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Retrofit strategies for the improvement of visual comfort and energy performance of classrooms with large windows exposed to East

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Abstract

The typical orientation of the facades of school buildings, along with the presence of large windows and permanent position of the students, can create uncomfortable environmental conditions caused by eye strain due to glare and local thermal discomfort due to asymmetrical thermal radiation. In this work, the effectiveness of various types of high performance glazing and external shading is evaluated, by means of simulations of visual comfort and energy efficiency. Simulations were carried out for a case study which is representative of a typical classroom of a school, located in a town of Tuscany, where instrumental monitoring of existing thermal and lighting conditions was conducted. The case study was selected through an analysis of energy consumption of the whole school building stock of the city, over a period of five years. The analysis has allowed to select the most critical one in terms of energy consumption and the most representative one regarding the Italian school building stock. The selected building has been analyzed by means of building performance simulation software. A survey about the school users' perception of comfort levels was also carried out by means of questionnaires.

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Keywords: school buildings, daylighting, visual and energy performance, shading devices

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1. Introduction

The problems of overheating and visual fatigue (glare) are very frequent in Italian schools. This is caused mainly by the conflict between the high requirements of daylighting of the schools and the frequency of clear days that characterize the Italian climate. The Italian legislation for daylighting of schools requires that the average daylight

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factor is greater than or equal to 3%. For kindergartens, the national standard UNI 10840 [1] recommends 5% of average daylight factor. This implies that in schools realized from the 70s, the width of the front is frequently entirely covered by windows. Since the use of sun shading devices have been imposed by the Italian legislation only recently, a great number of Italian schools is subject to problems of visual glare and overheating especially during sunny days. The only protection from the entrance of sunlight is frequently given by internal drapes or by reflective glasses which are not enough effective to avoid respectively summer overheating and glare; in addition, they greatly reduce the amount of direct and indirect light that enters the room and force to switch on the electric lighting with an increase of energy consumption. Recently, the spread of the teaching systems that use interactive media further aggravates the problem of glare from natural and electric light [2].

2. Analysis of the case study

The case study for the analysis and definition of intervention strategies was selected through an energy efficiency assessment of all the 10 school buildings of Greve in Chianti (a town near Florence). This assessment was conducted on the basis of actual energy consumption of natural gas and electricity, considering a sample of five years (2008-2012). The energy consumption was related to the heated volume of each building. The heating energy consumption varies between 23.4 and 27.6 kWh/(m^3yr) for kindergartens, between 11.9 and 25.7 for primary schools, and is 36.1kWh/(m^3yr) for the secondary school; the energy consumption for lighting and electric appliances is instead variable between 1.6 and 6.7 kWh/(m^3yr) for kindergartens, between 1.4 and 3.9 for primary schools and is 2.8 kWh/(m^3yr) in the case of the secondary school. Occupancy period is 12 hours per day for kindergartens and primary schools, 14 per day for secondary school. Despite this difference of approximately 10% in the occupation period, results showed that the building with the worst energy efficiency is the secondary school, with total annual consumption of about 10 kWh/(m^3yr) greater than those of the other buildings. Moreover this school, a two-story building built in the 70s, has a very high amount of large windows looking mainly to East, creating problems of visual discomfort to students. The structure of the building is made of reinforced concrete frame, with the external walls realized with lightweight concrete blocks. The windows have an aluminum frame and reflective glass; the heating system is a gas boiler with radiators.

In this building, selected as the case study, a monitoring of indoor thermal and lighting parameters, an IR thermograph analysis and an evaluation of the perception of comfort from users through questionnaires were carried out. The thermography, carried out in December 2013, revealed the low thermal insulation of walls, windows and heating distribution system. The thermohygrometric monitoring was carried out from December 2013 to January 2014; the dry bulb temperature and the relative humidity were measured at regular intervals of 15 minutes in two classrooms (at the ground and at the first floor) and outside. The values of air temperatures (θ) measured during a typical winter period (from 13 to 23 December 2013) are shown in Fig. 1. It can be noted the poor performance of the building envelope and the ineffectiveness of the heating regulation system, which leads to reach the thermal comfort conditions some hours after the start of school. The temperature fluctuation is due to the opening of the windows of the classrooms operated by students, teachers and staff.

Illuminances measurements, carried out on January 2014, were performed in the same two classrooms, with overcast conditions, to detect the daylight factor and the lighting levels. The average illuminances due to daylight with overcast sky in the classroom on the ground floor was about 37 lux, with values ranging from 12 to 100 lux in the various desks. The average daylighting of the classroom on the first floor was about 30 lux, with values ranging as on the ground floor. Illuminances on the vertical plane of the blackboard was equal to 17 lux. The average daylight factor in the classrooms was about 1.8%, less than the minimum value required by Italian law (3%). This very low level of daylighting is due, in addition to the overcast conditions, even to the presence of a reflective glass with light transmittance (τ_v) of just 0.24 (as measured in the site and declared by the manufacturer). The lighting with electric light of the classrooms (8 fluorescent tubes of 36 W each) leads the lighting at the center room to 300 lux, in line with the provisions of Italian standard [1].

In the same period, a questionnaire was filled by students and teachers to compare the data obtained from the monitoring with the feedback of those who normally use the classrooms. Survey questions were based on key issues related to the environmental comfort in classrooms: winter and summer thermal comfort, acoustic and visual comfort and indoor air quality. As regards winter thermal comfort, the classrooms are perceived as "acceptable"

(66%), “not evenly heated” (63%) and “with the presence of drafts” (70%). Summer conditions are considered between "normal" (47%) and "hot" (37%), and the drapes present in the classrooms are considered as the solution to the excessive morning solar radiation (54%), taking into account the fact that Italian schools are closed to students from June to September. The lighting is judged “good” (46%) or “sufficient” (48%), but only if electric lights are always on. The glare from the daylight is instead a general feeling (69%). Finally, the wall where there are the teacher and the blackboard (the south wall) is not considered well-lit (45%).

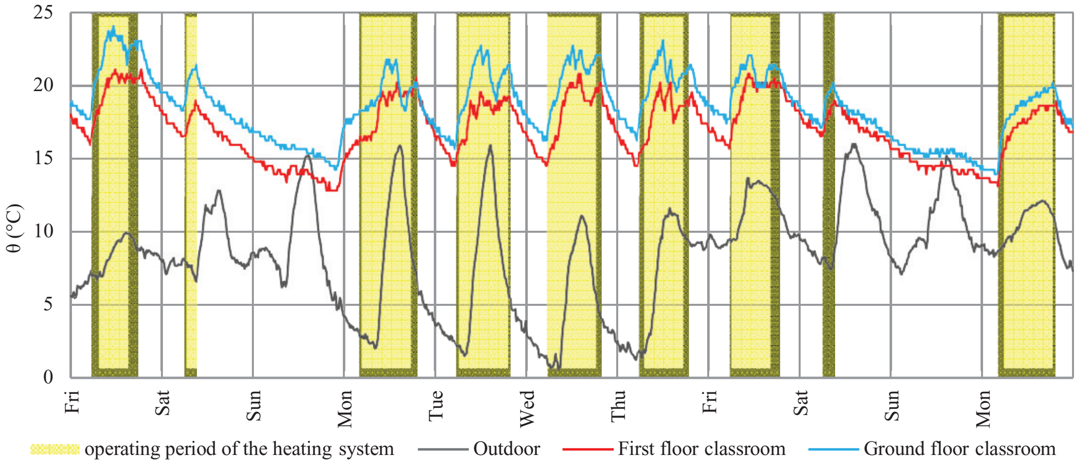


Fig. 1. Time profile of air temperature (θ) in two classrooms and outside

3. Retrofitting strategies applied to the test room

3.1. Methodology and description

The case study, for construction, geometrical and orientation characteristics, as well as for problems detected, is well representative of the majority of schools built in the 70s in Italy; for this reason the monitored classroom at first floor was taken as a test room, on which the performances of different refurbishment strategies were evaluated. These strategies have been selected from those available on the market based on the following main parameters: context of intervention and integration with the existing building, orientation and size of the openings to be shielded, maintenance of visual perception of the outdoor, excluding those configurations overly intrusive or hardly feasible for the building refurbishment [3, 4].

Each strategy was analysed before in terms of daylighting performances (with the calculation code ReluxPro both in condition of clear and overcast sky) and of the corresponding energy demand for lighting, in order to highlight the most valuable configurations; then each configuration was analysed in terms of the energy heating demand (by means of the dynamic calculation code EnergyPlus). The simulations were performed with regards to the opening period of the Italian schools, from 15 September to 15 June. Both for daylight analysis and energy simulation, it was considered that the entry of direct sunlight in the room (on the floor or on the walls) creates visual discomfort (Fig. 2) and then forces the closing of drapes [2]. The closing of drapes, given their low value of light transmission ($\tau_v = 0.3$), always forces switching on the electric lights (as confirmed by questionnaires). In the simulation it was assumed that the electric lighting is turned on when the average level of daylighting in the room is lower than 300 lux. The conditions of opening/closing drapes and switching on/off lights were determined at intervals of two hours (assuming that the closing of drapes and lighting control is normally done in changing teacher) on the following representative days of the year: October 15th, January 15th and April 15th. Electric consumption for lighting was calculated from the nominal power and the number of lamps installed in the room considering the statistical distribution of clear and overcast days derived from satellite Meteosat data [5]. As regard to climate conditions for energy simulation the Test Reference Year (TRY) for Greve in Chianti developed by Nier Ingegneria S.p.A. and University of Bologna, was used and the agreement with sky conditions from satellite data [5] was verified.

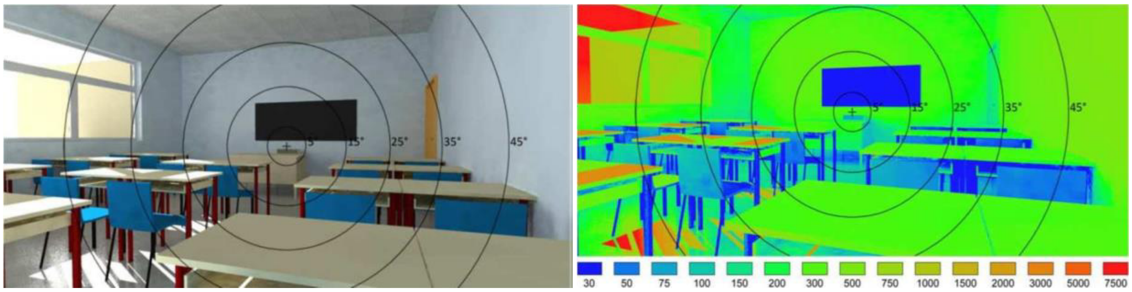


Fig. 2. Simulation of luminance values in a morning hour in the test room (values in cd/m^2)

The test room has a surface of 42m^2 and is suitable for a class of 25 students. The window is almost as long as the facade and is placed at 1m height from the floor; its surface is equal to 9.8m^2 corresponding to about 1/4 of the floor area. It is assumed that the room is located on the first floor of the building. The three interior walls of the room and the floor are considered adiabatic. The external wall, in which the window is inserted, and the roof are considered as outward heat dispersive surfaces. The energy and lighting behaviour of the room has been analyzed for East orientation, considered preferable in typical Italian design of schools and also suggested by the manuals for building design of the 60s [6]. Table 1 shows main characteristics of the test room.

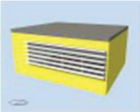
Table 1. Main characteristics of the test room used for simulations

Item	**Description**
Space geometry	Width=7.1m; Depth=5.9m; Ceiling height=3.2m
Exterior wall construction	1.5cm lime and gypsum plaster, 25cm expanded clay concrete brick, 2cm cement plaster; U-value=1.40 W/(m^2K)
Roof construction	1.5cm lime and gypsum plaster, 18cm hollow tile floor, 30cm air gap; 22cm hollow tile floor, 7cm concrete screed, 1cm bitumen sheet; U-value=0.93 W/(m^2K)
Room surfaces	Light reflectance ρ_v=0.8 for walls and ceiling, ρ_v=0.7 for floor
Windows dimensions	Window-to-wall ratio=43%; Window width=5.7m; Window height=1.72m
Window glass	6mm single layer tinted solar control glass; τ_v=0.24; U-value=5.7 W/(m^2K); glass solar factor g=0.43
Window frame	40mm thick aluminum frame without thermal brake; U-value=5.8 W/(m^2K)
Window drapes	Internal dark drapes closed when direct radiation reaches the classroom; τ_v=0.3; solar transmittance τ_e=0.3
Internal heat gain	Occupancy density=0.6 person/m^2; metabolic rate=1.2 Met; weekday occupied hours=08:00-14:00; Lighting density= 6.9 W/m^2
Ventilation	Natural ventilation by window opening=1.43 ach (constant rate) [7]

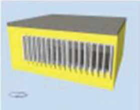
In order to evaluate the different refurbishment strategies, the following performance indicators, defined by regulations or conventionally applied, have been identified: average Daylight Factor DF_m (%) with overcast sky, daylighting uniformity E_{min}/E_{max}(-), electric power consumption for artificial lighting (kWh/(m^3yr)), energy need for space heating $Q_{H,nd}$ (kWh/(m^3yr)), winter solar gains Q_{Sw} (kWh/(m^3yr)) and the percentage of occupied hours when operative temperature (θ_o) is outside the upper comfort limit ($\theta_{i\,max}$). Daylighting uniformity was calculated both for clear and overcast sky conditions as the ratio between average values (in different hours and days of the teaching period) of minimum and maximum illuminances. The hours with θ_o outside θ_{imax} represent the percentage of occupied hours when the operative temperature is higher than the upper limit recommended in EN 15251 Annex A.2 [8] for existing buildings without mechanical cooling systems and with operable windows, category III, corresponding to an acceptable, moderate level of expectation.

Starting from the performance evaluation of the current state of the test room (A), in Table 2 are reported the characteristics of the analyzed strategies. In order to guarantee direct performances comparison, the geometric characteristics of shading devices have been uniformed regarding: slat width and thickness, slat separation and slat tilt, slat material (aluminium).

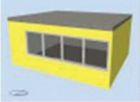
Table 2. Summary of the characteristics of the strategies analyzed



B—Horizontal louvers (tilting: 0°)
Replacement of existing window with a double low emissivity glazing and a thermal brake aluminium frame ($\tau_v = 0.78$, g = 0.60, U-value =2.1 W/(m^{2}K)), external louver shading device made of horizontal blades (blade dimensions: 0.3m depth, 5.7m width; blade spacing: 0.3m; blade thickness: 0.05m; blind to glass distance: 0.1m), internal operable drapes which are closed when direct solar radiation reachesthe internal surfaces of the classroom.



C— Vertical louvers (tilting: 0°)
Replacement of existing window with the same of Phase B, external louver shading device made of vertical blades (blade dimensions: 0.3m depth, 1.72m high; blade spacing: 0.3m; blade thickness: 0.05m; blind to glass distance: 0.1 m), internal operable drapes which are closed when direct solar radiation reachesthe internal surfaces of the classroom.



D— Solar control glass
Replacement of existing window with a double spectrally selective glazing and a thermal brake aluminium frame (τ_v = 0.64, g = 0.4, U-value = 2.1 W/(m^{2}K)), internal operable drapes which are closed when direct solar radiation reachesthe internal surfaces of the classroom.

3.2. Results and Discussion of the simulations

Fig. 3. (a) shows that both the horizontal (B) and vertical (C) louvers increase the Daylight Factor respect to the current state (A), allowing to reach approximately the minimum value of DF_m required by Italian legislation for schools (3%). The solution with selective glass (D) has a greater DF_m with overcast sky, while the best level of uniformity (Fig. 3 (b)) both with clear and overcast sky is achieved with horizontal louvers (B).

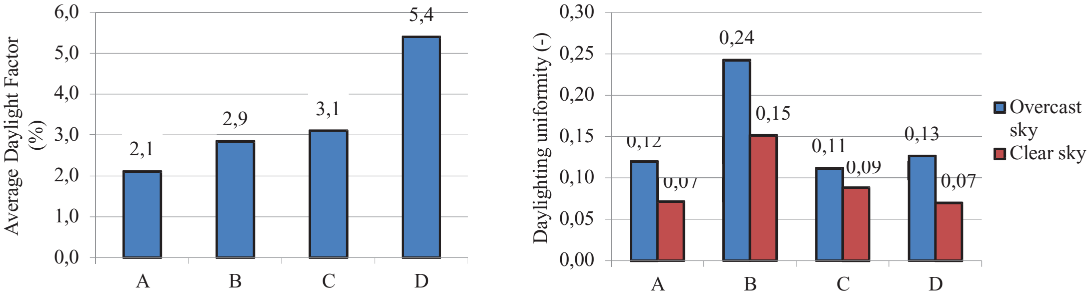


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Fig. 3. (a) Average Daylight Factor and (b) Daylighting Uniformity for the actual situation (A) and the different strategies.

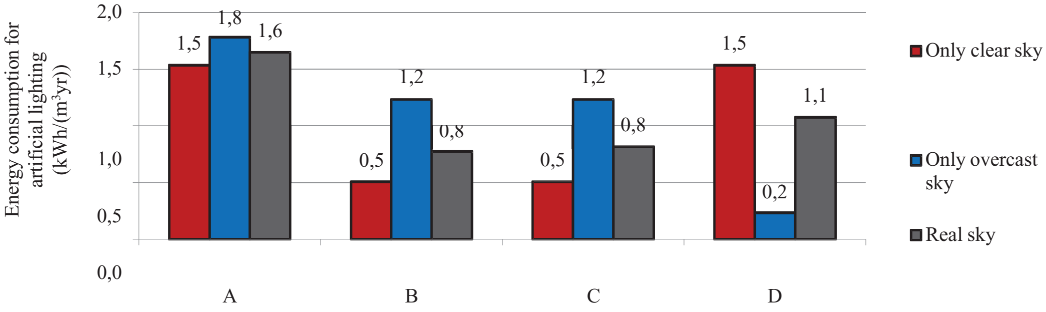

Fig.4. Electric energy consumption for artificial lighting for the actual situation (A) and the different strategies.

Fig. 4 shows that the greatest reduction of electric energy consumption for artificial lighting is achieved in conditions of real sky (according to the statistical distribution of clear and overcast conditions) with horizontal (B) or vertical louvers (C). Under permanent clear sky conditions this reduction would be almost 70% if compared to the actual case (A). In overcast conditions the most efficient system would be instead the selective glass (D).

Fig. 5 (a) shows the energy need for space heating $Q_{H,nd}$(kWh/(m^{3}yr)) and the winter solar gains Q_{Sw}(kWh/(m^{3}yr))for the different strategies compared with the current state (A) of the test room. From the results can be noted that all the strategies, even if involving the use of shading devices, do not reduce winter solar gains, but on the contrary, decrease energy need for space heating between 12% for vertical louvers (C) and 14% for selective glass (D).

As regard thermal sensation, Fig. 5 (b) shows that all the proposed strategies while allowing a greater level of illumination and an increase of solar gains are able to maintain the percentage of occupied hours when operative temperature is outside $\theta_{i\,max}$ below 5% for the entire year. In relation to this indicator, the best configuration is the shading with horizontal louvres (B) with only 1.9% of occupied hours over $\theta_{i\,max}$.

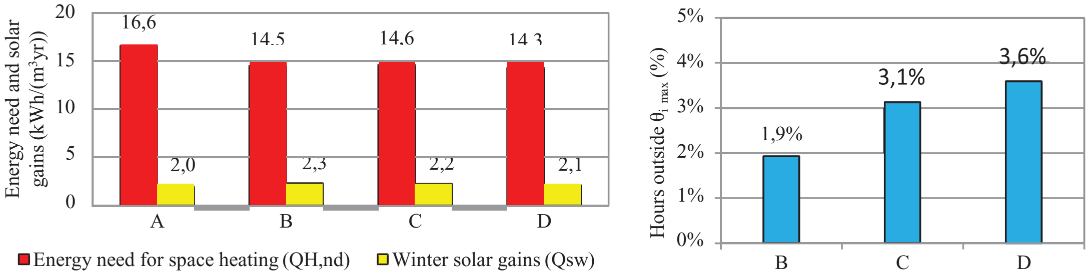

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Fig.5. (a) Energy need for space heating and solar gains for the actual situation (A) and the different strategies and (b) percentage of occupied hours outside $\theta_{i\,max}$ for the different strategies

4. Conclusions

Simulation results show that in the case study analyzed, that can be assumed as representative of many Italian school buildings, external louver shading devices made of horizontal or vertical blades allow the reduction of electric lighting demand and improve the daylighting uniformity, reducing the need of internal drapes.

The reduction of energy consumption for electric lighting with these external devices is higher with clear sky conditions, while in overcast conditions the use a selective glass would be more efficient. In the typical sky conditions of central Italy, the use of external blades is the most efficient solution as they improve the daylight availability without reducing the winter solar gains or producing overheating conditions.

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