Retrofit of school buildings with heavy structure

Interactions between solar control and insulation strategies

ANTONIO CARBONARI[1] MASSIMILIANO SCARPA[1]

[1] University IUAV of Venice, Venezia, Italy

ABSTRACT: This paper present a computer method for evaluating the effects of various retrofit strategies on energy demand and thermal and luminous comfort. The examined strategies are characterized by different types of additional insulation and windows solar control devices. The differences are particularly influencing in case of building with heavy masonry and extended glazed surfaces, such as old schools in Italy. A specifically tailored software has been used. The case study consists in two classrooms of a school in the city of Bologna, in Northern Italy. In order to assess the influence of internal gains and occupation time profile, the same building has been simulated in the case of typical office intended use. The results show that the external insulation is always the most performing, but the differences with the internal one are not relevant in the case of classrooms. The differences increase with the use as offices. All the examined types of slats improve luminous comfort and reduce energy demand for lighting and cooling. Slats inserted between glasses are the best performing ones as they provide daylight and luminous comfort for longer periods. On the other hand, external slats provide better thermal comfort during the warmer period.
KEYWORDS: Buildings Refurbishment, Energy Demand, Comfort

1. INTRODUCTION

Most of the Italian school buildings were built before the 1973 energy crisis, so they need retrofit interventions to reduce the energy demand and improve the indoor environment quality [1,2]. Generally, these buildings have heavy masonry. In these cases, it is critical to define where it is more convenient to place an additional layer of insulation: inside or outside the opaque building envelope elements [3]. Moreover, regardless of the age, these buildings have large windows; therefore, a solar control strategy is necessary to avoid glare and overheating.

In the case of buildings for intermittent use, it is usual to think that it is better to place the insulation inside, in order to obtain a low thermal inertia building, able to respond quickly to the actions of the Heating, Ventilation and Air Conditioning systems (HVAC). However, in practice, the choice is not obvious; the usefulness of thermal inertia depends on a number of factors, such as significant day-night temperature swings, the amount of cooling loads and the length of the daily use period.

As shown by previous research, if the cooling loads are prevalent, the thermal capacity can be useful to take advantage of nighttime free cooling in order to reduce cooling loads in hours of use. Even in the heating period, the heat stored in the thermal mass can be useful to reduce the heating load, especially in the early start-up phase of the HVAC systems. However, there are often practical or regulatory constraints to the placement of the insulation outside, such as in the case of historical buildings.

This work illustrates an application example of a computer method aimed to predict the effects of various retrofit strategies on primary energy demand and on thermal and luminous comfort. The examined strategies are characterized by different types of additional insulation and solar control devices, both internal and external to the widows. The effects of night-forced ventilation during the cooling period were explored too.

In order to assess the influence of internal gains and occupation time profile, the same building has been considered also with a different intended use, i.e. offices.

The computer simulations were performed using a tailored software, which simulates the dynamic thermal and luminous behaviour of a room at hourly time steps, and allows simultaneous energy and comfort analysis, by automatically taking into account the solar control actions [4].

Usually, Italian school buildings are only equipped with a hydronic heating system coupled with radiators. Therefore, due to the high internal and solar gains, with the exception of the colder period, classrooms are often overheated. In order to estimate the energy cost of obtaining thermal comfort, it is assumed that a full air centralized HVAC

Authors ORCID:
1st : 0000-0001-5373-2414
2nd: 0000-0001-8729-5646

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is installed to eliminate overheating and improve air quality. In the air treatment machines, the fluid for the cold water-to-air heat exchangers is provided by electrically driven chillers, while the fluid for the hot water-to-air heat exchangers is primarily provided by the condensers of the chillers, integrated by gas-boilers when necessary. Internal set-point temperatures are assumed to be 20 °C in winter and 26°C in summer (as prescribed by the Italian law), whereas in the middle seasons it is assumed equal to the daily average outdoor air temperature, because the clothing of the occupants is adapted to it. The relative humidity set point is assumed equal to 50% all over the year.

2. THE CASE STUDY

The case studies consist in two classrooms of the elementary school "G. Pascoli", situated in the city of Bologna, in Northern Italy (Fig. 1). The climate of the town is temperate, with cold winter and warm summer; in all the seasons there are significant daily temperature swings.

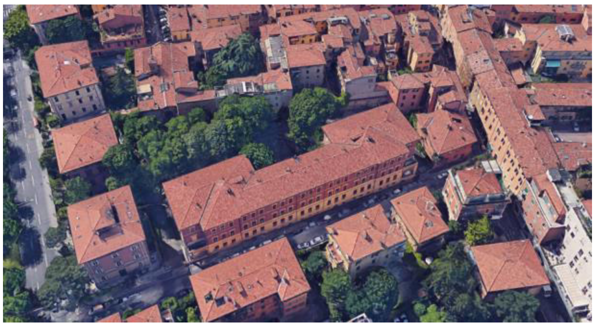

Figure 1: The elementary school G. Pascoli (in the centre).

The school was built in 1915; it has structural internal and external brick walls (0.25 m thick) with plaster on both sides (total thickness 0.3 m), horizontal elements in wood, with superimposed lime mortar and bricks. Vertical wide windows are present. The two classrooms are identical, with the same orientation of the windows (76° East azimuth), and are at the second and the third floors respectively, therefore the influence of surrounding urban obstructions, as regards solar gains and daylighting, is different.

The glazing is assumed to be typical and compatible with the existing standards: double glazing of 0.006 m glass layers and 0.012 air gap with a low emissive layer on the external side of the internal glass (overall U value: 1.8 $W \cdot m^{-2} \cdot K^{-1}$).

Internal sensible and latent thermal gains relating to the presence of twenty-seven pupils and a teacher were taken into account.

An hourly ventilation rate of 15 m^3/occupant was assumed. The hypothesized light system consists of fluorescent lamps (luminous efficacy: 91 lm/W, maximum total power: 756 W). This system is divided into two bands parallel to the external wall. There are no dimmers.

In the case of the offices, six occupants were hypothesized with the related equipment (six computers and one printer), in the same space previously used as a classrooms. A daily occupation period equal to twelve hours was supposed: from 8 a.m. to 8 p.m..

At first, two types of additional insulation layers have been hypothesized: an external insulation consisting of 0.10 m thick rock wool layer with an outer protective layer, and an internal insulation consisting of expanded polyurethane only 0.05 m thick, with an internal layer of plasterboard. These are the thickness values usually adopted in local construction practice, since, in this type of climate, it is not convenient to exceed the thickness of the insulation, given the advantage from heat loss in significant periods of the year. Furthermore, in the case of internal insulation, a greater thickness would reduce the internal space without causing significant energy savings. In a second time, a kind of ventilated wall was also examined.

Currently, the only solar control device is a diffusing curtain inside the windows. This device allows to control glare phenomena, but do not avoid unwanted solar gains, and penalizes daylighting. Instead the solar control strategies examined here are based on various types of packable arrays of tiltable slats: one external to the glasses and two inserted between the glasses, one of the last two has diffusing surfaces, while the other has a specular upper surface (Fig. 2). In the latter two cases the thickness of the air gap is 0.021 m. All the arrays of slat are controlled according to a logic that aims at minimizing thermal loads maximizing daylighting and avoiding glare.

The reflection coefficient of the external slats was assumed equal to 0.6, both in the solar and in the visible spectra, while for those inserted between glasses its value is 0.7 in the solar spectrum and 0.78 in the visible spectrum (these last two values are provided by the manufacturer). In the case of slats with a specular upper surface, the overall reflection coefficients are the same, but it has been assumed that 80% of the reflected radiation is mirrored whereas the rest is diffused.

The external slats are combined with an internal diffusing blind, which is lowered when necessary to avoid glare, while the slats inside the glasses use their inclination for the same purpose. Therefore, these devices are operated at first to minimize the thermal load, and then they can be further operated to eliminate glare phenomena.

The control logic of the mirror slats differs from that of the diffusing slats because, before checking

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the thermal load and the glare, the slats are arranged in such a way as to redirect upwards the direct radiation as deep as possible in the room.

Figure 2: External slats (left), from ©Internorm catalogue, and slats inserted between glasses (right), courtesy of Pellinindustrie S.p.A..

The transparency coefficient of the blind is assumed equal to 0.5 and the reflection coefficient equal to 0.4 on both sides, both in solar and visible spectra. The same characteristics of the blind have been assumed for the current configuration.

To explore the influence of solar gains, a hypothetical south orientation of the external wall was also examined. The effects of an external wall of greater thickness (0.4 m) and with no insulation layer was also simulated, in order to compare the performance of a greater thermal inertia with that of the various insulations.

3. ANALYSIS OF THE RESULTS

In all the following considerations, the reference configuration is the current one: without insulation and with only the curtains inside the windows.

3.1 Energy demand

Because of the high classrooms' internal gains both types of additional insulation result to be useful only during the coldest period. In the half seasons insulations only increase overheating, as they prevent the night's cooling of the masses (Fig. 3). In the warmer period, they have no particular effects because of the reduced heat flows throughout the envelope, due to the higher internal set point temperature (26 °C). The warmer period is June in the case of classrooms; July and August were considered only in the case of offices. The best performing insulation result to be the external one (Fig. 4-5). In the heating period this kind of insulation, allow lower thermal loads because the masses maintain higher temperatures until the early morning. For the same reason his behaviour is worse in the mid seasons. In any case, considering the whole year, the difference between the two types of insulation is contained under the 1% of the total primary energy demand.

Due to the usefulness of the thermal losses during a large part of annual time of use, an operable vented wall has also been studied. In it, a 0.05 m thick interspace void separates the external insulation layer from the existing wall. During the cooling period, the interspace (air space) is ventilated, while in the heating period it is not. To consent the comparison with the other configurations the overall U-value of the unventilated configuration is hypothesized as the same of the other examined external insulation. When it is ventilated, its U-value is assumed the same of the reference configuration, but the solar radiation on it is not considered.

Compared to other types of insulation, this configuration allows considerable further savings in mid-seasons, particularly in spring. However, a wall of this type, currently only tested in industrial buildings, is difficult to propose in the urban context considered.

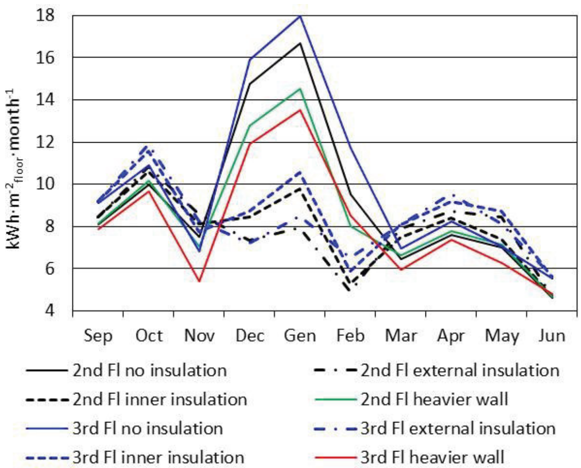

Figure 3: Monthly primary energy demand (per square meter of floor area) for HVAC and lighting system at the 2nd and 3rd floors classrooms (east oriented).

Due to the longer period of use, when the building is used for offices, the total energy demand is about twice as that of the school. Due to the lower internal gains, heating consumption is proportionally much greater than cooling. Consequently, the percentage savings due to insulation are higher, in particular in the case of the external insulation: from 12.5% of schools to 18% of offices (Fig. 4), and it strongly increases its convenience with respect to the internal one.

In the classroom of the upper floor, the total annual primary energy demand is slightly higher: from about 3% in the reference case, to about 4% in the case of internal insulation. This is due to the greater solar gains and the consequent greater cooling loads, 45% compensated by lower

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consumption for lighting. Only in the case of ventilated insulation, the energy demand is 6% lower, since in this case there are not the same overheating problems. If the rooms are used as offices, due to the lower internal gains, the location on the upper floor allows slight percentage savings entirely due to lighting.

With south orientation global consumption decreases, essentially due to the lower demand for artificial lighting, and the upper floor is slightly consuming for both the destinations.

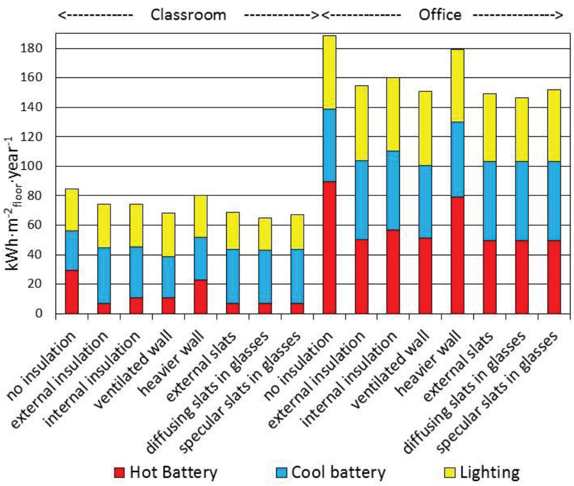

Figure 4: Room at the 2nd floor east oriented, annual specific primary energy demand (per square meter of floor area) for HVAC and lighting systems relatively to some combinations of different types of insulation and solar control devices and for different uses of the building. The configurations with slats mentioned in the figure are combined with not ventilated external insulation.

A possible night forced ventilation has been simulated. It is carried out by the same HVAC system and with air flow rates of three volumes per hour. It would reduce air conditioning consumption in mid-seasons, particularly in spring. The reduction is about 22% in the reference case at the second floor in May, 1.6% over the year. It would be more effective in configurations with insulation (around 25% in May and 2% on an annual basis), due to their higher energy demand for cooling. In the classroom on the upper floor, these savings are higher in spring (up to 30% with external insulation) but lower on an annual basis. It does not seem useful to increase the flow rate beyond three volumes per hour. In the case of offices, given the lower internal gains, the benefits of night ventilation are reduced by about 30%.

The effect that a greater wall mass could have on energy demand and thermal comfort was also explored (Fig. 3-4-5). Therefore, the behavior of the same classrooms was simulated with walls having a total thickness of 0.4 m, instead of 0.3 m, typical in older buildings. It has been found that the higher thermal capacity thus obtained is much less effective than insulation in reducing energy consumption. It would reduce the heating consumptions to a lesser extent, while in the mid-seasons it would allow greater useful losses. Adding the two effects the annual percentage savings would be about half of those achievable with insulation, in the case of classrooms, less than one-third in the case of offices.

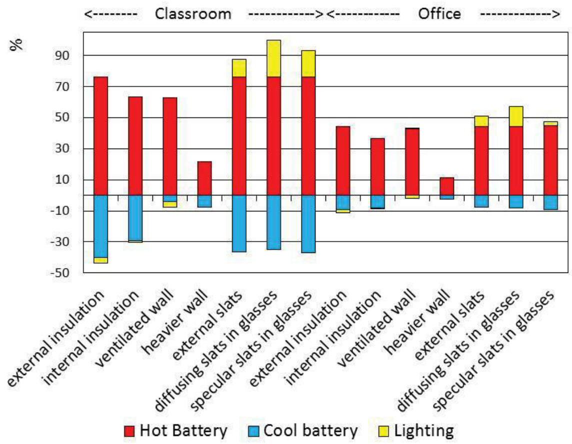

Figure 5: Room at the 2nd floor east oriented, annual percentage energy savings achievable with some combinations of different types of insulation and solar control devices, compared to the reference configuration.

The energy savings achievable with the use of more sophisticated solar control devices are much less than those due to insulation. Here are the results relating to the combination of the various devices with the non-ventilated external insulation, since this turned out to be the most efficient solution, if you exclude the ventilated wall, which is not a widespread solution (Fig. 4-5).

Compared to the use of the internal curtain only, all the types of examined movable slats entail energy savings (Fig.6). These savings are mainly due to lower consumption for artificial lighting, and secondly to the lower consumption for cooling. This is because all the types of slats reduce the number of hours in which the luminous discomfort would make it necessary to lower the internal curtain, with a consequent reduction of the average internal illuminance.

The diffusing slats positioned between the glasses give the highest energy savings, followed by the specular ones, always inserted between the glasses. The latter reduce lamp consumption less, since a large part of the incoming luminous flux (80%) is diverted upwards and 40% is absorbed by the plaster. The external slats have a lower reflection coefficient and reduce the incoming luminous flux much more, thus resulting in lower savings related to artificial lighting.

With office use, the total savings due to the slats also increase, but, given the higher consumption due

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to the longer hours of use, the percentage savings are less remarkable; therefore, the differences between the energy performance levels of the various devices are reduced.

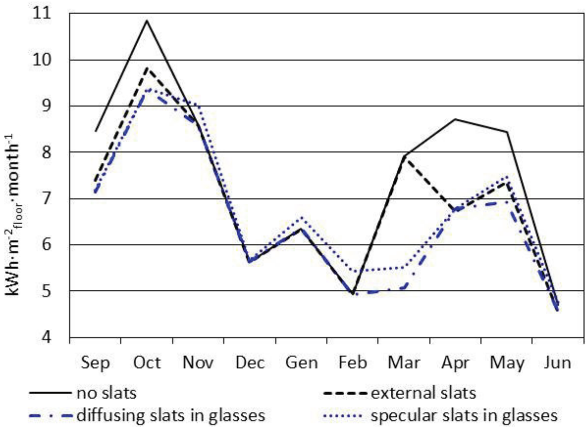

Figure 6: Monthly primary energy demand per square meter of floor area for HVAC and lighting systems of the 2nd floor classroom, with not ventilated external insulation and various solar control devices.

3.2 Thermal comfort

During the heating period and the mid-seasons, the mean radiative temperature (MRT) reaches higher values with the external insulation, therefore in these periods the predicted mean vote (PMV) [5] is closer to the comfort value (Fig. 7). During the warmer period, July-August, the school is not used; anyway, only during this period (considered only in case of offices) both types of insulation provide slightly worse performance than the reference configuration (PMV near 0.2 instead of around 0).

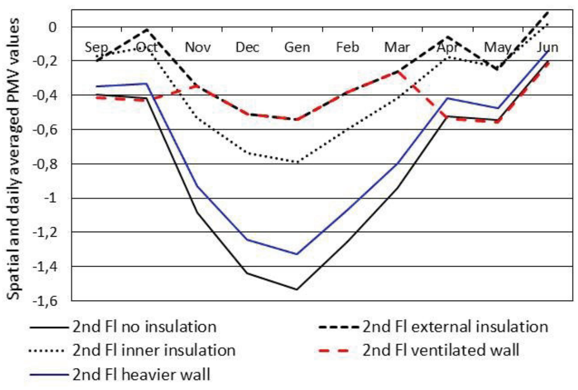

Figure 7: Spatially and daily averaged PMV values in typical monthly days with different types of insulation for the 2nd floor classroom.

The heavier wall simulated has slightly better PMV values than the reference case.

There are no significant differences between the effects of the various solar control devices. The two types of slats inserted between the glasses improve the comfort a little in spring by keeping the internal temperature of the glass higher. Instead, external slats provide better thermal comfort during the warmer period (July-August), by limiting overheating of the internal surface of the glass.

The strange trends in the PMV values in October and May are due to the assumptions made regarding the set point temperatures; the criterion for choosing this temperature can be improved.

3.3 Luminous comfort

The evaluation of the light comfort was carried out only in the hours of complete daylighting with both areas of the lamp set off.

Two types of glare were considered here: the disability glare from direct radiation on the visual task [6], and discomfort glare due to exceeding contrast of luminances inside the visual field. The latter is assessable with the Daylighting Glare Index (DGI), in case of extended light sources (typically the sky seen through the windows) [7], or Unified Glare Rating (UGR), in case of smaller sources [8]. To do this check, the software uses an algorithm simulating the visual field of the various occupants.

The presence of visual comfort was tested in six significant positions within the rooms; the presence of one of the two types of glare in one position involved the implementation of solar control actions.

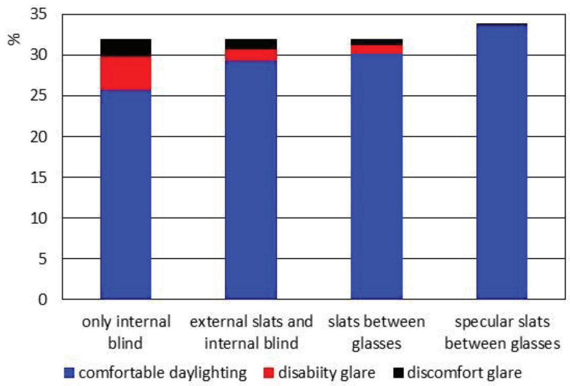

Figure 8: 2nd floor classroom east oriented - Percentage frequency of hours-occupant in discomfort conditions on the total hours-occupant of use after the thermal load control actions performed with the various devices and before the glare control actions

The graphs of Fig. 8 show the percentage frequency of the discomfort cases (as a percentage of hours-occupant in discomfort conditions on the total hours-occupant) after the thermal load control actions performed with the various devices and before the glare control actions. In the case of the office, due to the use even in the afternoon, with the South orientation, the daylighting hours increase significantly and the incidence of discomfort situations decreases.

The graphs in Fig. 9 show, for each device, both the daylighting hours possible after the heat load

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control actions and after the luminous comfort control actions. The internal curtain used alone is the device that penalizes the duration of daylighting the most, while the slats between the glasses penalize it less. Furthermore, the specular slats provide more daylighting hours, by favoring higher illumination values in the positions furthest from the windows. The fact that this does not lead to lower consumption from lamps is because, with specular slats, in many of the hours in which the lamps are used, the entire set of lamps is switched on, while, with the diffusing slats, only half of the lamps are switched on.

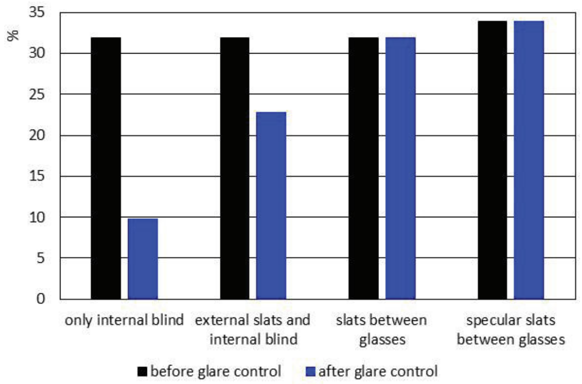

Figure 9: 2nd floor classroom east oriented, ratio between annual hours of visual comfort in daylighting conditions and the total number of hours of use, before and after glare control actions (right).

It can be observed that, in the case of slats between the glasses, the glare control actions do not reduce the number of daylighting hours (Fig. 9).

Before the glare control actions, the most frequent discomfort is due to the direct radiation on the visual task, especially in the case of the curtain used alone. With the South orientation, the number of daylighting hours increases, and the percentage frequency of discomfort conditions decreases; therefore, the differences between the performances of the various devices are reduced, in the case both of the classroom and the office.

Compared to the use of the single curtain all the slats improve the internal light comfort. Before the glare control action, all the types of slats reduce the frequency of disability glare due to direct radiation on visual tasks, in particular the specular one.

After the visual comfort control actions, all the slats guarantee a greater uniformity factor of the internal illuminances (U_o) for a longer period than just the curtain, especially the specular ones. U_o is here defined as the ratio between the minimum illuminance value on visual tasks and their average value [9]. However, specular slats also cause higher average DGI values (spatial and temporal), albeit within limits. On the other hand, the diffusing slats, both external and inserted between the glasses, provide the lower values of the DGI.

4. CONCLUSION

Simulations results show that, in the considered climate, the higher thermal inertia obtained by means of external insulation further reduces the annual energy demand for HVAC and improves thermal comfort.

However, there are not significant differences in the annual energy demand between internal and external insulation in the case of classrooms. Differences increase if the building is used for offices.

A hypothetical wall with external insulation separated from its mass with a ventilated interspace can improve energy performance in mid-seasons.

All types of slats improve light comfort and reduce energy consumption related to artificial lighting, but their energy savings are much lower than those due to insulation. The diffusing slats inserted between the glasses are the most energy saving solar control device, while the specular ones provide the better visual comfort. On the other hand, external slats allow a better thermal comfort in the summer.

Therefore, excluding the dynamically ventilated wall, which is an unusual solution, the best retrofit strategy consists in the external insulation combined with diffusing slats internal to the glasses.

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