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Energy retrofit of historic buildings: Environmental assessment of cost-optimal solutions

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A B S T R A C T

This paper describes the implementation of an integrated cost optimality and environmental assessment involving alternative energy efficiency retrofit packages for a building that dates from the beginning of the 20th century. A building typical of the building stock in the centre of Coimbra (located in the central region of Portugal and recently classified as a UNESCO World Heritage Site) was used to illustrate the methodology presented. The results were also analysed for the same building in two other locations. A life-cycle (LC) model was implemented to assess different energy efficiency measures for an apartment. The economic assessment complied with European Directive 2010/31/EU. The results show that the lowest life-cycle environmental impacts were obtained for insulation thicknesses between 50 and 120 mm, which are also cost-optimal. It is also shown that insulation thicknesses of more than 80 mm do not improve energy efficiency or global cost reduction. This paper shows that, even though historic buildings in Portugal do not have to comply with building energy codes, significant energy savings can be achieved for them without changing their historic character. It was also concluded that economic and environmental costs can both be minimised by choosing the most suitable energy efficiency retrofit measures.

1. Introduction

Buildings are an important source of environmental impacts, not only during the construction phase but also the due to the long term impact of energy use over their life span. The residential and commercial sectors in Portugal accounted for 18% and 12%, respectively, of the total final energy use in 2010 [1]. Moreover, it has been claimed that the use stage is the most costly for energy use and environmental impacts over a building's life-cycle [2–4]. However, as buildings become nearly zero energy (NZEBs), the balance shifts and the embodied phase become the most costly [5]. Moreover, user behaviour is not considered in most life-cycle and cost optimality studies.

Given their long life span, it is essential that buildings meet energy performance requirements in line with the local climate when major retrofit works are planned. European Directive 2010/31/EU (EPBD) [6] requires all EU state-members to establish a comparative methodological framework for the calculation of cost optimality levels for the energy performance requirements of buildings. However, buildings in World Heritage sites are not obliged to comply with these requirements since doing so may affect their architectural and historic value [7]. About 25% of the building stock in Europe was built in the middle of the 20th century. Most of those buildings have an architectural, cultural or even historic value and represent the unique character and identity of European cities; however, they are among the largest contributors to the poor energy performance of the building sector.

Various strategies can promote the fulfilment of sustainability criteria to achieve an optimum balance between return on investment, energy savings and minimisation of environmental impacts over a building's life span. In 2012, Delegated Regulation (EU) No. 244 [8] (supplementing the EPDB) laid down rules to compare energy efficiency measures using a cost optimality approach. This methodological framework is based on the primary energy performance and cost of each measure, looking at both the macroeconomic perspective (looking at the costs and benefits of energy efficiency investments for the society as a whole) or a strictly financial viewpoint (looking only at the investment itself) [9]. From the macroeconomic perspective, there are assumed to be additional costs related to greenhouse gas emissions. However, the environmental assessment aspect of our methodology is limited and does not represent a life-cycle perspective. Life-cycle assessment (LCA) addresses the potential environmental life-cycle (LC)

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Nomenclature

List of symbols and acronyms

AC	air conditioner
ADENE	Portuguese national agency for energy
CED	cumulative energy demand
CO_2	carbon dioxide
DHW	domestic hot water
EH	electric heater
EPBD	energy performance of buildings directive
EPS	expanded polystyrene
ERSE	Portuguese energy regulator
FIN	financial perspective
GB	gas boiler
GHG	greenhouse gas emissions
HDD	heating degree days
LC	life-cycle
LCA	life-cycle assessment
LCI	life-cycle inventory
LCIA	life-cycle impact assessment
MAC	macroeconomic perspective
NRPE	non-renewable primary energy
RPH	air changes per hour

impacts of products and systems (ISO 14040:2006) [10]. It can identify the critical components of the environmental performance of existing buildings and evaluate the potential benefit of different energy efficiency retrofit packages (set of measures applied to the building).

LCA methodology has been applied to assess the environmental impacts of building retrofit actions [11–16]. This approach has also been applied to redesign the concept of NZEB with the aim of reaching an electricity target of net zero energy assuming that these type of buildings can heavily be influenced by the energy carrier weighting factors chosen [17]. Moreover, extended input–output models have also been applied in environmental assessment of buildings retrofit [18,19]. For instance, Cellura et al. [19] developed an energy and environmental extended input output model, combined with life cycle assessment, to analyse the role of the building sector in the reduction of Italian energy consumption and CO_2 emissions.

The environmental and economic assessments have mainly been applied to products/services (e.g. energy systems, materials, etc. [20–22]) and recently also to buildings. Several studies have carried out an economic assessment of energy efficiency retrofit measures, but very few include an environmental assessment of existing buildings and none do so for historic buildings. Lollini et al. [23] studied the optimisation of opaque components regarding their energy, environmental and economic impacts. Anastaselos et al. [24] created a tool to perform an integrated energy, economic and environmental evaluation of thermal insulation solutions. Kim et al. [25] assessed the carbon emissions and related costs of apartment buildings, and Kneifel [26] assessed energy efficiency measures in new commercial buildings. In the Portuguese context, Silvestre et al. [27] performed an environmental, energy and economic assessment of building assemblies for new residential buildings.

Thermal dynamic simulation has been included in LCA studies to assess the potential contribution of the occupants' preferences not only to the operational energy use of buildings, but also to trade-offs between embodied and operational energy [28]. The occupancy level of a building influences the operational energy use and the contribution of the different LC stages to the overall life span of a building [28,29]. De Meester et al. [30] and Azar and Menassa [31] emphasised the need to properly take occupancy into account at the design stage, to arrive at more reliable building energy performance estimates.

This article implements an integrated cost optimality and environmental assessment by combining alternative energy retrofit packages that can also be used in historic buildings. A building that represents the building stock in the old part of Coimbra (a city in the central region of Portugal and recently classified as a UNESCO World Heritage Site) was assessed. The same building is analysed as if it was in two other places (in the north and south of Portugal) in order to encompass different climate conditions. These two places represent the mildest (south) and coldest (north) winters in Portugal.

Even though historic buildings do not have to comply with minimum energy performance requirements, we intend to show the importance of the energy retrofitting of old constructions by looking at the potential energy savings and environmental impact reduction in cost-effective terms, without affecting their historical and architectural value. This article sets out to identify cost-optimal solutions based on an occupancy pattern and to assess whether these solutions also ensure low LC environmental impacts. Thermal dynamic simulation results were compared to seasonal steady-state method based on the Portuguese regulation on the thermal performance of buildings [32]. This comparison allows a coefficient of reduction to be applied to the seasonal method results for a specific occupancy pattern (in the thermal dynamic simulation calculations). A sensitivity analysis was also performed on the insulation cost, energy price trends and discount rate (for the financial perspective), to assess the influence on heating energy needs.

Section 2 describes the methodology. The building's characteristics, the retrofit packages, and the economic and environmental inventories are described in Section 3. Section 4 presents the cost and environmental results, as well as the sensitivity analyses. Finally, Section 5 sets out the conclusions.

2. Methodology

The methodology includes the selection of the main energy efficiency retrofit packages. The energy retrofit packages combine thermal insulation options for the roof (7), exterior walls (7) and floor (7), solutions for windows (including an option of reinforcement with second window frames) (2) and the use of alternative heating (3) and domestic hot water (DHW) systems (2). The parametric assessment resulted in 4116 energy retrofit packages calculated for each location (12,348 in total). Each package was calculated for three different locations, HDD (Heating Degree Days) 987, 1304 and 1924. In conjunction with the average *U*-value, HDD provides a simple metric for roughly quantifying the amount of energy required to heat this historic building over a year, in these three locations.

A life-cycle model was developed to assess nine packages selected for each location (within the cost-optimal range) and alternative insulation materials, aiming to identify optimum thickness levels in terms of non-renewable primary energy (NRPE) and greenhouse gas emissions (GHG). A life span of 30 years was assumed. Subsections 2.1–2.3 describe the methodology for energy, cost optimality and environmental impact assessments.

2.1. Energy assessment

The energy needs for the use stage (operational energy) were calculated for the three locations using both the seasonal and dynamic methods, assuming the hygrothermal behaviour of the existing building (without energy efficiency retrofit measures). The seasonal steady-state method used to calculate the energy requirements was transposed from the European standards [33,34] into national law [32]. EnergyPlus software was used for the thermal dynamic simulation; it is a state-of-the-art open-source tool developed by the U.S. Department of Energy [35]. A detailed energy performance simulation was performed by modelling the geometry, construction systems, internal loads, weather parameters, heating and DHW systems.

Since most Portuguese residential buildings do not have a permanent occupancy, the thermal dynamic model assumed the average occupancy pattern for Portuguese residential buildings. This occupancy pattern consists in a four-person family with a low occupancy level with loads mainly at night on weekdays and all day on weekends. It can be described as active couple who works outside the house during the day while their two children go to school. The heating system was only partially activated during occupied hours. Coefficients of reduction were calculated for each location, to be applied to the seasonal steady-state method to account for user behaviour, together with other internal heat gains that can be modelled more accurately in a dynamic approach. The dynamic model accounts for internal heat gains associated with the number of persons estimated to be in each thermal zone (occupancy density) and their metabolic activity, and the schedules defined for lighting and appliances. A steady-state analysis usually assumes default values per area for internal heat gains ($4\ W/m^2$) [32].

2.2. Cost optimality assessment

Relevant economic and technical data was gathered and analysed for the cost assessment. Since the heating and DHW systems costs varied very little, the research focused on how the insulation cost variability influenced the cost-optimal retrofit packages. The cost assessment (heating and DHW systems, thermal insulation and windows) followed the EN 15459 standard and compared the different heating and domestic hot water systems, in €/kWh, and building envelope retrofit measures (thermal insulation and windows), in €/R (R-thermal resistance unit). A tool was developed to assess the cost optimality of energy efficiency retrofit measures in buildings according to the methodology defined by the Commission Delegated Regulation (EU) No. 244 [8]. This tool performs a parametric assessment of different energy efficiency measures by calculating optimum levels of profitability from both a macro-economic (including benefits for society) and a financial (only looking at the return on investment) perspective. All costs (materials, systems, operation and maintenance) were obtained from a market search using price sampling to assess the viability of current market costs [36].

2.3. Environmental assessment

An integrated life-cycle approach combining LCA and thermal dynamic simulation was implemented to assess the energy and environmental performance of selected energy efficiency retrofit measures. LCA addresses the potential environmental life-cycle (LC) impacts and consists of four interrelated steps: definition of goal and scope, life-cycle inventory (LCI), life-cycle impact assessment (LCIA) and interpretation (ISO 14040:2006) [10]. Two impact categories were assessed: non-renewable primary energy (NRPE), calculated using the cumulative energy demand (CED) method to address energy resource depletion, and greenhouse gas emissions (GHG), calculated using the IPCC assessment method [37]. The CO_2 emissions factor used for electricity was 360 g CO_2eq/kWh and 202 g CO2eq/kWh for natural gas, according to Portuguese regulations (Order (extract) 15793-D/2013 in Portuguese). The final and primary energy conversion factors used were 2.5 kWh_{ep}/kWh for electricity and 1 kWh_{ep}/kWh for solid, liquid and gaseous fuels [32].

3. Historic building: model and inventory

The historic building is in the centre of Coimbra, in Rua Fernandes Tomas, 58–66, in the parish of Almedina (also known as the former “Rua das Fangas”, the name given in the sixteenth century and related to trade in cereals). It has five floors (sub-basement, basement and ground floor for commercial use, and the first and second floors for residential use, divided into four independent apartments). This building, also known as *Casa das Talhas* (which means house of the large clay pots), is located in a recently classified UNESCO World Heritage site. These sites impose several constraints on the building stock, such as volume, façade height, materials and design, etc. in order to preserve their historic and cultural value. The main features of the building are single-glazed wooden windows, non-insulated stone walls (60 cm thick, on average) and a traditional wood frame roof with ceramic roof tiles. Fig. 1 shows a picture of the main façade of *Casa das Talhas* and its surroundings.

This article focuses on one apartment (with 119 m^2 of living area) characteristic of dwellings in historic city centres in Europe. Fig. 2 presents the technical drawings (main façade, sections and plans) of the apartment. Table 1 presents the building dimensions, where A is the living area in square metres, *h* the floor height in metres and *f*, *e*, *w* and *r* are the floor, walls, windows and roof, respectively.

The 4116 energy retrofit packages combined thermal insulation of the roof, exterior walls and floor, window replacement and two different heating and DHW systems. Table 2 gives details of the opaque building envelope assemblies (roof, walls, floor and windows) characterized by their thermal parameters, such as heat

Fig. 1. “Casa das Talhas” (“House of cereals clay pots”).

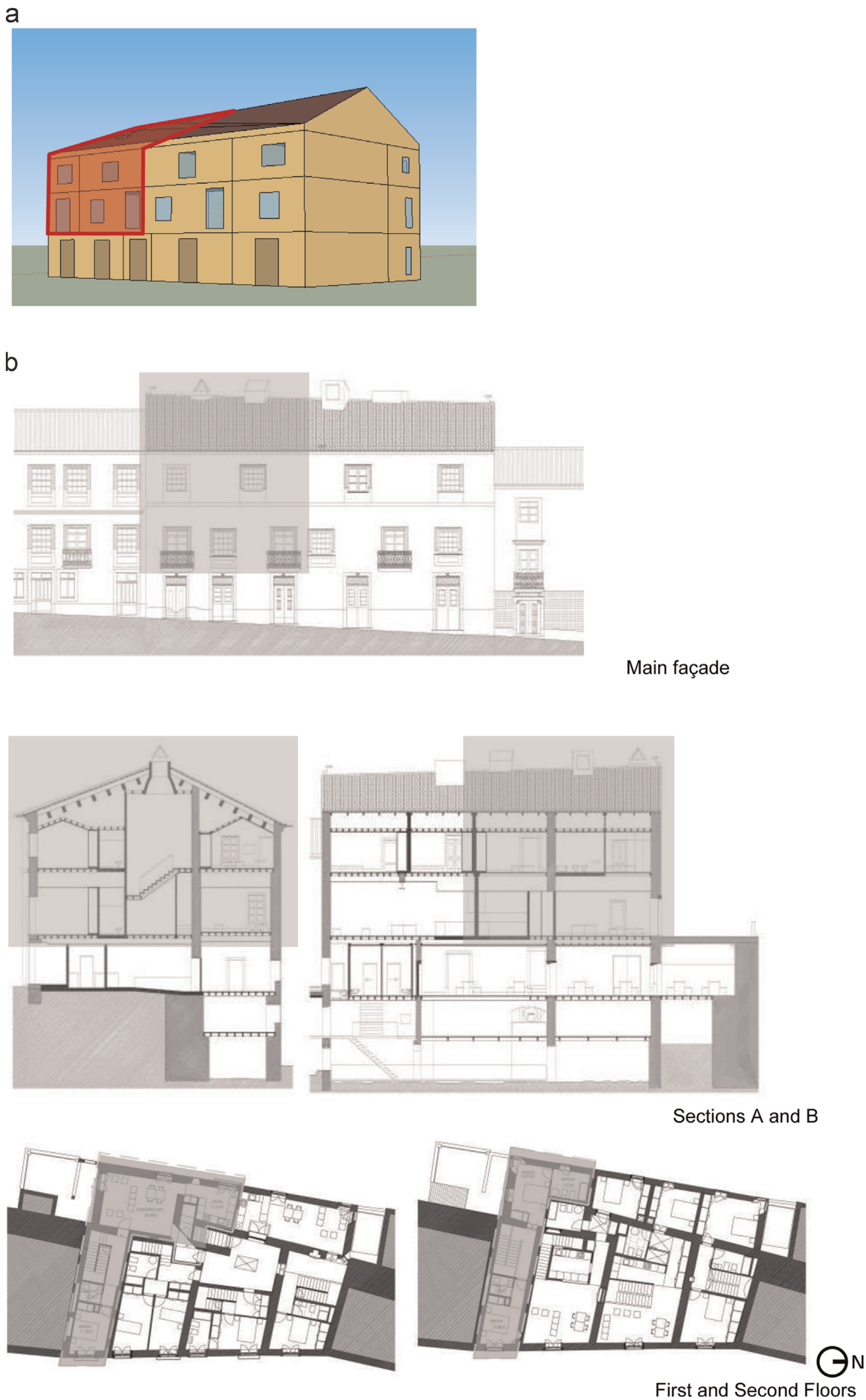

Fig. 2. Apartment: (a) 3D simplified model; (b) Main façade, sections A and B, first floor, second floor and roof plans (the apartment studied is identified with a transparency).

Table 1
Dimensions of [m^2] and air changes per hour [h^{-1}] in the apartment.

A_f	70 m^2
h	2.85 m
A_e	70.5 m^2
A_w	17.15 m^2
A_r	57 m^2
rph	0.4 h^{-1}

Table 2
Opaque envelope assemblies (roof, walls, floor and windows) characterisation-thickness in [mm] and heat transfer coefficient U in [W/(m^2 °C)].

Roof		Walls		Floor		Windows	
Thickness	U_r	Thickness	U_e	Thickness	U_f	g_w	U_w
0	2.10	0	1.84	0	1.40	0.85	5.10
40	0.63	40	0.60	40	0.55	0.66	1.53
60	0.47	60	0.45	60	0.42		
80	0.37	80	0.36	80	0.34		
100	0.31	100	0.30	100	0.29		
120	0.26	120	0.26	120	0.25		
140	0.23	140	0.23	140	0.22		

transfer coefficient U and solar heat gain coefficient g_w. The insulation thicknesses were selected based on previous studies [16], [38]. The thermal insulation material selected for this study was expanded polystyrene (EPS, with thermal conductivity of 0.036 [W/(m °C)]).

A life-cycle model was developed for the apartment including the following main processes: removal of the original components, construction and use stage (heating, DHW and maintenance). The end-of-life stage of the new components was not considered (dismantling scenarios and waste treatment after service life) because this cannot be accurately predicted due to the long life of buildings and is considered of minor importance for the residential sector accounting for less than 5% of total LC impacts [39,40]. However, this assessment included a demolition stage which represents the end-of-life of some components that will be replaced. Moreover, the end-of life may also depend on the maintenance strategy defined.The functional unit selected for this study was one square metre of living area over a period of 30 years. Inventory data for the alternative packages regarding material production and transportation was obtained from Kellenberger; Spielmann; and Althaus [41–43] and Spielmann et al. and Hischier et al. [44]. The model and life-cycle inventory were implemented using SimaPro 8 software [45].

A thermal dynamic model was implemented to calculate the energy needs of the whole building in the three locations. Each apartment and commercial area was modelled as a thermal zone with different thermal behaviour and a specific occupation pattern (internal heat gains and occupancy schedules). As this research focused on a single apartment, the operational energy considered was the heating needs of that apartment.

The Portuguese climate is classified as maritime temperate climate with Mediterranean influence under the Köppen–Geiger classification system (Csa/Csb; C: hot temperate climate; s:dry summer; a,b: hot,mild summer) [46]. The heating season begins in November and ends in mid-May (6.3 months, representing 1304 [°C.day] (heating degree days – HDD)). The heating and cooling setpoints were fixed at 18 °C and 25 °C, respectively, and a natural ventilation rate of 0.4 air changes per hour was considered, in keeping with the Portuguese building thermal regulation [32]. The cooling needs were not considered since the overheating period of this house is very short (heat gain coefficient is higher than the

Table 3
Heating and DHW system combinations.

	Heating system			DHW system		
	Equipment	Fuel	Efficiency	Equipment	Fuel	Efficiency
1)	Electric heater	Electricity	1.00	Gas water heater	Gas	0.60
2)	Air conditioner	Electricity	4.30	Gas water heater	Gas	0.78
3)	Gas boiler	Gas	0.93	Gas boiler	Gas	0.83

reference value [32]). A total volume of 160 l per day (40 l per person) was assumed for DHW, based on [32].

The heating and DHW systems defined as energy efficiency retrofit measures are an air conditioner (AC) (for heating only) and a gas boiler (GB) for both heating and DHW. The building is historical and would not hold panels to capture solar energy since the roof is visible from the street. Boiler biomass cannot be used due to lack of space for proper installation and heat pumps require infrastructure that would affect the building façade. Thus, the analysis does not include renewable energy technologies. Table 3 shows the possible combinations of heating and DHW systems. A set combining an air conditioner for heating and a gas water heater for DHW was compared with a gas boiler for both heating and DHW needs. The heating and DHW systems defined for the building have a coefficient of performance of 1.0 (electric heater, EH) and 0.6 (gas water heater), respectively.

A four-person family (representative of a Portuguese household) was considered, with loads mainly at night (16 h) on weekdays and all day at weekends. The heating system was only partially activated during hours of occupancy. The heating schedule defined for this apartment was from 6 to 8 am (9 am at weekends) and from 6 pm (5 pm at weekends) to 12 pm within the defined setpoint. The maintenance tasks include conservation of the interior and exterior finishes of the building throughout the 30-year life span.

The occupancy profile used in the thermal dynamic model showed that heating needs were 32–46% lower (depending on the location) than the needs estimated by the seasonal steady-state method. Thus, a multiplicative factor of 0.54 (HDD 987), 0.66 (HDD 1304) and 0.68 (HDD 1924) was applied to each of the 4116 packages to address the impact of the occupancy profile on the steady-state method estimates.

A cost optimality assessment was performed on 4116 energy retrofit packages for each location to identify the packages within the cost-optimal range. The most popular retrofit solutions in the Portuguese market were selected for the insulation, heating and DHW systems. The current market prices were obtained from [36] and manufacturers' associations to estimate the initial investment and maintenance costs (after retrofit). The insulation costs on the lower bound of prices include €2.3 per thermal resistance unit (€64 per m^3) and €17 per square metre for the installation costs (labour and other materials). For the upper bound of prices, we assumed €15.50 per thermal resistance unit (€360 per m^3) and €13.30 per square metre for installation. Higher installation costs (€34 per square metre) were assumed for the floor insulation, for both lower and upper bounds. These bounds represent the cost range in the Portuguese market. The total initial investment cost for the defined equipment was: €984 for an electric heater; €4434 for an air-conditioner; €2157 for a gas boiler (for heating and DHW); €440 for a gas water heater. Although ISO 15459 [13] gives different percentages for maintenance costs, we assumed a 1% index on the initial investment. Costs related to building elements which do not have an influence on the energy performance of the building were omitted from the calculation, for example, floor

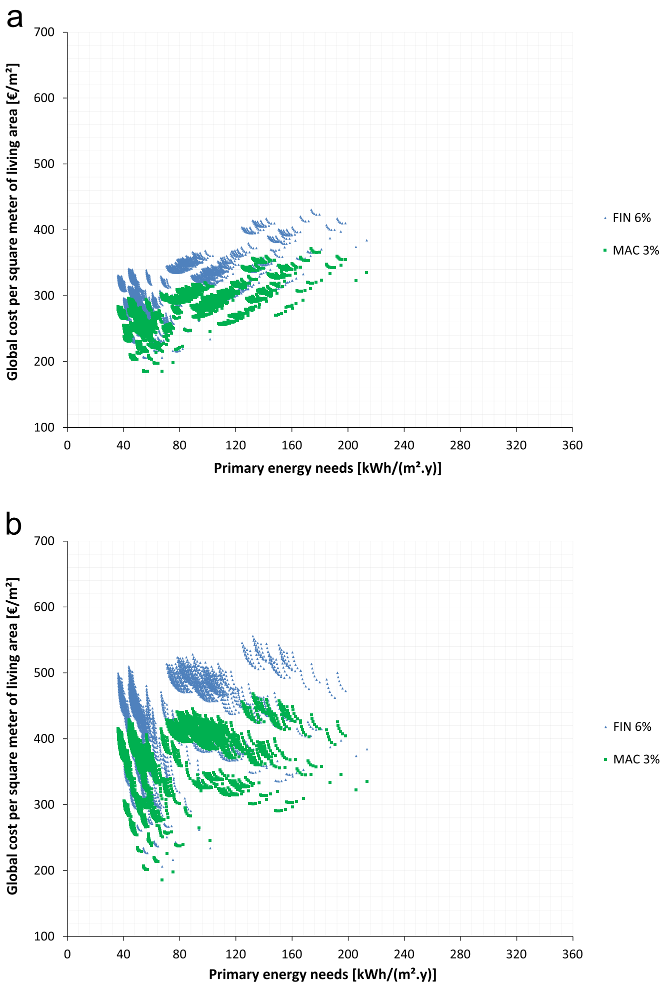

Fig. 3. Global cost [€/m^2] and primary energy [kWh/(m^2 year)] results for 4116 retrofit packages, HDD 1304 (Coimbra), considering (a) lower bound of insulation costs and (b) upper bound of insulation costs, over a period of 30 years, in both financial (FIN) and macroeconomic (MAC) perspectives.

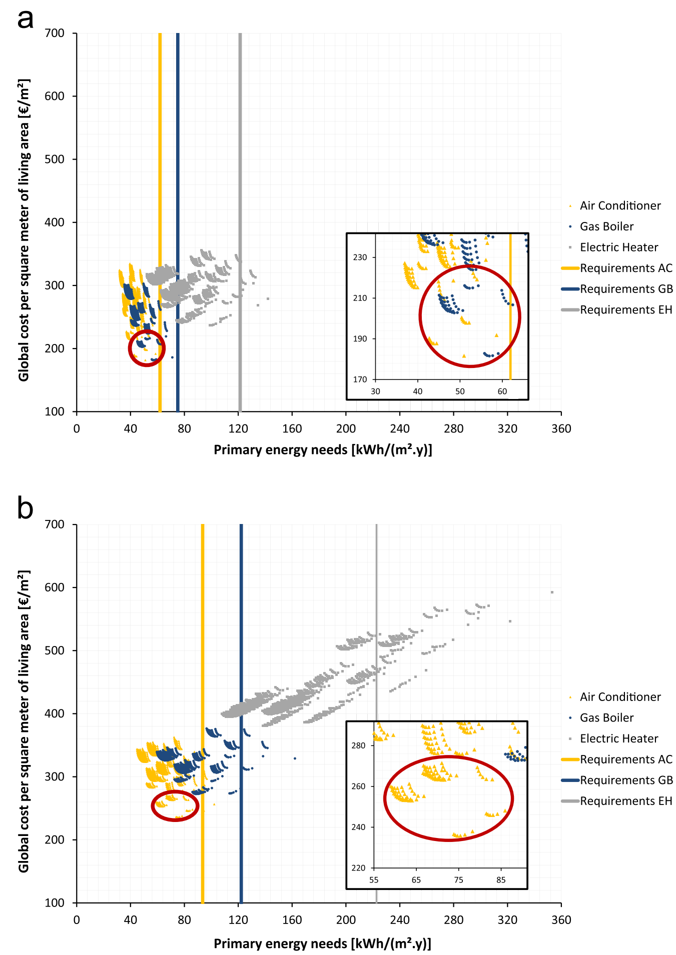

Fig. 4. Global cost [€/m^2] and primary energy [kWh/(m^2 year)] results for 4116 retrofit packages on the lower bound of insulation costs, for (a) HDD 987 and (b) HDD 1924, over a period of 30 years.

covering, wall painting or scaffolding costs.

The energy price trends are estimated by the EU up to 2050 [47]. The average energy cost of electricity (€0.2390) and natural gas (€0.1032) was obtained from the Portuguese energy regulator (ERSE) [48] and from current market prices analysis. A 6% discount rate was considered for the financial perspective. This is the rate used in Portugal for mortgages or retrofit projects [49], according to current market figures [50].

Nine energy retrofit packages were selected for each location (from 4116) within the cost-optimal range (as shown highlighted in Fig. 4), defined in a preliminary economic assessment, for detailed assessment regarding their environmental impacts. These packages combine roof and exterior wall insulation as a result of minimising both primary energy and global costs (Pareto optimum curve).

4. Results

4.1. Cost optimality assessment

The cost-optimal curve behaviour was analysed according to both the lower and upper bounds of the insulation cost. The primary energy results for the cost optimality assessment were calculated using the seasonal steady-state method with a reduction factor (occupancy pattern). The results show that cost-optimal curves change for each heating system. It can be seen in Fig. 3 that, for the same insulation thickness (just draw a vertical line to see this), the upper bound costs led to steeper curves than the lower bound, thus discouraging the investment in larger thicknesses. The cost-optimal levels in the financial and macroeconomic perspectives (FIN = 6%, MAC = 3%) have substantial differences. The energy costs, which are significantly higher in the financial perspective due to taxes, can somehow promote investment in retrofit in a private perspective.

In the lower bound of insulation costs, the cost-optimal range varied from 53 to 67 kWh/(m^2 y) of primary energy needs for HDD 1304 (Coimbra). However, the cost-optimal insulation thickness depends on the building envelope components, roof or exterior wall, and on the location of the building. Fig. 4 shows that the cost-optimal levels ranged from 43 to 63 kWh/(m^2 y) approximately, for HDD 987. For HDD 1924, the best cost-optimal level varied from 59 to 86 kWh/(m^2 y). Regarding global cost, the cost-optimal range varied from 181 to 224 €/m^2 for HDD 987, 205 to 235 €/m^2 for HDD 1304 and 236 to 270 €/m^2 for HDD 1924.

4.2. Environmental assessment

Nine energy retrofit packages per location were selected from the preliminary cost optimality assessment. It was concluded that thicknesses greater than 80 mm were not economically viable due to very low marginal energy savings. The cost-optimal range for Coimbra showed that the air conditioner plus gas water heater

Table 4
Useful energy needs [kWh/(m^2 year)] for heating the apartment, by location and exterior wall and roof insulation thickness [mm].

Location	HDD 987 (Southern Portugal)								
Roof insulation thickness	0	0	0	40	40	60	80	100	100
Exterior walls insulation thickness	0	40	60	40	80	0	0	0	40
Heating energy needs	43.56	35.59	34.62	**23.69**	**23.13**	31.17	30.45	29.98	**22.28**
Location	HDD 1304 (Coimbra, Central Portugal)								
Roof insulation thickness	0	0	0	40	80	100	40	40	140
Exterior walls insulation thickness	0	40	80	0	0	0	40	80	40
Heating energy needs	71.99	59.09	56.57	53.90	50.75	49.98	**41.28**	**38.84**	**36.54**
Location	HDD 1924 (Northern Portugal)								
Roof insulation thickness	0	0	0	40	40	40	40	60	80
Exterior walls insulation thickness	40	80	120	40	80	100	120	0	0
Heating energy needs	98.55	94.65	92.99	70.82	**66.98**	**66.03**	**65.35**	87.42	85.61

was the most cost-effective option (€0.055 per kWh for heating and €0.077 per kWh for DHW). Different insulation thicknesses from the cost-optimal range were assessed. The floor insulation was not in the cost optimal range since it was defined as a non-cost-effective measure in other studies that used market prices in Portugal [16], [38]. The high installation cost of this solution is one reason for its low economic performance. So, this measure was not included in the environmental assessment. The reinforcement with second window frames also was not in the cost optimal range since the original windows were retained in all the analysed packages. Table 4 shows the heating energy needs calculated for the three locations.

Fig. 5 shows that the exterior walls' optimum insulation level (LC tipping point) ranges from 40 (HDD 987) to 140 mm (HDD 1924) and the roof's optimum insulation level ranges from 40 (HDD 987) to 120 (HDD 1304). Additionally, embodied impacts account for 40% (HDD 1924) to 80% (HDD 987) while operational energy impact accounts for 20% (HDD 987) to 60% (HDD 1924). Nonetheless, embodied impacts offset the operational energy impacts in all retrofit packages in HDD 987, while in HDD 1304 this only occurs in those with exterior wall insulation. For HDD 1924, the operational energy impacts always offset the embodied impacts. Transportation accounts for about 7% (HDD 1304) to 12% (HDD 987) of the embodied impacts. An order 2 polynomial trendline was used for total LC impacts (correlation of about 98%) in all locations to assess the life-cycle tipping points of selected retrofit strategies (either fixing the roof insulation level and varying the exterior walls insulation level, or vice-versa).

The results by HDD are presented as follows. HDD 987 results show that the optimal insulation thicknesses (life-cycle tipping point) range from zero to 40 mm (exterior roof) and from 40 to 80 mm (exterior walls). HDD 987 embodied impacts accounts for about 60–70% of total LC impacts (varying between categories). Moreover, embodied GHG emissions offset the operational energy impacts in all retrofit strategies. The environmental benefits (reduction in total LC impacts) are very low (reduction of about 3%) for thicknesses higher than 60 mm (for both roof and exterior walls). HDD 1304 results show that the optimal insulation thicknesses (life-cycle tipping point) range from 100 to 120 mm (exterior roof) and from 40 to 80 mm (exterior walls). HDD 1304 embodied impacts account for about 30–50% of total LC impacts (varying between categories). Moreover, embodied GHG emissions offset the operational energy impacts in all insulated retrofit strategies with exterior walls insulation. The environmental benefits (reduction in total LC impacts) are very low (reduction of about 5%) for thicknesses higher than 80 mm (for both roof and exterior walls). HDD 1924 results show that the optimal insulation thicknesses (life-cycle tipping point) range from 80 to 100 mm (exterior roof) and from 100 to 140 mm (exterior walls). HDD 1924 embodied impacts account for about 35–60% of total LC impacts

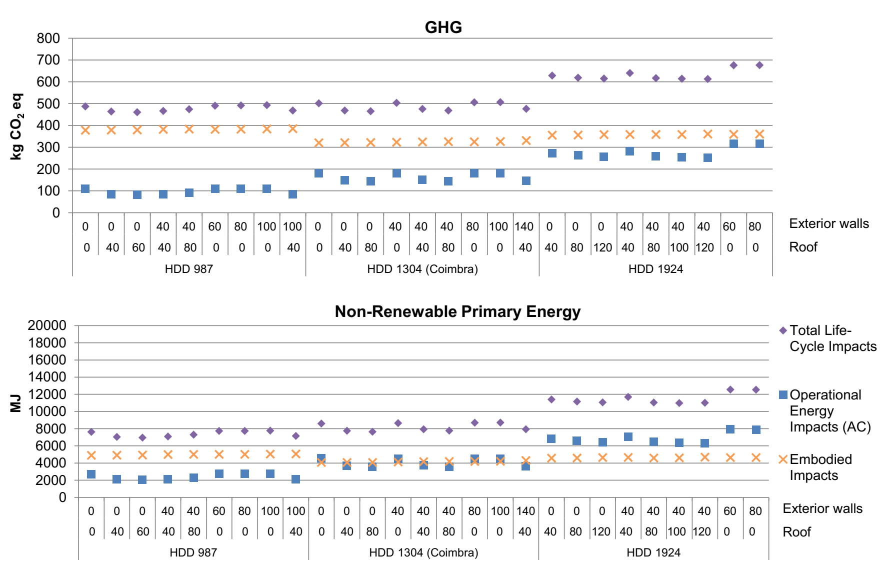

Fig. 5. GHG emissions and non-renewable primary energy impacts of the retrofit packages (roof insulation thickness + exterior wall insulation thickness) in three locations (HDD 987, 1304, and 1924), per functional unit (one square metre of living area over a period of 30 years).

(varying between categories) while operational energy accounts for 40–65%. Moreover, GHG and NRPE operational energy impacts offset the embodied impacts in all retrofit strategies. The environmental benefits (reduction in total LC impacts) are very low (reduction of about 3%) for thicknesses of more than 80 mm in exterior walls and 120 mm in the roof.

A sensitivity analysis performed for different heating systems shows that even though AC had lower final energy needs (25–30% less) than the gas boiler, the latter leads to lower GHG emissions (about 60%) than the AC as well as fewer non-renewable primary energy impacts (40%). These differences are due to the systems' efficiency (see Section 3) as well as electricity and natural gas primary energy conversion factors (see Section 2.3).

4.3. Sensitivity analysis

A sensitivity analysis was performed to assess the influence of energy price and discount rates on useful energy needs, for all energy efficiency retrofit packages. This analysis showed which variable was most important to the cost-optimal performance. The retrofit packages should comply with the minimum energy requirements [32] and be more cost-effective than the original scenario (existing building), which means they should have lower primary energy needs and life-cycle costs.

Fig. 6 shows significant differences compared with Fig. 3(a). Primary energy ranges from 27.7 to 306.8 [kWh/(m^2 year)], whereas with the reduction factor (0.66) it varies from 22.2 to 213.3 [kWh/(m^2 year)]. This analysis shows how the seasonal steady-state method overestimates the energy needs in its calculation by not assuming that households are not usually permanently occupied, as this method does. For example, in the reference building, the average monthly energy bill for heating and DHW alone would be €202.71 with the reduction factor and €290.84, considering 100% of the estimated energy needs by the seasonal method, for Coimbra.

Comparing Fig. 7 with Fig. 3(a) shows that the significant difference in scenarios of energy prices trends (linear increase of 2.5% versus Eurostat) does not provide significant changes in the cost-optimal range for Coimbra. Increasing just the insulation cost is not enough to significantly alter the cost-optimal packages. However, in the financial perspective the global cost ranges from 221.6 to 480 [€/m^2].

Fig. 8 shows the results for the cost-optimal retrofit packages using FIN = 12% and MAC = 6% as discount rates. Low energy prices combined with high discount rate estimates (as shown in Fig. 8

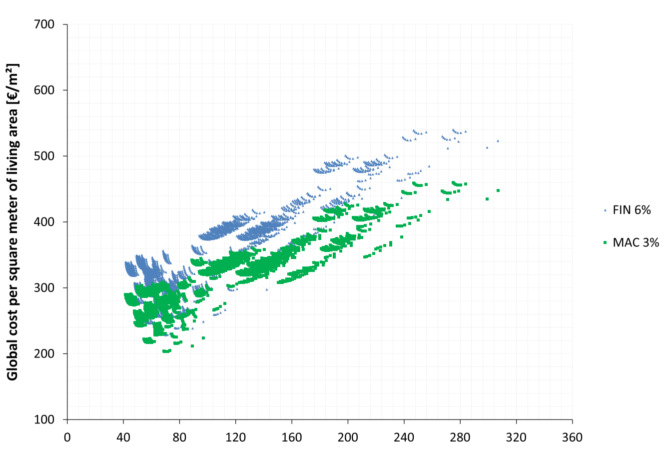

Fig. 6. Global cost [€/m^2] and primary energy [kWh/(m^2 year)] results for 4116 retrofit packages, HDD 1304 (Coimbra), considering 100% of energy needs and estimated by seasonal method, over a period of 30 years.

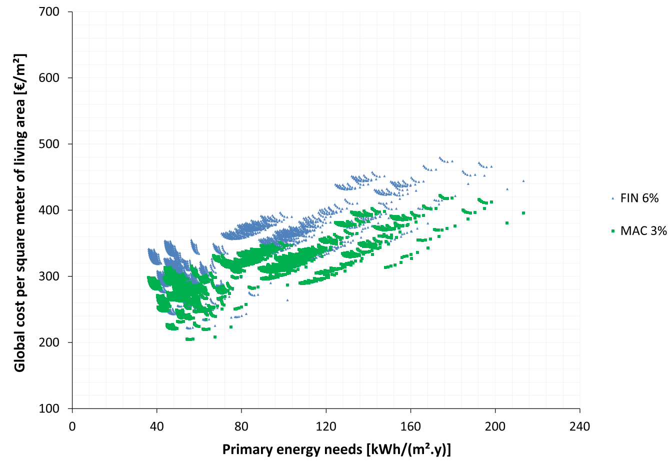

Fig. 7. Global cost [€/m^2] and primary energy [kWh/(m^2 year)] results for 4116 energy efficiency retrofit packages, HDD 1304 (Coimbra), assuming a linear trend of 2.5% for the energy price, over a period of 30 years.

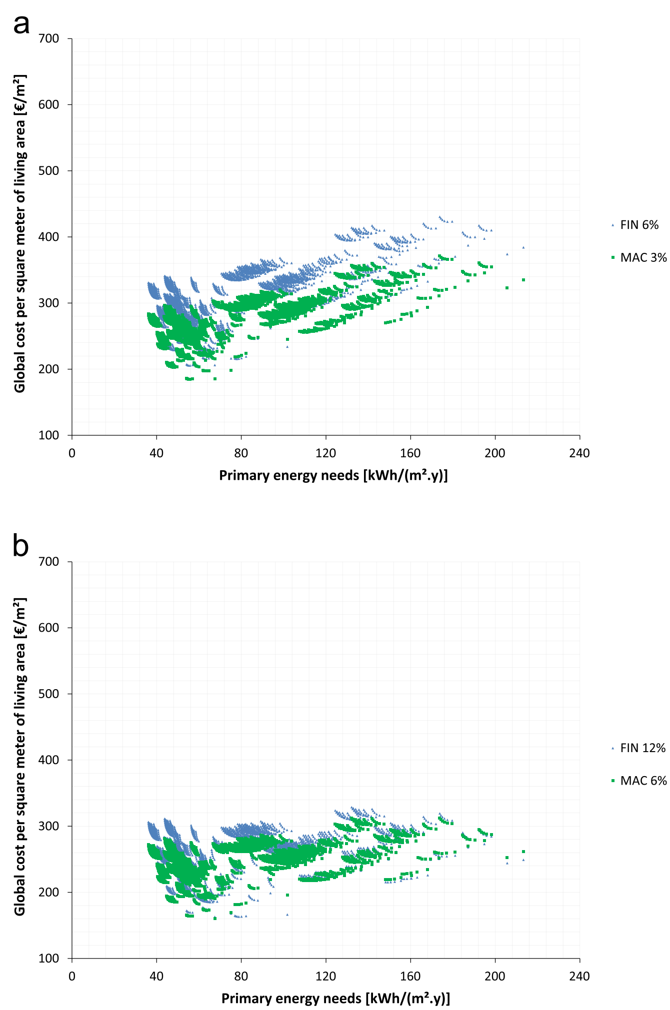

Fig. 8. Global cost [€/m^2] and primary energy [kWh/(m^2 year)] results of 4116 energy retrofit packages for HDD 1304 (Coimbra) considering (a) 6% and (b) 12% as discount rates; per square meter of living area over a period of 30 years.

(b) discouraged investment in packages with lower primary energy needs. For example, in the financial perspective the global cost ranges from 205.7 to 480.5 [€/m^2] for FIN 6% (Fig. 8(a) whereas with FIN 12% it varies from 162.9 to 347.2 [€/m^2] (Fig. 8(b). Note that potential savings on energy costs decrease more sharply in packages with higher primary energy needs when the discount rate rises to FIN 12%. In the scenario with the highest primary energy needs (a building without any efficiency measure, 213.3 [kWh/(m^2 year)]), the global cost decreases from 384.2 (FIN 6%) to 249.3 [€/m^2] (FIN 12%). There is a correlation between the discount rate and the energy price trend, which is relevant for the viability of investment in energy efficiency measures. A higher energy cost encourages increasing investments in retrofit because of the significant potential of energy savings.

5. Conclusions

This paper implements an integrated cost optimality and environmental assessment by combining alternative energy retrofit packages for a historic building located in the centre of Coimbra, Portugal (recently classified as a UNESCO World Heritage site). This building is representative of the Portuguese building stock in old city centres dating from the beginning of the 20th century. A number of energy efficiency retrofit packages (combining different energy efficiency retrofit measures) were selected from a preliminary economic assessment. GHG and non-renewable primary energy impacts were assessed. A parametric assessment was performed that combined roof insulation, exterior wall insulation, window replacement, heating and domestic hot water systems, in different locations. The variables assessed were the thermal resistance of the building envelope components (insulation thicknesses), heating and DHW system efficiency, location (heating degree days – HDD) and cost. The operational energy was calculated using both seasonal steady-state and thermal dynamic simulation methods. An occupancy pattern to be representative of the average Portuguese residential buildings was defined in the thermal dynamic model.

The cost optimality assessment was performed in accordance with the European Commission for the calculation of cost-optimal solutions compared with the building energy performance requirements in Portugal [8]. This method reduces the global cost and primary energy needs, which leads to better return on investment and lower environmental impacts. Finally, a sensitivity analysis was performed to assess the useful energy needs variability, energy price and discount rate.

The thickness of the nine retrofit packages selected for each location from the cost-optimal range varied from zero to 140 mm (when considering the lower bound of prices used in the Portuguese market). However, where the climate is warmer there is no advantage in using thicknesses of more than 80 mm. Price variation (from lower bound to upper bound) influences the cost optimality of the retrofit packages and this requires constant reassessment to achieve expected return on investment.

The economic assessment results showed that, first, there is a correlation between the discount rate and the energy price trend which is important for the viability of investments in energy efficiency measures; but just increasing the energy cost is not enough to significantly alter the cost-optimal packages. Second, lower energy prices combined with higher discount rate estimates discouraged investment in packages with lower primary energy needs. Third, insulation cost [€/R], heating and DHW systems operating cost [€/kWh] and its corresponding efficiency directly influence retrofit package performance. Finally, the energy costs, significantly higher in the financial perspective due to taxes, can encourage investment in retrofit in a private perspective, to take advantage of energy savings.

Extra insulation levels in temperate climates (buildings with lower energy needs) may lead to higher embodied impacts without significantly reducing the operational energy, resulting in higher total life-cycle impacts. Thus, a tipping point occurs when total life-cycle impacts are minimised (presenting an insulation level threshold).

Environmental life-cycle results show that each HDD location had a different insulation level threshold that minimised total LC impacts. The exterior walls' optimum insulation level (LC tipping point) ranged from 40 (HDD 987) to 120 mm (HDD 1924) and the roof's optimum insulation level ranged from 40 (HDD 987) to 80 mm (HDD 1304 and 1924). These ranges of insulation thresholds are also within the cost-optimal interval. Additionally, embodied impacts account for 35% (HDD 1924) to 70% (HDD 987) while operational energy impacts account for 30% (HDD 987) to 65% (HDD 1924). Locations with higher energy needs had higher insulation level thresholds. Lower operational energy needs led to higher embodied impacts. Low energy buildings offer more opportunities to reduce their environmental embodied burden.

Our work demonstrated that extra insulation, i.e. thicknesses of more than 80 mm, does not provide a significantly lower environmental impact or overall cost reduction. Furthermore, even though historic buildings in Portugal do not have to comply with building energy codes, significant energy savings can be achieved without adversely affecting their historic character. It was also concluded that both economic and environmental costs can be minimised by choosing the most suitable energy efficiency retrofit measures.

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