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Cost optimality ranking of measures to improve the energy performance of the Portuguese building stock

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ABSTRACT: The European roadmap towards a competitive low carbon economy in 2050 raised the awareness about buildings energy performance due to their potential for cost-effective energy consumption and carbon emissions reductions. For the evaluation of the levels of energy performance of buildings, the European Commission presented the Cost Optimal Methodology allowing comparing different energy performance levels of buildings and buildings components and identifying those with the lowest associated cost considering the building life cycle. This study, using four reference buildings from the Portuguese building stock, where some scenarios for the improvement of their energy performance were analysed with the purpose of identifying the cost-optimal levels, compares the economic performance of different measures. Results provide guidance for the assertive combination of elements for new buildings and for building packages of renovation of measures, as well as for the choice of individual measures in partial renovation scenarios, which, beyond common, are usually performed without the control of the national energy certification system.

Keywords: Energy efficiency, Building renovation measures, Cost Optimality

1 INTRODUCTION

In Europe, buildings represent a great share of final energy use [1] being responsible for 40% of the total energy consumption and 36% of the carbon emissions [2].

In an attempt to reduce these numbers in the building sector, in 2010, the European Parliament published a recast of the Energy Performance of Buildings Directive (EPBD), where it was introduced a comparative assessment for national energy performance requirements to determine the cost-optimal levels for buildings and building components [3]. In another words, the EPBD recast states that, after 2020, every building must be nZEB[4] and every member state should use a common methodology to establish minimum requirements to integrate in each national regulation which are based on cost-optimal energy performance levels [4].

The cost-optimal level consists on the balance between the different costs, such as investment, energy and maintenance costs. Usually, as the investment costs rise with the improvement of the energy performance of the buildings, the energy costs decrease due to better energy performances, during the buildings' life cycle [5]. The cost optimal level corresponds to the energy performance that presents the lowest global costs.

The methodology proposed by the European Parliament and the European Council predicts the analysis of different measures or packages of measures. When packages are analysed it is possible to observe the cost-optimal levels, but also a group of similar packages which form a range of cost-optimal solutions [6].

Each single measure has its own cost-effectiveness, which depend on the buildings construction characteristics, climate conditions, orientation and shading conditions [3]. The combination of measures may create synergies that lead to better energy performances than single measures [3].

Based on four single family reference buildings from the Portuguese building stock, where some measures to improve the energy performance were analysed through the cost-optimal methodology, an identification of the

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[4] nZEB is defined in article 2 of the recast EPBD as *"a building that has a very high energy performance… . The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources produced on-site or nearby".*

hierarchy of cost-effectiveness of different measures and also an analysis of the factors that affect the results, were performed.

2 METHODOLOGY

The cost-optimal analysis, from which the results of this study derive, followed the guidance of the Delegated Regulation from the European Parliament and the European Council [6]. The cost-optimal analysis requires the calculation of the energy needs to determine the energy costs related to the building use. These needs were calculated in accordance with the Portuguese thermal regulation for comfort temperatures of 20ºC in winter and 25ºC in summer, and also considering the energy needs for domestic hot water (DHW) preparation.

In accordance with the Delegated Regulation, the cost-optimal analysis was performed for a 30 year economic life cycle, for each building.

The measures that were analysed affect the buildings envelope (exterior walls, roof, floor and windows) and the building integrated technical systems (BITS). In most cases of the cost-optimal calculation, the packages included more than one measure in order to take advantage of the synergies that arise from their combination.

With the cost optimal results for the four analysed buildings, the global costs[5] for each renovation measure or package of renovation measures become available and they were used to rank the cost-effectiveness of the measures. The lowest the net present value (NPV[6]) is, the more secure the investment becomes. This value comes from the calculations of the costs related to each measure or package of measures studied, for the improvement of the energy performance of the four Portuguese single family buildings. This value includes investment costs, energy costs, maintenance costs and residual value after the end of the buildings economic life cycle. The global costs can be expressed by the expression (1).

$$C_g(\tau) = C1 + \sum_{j} \left[\sum_{i=1}^{\tau} (C_{a,i}(j) \times R_d(i)) - V_{f,\tau}(j)\right] \qquad (1)$$

Where:

τ means the calculation period

$C_g(\tau)$ means global costs (referred to starting year τ_o) over the calculation period

C1 means initial investment costs for measure or set of measures j

$C_{a,i}(j)$ means annual cost during year i for measure or set of measures

$V_{f,\tau}(j)]$ means residual value of measure or set of measures j at the end of the calculation period (discounted to the starting year τ_{0})

$R_d(i)$ means discount factor for year i based on discount rate r to be calculated as:

$R_d(p) = \left(\frac{1}{1+r/100}\right)^p$ where p means the number of years from the starting period and r means the real discount rate.

The study evaluates the impact on NPV of changing the energy performance of single elements within a package of measures and compares those differences between the global costs during the buildings economic life cycle.

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[5] The global cost calculation method results in a present value of all costs during a defined calculation period, taking into account the residual values of equipment with longer lifetimes.

[6] The net present value (NPV) is a standard method for the financial assessment of long-term projects. It measures the excess or shortfall of cash flows, calculated at their present value at the start of the project.

Mathematically, when the difference between NPV values has a negative value it means that the measure does not compensate, when it is close to zero it may be risky to invest. When it has a positive value then it is a profitable investment. With this comparison it became possible to rank the measures to improve the energy performance of the buildings according to their cost-effectiveness.

3 BUILDING CHARACTERIZATION

The analysed buildings are virtual buildings which represent the Portuguese residential building stock. Their characteristics result from average values drawn from a global database with data from the energy performance certificates.
These buildings were analysed in seven different locations which crosses the Portuguese climatic zones. The buildings represent four different construction periods, with different technologies on their envelopes and also with different dimensions. Table 1 summarises the general dimensions of each building and table 2 describes the construction solutions. These buildings were analysed in Porto, Lisbon, Bragança, Braga, Beja, Aveiro and Armamar, as these are the places considered representative of the different Portuguese climatic zones.

Table 1. Summary of the dimensional characteristics of the studied buildings

	Year of construction		< 1960	1961 - 1990	1991 - 2012	New
Dimensions	Floor area	m²	80	100	155	165
	Number of floors		1	1	2	2
	Windows area	m²	12	15	31	33
	Exterior walls area	m²	96,55	108	183,04	196,13
	Internal height	m	2,7	2,7	2,6	2,7

Table 2. Summary of the construction solutions of the studied buildings

Year of construction		< 1960	1961 – 1990	1991 - 2012	New
Solutions	Walls [WL]	Ordinary stone walls 50 cm thick with plaster on both sides	Simple brick walls 22cm thick with plaster on both sides	Double brick walls (11+11cm) with 3cm of XPS[7] with total thickness of 30cm with plaster on both sides	Simple brick walls 22cm thick with 3cm thick layer of ETICS[8] with EPS[9] and with plaster on the inside
		U value: 2.00 W/m^2.°C	U value: 1.30 W/m^2.°C	U value: 0.68 W/m^2.°C	U value: 0.50 W/m^2.°C
	Roof [RF]	Pitched roof with a light concrete slab 15cm thick covered with ceramic tiles and roof lining with plaster 2cm thick	Pitched roof with a light concrete slab 15cm thick covered with ceramic tiles and roof lining with plaster 2cm thick	Pitched roof with a light concrete slab 15cm thick and with 3cm of XPS, covered with ceramic tiles and roof lining with plaster 2cm thick	Flat roof with a light concrete slab 15cm thick and with 3cm of XPS, covered by asphaltic screen and roof lining with of plaster 2cm thick
		U value: 2.80 W/m^2.°C	U value: 2.80 W/m^2.°C	U value: 0.94 W/m^2.°C	U value: 0.48 W/m^2.°C

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[7] Extruded Polystyrene
[8] External Thermal Insulation Composite Systems
[9] Expanded Polystyrene

Table 2. Summary of the construction solutions of the studied buildings (continuation)

Year of construction		< 1960	1961 – 1990	1991 - 2012	New
Solutions	Floor [FL]	Light concrete slab 15cm thick, covered with concrete and ceramic tiles 4 cm thick	Light concrete slab 15cm thick, covered with concrete and ceramic tiles 4 cm thick	Light concrete slab 15cm thick and 3cm of XPS, covered with concrete and ceramic tiles 4 cm thick	Light concrete slab 15cm thick and 3cm of XPS, covered with concrete and floorboards 4 cm thick
		U value: 2.10 W/m^2.°C	U value: 2.10 W/m^2.°C	U value: 0.78 W/m^2.°C	U value: 0.58 W/m^2.°C
	Window [WD]	Wooden frames and simple glass	PVC frames and simple glass	PVC frames and double glass	PVC[10] frames with thermal barrier and double glass
		U value: 5.10 W/m^2.°C	U value: 4.10 W/m^2.°C	U value: 3.10 W/m^2.°C	U value: 2.80 W/m^2.°C

4 MEASURES TO IMPROVE THE ENERGY PERFORMANCE OF THE BUILDINGS

The measures to improve the energy performance of the buildings (renovation measures for the case of existing buildings and measures beyond the current normative reference values for the case of new buildings) that were analysed are presented in table 3. Only packages of measures that could be compared with each other with changes affecting only one of the building components were suitable for the purpose of this analysis. For the walls, the combination of measures from table 5 which were compared was nº 5 and nº 6 and also nº 8 and nº 9. For the roof it was nº 6 and nº 7 and for the floor it was nº 4 and nº 5. For the windows the comparison was between combination nº 1 and nº 4 and also between nº 9 and nº 10.

The packages of measures result from the combination of different envelope insulation thicknesses with different solutions for the BITS.

Table 3. Summary of the analyzed measures to improve the energy performance of the buildings envelope

Component	**Solution**
Wall [WL]	ETICS with EPS with thicknesses varying from 40mm to 160mm
Roof [RF]	Rockwool with thicknesses varying from 100 mm to 140mm
Floor [FL]	Rockwool with thicknesses varying from 40 mm to 80 mm
Window [WD]	PVC with U-value 2.4 and 2.1 [W/m^2.ºC]
DHW	Gas heater; Gas boiler; Heat pump; Electric heater and Biomass boiler
Heating	Gas heater; Gas boiler; Heat pump; Electric heater; HVAC and Biomass boiler
Cooling	Heat pump and HVAC
Renewables	Solar thermal panels

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[10] Polyvinyl chloride

In table 4 there is a summary of the combinations of BITS to deal with heating, cooling and domestic hot water preparation. The combinations with only two BITS (combinations nº 6 and nº 7) do not account with a cooling system. This situation is a normal scenario in Portugal because it is not usual to have a system just to deal with the cooling needs. The low energy needs for cooling experienced in most of the territory make this investment generally unjustified.

Table 4. Summary of the analyzed BITS combinations

Nº	**BITS (heating + cooling + DHW)**
1	HVAC + HVAC + Gas heater
2	Heat pump + Heat pump + Heat pump
3	HVAC + HVAC + Electric heater
4	Biomass boiler + HVAC + Biomass boiler
5	Gas boiler + HVAC + Gas boiler
6	Gas boiler + _ + Gas boiler
7	Biomass boiler + _ + Biomass boiler
8	HVAC + HVAC + Biomass boiler

Table 5 shows the generic combination of measures used in cost-optimal calculations for the four Portuguese reference buildings.

Table 5. Combination of measures

Nº	**Combination of measures**
1	Base intervention[11] + [BITS 1 to 8]
2	Base intervention + [BITS 1, 2, 3, 5 and 6] + ST[12]
3	Base intervention + [BITS 1, 2, 3 and 8] + PV[13]
4	WD_PVC + [BITS 1 to 8]
5	FL_RW40mm + PVC_U2.4 + [BITS 1 to 8]
6	WL_EPS40mm + FL_RW 40mm + PVC_U2.4 + [BITS 1 to 8]
7	WL_EPS40mm + RF_RW100mm +FL_RW40mm +WD_PVC 2.4 + [BITS 1 to 8]
8	WL_EPS80mm + RF_RW140mm + FL_RW80mm + WD_PVC 2.4 + [BITS 1 to 8]
9	WL_EPS100mm + RF_RW140mm + FL RW80mm + WD_PVC 2.4 + [BITS 1 to 8]
10	WL_EPS100mm + RF_RW140mm + FL RW80mm + WD_PVC 2.1+ [BITS 1 to 8]

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[11] Base intervention refers to a building renovation scenario without measures to improve the energy performance of the building for the case of the existing buildings and for the case of new buildings refers to a building with the normative reference values for each building component.

[12] Solar Thermal panels

[13] Photovoltaic panels

Global costs have been calculated for each one of the packages of measures described in table 5 in a total of more than 80 combinations for each building (four buildings representing four construction periods) in each location (seven locations representing main climatic zones).

5 RESULTS

The next figures show the differences in the NPV of the analysed packages of measures. Each point shows the impact of changing an envelope measure or a system in each of the analysed buildings.

Figure 1 shows the general results for the envelope components of the analysed buildings in the seven locations. Each column represents one of the components (roof, walls, floor and windows).

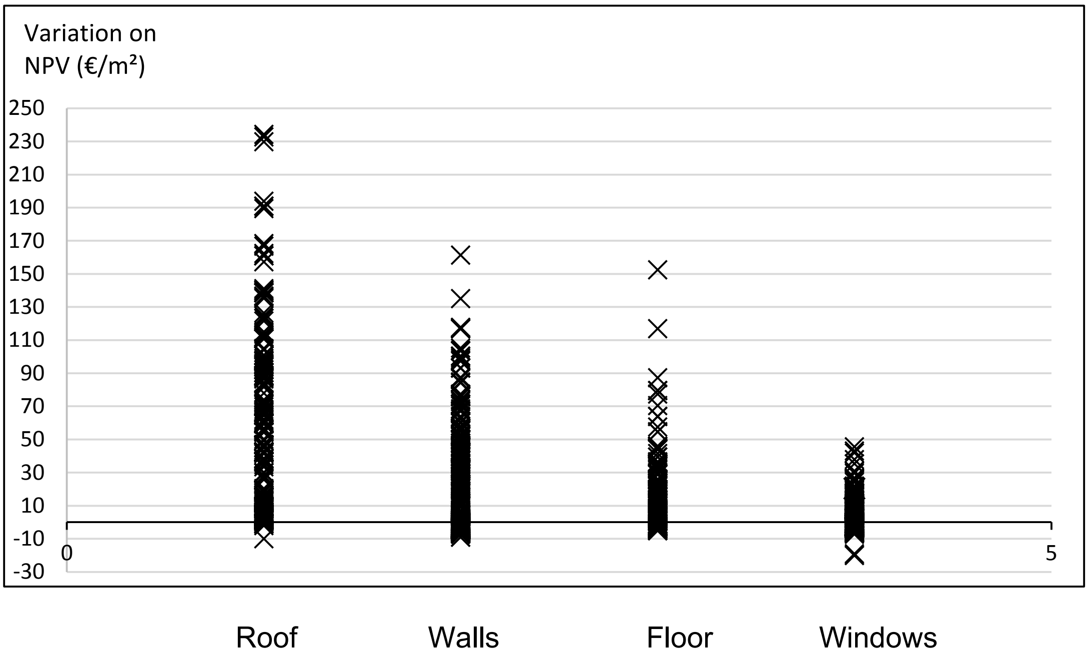

Figure 1. General results for NPV variations associated to the measures to improve the energy performance of each one of the components of the buildings envelope

From Figure 1 it is possible to see that the changes on the roof have the greatest impact, followed by the measures applied to the exterior walls. The improvements on the windows are the measures with less impact.

Figure 2 shows the results for the changes in the measures to improve the energy performance of the walls in the four reference buildings (each one from a different construction period) and for the seven locations (different climatic zones).

As expected, each one of the four buildings presents a higher payback on the measures in locations where the climate conditions are more extreme, such as Bragança and Armamar, which correspond to the 3rd and 7th positions in each group of seven columns. The energy performance of the original walls increases with the reduction of the age of the buildings resulting in a reduction of the NPV variations for the most recent buildings. In the new buildings the changes in the walls have the less impact and in most cases the increase of the insulation beyond the reference value does not compensate. The increase from ETICS with EPS with 8cm to EPS with 10cm has a negative NPV, so it is not a profitable measure, in every building for every location.

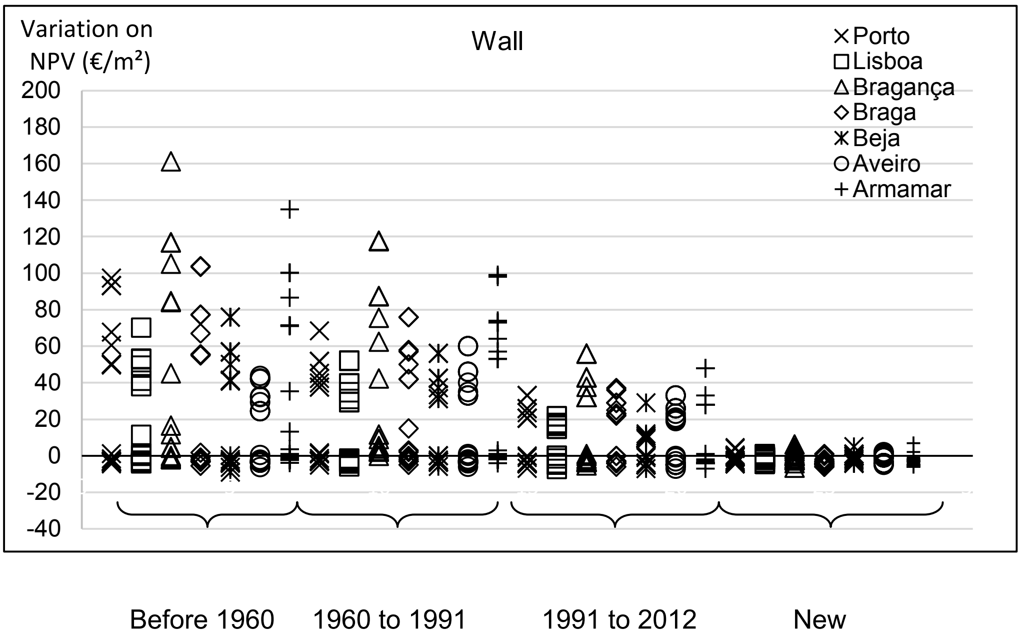

Figure 2. NPV variations resulting from measures to improve the energy performance of the walls, for the four construction periods and for the seven locations

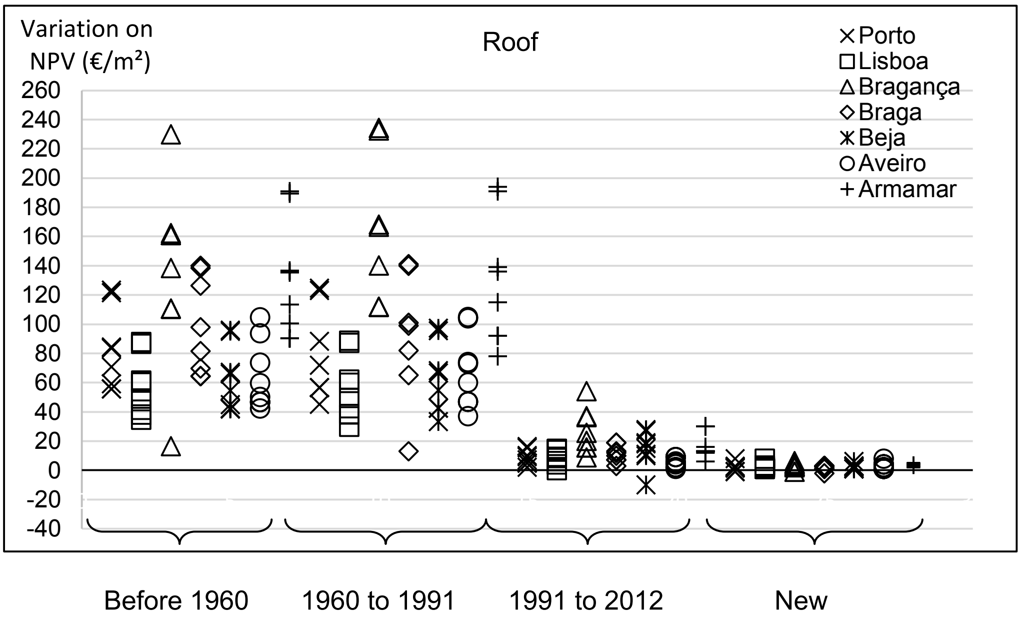

Figure 3. NPV variations resulting from measures to improve the energy performance of the roof, for the four construction periods and for the seven locations

In the roof (Figure 3), for the first two construction periods, the improvements in the roof insulation have higher NPV variations than in the buildings built after 1990. This is due to the fact that in 1991 it was the year of entrance into force of the first Portuguese thermal regulation, therefore these buildings already have insulation in the roof making the impact from the addition of more insulation on the energy needs less noticed. In what concerns the location, Bragança and Armamar are the ones with higher variations in the NPV in all the three existing buildings as a consequence of its more severe winter climate. For the case of new buildings, such variations are less noticeable, with small variations of NPV among measures and locations. The first two buildings do not present any measure leading to a negative variation of the NPV. For the buildings built after 1990, in most cases compensates to increase the insulation in the roof, especially in the most severe climates.

Figure 4 shows the results for the improvements of the energy performance of the floor. This component has a similar behaviour to the roof, but with smaller values for NPV variations, particularly in the relevant differences between the cost-effectiveness of these measures in the buildings built before and after 1990. In fact, in existing buildings after 1990, many of the tested improvements on the floors have negative variations of the NPV.

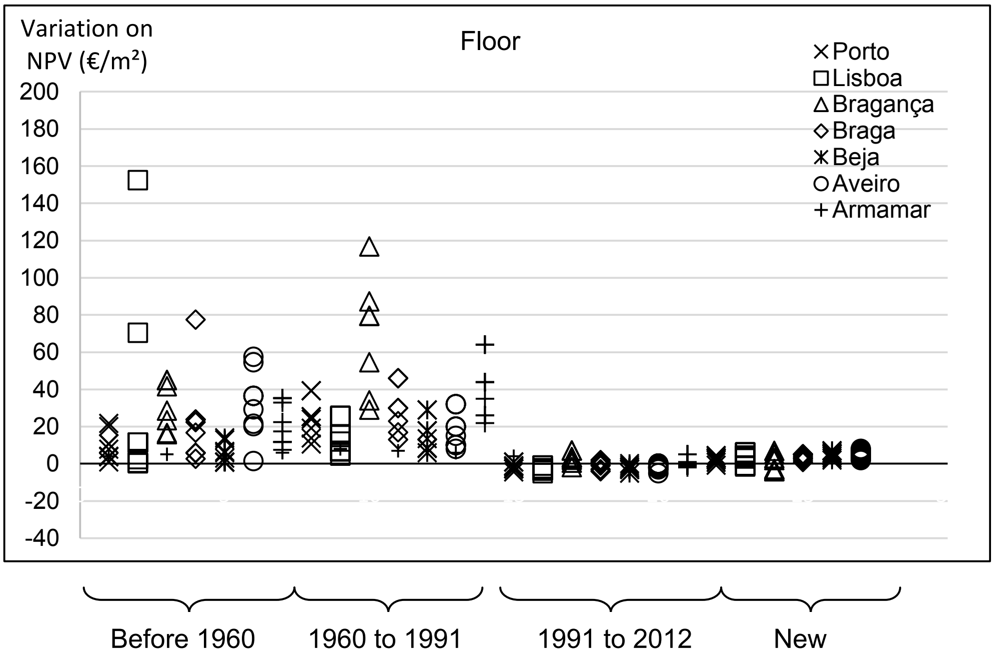

Figure 4. NPV variations resulting from measures to improve the energy performance of the floor, for the four construction periods and seven locations

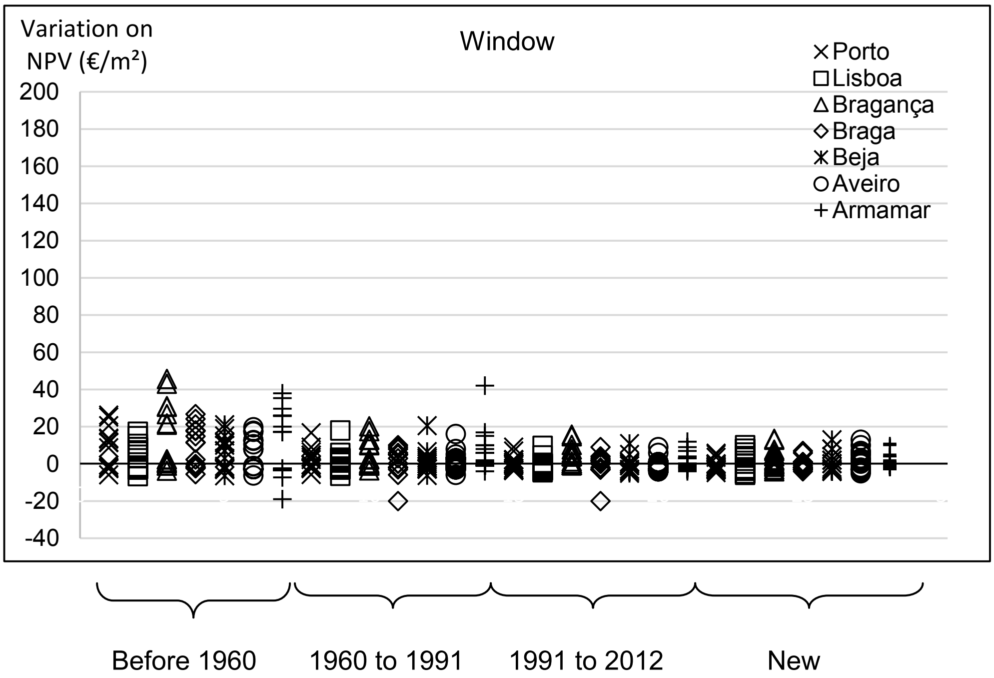

Figure 5. NPV variations resulting from the improvement of energy performance of the windows for the four construction periods and seven locations

Figure 5 represents the results for the windows for the four buildings in the seven analyzed locations. The changes in the windows are mainly the removal of the original ones and the introduction of new ones made of PVC with an

U-value of 2.4 W/m².ºC and then from this one to PVC with an U-value of 2.1 W/m².ºC. Generally the change from PVC 2.4 to 2.1 does not compensate and has a negative variation on NPV.

In general, among the analyzed measures on the envelope, the one which has greater cost-effectiveness is the application of insulation on the roof, followed by the improvement in the wall insulation. Even for new buildings, the improvements on the roof are measures which, in most cases, do not present negative NPV. So it compensates to invest in the improvement of the insulation of roofs in the majority of the buildings and locations. For buildings built after 1990, the impact is lower because the envelope conditions are already improved to fulfil the thermal regulation requirements, but for all the buildings that still do not have any insulation, most measures proved to be significantly cost-effective. The value of its cost-effectiveness depends also on the BITS used by the building for heating, cooling and DHW preparation, decreasing as the systems efficiency improves.

The measures less cost-effective are the ones related to the windows, where many measures present negative variation of the NPV.

In all of the four buildings from different periods, those exposed to more extreme climate conditions have higher NPV variations, meaning that it is worth investing a bit further on those buildings, especially in the existing ones located in Bragança and Armamar.

Figure 6 shows the impacts of the changes in the BITS of the buildings under analysis. Each group of seven columns represents one building in the seven locations. In every column, each point represents the change of the systems for heating, cooling and DHW preparation. In this case the comparison is always between the original BITS and possible new ones. The locations with higher NPV are Bragança and Armamar in each one of the four analyzed buildings. For the buildings built before 1991, the BITS with lowest NPV variation is the gas boiler for heating and DHW preparation, combined with HVAC for cooling and the one with highest NPV variation is the gas heater for DHW preparation combined with HVAC for heating and cooling. For the ones built after 1990, in most cases the BITS with the highest NPV variation is the biomass boiler for heating and DHW preparation, despising the cooling needs and the one with the lowest NPV variation is the biomass boiler combined with HVAC just for cooling. The results for the BITS which use the HVAC just to deal with the cooling needs prove that it is not cost-effective for the Portuguese reality to use a specific equipment to provide cooling, normally presenting the lowest variations in the NPV due to the investment and maintenance costs with an additional equipment.

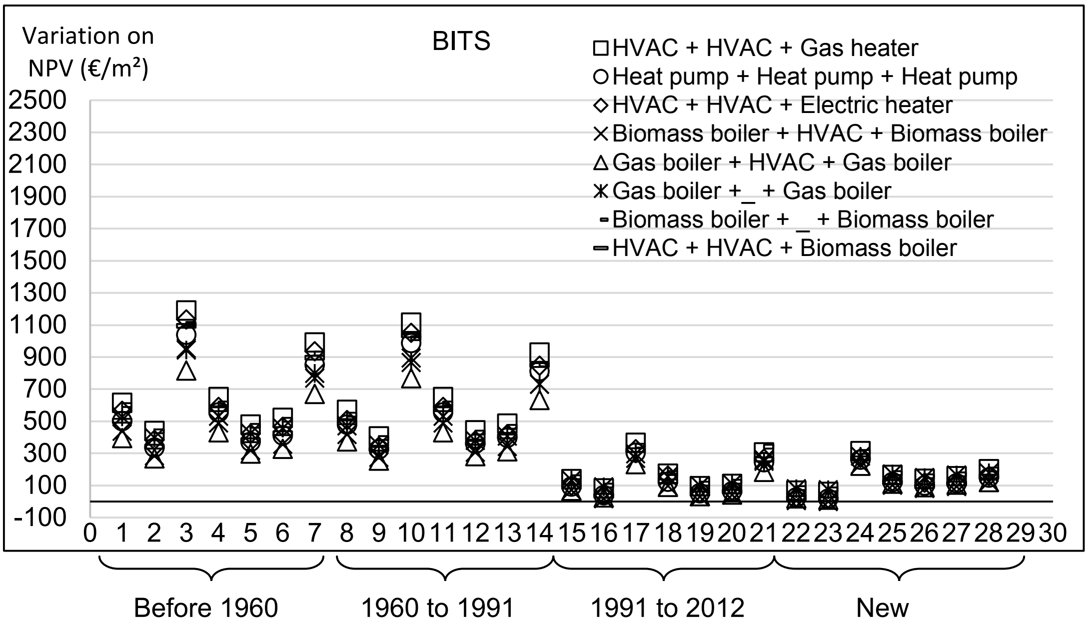

Figure 6. NPV variation resulting from the building integrated technical systems in four analyzed construction periods and seven locations

Generically, it is possible to conclude that the change of the building integrated technical systems (BITS) is a very cost-effective measure to improve the energy performance of buildings, particularly the older ones where the energy consumption is very high.

Complementary, it is also possible to notice that the range of values for the variations of the NPV is larger for the changes of the BITS than for the improvement of the envelope components. For the case of the buildings built before 1990, while the improvement of the building components only punctually makes the variations on the NPV goes over the 200€/m^2, with the change of the BITS on the same buildings, the variation of the NPV is always above 200€/m^2 and, for some cases, goes over 1000€/m^2.

All the presented values for the variations of the NPV should be considered as guidance for comparing the cost-effectiveness of different possible measures to improve the energy performance of the buildings. All the values derive from variations of the energy performance of a single element, which is not the usual real scenario. The composition of coherent packages of measures integrating several of these elements will reduce the cost-effectiveness of each component, so, the absolute values presented in Figures 1 to 6 should be considered only for comparison between measures and not as support for economic evaluation for the energy performance of buildings.

6 CONCLUSIONS

Cost optimal energy performance levels for building components and building integrated technical systems (BITS) have been explored for four virtual reference buildings representing typical single-family buildings from different periods characterizing the Portuguese building stock for this residential typology. Each building has been analysed in seven different climate locations, within the Portuguese territory, covering the main climatic zones.

The variations of the net present value of the global cost for a period of 30 years resulting from the application of singular measures to improve the energy performance of each building, allowed analysing and comparing the cost effectiveness of those measures.

From the measures to improve the energy performance of the building envelope, the higher variations in the net present value (NPV) were generically found for the insulation of the roof, followed by the insulation of the walls, the insulation of the floor and finally by the windows replacement, which, in many cases, presents a low or negative NPV variation. Regarding the age of the building, the measures applied to the buildings without any insulation in the envelope are naturally more cost-effective, but few differences were found between the two periods considered before insulation has become mandatory (1991, which is the year of entrance into force of the first Portuguese thermal regulation). In fact, results for buildings representing the period before 1960 and those representing the period between 1960 and 1991 are very similar for roof, walls, floor and windows. For buildings built after 1990, improvements on the envelope are less cost-effective because the initial conditions are already better. For buildings built in this period, the introduction of renovation measures to improve the building envelope should be carefully evaluated because from a purely financial perspective, the investments, especially on windows and floor, might not be cost-effective.

Regarding the climate conditions of the seven locations, it is possible to conclude that the winter conditions affect the results. Particularly in cities with more extreme winter climate conditions the variation of the NPV is significantly higher. It is therefore more cost-effective to invest on the improvement of the envelope in these locations and it is cost-effective to invest in higher levels of energy performance for the building components than in other locations. These differences between locations are also visible in the cost-effectiveness of the BITS, although, regarding its hierarchy, no significant difference is observed between locations.

For the BITS, some differences were found between the buildings with no insulation (buildings built before 1960 and built between 1960 and 1990) and the most recent ones. For the older buildings, the best results were found for the use of systems making a very efficient use of electricity such as HVAC with multi-split or heat pumps. For the most recent buildings, simpler systems, such as the gas boiler and the biomass boiler, both for heating and DHW preparation, have presented high variations in the NPV. From these results for the BITS it can be concluded that, while in the case of the older buildings, the high energy consumption increases the cost-effectiveness of very efficient systems to deal with heating, cooling and DHW preparation, in the case of more recent ones or new buildings, the better energy performance of the envelope makes economically justifiable to use simpler systems, cheaper to install and with lower maintenance costs, and not dealing with cooling needs.

This trade-off between the energy performances of the building envelope and the efficiency of the BITS can be explored in the renovation of existing buildings, particularly the older ones, in cases where the introduction of renovation measures on the envelope might be found difficult or expensive to fully implement due to technical or architectural constraints or even due to the annoyance caused to the occupants. It seems possible to compensate some of the measures to improve the energy performance of the envelope, particularly those with lower cost-effectiveness such as those on windows or on the floor, by the use of BITS with higher efficiency.

This work shows that the cost-effectiveness of the measures to improve the energy performance of buildings envelope depends on the buildings construction solutions and climate locations but a clear hierarchy between the envelope components is noticeable with the roof being the envelope component that is more cost-effective to improve, followed by the walls, the floor and finally the windows. The same happens with the building integrated technical systems, but in this case the construction solutions seams to play a more important role, due to the trade-offs between the energy needs derived from the building envelope and geometry and the efficiency of the BITS.

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