Retrofit of massive buildings in different Mediterranean climates

Interactions between mass, additional insulations and solar control strategies

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Abstract: In temperate climates, such as most Italian ones, the need to limit both winter heat losses of buildings and their overheating in other periods is present. Moreover, in warmer Mediterranean climates the convenience of insulation against the thermal inertia of the building must also be evaluated. Therefore, when the energy renovation of an old building with heavy masonry is performed it is a question of optimizing the position and the thickness of the additional insulation. In presence of extended glazed surfaces, another problem is the choice of the solar control strategy. Both problems are present in many old Italian public buildings.

In this paper is presented a computerized methodology for optimizing these choices taking into account the interactions between mass, additional insulation, internal and solar gains. The case study consists in a typical school building from the early 1900s. The thermal behavior of the building was simulated in different Italian climates: Bologna, Roma and Palermo. The effects on energy demand and comfort of various solutions were compared. The possible effects of different types of masonry, different building's orientations and various intended uses were also explored.

Simulation results provide some indications as function of climate and building's intended use. They show that the ideal strategy of intervention, for the type of building considered, depends not only on the climate but also on the building's intended use, which determines the internal gains and the time profile of use.

Keywords: Retrofit, Solar Control, Energy Saving, Comfort

1. INTRODUCTION

In temperate climates, such as most Italian ones, the need to limit both winter heat losses of buildings and their overheating in other periods is present. The second requirement is particularly relevant in the presence of high internal and solar gains. It is well known that, in these climates, it is not convenient to exceed the insulation thickness. In addition in warmer Italian climates the convenience of the insulation in comparison to the building's thermal inertia must be evaluated. The two things are often seen as alternatives.

When the energy renovation of an old building with heavy masonry is performed, it is a question of optimizing the position (internal or external) and the thickness of the additional insulation according to the intended use (Sami et al., 2011; Deng et al., 2019; Stazi et al., 2015; Tzoulis et al., 2017). The usefulness of a certain insulation depends on a number of factors, such as:

- local climate, in particular the presence in it of significant day-night temperature ranges,
- building's thermal inertia,
- building's thermal balance, in particular the relevance of the energy demand for cooling compared to that for heating,
- time profile of use.

Moreover, in the case of old public buildings, large, glazed surfaces are often present, which involve the well-known problems: high and undesired solar gains in the cooling period, high thermal losses in the heating period, thermal and luminous discomfort. Also the choice of the solar control strategy is connected to the building's intended use and windows orientation (Buvik et al., 2015; Erhorn, 2015).

This work presents a computerized methodology for optimizing these choices. The various retrofit strategies are evaluated in relation to the total primary energy demand, and the effects on thermal and light comfort. The primary energy demand considered is that for heating, ventilation, air conditioning (HVAC) and artificial lighting, since insulation and solar control strategies influence these end uses of energy. Furthermore, these final uses of energy are linked to each other; and analyzing them separately can lead to misleading results. For these reason the computer simulations were performed by using a specifically home made software (*Ener_Lux*), which simulates the dynamic thermal and luminous behaviour of the building at hourly time steps, and allows simultaneous analysis of energy and comfort issues. The peculiarity of this software is that, within each calculation time step, it calculates thermal and luminous comfort indexes values, on the base of these, it simulates the feedbacks on the solar control devices and/or on the set-point temperatures (Carbonari, 2017).

The case study consists in in two classrooms of a typical school building from the early 1900s with a heavy structure and large glass surfaces in a climate of Northern Italy (Bologna, 44.5° N, 2259 base 20°C heating degree-days). The climate of the town is temperate with cold winter and warm summer, in all the seasons there are not negligible daily temperature ranges. With regard to this building, a retrofit intervention was hypothesized; it includes the insertion of additional insulation and more efficient devices for solar control on the glazed openings.

In order to assess the influence of internal gains, time profile of use and solar radiation, two different intended uses, i.e. offices and dwellings, and a more problematic orientation, the one to the south, have been hypothesized for the same rooms. In addition, to evaluate the influence of thermal inertia, some different masonry, both heavier and lighter, were also simulated. Given the diffusion of this type of building in the Italian territory, its thermal and luminous behavior has also been simulated in two other Italian climates: that of Rome (41.91° N, 1415 base 20 °C heating degree-days) and that of Palermo (38.11° N, 751 base 20 °C heating degree-days).

2. THE CASE STUDY

The examined building has an elongated plan, with the major axis oriented approximatively nord-south. The classroom look out symmetrically on the two longer sides. Two identical classrooms were examined their windows are facing approximately east (76° East azimuth), since, considering the morning time of use, this is the most critical orientation. The two examined classrooms are situated at the second and the third floor respectively; therefore, the influence of surrounding urban obstruction as regards solar gains and daylighting is different. 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, transmittance (U-value) is 2.06 $W \cdot m^{-2} \cdot K^{-1}$, front thermal capacity (C_{front}) equal to 481 $kJ \cdot m^{-2} \cdot K^{-1}$, horizontal elements in wood, with superimposed lime mortar and bricks. Vertical wide windows are present.

In Bologna, it was assumed that the retrofit intervention involves the installation of a triple glazing with 0.004, 0.006 and 0.004 m thick glass layers. The external air gap can be 0.037 m thick if it contains movable and packable slats, otherwise it is 0.018 m thick. The other air gap is 0.018 m thick and it as a low emissive layer in the external side of the internal glass (overall U_{value}: 1 $W \cdot m^{-2} \cdot K^{-1}$).

In Rome and Palermo, glazing has been hypothesized with U-values close to the limit values set by the current Italian standards, which are: 3 $W \cdot m^{-2} \cdot K^{-1}$ in Palermo and 1.8 $W \cdot m^{-2} \cdot K^{-1}$ in Rome. Therefore, with only two glasses of various thicknesses and with various distances depending on the presence of devices inside the cavity. Transmittances close to the limit values have been chosen because lower values would lead to overheating problems. In all locations the same solar control devices were simulated.

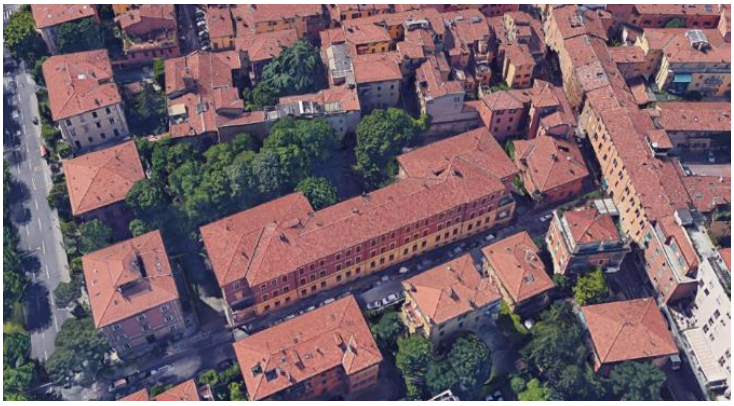

Figure 1: The elementary school G. Pascoli in the centre of the picture

In the case of classrooms, 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. It has been assumed a period of occupation only in the morning from 8 a.m. to 8 p.m. and a required illuminance of at least 500 lx, in harmony with Italian regulations for schools and offices. The hypothesized light system consists of fluorescent lamps (luminous efficacy: 91 lm/W, maximum total power: 756 W). This system is divided into two zones parallel to the external wall. There are no dimmers.

In the case of offices, six occupants were hypothesized with the related equipment (six computers and one printer) in the same space as the previous single classroom, and a more localized light system (maximum total power: 480 W) always based on fluorescent lamps. A daily occupation period equal to eleven hours was supposed: from 8 a.m. to 7 p.m.. In the case of housing, the internal gains suggested by the Italian standard (3.71 W/m^2, 260 W total) were assumed. To estimate the primary energy demand related to the artificial lighting system, the same type of office system has been hypothesized but sized on 2 occupants instead of 6 (therefore a power of 160 W), but during the daytime hours an average temporal presence of only 1 occupant was assumed.

At first two types of additional insulation layers have been hypothesized: an external insulation consisting of a layer of rock wool, with various thickness values, with an outer protective layer in plaster, and an internal insulation consisting of expanded polyurethane only 0.05 m thick, with an internal layer of plasterboard, according to current construction practice. This because a greater insulation thickness would reduce the internal space without causing significant energy savings.

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 in any season, it is assumed that a full air centralized heating, ventilation and air conditioning system (HVAC) is installed to eliminate overheating and improve air quality. In the HVAC system, electrically driven chillers provide the fluid for the cooling coils, while the fluid for the heating coil is primarily provided by the condensers of the chillers, integrated by gas-boilers when necessary.

Currently, the only solar control device is a diffusing curtain inside the windows. This device allows controlling glare phenomena but do not avoid unwanted solar gains and penalizes daylighting. Instead, the alternative solar control strategies examined here are based on various types of packable arrays of tilting slats: one external to the glasses and two inserted between the glasses in the outermost air gap, one of the last two has diffusing surfaces, while the other has a specular upper surface (Figure 2).

The external slats are coupled 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 but guaranteeing the required level of illuminance even in the most disadvantaged position. Then they can be further operated to eliminate glare phenomena if they are detected. The control logic of the mirror slats differs from that of the diffusing slats because: before checking 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. When necessary, all types of slats can be packed to ensure natural illuminance required, but if this causes glare phenomena they are unpacked. It is assumed that these control logics represent the actions that would be implemented spontaneously by the occupants.

Figure 2: External slats (left) and slats inserted between glasses (right) hypothesized in the climate of Bologna. From ©Internorm catalogue

In the various locations, the behaviours of hypothetical heavier and non-insulated masonry were also simulated: a brick wall 0.51 m thick and a stone wall 0.51 m thick, all with plaster on both sides. This in order to compare the performance of insulation with those of a greater heat capacity, which is characteristic of historical architecture, especially in the two southernmost, warmer climates. In order to evaluate the effect of a lower heat capacity of the envelope the behaviour of a more recent construction system was also simulated for the same building. It consists of a point structure: beams-pillars in reinforced concrete, with floors in brick concrete 0.3 m thick and external walls in hollow bricks 0.12 m thick. Although the U-value of the hollow bricks wall is similar to that of the current solid brick wall, in the absence of insulation, the average U-value of the façade is higher. This is due to the presence of structural thermal bridges: edge beams of the floors and pillars in reinforced concrete. With regard to this configuration, the optimal insulation was sought.

The main thermophysical characteristics of all these walls are summarised in Table 1.

Table 1: Main thermal characteristics of the classrooms

Configuration	U-value [W/(m^2·K)]	C_{front} [kJ/(m^2·K)]
Current brick wall 0.25 m thick	2.06	481
Heavier brick wall 0.51 m thick	1.27	917
Heavier stone wall 0.51 m thick	2.37	1285
hollow bricks wall 0.12 m thick	2.37	199

3. RESULTS

For reason of space, only a few graphs are reported, and these are mainly referred to the two most different climates: that of Bologna and that of Palermo. In the intermediate climate of Rome, the results are closer to those of Palermo. Any change in energy demand or in the degree of comfort is evaluated with respect to the reference case, which is constituted by the current configuration of the building.

3.1. Primary energy demand

In the climate of Bologna, if the rooms are used as classrooms or offices, any type of additional insulation results to be useful only during the coldest period, this because of the high internal gains. In the half seasons, insulation only increases overheating, as they prevent the night's cooling of the masses (Figure 3). In the warmer period, they have no relevant effects because of the reduced heat flows throughout the envelope, due to the higher internal set point temperature (26 °C). For these reasons, in Bologna, the optimal insulation thickness is between 0.06 and 0.07 m in the case of the classroom. The total annual energy demand decreases rapidly to this value, due to the reduction of winter losses, after which it slowly increases due to the increase of cooling loads. In the case of the office, on the other hand, this minimum point is around 2 cm (Figure 4).

In the case of office the lower number of occupants require a lower rate of ventilation, this significantly reduces the energy demand for heating, while it reduces less that for cooling, due to the smaller temperature differences between inside and outside in the cooling period. Given the longer period of daily use and the use even in summer, the total annual energy demand is greater than that of the classroom, on average 26-30% higher. The longer hours of use mainly affect the consumption of lamps, which almost double, despite the assumption that they have lower power due to a more localized lighting (Figure 4).

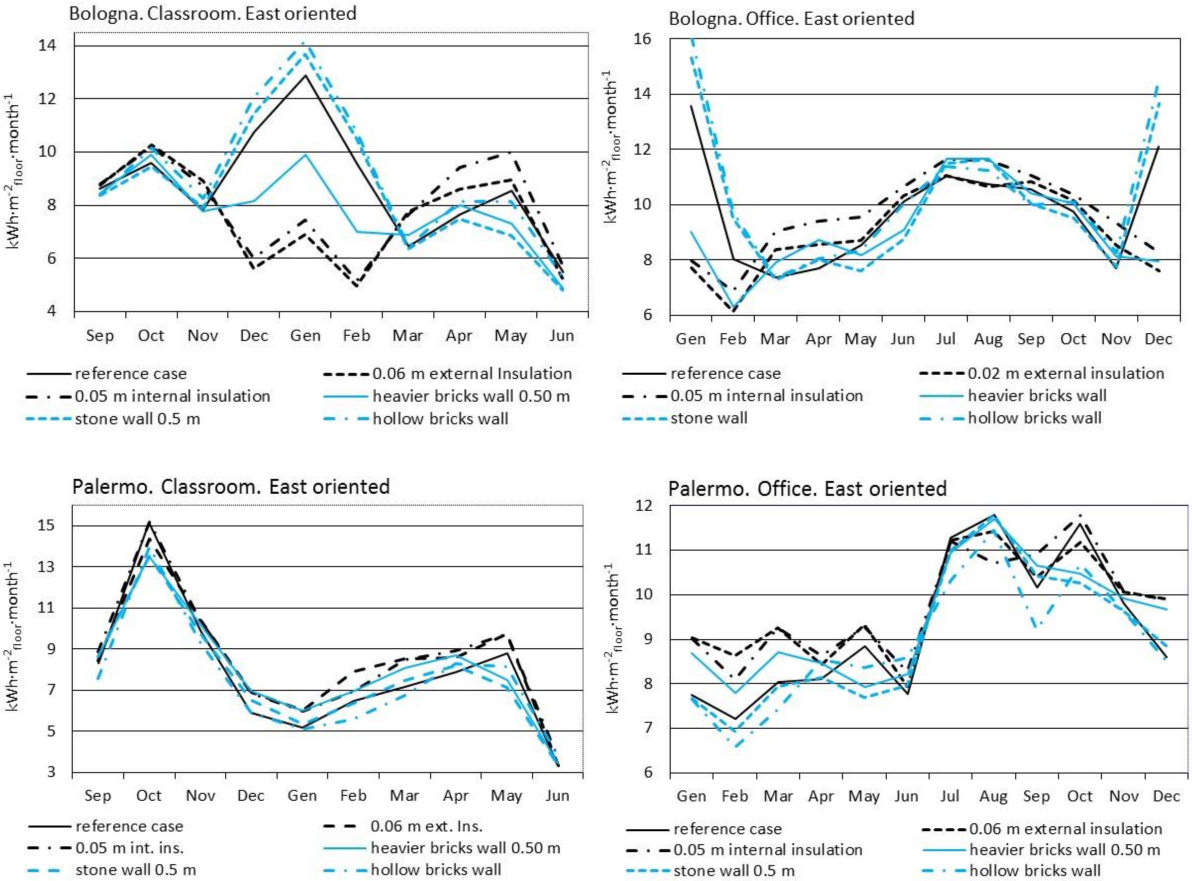

Figure 3: Monthly primary *energy demand (per square meter of floor area) for HVAC and lighting systems of the room at 2nd floors with various walls and various types of insulation*

In the case of the dwelling, heating energy demand is preponderant; therefore, it is not possible to identify a point of minimum in total energy demand (Figure 4).

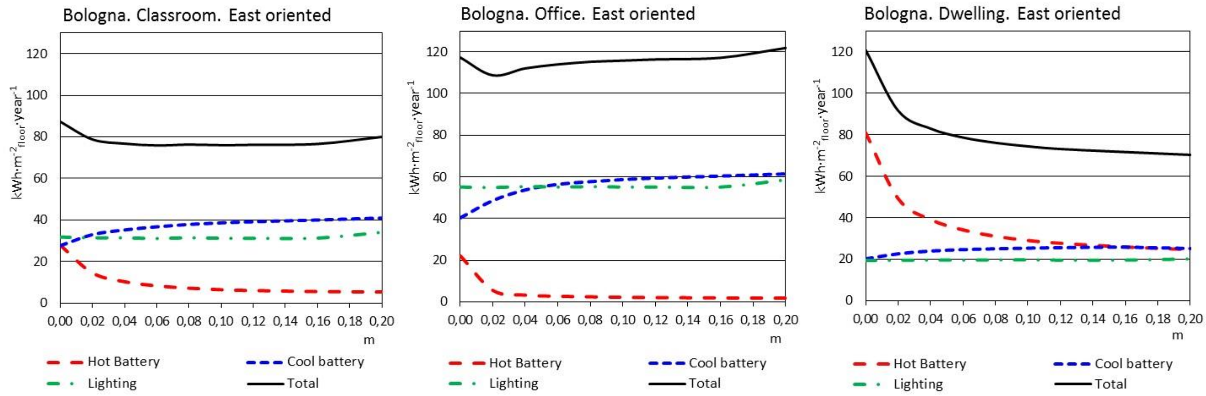

Figure 4: Room at 2nd floors, energy demand for the various uses as function of external insulation's thickness

In the rooms of the upper floor, in Bologna, the total annual primary energy demand is generally 3-4% higher. This is due to the greater solar gains and the consequent greater cooling loads, partially balanced by lower consumption for lighting.

In Bologna, in general, internal insulation is less convenient than the external one, particularly in the case of office use, where cooling energy demand is dominant (Figure 6). This because it avoids the effect of the wall's thermal inertia (Figure 3). Therefore, in warmer climates the disadvantages is even greater.

In warmer climates of Rome and Palermo, both in the case of the classroom and the office, the energy demand for cooling is much greater than that for heating, therefore any type of insulation only increases total annual energy demand, given the greater amount of useful dispersions compared to harmful ones. The effect is greater for the classroom due to the reasons mentioned above. This does not happen in the case of residential use, where heating energy demand is dominant, even if for it the advantages of insulation are minor in warmer climates.

The heavier brick wall without insulation 0.5 m thick is characterized by lower U-value and greater heat capacity than those of the reference masonry. Therefore, in Bologna, due to the first characteristic, it slightly reduces winter consumption for heating and increase that for cooling in the hottest period of July-August, since it reduces the useful dispersions. The greater inertia slightly reduces energy demand in the mid-seasons, because it reduce cooling loads, especially in the office. For these reasons, this wall has advantages only in Bologna, for the office and, in a more accentuated way, for the classroom. However, these advantages are slightly less than those due to the optimised external insulation are, in case of classroom an energy saving of 10.5% against 13%. On the other hand, this wall would be disadvantageous in the other two warmer climates examined, both for the classroom and for the office: the savings on heating do not compensate for the higher cooling costs due to the lower useful dispersions. Only in the case of housing, this wall is advantageous everywhere.

The 0.5 m thick stone wall is characterized by increased U-value and a significantly higher heat capacity (four times that of the reference case). Thermal inertia alone is advantageous especially in reducing cooling loads. Therefore, it would result in negligible energy savings in Bologna only for the classroom (0.52%), and in Palermo it would provide modest results for the classroom and the office (2.2 % and 2.42% respectively). While it would be disadvantageous in all the other cases. Both in the case of brick and stone walls, the greater thickness entails greater consumption for artificial lighting.

In Bologna, the construction technology in reinforced concrete and hollow bricks, without insulation, increases the total primary energy demand, essentially due to the higher consumption from heating. The thicknesses of the optimal external insulation are not significantly different from those found for the reference masonry. In warmer climates, on the other hand, this technology involves energy savings in the case of the classroom and the office, but these are essentially due to the lower consumption of the lamps, given the lower thickness of the masonry.

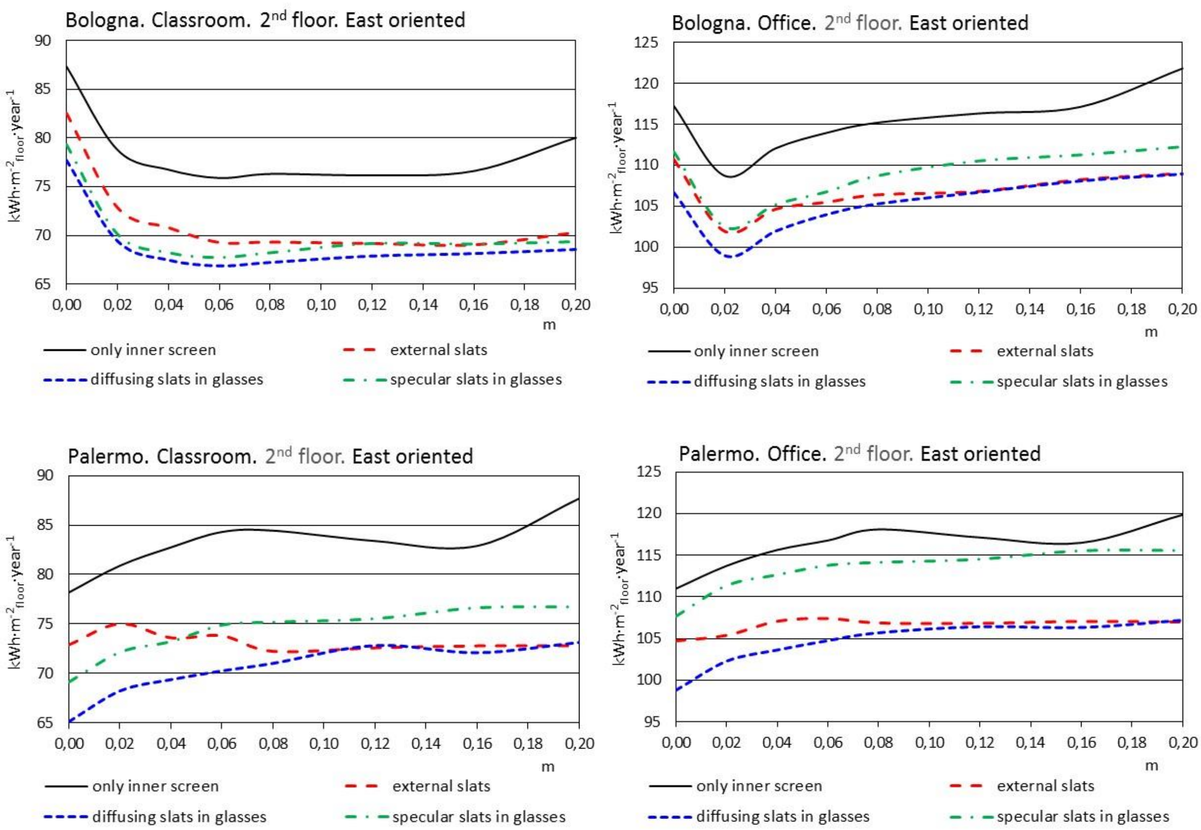

Figure 5: Total annual primary energy demand (per square meter of floor area) for HVAC and lighting systems of the 2nd floor room as function of external insulation's thickness and different solar control strategies

Here are the results relating to the combination of the various devices with the external optimized insulation since this turned out to be the most efficient one (Figure 5). Compared to the use of the internal curtain only, all the types of examined movable slats entail energy savings (Figure 5-6). This is because they reduce unwanted solar gains better than the internal curtain alone and avoid glare phenomena by reducing the incoming luminous flux less. Therefore, they reduce the use of lamps and the consequent thermal gains. The introduction of these devices does not change the ideal insulation thicknesses previously identified.

In general, 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 lamps 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.

In general, in Bologna, the energy savings of the slats are of the same order of magnitude as those due to optimal insulation. In warmer climates, the percent savings due to solar control are higher but always mainly due to savings in artificial lighting (Figure 6). With office use, the total savings due to the slats also is greater in absolute value, but, given the higher consumption due to the longer time of use, the percentage savings are less remarkable. Therefore, the differences between the energy performances of the various devices are smaller.

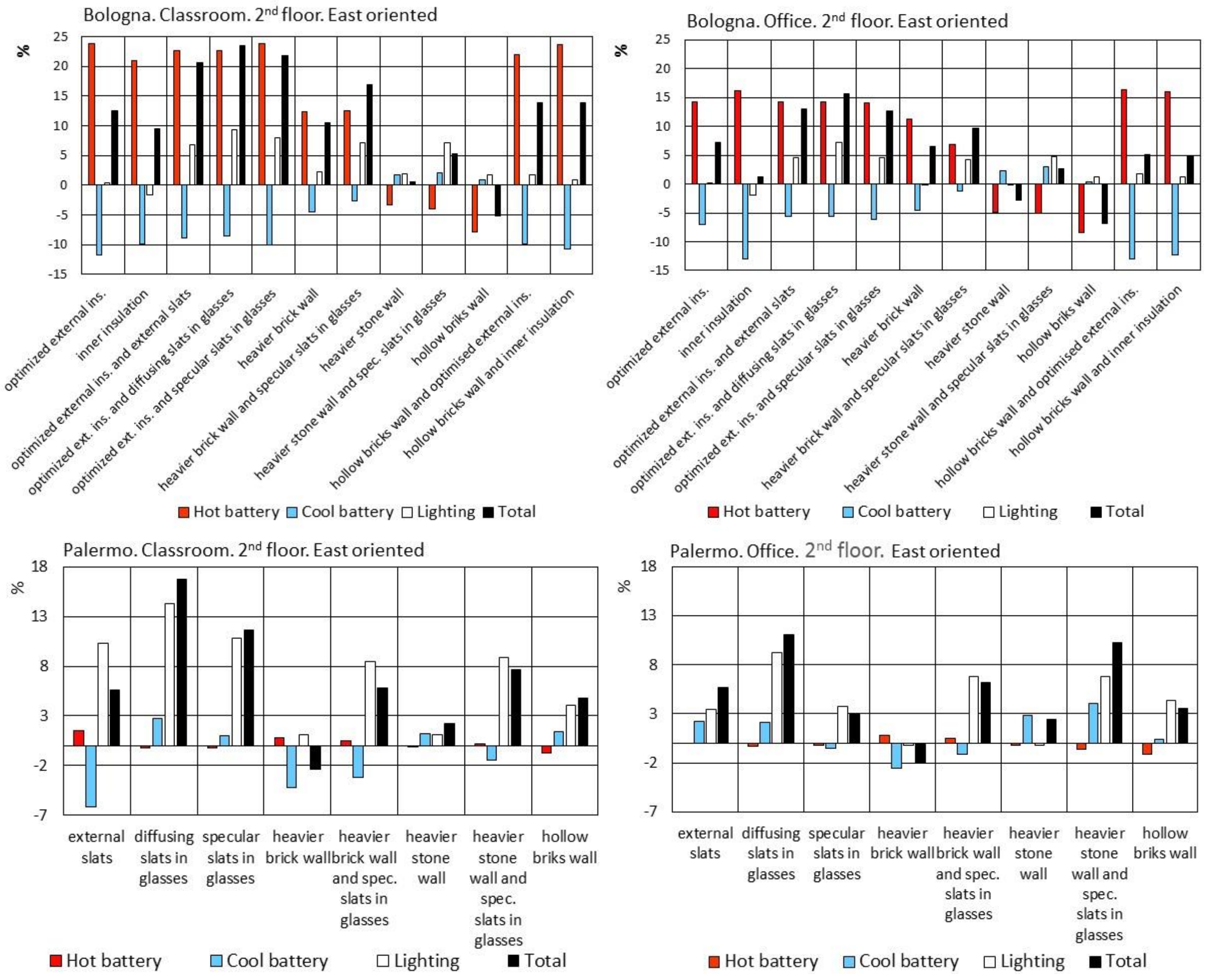

Figure 6: Percentage energy savings achievable compared to the reference configuration. The configurations with slats are combined with the optimized external insulation. In case of heavier walls or hollow bricks wall only the best performant solar control device is represented

In general, the greatest energy savings are found in Bologna for the classroom, and they are due to insulation that reduces the energy demand for heating. In Palermo the savings are generally lower and mostly due to lighting thanks to solar control devices (Figure 6).

A hypothetical facing south of the room's windowed external wall would result in a modest reduction in the total annual primary energy demand. This savings would be mainly due to the lower use of lamps, and would increase with the use of the most efficient solar control devices (slats between glasses). This effect would be greater in the case of the office, which presents greater consumption from lamps. These savings would be greater in Palermo. With the Southern orientation, the percentage savings due to all types of slats, compared with the screen alone, would increase, in particular in the case of the specular slats applied to the office. This different orientation would not alter the ideal insulation thicknesses previously identified.

3.2. Thermal comfort

Thermal and luminous comfort indexes were calculated with reference to six significant positions of occupants in the room. The results relating to the two most different climates, Bologna and Palermo, and to the intended office use are reported here, as they are also extended to the afternoon and to the summer. The predicted mean vote (PMV) was used as the main evaluation parameter (Fanger, 1970; UNI, 1997).

The thermophysical characteristics of the building envelope elements essentially affect the mean radiative temperature (MRT), which in turn affect the PMV, and the localized discomfort due to the asymmetry of the plane radiant temperature (t_{pr}). In order to explore the influence of insulation, an external insulation 0.06 m thick and an inner insulation 0.05 m thick have been hypothesized in both locations, although in Palermo they would be harmful from the energy point of view. Both in Bologna and in Palermo all the insulations, in particular the external one, improve comfort throughout the year, and the results are better in the mid-seasons. Only in the warmer period, the differences with the reference case are small (Figure 7).

The heavier brick wall, 0.5 m thick, having a lower U-value than the reference one, improves a little the degree of comfort compared to it, but in a less way than insulation. The hollow brick and the stone wall, both not insulated, having a U-value greater than that of the reference wall, slightly worsen comfort in the cold period and in the mid-seasons, because they reduce MTR and PMV more. However, in the hottest period the stone wall, thanks to its inertia, contains more the MRT and provides better performance even than the insulation in Bologna. In Palermo, instead it seems not to keep the MRT low enough, and the hypothesized insulations guarantee sensations closer to thermal neutrality.

Solar control devices mainly influence the internal temperature of the windows, therefore the MRT and the asymmetry of t_{pr}. The diffusing slats between glasses keep this temperature a little higher in the cold period and reduce it slightly in the hottest period.

The specular slats are less efficient in controlling this temperature. Given the different control logic adopted, in the cold period they tend to pack less frequently than the others; therefore, they reduce more the incoming radiation and reduce more the PMV value. Conversely, in the hottest period, when they are not packed, they assume a lower inclination and they heat up more and heat the inner glass more. Therefore, the MRT turns out to be slightly greater with them. In Bologna this happens only in the hottest period, in Palermo always.

In all locations external slats provide better thermal comfort during the warmer period, by limiting the temperature of the internal glass.

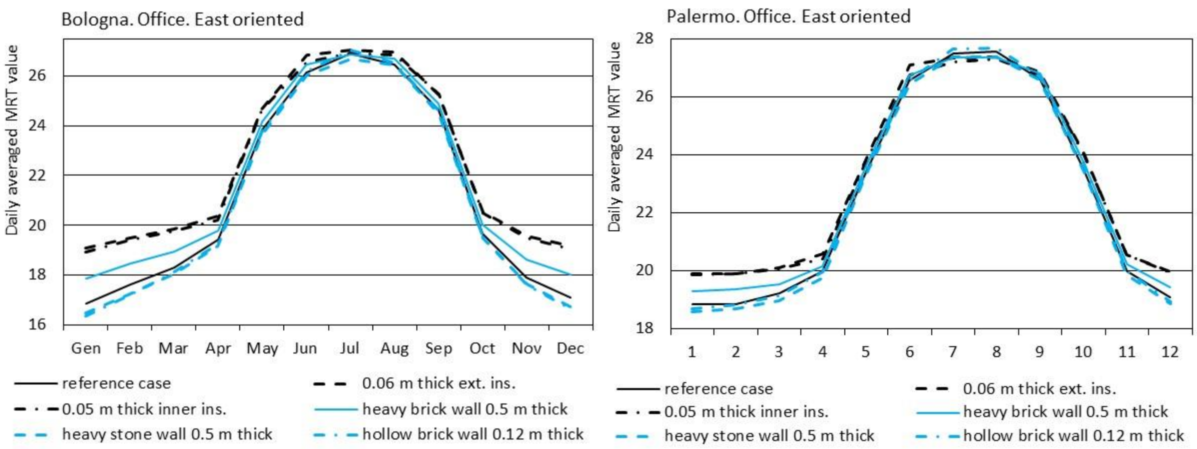

Figure 7: Bologna. Office. Spatially and daily averaged MRT values in typical monthly days, with different types of insulation and constructive technologies for the 2nd floor room

The t_{pr} asymmetry is greater with the devices that allow the internal glass to cool more in winter (i.e. slats that pack) and make it heat more in the hot period. However, these values are always very lower than the limit values provided by the Italian standard, which is 10 °C for horizontal asymmetry.

3.3. Visual comfort

The evaluation of the light comfort was carried out only in the hours of complete dayligting 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, and discomfort glare due to exceeding contrast of luminances inside the visual field. This last is assessed by means of the Daylighting Glare Index (DGI), in case of extended light sources (Chauvel et al., 1982; UNI, 2000), or Unified Glare Rating (UGR) in case of smaller sources (CIE, 1995). In this study, the first type of glare is considered excessive when the luminance of the task or its irradiated parts exceeds 580 cd/m^2 (Robbins, 1986). It has been assumed that the presence of glare of any kind in one occupant's position entails solar control actions.

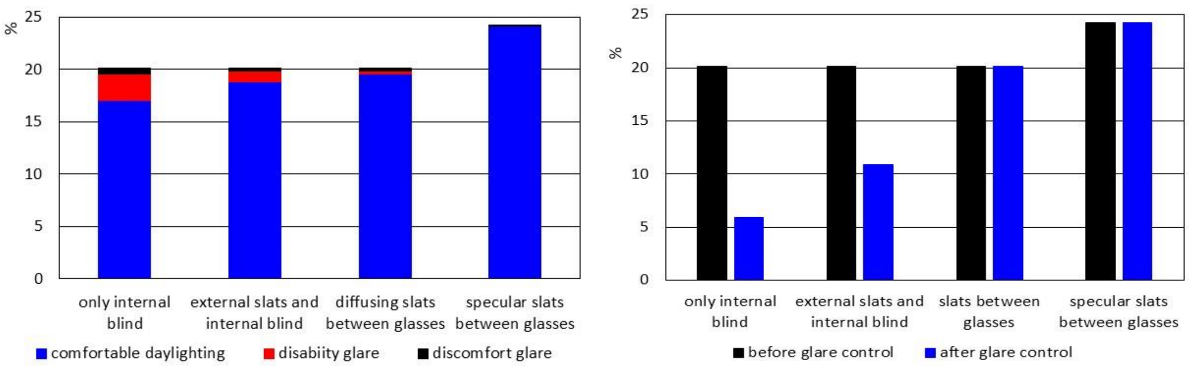

Figure 8: Bologna, office 2nd floor room, percentage frequency of hours-occupant in visual discomfort conditions on the total hours-occupant after the thermal load control actions, performed with the various devices, and before the glare control actions (left). Ratio between annual hours of daylighting and the total hours of use, before and after glare control actions (right)

The histogram on the left of Figure 8 show, for each solar control strategy, the percentage of hours-occupant in comfort or discomfort conditions on the total hours-occupant after the thermal load control actions, performed with the solar control devices, and before the glare control actions.

The histogram on the right of Figure 8 show, for each solar control strategy, both the daylighting hours possible after the heat load control actions and after the light comfort control actions. The internal curtain used alone is the device that reduces the hours of daylighting the most, while the slats between the glasses penalize it less, especially the specular ones. In particular, 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. It can be observed that, in the case of the slats between the glasses, the glare control actions do not reduce the number of daylighting hours that are possible after the load control actions.

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, because fewer situations with low sun in the middle seasons occur, and the differences between the performance of the various devices are reduced, both in the case of the classroom and of the office. In Palermo, the number of hours of comfort is greater, given the greater intensity of the solar radiation.

Compared to the use of the single curtain all the types of slats improve the internal light comfort. Before the glare control actions, all the types of slats reduce the frequency of disability glare due to direct radiation on visual tasks, in particular the specular ones. After the visual comfort control actions, all the slats guarantee a greater uniformity factor of the internal illuminances (U_o) than just the curtain. The diffusing slats between glasses provide the higher value of U_o in Bologna, whereas in Palermo the best performant are the external slats, but the differences between different types of slats are lower. U_o is defined as the ratio between the minimum illuminance value on visual tasks and their average value in the room (DIN, 1979). However, specular slats also cause higher spatial and temporal average DGI values, albeit within limits.

4. CONCLUSION

Simulations results show that the ideal strategy of intervention depends not only on the climate but also on the building's intended use, which determines the internal gains and the time profile of use.

The dominance of the energy demand for cooling compared to that for heating reduces the optimal insulation's thickness. Therefore, insulations, in particular the external one, brings energy advantages for all the examined intended uses only in the coldest climate of Bologna. While it would retain a certain usefulness in other climates for residential use only, for which the energy demand for heating is dominant.

In all the climates, the insulations, in particular the external one, improve comfort throughout the year, and the results are better in the mid-seasons.

Without insulation, only in Bologna a brick masonry of greater thickness has the advantages of lower U-value. Even its greater thermal inertia provides advantages especially in the mid-seasons. However, these energy savings are less than those obtainable with optimised external insulation are. In the other climates examined, the disadvantages related to the minor useful heat losses are dominant. A significantly higher heat capacity, but associated with greater transmittance, as in the case of thick stone masonry, brings modest energy savings only in the warmer climate of Palermo and for destinations other than the home.

Among the solar control strategies, the most energy efficient seems to be the use of diffusing slats inserted between the glasses, followed by the specular ones always between the glasses. The specular slats provide the best conditions of luminous comfort, while those outside the glasses provide the best thermal comfort in the hottest periods.

Therefore, in the climate of Bologna, from energy point of view the best retrofit strategy consists in the external insulation with the optimized thickness combined with diffusing slats internal to the glasses, while in the other warmer climates it consists in the introduction of the same solar control device and no insulation, except for the intended residential use.

A hypothetical facing south of the room's windowed external wall would result in a modest reduction in the total annual energy demand, mainly due to the lower use of lamps. With this orientation, the percentage savings due to all types of slats would increase, especially in case of the specular slats applied to the office. Therefore, windows orientation mainly influences the choice of solar control devices. This different orientation would not alter the identified ideal insulation thicknesses.

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