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Towards a feasible strategy in Mediterranean building renovation through a multidisciplinary approach

Antonio Serrano-Jimenez[a, *], Angela Barrios-Padura[a], Marta Molina-Huelva[b]

[a] Department of Building Construction I, University of Seville, Seville, Spain
[b] IUACC—Institute of Architecture and Building Science, University of Seville, Seville, Spain

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ABSTRACT

The energy-efficient retrofitting process of residential neighbourhoods in southern Europe has certain socio-economic and climatic uniqueness which are not included in the European guidelines, thereby rendering the corresponding action programs unviable. This research considers that an appropriate management of the energy retrofitting of buildings should not involve expensive and complex processes that are unaffordable to most residents.

The study is performed in a neighbourhood of Seville (Spain), which belongs to the Mediterranean climate, in multi-family housing, built in 1961, that presents an obsolete state of conservation and a low energy performance.

The methodology, through an energy assessment survey for residents, tries to adjust to each socio-economic situation by defining 3 levels of intervention: mild, moderate and intense; and evaluating 12 action packages from the disciplines of energy, sociology and economy.

The results show that the moderate level is the optimal level for the residents, resulting between 20 and 50% energy reduction and contributing a high socioeconomic benefit, assuming an initial cost 50% lower than other intense measures. In addition, results also make it possible to ascertain which packages are optimal for each level of intervention, thereby ensuring the success of the process.

1. Introduction

Tackling the climate change is a global challenge that can only be addressed effectively through a comprehensive strategy. According to the International Energy Agency (IEA), buildings in the European Union are responsible for up to 40% of total energy consumption and 36% of CO_2 emissions: a high enough proportion to justify the investment in research and development on energy renovation and its corresponding economic management (IEA, 2013b). The European Union aims to reduce emissions of greenhouse gases by up to 90% between 2020 and 2050, including the use of renewable energy and the introduction of measures for greater energy efficiency in the residential sector in 50% of all cases for 2050 (2012/27/EU, 2012; MF GE, 2014). Through the "European Directive on the energy performance in buildings (EPBD)" (2010/31/EU, 2010), the European Commission define the 'Cost-Optimal' methodology as a reference at European level in the energy retrofitting process of residential buildings.

However, the current economic situation, with its deep financial crisis and increasingly ageing population, demands new models of feasible interventions that promote an efficient regeneration of residential building stock in European cities, by considering minimum comfort conditions established in European policies and by satisfying the demands of citizens (IEA, 2013a; Sovacool et al., 2015). In this sense, certain studies consider the important role of countries and regions to carry out successful refurbishment processes in the building stock, as those that developed Caputo and Pasetti (2015), suggesting how to overcome local restrictions in small and medium Italian municipalities, Roders and Straub (2015), proposing specific implementation strategies in social housing from Netherlands, or Aste, Caputo, Buzzetti, and Fattore (2016), studying the investments process of the energy-efficient retrofitting in buildings from Lombardy region.

Abbreviations: Ach/h, air changes per hour; AP, action package; B4, specific climatic zone in Spain; COP, coefficient of performance; CTE, Spanish technical building code; DHW, domestic hot water; DOE, Department of Environment; EEM, energy-efficient measure; EER, energy efficiency ratio; EIFS, exterior insulation and finishing system; EPBD, energy performance of building directive; EPS, expanded polystyrene insulation; EU, European Union; G1, group 1 of individual EEM – specific passive measures; G2, group 2 of individual EEM – global passive measures; G3, group 3 of individual EEM – active measures; HP, heat pump; HVAC, heating, ventilation and air conditioning; IC, initial cost of each EEM (€/dwelling); IEA, International Energy Agency; LCC, life-cycle cost (€); LI, level of intervention; LI-1, level of intervention 1 – mild; LI-2, level of intervention 2 – moderate; LI-3, level of intervention 3 – intense; LPG, liquefied petroleum gas: butane/propane in cylinder; MC, maintenance cost (€/dwelling year); MW, mineral wool; N0, initial energy state of reference building; OECD, organisation for economic co-operation and development; SHGC, seasonal solar heat gain coefficient of shading devices; TB, thermal-break; U, thermal transmittance (W/m^2 K); UC, unit cost of each EEM; α, solar absorptivity.

* Corresponding author at: University of Seville, Department of Building Construction I, Reina Mercedes Avenue, nº2, 41002 Seville, Spain.
Email addresses: aserrano5@us.es (A. Serrano-Jimenez); abarrios@us.es (A. Barrios-Padura); martamolina@us.es (M. Molina-Huelva)

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According to the European Commission (2010/31/EU, 2010), the "Cost-Optimal" methodology of the European Union is defined as "the energy performance level which leads to the lowest cost during the estimated economic lifecycle, produced in a medium or long term" (15–30 years). In this way, by relating overall cost (€/m^2) and energy consumption (kWh/m^2), the best "Cost-Optimal" measures will be those with the highest levels of economic recovery and energy savings. However, EU Directive (2012/27 EU) specifies that each country and region must adjust and expand this methodology for each specific situation, by considering the most relevant climatic, social and economic factors in a successful way.

Current European research strive to generate ideas and to innovate in the energy retrofitting process by considering socioeconomic conditions of their inhabitants and the state of conservation of existing buildings. In this sense, Ascione, Bianco, De Stasio, Mauro, and Vanoli (2015) introduce a "multi-objective" methodology that compares, through an energy and economic analysis, the performance of some energy-efficient measures in different case studies. Araújo, Almeida, Bragança, and Barbosa (2016) propose a "cost-benefit" method in a case study from Portugal which includes the user's willingness, assessing the feasibility and social preferences in the energy renovation process. Kuusk and Kalamees (2015) define a "cost-effectiveness" methodology for a case study in Estonia, defining previously the energy-efficient levels to be achieved, grouping measures into packages which reach "Cost-Optimal" saving levels, and incorporating external funds to assume the investment. Ashrafian, Yilmaz, Corgnati, and Moazzen (2016) present a new method for the assessment of individual energy-efficient measures by pre-establishing three different budgets in three buildings in Turkey, and then they value each measure depending on the climatic conditions, the economic restrictions and taking into account the percentage of reduction of energy consumption. Lastly in this review, Park, Lee, Kim, Kwon, and Jeong (2016) pretend to advance in the "Cost-Optimal" methodology by highlighting the importance of using electricity bills to evaluate real consumption and to choose energy-efficient measures that guarantee success based on real economic and energy results.

However, despite having a large reduction in energy consumption and addressing issues beyond those established by the "Cost-Optimal" methodology, the advances offered in all these studies generally conclude with high investment results, and therefore these results would have no real application in Spain, and specifically in the region of Andalusia, without external assistance or public funding (Jones, Lannon, & Patterson, 2013; Vilches, Barrios Padura, & Molina Huelva, 2017).

In Spain, current legislation encourages the energy-efficient retrofitting of buildings in various laws and official regulations, but a greater coordination between administration and legal context is necessary, as proposed by Cuchí and Sweatman (2014), with which the state of buildings could be evaluated with greater accuracy. In this way, Spanish law 8/2013 on "Rehabilitation, regeneration and urban renovation in Spain" (L. 8/2013, 2013) seeks to promote the retrofitting process by eliminating some existing difficulties in current legislation and requirements, creating specific mechanisms and considering economic and sustainable aspects. In addition, to support this law, in 2014 the Spanish government introduced the "Long-term strategy for energy retrofitting in the Spanish building sector, in implementation of article 4 of Directive 2012/27/EU" (MF GE, 2014), which introduced guidelines to achieve European targets in energy retrofitting in the building sector and generated benefits for people involved in urban renovation processes. In Andalusia, the "Andalusian Energy Strategy 2014–2020" (CEEC JA, 2014) has been published, which follows the roadmap of European politics, but this has failed to have sufficiently considered the existing socio-economic situation in the region and the climatic particularities of the zone.

This European, National, and Regional regulatory framework, together with the obsolescence of the building stock in European countries, considering that over 50% of the Andalusian buildings were built before 1980 (INE, 2016), underline the need to implement protocols for a comprehensive evaluation in building renovation, to ensure viable and efficient operations, and to improve the quality of life of citizens while achieving environmental objectives.

In fact, different studies demonstrate the serious needs to renovate existing buildings in different European cities (Singh, Mahapatra, & Teller, 2013; Waddicor et al., 2016). In this sense, it is an important contribution the work developed by Singh, Attia, Mahapatra, and Teller (2016), demanding new methodologies for existing buildings prior to 1945 in Belgium, using real monitoring during some months and supplementing it with occupant surveys to demonstrate that modern comfort standards are not adapted to these old residential buildings. In fact, these authors also developed a related research based on a real monitoring in 20 buildings in Liege, Belgium, along with a questionnaire in 85 houses in order to stand out the importance to consider the occupant's preferences and expectations to improve the energy efficiency in their existing buildings (Singh, Mahapatra, & Teller, 2014).

Therefore, the present article considers that, in order to find optimized and efficient solutions in the residential energy retrofitting of buildings, is necessary to include technical, social and economic objectives in the urban renovation process so that a comprehensive viability can be guaranteed (De-Luxán, Gómez, & Román, 2015; Jensen & Maslesa, 2015)

This research, which is developed under the "(Re)Programa" research project (Barrios, González, Mariñas, & Molina, 2015), aims to focus on the design of a multidisciplinary evaluation methodology that progresses beyond the European "Cost-optimal" and considers the socio-economic and urban context of each case study, in southern Spain region, as a representative sample of the Mediterranean climate. This paper, which is applied in a residential neighbourhood of Andalusia, in Spain, considers real possibilities of intervention after a comprehensive analysis, considering the results of technical inspections, energy simulations and occupant surveys, by selecting and grouping those optimum actions in different levels of intervention, in terms of energy, social and economic parameters.

2. Energy retrofitting in the Mediterranean climate

It is necessary to point out the high potential for energy savings in the Mediterranean area, where, in spite of having mild temperatures, there is high energy consumption in winter due to the low energy performance in the residential building stock. However, current research on energy efficiency promoted in Europe generally focuses on much colder climates, where new innovative systems are successfully applied (Paiho, Pinto Seppä, & Jimenez, 2015; Tuominen, Klobut, Tolman, Adjei, & De Best-Waldhober, 2012), instead of considering the specific situation of southern European areas, with an important demand for cooling and an increased demand for heating.

In this sense, certain studies consider in their methodologies the specific situation in the Mediterranean climate. Baglivo, Congedo, D'Agostino, and Zacà (2015) show comparisons with other climatic zones and other building typologies with the same energy-efficient measures to demonstrate their energy performance variations, Domínguez, Sendra, León, and Esquivias (2012) seek to optimize the building envelope for the Mediterranean climate, ensuring from 20% to 25% of the energy reduction by acting specifically on windows, or Lizana, Barrios-Padura, Molina-Huelva, and Chacartegui (2016) who introduce a new "Multi-criteria" methodology which allows greater effectiveness in energy-efficient retrofitting measures applied to the Mediterranean residential sector.

It is also important the work developed by Ferrari and Zanotto (2016), who analysed the main affective issues related to the energy balance of representative buildings in Southern Europe, within the chapter "Energy performance analysis for typical buildings", simulating and evaluating the effectiveness of some action strategies in five different Mediterranean case studies.

In addition, regarding the application of the "Cost-Optimal" methodology in the Mediterranean countries, Zacà, D'Agostino, Congedo, and Baglivo (2015) adjust and assess the "Cost-Optimal" configuration through an advanced methodology that achieves between 56% and 90% of energy reduction in buildings located in the Mediterranean area. Tadeu et al. (2016) develop a comparison between cost-optimal solutions and the return of investment, using a multi-objective vestments. Finally, Desogus, Di Pilla, Mura, Pisano, and Ricciu (2013) demonstrate that cost-optimal performances are not completely cost-effective in a mild Mediterranean climate considering payback periods according to each case study analysed.

Therefore, the energy demand and consumption in the residential building stock are directly dependent on two fundamental factors:

- Building type: Energy performance is directly affected by the age of the building and the construction quality of its envelope.
- The climate zone in which it is located.

Regarding the first factor, in Spain and especially in Andalusia, high temperatures highly affect to the interior conditions because of the poor quality of the envelopes of the existing residential buildings, built between 1940 and 1980 with low-quality materials and traditional techniques.

Regarding the second factor, although Spain possesses Atlantic, Continental, and Mediterranean climate zones, southern Spain is almost entirely Mediterranean. The adjustment to this climatic situation and its particularities constitute enough reasons for the adaptation to the European methodology.

Hence, Mediterranean buildings in Spain present high levels of energy consumption and it is necessary to research new methods to perform the energy renovation of the existing building stock considering its particularities. In fact, if total annual values of heating energy consumed in terms of building type and climatic zones are compared, it can be observed that, in the Mediterranean climate, consumption exceeds that in a much colder climate, such as the Atlantic climate, and is close to or exceeds that in the continental climate, depending on the building type (MF GE, 2016).

3. Methodology

This research presents an open and flexible methodology, so the advances and the optimized solutions could be replicated in other existing urban environments. 11 case studies in southern Spain were selected within the framework of the research project "(Re)programa" (Barrios, González, Mariñas, & Molina, 2015), with the following criteria:

- Type of buildings: Residential buildings, built between the years 1940 and 1980, with an inadequate housing configuration for current social needs, with 2 or 3 small rooms, and not suitable accessibility and habitability conditions (Sabater & Maldonado, 2014).
- State of conservation: Buildings with a slightly deteriorated state of conservation but non-compliance with thermal conditions, as they were constructed before the "NBE-CT-79 on Thermal Conditions in Buildings", the first national legislation which officially included minimum thermal requirements in the design of residential building envelopes (INE, 2016; D.L., 1979).
- Kind of population: A predominantly elderly population, considering neighbourhoods with more than 30% of people over 65 years old. In addition, specific criteria of socioeconomic conditions were taken into account, selecting a medium socioeconomic level, which exceeds the requirements to benefit from a public subsidy. The reference parameter used was the Spanish IPREM public income index (D.L., 2008), which implies a limitation of the economic resources of the residents to carry out an energy retrofitting in their buildings.
- Climate zone: Mediterranean, typical of Southern-European countries. Reaching annual demand values for winter conditions (heating) from 30 to 100 kWh/m^2, and for summer conditions (cooling) from 10 to 60 kWh/m^2, in representative multi-family buildings (Ortiz, Salom, & Cubí, 2012).

This paper presents one case study selected from the 11 mentioned before, showing the methodology of the research through the consideration of its architectural, energy, economic, and social aspects (Ballarini, Corgnati, & Corrado, 2014).

This case study involves an urban settlement that was built between 1957 and 1961, located in Seville (Spain), and consists of 600 dwellings distributed across 10 identical multi-family buildings (Fig. 1). This building typology is free-standing, open, of 5 storeys, and with no lift. Each dwelling has three bedrooms, a bathroom, living room, kitchen, and a laundry area. This settlement was built using residential patterns from the expansion period of cities: high-density buildings, shoestring budgets, minimal spaces, and fast execution time.

The settlement is located in a consolidated district of the city, with a high-medium socioeconomic level, referring to the population income levels, 17% higher than the 25,709€ which mark the annual average of income per dwelling in the city (INE, 2016), however, the socioeconomic level of residents from this settlement has an opposite tendency, with a lower socioeconomic status according to the economic data collected in surveys. For this reason, it runs the risk of being subject to speculation and gentrification, in an area where the built price reached 2081€/m^2 in 2016, much higher than the 1455€/m^2, as an average in the city (IECA, 2016).

Once the case study and the sample patterns are defined, Fig. 2 shows the different stages in which the methodology is followed. This schematic process is composed of a previous stage 0, for detecting barriers, the stage 1–4 as the energy, social and economic work packages, and a final stage 5 which includes the action protocol.

Following Fig. 2, and considering the stage 0 as a previous phase where the initial barriers are defined, the next stages are explained below:

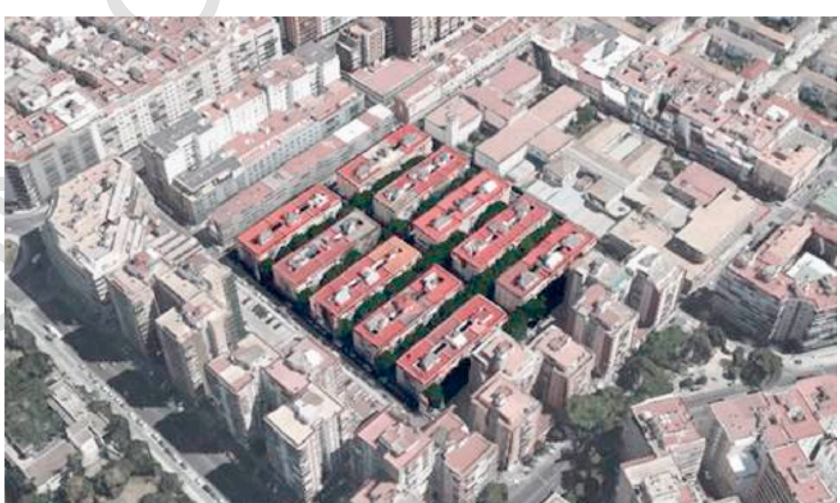

Fig. 1. Aerial image of the case study.

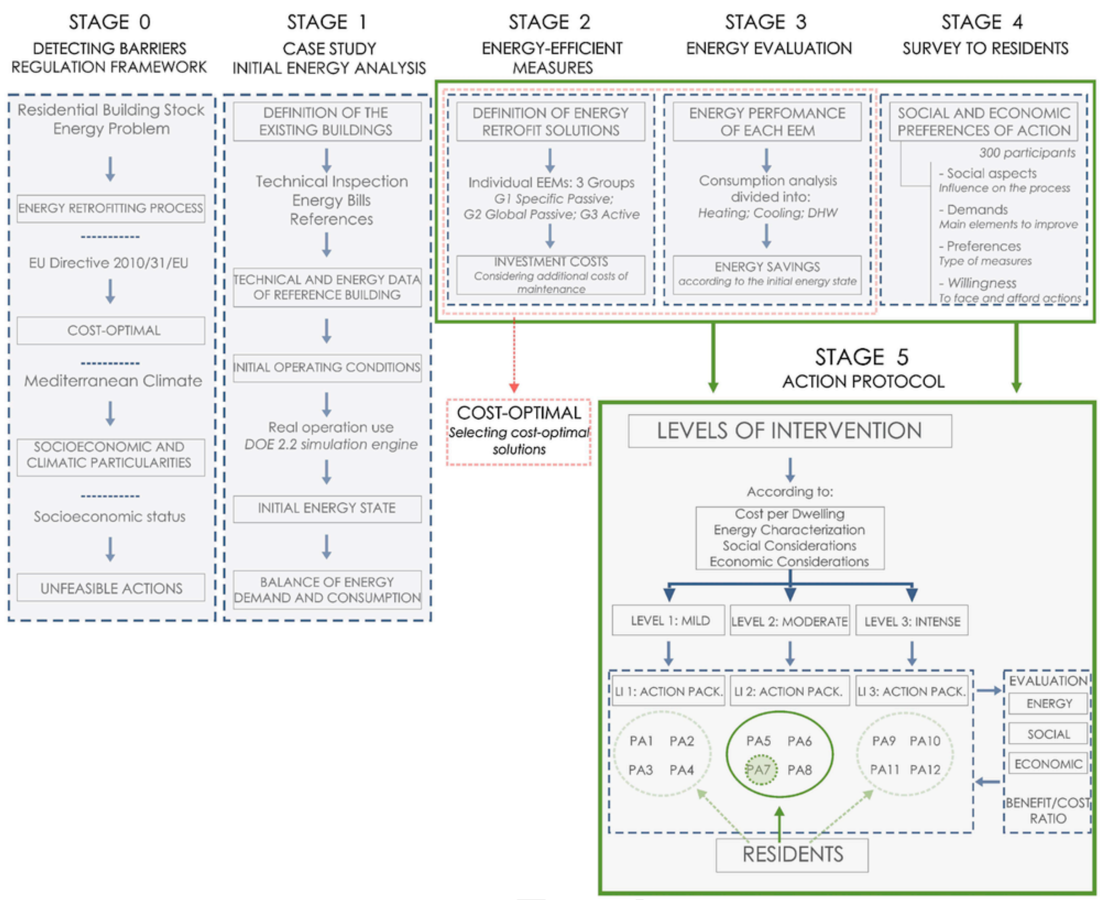

Fig. 2. Schematic process of the integrated methodology.

1- In stage 1, reference values are presented for the energy simulation through the DOE 2.2 simulation engine (DOE2, 2016), being the process explained in Section 3.1, to obtain a balance of demand (D = kWh) and consumption (C = kWh) in its initial state (N0), being these results detailed in Section 4.1.

- In stage 2, the compilation of energy retrofit solutions (EEM) are defined and divided into 3 groups in Section 4.2: Specific passive, global passive and active measures, including their corresponding initial investment (IC) and annual maintenance costs (MC) ($€_{EEMs}$).

- In stage 3, according to the simulation tool detailed in Section 3.1, an energy evaluation of each energy retrofit solution is shown, detailing the changes of each measure in the operating conditions. Energy results will be shown in Section 4.3., in order to compare energy savings with respect to the initial state. In addition, cost-optimal results are shown in Section 4.4, which would be obtained following the European guidelines (2010/31/EU, 2010), without taking into account the socio-economic considerations of the population.

- In stage 4, socioeconomic results obtained from real questionnaires filled by residents are detailed in Section 4.5, showing needs, demands, preferences and willingness to afford the actions through a participatory methodology (Engvall, Lampa, Levin, Wickman, & Ofverholm, 2014; Medineckienė & Björk, 2011; Pampuri, Cereghetti, Strepparava, & Caputo, 2016).

- The action protocol is defined as the stage 5, which allows citizens to decide on residential energy retrofitting by identifying the most suitable level of intervention according to their energy, social and economic requirements. Section 5 defines three levels of intervention (LI): Mild, moderate and intense, according to the cost per dwelling, energy characterization and social and economic parameters, which will facilitate the adjustment to each resident status. For its application, several action packages (AP) are defined by each level and are evaluated in an integral way, according to the energy, social and economic benefit and the benefit-economic ratio.

3.1. Energy simulation

The data used for the energy calculation of the reference building in its initial state were obtained from technical inspections in the neighbourhood, electric bills and other reference documentation (AENOR, 2009; D.L., 2013), within the research project along with surveys, and also from technical codes and manuals (AICIA, 2009; MF GE, 2016). The main required parameters and values from the technical characterization of the reference building are summarized in Table 1 and divided into two groups of information: Building envelope and existing systems.

The state of conservation of the structure and the envelope is adequate except for some small cracks in façades and capillarity humidity at the base of the walls (AENOR, 2009; D.L., 2013). About the existing systems, individual heating and cooling systems have been installed progressively throughout life with heat pump systems, while in many other cases, due to economic difficulties, there is no HVAC installation.

Once building profile is determined, the building simulation is carried out by DOE2.2 simulation engine (DOE2, 2016), developed by the United States Department of Energy, through a national dynamic simulation software (LIDER-CALENER, 2016), and officially recognized by the Spanish energy-efficiency regulations (Fig. 3).

Operation conditions, fixed variables and numerical methods used for the simulation software are detailed in AICIA (2009). The weather file was selected according to the specific building climatic zone (B4) defined in the Spanish Energy Code (MF GE, 2016) and whose Mediterranean climatic parameters are defined in Table 2.

Thermal performance of the envelope is defined in Table 3 in comparison to the minimum thermal requirements in B4 climate zone. It is observed that the values of the case study greatly exceed the limits set by current regulations

Table 1
Required parameters and values for energy evaluation.

Element		Characterization			Values
Envelope	Ventilation and infiltration [1]	Permeability of windows (P_{window})	80 (m^3/ m^2 at 100 Pa of pressure)		1.25 Ach/h
		Permeability of walls (P_{wall})	2.7 Volume (m^3/h)		
	Windows	Thermal Transmittance (U)	Frame (20%)	5.7 W/m^2 K	5.7 W/m^2 K
			Glass (80%)	5.7 W/m^2 K	
		Solar Factor (SF) (0-1 value)			0.75
		Absorptivity of frame (α)			0.70
		Permeability of windows			≥80 m^3/h m^2
		Seasonal solar heat gain coefficient of Window assembly (SHGC)[2]	30% of external solar protection for winter and summer		0.7
	Façade	Thermal transmittance (U)			2.68 W/m^2 K
	Roof				1.49 W/m^2 K
	Floor				3.58 W/m^2 K
Systems	Domestic Hot Water (DHW)	Type: LPG Boiler Percentage of use: 100%	Nominal yield (%)		0.85
			Nominal power (kW)		24 kW
			Minimum solar contribution (%)		0%
		DHW Demand [3]	Demand per dwelling (litres)		56 L
	Cooling[4]	Type: Air-air direct expansion, HP-E (Split) Percentage of use: 100%	EER [5]		2.5
			Capacity		4.2 kW
			Consumption		1.68 kW
	Heating[4]	Type: Air-air direct expansion, HP-E (Split) Percentage of use: 60%	COP [5]		2.7
			Capacity (kW)		4.5 kW
			Consumption		1.66 kW
		Type: Electrical heating (Joule Effect) Percentage of use: 40%	Nominal yield (%)		1
			Capacity (kW)		2 kW

Technical parameters have been defined according to the Spanish code (MF GE, 2016) and/or specific technical manuals: 1. Values depending on the permeability of existing frames, the surface of aperture and the interior volume of the building, obtained following the procedure described in UNE 13465.2004. (AENOR, 2004). 2. The default values of 0.7 established for summer and winter by the calculation software were maintained. 3. The domestic hot water (DHW) demand was established for an average occupation of 2 people per dwelling and 28 L/person/day, according to Spanish code. (MF GE, 2016) 4. 60% of dwellings were modelled with a reversible heat pump for heating and cooling; the other 40% of dwellings were modelled by means of only a cold heat pump system, and heating by means of electrical heating (Joule Effect). 5. Average performance determined according to inspected systems and the Technical Manual CE3. An. VIII, pages 123–124. (IDAE, 2012).

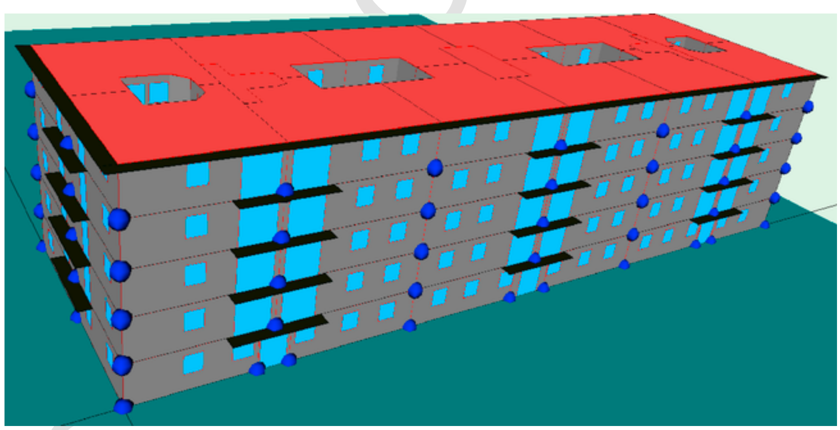

Fig. 3. Reference building model in the energy simulation.

Table 2
Annual climatic parameters of the climatic zone.

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
Aver. Max. Temp. (°C)	14.6	16.7	18.5	19.8	23.3	28.1	32.4	32.2	28.7	23.9	18,3	15.3	22.7
Aver. Temp. (°C)	10.7	11.7	13.1	14.9	18.2	22.3	26.3	26.1	23.2	18.9	14.0	11.4	17.7
Aver. Min. Temp. (°C)	7.2	6.6	7.6	9.3	12.3	15.3	19.2	19.3	17.1	13.7	9.6	7.6	12.1
Relative Humidity (%)	69,0	59,6	55,7	53,3	52,8	43,7	37,3	38,9	45,8	57,8	65,4	68,2	54,0

(R.D., 2013; 2010/31/UE), and hence the energy performance of the en-

Table 3
Thermal performance and comparison with the maximum permitted by the CTE.

Envelope	Thermal Transmission Case study	Thermal Transmission Limit according to CTE DB-HE 2016 [2]
Walls (U: W/m² K)	2.68	1.00
Roof (U: W/m² K)	1.49	0.65
Floor (U: W/m² K)	1.76	0.65
Windows (U: W/ m² K; SF:%) (Permeability: m³/ m²)[1]	5.7; 0.75 ≥80 m³/h m²	4.20; – ≤50 m³/ m²

1 Average permeability of Windows with an overpressure of 100 Pa. 2 Maximum values of the performance of the envelope for climate zone B, according to CTE DB-HE (MF GE, 2016).

4. Results

In the next sections the paper presents the results to overcome the detected barriers, showing the energy-efficient measures, the energy and socioeconomic results, which were obtained through an energy simulation and surveys, serving as a basis for designing action packages, framed on three levels of intervention, according to the socio-economic context of the case study.

4.1. Initial energy state of reference building (N0)

Following the calculation procedure detailed in Section 3.1, it is obtained the energy demand of the whole year in the reference building. The energy demand for the building is 43.1 kWh/m² in winter conditions (heating), and 26.3 kWh/m² in summer conditions (cooling).

These results are quite unfavourable if they are compared to the reference values, 16.6 kWh/m² for heating and 23.4 kWh/m² for cooling, established by the Spanish energy code for this Mediterranean climatic zone (MF GE, 2016). Although it is located in a warm Mediterranean climate, the reference building (N0) demands more energy consumption for heating than cooling, mainly due to the poor performance of its envelope.

Fig. 4 shows the balance of energy demand for heating and cooling in kWh/m², according to each month of the year. Heating demand is predominant in 6 months of the year, with values much higher than the cooling demand in the 4 months of summer when the demand for cooling predominates.

In addition, through the internal calculation parameters in DOE 2.2 simulation engine, it is possible to obtain the annual gains and losses of energy balance according to each component of the building envelope, which are shown in Fig. 5. This calculation enables the identification of which passive energy-efficient measures provide the greatest energy savings, through determining the most unfavourable parts of the envelope and also determining where it is necessary to reduce losses due to ventilation and infiltration.

Analysing the results in Fig. 5, it is precisely through the exterior walls where the biggest loss of heating energy occurs, and through the windows where the biggest loss of cooling energy occurs, due to the lack of insulation in the walls and the presence of the original simple glazing, with very low quality and a limited hermitic seal.

4.2. Energy-efficient measures (EEM)

The selection of action measures is based on the energy performance of the initial energy state of the building (N0) and on the Delegate n°244 Regulation (2010/31/EU, 2010) to ascertain the measures most commonly used and standardized in the construction sector today.

Intervention measures are defined in Table 4. For each of the individual measures it is presented the unit cost (UC), initial cost (IC) per dwelling, and additional cost for maintenance (MC), which considers a permanent and

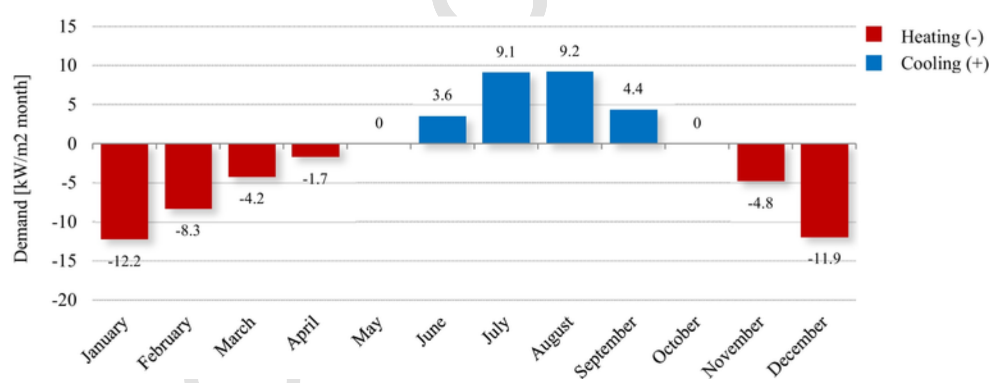

Fig. 4. Balance of energy demand of Heating (−) and Cooling (+) in kWh/m² per months.

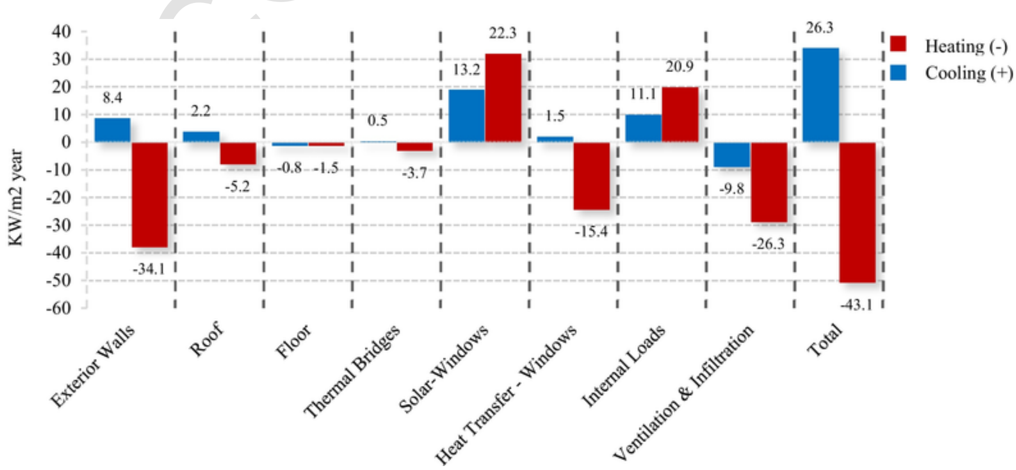

Fig. 5. Annual balance of energy demand per building element (KWh/m² year).

Table 4
Breakdown of the Energy-efficient measures (EEM).

Definition of EEM		UC Unit Cost[1]		IC Initial Cost per dwelling[1]		MC Additional cost of maintenance per year [2]	
Group 1. Specific passive measures							
G1-1	Sealing of window frames	4	€/mL	93.95	€	–	€
G1-2	Exterior rolling awnings with rigid slats	115	€/m^2	432.23	€	–	€
G1-3	Exterior hanging textile awnings	130	€/m^2	459.92	€	–	€
G1-4	Exterior metal blinds	100	€/un	113.33	€	–	€
G1-5	Double window. Adding aluminium frames and double glazing	220	€/m^2	1,759.49	€	–	€
G1-6	Replacement of window with TB aluminium frames and double glazing	280	€/m^2	2,239.35	€	–	€
G1-7	Replacement of window with PVC frames and double glazing	270	€/m^2	2,159.37	€	–	€
G1-8	Water-flow reducers in taps (aerators)	69	€/dwe	69.00	€	–	€
Group 2. Global passive measures							
G2-1	Exterior insulation and finishing system (EIFS with EPS)	50	€/m^2	2,126.80	€	–	€
G2-2	Exterior insulation and finishing system (EIFS with MW)	50	€/m^2	2,126.80	€	–	€
G2-3	Exterior insulation and finishing system (EIFS with cork)	56	€/m^2	2,382.02	€	–	€
G2-4	Exterior Insulation with application of liquid ceramic	28	€/m^2	931.01	€	–	€
G2-5	Exterior roof insulation	41	€/m^2	528.52	€	–	€
G2-6	Roof insulation by means of interior cladding	8	€/m^2	180.52	€	–	€
G2-7	Green Façade	350	€/m^2	3,440.03	€	108.12	€
G2-8	Extensive green roof	150	€/m^2	1,933.63	€	16.67	€
Group 3. Active measures							
G3-1	Change to heat pumps of greater efficiency	1,700	€/dwe	1,700.00	€	30.00	€
G3-2	Change to a DHW gas boiler of greater efficiency	350	€/dwe	350.00	€	30.00	€
G3-3	Change to a gas accumulator for DHW	650	€/dwe	650.00	€	30.00	€
G3-4	Aerothermal heat pump system for heating, cooling and DHW	6,800	€/dwe	6,800.00	€	30.00	€
G3-5	DHW support system by means of solar thermal energy	86,760	€/buil	1,446.00	€	21.00	€
G3-6	Support system by means of photovoltaic energy	18,480	€/buil	308.00	€	21.00	€
G3-7	Biomass centralization system for DHW and heating	121,000	€/buil	2,016.67	€	6.67	€
G3-8	Individual biomass boiler for heating	1,610	€/dwe	1,610.00	€	15.00	€
G3-9	Centralised condensation boiler for DHW and heating	39,120	€/buil	652.00	€	6.67	€
G3-10	Micro-cogeneration for DHW and heating	78,120	€/buil	1,302.00	€	174.65	€

1 All costs consider the final cost for the user, with the measure ready to be used. These costs include design, purchase of building elements, connection to suppliers, and installation and commissioning processes, but exclude national taxes. 2 Increases in annual costs of permanent and mandatory maintenance tasks. National taxes excluded.

mandatory extra cost for annual maintenance tasks, beyond the possible added costs due to accidents and other non-standard circumstances. Prices have been obtained from databases, manufacturers and insurance companies in various meetings held within the research project. These measures are organized into three main groups, depending on the scope of action:

- Group 1: Specific passive measures.
- Group 2: Global passive measures.
- Group 3: Active measures.

4.3. Energy evaluation

The results obtained in the energy calculation of each action measure, following the procedure detailed in section 3.1, enable the determination of the degree of energy efficiency. In Table 5, the energy performance of each of these measures is evaluated with respect to the initial energy state of the building (N0). In addition, under the definition of each measure is included the modification of the calculation parameters in the energy model, in fact, it should be taken into account that despite building model was calibrated according to the real operation conditions, different actions can affect the final energy and environmental savings after energy retrofitting due to changes in operation and consumption habits. The consumption of heating, cooling, domestic hot water (DHW) and the total consumption per dwelling of each action measure is detailed in Table 5.

From the analysis of the performance of specific passive measures (G1), it can be seen that the interventions with the highest percentage of energy savings are those involving the improvement or replacement of windows (G1-5,6,7) with a percentage of overall savings of approximately 15–20%. It may also be noted that the arrangement of exterior sun protection in windows reduces consumption by 2% of the total; however, in summer months this reduction rises to 12–15% tions and therefore in quality of life, which constitutes one of the main objective of energy retrofitting in residential buildings.

Regarding the results of global passive measures (G2), the highest percentage of energy savings is provided by those measures that improve the thermal performance of the envelope, specifically on the walls, (G2-1,2,3,4). These measures exceed a total savings of 45–50%, depending on the material incorporated as insulation. Retrofitting measures which improve the roof transmittance (G2-5,6) are local and their impact on the building is limited. In the case study, they produce high savings in energy consumption of dwellings located on the top floor, rising to 35%, while for the whole building this saving is of 6%.

Finally, measures which improve the efficiency of systems (G3) do not alter the energy demand since they do not act on the building envelope, but they highly reduce the energy consumption. In this case study, the interventions with the highest percentage of energy savings involve the replacement of the heat pump with a more efficient device (G3-1) and micro-cogeneration for DHW and heating (G3-10), which reach a total percentage of savings of 47% and 40%, respectively.

4.4. Energy evaluation of measures of intervention in terms of the "Cost-optimal" methodology

Considering the "Cost-optimal" methodology, in accordance with the European Parliament and the Governing Council of the European Union (2010/31/EU, 2010), an analysis is performed to determine which measures are the most optimal, so that their results can be compared with those obtained in the new proposed methodology.

The energy consumption and the overall cost ratio is shown in Fig. 6 in €/m^2. The most optimal measures are those that offer the greatest energy efficiency in relation with the amortization of the investment over a 30-year life cycle cost (LCC), and with the reduction of primary energy consumption. In this way, the most favourable points of the "Cost-optimal" curve in Fig. 6 are

Table 5
Breakdown of the energy performance of each individual action measure.

		Heating Cons. (kWh/m^2)	Cooling Cons. (kWh/m^2)	DHW Cons. (kWh/m^2)	Total Cons. (kWh/m^2)
N0	Initial energy state of reference building	75.5	39.0	25.0	139,5
Group 1. Specific passive measures					
G1-1	Sealing of frames (improvement of airtightness) (1.17 ach/h)	72.6	38.2	25.0	135.8
G1-2	Exterior rolling awnings with rigid slats (SHGC: Summer = 0.2;Winter = 0.7)	75.5	34.5	25.0	135.0
G1-3	Exterior hanging textile awnings (SHGC: Summer = 0.4;Winter = 0.7)	75.5	35.7	25.0	136.2
G1-4	Exterior metal blinds (New element: 1.2 × 0.5m, 75° angle)	75.5	38.4	25.0	138.9
G1-5	Double window. Adding aluminium frames (0.97 ach/h, ≤27 m^3/h m^2; Uwindow correct. factor = 0.37)	58.1	35.9	25.0	119.0
G1-6	Replacement of window with TB aluminium frames (0.90 ach/h, ≤9 m^3/h m^2; Uwindow = 2.3W/m^2 K; α=0.30)	60.9	34.7	25.0	120.6
G1-7	Replacement of window with PVC frames (0.90 ach/h, ≤9 m^3/h m^2; Uwindow = 1.9W/m^2 K; α=0.30)	59.3	34.8	25.0	119.1
G1-8	Water flow reducers in taps (aerators) (DHW demand correct. = 0.85)	75.5	39.0	21.2	135.8
Group 2. Global passive measures					
G2-1	Exterior insulation and finishing system (EIFS with EPS) (0.90 ach/h; Ufaçade = 0.57W/m^2 K)	32.2	35.4	25.0	92.6
G2-2	Exterior insulation and finishing system (EIFS with MW) (0.90 ach/h; Ufaçade = 0.57W/m^2 K)	31.9	35.4	25.0	92.3
G2-3	Exterior insulation and finishing system (EIFS with cork) (0.90 ach/h; Ufaçade = 0.61W/m^2 K)	32.8	35.5	25.0	93.3
G2-4	Exterior Insulation with application of liquid ceramic (0.90 ach/h; Ufaçade = 0.27W/m^2 K)	26.0	34.9	25.0	85.9
G2-5	Exterior roof insulation (1.25 ach/h; Uroof = 0.39W/m^2 K)	71.4	38.0	25.0	134.4
G2-6	Roof insulation by means of interior cladding (1.15 ach/h; Uroof = 0.37W/m^2 K)	69.2	37.2	25.0	131.4
G2-7	Green Façade (Ufaçade = 1.91W/m^2 K)	74.1	38.7	25.0	137.8
G2-8	Extensive green roof (Uroof = 0.85W/m^2 K)	72.8	38.2	25.0	136.0
Group 3. Active measures					
G3-1	Change to heat pumps of greater efficiency (EER = 4.2; Cap: 4.2 kW; Cons:1.00kW- COP: 4.6; Cap:4.5 kW; Cons: 4.5 kW)	29.6	20.1	25.0	74.7
G3-2	Change to a DHW gas boiler of greater efficiency (Nom. Yield: 87%; Nom. Power: 22.1 kW)	75.5	39.0	22.1	136.6
G3-3	Change to a gas accumulator for DHW (Nom. Yield: 87%; Nom. Power: 7 kW)	75.5	39.0	23.2	137.7
G3-4	Aerothermal heat pump system for heating, cooling and DHW (EER = 3.8; Cap: 7.1 kW; Cons:1.9 kW − COP: 3.6; Cap:8 kW; Cons: 2.3 kW)	48.6	25.9	13.3	87.7
G3-5	DHW support system by means of solar thermal energy (Minimum Solar Contribution: 70%)	75.5	39.0	8.1	122.6
G3-6	Support system by means of photovoltaic energy (Contribution: 2,050kWh; 14m^2 panels; Forecast gen. 2.78 kWh/year)	72.3	35.9	25.0	133.2
G3-7	Biomass centralization system for DHW and heating (Nom. Yield: 78%; Nom. Power: 130 kW − Num.radiator: 4; Power:1.6 kW)	50.4	39.0	20.2	109.7
G3-8	Individual biomass boiler for heating (Nom. Yield: 91%; Nom. Power: 5 kW)	54.0	39.0	25.0	118.0
G3-9	Centralised condensation boiler for DHW and heating (Nom. Yield: 93%; Nom. Power: 170 kW − Num.radiator: 4; Power:1.6 kW)	48.0	39.0	20.0	107.1
G3-10	Micro-cogeneration for DHW and heating (Nom. Yield: 81%; Nom. Power: 30.5 kW − Num.radiator: 4; Power:1.6 kW)	37.9	22.6	22.7	83.2

those that are the lowest, thereby supposing major economic amortization, and the furthest to the left, with the lowest energy consumption.

For this case study, the most favourable points would be the G3-1 and G3-10 measures, which are active measures, followed by those measures that incorporate thermal insulation on the exterior walls (G2-1,2,3,4) and other measures to improve the efficiency of the systems (G3-7,8,9). However, although those specific passive measures, such as G1-1,2,3, and 4, and several global passive measures, such as G2-5,7, and 8, present very low energy savings and they are not considered appropriate according to this "Cost-optimal" methodology, they clearly represent a significant improvement in comfort and satisfaction of residents, according to the socioeconomic considerations.

4.5. Social and economic considerations

This research considers essential to satisfy the specific criteria, preferences and needs of residents who are living and owning these buildings. This section presents the level of satisfaction and social demands achieved through a survey, as a useful way to introduce successful proposals on the energy

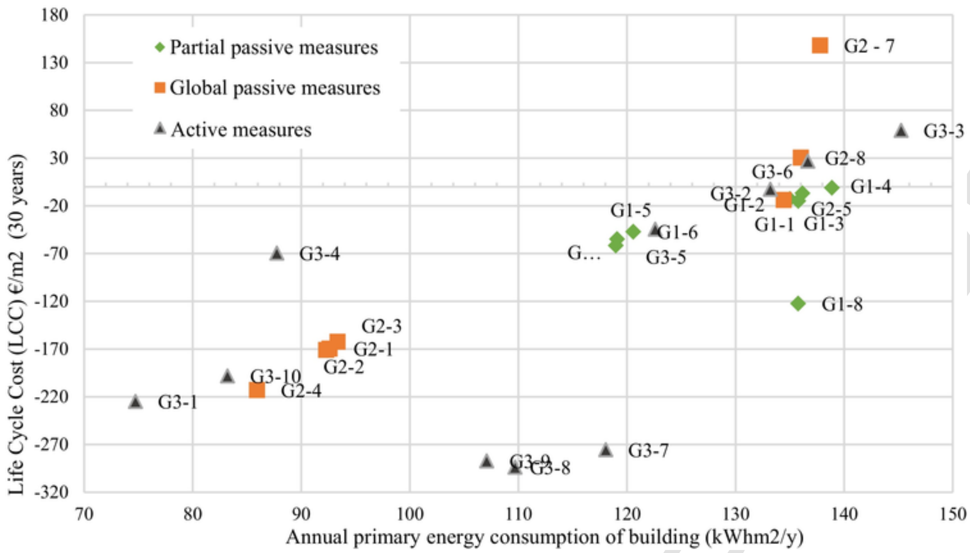

Fig. 6. Cost-Optimal ratio for all measures in a 30-year life cycle.

retrofitting methodology (Hast, Alimohammadisagvand, & Syri, 2015; Khashe, Heydarian, Becerik-Gerber, & Wood, 2016).

The survey, defined by researchers from the area of social sciences within the research project, were based on the needs, demands and priorities of a sample of 300 people regarding the retrofitting process in their buildings, their economic affordability and their willingness to assume the payments. During the delivery of the questionnaires, residents were briefly informed about the concept of energy renovation in the residential building stock, as well as the advantages in interior comfort and energy and economic savings that can be achieved.

The main questions which offered a greater influence in defining the parameters of the levels of intervention are defined below and their results are shown in Fig. 7:

- What kind of action measures would you prefer: Passive (on the envelope); Active (HVAC and/or DHW systems); or are you indifferent?
- What factor do you consider to be the most important in an action measure: Cost; discomfort created and execution time; or efficiency?
- How much would you be willing to pay?
- What element of your dwelling do you think is the most important to improve?

Some considerations can be extracted and detailed through the results shown in Fig. 7:

4- In Fig. 7.1, residents prefer passive interventions on the envelope (G1–G2) in a 74%, which reduce energy demand and consequently energy con-

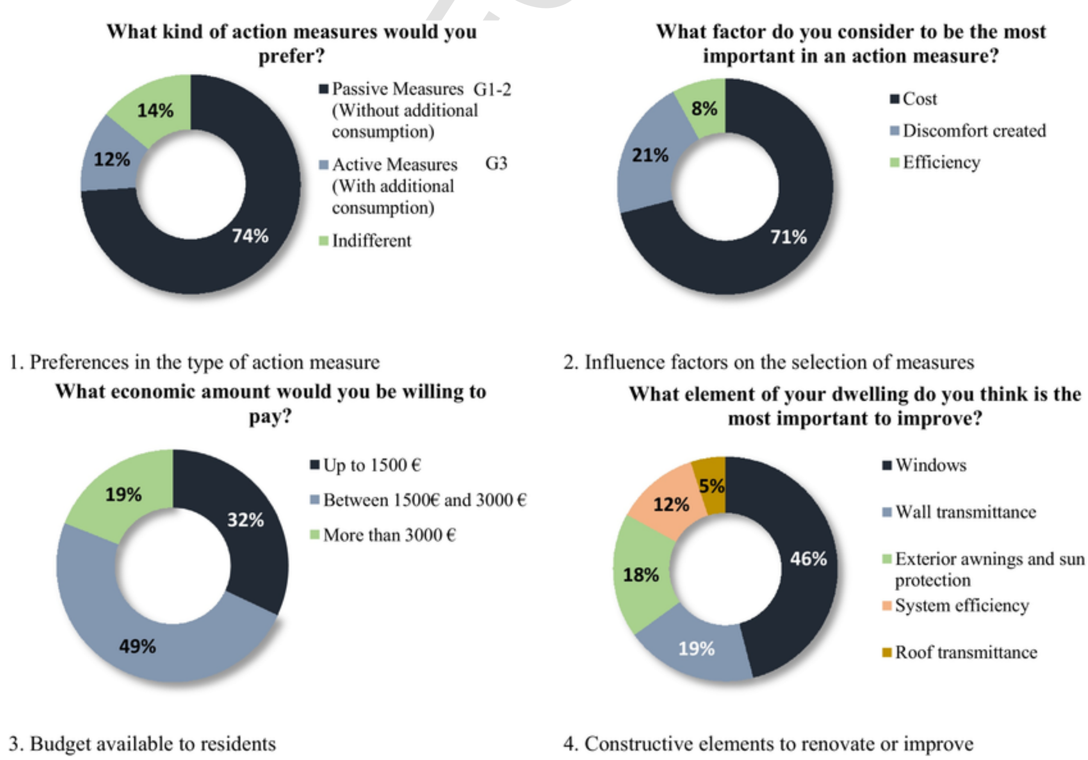

Fig. 7. Most relevant questions of the survey.

sumption. These actions improve the comfort conditions, instead of acting with the addition of, or replacement with, systems of greater efficiency (G3).

- Fig. 7.2 shows that the cost of the intervention is the highest priority in a 71% so it is necessary that the "Levels of intervention" would be adapted to their economic possibilities. In addition, 21% give priority to discomfort issues such as execution time, noise, dust, presence of scaffolding, and possible evacuation.

- Fig. 7.3 reflects that in 80% of cases, the residents are unable to pay more than 3000€, which makes evident the economic difficulties in assuming the costs of the energy-efficient retrofitting works.

- In Fig. 7.4, the need for the replacement of windows predominates in a 46% of responses (G1-6,7), leaving as a second option the improvement in wall transmittance (G2-1,2,3) or the exterior sun protection awnings (G1-2,3), with 19% and 18%, respectively.

In addition, action measures on the envelope, such as G1-1, G1-2, G1-6 or G2-1, are well received by residents, since they are involved in improving both the habitability of dwellings and the image of the neighbourhood. This is a question that remains unappreciated in most European research and policies, but is essential for the financing of the operations.

5. Action protocol: levels of intervention (LI)

This research proposes a new itinerary of building renovation with the establishment of "Levels of intervention" (LI), defined as volume of work to be carried out to ensure the objectives of improving both energy efficiency and quality of life of residents. Three levels are proposed: Mild (LI-1), Moderate (LI-2) and Intense (LI-3).

For designing the three levels of intervention, it is necessary to stablish those parameters that delimit the levels according to the social factors, economic issues, and energy impacts, according to the type of energy efficiency measures and the residents' opinion obtained through surveys, so that the success of energy retrofitting processes can be guaranteed.

Table 6 shows the definition of the main parameters in each level: Cost per dwelling, energy characterization, social and economic considerations, and possible measures in each level. Generally, specific passive measures are included at the mild level (LI-1), specific and global passive measures are included at the moderate level (LI-3), and active measures are added at the intense level (LI-3). It has to be noticed that these parameters and the design

Table 6
Definition of the three Levels of Intervention.

Level of Intervention	Cost per Dwelling	Energy characterization	Social Considerations	Economic Considerations	Action Measures
Level of intervention 1 (LI-1): **MILD**	Initial Cost: < **1500**€ There is no added cost of consumption	-Specific and global passive measures which act on the building envelope -Low energy savings, around 5-20% regarding the current level -Unfavourable "Cost-optimal" ratio	-Elevated level of social interest -Improved perception of comfort and satisfaction of residents -Guarantee of use of passive measures -Execution time of 2 or 3 days -Reduced visibility of works	-Low savings -Null amortization periods -Repetitive and serial -Reduced costs associated to the execution -Low revaluation of the property	G1-1: Sealing of frames G1-2: Rolling awnings with rigid slats G1-3: Hanging textile awnings G1-4: Exterior metal blinds G1-8 Water flow reducers in taps G2-4 Insulation with application of liquid ceramic G2-6 Roof insulation by means of interior cladding
Level of intervention 2 (LI-2): **MODERATE**	Initial Cost: **1500–3000**€ There is no added cost of consumption	-Specific and global passive measures which act on the building envelope -Medium energy savings, around 20-50% regarding the current level -Favourable "Cost-optimal" ratio	-High level of social interest -High improved perception of comfort and satisfaction of residents -Guarantee of use of passive measures -Execution time up to 15 days -Elevated visibility of works	-High savings with an improvement of the interior comfort. -Long amortization periods -Medium costs associated to the execution -High revaluation of the property	G1-5: Double window with aluminium frames G1-6: Replacement of window with TB aluminium frames G1-7: Replacement of window with PVC frames G2-1: Exterior insulation and finishing system (EIFS with EPS) G2-2: Exterior insulation and finishing system (EIFS with MW) G2-3 Exterior insulation and finishing system (EIFS with cork) G2-6: Exterior roof insulation G2-7: Green Façade G2-8 Extensive green roof
Level of intervention 3 (LI-3): **INTENSE**	Initial Cost: > **3000**€ There may be an added cost of consumption	- Combination of passive and active measures -High energy savings, around 50-60% regarding the current level -Very favourable "Cost-optimal" ratio	-Moderate level of social interest -Very high improved perception of comfort -No guarantee of use in active measures -Execution time greater than 15 days -Very high visibility of work	-Very high savings -Short amortization periods -High costs associated to the execution -Very high revaluation of the property	G3-1: More efficient heat pump G3-2: More efficient DHW gas boiler G3-3: Gas accumulator for DHW G3-4: Aerothermal heat pump G3-5: DHW support system by solar thermal energy G3-6: Support system by photovoltaic energy G3-7: Biomass centralization system G3-8: Individual biomass boiler G3-9: Centralized condensation boiler

criteria of action packages can vary depending on each case study, and they can be extrapolated to other socio-economic circumstances.

As an application of the methodology to this case study, a dwelling with representative values of the building is chosen, based on the average of energy bills, in order to generalize the results and be able to extrapolate to any dwelling of the building. Nevertheless, it is noticed that it is necessary to take into account in future processes that according to solar exposition of different dwellings, results, effectiveness and use of some passive measures can be slightly affected.

Table 7 shows the energy, social and economic factors from which the benefit attributed to each measure or action package will be weighted through four valuations, in order to carry out a comprehensive evaluation of each proposal.

The action packages (AP), proposed for each level of intervention, are defined in Table 8. There are twelve action packages (AP1-12), presenting each of them its cost per dwelling and the energy, social and economic benefits, taking into account the energy results and the conclusions of the survey through the different factors that have been detailed in Table 7. The benefit is evaluated between "no benefit" (−) to "high benefit" (+ + +).

The economic, social and energy benefits of each package are shown in Fig. 8 together with their comprehensive evaluation. It can be observed which packages introduce the best partial and total benefit in their respective levels, in terms of energy, social and economic factors.

It is noted that those packages of measures located in the intense level (LI-3), such as AP-9 and AP-11, generally are favourably evaluated, although there are other very beneficial packages if they are related to the overall economic cost of the intervention, such as AP-5 and AP-7.

Therefore, it is necessary to relate the cost-benefit by analysing the ratio between the comprehensive evaluation and the total cost, having considered economic viability and social variables, the most advantageous packages of measures can be determined. According to Fig. 9, the most suitable packages would be those which have the best comprehensive evaluation and lowest economic cost, in other words, the points which are close to the optimal trend line for the cost-benefit ratio. Thus, the most appropriate packages according to this methodology would be AP-1 in the mild level (LI-1), AP-5 and AP-7 in the moderate level (LI-2), and AP-9 and AP-11 in the intense level (LI-3).

6. Conclusions

This article aims to improve the impact of energy retrofitting in residential buildings by introducing new mechanisms which go beyond the Cost-Optimal methodology proposed by the Delegate 2010/31/EU Regulation. In this sense, to ensure feasible and satisfactory actions, the socio-economic needs and preferences of the resident population, obtained through the use of surveys, are considered.

The research is conducted in the Mediterranean climate, typical from southern European countries, in a characteristic neighbourhood located in Seville (Spain) which was selected in the context of a publicly funded research project. The neighbourhood consists of a set of ten identical buildings which were built in 1962 and whose thermal performance is highly inefficient.

Through an energy assessment of the initial state of the building and an evaluation of different energy-efficient measures (EEM), a protocol of action is defined based on three "Levels of intervention", according to energy, social and economic parameters. From there, 12 action packages (AP) are evaluated, showing the energy, social and economic benefit that each operation produces to ensure successful and feasible interventions.

This paper introduces an open and flexible methodology that can be adapted to various situations and requirements, so the "Levels of intervention" and the design of action packages can be adapted to incorporate new energy, social and economic circumstances of each case study.

After having evaluated twelve packages, classified into three levels, it is shown that:

- It is ineffective to consider only cost-optimal issues in neighbourhoods with a medium socio-economic level and a high percentage of elderly residents. Low-medium investment operations are much more demanded because they produce significant social satisfaction, instead of producing long-term economic refunds.
- There is no direct relationship between the best measures in the "Cost-optimal" and those measures that are highly rated from a multidisciplinary view that includes energy, economic and social factors.
- The resident population, especially elderly people, prioritise the cost of the intervention in 71% of the responses, showing great reluctance to become involved in expensive and impactful operations on the environment. In fact, 80% of residents cannot afford interventions of more than 3000€. In order to ensure the feasibility of the operation, mild to moderate levels of intervention are applied, which provide a significant improvement in comfort and quality of life of the residents at an affordable price.
- Passive measures in energy retrofitting are preferred in 74% of residents surveyed, having a more positive social evaluation than for active measures, mainly because passive measures include a much lower investment cost and they generally cause only a minor inconvenience to the residential population during the construction process.
- There is a nuanced difference between the reduction of energy consumption that may involve an energy-efficient measure, and the degree of comfort induced in residents. Some action measures in the Mediterranean climate, such as the placing of exterior solar protection and the sealing of exterior frames, are considered beneficial for residents because they highly improve the interior conditions, although the percentage of energy reduction is very low and the economic reinvestment has a non-existent amortization period.
- The use of surveys in the retrofitting process, as a method of introducing social and economic aspects, ensures that the resident population can be made aware of the pros and cons in the energy-efficient retrofitting process, thereby ensuring social engagement in the intervention and increasing the chances of success.
- The "Levels of intervention" incorporates: A mild level with an initial cost per dwelling of less than 1500€ that produces between 5 and 20% of energy savings; A moderate level with an initial cost per dwelling between 1500€ and 3000€ that produces between 40 and 50% of energy savings; Finally, an

Table 7
Definition of energy, social and economic evaluation factors.

Factors		No benefit	Low benefit	Medium benefit	High benefit
		–	+	+ +	+ + +
Energy evaluation	Consumption reduction	0–5%	5–20%	20–50%	50–100%
	"Cost-Optimal" Ratio	Unfavourable	Favourable	Very favourable	Optimum
	Comfort introduced	Non-existent	Significant	Important	Very Important
Social Evaluation	Use of measures	0–50%	50–80%	80–99%	100%
	Execution time	More than 3 months	1–3 months	1–4 weeks	1–7 days
	Visibility of work	Non-visible	Specific	Medium	High
Economic evaluation	Affordability	Difficult	Medium	Appropriate	Very appropriate
	Amortization period	Non-existent	15–30 years	5–15 years	0–5 years
	Revaluation of the property	Non-existent	Significant	Important	Very Important

Table 8
Definition of action packages with energy, social and economic evaluation.

Levels/ action packages		Definition	Cost (€)		Energy evaluation			Social evaluation			Economic evaluation		
			Initial	Maint.	Consumption reduction	"Cost-Optimal" Ratio	Comfort introduced	Use of measures	Execution time	Visibility of work	Affordability	Amortization period	F o p
LEVEL 1 (LI-1) MILD	AP-1	G1-1 + G1-3 + G2 *Sealing of frames + Exterior hanging awnings + Exterior wall insulation with elastic paint*	735	-	+	+	+	+ +	+ + +	–	+ + +	–	–
	AP-2	G1-1 + G1-3 + G2 *Sealing of frames + Exterior hanging awnings + Roof insulation by interior cladding*	1484	-	–	–	+	+ +	+ + +	+	+ +	–	–
	AP-3	G1-1 + G1-4 + G2-4 + G2-6 *Sealing of frames + Exterior metal blinds + Exterior wall insulation with elastic paint + Roof insulation by interior cladding*	1318	-	+	–	+	+ + +	+ +	–	+ +	–	–
	AP-4	G2-4 + G2-5 *Exterior wall insulation with elastic paint + Exterior roof insulation*	1459	-	+	–	+	+ + +	+ + +	–	+ +	–	–
LEVEL 2 (LI-2) MODERATE	AP-5	G1-1 + G1-3 + G2-1 *Sealing of frames + Exterior hanging awnings + Exterior wall insulation (EIFS with EPS)*	2680	-	+ +	+	+ +	+ +	+ +	+ +	+ +	+ +	-
	AP-6	G1-3 + G1-6 + G2-6 *Hanging awnings + Replacement of windows with aluminium frames + Exterior roof insulation*	2879	-	+	+	+	+ +	+ +	+	+ +	+	-
	AP-7	G1-1 + G1-4 + G2-1 + G2-5 *Sealing of frames + Exterior metal blinds + Exterior wall insulation (EIFS with EPS) + Exterior roof insulation*	2861	-	+ +	+	+ +	+ + +	+ +	+ +	+ +	+ +	-
	AP-8	G1-7 + G2-4 *Replacement of windows with PVC frames + Exterior wall insulation with elastic paint*	2989	-	+ +	+ +	+ +	+ +	+ +	+	+ +	+ +	-
LEVEL 3 (LI-3) INTENSE	AP-9	G1-3 + G1-6 + G2-1 + G2-5 *Exterior hanging awnings + Replacement of windows with aluminium frames + Exterior wall insulation (EIFS with EPS) + Exterior roof insulation*	5353	-	+ +	+ +	+ + +	+ +	+ +	+ + +	+	+ +	-

Table 8 (*Continued*)

Levels/ action packages	Definition	Cost (€)		Energy evaluation			Social evaluation			Economic evaluation	
		Initial	Maint.	Consumption reduction	"Cost-Optimal" Ratio	Comfort introduced	Use of measures	Execution time	Visibility of work	Affordability	Amortization period
AP-10	G1-3 + G1-6 + G2-5 + G3-1 + G3-2 *Exterior hanging awnings + Replacement of windows with aluminium frames + Exterior roof insulation + More efficient heat pump + DHW gas boiler*	5330	60	+ +	+ +	+ +	+	+	+ +	+	+
AP-11	G1-6 + G2-1 + G3-1 *Replacement of windows with aluminium frames + Exterior wall insulation (EIFS with EPS) + More efficient heat pump*	6065	30	+ + +	+ + +	+ + +	+ +	+ +	+ + +	–	+ + +
AP-12	G1-3 + G1-6 + G2-1 + G2-5 + G3-7 *Exterior hanging awnings + Replacement of windows with aluminium frames + Exterior wall insulation (EIFS with EPS) + Exterior roof insulation + Biomass centr. system for DHW & heating*	7369	30	+ + +	+ +	+ + +	+	–	+ + +	–	+ +

"–" No benefit/"+" Low benefit/"+ +" Medium benefit/"+ + +" High benefit.

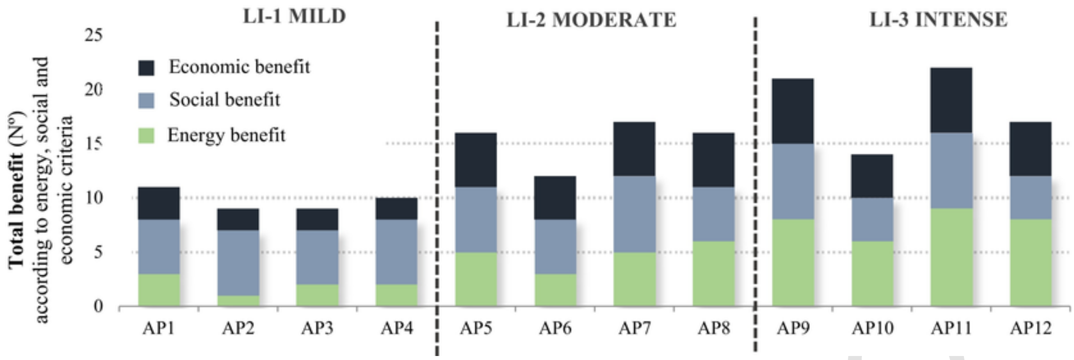

Fig. 8. Comprehensive evaluation of action packages (AP1-12).

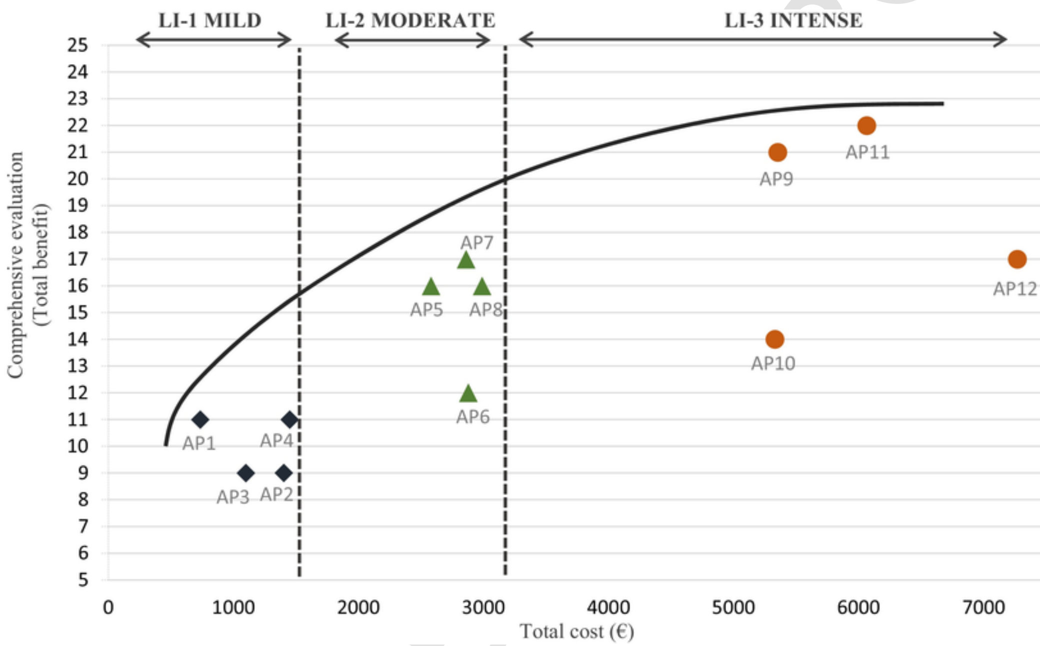

Fig. 9. Comprehensive evaluation and total cost ratio.

intense level with an initial cost per dwelling of more than 3000€ in which greater energy savings of more than 50% are obtained.

- The benefit-cost ratio obtained through a comprehensive evaluation and the total cost enables viewing those optimal action packages in each level of intervention. This method provides a multidisciplinary contribution to the "Cost-optimal" methodology, since it is complemented by social and economic studies.

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Uncited references

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