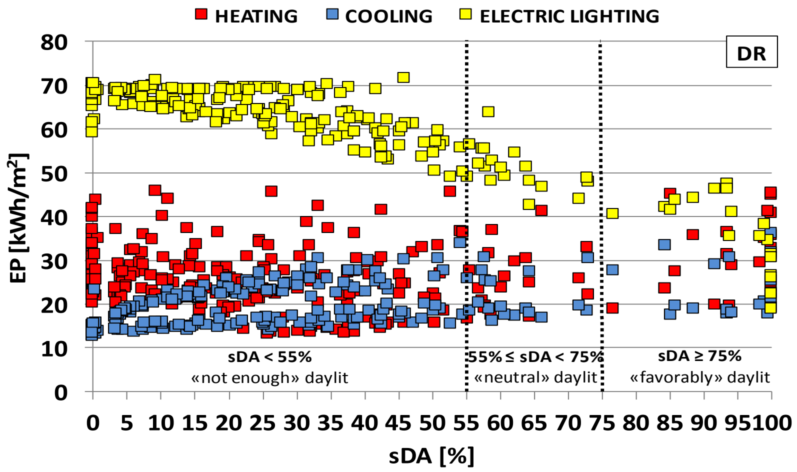


Figure 10 - Overall database of EP for lighting, heating and cooling and sDA results (Daylight Responsive dimming system).

Furthermore the mean primary energy demand for lighting, heating and cooling together with the mean total primary energy demand ($EP_{tot,m}$) were calculated for each performance class of $sDA_{300,50\%}$, as shown in Figure 11.

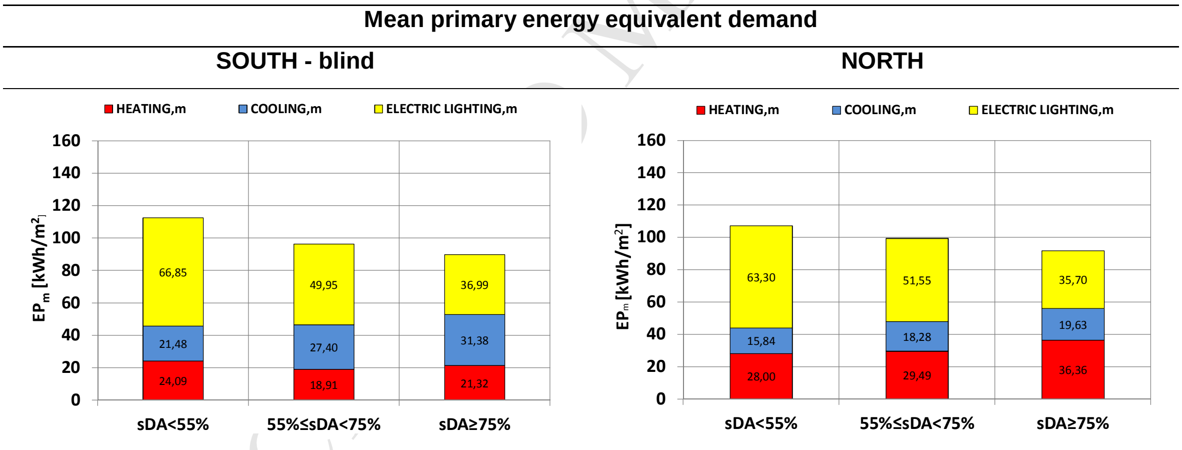


Figure 11- Mean EP for lighting, heating and cooling and mean EP_{tot} for each sDA performance class.

The variation of $sDA_{300,50\%}$ has different effects on South and North orientations. For the South orientation the increase in the $sDA_{300,50\%}$ doesn't affect the heating sensibly, while the cooling demand sensibly increases even if it is more than balanced by the decrease in the lighting demand. For the North orientation, on the contrary, the increase in the $sDA_{300,50\%}$ slightly increases both heating and cooling, but this effect is completely balanced by the decrease in the lighting demand.

It could be noted that the higher the daylight amount in a space ($sDA_{300,50\%} \geq 75\%$), the lower the total primary energy demand ($EP_{tot,m}$). For both South and North-facing rooms, $EP_{tot,m}$ is lower for 'favorably' daylit spaces ($sDA_{300,50\%} \geq 75\%$) than for insufficiently daylit spaces ($sDA_{300,50\%} < 55\%$). For South-facing rooms $EP_{tot,m}$ is 112.4 kWh/m^{2}a when $sDA_{300,50\%}$ is below 55% and 89.7 kWh/m^2·a when $sDA_{300,50\%}$ is above 75%. The mean global reduction that can be obtained is 20%. For North-facing rooms $EP_{tot,m}$ is 107.1 kWh/(m^2a) when $sDA_{300,50\%}$ is below 55% and 91.7 kWh/(m^2a) when $sDA_{300,50\%}$ is above 75%. The mean total reduction that can be obtained is 14%.

In Figure 12 the primary energy demand for each room configuration modelled is shown. A red, dotted border is used to point out the room configurations which achieve a sDA ≥ 55 % (sufficient or favorable daylighting condition).

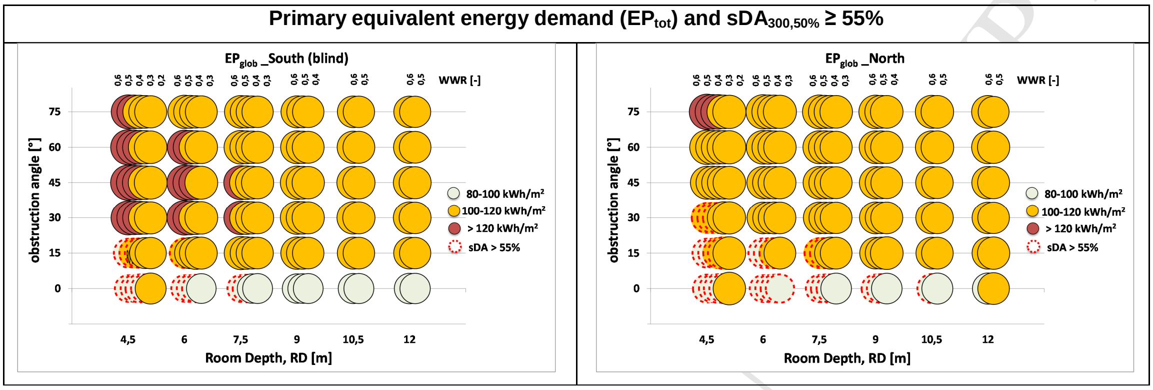


Figure 12 – Primary energy demand for each room configuration modelled.

4. Conclusions

The study presented in this paper investigated the relationship between buildings features, indoor daylighting, electric lighting energy demand and total energy demand (lighting, heating and cooling) of rooms with unilateral fenestration that might be representative of different types of offices, from single perimeter offices to open plan spaces. The room features were changed in terms of room depth, window to wall ratio, external obstruction and window orientation, while glazing visible transmittance, reflectance of internal surfaces, and climate conditions were kept constant. The assumption of a specific climate condition reduces the possibility to generalize the results of the study. Nonetheless, the climate condition of Torino can be assumed as representative of large areas in the North of Italy and in general of regions with subtropical climates. Furthermore, the electric lighting energy performance was calculated taking into account an installed power density of 12 W/m^2 and two different lighting control strategies: a manual on/off switch control and a daylight responsive dimming control system, while to assess the total energy demand only the DR control system was considered. To calculate the heating and cooling loads the room surfaces were considered adiabatic with the exception of the wall with windows. The input parameters that were assumed are consistent with Italian best practices and Standards.

The analysis was carried out using Daysim for the lighting simulation (to get more precise results in terms of daylight illuminance distribution) and integrating the Daysim output in EnergyPlus for the energy simulation.

The first step of the analysis was focused on the daylighting with respect to the room architectural features and the sDA metric was used to assess the “sufficiency” of the obtained daylighting condition, taking into account both the temporal and spatial domains. The results pointed out that the North-facing rooms achieve higher daylighting (the sDA for North facing rooms exceeds the one for South facing rooms of 10% on average, with maximum difference of 36%). The difference is due to the presence of a blind in the South-facing rooms, used to reduce glare and overheating and, to an even greater extent, to the specific optical features and control algorithm implemented in Daysim. Different shading systems or control models would determine different results.

The overall dataset of results, condensed in graphical tool, allowed which combination of rooms architectural features determined an insufficient, acceptable or favourable daylighting condition to be pointed out. A significant result, showed in the graphs, concerns the impact of external obstruction: nearby buildings, which cause an obstruction angle greater than 30°, drasti cally reduce daylight, determining sDA values always below 55%.

The second step of the analysis was aimed at evaluating the energy demand for lighting and the energy savings that can be achieved increasing the daylight exploitation. The results highlighted the theoretical potential of daylight responsive control systems in reducing energy consumption, especially when rooms are designed to have at least sufficient (sDA>55%) or, even better, favourably (sDA>75%) daylighting conditions. In this latter case the energy saving with respect to a manual on/off switch can be 42% on average.

As regards the assessment of the total energy demand, the results highlight the predominance of lighting over the other energy services and the significant correlation between the increase in daylighting and higher total energy savings. Nevertheless, the dominance of the lighting use is affected by the value of the primary energy conversion factor and the conclusions could be different in countries where the primary energy factor conversion for electricity is lower.

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Highlights

- Thermal and daylighting analysis is carried out in synergy.
- The parametric study considers all affecting factors
- The energy potential savings are correlated to different classes of daylighting performance (sDA)
- The results are intended to be used in the earlier stages of the building design process.