EVALUATING NON-INTRUSIVE ENERGY RETROFITS FOR THE BUILT HERITAGE OF THE HISTORIC CENTRE OF OPORTO

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ABSTRACT

Traditional building materials and techniques should be preserved when selecting retrofit strategies. The most recurrent energy retrofit strategies proposed for the historic centre of Oporto are mainly focused on achieving, or even overlapping, the reference U-values established for the external envelope on national energy regulations, although historic sites are not obliged to comply with it. On the other hand, national cultural heritage preservation policies, by allowing alterations on these historic buildings interior, validate the adding of thermal insulation materials on internal walls. Nevertheless, these interventions may put to risk architectural patrimonial values, hence, sustainable ones. A more opportune intervention could be the enhancement of the windows performance, due to its most common bad state of conservation. This article analyses the performance of two non-intrusive retrofit strategies, in a representative model of these buildings: the enhancement of ventilation and the substitution of the single glazed windows for double glazed ones, and the two combined. On a first approach, using as a reference the heating loads limits established in the energy regulation of 2013 and the normative methodology, it is calculated the corresponding number of hours of daily heating use, in order to stand below these limits. The results obtained showed that this is attainable, in comfortable conditions of heating use. In order to achieve more accurate results and conclusions a dynamic simulation was performed using energy models, for the heating and cooling season. The enhancement of ventilation proved to be the most effective retrofit strategy.

Keywords: energy efficiency, glazing, heritage buildings, historic centres, retrofitting, ventilation.

1 INTRODUCTION

Vernacular architecture is an example of building within inherent sustainable characteristics: energy, materials and local resources. The Historic Centre of Oporto (HCO), inscribed as UNESCO's World Heritage since 1996, is nowadays still threatened by the degradation of its urban built heritage, partly due to the exit of resident population. In order to invert the current tendency of desertification of the historic centre, it is crucial to adapt these buildings to a complexity of contemporary demands: thermal performance, technical systems, maintenance, ecological and recyclable materials, waste management and others. Nowadays, Europe's approach to the heritage retrofitting of historic centres is associated with sustainability criteria, seeking to incorporate European regulations on building's habitability and energy efficiency. Although the buildings located in historic areas are exempt from these regulations, studies were carried out [1, 2], recommending to the HCO buildings some energy retrofit strategies. In the opaque envelope (walls and roofs) it is proposed the adding of thermal insulation in order to approach the heat transfer coefficients (U-value) defined in the energy regulations, or even to overcome them. This approach tends to evaluate architecture only by its level of energy efficiency and external image. These recommendations can however enhance the loss of heritage values, such as original plaster work. The glazed areas are also the subject of proposals that can reduce both the U-value and the solar factor. These windows interventions are quite opportune, due to its most common state of conservation.

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Besides some key factors acknowledged to determine the influence of daylighting in buildings thermal performance [3, 4] such as the fenestration factor (FF = window area/room area), the window wall ratio (WWR = glazing area/external facade area) and the effective aperture (EA = WWR × solar factor), it also recognized the importance of ventilation in the hygrothermal performance of buildings. Whereas, in Oporto, the cooling demand is about 10% of the heating demand, ventilation has a great impact in the winter season and ventilation may be responsible from 30% up to 50% of the total heating demand, which leads to a need to minimize the infiltration rates in order to reduce energy consumption [1]. This has been confirmed in different countries [5–8]. Recent studies [9] confirm that, in the HCO buildings, it is possible to obtain a significant reduction in the heating demand, improving the infiltration rate. Moreover, by measuring the airtightness in two non-refurbished characteristic buildings, some relations between the infiltration rates and the buildings' morphological and typological characteristics were pointed out [10].

This article establishes an operative methodology aiming to position these buildings in relation to the Portuguese regulation on building's energy demand, and the limits thereby defined, focusing on the heating loads as the most expressive comfort request in Oporto. According to this city's climate, some authors [1] defend the notion of 'real use', which states that no cooling is used and the heating is used at 30% of its total load. On the other hand, we can determine the heating loads in a permanent regime and then define the hours of use in order to maintain the building below the energy loads limits.

2 ENERGY REGULATIONS

Nowadays, Europe's approach to the heritage retrofitting of historic centres is associated with sustainability criteria, seeking to incorporate European regulations on building's habitability and energy efficiency. Regarding the thermal performance of buildings, the EPBD 2002/91/CE [11] was incorporated in 2006 in the Portuguese regulation, comprising a revised version of the RCCTE [12], formerly published in 1990. The 2010 Energy Performance of Buildings Directive [13], and the 2012 Energy Efficiency Directive [14], generated in 2013 the current REH [15], regarding specifically the housing buildings. The REH establishes the parameters and methods of characterization of the energy performance of the housing buildings as well as promoting the improvement of its thermal performance.

This regulation is mainly focused on new buildings, excluding 'buildings integrated on classified sites, (…) whenever the accomplishment of the minimum energy performance requirements is susceptible to modify in an unacceptable way its character or feature'. Although the buildings located in historic areas are exempt from these regulations, studies were carried out [1, 2], recommending to the HCO buildings some energy retrofit strategies. In the opaque envelope (walls and roofs) it is often proposed the adding of thermal insulation in order to approach the heat transfer coefficients (U-value) defined in RCCTE, or even to overcome them. The glazed areas are also the subject of proposals that can reduce both the U-value and the solar factor. These windows interventions are quite opportune, due to its most common state of conservation and the energy potential of daylighting.

3 ARCHITECTURAL AND ENERGY HERITAGE

Mostly erected between the 17th and the 19th centuries, the HCO buildings present morphologically a quite narrow width and a large length. The typology of the facades is mainly characterized by three windows per floor. These typologies create a harmonic street design, quite determinant in the UNESCO's classification (Fig. 1). However, this historic centre should

Figure 1: Street facades.

not be acknowledged merely as a set of harmonic facades to preserve. National cultural heritage preservation policies tend to interpret as the unique heritage value of these buildings, by allowing alterations on its building's interior. We must explore the potential of non-intrusive retrofit strategies, once internal adding strategies may put to risk these building's sustainable inherent value. In these buildings interior, there is both an architectural and energetic heritage to preserve, such as original plaster work and its internal wooden shutters (Figs 2 and 3).

Figure 2: Plaster work (left, middle) and wooden shutters (right).

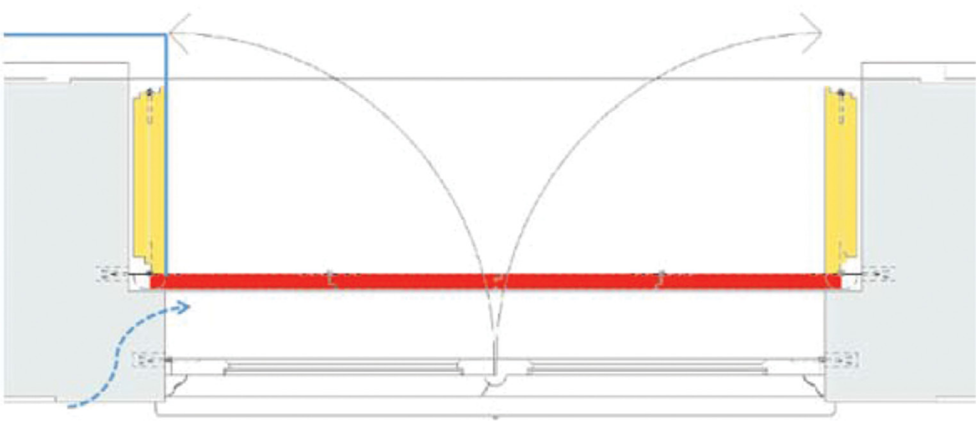

Figure 3: Wooden shutters detail (no scale).

These wooden shutters are an example of a refined architectural design. The masonry walls are dimensioned to embrace them, when they are in the opened position (yellow). Energetically speaking, as a shading device, they reduce the solar heating gains in summer and reduce the heating losses in winter. The window's medium U-value is 5.1, when opened all day, achieving 3.4, when closed by night (U_{ref} for glazing = 3.3). By proposing the adding of internal insulation on the walls, we may threaten the maintenance of these wooden shutters and the original design. If not, the risk of thermal bridges is also increased (blue). On the other hand, we may redesign the original carpentry and substitute the single glazing window for a double one. This is particularly opportune due to its most common bad state of conservation. In addition, this may lead us to an improvement of the air infiltration rate.

In a previous study [16], two retrofit strategies were simulated in a representative model of these buildings, according to national RCCTE's methodology: the enhancement of ventilation (R.1) and the substitution of single glazed windows for double glazed ones (R.2). Three models of typological retrofits were defined, using as a criterion the most usual ownership of these buildings. Analysis of data obtained evidenced the energetic potential of these buildings on its genesis. Considering the existing building, before any constructive retrofit intervention, it is possible to achieve a variable daily heating use, according to each dwelling pattern. The fact of closing the internal wooden shutters by night corresponds to a minimum hour gained in the heating use for all dwellings. Even with the shutters left open, the hours of heating use go from a minimum of 12 h to a maximum of 15 h and 17 h. The intervention R.1, using double glazing, allows one more hour gained of heating use. On the other hand, the enhancement of ventilation (R.2) corresponds to a gain of 2 h. The conjunction of these two strategies (R.3) permits a heating use from a minimum of 15 h to a maximum of 22 h. These results are rather superior to the previously referred notion of a real use of 30% of the heating loads, equivalent to 8 daily hours. In addition, it was possible to infer that the FF (FF = window area/room area) and the WWR (WWR = glazing area/external facade area) are morphological parameters determinant in the hygrothermal performance of the buildings.

4 METHODOLOGY

In the study area, a representative model of these buildings was elected, taking into account both its length/width proportion and its facade characteristics (Fig. 4): three windows per floor comprising the existing three windows typologies. The main street facade is in São João street, 12 m width, west oriented (+22°), and the other one is in Mercadores street, 4 m width, east oriented (+13°).

4.1 Dwelling units definition

This building has six storeys, lagged on the ground floor and top floor, due to the different street levels. The ground floor is usually for commerce, with a private staircase. The garret is non-habitable. This article defines three dwelling units (Fig. 5), corresponding to three models of typological retrofits, using as a criterion the most usual ownership of these buildings: A – one residence with five storeys; B – one residence per storey (four dwellings adapting top floor, B.4); C – one residence per storey and orientation (9 dwellings).

Figure 4: West facade (left) and east facade (right).

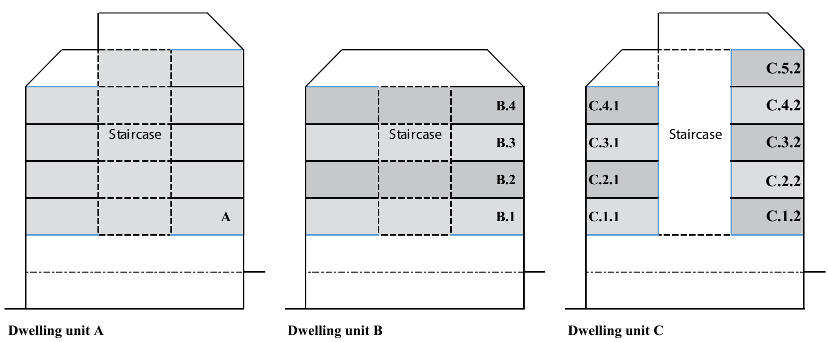

Figure 5: Dwelling units' schemes.

Table 1: Morphological characterization of the dwelling units.

Dwelling units	Area	Volume	External surfaces			Internal surfaces			
	m^2	m^3	m^2			m^2			
	Floor		Window	Wall	Total	$b_{tr} = 0.3$	$b_{tr} = 0.6$	$b_{tr} = 0.6$	$b_{tr} = 0.9$
A	490.8	1572.6	67.4	107.6	175.0	–	113.6	535.9	110.1
B.1	113.6	369.3	15.1	20.5	36.0	46.0	113.6	124.7	–
B.2	109.4	372.0	15.1	27.8	42.9	50.7	–	127.9	–
B.3	109.4	366.5	17.8	24.5	42.2	50.0	–	126.0	–
B.4	109.4	342.4	13.8	25.6	39.4	46.7	–	117.8	109.4
C.1.1	57.4	186.5	10.4	10.2	20.6	20.5	57.4	58.7	–
C.2.1	57.4	195.1	7.7	13.9	21.6	21.5	–	61.4	–
C.3.1	57.4	192.2	10.4	10.8	21.3	21.2	–	60.5	–
C.4.1	57.4	179.6	7.7	12.1	19.9	19.8	–	56.5	57.4
C.1.2	53.8	174.8	5.0	10.3	15.3	20.4	53.8	55.9	–
C.2.2	49.0	166.5	7.3	14.0	21.3	21.4	–	53.6	–
C.3.2	49.0	164.0	7.3	13.6	21.0	21.1	–	52.8	–
C.4.2	49.0	153.2	6.1	13.5	19.6	19.7	–	49.4	–
C.5.2	49.0	122.4	5.4	9.1	14.5	15.7	–	39.4	49.0

Table 2: Constructive characterization and heat transmittance of the building's elements.

	External finish	Structure	Internal finish	U–value ($W/m^2 K$)
Facade wall – W	Lime mortar	Granite 86 cm	Plaster	1.87
Facade wall – E	Lime mortar	Granite 53 cm	Plaster	2.39
Roof	Ceramic tile	Wood	Plaster	2.30
Party wall	–	Granite 60 cm	Plaster	2.01
Floor	–	Wood	Plaster	1.20
Internal wall	–	Wood	Plaster	1.20

Table 1 specifies the areas and volume of each dwelling unit, while Table 2 presents its constructive materials and corresponding heat transmittance (U-value). The building has a 5 mm single glazing, within a wooden frame, with internal wooden shutters (U-value = 5.1 $W/m^2 K$).

4.2 Simulation schedule

Two different scenarios were established for the existing building (E). The simulation E.a corresponds to closing the shutters at night, presenting a medium U-value of 5.10 $W/m^2 K$. Simulation E.b supposes leaving the shutters open, presenting a medium U-value of 3.40 $W/m^2 K$. For the heating demand calculation, REH defines the use of a transparent inner curtain, equivalent to a solar factor (g-value) of 0.70 for single colourless glass and 0.63

Table 3: Simulation schedule.

ID	Parameter	Variable
E.a	Single glazing with internal curtain	g-value = 0.70
	Wooden shutters closed by night	U = 3.40 W/m^2 K
E.b	Single glazing with internal curtain	g-value = 0.70
	Wooden shutters opened by night	U = 5.10 W/m^2 K
R.1	Double glazing with internal curtain	g-value = 0.63
	Wooden shutters closed by night	U = 2.00 W/m^2 K
R.2	Enhancement ventilation	0.60 ACH
	E.a	
R.3	R.1	
	R.2	

for double colourless glass. For the existing building simulations, it was considered a natural ventilation with a value of 0.90 ACH, as established by the normative for non-classified windows. Three retrofit strategies (R) were defined. The intervention R.1 corresponds to the replacement of single glazing for a double glazed one, which can be done by constructing a new wooden frame following the original design. The intervention R.2 establishes for natural ventilation the regulation's minimum value of 0.60 ACH. The simulation R.3 comprises R.1 and R.2 altogether. Table 3 presents the different parameters defined and the respective variables affected.

4.3 Heating loads calculation

All the calculation methodology is fully detailed in the normative [14]. The main changes in the new regulation (REH) comprise an actualization on the 2006's climate data; the degree days (DD) for the heating season, on a basis of 18°C (formerly 20°C); corrections of several parameters due to altitude (M – heating season period, DD – number of degree days, θ_{ext} – mean exterior temperature for both heating and cooling). The criteria for defining the heating demand limits (N_i) is now based on a reference building model, instead of the RCCTE's parameters, which was determined by the buildings form factor and the degree days (DD) of the local climate.

4.3.1 Climatic parameters

The values of the climatic parameters X associated to a specific zone are obtained from the reference values X_{REF} for each established region, adjusted to zone altitude, z. The corrections due to altitude are linear, with a slope a, proportional to the difference between the zone altitude and a reference altitude for the region z_{REF}, according to eqn (1):

$$X = X_{\text{REF}} + a\left(z - z_{\text{REF}}\right) \qquad (\text{months or } °\text{C}) \quad (1)$$

The climatic parameters applicable to the heating season are the following: DD – number of degree days, on an 18°C basis, corresponding to the conventional heating season;

Table 4: Climatic parameters of the historic centre.

	z	M		DD		$\theta_{ext,\ i}$		G_{South}
	REF	REF	*a*	REF	*a*	REF	*a*	kWh/m²
	m	months	month/km	°C	°C/km	°C	°C/km	per month
Oporto	94	6.2	2	1250	1600	9.9	–7	130
Historic centre	50	6.1		1180		10.2		130

M – duration of the heating season (months); $\theta_{ext,\ i}$ – mean exterior temperature of the coldest month of the heating season; G_{South} – monthly mean solar energy during the season, acquired on a vertical surface south oriented (kWh/m^2 month). Table 4 shows the reference values for Oporto and those calculated for the historic centre, considering mean altitude of 50 m.

Therefore, three winter climatic zones are established, according to the number of degree days (DD), on an 18°C basis: 'I1' – DD ≤ 1300; 'I2' – 1300 < DD ≤ 1800; 'I3' – DD > 1800. The historic centre is classified as an 'I1' winter climatic zone, corresponding to 6.1 months of heating season and 1180 degree days (DD) on an 18°C basis. The monthly medium value of the medium solar energy incident on a vertical surface south oriented, during the heating season (G_{Sul}), is 130 kWh/(m^2 month).

4.3.2 Heating demand limits – N_i

The maximum value for the heating energy demand (N_i) should be established considering reference values and conditions, according to eqn (2), being Q_t – heat losses through the reference envelope in the heating season (kWh); Q_v – heat losses due to reference ventilation in the heating season (kWh); Q_g – net heat gains in the heating season (kWh); Ap – internal floor area (m^2).

$$N_i = \left(Q_{tr,i\ (ref)} + Q_{ve,i\ (ref)} - Q_{gu,i\ (ref)}\right)\ /\ A_p \qquad \text{(kWh / m}^2\text{year)]} \quad (2)$$

For the winter climatic zone of Oporto, established in the REH as 'I1', the U_{ref} values to be applied after 2015 are the ones showed in Table 5.

Table 5: U_{ref} values for the HCO.

Envelope element		U_{ref} (W/m^2 K)
External or internal with a heat loss reduction coefficient $b_{tr} > 0.7$	Vertical opaque	0.40
	Horizontal opaque	0.35
Adjacent to other buildings	Vertical opaque	0.80
With a heat loss reduction coefficient $b_{tr} \leq 0.7$	Horizontal opaque	0.70
Glazing (U_w)		2.80
In contact with terrain		0.50

The reference value for heat losses due to ventilation through the envelope, $Q_{ve,i\,(ref)}$, should be established considering a reference air infiltration rate, $R_{ph\,(ref)}$, equal to the building in study, with a maximum of 0.6 ACH.

4.4 Energy simulation models

In order to achieve more accurate results and conclusions a dynamic simulation was performed, regarding the three retrofit strategies, as well as the original building, with the wooden shutters open by night (E.b). One of the most acknowledged assessment tools to test the hygrothermal performance of buildings and its energy demands is to create energy simulation models. In this investigation it was elected the Design Builder program that uses the Energy Plus dynamic simulation engine to generate performance data. Energy Plus is the US DOE building energy simulation program for modelling building heating, cooling, lighting, ventilating and other energy flows. Design Builder works with the main features and capabilities of BLAST and DOE-2. Once the program already includes the ASHRAE design weather data of Oporto, we introduced both the constructive and morphological data of the selected model for the heating and cooling load calculation. The operative temperature conditions (heating 18°C; cooling 25°C) for a residential use were settled based on a typical working week (week 18–23 h, weekend 8–23 h). In the remaining hours the system is considered to be turned off.

This analysis was focused on the building as a whole (A) and on the intermediate dwelling units that have no heat losses to the ground floor or roof (B.2, B.3, C.2.1, C.2.2, C.3.1, C.3.2, C.4.2). The simulations comprised E.b – considered as the original, with wooden shutters opened all day and 0.90 ACH; R.1 – renovation with double glazing and 0.90 ACH; R.2 – enhancement of ventilation for 0.60 ACH; R.3 – combination of R.1 and R.2. The glazing characteristics are presented in Table 6.

Table 6: Glazing characteristics.

Calculated values	E.b – single glazing 5 mm	R.1, R.3 – double glazing 6 + 6 + 6 mm
Total solar transmission	0.809	0.237
Direct solar transmission	0.775	0.136
Light transmission	0.881	0.173
U-value (ISO 10292/ EN673) ($W/m^2 K$)	5.500	2.863
U-value ($W/m^2 K$)	5.048	2.863

5 RESULTS AND DISCUSSION

5.1 Heating loads calculation

Table 7 presents the heating loads (N_{ic}) obtained for each dwelling unit and respective simulation for both the existent and retrofitted building and the limits defined by the regulation (N_i). These values were converted in daily hours of heating use, calculated in order to not exceed the calculated limits (Table 8).

Table 7: Heating loads.

Dwelling units	N_i (kWh/m^2 year)	Existent		Retrofit		
		E.a	E.b	R.1	R.2	R.3
A	38.10	73.90	80.37	69.91	64.18	60.21
B.1	47.49	85.41	91.88	81.26	76.17	72.02
B.2	38.74	74.47	80.98	70.36	64.88	60.77
B.3	39.79	72.11	79.72	67.44	59.65	55.00
B.4	43.45	94.74	100.73	91.26	85.83	82.35
C.1.1	49.69	83.83	92.43	78.27	71.59	66.06
C.2.1	36.41	67.49	73.83	63.53	57.96	54.02
C.3.1	38.99	61.71	70.09	56.71	49.57	44.62
C.4.1	42.07	86.53	92.89	83.11	76.25	72.83
C.1.2	43.20	85.65	90.09	82.80	76.36	73.52
C.2.2	38.77	76.14	83.21	71.58	66.54	61.99
C.3.2	38.12	74.77	81.84	70.21	65.32	60.77
C.4.2	33.77	69.79	75.64	66.02	60.96	57.19
C.5.2	33.65	70.69	75.84	67.83	63.67	60.81

Table 8: Daily heating hours.

Dwelling units	Existent		Retrofit			mean	max.	min.	CV
	E.a	E.b	R.1	R.2	R.3				
A	12	11	13	14	15	13	15	11	0.1
B.1	13	12	14	15	16	14	16	12	0.1
B.2	12	11	13	14	15	13	15	11	0.1
B.3	13	12	14	16	17	15	17	12	0.1
B.4	11	10	11	12	13	12	13	10	0.1
C.1.1	14	13	15	17	18	15	18	13	0.1
C.2.1	13	12	14	15	16	14	16	12	0.1
C.3.1	15	13	17	19	21	17	21	13	0.2
C.4.1	12	11	12	13	14	12	14	11	0.1
C.1.2	12	12	13	14	14	13	14	12	0.1
C.2.2	12	11	13	14	15	13	15	11	0.1
C.3.2	12	11	13	14	15	13	15	11	0.1
C.4.2	12	11	12	13	14	12	14	11	0.1
C.5.2	11	11	12	13	13	12	13	11	0.1
mean	13	12	13	15	16				
max.	15	13	17	19	**21**				
min.	11	**10**	11	12	13				
CV	0.1	0.1	0.1	0.1	0.1				

Analysing the daily heating hours obtained, it is clear that in all the simulations the heating can be used for more than 8 h, the recognized notion of 'real use' (30% of the heating loads), according to Oporto's climate conditions. The minimum range of hours was registered in the existing building with the wooden shutters left open by night (E.b), from 10 to 13 h, while the conjunction of the two retrofit strategies (R.3) achieved a maximum of 13–21 h. The fact of closing the internal wooden shutters by night (E.a) corresponds to a minimum hour gained in the heating use for all dwellings. The enhancement of ventilation (R.2) from 0.90 to 0.60 ACH proved to be the more effective isolated strategy of intervention, gaining from 2 to 4 h, comparing it to situation E.a. Regarding the results obtained per dwelling unit, these values show a significant reduction in the dwellings with heat losses through the roof (B.4, C.1.4, C.2.5). This fact is clearly expressed in Fig. 6, which shows the percentage of heating use achievable per dwelling unit and the mean values per intervention strategy. It also summarizes the hierarchical relations between the interventions and emphasizes the difference between the results obtained in the dwelling typologies C.1 (west oriented) and C.2 (east oriented). Figure 7 graphically quantifies this difference, much more expressive in the maximum values. The correlation between heating loads and heating hours below the limits, in all

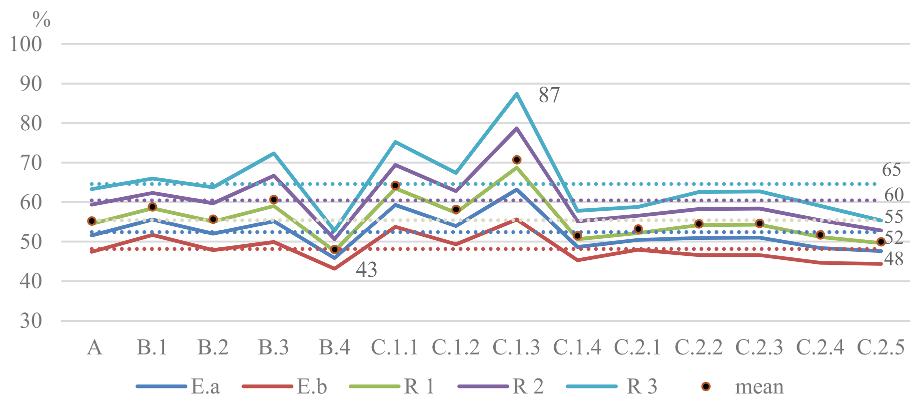

Figure 6: Percentage of heating use per dwelling unit.

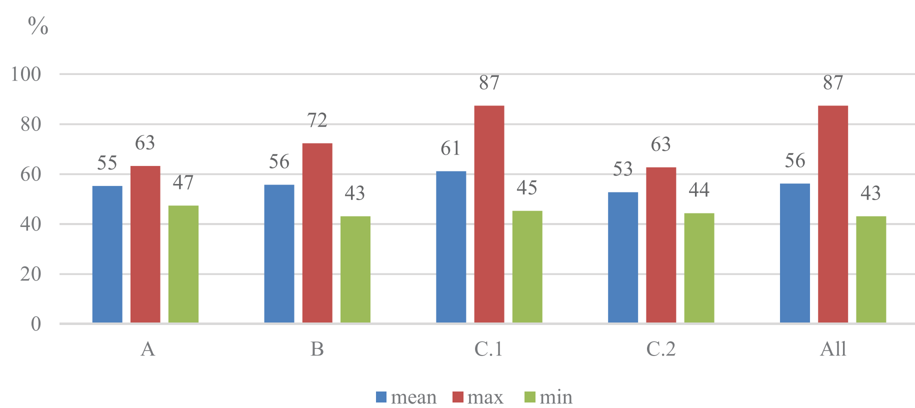

Figure 7: Percentage of heating use per dwelling typology.

strategies, is very strong in dwellings B (R = –0.86) and C.1 (R = –0.79), being moderate in dwellings C.2 (R = –0.63). The mean coefficient of correlation for all dwellings and strategies is –0.72. Analysing by retrofit strategy, there is an expected increasing correlation with the level of intervention, E.b (R = –0.22), E.a (R = –0.4), R.1 (R = –0.5), R.2 (R = –0.6) and R.3 (R = –0.7).

Once the heating calculation methodology uses the same factor for both windows orientation (0.56), it is opportune to analyse the relation between the energy savings and the dwellings morphological characteristics, as detailed in Table 9. Analysing the data obtained per dwelling typology, it is possible to infer that the FF (FF = window area/room area) and the WWR (WWR = glazing area/external facade area) are morphological parameters determinant in the hydrothermal performance of the buildings. The correlation coefficient (R) measures the strength and direction of the linear relationship between two variables. It is commonly classified as a strong correlation if its value is superior to 0.60, and a very strong one if its value is superior to 0.80. Figure 8 presents the correlation coefficients obtained between WWR and FF and the percentage of heating use achievable per retrofit energy saving. It is recognizable that both the WWR and the FF present a very strong positive correlation in all the interventions. The FF is slightly less determinant in simulation E.b, the existing building with the wooden shutters left open by night.

5.2 Energy simulation models

The results obtained for cooling and heating loads after the model simulation of the four building features are presented in Table 10.

Table 9: Energy saving per retrofit strategy.

Dwelling units	Area			Ratio		Energy saving to E.a		
	m^2	m^2	m^2	%	%	(kWh/m^2 year)		
	Floor	Window	Wall	WWR	FF	R.1	R.2	R.3
A	490.80	67.40	175.00	38.50	13.70	3.98	9.71	13.69
B.1	113.60	15.50	36.00	43.00	13.60	4.15	9.24	13.39
B.2	109.40	15.10	42.90	35.10	13.80	4.12	9.59	13.70
B.3	109.40	17.80	42.20	42.00	16.20	4.67	12.46	17.11
B.4	109.40	13.80	39.40	35.00	12.60	3.48	8.90	12.38
C.1.1	57.40	10.40	20.60	50.60	18.20	5.55	12.23	17.77
C.2.1	57.40	7.70	21.60	35.80	13.50	3.96	9.52	13.47
C.3.1	57.40	10.40	21.30	49.10	18.20	5.00	12.14	17.09
C.4.1	57.40	7.70	19.90	39.00	13.50	3.42	10.28	13.71
C.1.2	53.80	5.00	15.30	32.70	9.30	2.85	9.28	12.13
C.2.2	49.00	7.30	21.30	34.40	15.00	4.56	9.60	14.15
C.3.2	49.00	7.30	21.00	34.90	15.00	4.56	9.45	14.00
C.4.2	49.00	6.10	19.60	31.00	12.40	3.78	8.83	12.60
C.5.2	49.00	5.40	14.50	37.00	11.00	2.86	7.01	9.88

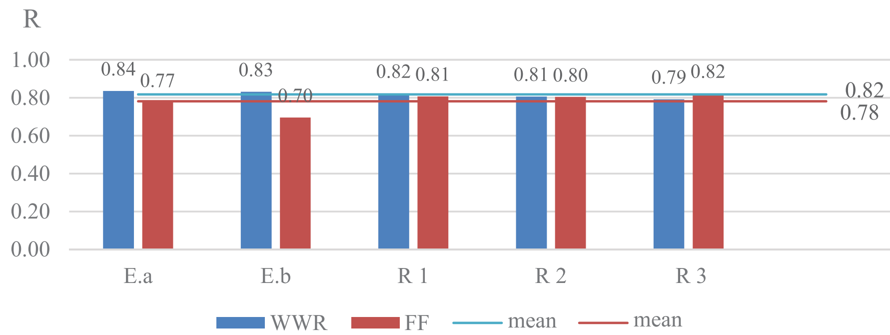

Figure 8: Coefficients of correlation between percentage of heating use and dwellings morphological characteristics.

5.2.1 Heating loads

As presented in Fig. 9 and Table 10, all the simulations registered heating loads below the limit (N_i), except for some minor values, which revealed some increases in dwelling A, R.1 (+1.17 kWh/m²); dwelling C.3.2, E.b (+1.87 kWh/m²) and R.1 (+1.01 kWh/m²). On the other hand, the values of dwelling C.4.2, with the lowest heating demand limit (N_i) due to both its WWR and FF, were above the limit in all simulations: E.b (+12.99 kWh/m²); R.1 (+13.22

Table 10: Cooling and heating loads.

		Heating (kWh/m²)				Cooling (kWh/m²) N_i			
	N_i	E.b	R.1	R.2	R.3	E.b	R.1	R.2	R.3
A	38.10	37.21	39.27	30.76	32.65	0.31	0.08	0.42	0.10
B.2	38.74	35.09	36.35	26.36	**23.85**	0.07	0.00	0.10	0.00
B.3	39.79	35.91	38.53	27.37	24.10	0.19	0.01	0.31	0.00
C.2.1	36.41	32.13	35.38	24.21	31.76	0.21	0.00	0.35	0.00
C.2.2	38.77	40.54	39.10	31.84	30.34	0.00	0.00	0.00	0.00
C.3.1	38.99	**28.25**	**32.87**	**20.79**	28.97	**1.40**	0.07	**2.74**	0.10
C.3.2	38.12	40.64	39.77	32.74	31.80	0.00	0.00	0.00	0.00
C.4.2	33.77	**46.76**	**46.99**	**40.24**	**40.44**	0.17	**0.09**	0.21	**0.10**
mean	**37.84**	37.07	38.53	29.29	30.49	0.29	0.03	0.52	0.04
max.	39.79	46.76	46.99	40.24	40.44	1.40	0.09	2.74	0.10
min.	33.77	28.25	32.87	20.79	23.85	0.00	0.00	0.00	0.00
SD	1.91	5.68	4.15	5.99	5.27	0.46	0.04	0.91	0.05
CV	**0.05**	0.15	0.11	0.20	0.17	1.56	1.29	1.77	1.38
Mean % of total		99.4%				0.6%			
CV		0.19				2.14			
Coefficient of correlation (R)	Window	–0.07	0.00	0.00	–0.01	0.03	0.42	–0.03	0.42
	WWR	**–0.79**	**–0.70**	**–0.75**	–0.47	**0.85**	0.20	**0.86**	0.28
	FF	–0.62	–0.64	–0.64	–0.52	**0.70**	–0.07	**0.74**	0.02
	N_i	–0.56	–0.67	–0.62	**–0.88**				

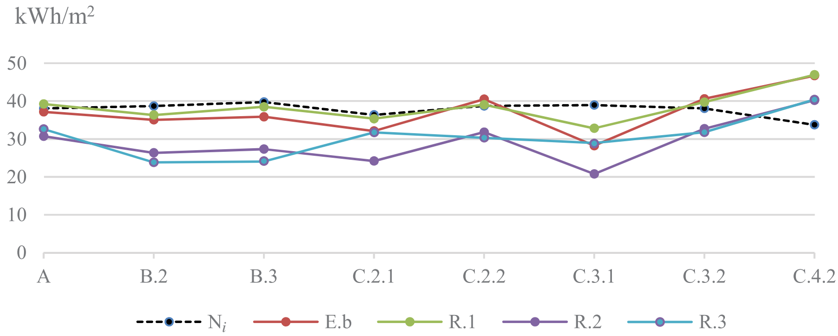

Figure 9: Heating loads and N_i limits per dwelling typology.

kWh/m²); R.2 (+6.47 kWh/m²); R.3 (+6.67 kWh/m²). The heating loads of E.b, R.1, R.2 revealed a strong negative correlation with the WWR, with a coefficient of correlation (R) of –0.79, –0.70 and –0.75, respectively. These simulations presented a moderate relation with the FF (R = 0.62/0.64). The heating loads of R.3 presented a very strong negative correlation with the heating limits (N_i), with R = 0.88.

Focusing on the heating energy savings of the three retrofit strategies in comparison with the original E.b (Table 11) it is noticeable that retrofit R.1 (double glazing) corresponds to an increase in the heating loads, due to a significant average reduction of 85% in the solar gains (CV = 0.01). There is a strong relation with the WWR (R = 0.88). Dwelling C.3.1, with the highest WWR and FF, registered the maximum increase of the heating loads (+16.3%), with the predictable minimum increase in dwelling C.4.2 (+0.5%). Retrofit R.2 (0.60 ACH), as in the normative calculation, proved to be the most effective in the heating energy savings with a minimum saving of 14% (C.4.2) and a maximum of 26.4% (C.3.1).There is a moderate negative correlation between the percentage of energy savings and the WWR, FF and heating load limits N_i (R = –0.61, R = –0.63, R = –0.65, respectively). Retrofit R.3 (double glazing and 0.60 ACH), also penalized by the loss of the solar gains, corresponds to an increase of the heating loads only on dwelling C.3.1, due to the highest WWR and FF (+2.5%), achieving the maximum savings on dwellings B.2 and B.3, around 32%. Both retrofit strategies R.1 and R.3 presented a very high coefficient of variation in the savings of all dwellings. R.2 is the most regular in the savings per dwelling (CV = 0.2; mean = –21.5%). It is quite recognizable in Fig. 10 that strategies R.1 and R.2 present a very strong correlation with the original E.b (R = 0.96; R = 0.99), not so noticeable in R.3 (R = 0.61).

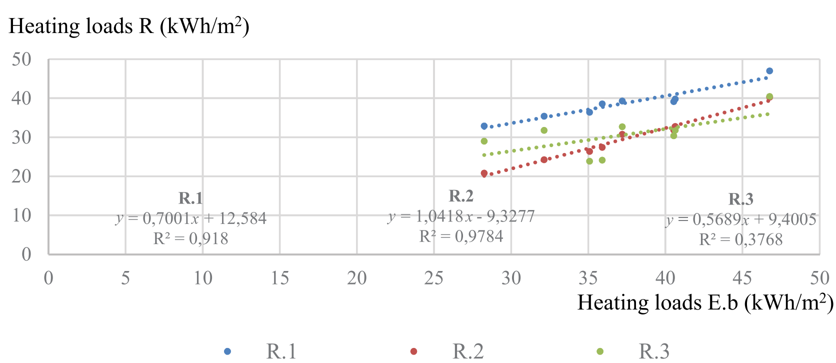

Figure 10: Heating loads correlation between R.1, R.2, R.3 and E.b.

Table 11: Heating savings and dwelling characteristics.

	Window (m2)	WWR (%)	FF (%)	Heating saving R.1–E.b (%)	Heating saving R.2–E.b (%)	Heating saving R.3–E.b (%)	Solar gains R.1/R.3–E.b (%)
A	67.40	38.50	13.70	5.55	–17.33	–12.24	–84.33
B.2	15.10	35.10	13.80	3.61	–24.87	–32.03	–84.62
B.3	17.80	42.00	16.20	7.32	–23.78	**–32.88**	–84.36
C.2.1	7.70	35.80	13.50	10.11	–24.65	–1.17	–84.46
C.2.2	7.30	34.40	15.00	**–3.55**	–21.46	–25.15	–84.21
C.3.1	10.40	**49.10**	**18.20**	**16.32**	**–26.43**	**2.53**	–85.98
C.3.2	7.30	34.90	15.00	–2.13	–19.42	–21.75	–85.52
C.4.2	6.10	**31.00**	**12.40**	0.49	**–13.95**	–13.52	–84.77
mean		37.60	14.73	4.72	–21.49	–17.03	**–84.78**
max.		49.10	18.20	16.32	–13.95	2.53	–84.21
min.		31.00	12.40	–3.55	–26.43	–32.88	–85.98
SD		5.64	1.82	6.61	4.30	13.28	0.63
CV		0.15	0.12	1.40	–0.20	–0.78	**–0.01**
Coefficient of correlation (R)			Window	0.12	0.28	0.03	0.32
			WWR	**0.81**	**–0.61**	0.35	–0.50
			FF	0.52	**–0.63**	0.13	–0.57
			N_i	0.20	**–0.65**	–0.37	

5.2.2 Cooling loads

The results obtained confirmed that the cooling loads are quite insignificant in all the dwelling units and all the simulations. The mean percentage of the cooling loads corresponds to 0.6% of the total annual loads. The maximum load of R.1 (double glazing) was 0.09 kWh/m^2, in dwelling C.4.2, the one that presents the lowest WWR and FF. Simulation R.3 presented very similar results. Regarding the single glazing simulations the maximum value was 1.40 kWh/m^2 in E.b (0.90 ACH) and 2.74 kWh/m^2 in R.2 (0.60 ACH) in dwelling C.3.1, the one that presents the highest WWR and FF. It is recognizable that there is a very strong correlation between the WWR and both E.b (R = 0.85) and R.2 (R = 0.86) cooling loads. There is also a significant relationship with the FF, in both E.b (R = 0.70) and R.2 (R = 0.74).

6 CONCLUSIONS

Regarding the results obtained with this study we can conclude that, although the building's envelope presents heat transmittance values (U) quite distant from the limits thereby defined, its energy heating demand can be placed below its corresponding limit, in comfortable conditions of heating use. In all the simulations the heating can be used for more than 30% of the total heating loads, the recognized notion of 8 hours of 'real use' in Oporto. Using the normative methodology, the minimum range of hours was registered in the existing building with the wooden shutters left open by night, from 10 to 13 h, while closing them by night enables a daily heating use of 11–15 h. The enhancement of ventilation proved to be the more effective isolated strategy of intervention, with a range of 12–19 h. The substitution of single glazing for a double glazing registered from 11 to 17 h, while the conjunction of the two retrofit strategies achieved a maximum of 13–21 h.

On the other hand, a dynamic simulation with energy models exposed the importance of the loss of solar gains in the heating season, when retrofitting single glazed windows by double glazed ones. However, the acoustic advantages of this strategy should be taken into account. It is important to associate this intervention with the enhancement of ventilation, in order to achieve an optimized solution. Energetically, the enhancement of ventilation as a single intervention proved to be the most unvarying in the heating energy savings with a minimum saving of 14% and a maximum of 26.4%.

A primary measure to ensure the energy performance of these buildings is to take advantage of its architectural heritage, namely its typical internal wooden shutters, closing them by night in order to reduce the heat losses. Following the principle of non-intrusive interventions *versus* increase of the energy efficiency, we should improve the windows infiltration rate, which proved to be an important retrofit strategy. The most common bad state of conservation of the windows potentiates this intervention, by avoiding any cracks in the window assembly. In addition, it is particularly opportune for the replacement of single glazing for a double glazed one, by constructing a new wooden frame following the original design. These non-intrusive interventions, while not adding any new materials to the external envelope, enhance the architectural heritage values of these buildings. Hence, it is crucial to have an overall knowledge of these historic buildings' morphological characteristics, once the FF and the WWR proved to be quite determinant in the heating energy savings, within the defined retrofit strategies. These results were obtained for a typological representative building of the HCO, although in a specific urban context, namely the streets width and respective east–west orientation. Further investigations should be developed embracing a wider range of situations.

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