PASSIVE FAÇADE SOLUTIONS: TROMBE WALL THERMAL PERFORMANCE AND GLAZING DAYLIGHTING PERFORMANCE FOR GUIMARÃES - PORTUGAL

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ABSTRACT

Recently façade systems have integrated passive solutions to reduce the energy consumption in buildings and improve their occupants' comfort. This paper reports the results of the thermal performance of Trombe walls and daylighting of glazing modules of a façade system in Portugal. Trombe walls are massive walls separated from the outdoors by glazing and an air space, which absorbs the solar energy and releases it selectively to the inside of the building at night. Computational simulations were carried out with the Design Builder, Ecotect and Desktop Radiance programs. The use of Trombe walls and double self-cleaning glass in the façade system led to a decrease in the heating energy needs.

INTRODUCTION

Passive solar design can substantially increase the energy efficiency of a building. It includes a variety of strategies and technologies that use the free energy received from the sun to heat and light building environments. Trombe walls are an example of this type of technology, which can also be used in building refurbishment.

An American named Edward Morse was the first to describe the Trombe wall concept in a patent (Morse, 1881) (Fig. 1). This idea was repatented and popularized by French engineer Felix Trombe and architect Jacques Michel (Trombe, 1972). The Trombe wall is also known as Trombe-Michel wall, solar wall, thermal storage wall, collector storage wall, or simply storage wall.

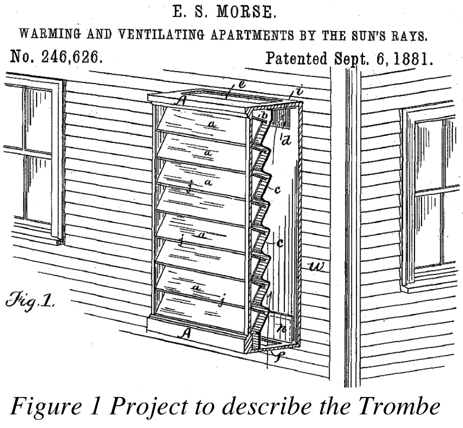


Figure 1 Project to describe the Trombe wall concept according to Morse [1].

A typical Trombe wall consists of a 10-to 41-cm-thick southern-facing wall with a dark, heat-absorbing material on the exterior surface and faced with a single or double layer of glass. The glass is placed 2 to 5 cm from the massive wall to create a small airspace. The heat from the sunlight, which passes through the glass, is absorbed by the dark surface, stored in the wall and slowly conducted inward through the wall. The high-transmission glass maximizes the solar gains to the wall. As an architectural detail, patterned glass can limit the exterior visibility of the dark concrete wall without sacrificing transmissivity.

The apparent amenity of the climate in Portugal has led to the non-existence of central heating or cooling systems in most part of the buildings, except for service buildings. Gonçalves et al. (1997) presented some examples of Trombe wall uses. Figure 2 shows an example of a Trombe wall use in Portugal. This system is on the first floor and its function is to capture, store and slowly conducts the heat to the indoors.

Figure 2 "Casa Termicamente Optimizada" – Southern Façade, Porto. Gonçalves et al. (1997).

Concerning the study of daylighting in façades, the most important factors involved are available daylight from the sun, glazed area and positioning of glazed surfaces, glass light transmission characteristics, geometry and internal reflection of surfaces positioning and reflection characteristics of the external obstructions, latitude, season, time and weather conditions. Daylighting calculations are commonly based on the daylight factor and illumination levels.

The daylight factor is defined as the quotient (expressed as a percentage) between illuminance at a given point on a plan inside a room due to the distribution of sky illuminance measurements known and the outside luminance on a horizontal plane from the sky. It can be a significant parameter to quantify the daylighting under overcast sky conditions. However, under certain conditions it has limitations. For example, under partly cloudy sky conditions, the daylight factor may be 0.2 to 5 times increased than for overcast skies (Goulding et al.,1994).

For an overcast sky, regardless of the solar orientation, the level of radiation is the same, therefore the effect of the orientation factor does not appear in the daylight factor (DF) calculation. However, the simplification introduced by the use of DF does not consider the location and building orientation, season, time of day, radiation direct effect and variation in both conditions and sky. Illuminance levels on specific days in the summer and winter solstices have to be observed for the evaluation of daylighting conditions.

The ideal goal for new façade systems would be the development of a dynamic and flexible system to adapt to the climatic changes, the occupants' requirements and the building condition (buildings and renovation).

Other elements, as passive solutions, glazing and reception of solar energy are also important. In agreement with the climatic needs and to improve comfort conditions, different solutions can be proposed according to the solar orientation and desired functions in a façade system.

In the proposed façade system, the differentials are the versatility and flexibility of the modules (60x60cm single modules), which allow a different architectural approach for each application. Versatility and flexibility features are not usually found in façade systems, which generally comprise all functions in a single module. These small modules can be installed in the façade and combined in different ways according to the needs, climate and available solar radiation (SACHT, 2010; SACHT, 2011; SACHT, 2012).

This paper presents partial results of an investigation about glazing modules and Trombe wall modules of this new façade system.

SIMULATIONS

Simulations of Thermal Performance

Computational simulations were carried out applying the DesignBuilder 1.8 software to analyze a case study, which consists of a room (25m^2) with different arrangements of façade modules. The following parameters were considered:

(i) Two different double glazing types (composed of green solar control glass and low-e glass, self-cleaning glass and float clear glass);

(ii) One or two Trombe walls;

(iii) Four solar orientations (northern, southern, eastern and western)

(iv) Two envelopes: a conventional Portuguese system (double masonry) and a light gauge steel framing system (LGSF);

(v) Climate of Guimarães city.

For validation purposes, the values of the heating energy needs obtained by thermal simulations were compared with the ones calculated in accordance with the Portuguese thermal regulation for residential buildings - "Regulamento das Características do Comportamento Térmico dos Edifícios - RCCTE" (RCCTE, 2006).

For the thermal performance simulations the climate of Guimarães, in Portugal was analyzed. Simulations were carried out for four solar orientations (northern, southern, eastern and western) considering the annual period, and a façade with one or two set modules of Trombe walls was used (Table 1).

Table 1 Guimarães Climate.

Climate	Climatic Zone	
Guimarães	Winter	Summer
	I2	V2
	Energy Needs	
	Heating (kWh/m^2.year)	Cooling (kWh/m^2.year)
	81.64	18.00
	Duration of Winter (months)	
	7,0	

The "standard model" was defined considering a one-storey isolated room, of regular 5,0 x 5,0 (25m^2) geometry and ceiling height of 2,80m. These dimensions followed the recommendations of the Portuguese Urban Building Regulation "Regulamento Geral das Edificações Urbanas" (RGEU, 2007).

The total dimension of the façade modules was 2,5 x 2,5 (6,25 m^2). The standard model was simulated considering the implementation of one and two Trombe walls. A set of five Trombe modules makes a complete "Trombe wall". The isolated cell was simulated considering the implementation of one and two Trombe walls (Figs. 3 and 4).

Figure 3 Model: One Trombe wall.

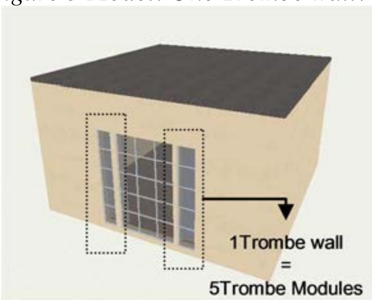


Figure 4 Model: Two Trombe walls.

For the Trombe wall module, the use of a double glazing with a high shading coefficient was considered. The double glazing had two panes made of 4mm Diamant glass (Saint-Gobain Glass) and 12mm air space, allowing maximum solar radiation penetration.

The area of a complete Trombe wall composed of five modules is 0.50 x 2.50m (1.25m²). Higher and lower modules had ventilation openings on the massive wall, whose area was 0.02m² (0.10x0.20m²), as previously mentioned. The operating time considered for such openings was 9:00 to 18:00 in the winter, in the summer the openings remained closed during the day and opened at night.

A Portuguese conventional construction system (double-wall masonry) and a light gauge steel framing system (LGSF) were considered in the model for the opaque envelope. The conventional system is composed of lightweight concrete slabs and insulation (stone wool), external walls in double masonry with interior insulation and cement mortar plaster. The LGSF envelope composition was based on the work of Santos et al. (2011). The light gauge steel framing system is also composed of lightweight concrete slabs and other insulation components (expanded polystyrene - EPS), and EIFS (External Insulation and Finish System), OSB boards, stone wool and gypsum plasterboard were used in the walls.

Table 2 shows the values of the overall heat transfer coefficient - U-factor (W/m² ºC) for a Portuguese conventional construction system and light gauge steel framing system.

Table 2: Overall Heat Transfer Coefficient (W/m² ºC)

Heat Transfer Coefficient (W/m² ºC)		
Element-Envelope	Portuguese Conventional System	
	Total Thickness (cm)	U (W/m²ºC)
External Walls	0.365	0.46
Roof Slab	0.280	0.55
Element-Envelope	Light Gauge Steel Framing System	
	Total Thickness (cm)	U (W/m²ºC)
External Walls	0.200	0.14
Roof Slab	0.333	0.22

Important factors, such as solar factor (or g-value), solar heat gain coefficient, shading coefficient, transmittance, and U-factor resulting from the glazing composition must be observed in the selection of the glazing. The glasses selected for the standard façade module simulations were supplied by Saint-Gobain Glass.

The glasses shown in Table 3 were used in the computational simulations with DesignBuilder software to obtain heating energy needs for the climate of Guimarães city. Furthermore, a 12mm air layer between the outermost and inner panes was considered. The values were obtained by Window 6.2.33.0 software (LBNL, 2013).

According to the manufacturer, green cool Lite KNT 155 is a temperable solar control glass, planitherm futur ultra N is a glass of extremely low emissivity, bioclean is a self-cleaning glass, planilux is a multi-purpose clear float glass, and diamant is a clear float glass. Table 3 shows the double glazing compositions.

Table 3 Glazing Properties.

Properties	**Glazing**		
	Glazing 04	**Glazing 07**	**Trombe Glazing**
Outermost Pane	Green Cool Lite KNT 155 4mm	Bioclean 4mm	Diamant 4mm
Inner Pane	Planitherm Futur Ultra N 4mm	Planilux 4mm	Diamant 4mm
U (W/m²K)	1.66	2.69	2.72
Solar Factor	0.28	0.40	0.83
Shading Coefficient	0.33	0.46	0.95
Visible Transmittance	42	71	84

The Portuguese code RCCTE (RCCTE, 2006) has established 4W/m² as an average value for the total internal gains (occupation, lighting and equipment). However, due to possibilities and simulation options offered by the Design Builder software, the internal gains were separated for the occupation, lighting and equipment (Table 4).

Table 4 Internal Gains (W/m²)

Internal Gains	**Values (W/m²)**	**Details**
Occupation	5,6 W/m² (2 people)	70 W per person
Lighting	9,4 W/m²	Illuminance (incidence): 300 lux; Fluorescent lamp (40 W); Efficiency 80 lm/W (40 % delivery efficiency).
Equipment	8 W/m²	Equipment potency: 200 W.

As the RCCTE code does not indicate schedules (days of the week, hour and time) of occupation, lighting and equipment use for housing buildings, the values were obtained from Souza (2009). 20°C and 25°C were considered the references of heating indoor temperature (winter) and cooling indoor temperature (summer), respectively, in agreement with the RCCTE.

Simulations of Daylighting Performance

The "standard model" and glazings defined previously in the thermal analysis were used in the daylighting performance simulations. The model was simulated for daylighting considering the implementation of two Trombe walls, glazing modules in the center of the façade and southern solar orientation.

Ecotect 5.6 software was used to obtain illuminance levels and daylight factor (DF) for glazings (Fig. 5). It is an environmental assessment tool that permits simulating a model in terms of thermal, acoustic and lighting performances. It offers several detailed analysis functions with a visual and interactive display that shows test results directly within the context of the model of the building. It also offers a range of lighting analysis options and implements the Building Research Establishments (BRE) split flux method for determining the natural light levels at points within a model.

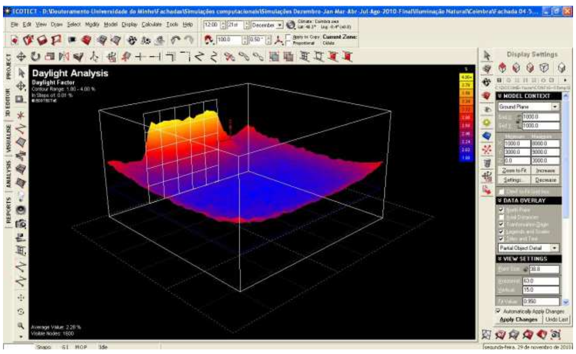


Figure 5 Ecotect Main screen.

The new version of Ecotect software is "Autodesk Ecotect Analysis". It is now sustainable design analysis software with a comprehensive concept-to-detail sustainable building design tool.

For a more detailed and accurate analysis of the daylight factor and illuminance level, the Ecotect model was exported directly to Desktop Radiance tool. Desktop Radiance is a design tool that facilitates the design and analysis of buildings to optimize the efficiency of daylighting systems and lighting technologies. It permits computing horizontal illuminance across an arbitrarily oriented grid of points and generating an image of a space that can be queried for the illuminance or luminance of any surface in a rendered figure of a room.

Interior illuminance levels were determined based on a square mesh of points spaced approximately 0.125m, on a horizontal plan 0.80m above the floor. The distance between the mesh and the interior walls was approximately 0.10m. The daylight factor (DF) was calculated by Ecotect 5.6 software from the arithmetic mean points defined by the mesh.

For the evaluation of illuminance levels within the space, the summer (June 21) and winter (December 21) solstices (Figure 20) at 12:00 P.M. (Figs. 6 and 7) and overcast sky standard CIE and southern solar orientation were considered. The southern solar orientation was chosen because it provided the best results in previous studies on thermal performance.

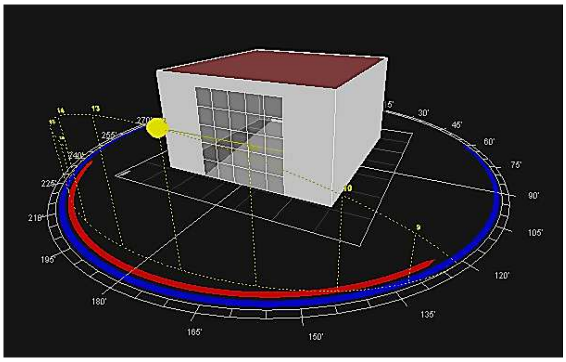


Figure 6 3D Illustrative Diagram: Winter Solstice, December 21, 12:00

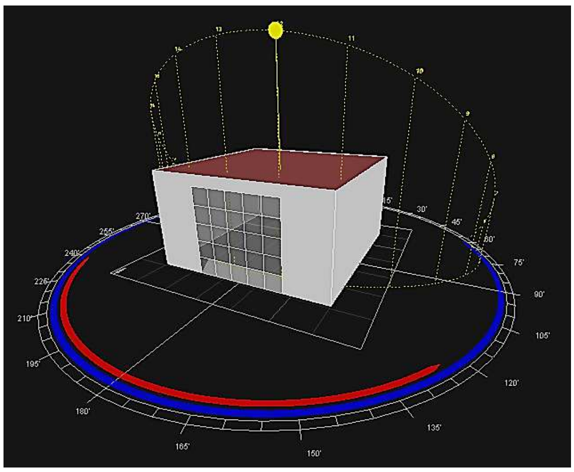


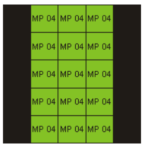
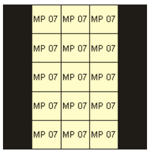
Figure 7 3D Illustrative Diagram: Summer Solstice, December 21, 12:00

The model was occupied by two people exactly as in the DesignBuilder software, and the occupation schedule was the same. No value of setting indoor temperature was used in Ecotect.

No operation schedule was used for artificial light in the daylighting simulations, because only the daylighting performance (daylight factor and illuminance levels) were evaluated without artificial light source.

The net glazing area (window area minus mullions and framing, or ~80% rough opening) divided by the gross exterior wall area (e.g., multiply width of the bay by floor-to-floor height) equals the window-to-wall ratio. Considering the total dimension of the façade (6,25 m²), the use of two passive Trombe walls implied a minimum glazing area with window-to-wall ratio (WWR) of 19%, as shown in Table 5.

Table 5. Façade Settings for Daylighting Performance Simulations.

Cases	Design	Observations
Glazing 04		- Glazing 04* - Glazing Area = 3,75 m² - WWR= 19,0%- Standard Modules 50 x 50 cm - Southern Solar Orientation
Glazing 07		- Glazing 07* - Glazing Area = 3,75 m² - WWR= 19,0%- Standard Modules 50 x 50 cm - Southern Solar Orientation

* Shown previously in Table 3.

Both illuminance level and daylight factor (DF) were compared based on values recommended by Goulding et al. (1994), A Green Vitruvius (1999), CIBSE (1999) and CIBSE (2002).

ANALYSIS OF RESULTS

The heating energy needs for the four solar orientations (northern, southern, eastern and western) in Guimarães, considering the annual period are shown in the thermal performance results. The analysis of the results was based on the estimate of the values of heating energy needs values calculated according to the RCCTE method.

The Daylight factor (DF) obtained was compared with values indicated by Goulding et al. (1994), A Green Vitruvius (1999) and CIBSE (1999) for residential buildings. The illuminance levels were compared with values recommended by Goulding et al. (1994) and CIBSE (2002).

Simulations of Thermal Performance

The values of the heating energy needs for all façade types analyzed for the climate in Guimarães were lower than the value calculated according to RCCTE (81.64 kWh/ m².year) for the analyzed model (Figs. 8 and 9). The façade solution with Glazing 07 and 1 or 2 Trombe walls provided better results in comparison with the other façade types.

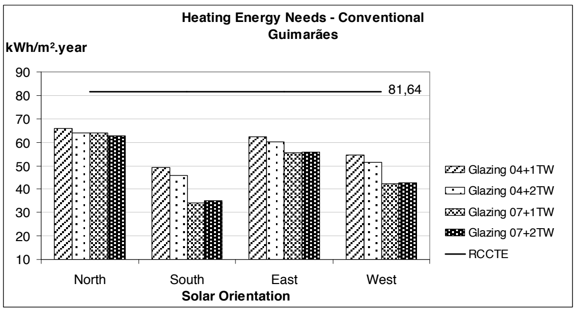


Figure 8 Guimarães: Heating Energy Needs for the Conventional System.

For the northern orientation, the variation in the solutions did not show any significant differences among the results. For the southern solar orientation, a minimum energy consumption by the use of passive solutions was observed. The heating energy needs showed approximate values for both envelopes for Guimarães climate.

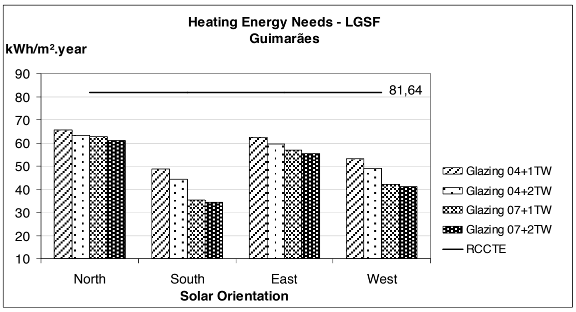


Figure 9 Guimarães: Heating Energy Needs for LGSF System.

Based on the results of thermal performance, Designbuilder software seems adequate for simulations of passive systems.

The main objective of this study was to determine heating energy needs, due to climatic conditions of Portugal. However, it is also very important to consider the cooling energy needs, although they are not presented in this study. The use of better façade solutions for winter can cause a 16-40% energy consumption increase in the cooling needs in summer. This consumption can be reduced using shading systems during the summer. The heating passive modules must be inactivated in summer. For example, the openings of Trombe walls have to remain opened during the summer at night. For this purpose shading modules were also foreseen in the façade system.

However, it is also very important to consider the cooling energy needs As an example, Lisbon shows the highest values of cooling needs based on RCCTE for the simulated model. Therefore, the best performance solutions in the heating energy needs caused a 16-40% (on 32kWh/m².year) energy consumption increase in the cooling needs. Such an increase can be reduced by using shading systems during the summer (this module is foreseen in the façade system developed).

Simulations of Daylighting Performance

Table 6 shows the values obtained on a horizontal plan (0,8m) of the simulated room. The daylight factor values agreed with the values recommended. The higher average of illuminance level was obtained using glazing 07. Glazing 04 showed lower daylighting performance.

Table 6: Bragança: Daylight Factor and Illuminance Level.

Façades	DF (%)	Verification of DF (%)		
		Bedrooms 0.3% a 1%	Living Rooms 0.5% a 1.5%	Kitchens 0.6% a 2%
Glazing 04	2,53	OK	OK	OK
Glazing 07	3,63	OK	OK	OK
Façades	Illuminance Level (Lux)	Verification of Illuminance Level (Lux)		
		Bedrooms 100-200 lux	Living Rooms 100-300 lux	Kitchens 150-300 lux
Glazing 04	94,21	-	-	-
Glazing 07	103,87	OK	OK	-

For illustration purposes, Figures 10 to 13 show charts of daylight factor (DF) and illuminance levels distribution in the model simulated for the use of Glazing 04 and Glazing 07.

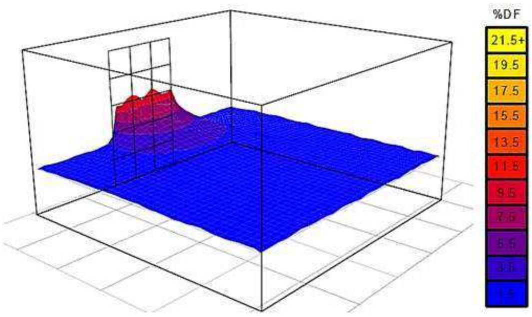


Figure 10 Glazing 04: Daylight Factor

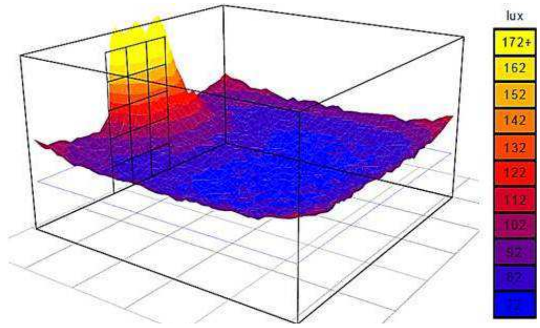


Figure 11 Glazing 04: Illuminance Level

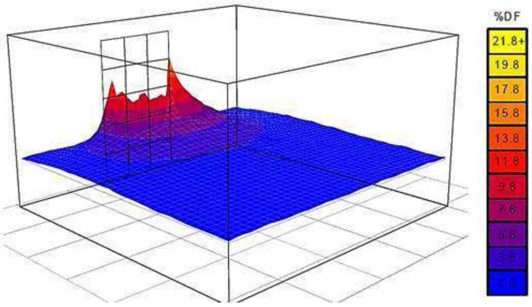


Figure 12 Glazing 07: Daylight Factor

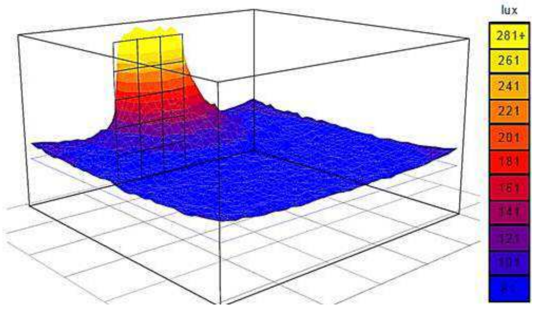


Figure 13 Glazing 07: Illuminance Level

Visible transmittance bears a direct relation to daylighting performance. The results of the simulations and visible transmittance values in Table 3 show that medium to high values of visible transmittance lead to a better performance of glass in terms of daylighting. Although medium to high visible transmittance glazings are relatively clear and provide sufficient daylight and unaltered views, they can cause glare problems, depending on the visual tasks, window size and glare sensitivity.

CONCLUSIONS

In this study, glazing 07 achieved the best thermal and daylighting performance. The results of the heating energy needs in the simulations showed that the values of all façade types were lower than the maximum limits calculated according to RCCTE. In this case, façades with Glazing 07 (Bioclean 4 mm - Planilux 4 mm) with one or two Trombe walls stood out due to the smallest heating energy need required in comparison with the others.

The values of heating energy needs in the simulations were similar in both envelopes analyzed. The results were practically identical regardless of the use of one or two Trombe walls for glazing 07. The southern solar orientation showed the minimum energy consumption with the incorporation of passive solutions.

According to RCCTE (RCCTE, 2006), the period of heating seasons for the Guimarães climate is 7 months. It means that during these months, heating is necessary to maintain comfortable conditions. Based on this period (7 months) and results of simulations, the integration of passive heating solutions into the façade modules seems to be the adequate strategy for a better performance and a decrease in the heating energy needs.

Glazing 07 (double self-cleaning glazing) showed better daylighting performance than glazing 04 (double green solar control glazing).

The glazing color is the first property for the glazing selection and can constrain or complicate the daylighting design, as observed for glazing 04 (green color). Studies about glazing in façades systems can contribute to a reduction in the energy consumption with heating systems and improvement in the daylighting performance.

ACKNOWLEDGEMENTS

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