JOURNAL OF CIVIL ENGINEERING AND MANAGEMENT
2010
16(4): 567–576

RETROFIT MEASURES IN OLD ELEMENTARY SCHOOL BUILDINGS TOWARDS ENERGY EFFICIENCY

Jorge S. Carlos[1], **Helena Corvacho**[2]
[1]*C-MADE, Centre of Materials and Building Technologies, University of Beira Interior, Calçada Fonte do Lameiro, Covilhã, Portugal*
[2]*Department of Civil Engineering, Building Division of the University of Porto, Laboratório de Física das Construções Rua Dr. Roberto Frias, Porto, Portugal*
E-mails: [1]jcarlos@ubi.pt; [2]corvacho@fe.up.pt

Received 20 July 2009; accepted 11 June 2010

Abstract. A study on thermal retrofit of Portuguese elementary school buildings is presented. The type of school under analysis is one adopted by a large construction campaign that began in the 1940's. This building stock has a very poor thermal performance and their retrofit was evaluated starting with a case study of a school in the central region of Portugal, where some experimental measures were performed and a calculation method was applied for the heating energy consumption estimation. A solution for the thermal retrofit of the school building external envelope was optimized and the effect on heating energy consumption was evaluated, using ECOTECT, resulting in a reduction of 52% of heating energy needs. The national impact of the thermal retrofit of the whole building stock was characterised in terms of energy savings. Finally, the pre-heating of the ventilation air was also tested as a complementary measure and its effect evaluated. The solution tested may provide up to 1000 kWh/year of extra heat gains by pre-heating the ventilation air. It must be underlined though that the performance of these systems is dependent on the thermal properties of their components so higher reductions can be achieved with the improvement of these properties.

Keywords: thermal performance, energy efficiency, thermal retrofit, pre-heating of the ventilation air, elementary school building, thermal simulation.

1. Introduction

From the middle of the 1940's until the late 1960's (Beja *et al.* 1990, 1998) a large campaign for the construction of elementary schools was carried out in Portugal to provide the country with the necessary education facilities. This plan, known as "*Plano dos Centenários*", adopted uniform building typologies throughout the country. The buildings were all based on the same plants and they conformed to two different types: buildings for one gender, only; buildings for the two genders but with a physical separation. They were built in a traditional way, mainly with stone walls and wooden floors and roofs, without any insulation material, still very far from energy or environmental concerns.

There were slight differences between the schools meant for an urban environment and those, generally smaller, for a rural one. The number of classrooms went from 1 to 4. Until the late 1960's, about 6864[1] school buildings were constructed all over the country. Since then, there have been some refurbishments and enlargements in those buildings to adapt them to modern needs. However, for the most part this large stock is still in its original condition and still in use. In most cases, thermal comfort requirements are not fulfilled or a high consumption of heating energy is needed to fulfil them. In fact, it is easy to recognize the potential energy savings of such a large and old stock.

At the beginning of the 1990's, the first Portuguese regulations related to building energy performance and thermal comfort (MOP 1990) came into force and required that new buildings and great refurbishments of existing buildings implement measures to improve building energy performance. The new and current regulation (MOP 2006), more severe than the first one, still applies to new buildings and existing buildings submitted to a great refurbishment (whenever the total cost of the refurbishment is over 25% of building's value). Old buildings still in operation, like the kind of school buildings under analysis, if not subject to a refurbishment, will keep on with high energy consumption. This situation needs an urgent evaluation. A few studies were carried out (Lollini *et al.* 2006; Carlos 2005) showing how energy performance and the related costs can improve with an adequate refurbishment of the buildings.

Beginning with the analysis of the thermal behaviour of a specific school, thermal refurbishment strategies were studied and their reproducibility evaluated to quantify the national impact of a global refurbishment of these schools. Fig. 1 shows us some examples of the type of school buildings under analysis.

[1] Source: *Secretaria-Geral do Ministério da Educação* (Ministry of Education).

Fig. 1. Examples of Portuguese elementary school buildings integrated in the "Plano dos Centenários"

2. The studied school building

Covilhã is located in the central region of Portugal, between 450 and 700 metres above the sea level. Its climate is quite cold in winter for the Portuguese patterns (2250 heating degree-days for a reference temperature of 20 °C) and mild in summer, so it is included in the most severe Portuguese winter climatic region (I3) and in a mild summer region (V2), for regulatory purposes (MOP 2006). A school building in Covilhã, among the schools of the same type, was chosen as the object of our analysis.

The school is a two floor building in the city of Covilhã, as illustrated in Fig. 2, with two different parts with no interior connections between them. The atriums and staircase are located at the lateral edges of the building. The main façade is southeast oriented. This is a traditional building of "Plano dos Centenários" with resistant walls of stone masonry, floor and roof supported by a wooden structure. The roof is covered by ceramic red tiles. The wall's U value is of 3.56 W/m^{2}K; the floor and roof has a U value of 2.17 W/m^{2}K and 3.48 W/m^{2}K, respectively and the windows a U value of 5.00 W/m^{2}K.

Fig. 2. Elementary school under analysis, at Covilhã

There is a huge amount of energy loss for this kind of building school compared to new ones. The windows are single glazed and have a wooden or aluminium frame. Ventilation is natural and uncontrolled. Building envelope is not thermally insulated at all. Windows and outside doors are not tightly fitted. Since there was no information available about the normal use of these kinds of schools throughout the country, it was decided to carry out a detailed characterisation of the conditions of use of the chosen example, namely in what concerns its thermal behaviour.

3. The in-use conditions

3.1. The heating system

The school has a wood boiler heating system, delivering hot water to radiators located in the classrooms. The boiler is without automatic regulation and has a low efficiency. The heaters do not use thermostatic valves. Sometimes individual electric equipment is also used in a classroom or at the atrium. Action for the maintenance of the heating system is not performed as often as would be necessary. There is no cooling equipment.

From Monday to Friday, the classes take place from 9 a.m. to 4 p.m., with a lunch break from mid-day to 1.30 p.m. The boiler of the central heating system is generally turned on at the beginning of the day (at 8 a.m.) and provided with wood for the last time in the day at about 3 p.m. At night, the heating system is turned off. The school is closed at the weekend and the heating system is also turned off.

There was no data available for the consumption of firewood in the boiler and it was not possible to control it during the period of our experimental measures. Given this difficulty, our option was to make some temperatures and humidity experimental measurements to evaluate comfort conditions in the school and also to estimate the necessary heating energy consumption, allowing, for this purpose, the validation of a simulation model.

3.2. Temperatures and humidity experimental measurements

Two thermal hygrometers were used for the measurement of air temperatures and relative humidity within the building during winter season (January to March 2004) (Carlos 2005). One was placed in the classroom 1 of the second floor, while the second was placed first of all in the classroom 2 of the first floor and then at the atrium, circulation 1 (Fig. 2). The outdoor data were collected from a weather station located at Covilhã. The collected data are summarized in Tables 1 and 2.

Values in Tables 1 and 2 clearly show that thermal comfort requirements are not satisfied. As recommended by ISO 7730 Standard (1994), the air temperature in the classrooms should be between 17 ºC and 21 ºC, for the

Table 1. Air temperature (ºC) during the operating schedule of the school

	January to March		
	Min	Average	Max
Outdoor air	–1	10	19
Room 1 (2nd floor)	7	13	19
Room 2 (1st floor)	10	16	20
Atrium	6	8	12

Table 2. Relative Humidity (%) during the operating schedule of the school

	January to March		
	Min	Average	Max
Outdoor air	24	60	99
Room 1 (2nd floor)	44	67	87
Room 2 (1st floor)	53	72	89
Atrium	51	59	67

winter period. In both monitored rooms the minimum temperature is far below this level and even the average of the air temperatures is lower than 17 ºC. In what concerns relative humidity, the values should be between 30% and 70%. With such low temperatures it was expectable that RH would reach higher values. In classroom 1, RH was above 70% for 40% of the measurement period of time and in classroom 2, the same occurred for 77% of the time, this last room was more crowded and had some plants in it. The measurements carried out have shown the absolute need for a thermal refurbishment to reach acceptable comfort conditions, without increasing heating energy consumption and even reducing it.

3.3. Heating energy consumption estimation

As said before, there is no data available for the firewood consumption of the heating system. Wood is supplied by chopping down old trees, with no measurements available concerning quantity. ECOTECT[2] was then used to calculate the energy consumption of this building.

ECOTECT is a computer program from SQUARE ONE research PTY LTD, from Australia which enables conceptual building design 3-D interfaces. It is possible to model its geometry while using interface visualisation. Its code follows the methodology proposed by CIBSE (Chartered Institute of Building Services Engineers). This method requires a careful organization of data into a convenient and flexible format. Based on an hour-by-hour climate data and transient simulations (transfer function or heat balance method) it is an adequate model to study buildings thermal performance, which has been compared to other similar commercial programs (Boutet *et al.* 2007; Marsh 2003; Starvoravdis and Marsh 2005). ECOTECT gives us monthly and yearly heating or cooling energy consumption. The input data for all the simulations were obtained from the weather station located at Covilhã. In Fig. 3, monthly mean data are presented: minimum and

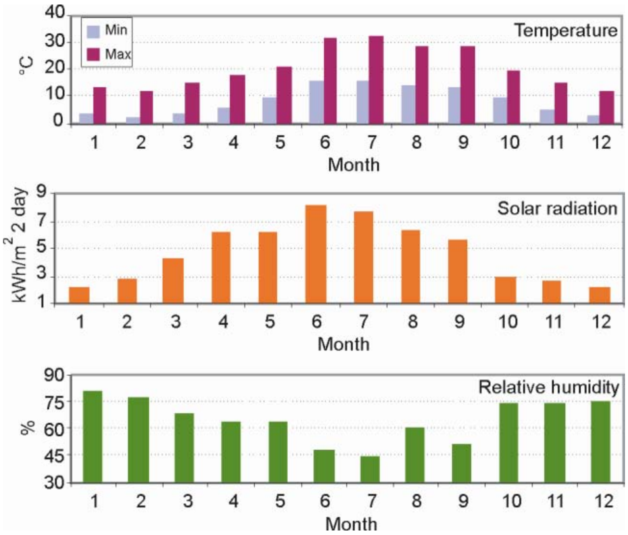

Fig. 3. Local climate data (Monthly averages of the minimum and the maximum daily temperatures; Monthly average of the daily solar radiation; Monthly average of the daily mean relative humidity)

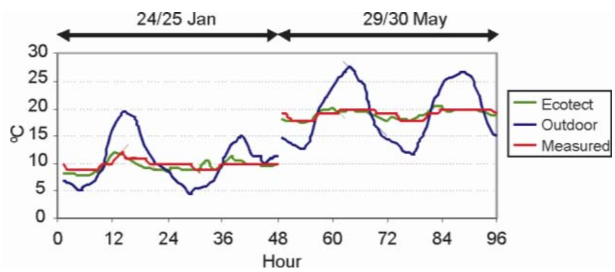

Fig. 4. Local measurements vs. ECOTECT simulations

maximum values of temperature, global solar radiation on horizontal surface and relative humidity.

In order to validate ECOTECT's use, simulations were conducted considering periods of time where no heating energy was provided, since there was no information of the real energy consumption of the school building during the week. To validate ECOTECT's simulation a winter weekend period was chosen for comparison, being that the heating system is off. In the same way, a spring weekend period was also chosen. Fig. 4 shows a comparison between local measurements and ECOTECT simulations for two periods of the heating season. Simulation shows a very good approximation to the measured values. In fact, the average of temperatures for the first period was 9.5 ºC for ECOTECT's simulation vs. 9.9 ºC for measured temperatures. For the second period, the average of temperatures was 19 ºC and 19.2 ºC for simulation and measured values, respectively. In the simulations, two air changes per hour were considered (MOP 1979).

The studied building, as all these kinds of buildings in the country, was built before any regulation concerns on energy efficiency. It's a poor thermal performance building, far below the minimum standards defined by Portuguese thermal regulation. Therefore, besides the characterisation of the current thermal behaviour of the building, several simulations were carried out with

[2] Available from Internet: <http://www.squ1.com.>

ECOTECT incrementing thermal resistance of the envelope to improve energy efficiency. The objective was to guarantee an indoor thermal comfort in agreement with ISO 7730 Standard (1994) for school's schedule operation (8:00–17:00).

4. Thermal retrofit of the school's exterior envelope

Without any retrofitting measures, a heating energy consumption of approximately 18 968 kWh per year was estimated for school days period, in order to guarantee indoor thermal comfort. Searching for the best solution for building thermal refurbishment, several simulations were carried out with common materials and constructive techniques that are used in the construction sector, in Portugal. The most suitable retrofit solution proved to be as follows, excluding the external insulation of the wall, as recommended by Zavadskas *et al.* (2008):

- Walls – 80 mm of expanded polystyrene on the inside surface of walls with 13 mm of plaster plate covering it (U = 0.36 W/m^{2}K);
- Roof – 120 mm of rock wool blanket on the flagstone or 180 mm of loose mineral wool (U = 0.25 W/m^{2}K);
- Windows – double glass in windows and double door on balcony (U = 3.00 W/m^{2}K);
- Floor – 50 mm of rock wool blanket under the floor (U = 0.57 W/m^{2}K).

With these retrofit measures a heating energy consumption of 9164 kWh per year was estimated which represents a decrease of 52% in relation to the original building's heating energy consumption. The highest economic effect is also obtained (Ginevičius *et al.* 2008). In the overall balance analysis the heat gain due to the solar radiation represents about 7% of the heat loss while before the retrofitting measures barely reaches 3%.

5. National impact evaluation of a large scale retrofit of the studied type of schools

5.1. Portuguese climatic regions

RCCTE (MOP 1990) that came into force in 1990 was the first Portuguese regulation law to define buildings thermal requirements to maintain thermal comfort without excessive energy consumption. Without being too demanding, the first regulations lead to new construction practices throughout the whole country and often with some improvements in relation to minimum standards. Recently, in 2006, RCCTE was revised and a new and more demanding regulation was approved (MOP 2006). In both regulatory documents, Portugal was divided into three winter climatic regions and three summer climatic regions, with some adjustments in the new regulation (Fig. 5). Climatic regions are related with the Country's administrative division and local altitudes. Portuguese winter climatic regions go from I1, corresponding to the mildest climate, to I3, corresponding to the most severe one. As it was already said the studied school is located at Covilhã, belonging to region I3.

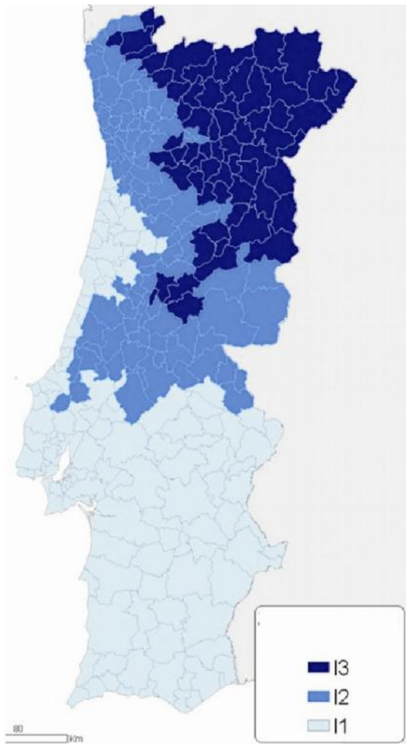

Fig. 5. Portuguese winter climatic regions

5.2. Evaluation of the reduction of heating energy consumption at a national level

Since the studied building is located in I3 climatic region, Porto (I2) and Faro (I1) were the chosen cities to make a comparative study of heating energy needs in the three winter climatic regions. The same indoor comfort temperature was chosen, with the average climatic data presented in Table 3. In this table monthly outdoor mean air temperature (air – ºC), heating degree-days (DD), daily solar radiation for SE facade (Rad – SE, kWh/m^2), and daily solar radiation for NW facade (Rad – NW, kWh/m^2) can be found, for the three studied locations.

For buildings with the same envelope construction and for the same operation schedule ECOTECT calculation lead to the values presented in Table 4, for the original building and also for the retrofitted building. For identical buildings and for the same pattern and environmental comfort, heating energy needs are quite different for each of these three cities. These different values, as was expected, correspond to the different climatic regions where they are located.

There are about 6864 elementary school buildings of type "Plano dos Centenários". Analysing the available data, the estimated distribution of the schools throughout the country is as follows: 2431 buildings in I1 climatic region, 2902, in I2 and 1531, in I3. The average number of classrooms per school building is 1.7. The values in Table 4 reflect a 3 classrooms school building. By working out total value of classrooms for all the buildings in each climatic region, energy consumption for all the buildings can be calculated. Since there is some variation in the number of classrooms of the schools, for calculation purposes, it

Table 3. Climate data for Covilhã, Porto and Faro (heating season)

		January	February	March	April	May	October	November	December
Covilhã	Air – ºC	7.3	8.6	10.9	11.7	15.8	14.4	9.7	7.5
	DD	300	292	251	220	134	153	281	357
	Rad – SE	2.62	2.12	2.42	2.86	2.53	2.80	2.34	2.06
	Rad – NW	0.01	0.44	1.09	1.43	2.08	0.33	0.35	0.00
Porto	Air – ºC	10.1	10.8	11.7	12.9	14.6	15.8	12.2	10.4
	DD	276	231	226	189	142	115	206	266
	Rad – SE	1.16	1.57	1.97	2.17	1.74	1.68	1.03	1.23
	Rad – NW	0.00	0.04	0.16	0.13	0.35	0.16	0.00	0.00
Faro	Air – ºC	11.8	12.5	14.7	15.7	18.2	20.3	15.5	13.2
	DD	180	184	139	115	52	24	118	224
	Rad – SE	1.97	1.96	2.52	2.47	2.23	2.16	2.00	1.71
	Rad – NW	0.00	0.11	0.23	0.17	0.45	0.19	0.03	0.00

Table 4. Heating energy needs (ECOTECT) for Covilhã, Porto and Faro – original building and retrofitted building

	Original (kWh/year)	Retrofitted (kWh/year)
Covilhã	18968	9164
Porto	12908	6152
Faro	5408	2368

was assumed heating energy consumption proportional to the number of classrooms. The same occupancy profile was assumed as in 3.1. This corresponds to a public schedule defined by the government for the country. All these buildings are similar. The walls of stone masonry depend on the kind of rock found in the region of each school. Even so, the same construction characteristics were assumed to be compared as in 2. Table 5 shows the sum for all the schools of heating energy consumption for the original building characteristics and for the retrofitted one in I1, I2 and I3 climatic regions. In this way, heating energy consumption in the whole country was estimated and the heating energy savings for retrofit proposals for this kind of buildings were obtained.

Table 5. Heating energy global consumption estimation and savings for the three Portuguese climatic regions (MWh/year)

Climatic region	Classrooms n.º	Original	Retrofitted	Savings
I1	4133	7451	3263	4188
I2	4933	21226	10115	11110
I3	2603	16458	7951	8507
Total (whole country)	11669	45134	21329	23805

The heating energy consumption estimation leads to different values depending on the climatic region but also on the number of classrooms in each region. While in the region I2 and I3 the energy consumption might be reduced down to 48% from the original building with a standard indoor comfort in the region I1 the reduction could be of about 44%. In spite of the fact that a large number of the elementary schools already have another use, these kinds of buildings represented about 40% of the 17250 national always be worthy of evaluation. From a health point of view, thermal comfort must be achieved. From the thermal comfort point of view, the present indoor temperature must be raised, so energy consumption will be incremented. Therefore retrofit measures are needed to enhance comfort and reduce energy consumption (Thormark 2006).

6. Test of a complementary measure: pre-heating of the ventilation air

6.1. The principle

Previous simulations showed a considerable improvement in the building thermal performance as a consequence of building envelope retrofit. The heating loss through the walls represents more than 60% over the total losses through the envelope at the initial stage of the building. After retrofitting measures this represents less than 50%. As heat losses by transmission through the envelope are reduced due to an increase of insulation, heat losses due to ventilation, for the same air change rate, become increasingly important in the total amount of heat losses. In Fig. 6, monthly total envelope transmission heat losses and heat losses through ventilation are presented. As it can be seen, for the retrofitted building the losses through ventilation become clearly the most important one. While for the original building the ventilation represents about 48% of the total building's thermal losses; after retrofitting this can represent up to near 90% of the total losses. One way to reduce energy consumption due to ventilation is the pre-heating of the ventilation air. There are several ways to pre-heat the ventilation air without mechanical devices. Probably the most expensive solution for the moment would be using earth-to-air heat exchangers through buried pipes as it was used, for instance, on DB Netz AG (Hamm), Fraunhofer ISE (Freiburg) and Lamparter (Weilheim) (Pfafferott 2003). Fresh air would be heated by heat transfer from energy accumulated on ground to buried pipes and then to air by convection. This air enters the building through vents warmer than outside cold air. This would represent a great deal of construction work. Another solution would be the construction of a conservatory, an enclosed glazed space attached to the main building (Lechner 1991). Fresh air enters the bottom of the conservatory, is

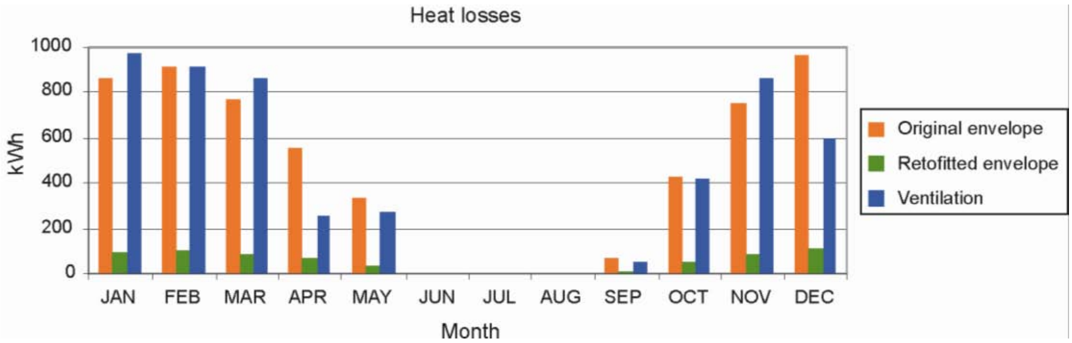

Fig. 6. Monthly heat losses through the envelope and heat losses through ventilation

pre-heated within the space and enters the main building through top vents. Occupying part of the courtyard of the school where children play with a large glazed construction would be expensive and also potentially unsafe for young people. Another solution could be the use of unglazed transpired solar collectors.

This is a dark perforated metal sheet cladding mounted several centimetres from the sun-facing surfaces of the building to form an air cavity. The ventilation fans draw the required air through the perforated wall into the air cavity and then to the building. The metal cladding absorbs incident solar energy and a proportion of it is transferred to the air stream (Summers *et al.* 1996). The big disadvantage would be an aesthetic change of the building which would cause a loss of identity. Solar air collectors could be mounted on the sun-facing wall too (as it was done on ZAE building in Würzburg, Germany) (Pottler *et al.* 1999). Air collector types are very varied. Basically they have a dark absorber which allows the transformation of the solar radiation into heat, enclosed in a casing with an appropriate heat insulator meant to reduce losses and usually covered with glazing to allow incident solar radiation on the absorber. Bottom and top covers permit fresh air to be heated before it enters the building. This would be an intrusive and strange object at the building facade, changing the architectural image.

Changing sun-facing windows would be the cheapest solution without changing outdoors aesthetics. A window air collector, a supply air window or a ventilated double window can be used for the purpose of pre-heating the ventilation air.

A window air collector consists of two glazed windows with an intermediate device, usually a Venetian blind, which act as an absorbent of incident solar energy (Hastings and Morck 2000). The ventilated cavity formed by the two windows is then used to pre-heat the ventilation air before entering the room. The air stream enters in this cavity through vents at the bottom of the outer window and enters through another vent on the top of the inner window, warmer than it is outside. This window air collector also reduces daylight, which is a big disadvantage for a school building.

The supply air window consists of a window with two sashes, joined by opener clips that are separated by an air gap (Baker and McEvoy 2000). Outdoor air is drawn into the air gap at the vent on the outside bottom of the window. This air is heated within the gap and enters the room through top inside vent. A ventilated double window (Arons and Glicksman 2003) is basically the same as a window air collector but without any intermediate device (Fig. 7). Air stream is pre-heated by a portion of absorbed heat contained in the glazing.

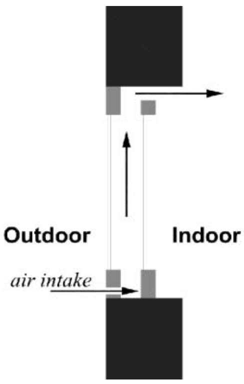

Fig. 7. Ventilated double window (Arons and Glicksman 2003)

These systems are all alike in modus operandi. Solar gain and warmth of the room warms the glass and thereby pre-heats the air stream which rises by stack effect and wind pressure. Sometimes an intermediate solar absorber is used between glazings to collect solar radiation, but with a disadvantage of reducing direct solar gains and daylight. A fan can be associated to increase or maintain the air flow.

6.2. Thermal improvement

Each and every fenestration solution interferes with the U-value of the window and besides pre-heating the ventilation air, it changes the transmission heat losses and so the overall building's performance. For a double window with a ventilated gap, the heat flow through the inner window (Q_{w_int}, W) is:

$$Q_{w\_\text{int}} = A_{w\_\text{int}} U_{w\_\text{int}} (T_\text{int} - T_{gap}) , \qquad (1)$$

where $A_{w\,\text{int}}$ and U_{w_int} are the area (m^2) and the Heat Transmission Coefficient (W/m^{2}K) of the inner window, T_int is the indoor air temperature (K) and T_{gap} is the air temperature within the gap (K). The heat flow through the outer window (Q_{w_ext}, W) is:

$$Q_{w\_ext} = A_{w\_ext} U_{w\_ext} (T_{gap} - T_{ext}) , \qquad (2)$$

where A_{w_ext} and U_{w_ext} are the area (m^2) and the Heat Transmission Coefficient (W/m^{2}K) of the outer window and T_{ext} is the outdoor air temperature (K). The U-value of the double window (U, in W/m^{2}K), excluding ventilation heat recovery, becomes (McEvoy *et al.* 2003):

$$U = \frac{(T_{\text{int}} - T_{gap})U_{w\_\text{int}}}{T_{\text{int}} - T_{ext}}. \quad (3)$$

Including ventilation heat recovery the U-value of the double window, named U equivalent (U_{eq}, W/m^{2}K) is obtained from:

$$U_{eq} = \frac{(T_{\text{int}} - T_{gap})U_{w\_\text{int}} - (T_{gap} - T_{ext})\rho cV}{T_{\text{int}} - T_{ext}}, \quad (4)$$

where ρ is the density of the air (kg/m^3), c is the specific heat capacity of the air (J/kgK) and V is the air flow rate (m^3/s). For a triple glazed fenestration (double glazed at the inner window and single glazed at the outer window), U_{eq} was found as low as 0.67 W/m^{2}K for about 50 m^3/h of ventilation air rate (McEvoy *et al.* 2003). For this 1.2 m × 1.2 m fenestration, the U_{eq} rises up to 1.12 W/m^{2}K for a lower ventilation rate of about 20 m^3/h. U-values are a function of material's thermal properties and are also dependent on air stream. Values of U_{eq} even lower can be achieved using a low e-coating facing the ventilation channel, a value of 0.75 W/m^{2}K for about 19m^3/h of ventilation air rate. For a supply air window, a correlation was found in function of fenestration area (Southall and McEvoy 2006). For an air flow rate of 32 m^3/h, with a low e-coating facing the ventilated air channel, U_{eq} for a triple glazing was found to be as follows:

$$U_{eq} = 0.225 + 0.342A - 0.042A^2, \quad (5)$$

where A is the fenestration area (m^2). For double glazing (two single glazed windows), U_{eq} can be obtained as follows:

$$U_{eq} = 0.256 + 0.536A - 0.077A^2. \quad (6)$$

Correlation for triple glazing can lead to a U_{eq} of 0.84 W/m^{2}K for each of 2.7 m^2 of this school's fenestration. For a window air collector, Hasting and Morck (2000) shows U_{eq} – value in function of ventilation air rate (Fig. 8). Park (2003) shows how Ueq changes in function of air temperature's difference between indoor and outdoor (Fig. 9).

Heat losses through ventilation due to air renovation (Q_{rn}, W) are:

$$Q_{rn} = \rho cV(T_{\text{int}} - T_{ext}), \quad (7)$$

where V is the air flow rate (m^3/h). Energy flow that any air channel within a supply air window, double skin facades or doubled window can deliver into the building (Q_{vnt}, W) is:

$$Q_{vnt} = \rho cV_{vnt}(T_{out} - T_{in}), \quad (8)$$

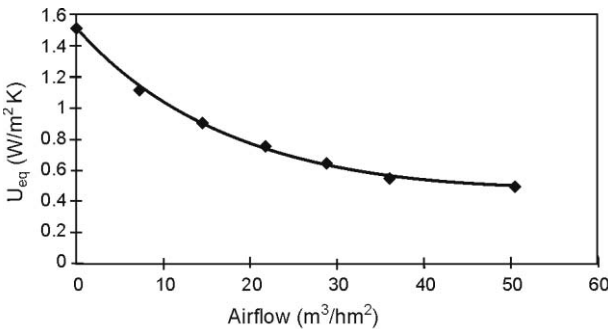

Fig. 8. U_{eq} for different air flow rates (Southall and McEvoy 2006)

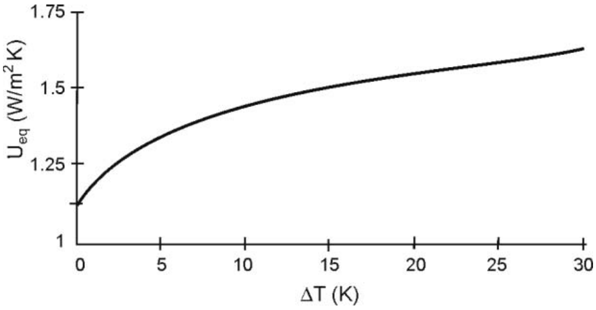

Fig. 9. U_{eq} in function of temperatures difference (indoor-outdoor) (Park 2003)

where T_{out} is air temperature at the outlet vent of the air channel (K), V_{vnt} is pre- heated air flow rate (m^3/h) and T_{in} is air temperature at the inlet vent of the air channel (K), usually the same as outdoor air temperature. Thus, heat losses due to air renovation and after pre-heating the ventilation air (Q, in W) become:

$$Q = [\rho cV(T_{\text{int}} - T_{ext})] - [\rho cV_{vnt}(T_{out} - T_{in})]. \quad (9)$$

Southall and McEvoy (2006) has compared ventilation heat recovered by a supply air window with different air channels widths (10 mm, 20 mm and 30 mm, glass to glass) and same air flow rate of 14 l/s and 6l/s (50.4 m^3/h and 21.6 m^3/h). Fig. 10 shows the amount of energy that is delivered in function of incident solar radiation. For a wider air channel and highest solar radiation more energy is transferred to the air stream entering the room. Without solar radiation the heat delivered by passing air is a part of the heat losses through the inner window, allowing the partial recovery of it.

For this building, with 9 windows (3 per classroom), each 2.8 m^2, totalizing 25.2 m^2 simulations were carried out, supposing that one half of the building's needs for air renovation are supplied by nine ventilated windows.

The calculation method was derived from previous work done by Baker and McEvoy (2000) and McEvoy *et al.* (2003) supported by COMIS and CAPSOL. COMIS is a multizone air flow and contaminant transport modelling software (LBNL 2003) and CAPSOL is a heat and mass transfer program.

For the situation of an extra single glazed window at the outer side of the fenestration, allowing the pre-heating of ventilation air, as shown in Fig. 7, the amount of heat

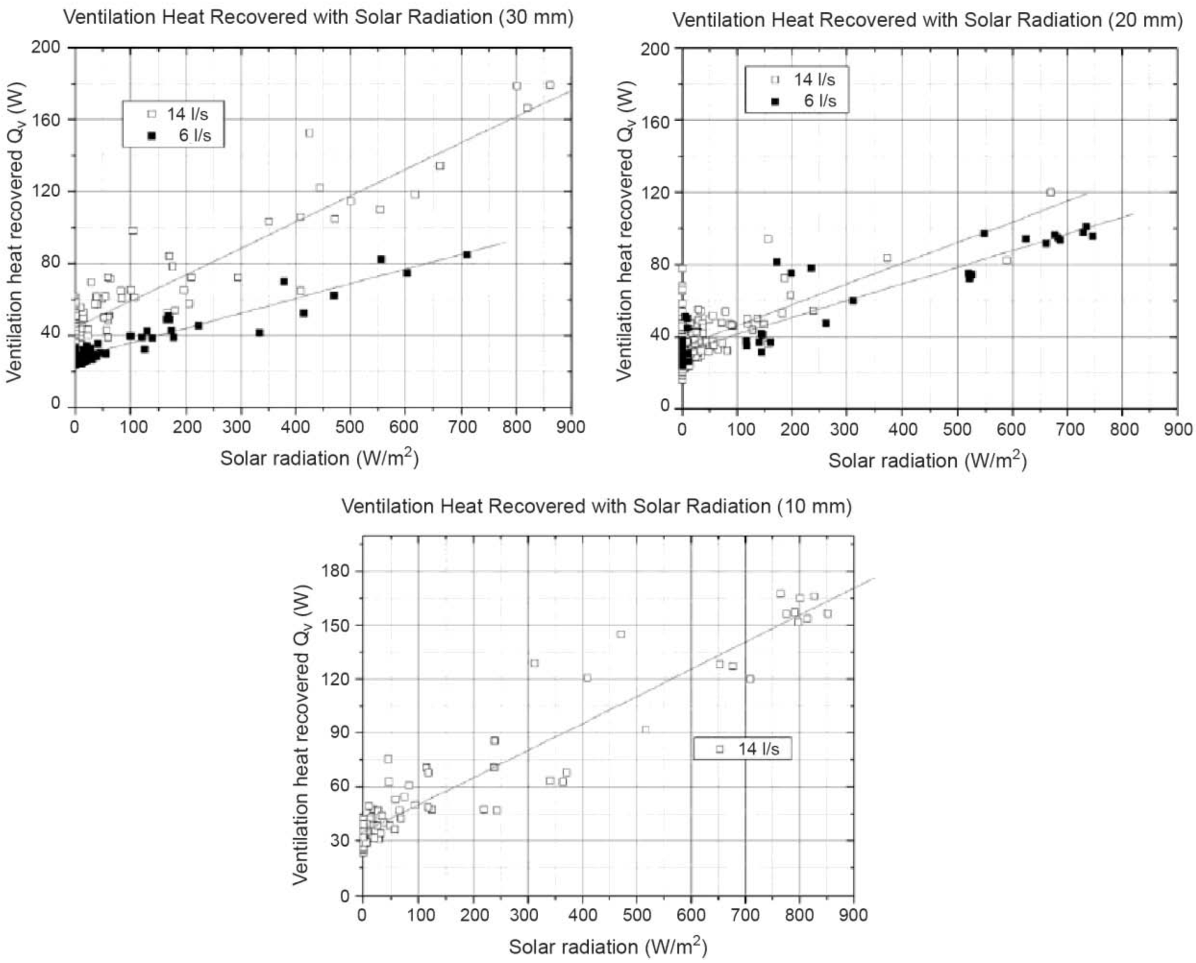

Fig. 10. Ventilation heat recovered vs. incident solar radiation for different air gap widths (Southall and McEvoy 2006)

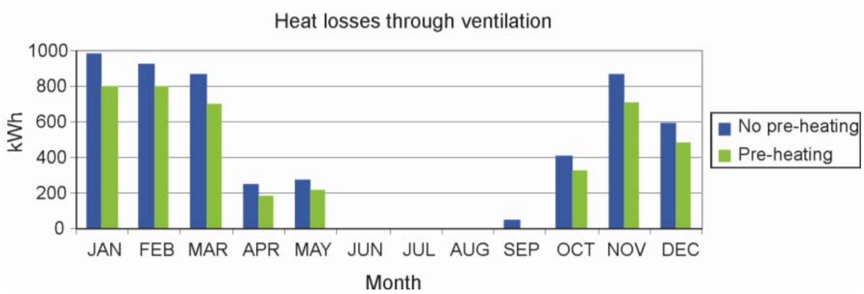

Fig. 11. Monthly heat losses through ventilation with and without pre-heating of ventilation air

losses due to ventilation can be seen on Fig. 11 and compared with the situation without pre-heating. This solution may provide up to 1000 kWh/year of extra gains by pre-heating the ventilation air with the sun. Adding this passive technology to the retrofitting measures already mentioned, instead of decreasing 52% in the thermal losses (vide chapter 4) it would decrease up to about 57%. In the retrofitted scenario, the heat gain through the pre heated ventilation air would add an extra gain of 2% to the 7% of solar heat gain that was mentioned before. Nevertheless this is thermal properties dependent so higher reduction gains can be achieved.

7. Conclusions

Our study has revealed the advantage of the thermal retrofit of these schools, with much improvement of thermal comfort and reduction of heating energy consumption. From the energy point of view, changing building's envelope was investigated and it is certainly the most important measure to take place, as previous works reported (Butala and Novak 1999). A retrofit solution for the external envelope of a school building which is located in one of the coldest regions of Portugal was selected and analysed. For this solution, a reduction in heating energy consumption of 52% was achieved.

The same solution can be adapted to hundreds of building schools of the same construction typology all over the country. Since the studied building stock is quite representative of Portuguese elementary school buildings, it was proved that a generalised intervention will have a significant national impact.

Some reduction of heating energy consumption can also be achieved by pre-heating the ventilation air with passive strategies.

Pre-heating of the ventilation air, when ventilation losses become the most important way for heat to escape from the building, would be an efficient measure. The solution tested in the school under analysis, consisting of 9 double ventilated windows, may provide up to 1000 kWh/year of extra gains by pre-heating the ventilation air.

To reach more energy savings, the systems would need some adjustments and reorganisation measures and also the way the building is used should be rethought, leading to an optimised use of energy.

Nomenclature

A	fenestration area (m^2)
A_{w_ext}	area of the outer window (m^2)
A_{w_int}	area of the inner window (m^2)
c	specific heat capacity of the air (J/kgK)
Q	heat losses due to air renovation (W)
Q_{vnt}	heat delivered into the building through ventilation air (W)
Q_{w_ext}	heat flow through the outer window (W)
Q_{w_int}	heat flow through the inner window (W)
T_{ext}	outdoor air temperature (K)
T_{gap}	air temperature within the gap (K)
T_{in}	air temperature at the inlet vent of the air channel (K)
T_{int}	indoor air temperature (K)
T_{out}	air temperature at the outlet vent of the air channel (K)
U	U-value (W/m^2K)
U_{eq}	U equivalent (W/m^2K)
U_{w_ext}	heat transmission coefficient of the outer window (W/m^2K)
U_{w_int}	heat transmission coefficient of the inner window (W/m^2K)
V	air flow rate (m^3/s)
V_{vnt}	pre-heated air flow rate (m^3/h)
ρ	density of the air (kg/m^3)

References

Arons, D. M. M.; Glicksman, L. R. 2003. Double skin, airflow facades: Will the popular European model work in the USA? *Building Technology Program*, Massachussetts Institute of Technology.

Baker, P. H.; McEvoy, M. 2000. Test cell analysis of the use of a supply air window as a passive solar component, *Solar Energy* 69: 113–130. doi:10.1016/S0038-092X(00)00048-7

Beja, F.; Serra, J.; Machás, E.; Saldanha, I. 1990. *Muitos anos de escolas – Ensino Primário – 1941* (Many years of school – Elementary School – 1941). Ministério da Educação – Departamento de Gestão de Recursos Educativos*.

Beja, F.; Serra, J.; Machás, E.; Saldanha, I. 1998. *Muitos anos de escolas – Ensino primário – Anos 40 a Anos 70* (Many years of school – Elementary School – from 40's to 70's). Ministério da Educação – Departamento de Gestão de Recursos Educativos*.

Boutet, M. L.; Alías, H. M.; Jacobo, G. J.; Busso, A. J.; Sogari, N.; Baranda, L. D. 2007. Verificación del comportamiento termico de un prototipo de vivienda familiar de madera mediante "ecotect" y "quick ii" (Verification of the thermal behavior of a prototype timber homestead by "ecotect" and "quick ii"), *Avances en Energías Renovables y Medio Ambient* 11: 05.73 – 05.80.

Butala, V.; Novak, P. 1999. Energy consumption and potential energy savings in old school buildings, *Energy and Buildings* 29(3): 241–246. doi:10.1016/S0378-7788(98)00062-0

Carlos, J. S. 2005. *Escolas do Ensino Básico Tipificadas (Plano dos Centenários). Avaliação do seu desempenho térmico e propostas de intervenção (Primary Schools typified (Plan of the Centennial). Evaluation of their thermal performance and proposals for action)*. Master thesis of Applied Science, Faculdade de Ciências e Tecnologia da Universidade de Coimbra. Available from Internet: <http://www.c-made.ubi.pt/pdf/teses_mestrado/Tese_JC.pdf>*.

Ginevičius, R.; Podvezko, V.; Raslanas, S. 2008. Evaluationg the alternative solutions of wall insulation by multicriteria methods, *Journal of Civil Engineering and Management* 14(4): 217–226. doi:10.3846/1392-3730.2008.14.20

Hastings, S. R.; Morck, O. 2000. *Solar air systems – A design handbook*. International Energy Agency (IEA).

ISO 7730. 1994. Moderate thermal environments – Determination of the PMV and PPD indices and specification of the conditions for thermal comfort. International Organization for Standardization.

LBNL – Lawrence Berkeley National Laboratory. 2003. COMIS multizone air flow model, International Energy Agency (IEA), [consulted by November of 2007], Available from Internet: <http://epb.lbl.gov/comis/>.

Lechner, N. 1991. *Heating, Cooling, Lighting – Design methods for Architects*. John Wiley & Sons, Inc.

Lollini, R.; Barozzi, B.; Fasano, F.; Meroni, I.; Zinzi, M. 2006. Optimisation of opaque components of the building envelope, *Energy, Economic and Environmental Issues, Building and Environment* 41(8): 1001–1013. doi:10.1016/j.buildenv.2005.11.011

Marsh, A. 2003. Ecotect ans EnergyPlus, *Building Energy Simulation User News* 24(6).

McEvoy, M. E.; Southall, R. G.; Baker, P. H. 2003. Test cell evaluation of supply air windows to characterise their optimum performance and its verification by the use of modelling techniques, *Energy and Buildings* 35(10): 1009–1020. doi:10.1016/S0378-7788(03)00042-2

MOP – Ministério da Habitação e Obras Públicas. 1979. Regras de qualidade relativas ao conforto térmico dos edifícios escolares (Quality rules relating to thermal comfort of the school buildings). Laboratório Nacional de Engenharia Civil*.

MOP – Ministério das Obras Públicas, Transportes e Comunicações. 1990. Regulamento das Características de Comportamento Térmico dos Edifícios – RCCTE (Regulation Characteristics of Thermal Behavior of Buildings). D. L. 40/90*.

MOP – Ministério das Obras Públicas, Transportes e Comunicações. 2006. Regulamento das Características de Comportamento Térmico dos Edifícios – RCCTE (Regulation Characteristics of Thermal Behavior of Buildings). D. L. 80/2006*.

Park, C.-S. 2003. *Occupant responsive optimal control of smart façade system*: Doctoral thesis of Philosophy. College of Architecture, Georgia Institute of Technology.

Pfafferott, J. 2003. Evaluation of earth-to-air heat exchangers with a standardised method to calculate energy efficiency, *Energy and Buildings* 35(10): 971–983. doi:10.1016/S0378-7788(03)00055-0

Pottler, K.; Sippel, C. M.; Beck, A.; Fricke, J. 1999. Optimized finned absorber geometries for solar air heating collectors, *Solar Energy* 67(1–3): 35–52. doi:10.1016/S0038-092X(00)00036-0

Southall, R. G.; McEvoy, M. E. 2006. Investigations into the functioning of a supply air window in relation to solar energy as determined by experiment and simulation, *Solar Energy* 80(5): 512–523. doi:10.1016/j.solener.2005.04.016

Stravoravdis, S.; Marsh, A. 2005. A proposed method for generating, storing and managing large amounts of modelling data using scripts and on-line databases, in *Building Simulation – Ninth International IBPSA Conference.*

Summers, D. N.; Mitchell, J. W.; Klein, S. A.; Beckman, W. A. 1996. Thermal Simulation and economic assessment of unglazed transpired solar collector systems, in *Proceedings of Solar 96*, American Solar Energy Society.

Thormark, C. 2006. The effect of material choice on the total energy need and recycling potential of a building, *Building and Environment* 41(8): 1019–1026. doi:10.1016/j.buildenv.2005.04.026

Zavadskas, E. K.; Kaklauskas, A.; Turskis, Z.; Tamošaitienė, J. 2008. Selection of the effective dwelling house walls by applying attributes values determined at intervals, *Journal of Civil Engineering and Management* 14(2): 85–93. doi:10.3846/1392-3730.2008.14.3

* Available only in Portuguese.

ENERGINIO EFEKTYVUMO DIDINIMO PRIEMONĖS SENIEMS PRADINĖS MOKYKLOS PASTATAMS ATNAUJINTI

J. S. Carlos, H. Corvacho

S a n t r a u k a

Straipsnyje pateikiami Portugalijos pradinės mokyklos šiluminio atnaujinimo tyrimai. Analizuojamos mokyklos tipas yra vienas iš taikytų po 1940 metų prasidėjusioje plačioje statybos kampanijoje. Šios pastatų grupės šiluminės charakteristikos yra labai prastos. Jų atnaujinimo vertinimas buvo pradėtas nuo centrinėje Portugalijoje esančios mokyklos, kurioje buvo įgyvendintos kai kurios eksperimentinės priemonės, ir energijos sąnaudoms nustatyti pritaikytas skaičiavimo metodas. Pastato išorinių atitvarų šiluminio atnaujinimo sprendimas buvo optimizuotas ir jo įtaka šiluminės energijos sąnaudoms nustatyta naudojant ECOTECT. Šiluminės energijos poreikis sumažėjo 52 %. Iš viso pastatų fondo šiluminio atnaujinimo įtaka nacionaliniu mastu vertinta sutaupytos energijos kiekiu. Pabaigoje kaip papildoma priemonė buvo išbandytas pirminis vėdinamo oro pašildymas, nustatytas jo naudingumas. Išbandytasis pirminis vėdinamo oro pašildymas gali suteikti iki 1000 kWh/metus papildomo išsiskiriančio šilumos kiekio. Pabrėžtina, kad nors šių sistemų veikimo charakteristikos priklauso nuo jų komponentų šiluminių savybių, gerinant šias savybes galima daugiau sumažinti energijos sąnaudų.

Reikšminiai žodžiai: šiluminės charakteristikos, energijos efektyvumas, šiluminis atnaujinimas, pirminis vėdinamo oro pašildymas, pradinės mokyklos pastatas, šiluminis modeliavimas.

Jorge Silva CARLOS. An architect (Ph. D.) at the local administration. He is a member of the Portuguese Architects Order since 1986 and a research assistant at the C_MADE, Centre of Materials and Building Technologies, University of Beira Interior (www.c-made.ubi.pt) since 2008. His research interests include architectural design science, thermal comfort, building and urban rehabilitation.

Helena CORVACHO. Teacher at the Faculty of Engineering of the University of Porto, Portugal, Department of Civil Engineering, Building Division. Her research interests include several issues in the building physics domain like thermal behaviour of buildings, building pathology and durability. She is responsible for investigation carried out in these fields at the Laboratory of Building Physics of DEC/FEUP. She has been involved in several international projects and participates at the moment in IEA ECBCS Annex 50 Prefabricated Systems for Low Energy Renovation of Residential Buildings.