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Light versus energy performance of office rooms with curtain walls: a parametric study

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Abstract

A parametric study aimed at identifying the best performing solution in terms of lighting, heating and cooling demand minimization for an office room is presented. Different orientations, room and façade lay-outs, glazing and lighting control systems have been combined and 192 configurations have been analysed through a two-step process: daylight factor and dynamic daylighting metrics and the corresponding energy demand for lighting were calculated in step 1 using Daysim; the energy demand for heating and cooling was determined in step 2 using a quasi-steady state approach, to verify whether the best configurations obtained in step 1 also resulted in the lowest global energy demand.

1. Introduction

The issue of directives and legislations, aimed at reducing energy consumption in private and public buildings, has noticeably changed the focus of the building design approach over the last decade. Attention towards the global energy performance of buildings, which results from the energy consumptions for heating, cooling, lighting and hot sanitary water, has increased as a consequence [1-2]. Accounting for all these energy demand contributions plays a crucial role in pursuing the goals set by the European Union to reduce building energy consumption [3] and in promoting the diffusion of Zero or Near-Zero Energy Buildings [4]. Moreover, new technologies have been developed and made available to enhance the performances of building façades, mainly pertaining to an increased use of advanced transparent components, such as selective low-e double/triple glazing, double skin façades or mechanically ventilated transparent façades.

In this context, a detailed research activity has been carried out in the Department of Energy at the Politecnico di Torino, focusing on assessing the role played by the transparent components on the overall energy performance of an office room. In this research, the performances of innovative transparent

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configurations have been tested in a dedicated facility, named "twins cells": the main results of these measurements were presented in [5-6]. Similarly, the performances of an active transparent façade have been investigated through field measurements in a specifically set-up mock-up of a real high rise office building: the first results of these campaigns have been published recently [7]. This paper also presents the results of a parametric study that was carried out to analyze the lighting and energy performance of an office room with different lay-outs, in the presence of an opaque or transparent façade equipped with different glazing technologies and in the presence of different lighting control systems. The study had the final aim of highlighting the best performing solutions that were able to minimize the global energy performance index of the room. This index was obtained by separately calculating the energy performance indices for lighting, cooling and heating and then summing them together. The best performing solution was then derived from the trade-off between the lighting and the summer and winter air conditioning energy requirements.

2. Methodology

The study was based on an analysis of an existing office building in Moncalieri (a town in the suburbs of Turin, lat.: 45.0°N, long.: 7.7°E) which had to be refurbished due to the obsolescence of the existing façade [8]: starting from the geometries of both the façade and the internal lay-out of the case study, different optical and thermal solutions of three parts of the façade were analyzed to cover a wide range of glazing that would be able to control the thermal losses, solar gains and the daylight admitted to the spaces, adopting high-performance conventional components, according to the clients' requirements. The lighting controls were also changed to assess how the available daylight in the rooms would be exploited and how this would influence the energy performance of the rooms. The study was subdivided into two phases:
a) selection of the variables that had to be used in the parametric study, as well as their ranges
b) a two-step analysis: each room configuration was analyzed in detail in step 1 in terms of daylighting performances (daylight factor and illuminance values) and of the corresponding energy demand for lighting, in order to highlight the most valuable configurations; each configuration was then analysed in step 2 in terms of the energy cooling and heating demand. At the end of the two-step process, the *global* (lighting + heating + cooling) primary energy demand was derived for each configuration, with the final aim of verifying whether the best configurations obtained from the lighting analysis also resulted in the best global energy performance (in terms of the lowest global energy demand values for the room) or, alternatively, whether the most promising lighting solutions resulted in a lower global energy performance, thus highlighting in this case a different set of 'best performing' solutions.

2.1. Variables used for the parametric study

The existing building is a 7-storey building with a modular façade, in which each module is 4.8 m wide and 3 m high (floor-to-floor distance) and which is further subdivided into four vertical stripes and three horizontal stripes: the upper stripe, the window head, and the lower stripe, the balustrade, are both 0.73 m high, while the central stripe (1.54 m high) contains the windows (three glazing plus a 8.5 cm thick frame). This horizontal subdivision allows a great flexibility to be obtained, as different technologies can be applied to each area: for instance, a selective double pane glazing can be installed in the central stripe to reduce solar gains in summer and heat losses in winter and to allow a great amount of daylight into the room, while a translucent glazing and an opaque panel could be used in the upper stripe and in the lower stripe to screen direct solar radiation and to further reduce thermal losses in winter.

The variables that were changed to carry out the parametric study were set as follows:
- *orientation*. The building has both a south-north and an east-west orientation, therefore the orientation was treated as a variable in order to investigate the role played by the solar radiation hitting the façades
- *room lay-out.* Two typical lay-outs of the internal spaces were considered: private cellular perimeter offices and a large open-plan office. Each cellular office had the same width as one façade lay-out

module (4.8 m) and a depth of 6.6 m: the corridor in the center of the building had no access to daylight. The open-plan office had a width equal to three façade modules (14.4 m) and a depth equal to the depth of the building (18.6 m)

- *glazing*. Five transparent technologies were considered to assess the influence of the glazing parameters, that is visible transmittance (τ_{vis}), solar factor (g-value) and thermal transmittance (U-value), on the global energy demand of the considered room. Fig. 1 summarizes the five transparent components typologies that were used in the study. All the typologies include a double pane glazing to reduce thermal losses in winter; one glazing pane was kept clear, while the other one was changed from low-emitting to selective and to translucent glazing. An opaque panel was also considered
- *lay-out of the façade module*. The five glazing typologies were combined on the basis of the subdivision of the façade module into three horizontal stripes, to obtain four lay-outs, which are shown in Fig. 2. These four lay-outs were selected to be representative of commonly used solutions, aimed at privileging the lighting aspect, the thermal aspect, the aesthetical purpose or a combination of these aspects. The four configurations consisted of: a) three transparent glazing installed in three horizontal stripes (window-to-wall ratio WWR=0.85); b) two opaque panels in the upper and lower stripes (WWR=0.40); c) a clear glazing in the central stripe, a translucent glazing in the upper and the lower stripes (WWR=0.85); d) a translucent glazing installed in the upper stripe and a clear glazing in both the central and the lower stripes (WWR=0.85). The opaque panel was coupled to an insulating panel and an internal timber-frame panel, in order to reduce thermal losses in winter and to compensate for the reduction in the daylight amount globally admitted into the rooms
- *presence of a blind*. Configurations with and without a shade were simulated. The shade was a roller blind that blocks direct sunlight and transmits 25 percent of diffuse daylight, which was automatically lowered as soon as direct sunlight above 50 W/m^2 hit the working plane and retracted otherwise [9].
- *lighting control*. Two different configurations were assumed: a manual on/off switch activated by the users and a daylight responsive automatic control (DR), operated by a photosensor which measures the illuminance over the working plane and, through a closed-loop control, dims the light output whenever the measured illuminance is under the threshold of 500 lux, or switches off the lights whenever the illuminance is over the threshold. A lighting power density (LPD) of 12 W/m^2 was assumed and a stand-by power of 0.10 W/m^2 and a ballast loss of 10% of the LPD were associated to the DR control.

The combination of all the above described variables yielded a total of 192 configurations.

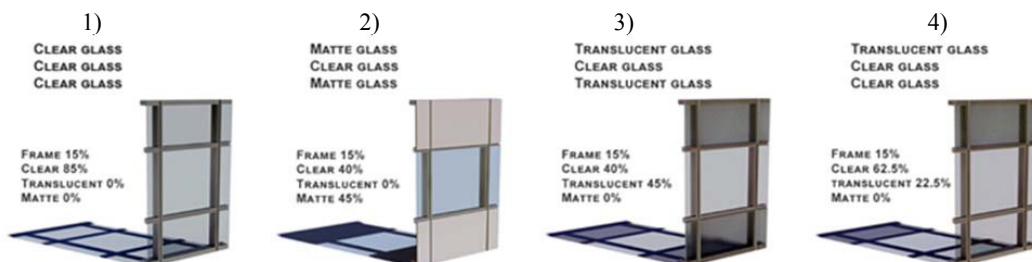Fig. 1. Characteristics of the five typologies of glazing used in the parametric study.

Fig. 2. Characteristics of the four lay-outs of the façade module used in the parametric study.

2.2. A two-step analysis to identify the best configurations to reduce the global energy demand of a room

2.2.1 Step 1: analysis of the lighting performances

This analysis had two different but interconnected aims: a) to calculate the daylight available for all the 192 room configurations; b) to calculate the corresponding energy demand for lighting, considering integration with electric lighting.

As for as the daylight amount is concerned, the index prescribed by the Italian legislation was used, that is the average daylight factor, DF_m. A greater value than 1% is required for offices, according to the Italian Law Decrees in forces. Stricter requirements have recently been introduced in building environment rating systems: for instance the national ITACA protocol [10] grants a credit of 3 points if $DF_m \geq 2.6\%$ and of 5 points if $DF_m \geq 3\%$. The lighting analysis was extended to include the recent Dynamic Daylighting Performance Metrics (DDPM) [11], which (unlike the DF) accounts for the specific climatic conditions of a site (dynamic sunlight and skylight variation throughout the year), the occupancy profile of a room, the presence of blinds and the occupants' behavior towards shading and the lighting systems. Among the group of DDPMs, the following were used: Daylight Autonomy, DA; continuous Daylight Autonomy, DA_{con}; maximum Daylight Autonomy, DA_{max}. Both the DF and the DDPMs were calculated by means of the Daysim software package. Ecotect was used to create the 3D model and to assign its pertinent Radiance compatible material to each surface and then to launch Daysim to run the annual simulation.

The energy demand for lighting ($ED_{lighting,room}$) was also calculated with Daysim, considering the LPD of the room and the parasitic power due to the sensors (occupancy or photodimming) and to the ballasts. From the legislation viewpoint, it should be stressed that no prescription is at present available for a limiting value of $ED_{lighting,room}$: the recommended maximum value of 10 kWh/m^{2}yr [12] was thus used as a reference.

2.2.2 Step 2: analysis of the heating/cooling performances

The assessment of the cooling and heating energy demand for the considered room was carried out for all of the 192 configurations of the parametric study. It was calculated on a monthly basis, assuming a quasi-steady state, according to the procedures specified in the UNI-TS 11300-1 technical standards [13-15], on the basis of the methodology adopted in EN 13790 [16]. The energy demand for cooling ($Q_{cooling,room}$) and for heating ($Q_{heating,room}$) was calculated using a specifically developed Excel™ spreadsheet in which all the equations defined in the UNI-TS standards were implemented. According to the technical standards, two temperature values, equal to 20°C and 26°C, were assumed as set-points for the heating system (winter season) and for the cooling system (summer season), respectively. The internal gains and the air exchange rate were assumed to be 6 W/m^2 and 1.43 m^3/h [13], respectively.

All the energy demands were transformed into primary energies (in tonnes of oil equivalent [toe]) and summed to obtain the global energy performance index EP_{gl}, through the following formula [17]:

$$EP_{gl} = EP_h + EP_c + EP_{dhw} + EP_l \qquad (1)$$

where EP_{gl}, Ep_h, EP_c, EP_{dhw} and EP_l are the energy performance indices (global, for heating, for cooling, for domestic hot water production and for lighting, respectively) of the building, in [kWh/m^{3}yr].

At the end of the process, it was possible to quantify the global energy demand and the weight of each system, lighting or HVAC, on the final consumption for each configuration. The huge database of results was progressively reduced by eliminating the cases with the highest EP_{gl} values for each combination of variables and a set of configurations which represented the best solutions was thus derived.

3. Results

3.1. Results of the parallel lighting and cooling/heating analyses

For the sake of brevity, only the data relative to the cellular offices are reported. The results are summarized in Figures 3-4. It can be observed that the minimum daylighting requirement, according to the Italian legislation ($DF_m \geqslant 1\%$), is met for all the analyzed configurations. Apart from a few exceptions, all of which have the lowest τ_{vis} of 41%, the cases also all meet the strictest requirements ($DF_m \geqslant 3\%$ [10]). A high daylight amount in all the rooms has also been confirmed from the DDPM values: generally $DA_m \geqslant$ 60%, i.e. a 'good' daylight availability according to Rogers [18] and $DA_{con,m} \geqslant 80\%$ ('optimal' value).
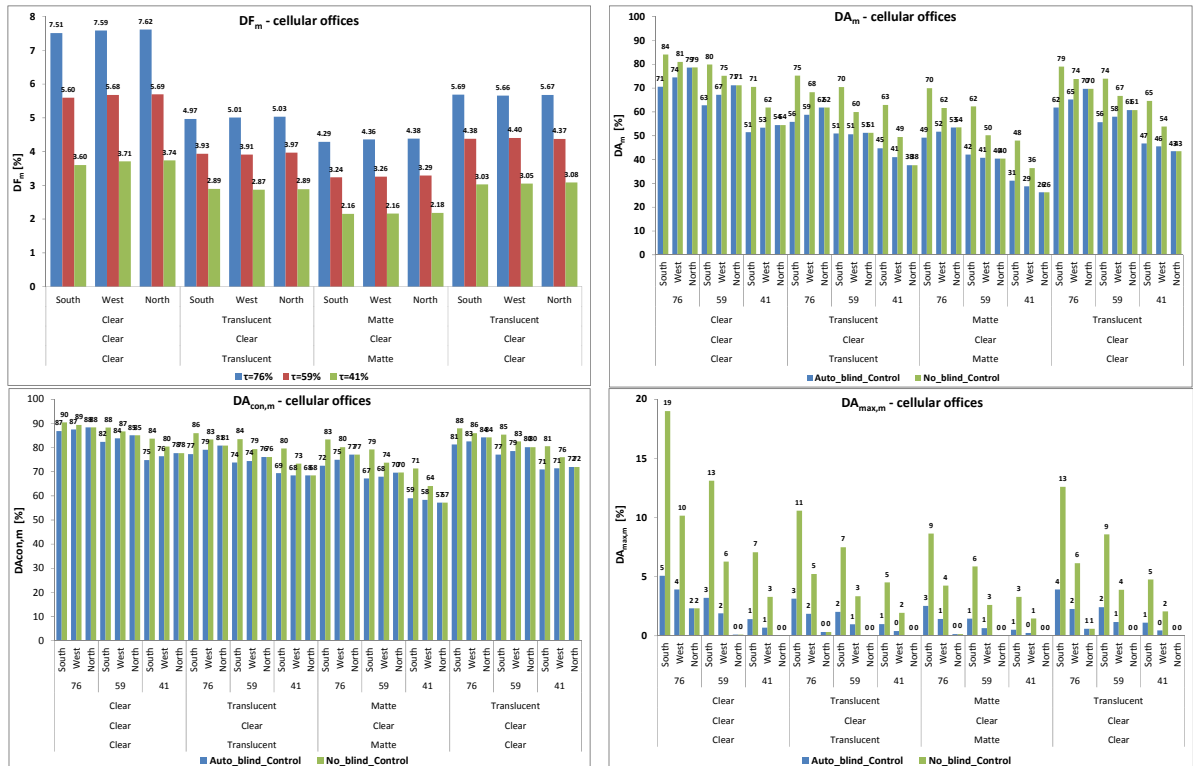

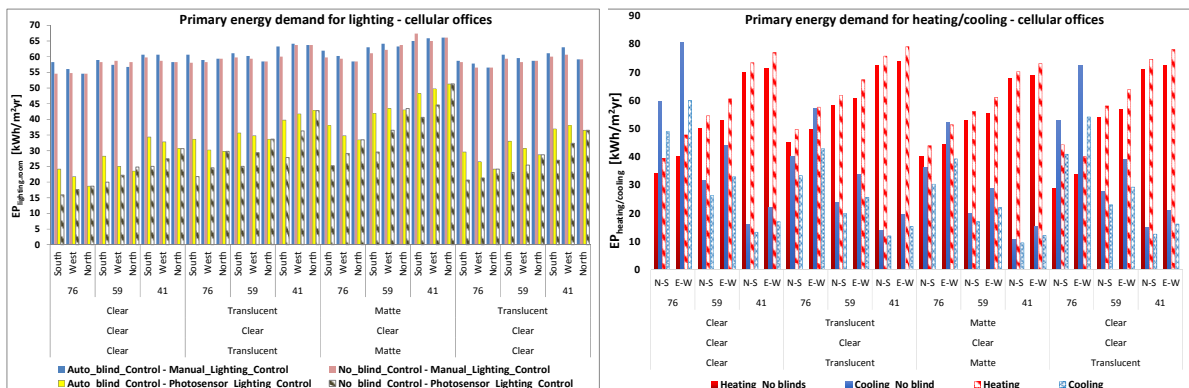Fig. 3. Daylighting results for the parametric study: average DF, DA, DA_{con}, DA_{max}.

Fig. 4. Results of the parametric study for the primary energy demand for heating, cooling and lighting for all the configurations.

As can be expected, the results of the two parallel analyses are somewhat contradictory (Fig. 4): from the lighting viewpoint, the best cases are characterized by the highest transparency of the façade (clear-clear-clear lay-out) with higher visible transmittances, as this allows a greater amount of daylight to enter the rooms. Instead, from the heating and cooling viewpoint, the cases with opaque stripes in the façade are the best performing, as they reduce thermal losses in winter and solar gains in summer. For example, for a north-south orientation, the case with the lowest $EP_{heating,room}+EP_{cooling,room}$ value (56.2+17.1= 73.3 kWh/m^{2}yr) was the one with two opaque stripes, a clear selective glazing (τ_{vis}=59%) and a moveable blind, while the configuration with the lowest $EP_{lighting,room}$ value (15.9 kWh/m^{2}yr) was the south-facing one with three stripes, a clear + low-e double glazing (τ_{vis}=76%), without blinds and with a DR control. The $EP_{lighting,room}$ value for the best cooling/heating configuration was 35.60 kWh/m^{2}yr (+124% with respect to the lowest value), while the $EP_{heating,room}+EP_{cooling,room}$ value for the best lighting configuration was 94.1 kWh/m^{2}yr (+28.4% with respect to the lowest value).

As a consequence, it appears evident that defining the most valuable configurations, in terms of global energy performance, requires a trade-off between lighting and heating/cooling performances.

3.2. Results in terms of global energy demand: definitions of the best performing configurations

The 192 result database, obtained in terms of global energy performance index (EP_{gl}), is summarized in Fig. 5: both the individual and global energy indices in [toe] and the percentage of each index with regard to the global index are shown. Considering that the final aim of the study was to highlight the best performing configurations, in terms of minimum EP_{gl} values, a progressive 'elimination' of the worst performing configurations was carried out, on the basis of the following criteria/steps:

I) it appeared clear that the entire sub-dataset of configurations with a manual on-off switch lighting control were characterized by higher values of the $EP_{lighting,room}$ and of EP_{gl} than the corresponding configurations with a daylight responsive lighting control. This result was expected considering the principle on which these two controls are based. As a consequence, all the configurations with a manual on-off control were eliminated; 96 configurations remained for further analyses
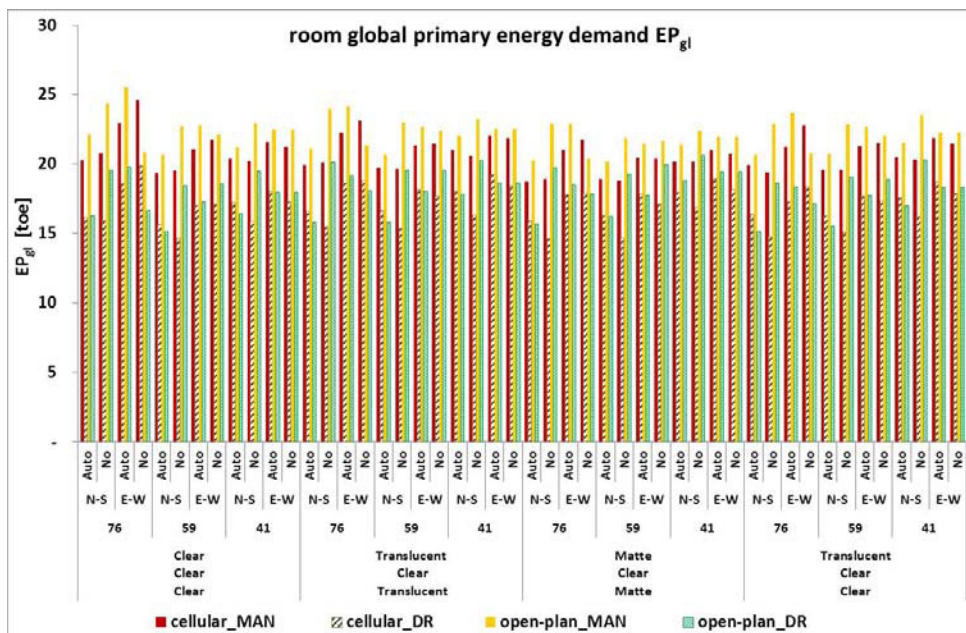

Fig. 5. Whole database of EP_{gl} values for the 192 configurations.

II) focusing on how the presence of the moveable blind influences the results of the database, it was not possible to observe a constant trend, unlike for the previous step: for approximately half of the configurations the global energy performance indices were higher in the presence of a shading system than in its absence, but the opposite applied for the other half of the database. In order to decide which configurations to maintain and which to eliminate, a comfort rather than an energy criterion was applied: the configurations without the shading systems were eliminated as they are more likely to cause glare problems for the occupants, especially in winter: as shown in Fig. 3, with the moveable shading system, the average DA_{max} are lower than 5% for all of the spaces, while it rises up to 20 % for unshaded spaces**.** As a consequence, 48 configurations remained for further analyses

III) the variables that needed to be further analyzed were the room lay-out, the lay-out of the façade module, the typology of glazing and the room orientation, while the presence of a moveable blind and the use of a daylight responsive lighting control system were treated as constant. Fig. 6 shows the variation in the EP_{gl} in [toe] for the different glazing typologies and for the orientation in a disaggregate way, for each room lay-out and for each façade module lay-out. The histograms reveal how the global energy consumption is higher for east-west facing rooms than for north-south rooms. This latter orientation showed a higher consumption of lighting for some configurations, due to the lower amount of direct solar radiation that hits the north façade, although the global consumption is lower. The analysis was then restricted to just the north-south facing room configurations

IV) the EP_{gl} values of the remaining configurations are shown in Fig. 7. The histograms highlighted that the best performing façade lay-out was the same for both room lay-outs (clear-clear-clear - labeled 1 in the figure), even though the typology of glazing was different: three selective glazings with τ_{vis}=59% for the cellular offices, three low-emitting glazings with τ_{vis}=76% for the open-plan offices. The higher transparency resulted in a slightly higher global energy consumption (16.83 versus 15.62 toe).

Fig. 6. Variation of the EP_{gl} values as a function of orientation vs. glazing type and façade lay-out (step III).
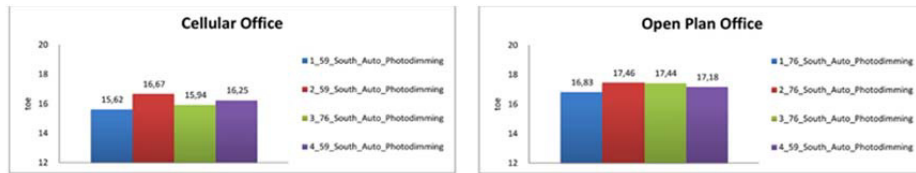
Fig. 7. EP$_{gl}$ values as a function of the façade lay-out vs. the glazing type (step IV).

At the end of the selection procedure, the most performing configuration for the north-south cellular offices resulted to be a fully glazed façade, with a selective glazing (τ_{vis}=59%, g=0.37, U$_g$=1 W/m^{2}K), blinds and a daylight responsive control. Open-plan offices offer a slightly higher energy consumption, but perform less from the daylight availability point of view.

4. Conclusion, discussion and future work

A parametric study has been carried out to identify the best configurations to minimize the global energy demand for lighting, heating and cooling in an office building, on the basis of a combination of design options in order to guide clients in the choice of the most energy efficient retrofit solution. The analysis was then extended to generalize the results and to provide the design team, from the earliest design stages, with tools to address the preliminary choices concerning orientation, building lay-out, the presence of moveable blinds, façade lay-out (opaque/transparent horizontal stripes), the optical and thermal properties of glazing and lighting control systems. The following information emerged for each variable:

- *orientation*: when a new office building is designed, it should be conceived with a north-south orientation to minimize the global energy consumption
- *room-lay-out*: the presence of peripheral cellular spaces and corridors in the center of the floor plan results in a lower global energy consumption than that of the open-plan offices, mainly because of the limited penetration of daylight into the back part of the spaces
- *presence of a moveable blind*: the results of the parametric study do not show any univocal optimal solution (with or without a moveable shading system) for the purpose of minimizing the global energy consumption. The use of a moveable blind is preferable, from the point of view of the visual and thermal comfort for the occupants, as the solar radiation entering the space can be controlled more easily
- *lighting control system*: the presence of an automatic daylight responsive control system, rather than a manual on/off switch, guarantees a reduction in the global energy consumption of the building as a consequence of the reduction in the energy demand for lighting
- *lay-out of the façade module and glazing typology*: a fully transparent façade shows the lowest global energy consumption. From the heating/cooling energy consumption viewpoint, a façade module with an opaque head and balustrade represented the best solution as it reduces the thermal losses in winter and overheating in summer, but this advantage is overwhelmed by the reduced energy demand for lighting throughout a year due to the fully transparent façade. For the case of cellular offices, selective glazing with a τ_{vis} of 59% yields the best results, while glazing with a higher τ_{vis} (76%) are needed for open-plan rooms to compensate for the scarce daylight penetration at a distance from the windows. These findings may seem to be in contradiction with the results of other studies [for example 19-21] and with the quite common practice of limiting the WWR in a building façade to less than around 50%. However, it should be noted that the façade lay-out analyzed in this study has taken advantage of a synergic combination of technologies: a high WWR (=0.85) coupled to the use of selective glazing, which optimize the daylight admittance to a room, insulation in winter and control of solar gains in summer, a

moveable blind and a daylight responsive lighting control system. It is worth noting that the clients were happy with this configuration, which was installed through a retrofitting process in the office building.

It is evident that the conclusions drawn in the study are linked to the procedure that was adopted and are therefore somewhat limited: for instance, all the configurations only refer to the town of Moncalieri, as the site was not introduced as a variable in the parametric analysis. However, even though the study did not cover all possible sites or building configurations, it provides, through a rigorous methodology, a set of useful information for a design team on the impact of architectural choices on the energy demand for lighting, cooling and heating during the first stages of a design process, when the use of simulation tools for more detailed calculation is still premature. In this way, designers can be assisted in crucial decisions concerning the façade lay-out, the use of glazing and opaque envelope components and in the choice of consciously adopting a daylight responsive lighting control system and a moveable shading system.

The research activity, which is still on-going, is aimed at developing a tool in Grassopphers to manage Daysim and Energy Plus in order to calculate the global energy demand of a building through dynamic climatic annual simulations of both the lighting and the heating/cooling energy demand, with the final scope of developing a more general tool which would allow the different contributions to the overall energy use to be predicted, without the need to run advanced simulations, from the earliest design stages. For this purpose, the Daysim output concerning lighting energy use throughout the year has been used as input to run annual simulations in Energy Plus and to calculate the global energy use of the building.

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