Energy Cost-Efficient Rehabilitation Measures for the Portuguese Residential Buildings Constructed in the 1960–1990 Period

A. Brandão de Vasconcelos, M. Duarte Pinheiro, A. Cabaço and A. Costa Manso

Abstract The Directive on the revised Energy Performance of Buildings (EPBD) 2010/31/EU required the Commission to establish, by means of a delegated act, a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements. This chapter aims to contribute to the phasing proposed in the Directive mentioned. The results obtained from the thermal rehabilitation of the building envelope of a Portuguese residential reference building constructed in the 1960–1990 period make it possible to identify the best cost-efficient thermal rehabilitation measures. Conclusions on cost-efficient thermal rehabilitation are as follows: (i) the thermal rehabilitation of the roof produces the greatest variation in the primary energy building consumption (and the floor measures the smallest), (ii) the combination of thermal envelope rehabilitation measures creates synergy effects that lead to better results than single measures (regarding global costs and primary energy consumption), and (iii) it is more advantageous to proceed with a thermal rehabilitation package of measures rather than doing nothing.

Keywords Energy performance · Energy efficient measures · Reference building · EPBD directive

A. Brandão de Vasconcelos (✉) · A. Cabaço · A. Costa Manso
Buildings Department, National Laboratory for Civil Engineering (LNEC), Lisbon, Portugal
e-mail: avasconcelos@lnec.pt

A. Cabaço
e-mail: acabaco@lnec.pt

A. Costa Manso
e-mail: armando.costa.manso@gmail.com

M. Duarte Pinheiro
Department of Civil Engineering, Architecture and Georesources, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal
e-mail: manuel.pinheiro@tecnico.ulisboa.pt

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1 Introduction

The building sector is responsible for about 40 % of Europe's total energy consumption and for one third of the global greenhouse gas (GHG) emissions (Directive 2010; Graham 2010). As urbanization is increasing in the world's most populous countries, building sustainability is seen as a key factor in achieving sustainable development. Therefore, a major effort is being done nowadays, all over the world, to find methods for optimising the energy performance of buildings.

Refurbishment, as part of the construction industry, has a strong global impact, not only from the viewpoint of economies but also from social and energy-efficiency perspectives. A thermal refurbishment process, in particular, relies on the making of numerous decisions and choices. Therefore, life-cycle perspectives are being increasingly considered in the decision-making process and involving participants with different interests (Hernandez and Kenny 2011; Sartori and Hestnes 2007).

At European level, as a result of these energy efficiency challenges, the European Energy Performance of Building Directive (EPBD) (Directive 2010) recast, which aims to ensure energy savings and CO_2 emission reduction, required the Member States to establish, by means of a delegated act, a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements. This Directive was further supplemented by the Commission's Delegated Regulation (EU) No. 244/2012, of 16 January 2012 (Regulation No. 244 2012), and by the guidelines accompanying this Regulation (Guidelines Regulation No. 2012), which are not legally binding.

Following these EU Directives' recommendations, the authors propose a criterion based on technical and economic points of view, with a view to identify the cost-optimal package of energy efficient solutions from among a set of possible refurbishment construction solutions (Brandão de Vasconcelos et al. 2014, 2015a, b, c), within the life cycle of buildings. By 'cost-optimal level' we mean the energy performance level which leads to the lowest cost during the estimated economic life-cycle.

In this chapter it is proposed the steps and objectives involved in the calculations of the cost-optimal levels referred to in the EPBD recast, within the Portuguese context. It is particularly focused on cost categories and cost calculations applicable to a Portuguese reference building, with a view to develop a national optimal methodology within the Portuguese market conditions. The results obtained for the Portuguese reference building make it possible to determine which thermal rehabilitation measures of a building envelope are the most cost-efficient.

In the introduction (Sect. 1), this paper sets out the main objectives of the research work. Section 2 proceeds with the definition of the steps that make up the cost-optimal methodology and it is then applied to a Portuguese residential building constructed in the 1960–1990 period. The results obtained are discussed in Sect. 3. Finally, in Sect. 4, the conclusions of all the research work are presented.

2 Cost-Optimal Methodology: Application to a Portuguese Reference Building

The cost-optimal methodology phasing proposed in this chapter is based on the requirements established by the Commission's Delegated Regulation (EU) No. 244/2012, of 16 January 2012 (Regulation No. 244 2012), and by the guidelines accompanying this Regulation (Guidelines Regulation No. 2012). Through the phasing proposed, it is possible to determine the energy performance of buildings and building components and its economic issues, in order to establish an optimal balance between the investments made and the energy savings achieved throughout the life cycle of the building. The five proposed phases are characterised in the following sections.

2.1 Phase 1: Definition of the Reference Building

The first phase of the cost-optimal methodology involves the definition of the reference buildings. This is an important step as these buildings must be as representative as possible, in order to determine, as well, a representative economic optimum point for each building or for a market segment.

In Portugal, the first earthquake-resistance code in the '60s [RSCCS (Decree-Law No. 41658 1958) and RSEP (Decree-Law No. 44041 1961)] as well as the first code on thermal behaviour characteristics of buildings in the '90s [RCCTE (Decree-Law No. 40/90 1990)] constituted historical boundaries in the evolution of the housing stock. From 1960 to 1990, 50 % of the total housing stock was built (INE [Statistics Portugal] 2012). More than 85 % of buildings constructed before 1990 are classified as a C or less energy label (ADENE 2011) and many of its constructive elements have reached today the end of their useful lifespan (Silva 2011). These aspects make buildings constructed between 1960 and 1990 representative of the Portuguese building stock, having rehabilitation needs and presenting a large potential for an energetic performance improvement (Brandão de Vasconcelos et al. 2012).

Therefore, the reference building selected takes into consideration the most representative characteristics and construction solutions of buildings completed over this period in Lisbon. The reference building consists of a 7-storey residential building with two dwellings per floor, each having a 78 m^2 net internal floor area. This reference building has been fully described in Brandão de Vasconcelos et al. (2015) and its main characteristics are presented in Table 1. The climatic conditions considered correspond to Lisbon's ones [source: LNEG (Aguiar 2005)].

For this reference building Fig. 1 depicts the common floor plan of the reference building and Fig. 2 its principal façade.

Table 1 Main characteristics of the reference building

Main characteristics		Unit	Reference building solution
Net internal floor area		m^2	78
Clear height		m	2.7
Type of structure		–	Reinforced concrete
Location		–	Latitude: 38.73°; Longitude: −9.15°; Elevation: 71 m
Orientation		–	North-South
Building configuration	Number of rooms	–	2
	Number of floors	–	7
	Number of floors of the dwelling	–	1
	Number of dwellings/floor	–	2
	Number of façades	–	2
Roof	Total gross area	m^2	215.3
Vertical envelope	Façade width	m	16.3
	Façade total area	m^2	684.6
	Area of the opaque external envelop	m^2	458.56
	Share of window area of total building envelope	%	15 %
External walls (Wall 00)	Construction solution	–	Single walls of hollow ceramic brick, with 30 × 20 × 22 mm and without thermal insulation, plastered and painted
Roof (Roof 00)	Construction solution	–	Sloped roof without thermal insulation with a horizontal solid reinforced concrete slab, 0.23 m thick, with ceramic roof tiles
Ground floor (Floor 00)	Construction solution	–	Ground floor without thermal insulation with a solid reinforced structure slab, 0.23 thick, and application of wooden blocks coating directly on the screed
External windows (Wind 00)	Construction solution	–	Aluminium window frames (no thermal break) with single clear glass, 6 mm thick.
Internal walls	Solar shading	–	Outdoor clear plastic blinds
	Internal walls for room separation	–	Single walls of hollow ceramic brick, with30 × 20 × 11 mm and without thermal insulation, plastered and painted
	Internal walls for dwelling separation	–	Single walls of hollow ceramic brick, with 30 × 20 × 15 mm and without thermal insulation, plastered and painted
	Internal walls for circulation area separation	–	Reinforced concrete wall, 0.30 thick

(continued)

Table 1 (continued)

Main characteristics		Unit	Reference building solution
Internal floors	Construction solution	–	Internal floor without thermal insulation with a solid reinforced structure slab, 0.23 m thick, and application of wooden blocks coating directly on the screed
Ventilation	Natural/mechanical	–	Natural
Solar thermal collectors		–	Not installed
Heating system			Split (COP: 3.4)
Cooling system			Split (EER: 3.0)
Heating energy source		–	Electricity
Cooling energy source		–	Electricity

Fig. 1 Reference building common floor plan

Fig. 2 Reference building principal façade

2.2 Phase 2: Identification of Energy Efficiency Rehabilitation Measures for the Reference Building

In accordance with Directive 2010/31/EU (2010) and the Regulation (EU) No. 244/2012 (2012), the Member States must define the energy efficiency measures to be applied to the established reference building. By energy efficiency measure we mean a change to a building leading to a reduction in the building's primary energy needs (Regulation No. 244 2012).

Several sources list a number of possible energy efficiency measures that can be considered as a starting point for defining packages of measures to be applied to the reference building. Annex III of Directive 2006/32/EC (2006) shows an indicative list of examples of eligible energy efficiency improvement measures in the residential sector, divided into 7 groups: (a) heating and cooling; (b) insulation and ventilation; (c) hot water; (d) lighting; (e) cooking and refrigeration; (f) other equipment and appliances; (g) domestic generation of renewable energy sources, whereby the amount of purchased energy is reduced.

Annex III of Commission Delegated Regulation (EU) No. 244/2012 (2012) presents an illustrative table containing a list of characteristics of the measures selected for the cost-optimal calculation. Examples of measures, such as roof insulation, wall insulation, windows, heating system, ventilation system, building-related measures, DHW, among others, are presented.

Paragraph 4.1 of the guidelines accompanying the Commission's Delegated Regulation (EU) No. 244/2012 (2012) lists both the possible energy efficiency measures and the renewable energy source-based measures, which can be taken into account as a starting point for establishing the measures for the calculation process. These can be applied both at building structure level (additional insulation system of existing walls, roofs and existing slabs, increased thermal inertia, better framing of doors, windows and sun shading, better air tightness, building orientation and solar exposure for new buildings, change of share transparent/opaque surfaces, etc.)

and at system level (installation or improvement of heating systems, hot water supply system or ventilation, insulation of pipes, etc.).

Several authors (IEA 2013; Sadineni et al. 2011) point out a number of other energy efficiency measures to be applied to buildings. However, building energy refurbishment requires a variety of solutions to work with different types of support. These solutions should be easy to implement and quick to carry out, hence avoiding the need for demolition, with satisfactory results, and should contribute to reduce energy consumption.

Thus, to improve the energy efficiency of an existing building, some of the following specific measures can be adopted (Paiva 2000; Paiva et al. 2006):

(a) Thermal rehabilitation of the building envelope—by reducing the building's energy consumption, through reinforcement of the protection of opaque elements (external walls, roofs and floors over unheated spaces) and windows and through the use of passive solar technologies;
(b) Use of active solar technologies—by implementing renewable energy, particularly solar thermal, for DHW production;
(c) Rehabilitation of energy systems and facilities—through the deployment of more efficient and less consumption equipment;
(d) Energy sources available—change in the energy source by diversification of sources and guidance to less polluting energy resources.

The building envelope has been reported by several authors (Florides et al. 2002; IEA 2013; Ramesh et al. 2010; Sadineni et al. 2011) as a key element in determining levels of comfort, natural lighting and ventilation, as well as in determining the amount of energy required for heating and cooling a building.

The building envelope, also known as the building shell, fabric or enclosure (IEA 2013), is the boundary between the conditioned interior of a building and the outdoors. The energy performance of building envelope components, including external walls, floors, roofs, ceilings, windows and doors, is critical in determining how much energy is required for heating and cooling. Energy loss through the building envelope is highly variable and depends on numerous factors, such as the building's age and type, the climate, the construction techniques, the orientation, the geographical location and the user's behaviour.

Results from several studies (Balaras et al. 2005; Lechtenböhmer and Schüring 2010; Petersdorff et al. 2006) indicate that major energy savings lie in improving the building envelope of the existing building stock. Other authors (Altan and Mohelnikova 2009) stress the importance of insulation of the building envelope, together with the application of new windows, to reduce total energy consumption. Morelli et al. (Morelli et al. 2012) shows in a study that the theoretical energy use can be reduced by 68 % as compared to the energy use prior to retrofitting by the installation of insulation, new windows and a ventilation system with heat recovery (Arumägi and Kalamees 2014).

The energy efficiency measures selected for the reference building are considered in the context of energy rehabilitation. These measures are applied to the building envelope, in line with the research studies mentioned.

Table 2 illustrates the energy efficiency rehabilitation measures selected for the reference building described in this chapter. For the determination of the cost-optimal level, these measures were combined with each other creating 35.000 combinations of packages of measures.

2.3 Phase 3: Calculation of the Primary Energy Demand Resulting from the Application of Measures to the Reference Building

The comparative methodology framework defined in Directive 2010/31/EU (2010) requires Member States to assess the final and primary energy needs of the reference building, both with and without the application of energy efficiency measures. In the present case study, these energy efficiency measures are the ones listed in Table 2.

According to Directive 2010/31/EU (2010) "the energy performance of a building shall be determined on the basis of the calculated or actual annual energy that is consumed in order to meet the different needs associated with its typical use and shall reflect the heating energy needs and cooling energy needs (energy needed to avoid overheating) to maintain the envisaged temperature conditions of the building, and domestic hot water needs".

The energy efficiency measures selected in Sect. 2.2 are included in a group of previously described solutions: "(a) Thermal rehabilitation of the building envelope". This group of measures affects directly the energy consumption for heating and cooling, without contributing to greater efficiency of the energy requirements for the preparation of hot water for domestic use. Since the measures for increasing efficiency in energy consumption for hot water preparation are within group "(b) Rehabilitation of energy systems and installations" (not addressed in this work), the energy needs for this type of consumption were not calculated.

Thus, this study refers only to the calculation of the energy performance of the energy needs for heating and cooling, with and without the application of the measures defined in Table 2. This calculation provides the energy needs for heating and cooling per net internal floor area of dwellings. The primary energy needs are calculated according to the conversion factors of primary energy established in the Portuguese Legislation (Decree order (extract) No. 1579).

The measures presented in Sect. 2.2 are grouped into a set of energy efficiency measures forming packages of measures. The latter are applied to the reference building and the energy needs for heating and cooling, associated to the 35.000 packages of measures, were calculated (Coelho et al. 2015), following the EPBD procedure and using the EnergyPlus software. The parameters considered in the calculation were based on the Portuguese EPBD thermal regulations for Residential Buildings—REH, 2013 (Decree-Law No. 118/2013 2013). The reference building primary energy demand was calculated for the climatic conditions of Lisbon, Portugal.

Table 2 Energy efficiency rehabilitation measures applied to the reference building envelope

Measure ID	Measure location	Solution
Existing solution		
Wind 00	Window	Aluminium window frames (no thermal break) with single clear glass, 6 mm thick
Roof 00	Roof	Sloped roof without thermal insulation, with a horizontal solid reinforced concrete slab, 0.23 m thick, with ceramic roof tiles
Floor 00	Ground floor	Ground floor without thermal insulation with a solid reinforced structure slab, 0.23 thick, and application wooden blocks coating directly applied on the screed
Wall 00	External wall	Single walls of hollow ceramic brick of 30 × 20 × 22 mm without thermal insulation, plastered and painted
Proposed solution		
Wind 01–Wind 03	Window	Replacement of the existing window by an aluminium window frame (no thermal break): with double clear glass (4 + 6 mm thick) and 6 mm air space (Wind 01), with double clear glass (4 + 6 mm thick) and 16 mm air space (Wind 02) and with double low emissivity clear glass (4 + 6 mm low-e thick) and 16 mm air space (Wind 03)
Wind 04–Wind 06	Window	Replacement of the existing window by a PVC window frame: with double clear glass (4 + 6 mm thick) and 6 mm air space (Wind 04), with double clear glass (4 + 6 mm thick) and 16 mm air space (Wind 05) and with double low emissivity clear glass (4 + 6 mm low-e thick) and 16 mm air space (Wind 06)
Wind 07–Wind 09	Window	Replacement of the existing window by an aluminium window frame (thermal break): with double clear glass (4 + 6 mm thick) and 6 mm air space (Wind 07), with double clear glass (4 + 6 mm thick) and 16 mm air space (Wind 08) and with double low emissivity clear glass (4 + 6 mm low-e thick) and 16 mm air space (Wind 09)
Roof 01–Roof 06	Roof	Application of EPS, with the thicknesses as follows: 20 mm (Roof 01), 30 mm (Roof 02), 40 mm (Roof 03), 60 mm (Roof 04), 80 mm (Roof 05), 100 mm (Roof 06), over the concrete slab
Floor 01–Floor 07	Ground floor	Application of vinyl floor coating without thermal insulation (Floor 01), over EPS with the thicknesses as follows: 20 mm (Floor 02), 30 mm (Floor 03), 40 mm (Floor 04), 60 mm (Floor 05), 80 mm (Floor 06), and 100 mm (Floor 07)
Floor 08–Floor 13	Ground floor	Application of marble natural stone over EPS with the thicknesses as follows: 20 mm (Floor 08), 30 mm (Floor 09), 40 mm (Floor 10), 60 mm (Floor 11), 80 mm (Floor 12), and 100 mm (Floor 13)
Floor 14–Floor 19	Ground floor	Application of pine wood parquet (on wooden intermediate support structure) over EPS with the thickness as follows: 20 mm (Floor 14), 30 mm (Floor 15), 40 mm (Floor 16), 60 mm (Floor 17), 80 mm (Floor 18), and 100 mm (Floor 19)
Wall 01–Wall 06	External wall	Application of ETICS with 20 mm of EPS (Wall 01), 30 mm of EPS (Wall 02), 40 mm of EPS (Wall 03), 60 mm of EPS

(continued)

Table 2 (continued)

Measure ID	Measure location	Solution
		(Wall 04), 80 mm of EPS (Wall 05), and with 100 mm of EPS (Wall 06), from the outside of the existing external wall
Wall 07–Wall 12	External wall	Ventilated façade of metal plates over EPS with the thicknesses as follows: 20 mm (Wall 07), 30 mm (Wall 08), 40 mm (Wall 09), 60 mm (Wall 10), 80 mm (Wall 11), and 100 mm (Wall 12)
Wall 13–Wall 18	External wall	Construction of a drywall (with metallic intermediate support structure) from the inside of the existing external wall over EPS with the thicknesses as follows: 20 mm (Wall 13), 30 mm (Wall 14), 40 mm (Wall 15), 60 mm (Wall 16), 80 mm (Wall 17), and 100 mm (Wall 18)
Wall 19–Wall 24	Exterior wall	Construction of a 7 cm brick wall from the inside of the existing external wall over EPS with the thicknesses as follows: 20 mm (Wall 19), 30 mm (Wall 20), 40 mm (Wall 21), 60 mm (Wall 22), 80 mm (Wall 23), and 100 mm (Wall 24)

2.4 Phase 4: Calculation of the Global Costs for the Reference Building

The definition of an economic calculation method is necessary for calculating the costs of the energy efficiency measures defined in Phase 2, during the expected economic life cycle applied to the reference building. This economic calculation method should take into account: the initial investment, the sum of the annual costs for every year and the final value, as well as the disposal costs.

In order to calculate the global cost of the energy efficiency measures it is also necessary to define the type of individual perspective and expectations as regards the investment to be made: the financial perspective or the macro economical one (Aggerholm et al. 2011; Guidelines Regulation No. 244 2012).

2.4.1 Financial Perspective

In the financial perspective, only the immediate costs and benefits from the investment decision are taken into account. Thus, the global cost of each package of solutions corresponds to the price paid by the end consumer, including taxes, such as VAT, and all applicable subsidies and incentives. The global cost for the financial perspective is (1):

$$C_g(\tau) = C_t + \Sigma[\Sigma(C_{m,i}(j) \times R_d(i) + C_{s,i}(j) \times R_d(i) + C_{e,i}(j) \times R_d(i) - V_{f,\tau}(j)] \quad (1)$$

where τ is the calculation period, $C_g(\tau)$ the global cost referring to the starting year (τ_0) over the calculation period, C_t the initial investment costs per measure or set of measures *j*, $C_{m,i}(j)$, $C_{s,i}(j)$ and $C_{e,i}(j)$ maintenance, replacement and energy costs, respectively, during year *i* per measure or set of measures *j*, $V_{f,\tau}(j)$ the residual value per measure or set of measures *j* at the end of the calculation period (discounting the starting year) and $R_d(i)$ the discount factor for year *i*. The discount factor is calculated using formula (2), where *p* means the number of years since the starting period and *r* means the real discount rate:

$$R_d(p) = (1/(1 + r/100))^p \tag{2}$$

The different types of costs considered (initial investment costs, maintenance costs, operational costs, energy costs, GHG emission costs, and disposal costs) (EN 15459 2007; Guidelines Regulation No. 244 2012) are calculated in reference to the starting year by applying the selected discount rate. The discount rate adopted in this perspective is 6 %. This value was established in accordance with the discount rates considered in the Portuguese energy private investment studies (Ferreira et al. 2014) and in other cost-optimal reports published by EU countries (Department for Communities and Local Government 2013; European Commission 2015).

2.4.2 Macroeconomic Perspective

The macroeconomic perspective is used when the justification for introducing energy performance regulations is to make organisations or individuals to take actions that do not reflect their own direct interests (and are therefore unattractive as investments) but that can prove to be beneficial to society as a whole (Aggerholm et al. 2011). This macro perspective includes benefits and costs of "externalities", such as damages from climate changes associated with carbon dioxide emissions. Thus, the global cost of each package of solutions corresponds to the price paid by the end consumer, excluding all applicable taxes, subsidies and incentives, and including the cost of GHG emissions—$C_{c,i}(j)$—, as indicated in formula (3):

$$C_g(\tau) = C_t + \sum\left[\sum(C_{m,i}(j) \times R_d(i) + C_{s,i}(j) \times R_d(i) + C_{e,i}(j) \times R_d(i) + C_{c,i}(j) \times R_d(i) - V_{f,\tau}(j)\right] \tag{3}$$

The discount rate adopted in the macroeconomic perspective should give emphasis to political priorities rather than to the financial context and to the mortgage credit conditions in the country. The value adopted is 3 % and corresponds to one of the two values (3 and 4 %) most cited in studies (Department for Communities and Local Government 2013; European Commission 2015; Ferreira et al. 2014; Regulation No. 244 2012).

2.4.3 Cost Calculation

For both perspectives, the investment costs, the maintenance costs and the replacement costs are obtained from the ProNIC (Protocol for Technical Information Standardization in Construction) database (Monteiro et al. 2014) and are complemented by prices taken from standard offers of construction companies and from LNEC's database on construction prices (Manso et al. 2004). The residual value of each measure is calculated on the basis of the remaining lifetime of the last replacement of the measure until the end of the calculation period, assuming a straight-line depreciation over its lifetime. For the macro perspective, the GHG emission costs are calculated according to the Portuguese information on GHG emission allowances (DGEG 2014).

The definition of the maintenance activities, periodicity and lifespan of each construction element and solutions, are obtained from the information included in preventive maintenance plans and scientific publications (Abate et al. 2009; Albano 2005; Housing Association Property Mutual—HAPM 2003; Institut de Tecnologia de la Construcció de Catalunya 1991; Silva 2011; Viegas 2006). The energy costs are directly calculated from the energy needs for heating and cooling the building (obtained in Phase 3), multiplied by the Portuguese annual energy costs (DGEG 2014), which are defined on the basis of EU's forecasts for energy cost trends (European Commission 2014). The different types of costs considered (initial investment costs, maintenance costs, operational costs, energy costs, greenhouse gas emission costs, and disposal costs) (EN 15459 2007; Guidelines Regulation No. 244 2012) are calculated in reference to the starting year by applying the selected discount rate. The calculation period adopted is 30 years, as proposed in the EPBD.

2.5 Phase 5—Determination of the Cost-Optimal Level of Energy Performance

The cost-optimal level is obtained after calculating the global cost (phase 4) of the packages of measures (defined in phase 2) applied to the reference building (characterised in phase 1) and by considering the reference building energy performance (phase 3).

Figure 3 shows the cost-optimal curve that is found when assessing all the combinations of measures of the reference building from a macroeconomic perspective. The primary energy consumption (x-axis) represents the total energy consumed by all the 14 dwellings belonging to the reference building and the global cost (y-axis) refers to each package of measures applied to the reference building. The lowest point of the curve (red point) corresponds to the package of measures with the lowest global cost. The cost-optimal level of minimum energy performance requirements is given by the x-axis position of the lowest cost. The cost-optimal level of packages with the same or similar costs corresponds to the one with the lower primary energy use (circle dots with different colors). The part of the curve to the right of the cost-optimal level represents solutions that underperform in both aspects (environmental and financial). The left part of the curve, starting at the cost-optimal level, represents the cost-optimal energy-performance levels for both low and nearly zero energy buildings (BPIE 2010).

The cost-optimal level package of reference building measures corresponds to Wind 01, Wall 24, Roof 04 and Floor 02. This package consists of the procedures as follows: replacement of the existing window by an aluminium window frame (no thermal break) with double clear glass (4 + 6 mm thick) and 6 mm air space, construction of a 7 cm brick wall from the inside of the existing external wall over a 100 mm thick EPS, application of a 60 mm thick EPS over the roof concrete slab and application of vinyl floor coating over a 20 mm thick EPS.

The shadowed zone illustrated in Fig. 3 includes the thermal refurbishment packages of solutions having less primary energy consumption and less global costs than the ones assigned to the reference building base package of solutions. Therefore, from the cost-optimal point of view, it is more advantageous to proceed with any thermal refurbishment package of measures located inside the shadowed zone rather than doing nothing on the reference building considered.

The cost-optimal package of solutions found in the financial perspective is exactly the same as the one obtained for the macro perspective. The graphics for both perspectives have the same shape, differing only as refers to the position of the dots cloud. The dots cloud, in the financial perspective, is located above (on y-axis)

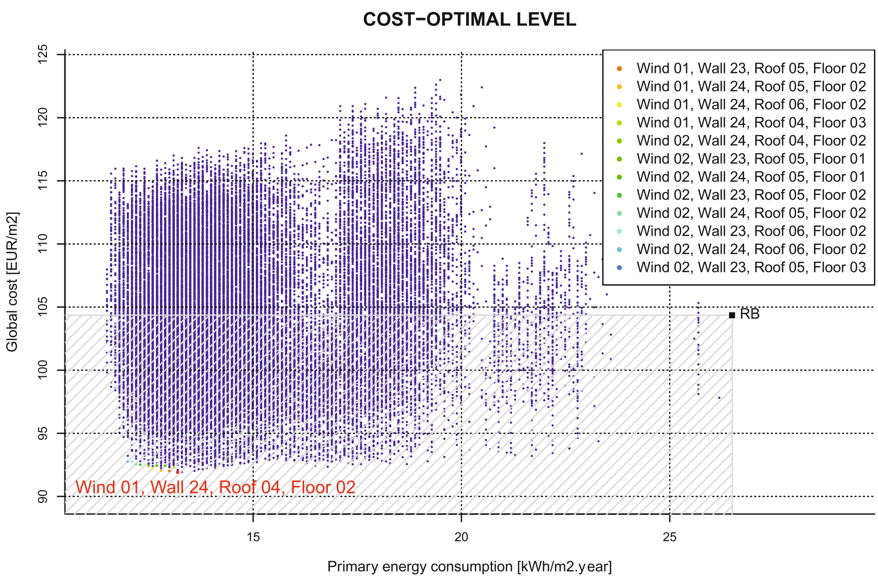

Fig. 3 Cost-optimal level from the macroeconomic perspective

the macroeconomical one, which means that the global costs assigned to the first are higher than the latter.

3 Discussion of Results

In Sect. 2 a phasing methodology to obtain the cost-optimal package of measures for residential buildings was proposed. Following that methodology, the approaches, tools and parameters chosen have led to the analysis of a particular Portuguese residential building case. Similar analyses can be also done for different residential buildings in other countries, by following the same described phasing methodology. Taking into consideration the results obtained in phase 5 for a Portuguese reference building, as refers to the application of the different thermal rehabilitation measures to the building envelope, some concluding remarks are presented.

Figure 4 illustrates the cost-efficiency of the different thermal rehabilitation packages of measures applied to the reference building envelope, in terms of primary energy consumption versus global cost. The sets of "W_", "F_", "R" and "WW_" lines summarise, respectively, the results obtained from the applications of the package of measures to the walls, floor, roof and windows. Each line specifically refers to a certain type of measure (e.g.: "Fv"—application of vinyl coating on the floor surface with different types of thermal insulation thickness), being drawn by points that represent, in the case of walls, floor and roof measures, the primary

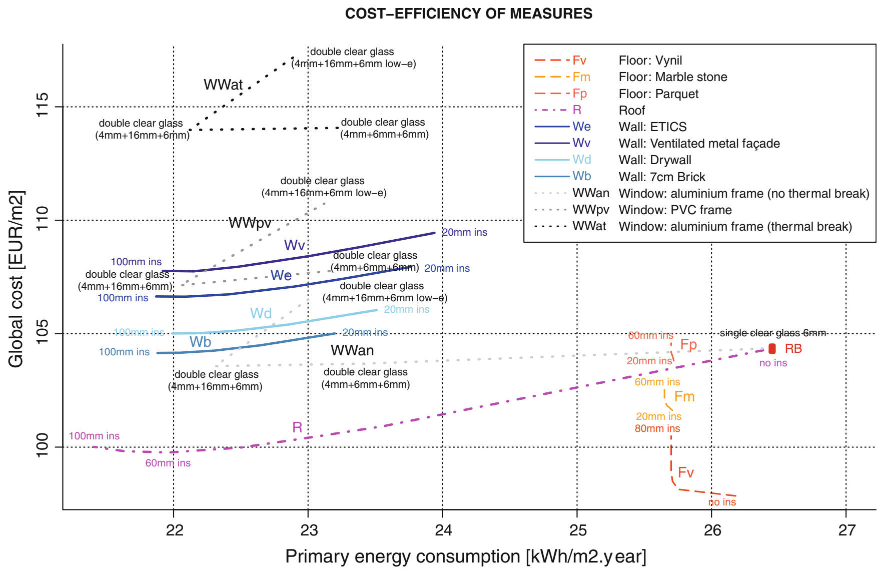

Fig. 4 Overview of the cost-efficiency of the thermal rehabilitation measures applied to the reference building envelope

energy consumption and the global cost resulting from each thermal insulation thickness, and, in the case of windows measures, the results from each type of glass considered.

The base solutions adopted correspond to the construction solutions that characterised the reference building (Floor 00, Roof 00, Wall 00 and Wind 00). For each set of lines ("W_", "F_", "R" and "WW_"), each specific rehabilitation type of measure is made to vary by keeping the other base solutions fixed. The "W_" set of lines (solid line ———) is drawn by taking into consideration a variation in the wall measures. The "F_" set of lines (longdash line - - - - - -) considers variations in the floor measures. The "R" line (dotdash line - · - · - · -) corresponds to variations in the roof thermal insulation. The "WW_" set of lines (dotted line ·········) considers variations in the type of window.

The imposition of the different measures to the reference building base solutions leads to the curves shown and allows identifying which are the best rehabilitation solutions from a cost-efficiency point of view. The influence of the efficiency of each thermal insulation thickness or of each type of glass is illustrated in Fig. 4, considering the eleven types of measures. If other than the reference building construction solutions were considered as the basis, the results and lines shown would not change significantly in the geometry and in the range of values of each line; and only the translational movements in x-axis and y-axis would occur.

Figure 4 also shows the reference building base solution with its associated cost-efficiency ("RB" dot). As expected, when compared with the reference building solution, all the rehabilitation measures considered have led to lower primary energy consumption, but not all of them have led to a lower global cost.

The results obtained for the wall set of lines ("W_") show that, considering the wall type rehabilitation measures, the construction of a 7 cm brick wall from the inside of the existing external wall (22 cm brick wall) of the reference building is the best cost-efficient type of wall solution. This solution achieved better results than the application of drywall from the inside or the application of ETICS and ventilated façade of metal plates from the outside. For the reference building considered, interior solutions achieved better results than solutions from the outside of the external wall as these have shown to lead to lower global costs.

As for the floor set of lines ("F_"), referring to floor type rehabilitation measures, the results obtained have shown that the application of vinyl floor coating is the best cost-efficient floor solution from among the solutions studied. As floor rehabilitation measures do not significantly influence the energy consumption of the reference building, the best cost-efficient solutions correspond to the ones having the lower global cost. Although vinyl coatings are not commonly adopted as floor solutions in Portuguese residential buildings, their study aimed to assess how a low investment and maintenance cost floor solution can be included in a cost-optimal package of measures.

The roof line ("R") indicates that the thermal insulation measures on the roof have the biggest range of the total energy consumption on the reference building, much depending on the thickness of the thermal insulation. The cost-effectiveness of these insulation measures is also highly dependent on the thermal insulation thickness, with good or poor performances just within a small interval variation in that thickness.

Finally, the types of window frames ("WW_"), indicate that aluminium window frame (no thermal break) is the best cost-efficient window frame solution, when compared to PVC and aluminium (thermal break) window frames. The type of glass strongly influences the energy consumption of the building, whereas the double clear glass (4 + 6 mm thick) and 16 mm air space has proven to be the best cost-efficient type of glass solution. However, the low emissivity glass solution does not seem to be the most adequate for a North-South reference building orientation under Lisbon's climate.

By comparing the results shown in Figs. 3 and 4, it can be noticed that the cost-optimal package solution (Wind 01, Wall 24, Roof 04, Floor 02—red dot in Fig. 3) does not correspond to all the best cost-efficient solutions identified in Fig. 4. The wall (construction of a 7 cm brick wall from the inside of the existing external wall over EPS, 100 mm thick) and roof (application of EPS 60 mm thick over the concrete slab) measures correspond to the cost-optimal package solution. Nonetheless, the floor (application of vinyl floor without thermal insulation) and window (aluminium window frame—no thermal break, with double clear glass and 16 mm air space) measures do not correspond to the cost-optimal package solution as they consider a 20 mm thermal insulation thickness for the floor and a 6 mm air space for windows. This means that the energy performance of one solution affects the energy performance of the other solution and that the combinations of measures create synergy effects that lead to better results (regarding global costs and primary energy consumption) than single measures (as can be seen by the primary energy consumption of each measure in Fig. 4, when compared to the primary energy consumption of the package of measures in Fig. 3). For instance, the cost-optimal package solution includes a floor measure (20 mm of thermal insulation) that is not cost-effective (as shown in Fig. 4); however, its results, in terms of primary energy consumption and CO_2 savings associated to the building unit, reveal that the overall package provides more benefits than costs over the lifetime of the building.

Combining these results with those obtained from phases 3 and 4, we can point out the existence of some packages of measures with lower life cycle costs, comparatively with other packages with lower investment costs (e.g.: marble natural stone floor vs. pine wood parquet floor).

Globally, and for the reference building characterised in this chapter, measures applied to the roof are the best cost-efficient ones and lead to the lowest energy consumption. This is due to the fact that the energy consumption of the last floor (7th floor of the reference building) has a strong impact on the overall energy consumption of the building; so, from a global energy building perspective, acting on the thermal insulation of the roof is more effective than insulating the external walls and replacing all the windows in all the floors. Together with the best global building energy performance, the roof thermal insulation also leads to the best cost-efficient solution. This is due to the low investment costs associated with the easy application of a thermal insulation on a horizontal solid reinforced concrete roof slab, which requires no extra mechanical protective layer (contrary to external walls and floors).

Similarly but conversely, the construction solution that leads to the smallest variation in the total energy building consumption corresponds to the measures applied to the floor.

4 Conclusions

This chapter clarifies the phasing methodology referred to in the EPBD Directive for determining the cost-optimal packages of measures. The analysis done for a Portuguese residential reference building can be similarly done for other countries' residential buildings under similar conditions.

The methodology phasing proposed in this chapter works as a decision model tool that is helpful to assist construction stakeholders (private or public decision makers) in deciding on which building components should they focus and where, so as to establish an optimal balance between the investments made and the savings in energy costs attained throughout the life cycle of the building. Ultimately, the main goal to pursue is to achieve more sustainable buildings, as a whole, from the energy efficiency viewpoint.

Results obtained from the application of the methodology to a thermal rehabilitation of the building envelope of a Portuguese residential reference building constructed in the 1960–1990 period are limited to the reference building characteristics and to Lisbon's climatic conditions. However, these results have led to the following main conclusions:

- the thermal rehabilitation measures with the best cost-efficient results correspond to measures applied to the roof, from a total energy building consumption perspective. The variation in the thermal insulation thickness implies a great variation in the total primary energy building consumption (even in a 7-storey building);
- the thermal rehabilitation measures that lead to the smallest variation in the primary energy building consumption correspond to measures applied to the floor;
- internal wall thermal rehabilitation measures achieved better results than measures from the outside of the external wall, as they have shown to have lower global costs;
- combinations of thermal envelope rehabilitation measures create synergy effects that lead to better results than single measures (regarding global costs and primary energy consumption).

Following these findings, the private and public decision makers in Portugal are encouraged to strongly focus their thermal rehabilitation investments on measures applied to roofs of residential buildings. This study has also demonstrated that it is more advantageous, from the cost-optimal point of view, to proceed with any thermal rehabilitation package of measures located inside the shadowed zone illustrated in Fig. 3 rather than doing nothing on the reference building considered (representative of the Portuguese residential buildings).

The work presented has been developed as part of a LNEC/IST PhD thesis, of which the main purpose is to define a cost-optimal comparative methodology for the energy performance of buildings. In this work, sensitive analyses of the results achieved in this research are also performed, such as the assessment of variations in the building orientation, in climatic conditions, in discount rates, in energy costs evolution, among others.

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