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An investigation of the energy efficiency of traditional buildings in the Oporto World Heritage Site

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Abstract – *Oporto's traditional buildings are the major contributors for shaping the World Heritage Site Despite this, and as is the case in most European historic cities, they are not individually listed and any adaptations to make them comply with current energy efficiency requirements may cause negative impacts on their authenticity and integrity. This paper aims to identify which energy efficiency improvement measures can be applied without damaging the buildings' heritage value. For this purpose, fieldwork and simulation data of ten case studies were used. On-site results revealed that the energy consumption in Oporto's traditional buildings was below European average and the households expressed that their home comfort sensation was overall positive. Simulations showed that introducing insulation and solar thermal panels would be ineffective in terms of energy and cost efficiency as well as comfort improvement.*

This study reinforces the idea that traditional buildings perform better than expected in terms of energy consumption and can be retrofitted and updated at a low-cost and with passive solutions.

Keywords – Oporto traditional buildings; energy efficiency; assessment and simulation; fieldwork

1. INTRODUCTION

In Oporto, traditional buildings are the major contributors for shaping the World Heritage Site (WHS). Despite their heritage relevance, like in most European historic cities, these are not individually listed. For this reason, their adaptation to make them compliant with current energy efficiency requirements may provoke negative impacts on their authenticity and integrity. Furthermore, the cumulative impact of such changes to individual buildings may also endanger the overall significance of the WHS.

1.1 Traditional buildings and energy efficiency

Over the past 15 years, an increasing number of literature on the thermal behaviour and energy efficiency of traditional buildings has been published. The Building Research Establishment (BRE) in England successfully promoted the sustainable refurbishment of several Victorian and Edwardian era buildings, providing effective measures to promote energy efficiency in these types of dwellings [1, 2]. The use of renewable energy sources in traditional buildings was addressed by English Heritage, which evaluated the impacts that introducing such systems into a historic environment would cause to the heritage values [3, 4].

Figure 1. Oporto World Heritage Site

Moreover, the Society for the Protection of Ancient Buildings (SPAB) has undertaken on-site research focusing on several aspects of the thermal behaviour of traditional buildings that showed a clear gap between the calculi and the effective measurements taken, revealing that traditional buildings have a better thermal performance than predicted [5, 6]. Previous literature has established that the perception of traditional buildings as having poor thermal performance and being inadequate to meet the current targets of energy efficiency is erroneous. The passive characteristics of this type of building give them some potential to achieve higher levels of energy efficiency. The literature also points to a gap between the technical approach and heritage conservation in the process of improving the energy efficiency of traditional buildings.

Using traditional buildings in Oporto that are part of the WHS, this research aims to identify the means by which urban traditional residential buildings can be upgraded to improve their energy performance while preserving their heritage significance.

2. MATERIAL AND METHODS

2.1 Methods

The current research uses ‘environmental impact assessment’ methodologies [7] and their adaptation to the specific field of ‘heritage impact assessment’ [8, 9]. A baseline situation was established, a plan of adequate changes drawn and its impact determined at both building and historic urban townscape level. Measuring impact included several components: heritage (impact of change measurement), energy and CO_2 (measured improvements), cost-effectiveness (pay-back time measured), and comfort (acceptable Predicted Percentage of Dissatisfied - PPD). These components were ranked in hierarchical order, with heritage impact assessment at the top and comfort at the bottom of the list.

Through a bottom-up process, ten case studies from the Oporto WHS were selected to apply the previously described methodology. The selected cases were measured on-site (fieldwork), followed by computational model analyses using the IES-VE software for the baseline scenario and for the dynamic simulation of the improvement measures. The developed models were based on detailed data that had been obtained through fieldwork: geometry and construction systems were identified, as well as equipment and the household's behaviour pattern. On-site temperature and humidity data for model calibration purposes was also collected.

2.2 Oporto traditional buildings

Traditional buildings in Oporto have mainly been built or transformed between the 17th and 19th century. They can in short be described as terraced houses facing the street, inserted in narrow and long lots and mainly residential (with shops on the ground floor). They have hip roofs, three to five floors, two or three windows per floor, solid granite exterior walls, inner wood structure, and plaster or tiles on the main facade. In the centre of the building, a staircase connects the multiple floors and provides light and ventilation from the skylight above for the inner rooms.

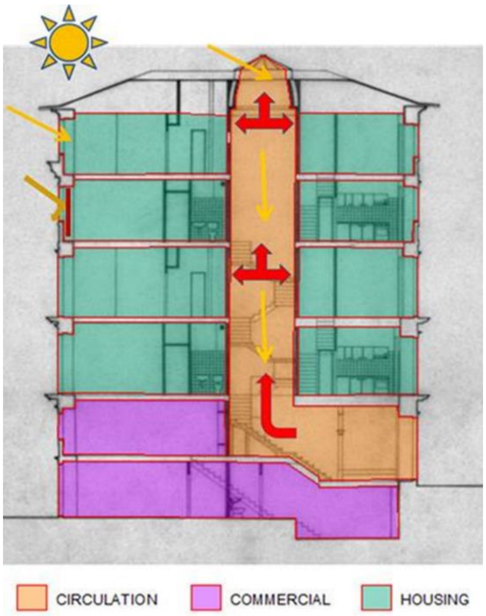

Figure 2 – Oporto traditional buildings schematic longitudinal section

2.3 Fieldwork

2.3.1 Identification of typological variants

A research area representative of Oporto's historical centre was delimitated and typologies of traditional buildings collected and described. The area selection was based on the following criteria: it had to be part of the WHS and contain a majority of traditional buildings with a high level of apparent integrity. This accounted for 89.4% of the total number of buildings. From a total of 316 buildings, 191 met the inclusion criteria (built before 1919 and mainly residential) and were examined.

The analysis of the selected buildings showed a typological homogeneity of the sample, which was composed almost exclusively of similar terraced houses. Hence, instead of different typologies, the survey showed the existence of several variants of one main typology. Taking into account the building's urban insertion and form factors, six variants were identified. These can be grouped into three main categories: corners (end-terraced), including V1 and V2 (with 3 and 2 street facades, respectively); row houses facing the street (mid-terraced), including V3a (2 street facades), V3b (1 street and 1 back facade) and V4 (solely 1 street facade); and detached, comprising V5, which was excluded due to its irrelevance (representing less than 1%). The mid-terraced group (V3a, V3b and V4) is largely predominant, accounting for 91% of the total number of buildings. This is consistent with the predominant compact urban block identified in the historic city. The five variants (V1, V2, V3a, V3b and V4) to be modelled as case studies were further subdivided into middle and top floor sub-variants.

Figure 3 – Research area building variants

2.3.2 Case Studies

Following the process of determining the variants, ten real cases representing each of the variants were identified. The selection was made with the support of local institutions and professional knowledge of the field. All households that participated did so with informed consent. The cases were scattered throughout the research area and comprised mainly 18th and 19th century buildings. The cases also covered several types of integrity, ranging from buildings with their original spatial and architectural structures intact, to buildings that had been subject to profound refurbishing measures. The data collected in the field included real energy consumption (monthly, over 2 years from the energy supplier), temperature and humidity (half-hour intervals, for 3 months with on-site sensors), noise and light (during the household interview), survey of the geometric and constructive characteristics of the houses (direct measurement and visual survey), and assessment of all household equipment and appliances.

Additionally, the households answered a semi-structured questionnaire, with both open- and closed-ended questions in order to provide information about their behaviour towards energy use and comfort perception.

2.3.3 Modelling

Based on literature, several improvement measures were identified and, taking into account the specificity of the case studies, a set of 19 design scenarios was selected to be simulated. Two types of simulation methods were used, a spread sheet software for equipment and appliances and dynamic simulation software for all other data.

The design scenarios were further classified as 'short-term' and 'long-term', based on their cost effectiveness and their feasibility of implementation, with 'short-term' being classified as a pay-back period of less than three years.

Table 1. Design scenarios

Scenario	***Measure***	***Simulation Method***
1	Nulling equipment standby	Spreadsheet
2	Replace existing lamps with more efficient Compact Fluorescent Lamps	Spreadsheet
3	Replace existing equipment with more efficient models	Spreadsheet
4	Draught-proofing windows and doors	Dynamic
5	Improve single glazing with insulating film	Dynamic
6	Use of internal shutters	Dynamic
7	Use internal shutters plus change the profile	Dynamic
8	Reduce Domestic Hot Water (DHW) temperature from 60° to 55° C	Dynamic
9	Upgrade DHW storage tank insulation (to 100mm)	Dynamic
10	Introduce double glazing	Dynamic
11	Introduce secondary glazing	Dynamic
12	Introduce insulation in floors and ceilings	Dynamic
13	Introduce insulation in roofs	Dynamic
14	Introduce exterior insulation in party walls	Dynamic
15	Scenario 14 plus introduce exterior insulation in facades	Dynamic
16	Composite scenario (4, 8 and 9)	Dynamic
17	Composite scenario (4, 6, 8 and 9)	Dynamic
18	Introduce solar thermal DHW	Dynamic
19	Introduce solar thermal DHW plus scenario 8	Dynamic

3. RESULTS

3.1 Baseline

The baseline results for energy, comfort and cost for each case study are listed in Table 2.

Table 2. Baseline results

Variant	Results		
	Energy consumption (yearly mean - kWh/m²)	*Comfort (mean PPD - %)*	*Yearly energy cost (€/m²)*
V1 mid	73.69	17.43	12.73
V1 top	37.28	30.17	5.48
V2 mid	138.75	26.29	17.31
V2 top	128.19	26.63	10.78
V3a mid	76.99	22.29	10.45
V3a top	57.59	26.49	11.29
V3b mid	93.72	16.63	12.42
V3b top	63.94	27.49	10.00
V4 mid	201.92	33.42	26.97
V4 top	60.34	26.75	9.25

3.2 Simulation

The average energy savings from introducing more efficient lighting and stand-by avoidance in the ten case studies were 3.76% and 1.78% respectively.

Small gains were obtained from the draught proofing of external windows and doors, reaching a maximum of 1.39%.

The introduction of double and secondary glazing in the traditional windows reduced the average simulated U-values from the initial 4.6 W/m^{2}K to 3 and 2.8 W/m^{2}K respectively.

The insulation of roofs and walls achieved relatively low reductions for energy consumption. While the top saving value reached 9.58%, the majority of the cases presented insignificant savings. However, the improvement obtained from insulating the case studies' external walls was relevant as it achieved average simulated U-values of circa 0.54 W/m^{2}K, down from the original 2.28 W/m^{2}K.

The introduction of solar thermal panels, also presented relatively low savings, with an average reduction in the energy consumption of 7.9%.

4. DISCUSSION

4.1 Baseline situation

In Portugal, residential buildings built before 1950 consume an average of 200 kWh/m^2, while the ones built between 1950 and 2005 consume on average 140 to 110 kWh/m^2 [10]. Further data states that the most recent and most efficient residential buildings (2006-2010) consume an average of 109 kWh/m^2 per year [11].

The current study shows that for the most numerous building variants (V3a and V3b) the average energy consumption was below these values (63.94 to 93.72 kWh/m^2), thus showing better results than the expected. These values were not only below the European and Portuguese averages for residential buildings, they were also close to the values that have been verified for the most recently built buildings. In terms of the cost spent on the energy per dwelling, the average for the ten cases (€ 710.30 per year) was again below the national average (€ 840.00 per year) [12]. It is necessary to stress that the householders reported a reasonable overall comfort sensation in all ten cases, with the mean PPD of the living areas remaining under the peak result of 35%. This suggests that fuel poverty is not the reason for the low consumption measured, rendering increased heating and/or cooling unnecessary. This is in accordance with the general tendency for Portugal and Oporto, where cooling was identified as irrelevant and heating represented around 20% of the overall domestic sector energy consumption [12, 13].

4.2 Simulations

Simulations addressing the residents' behaviour showed a high efficiency, in particular for low-cost measures like the upgrade of lighting and stand-by nulling. The results from this last measure confirm the outputs of similar studies that were performed either in Portugal [14, 15] or at a European level [16, 17]. The Portuguese studies identified a potential energy saving of 5.1% in the domestic sector, simply by not leaving devices in stand-by mode and a saving of 2.6% by adopting more efficient lighting. The averages identified in the ten case studies were slightly lower and revealed an inverse trend, with lighting presenting a higher potential than stand-by avoidance.

Glazed elements in the ten cases represent on average 40% of the total area of the main facade (ranging from 25% to 51%). This high share highlights the importance of potentially upgrading these glazed elements. The small gains obtained from the draught proofing of external windows and doors verify the laboratory tests carried out by Baker [18]. Nonetheless, the comfort improvement obtained in most of the case studies' simulation favours the use of these measures.

The introduction of double and secondary glazing in the traditional windows allowed reducing the U-values from the initial 4.6 W/m^2K to 3 and 2.8 W/m^2K respectively. This highlights the fact that the introduction of secondary glazing is slightly more effective than upgrading to double glazing. This also confirms Baker's results [18] and is in line with the ones obtained in the Oporto guidance [19]. It is worth noting that these results were consistent across all ten case studies.

The use of insulation in the envelope is widely promoted in the literature and in thermal regulations as one of the most effective measures [19, 20]. However, this could not be verified in the simulations of this study, where the insulation of roofs and walls achieved relatively low reductions in energy consumption. The top saving value was 9.58%, but the majority of cases presented insignificant savings. These results, combined with the high cost of such measures, the heritage limitations, and the relatively reduced area of walls in the facades leads to the conclusion that the insulation of the envelope of traditional buildings in Oporto is surprisingly ineffective. This is in contrast with the results obtained in the Oporto guidance, which presented an energy consumption reduction of up to 60% from the baseline situation [19]. These results may be explained by the use of the standard steady calculation method promoted by the thermal behaviour regulation, which is based on fixed heating and cooling loads, which is not in line with the real-life behaviour verified in the surveyed case studies. Nonetheless, it is worth to analyse the energy savings and the fabric's thermal behaviour improvement separately. While the first was found to be ineffective, an improvement of the fabric's thermal behaviour could be observed, thus confirming the expected improvements widely disseminated in the literature.

The introduction of solar thermal panels, another widely promoted measure, also showed lower savings than expected, with an average reduction in the energy consumption of 7.9%. This result is consistent with the simulation performed in the Oporto guidance, which achieved a reduction of 6% in the energy consumption through the use solar collectors by addressing 40% of the total DHW demand [19]. When comparing the cost savings with the required investment, solar thermal systems lose their efficiency and attractiveness as their average pay-back period amounts to 86 years. Additionally, the multifamily occupation identified in the case studies would result in a high demand and thus a high number of solar panels for each roof. The consequences to Oporto's historic townscape caused by the massive use of solar panels are highly disruptive for the World Heritage Site's authenticity. Considering all these factors, it can be concluded that solar thermal solutions are not adequate for historic buildings in the Oporto World Heritage Site.

5. CONCLUSION

The overall energy efficiency performance of Oporto's traditional buildings was better than expected and previously described.

The most effective solutions to improve energy efficiency of Oporto's traditional buildings are upgrading the DHW tank insulation and the efficient use of existing equipment. From the simulated short- and long-term scenarios, yearly cuts on energy use and carbon emissions of 464.76 MWh and 106 tonnes of CO_2, and 914.65 MWh and 209 tonnes of CO_2 respectively, were identified. On average, each dwelling could save € 121 and € 238 per year in the short- and long-term scenarios, respectively, corresponding to a decrease of 17% and 33.5% from actual average costs.

Upgrading the fabric was found to be less important than is commonly pointed out in literature, which relieves the pressure on the heritage values of these traditional buildings. Surprisingly, envelope insulation was ineffective overall, resulting in irrelevant energy savings and low comfort improvements on the top of its high-cost and negative impact on the building's heritage values. The same situation was verified for the introduction of solar thermal panels, which additionally cause a high negative impact on the historic townscape of the HWS.

This study supports an approach diverging from the established envelope-centred upgrade and reinforces the role of behavioural and passive enhancement solutions for the energy efficiency improvement of traditional buildings

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