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Residential building rehabilitation in Porto historic center: Case study analysis by using a simulation model

Alexandre Soares dos Reis[a,*,1], Petra Vaquero[a,1], Marta Ferreira Dias[a], Alice Tavares[b,c], Aníbal Costa[b], Jorge Fonseca[b]

[a] *Research Unit on Governance, Competitiveness and Public Policies (GOVCOPP), Department of Economics, Management, Industrial Engineering and Tourism (DEGEIT), University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal*

[b] *Research Centre for Risks and Sustainability in Construction (RISCO), Department of Civil Engineering (DECivil), University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal*

[c] *Centre for Research in Ceramics and Composite Materials (CICECO), University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal*

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Abstract

Nowadays, rehabilitation in historic centers can become a challenge due to the restrictions concerning the requirements for the building envelope. Portugal has conducted studies to define the maximum U values [W/(m^2 K)] for single building components based on the indoor temperature. Despite the relative humidity being crucial for thermal comfort, the current Portuguese scheme for energy certification of buildings does not consider it. Additionally, it is essential to know that most of the dwellings in Portugal are in a fleet-float regime due to cultural habits and energy poverty. Therefore, increasing the insulation thickness of exterior walls might not have a relevant impact on the indoor temperature. There is even the risk of harming the authenticity of the built heritage. Using a calibrated dynamic simulation model developed with TRNSYS software, we found that, in winter, the effect of external wall insulation on the indoor temperature is tiny. Results suggest that maximum U values [W/(m^2 K)] for exterior walls might be over-defined. Further studies of cost-optimal levels should be conducted with calibrated models in a free-float regime to define the maximum U values [W/(m^2 K)] of external walls for this type of buildings.

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Keywords: Dynamic simulation; Indoor temperature; Historic centers; Rehabilitation; Residential buildings

* Corresponding author.
E-mail address: alexandre.soares.reis@ua.pt (A.S. dos Reis).

[1] These authors contributed equally to this study.

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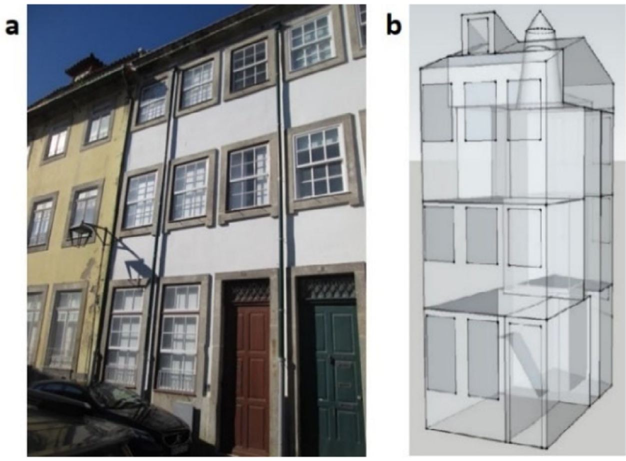

Fig. 1. (a) rehabilitated building, Porto; (b) 3D building model.

1. Introduction

In 1979, Portugal joined the Protection of the World Cultural and Natural Heritage Convention, adopted in 1972 by the United Nations Educational, Scientific and Cultural Organization (UNESCO) General Conference that establishes the duties of each member state concerning heritage preservation and protection [1]. The responsibility to safeguard the identity of the historic center of Porto, recognized by UNESCO in 1996 as a World Heritage Site, represents a massive challenge for the Portuguese Government because of legal constraints. The Energy Performance of Buildings Directive (EPBD) [2] is one of them. There may be an incompatibility between two critical objectives: first, preserving the architectural heritage and, second, fulfilling the minimum requirements of the surface thermal transmission coefficient as, for instance, of external walls. Therefore, it is essential to introduce a new variable in the equation of the cost–benefit balance of the measures to be implemented [3]. The architectural and the historic value, in the sense that the supposed benefit created by renovating may not outweigh the loss [4], especially given the low heating practice of the Portuguese families [5]. There is even a difference between the theoretical and the actual energy consumption, the so-called "rebound effect" [6,7].

The main objectives of this paper are to study the variation of the indoor temperature caused by the application of thermal insulation on the exterior walls of a recently retrofitted building located in the historic center of Porto. For that purpose, a calibrated dynamic simulation model was developed with TRNSYS software in a free-float regime. The final goal is to evaluate if the minimum requirements for the U values [W/(m^2 K)] of exterior walls for historic or ancient buildings are adequately defined.

The structure of this paper is as follows. Section 2 describes the case study. The dynamic simulation model is described in Section 3. In Section 4, the results of the simulated scenarios are presented. This section is followed by a concluding paragraph that summarizes the main findings.

2. Case study

The building under study (Fig. 1), located next to the Porto Cathedral, at Rua D. Hugo, house 10, represents a typical architectural typology of the historic center of Porto, with a narrow front (4.94 m) and a depth of 7.70 m. It is integrated into the middle of an urban block, with a semi-underground floor since the front faces the street, but the backyard has approximately 3 m underground. It has four floors (P0, P1, P2, and P3) and two independent social housing units, one with a T0 typology on the ground floor (Floor 0 — P0) and another with a T2 typology on the remaining floors (Floor 1 — P1, Floor 2 — P2 and Floor 3 — P3).

The building has a centralized staircase, positioned transversely, which defines the distribution of rooms, with one room for the front and another for the back. A traditional skylight tops the interior staircase. Concerning sun exposure and conditions for natural light, the main façade faces east, and the back one faces west. However, Porto Cathedral permanently shades the west façade.

Table 1. Uncertainty analysis indices.

	NMBE	CV(RMSE)	R^2
ASHRAE	±10%	<30%	>75%
IPMVP	±5%	<20%	
FLRF0	−9%	14%	83%
FLRF1	−1%	12%	71%
FBRF2	0%	11%	78%
BBRF2	−2%	11%	76%

The project's mandatory principle was to preserve all original architectural-constructive elements of the building and a compromise of balance concerning the improvements of the interior thermal comfort with the least possible intrusiveness. In this sense, the rehabilitation solution was thought to optimize the passive behavior of the building. Some improvements were made to avoid the need to use heating equipment as this depends on the economic capacity of the occupants. For this reason, aspects associated with the use of solar gains in winter were valued. No thermal insulation was applied to the exterior walls since, from the outside, it would interfere with the existing differentiation of the granite edges of the openings, and from the inside, it would compromise the thermal inertia. Thus, only the roof was insulated, with 12 cm of expanded insulation corkboards. The windows of the main façade have been rehabilitated, keeping the wood and the single glass. Because of the high state of degradation of the windows of the back facade, they were replaced by a new wooden frame with double glazing. Windows correspond to 17% (single glass) and 7% (double glass) of the total area of the external vertical envelope.

3. Dynamic simulation model

Using TRNSYS software and SKETCHUP 3D plugin, the dynamic simulation model was developed using 13 thermal zones and considering a loss reduction factor of 0.6 to adjoining buildings [8]. The construction materials used in the simulation were based on the publication ITE 50 [9] published by National Civil Engineering Laboratory (LNEC) and Order N.° 15793-K/2013 [8]. Regarding the climatic data used for these simulations, it was decided to use the database provided by Directorate-General for Geology and Energy (DGEG) [10].

The accuracy of dynamic simulation models is essential since, after validating the model, through a calibration procedure, it can predict various scenarios that lead to a reduction in energy consumption and an improvement in comfort conditions inside the buildings. According to Guideline 14-2014 [11] of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), calibration is the process of reducing the model's uncertainty output data under certain conditions, given the actual measured results under the same conditions. A calibrated model is one that, under the same set of conditions, can reproduce monitoring performed, and its accuracy is assessed through an uncertainty analysis [12].

As no mention of relative humidity is made in the Portuguese scheme for energy certification of buildings, the model was calibrated based on the temperature. Between March 1, 2020, and December 21, 2020, with the building still unoccupied, the room temperature values of several spaces were recorded based on a monitoring campaign that was already being developed. Model's calibration was carried out by comparing the temperatures recorded and the results obtained through the simulation in Front Living Room on Floor 0 (FLRF0), in Front Living Room on Floor 1 (FLRF1), in Front Bedroom on floor 2 (FBRF2), and Back Bedroom on Floor 2 (BBRF2).

We took the guidelines of ASHRAE 14-2014, as well as the document Concepts and Options for Determining Energy and Water Savings, Volume I of the International Performance Measurement and Verification Protocol (IPMVP) [13], which consider the following indices for the uncertainty analysis of a simulation model results:

- Normalized Mean Bias Error (NMBE);
- Coefficient of Variation of the Root Mean Square Error (CV(RMSE));
- Coefficient of determination, R^2.

Table 1 shows that NMBE and CV (RMSE) values are within limits proposed by ASHRAE and IPMVP, except for FLRF0, in which the NMBE exceeds, in some percentage points, the interval of ± 5% referred by IPMVP, fulfilling the range of ± 10% proposed by ASHRAE.

Table 2. Percentage reduction of the number of hours with temperatures below 16 °C (related to base).

November to February		FLFR0	FLFR1	FBRF2	BBRF2
T < 16 °C	PextI2cm	−11%	−13%	−14%	−14%
	PextI8cm	−17%	−20%	−24%	−23%

Table 3. Percentage increase of the number of hours with temperatures above 27 °C (related to base).

June to September		FLFR0	FLFR1	FBRF2	BBRF2
T > 27 °C	PextI2cm	21%	28%	19%	36%
	PextI8cm	30%	40%	30%	61%

ASHRAE and IPMVP do not consider the determination coefficient (R^2) as a prescriptive value. It is only a recommendation that R^2 is greater than 75%. As only one of the spaces had a lower value, quite close (71%), we have assumed the model as calibrated.

4. Results

With the calibrated model, we have carried out simulations to assess the impact of thermal insulation on building external walls, on the indoor temperature. The exterior walls to be insulated represent about 17% of the total area of the building envelope.

The first simulation (base) considered the occupied building on a free-float regime and respected the heritage constructive solutions. The second and third simulations were like the first one. Still, it was considered the application of 2 cm and 8 cm, respectively, of expanded agglomerate cork, vapor barrier, and 1.3 cm gypsum board on the inner face of the external walls. The second simulation (PextI2 cm) is following Decree-Law N° 95/2019 [14], the most recent Portuguese legislation respecting residential buildings rehabilitation, in compliance with the thermal transmittance maximum values (U-value) allowed by Ministerial Order N° 297/2019 [15]. PextI8 cm, the third simulation, is based on Decree-Law N° 118/2013 [16] and requirements for new buildings or interventions in building components defined by Ministerial Order N° 379-A/2015 [17].

Simulation results indicate that external wall insulation has a low impact on indoor temperatures. First, it appears that the placement of insulation on the inside face of the exterior walls reduces the number of hours with lower temperatures and increases the hours with higher temperatures. However, the change is not significant, even when the insulation thickness is increased from 2 cm to 8 cm (Tables 2 and 3). In contrast, applying this material on the inner side of the external walls causes spaces to overheat in summer with differences between 19% and 36% and between 30% and 61%, compared with the situation without any insulation second and third simulation, respectively.

5. Conclusions

This research was based on a residential building located in the historic center of Porto, which was subjected to recent rehabilitation work. With the building still unoccupied, the indoor temperatures of several rooms were monitored. Using that data, it was possible to calibrate a TRNSYS simulation model and perform an uncertainty analysis accomplishing the calibration criteria from ASHRAE and IPMVP.

After calibration, three scenarios were simulated: In the base scenario, it was assumed a typical Portuguese building use and the architectural-constructive rehabilitation that was performed; in the second scenario, the building complied with the current legislation for the rehabilitation of residential buildings; finally, in the third scenario, the building complied with mandatory requirements for new buildings.

Indoor temperatures were compared only in occupied periods from November to February. Results seem to indicate that the reduction in the number of hours with temperatures below 16 °C is noteworthy. The application of thermal insulation in the external walls, in this type of buildings, for purely legislative reasons, is highly discussable due to the reduced impact. Furthermore, there is a growing risk of overheating in summer due to the number of hours with temperatures above 27 °C increasing.

Incompatible energy efficiency requirements cannot so condition the Portuguese State responsibility to safeguard Historic Centers. Under a free-float regime, thermal insulation on external walls has a reduced impact on indoor temperatures in this type of buildings. Still, it harms preserving the authenticity of the built heritage.

Future developments should consider reviewing the maximum U values [W/(m^2 K)] of external walls for this type of buildings.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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