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Sustainability assessment of government school buildings in Portugal

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ABSTRACT
An accepted design feature of passive buildings in the northern hemisphere has been to have small windows facing north and large windows facing the equator, in order to minimize losses on the north side while gaining solar heat on the south. Solar gains and daylight are key passive strategies to improve energy performance without incurring additional construction and operational costs. The purpose of this research was to investigate how sustainable traditional government school buildings that can be found all over Portugal are in terms of more efficient use of energy and materials through design solutions. The selected case study is a typical vernacular located in Covilhã with cold winter and hot summer climate. The findings demonstrated that solar gains reduced the heating load in winter; however, the internal daylight level in the building was insufficient.

1. Introduction

Vernacular architecture uses reliable design strategies to respond to the surrounding environment (Singh, Mahapatra, and Atreya 2009). The analysis of vernacular dwellings based on bio-climatic concepts may provide an insight into well-adapted popular solutions (Coch 1998) that deal with the local climatic conditions (Zhai and Previtali 2010) and which are not usually found in the literature (Bouillot 2008). A recent paper that covers the subject of sustainable building design in Portugal (Correia Guedes, Pinheiro, and Manuel Alves 2009) focuses on how the evolution of vernacular buildings informs contemporary architecture. Besides a summarized review, it presents some relevant examples. It describes vernacular architecture in one of the hotter zones in Portugal, stating that

White paint is used to reflect back solar radiation, the thick walls are made with adobe (earth) to provide thermal inertia, streets are narrow to provide shading, windows are small to increase (Summer and Winter) insulation, the large chimney is used for stack-effect ventilation. (Correia Guedes, Pinheiro, and Manuel Alves 2009)

There is a big gap between the vernacular examples shown in the paper and contemporary architecture – designed building. Possibly, architects have paid little attention to the bio-climatic approach due to the lack of studies in vernacular architecture and the anonymous nature of popular traditions (Coch 1998), which may be seen as lacking credibility. To understand culturally relevant sustainable solutions, it is crucial to create a relationship between the designer and the occupant of the architecture and hence assume the concept of ‘work with nature’ (Mottaki and Amini 2013). Vernacular traditions are now repeatedly cited in the academic literature as exemplary models of environmental strategies (Foruzanmehr and Vellinga 2011). The methods used by the anonymous empirical builders’ vernacular architecture show simple ways of addressing human needs reflecting local traditions.

Analysis of the indoor environment of heritage buildings has become very useful for defining measures to develop techniques and strategies for maintenance and even new conservation and exhibition to preserve the works of art (La Gennusa et al. 2005). The interest in heritage buildings has been growing among researchers all over the world, especially on the energy efficiency measures that have become topics of high interest during the last decade (De Santoli 2015). This represents a very important issue when the energy consumption is generated by a low technological level in the building structure and plant system (L. De Santoli et al. 2014). Several authors have shown that each historical building has its own specific indoor environment that depends on different factors (Said et al. 1999; Ascione, de Rossi, and Vanoli 2011; Fabbri, Zuppiroli, and Ambrogio 2012). Old schools are among other buildings to be addressed in regard of the uncontrolled use of heating and cooling systems beginning in the twentieth century, which are one of the most important establishments in our communities (Varas-Muriel et al. 2014). Public school buildings in Portugal reflect the vernacular tradition. A shortage of elementary school buildings led the Portuguese Government to replicate a standard school building design based on local low-tech construction methods all over the country. In spite of the same design base, local materials were used, however with the same concern – to capture benefits from the sun and to use local materials and skills, therefore making construction and maintenance very economical. These schools with large playgrounds were located near their feeder population (Beja et al. 1998). As lessons can be drawn from vernacular architecture, this typical school building was chosen for analysis to explore some issues of sustainable buildings.

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1.1. Public school buildings – Portugal

During the first half of the past century, the Portuguese Government built hundreds of elementary schools, known as ‘Plano dos Centenários’ all over the country (Beja et al. 1998). The projects were designed to be built in series, based on characteristics of the regional architecture influenced, local imposed not only by the availability of local materials in each region, but also by the local climate. The comparison of building materials in terms of sustainability is difficult; however, materials selection represents an important strategy in building design (Akadiri, Olomolaiye, and Chinyio 2013). Daylight and ventilation are critical issues to these schools, and influence the fenestration and orientation. As children are at higher risk to poor indoor air quality than adults, air quality is an important factor in school design (Freitas et al. 2011). Poor indoor air quality and construction and/or maintenance of school buildings may reduce children’s performance of schoolwork (Wargocki and Wyon 2013) and lead to absenteeism (Turunen et al. 2014). Although these buildings do not meet modern building and school standards, they are still in use after more than 50 years. Correia Guedes, Pinheiro, and Manuel Alves (2009) state that sustainable architecture aims at producing buildings that are adapted to local social-economic, cultural and environmental contexts, having in mind the consequences to future generations. Within these frames, top priority must be given to minimize energy consumption in buildings through the use of passive design strategies, that is, reducing energy consumption through a wise adaptation of the building to the local climatic context. The big question is to know whether any lessons in sustainable design can be drawn from the traditional public schools in the municipality of Covilhã.

More than 6000 of these typical school buildings were built throughout the country (Carlos 2005). The main characteristics of these buildings are their geometry, heavy walls and large classroom windows usually facing southeast to capture the sun for solar gain in the winter and daylight. Even so, windows are commonly the weakest part of the building envelope in terms of heat, air and noise transmission (Baldinelli et al. 2014). Baldinelli et al. (2014) have concluded that the improvement of the window thermal characteristics, obtained through proper control of solar radiation, is the most relevant criterion to optimize the overall energy and environmental performance of the window itself. The orientation of a building is critical to its thermal performance (Yannas 1994), especially due to solar loss and gain.

The purpose of this paper is to investigate how closely these typical school buildings match some of the sustainability indicators important to the Portuguese Government, in particular energy efficiency. This research shows that the buildings’ thermal performance and consequent energy demand to achieve thermal comfort fundamentally hinge and highlight the best orientation regarding solar availability.

2. Thermal performance – assessment method

Firstly, the typical school buildings of Covilhã are described in terms of considerations about geometry, orientation, physical properties, occupancy (internal loads) and external shading (trees). Secondly, general settings of the computer simulation such as zones, locals, climate and scheduling, and use of daylight factor (DF) are established.

2.1. Building description

The building model used in this study is based on the traditional design typology of public school buildings (shown in Figure 1), located in the municipality of Covilhã, Portugal (Figure 2). Analysis will assess the performance of classrooms, on both the first and second floors. There are 39 school buildings within the municipality based on the same type of building design in different configurations and orientations largely related to the particular location, quantified in Table 1. The main façade orientation of 34 out of 39 buildings is from 90° to 180° from the North and one of them orientated to 80°.

The traditional buildings of ‘Plano dos Centenários’ comprise walls of stone masonry with cement mortar on both sides, classroom floors and roof supported by a timber structure, entrance halls floors of concrete covered with ceramic mosaic and roof covered with red ceramic tiles. Classroom floors are raised off the ground to protect the structure from water infiltration and to provide a ventilated space, reducing potential mould growth and consequently maintenance needs (Figure 3). The windows
are timber framed with 3 mm single glazing. Classroom windows have an estimated solar heat gain coefficient of 0.67. Ventilation is natural and there is a high level of leakage mainly due to windows and doors that are not tightly fitted. Table 2 shows the thermal properties of the construction components adopted in this study.

The building model has 430 m² of built area, distributed over two floors. The heated space zones (4 classrooms) have an area of 200 m² (Figure 4). The internal loads solely account for the metabolic rate that was set at 100 W/person, regardless of activity and based on 25 persons per classroom. There is no equipment and lighting was considered negligible as it is turned on only during a very cloudy day and at the end of the shortest days of the winter. In order to simplify the balance between the activities of equivalent thermal zones, the schedules were considered to be representative for occupancy, from 8:00 am to 5:00 pm, on working days, from the middle of September to the middle of June.

2.2. Simulation settings

EnergyPlus software version 8.0 was used to perform the dynamic simulations. The weather file used is from the city of Covilhã – Portugal. The climate of Covilhã is temperate, moderately cold in winter, and the city is located at 40.2° Latitude north and 463 m above the sea level, being in the southern and Mediterranean climatic zone (Lewis, Goulding, and Steemers 1992). The heating season temperature from the used weather data reaches as low as −3.8°C with an average of 10.1°C. Covilhã has about 896 kWh/m² of available solar radiation and an average wind speed of 2.7 m/s, with a maximum of 11.7 m/s. Figure 5 shows the monthly mean air temperature and the mean global solar radiation.

The classrooms of the building are hypothetically set to 22°C for heating and no cooling system is used. Unconditioned areas were modelled as simplified natural ventilation without any mechanical system. During previous investigation through questionnaires (Carlos 2005), teachers reported varied behaviour towards the opening of windows and blinds. Therefore, for the present study, a schedule to open windows and a schedule to open blinds to optimize comfort were set on EnergyPlus. The windows are assumed open during the heating season when the air temperature of the classroom is ≥ 22°C and the exterior air temperature is ≥ 20°C. During the cooling season, the windows are assumed open when both indoor and outdoor air temperatures are ≤ 26°C. The blinds are closed during the cooling season every time the air temperature of the classroom is ≥ 23°C. The aim is to keep a uniform schedule to compare indoor thermal comfort results according to ISO 7730 (ISO 7730 1994). Nevertheless, the optimization of opening/closing the windows and blinds is closely related to the comfort/discomfort that the users may feel. Not only are these building components operable, but also the heating system may be shutdown manually. Different tree transmissivity was also set for each month as used by Carlos and Martins (2014), shown in Table 3. Trees are situated in front of the main façade, corresponding to the conical...
Table 2. Thermal properties of the construction components.

<table>
<thead>
<tr>
<th>Component</th>
<th>Thickness (m)</th>
<th>Density (Kg/m³)</th>
<th>Conductivity (W/m °C)</th>
<th>Specific heat (J/kg °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof</td>
<td>0.06</td>
<td>1900</td>
<td>0.85</td>
<td>837</td>
</tr>
<tr>
<td>Ceiling</td>
<td>0.03</td>
<td>600</td>
<td>0.14</td>
<td>1200</td>
</tr>
<tr>
<td>Air gap</td>
<td>0.02</td>
<td>750</td>
<td>0.35</td>
<td>840</td>
</tr>
<tr>
<td>Gypsum plasterboard</td>
<td>0.013</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ground Flooring</td>
<td>0.03</td>
<td>600</td>
<td>0.14</td>
<td>1200</td>
</tr>
<tr>
<td>Walls Plaster</td>
<td>0.02</td>
<td>1800</td>
<td>1.15</td>
<td>1000</td>
</tr>
<tr>
<td>Granite</td>
<td>0.485</td>
<td>2300</td>
<td>3</td>
<td>840</td>
</tr>
<tr>
<td>Plaster</td>
<td>0.02</td>
<td>1800</td>
<td>1.15</td>
<td>1000</td>
</tr>
</tbody>
</table>

Figure 4. Plan of the model school building with two similar floors.

Figure 5. Monthly climate characteristics – air temperature and solar radiation.

trees generally observed around school buildings. In spite of the trees, all second floors were exposed to solar beams when the sun was high in the sky. Simulations were carried out using the same building characteristics in five different orientations. Two hypothetical ‘wrong’ orientations of 0° and 270° and three orientations representative of the actual schools, being 90°, 135° and 180°, were simulated for comparison.

The simulation is made only for the standard heating season, that is, the period from October until May, calculated according to clause 8 of the Standard EN 832 (EN 832 1998) for the specific location of the school building under analysis. The weather file does not have any records on illuminance. Therefore, daylight availability in the classrooms is calculated using the DF.

Table 3. Monthly foliage transmissivity values for deciduous trees.

<table>
<thead>
<tr>
<th>Month</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>January, February, December</td>
<td>60</td>
</tr>
<tr>
<td>March, November</td>
<td>50</td>
</tr>
<tr>
<td>April, October</td>
<td>40</td>
</tr>
<tr>
<td>May, September</td>
<td>30</td>
</tr>
<tr>
<td>June, July, August</td>
<td>20</td>
</tr>
</tbody>
</table>

Figure 6. Sky view angles as seen from the windows to estimate the DF.
Table 4. Reflectance and surface area of the classroom.

<table>
<thead>
<tr>
<th>Surface</th>
<th>%</th>
<th>Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood floor and door</td>
<td>20</td>
<td>61.70</td>
</tr>
<tr>
<td>White paint (walls and ceiling)</td>
<td>85</td>
<td>158.17</td>
</tr>
<tr>
<td>Window</td>
<td>10</td>
<td>8.28</td>
</tr>
<tr>
<td>Chalkboard</td>
<td>15</td>
<td>2.00</td>
</tr>
</tbody>
</table>

Note: Mean reflectance = 64; total area = 230.15 (m²).

(Tregenza and Wilson 2011), which is obtained through the following equation:

\[
DF = \frac{\theta A_g \tau_g}{A_c (1 - \rho_c^2)}
\]

where DF is the average daylight factor, \(\theta\) is the angle view of the sky (degrees), \(A_g\) is the area of the glazing (m²), \(\tau_g\) is the glazing transmittance, \(A_c\) is the classroom surface area (m²) and \(\rho_c\) is the average reflectance of the classroom. The different sky view angles as seen from the windows are illustrated in Figure 6. The reflectance of the classroom is shown in Table 4.

3. Results, discussion and future work

Firstly, this section discusses the analysis of the effects of window/glazed area, shading, ventilation and building geometry in relation to the orientation of the building, heating load and daylight availability. Secondly, some directions for future work to better understand the overall sustainability of these types of buildings are presented.

3.1. Analysis and results: thermal performance

Figure 7 shows the monthly mean air temperature in each classroom assuming different orientations. During the heating season, there is little temperature difference between classrooms and between different façade orientations. This might lead to the conclusion that incident solar radiation has little effect on the classroom temperature in winter, which corresponds to the time of the year with lower solar irradiation. Hence, in addition to deciduous trees, there is always an obstacle to the low-angle winter sun.

During the heating season, the mean air temperature of the classrooms drops below the comfort zones. The temperature set for heating (22°C) operates only on school days and from 8:00 am to 5:00 pm, representative of 9 hours per day. Over the whole week, it represents 45 hours of conditioned space out of a total of 168 hours, meaning that the classrooms are only heated about 20% of the entire week. When the mechanical heating device is shut down, the air temperature drops due to high thermal losses through the envelope of low thermal resistance. Thus, 73% of the time, low external temperatures highly influence the average internal temperature.

During the cooling season the highest indoor temperature is in July. The school is closed during the last two weeks of July and throughout August; however, the teachers and students may feel thermal discomfort during the last period of school, in June and July (Carlos 2005). The teachers have confirmed relative high air temperatures in the classrooms, with higher discomfort on the second floor (Carlos 2005). The solar gains increase through the poor insulated roof; based on Figure 7, one could say that the rising heat from the floor below and less shading from trees contribute to the overheating of the second floor. Simulation results of the north orientation of the main facade show little difference in the mean air temperature during the heating season, but lower mean air temperature during the cooling season. This is due to low solar gains during summer since the big windows of the classrooms are facing due north. East and west orientations present higher mean air temperatures. When the main façade of the building has an azimuth of 90° or 270°, from the north, the space between the building and the trees with no obstacles to the sun (Figure 4) receives solar radiation from southeast to south and from south to southwest, respectively. This increases the solar heat gain inside the classrooms, which leads to an increase in air temperature.

In the winter, when the mechanical device is on, the school also receives solar radiation. The latter may not affect the indoor air temperature that was set to 22°C, but it helps to reduce energy consumption during the heating period. Figure 8 shows the heating load during the heating season for the five main façade orientations mentioned above.

Figure 7. The monthly mean air temperature of the classrooms obtained through simulation.
Figure 8. The heating load for five main façade orientations obtained through simulation.

Table 5. Total heating load of the school and its reduction.

<table>
<thead>
<tr>
<th>Orientation (degrees)</th>
<th>0</th>
<th>270</th>
<th>90</th>
<th>135</th>
<th>180</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating load (kW)</td>
<td>23.9</td>
<td>21.3</td>
<td>20.7</td>
<td>18.2</td>
<td>18.3</td>
</tr>
<tr>
<td>Reduction (%)</td>
<td>–</td>
<td>10.9</td>
<td>13.4</td>
<td>23.9</td>
<td>23.4</td>
</tr>
</tbody>
</table>

As can be seen, if the main façade of the school was orientated due north, it would consume more energy to keep the indoor environment at the comfort level. The lowest heating load is when the main façade is orientated due south or southeast. Even so, the classrooms on the second floor always present higher heating load due to thermal losses through the uninsulated roof.

Table 5 presents the total heating load of the school building for the main façade orientation. It also presents the percentage of the heating load reduction when compared to the hypothetical worse scenario (north orientation). The reduction is obtained through:

\[
\text{Heating load of worse scenario} - \text{Heating load of studied scenario} \times 100\%.
\]

The range of the heating load reduction is related to the solar heat gain through the windows, shown in Figure 9 for each classroom. Definitely, the south and southeast main façade orientation has the highest solar heat gain during the heating season.

Once more, the results obtained for the second floor are different from those obtained for the first floor (classrooms 1 and 2). The trees in front of the main façade do not block as much sun to the second floor compared to the first floor. This is why classrooms 3 and 4 have higher solar gains. With the exception of the north orientation, the south orientation presents lower solar gains through all the windows during winter in the final term of school. Firstly, the low transmissivity of the trees creates a great obstacle to the solar beam, especially to the windows on the first floor. The large leaves are also an external shading device when the sun is high at noon, during June and July. When the main façade is orientated southeast, the noon solar radiation has no obstacle (see Figure 4), which differentiates the solar gain between floors, due to the sun height.

Figure 9. Solar heat gains through the windows.
Table 6. Total heating load of the classrooms with and without trees in front of the main facade.

<table>
<thead>
<tr>
<th>Classroom</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating load (kW)</td>
<td>4.0</td>
<td>4.3</td>
<td>4.8</td>
<td>5.2</td>
</tr>
<tr>
<td>With trees</td>
<td>2.9</td>
<td>3.1</td>
<td>4.2</td>
<td>4.6</td>
</tr>
<tr>
<td>Reduction (%)</td>
<td>27.5</td>
<td>27.9</td>
<td>12.5</td>
<td>12.0</td>
</tr>
</tbody>
</table>

All of about 7000 school building types spread through the country have trees in front of the main facade. It is worth to know to what extent the trees benefit these buildings when concerned with energy consumption. The heating load reduced when there were no trees in front of the main facade. In spite of the leafless trees, the branches always block part of the solar radiation, especially on the first floor. Therefore, classrooms 1 and 2 had an increase in solar gains higher than classrooms 3 and 4 and a higher reduction of heating load. Table 6 presents the total heating load of the classrooms of the school building for the main facade south orientation, with and without trees, and the percentage of the heating load reduction.

Comparing these results, one may say that the trees do not benefit the school building. These buildings have mechanical devices to heat the interior ambient, but no such measures to cool down. Cooling down the building is entirely dependent on shadow and ventilation. This is where the trees act. They block the sun by casting shadow on the building. They also provide fresh breeze. As can be seen in Figure 10, the mean indoor air temperature increased when there were no trees in the playground of the school. The mean air temperature increased from 26°C to 28°C in June due to higher solar heat gains. As there was no cooling device, the thermal comfort worsened. The peak indoor temperature in classrooms 3 and 4 was 31°C in the middle of June.

3.2. Analysis of results: daylighting

Hypothetically, the average DF does not depend on the orientation of the building, as it is obtained under uniform overcast sky conditions. The diffuse radiance is considered to have a constant luminance distribution over the whole sky hemisphere (Tsangrassoulis et al. 1999). Thus, the average DF depends only on the visible portion of the sky as seen from the windows. Figure 6 shows that part of the visible sky has an obstacle which transmissivity varies during the year (Table 3). Figure 11 shows the average DF estimated in each classroom for all months of the year.

The classrooms on the second floor have a higher DF due to a greater angle of sky visibility. During the summer months, the DF decreases due to the increasing opacity of the trees. According to Tregenza and Wilson (2011), areas distant from a window may seem underlit if DF = 2. They also state that an average DF should be at least 2% on a horizontal working plane at desktop height. The average DF only drops below 2 during the cooling season, when overcast sky is less likely to occur. As a rule of thumb, the maximum depth for daylight penetration in a space should not exceed 2.5 (two and half times) the window head height. In the present case it is higher, going over 3.0. Lim et al. (2012) found that under the rule of thumb, the areas away from the window had low levels of illuminance. Nevertheless, there were no complaints about the levels of illuminance from the windows (Carlos 2005). Given the limitations of DF analysis, and the inconsistency between the modelled results compared to the satisfaction with daylight reported by surveyed occupants, the extent and benefits of daylighting need closer investigation.

3.3. Sustainable energy building

A study on school building refurbishment shows that refurbishment may result in 50% energy savings (Carlos and Corvacho 2010) from reduced demand for space heating. The typical school building does not use fossil fuel for heating. Instead it...
uses renewable energy through the use of a fireplace, and the use of biomass incurs some pollution. On the contrary, solar gain through the big windows for heating results in no pollution at all. For the best orientation of the main façade, the building must gain as much solar energy as possible during the heating season. During the cooling season, the trees protect the building from the sun. Daylight is also available through the big windows, avoiding energy consumption by the installed electric lamps. The use of renewable energy which is renewed by nature was contemplated. By using local materials, transportation of the materials is minimized when compared to contemporary building materials. The latter may comprise materials from massive production that involves long-distance transport. Apart from the embodied energy for production, long-distance transportation may cause significant environmental impacts.

The demand for sustainable buildings with minimal environmental impacts by the construction industry is increasing (Jrade and Jalaei 2013). Although there is no single standard for rating sustainability, there is literature that focuses on this issue. Smutny, Neururer, and Treberspurg (2012) presented a sustainable building assessment that covers three dimensions of sustainable development: (1) environmental sustainability: energy efficiency; (2) social sustainability: resident satisfaction; and (3) economic sustainability: construction costs and life cycle costs. Further studies to assess the sustainability of school building, as Bragança, Mateus, and Koukkari (2010) proposed for Portuguese residential buildings, are needed to better identify the lessons for future design. Nevertheless, from the present study some key passive design attributes of typical school buildings are identified:

- Spatial arrangement of long thin rectilinear form orientated northeast/southwest with large windows to southeast contributes to passive heat gain in winter;
- Spatial arrangement of unconditioned spaces such as hallways and attics minimizes the need to condition all spaces and provides an insulating buffer by reducing the conductive losses through the separating wall and ceiling and also reducing heat loss through ventilation;
- Windows on opposite walls allow cross ventilation; as well, the internal openings to the hallway may provide cooler air than the existing air outside, in summer. Big windows along the classroom to optimize daylight;
- Walls of high thermal mass, particularly internal walls, contribute to temperature stability;
- The clay tile roof provides natural ventilation to the attic through the opening spaces between tiles, preventing mould during winter and reducing the risk of overheating during summer;
- Vegetation (trees) provides shade in summer to reduce heating loads and contributes to biodiversity (misting of trees in summer could provide evaporative cooling to external spaces around the building and influence the internal temperature).

### 3.4. Future work

An environmental analysis would focus on the impact of the building in the environment and is beyond the scope of this paper; however, the following comments touch on some of the issues. At the time these buildings were constructed, heating was delivered through fireplaces installed in each classroom. During the eighties, a national programme replaced the fireplaces by heating systems based on a central wood boiler (Carlos and Corvacho 2010) which delivers hot water to radiators located in the classrooms only. There is no recorded data on firewood consumption which was provided by local community services and mostly sourced from clearing of the nearby forest. There is only energy consumption data from the initial building construction related to lighting. In the recent times mechanical equipment has replaced the wood boiler in some schools. There is no hot water in these buildings for sanitary purposes, even on those buildings recently upgraded. There are no cooling systems, although installation may be considered in the future.

The construction of these school buildings generally uses local materials, mostly stone and wood. This helps to reduce embodied energy, since material transportation was reduced. The centrality of the school building in an urban area reduces energy usage (Desideri et al. 2014). From a life cycle perspective, building materials are highly relevant as the embodied energy in building materials may be 10–15% of the operational energy (Mateus et al. 2007). These school buildings are more than fifty years old, the comparison of the life cycle assessment would help to demonstrate the real cost benefit, both environmental and operational, of the traditional design.

Most of the schools in the municipality of Covilhã have a wood boiler heating system, delivering hot water to radiators located in the classrooms. The boiler has no automatic regulation and therefore has low efficiency. The classroom temperature was always rising from morning, when the boiler was turned on, until the end of the day (Carlos and Corvacho 2010). Thermal comfort was not achieved in accordance with the ISO Standard (ISO 7730 1994), poor insulation and low efficiency of the heating system being the key reasons. The top issue of complaints is the lack of thermal comfort, followed by low air quality. In spite of existing small windows facing northwest, ventilation does not seem to be practical as the windows’ sills are 2.15 m above the floor, which makes them difficult to operate. Unfortunately, these windows are not opened, even when they could be open all night to cool down the structure of the building. Late post-occupancy evaluation is needed to better understand what could be improved in further refurbishment based on the satisfaction of occupants over time (Mendler, Odell, and Lazarus 2006).

### 4. Conclusions

Some of the traditional government architecture around Portugal, old school buildings in particular, are impressively rich with simple techniques which have evolved in response to protect diverse weather conditions and locally available material. The north facades have almost no windows in order to prevent the interior from cold wind and high thermal losses. The orientation of the big windows in the classrooms towards the south allows the incoming sun during the winter. During summer, solar radiation can be controlled using trees. From the solar access perspective, these deciduous trees are beneficial because they are translucent to solar radiation in winter (low solar altitude).
and semi-opaque to high summer rays which generate overheating. The simulations indicate that an optimal window area to the south could be identified from an energy perspective based on the demand for space heating. Nevertheless, these design typologies do not meet the recommended rule of thumb for daylighting design which would result in larger windows to the north. This implies that the school buildings generally have poor daylighting due to inappropriate building façade design, which could be improved in future design or with refurbishment. However, in terms of solar penetration, it has been shown that urban trees act as solar control systems on lower level façades. Further daylighting simulations are needed to determine the optimum size and orientation for a comfortable light situation and to find the appropriate balance between daylight and heat gain/loss.

The climate conscious design approach that has evolved in these vernacular buildings enhances the qualitative aspects of the classroom spaces. The windows on opposite walls create good cross ventilation during warm weather. Further work is needed to assess the elevated building floor (at least 0.4 m height from the ground), as there is the possibility of uncontrolled air leakage through the floor in winter, and to assess the benefits of underfloor ventilation to cooling in summer. An important factor to keep in mind is the fact that all the classrooms share as many as two interior walls, which helps avoid heat loss/gain from exposed facades. Each classroom has a lower surface to volume ratio which is very efficient thermally. However, the orientation affects the indoor air temperature, which was recorded high at the areas facing direct sunlight. The thermal post-performance analysis clearly indicates that the thermal comfort conditions of the classrooms are achieved mainly during the winter heating. During extreme summer temperatures, it is difficult to achieve thermal comfort conditions in a free-running building.

To conclude, the architectural form and construction of traditional school buildings embody some of the key principles of sustainability. These buildings minimize energy requirements, use local materials which are of low environmental impact, have inherent low embodied energy and enhance human health and well-being. These school buildings were initially developed for cost and space efficiency and also to take advantage of the available sun. They have been widely replicated throughout Portugal with little change regardless of the climate zone. Even though they were built using the same building design, the materials varied according to what was locally available. Nevertheless, heavy mass walls and wooden structure were common to all of them and this study demonstrates the passive design. Lessons can be drawn from traditional architecture. Although the case study is set in an extreme climatic zone, the techniques could be successfully implemented in temperate climate zones.

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