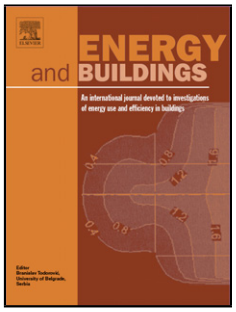
Accepted Manuscript



Title: Sustainability assessment of energy saving measures: a multi-criteria approach for residential buildings retrofitting–A case study of the Spanish housing stock

Author: Olatz Pombo Karen Allacker Beatriz Rivela Javier Neila

PII: S0378-7788(16)30019-6
DOI: http://dx.doi.org/doi:10.1016/j.enbuild.2016.01.019
Reference: ENB 6392

To appear in: *ENB*

Received date: 14-10-2015
Revised date: 13-1-2016
Accepted date: 16-1-2016

Please cite this article as: O. Pombo, K. Allacker, B. Rivela, J. Neila, Sustainability assessment of energy saving measures: a multi-criteria approach for residential buildings retrofittingndashA case study of the Spanish housing stock, *Energy and Buildings* (2016), http://dx.doi.org/10.1016/j.enbuild.2016.01.019

Sustainability assessment of energy saving measures: a multi-criteria approach for residential buildings retrofitting – A case study of the Spanish housing stock.

Olatz Pombo[a,]*, Karen Allacker[b], Beatriz Rivela[c,d], Javier Neila[a]

[a] Department of Construction and Technology in Architecture (DCTA), School of Architecture (ETSAM), Technical University of Madrid (UPM), Avda. Juan de Herrera 4, 28040 Madrid, Spain. e-mail: *o.pombo@alumnos.upm.es (O. Pombo), fjavier.neila@ump.es (J. Neila)*

[b] Department of Architecture, Faculty of Engineering Science, KU Leuven, Kasteelpark Arenberg 1, 3001, Leuven, Belgium. e-mail: *karen.allacker@kuleuven.be*

[c] inViable Life Cycle Thinking, Don Ramón de la Cruz 89, 28006 Madrid, Spain. e-mail: *beinha@inviable.is*

[d] Department of Organizational Studies and Human Development. National Polytechnic School. Av. Ladrón de Guevara E11-253, Quito, Ecuador

* Corresponding author: E-mail address: o.pombo@alumnos.upm.es. Phone: +34 91 336 38 89

Abstract

The building sector is well known to be one of the key energy consumers worldwide. The renovation of existing buildings provides excellent opportunities for an effective reduction of energy consumption and greenhouse gas emissions but it is essential to identify the optimal strategies. In this paper a multi-criteria methodology is proposed for the comparative analysis of retrofitting solutions. Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) are combined by expressing environmental impacts in monetary values. A Pareto optimization is used to select the preferred strategies. The methodology is exemplified by a case study: the renovation of a representative housing block from the 60s located in Madrid. Eight scenarios have been proposed, from the Business as Usual scenario (BAU), through Spanish Building Regulation requirements (for new buildings) up to the Passive House standard. Results show how current renovation strategies that are being applied in Madrid are far from being optimal solutions. The required additional investment, which is needed to obtain an overall performance improvement of the envelope compared with the common practice to date, is relatively low (8%) considering the obtained life cycle environmental and financial savings (43% and 45% respectively).

Keywords: renovation; housing retrofit; life cycle assessment; life cycle cost; monetary valuation; environmental external costs; Pareto optimization.

Introduction

Buildings worldwide account for 16-50% of the total energy consumption [1], while the corresponding value in Europe is 40% [2,3]. The renovation of existing buildings provides excellent opportunities for reducing energy consumption and greenhouse gas emissions. The majority of the current European residential building stock was built during 1940-1970s, with low standard especially with regard to energy performance [4]. In Spain, 54% of the housing stock was built before 1980, i.e. before the first regulation concerning energy efficiency in buildings [5]. This large stock is a consequence of the high housing need in the middle of the last century, in a context with a low industrial production and without any comfort standards. Improving these buildings with a low energy performance is hence an urgent and important challenge. Many authors have emphasized the importance of building renovation in energy savings and reduction in greenhouse gas emissions [6–9]. In a previous work [10], a critical review of the works concerning energy efficiency strategies and the approaches driving the assessment of the housing retrofits was conducted. It was observed that retrofitting strategies were quite similar. Passive strategies, such as insulation of the envelope, replacement of windows and air sealing were found to be the most common energy saving measures. However, the assessment methodologies applied to evaluate the efficiency of the energy saving measures differed broadly and widely [10].

Further work is needed on the development of consistent multi-criteria methodologies for decision-making on the retrofitting strategies. In this context, Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) are promising instruments for the modeling and calculation of the respective effects

[11]. However, LCA and LCC have been developed quite independently, and so there are differences in terminology, framework, and calculation rules. In the review of the existing literature [10] inconsistencies were found when LCA and LCC were conducted in the assessment of retrofitting solutions. System boundaries were different in the LCA and LCC parts of the studies [i.e. 6,12]. Where for LCA studies, a classification into the different life cycle stages of the cradle-to-grave is most often applied, for LCC studies this classification is rarely used: LCC studies are most often restricted to investment and use phase costs. Besides, the time horizons for environmental impact and economic cost are often different [i.e. 13]. Moreover, the different normalization and weighting methods, as well as the diverse environmental external cost calculation approaches, not only reduce the transparency of the studies but also make the results uncertain and subjective, preventing the comparison of the results [14]. There is, however, an important harmonization effort with regard to the on-going policy development processes in the European context (CEN standards).

These findings indicate the need for further methodological support for integrated LCA-LCC studies. To meet this need, a multi-criteria assessment method was proposed for the optimization of the energy saving measures (ESM) in housing renovation, combining LCA and LCC, through a Pareto optimization approach. In the approach proposed, environmental impacts were expressed as external environmental costs via monetary valuation. The methodology is illustrated by a case study in order to provide an in-depth understanding of the approach followed. A representative residential building from the Spanish housing stock was selected as case study. Current strategies used in Spain were analyzed in terms of efficiency by applying the multi-criteria approach proposed. Different scenarios were analyzed from the Business as Usual scenario (BAU), through the requirements for new buildings of the Spanish Building Regulation [15] up to the Passive House standard.

Methods

In order to avoid inconsistencies as identified in the literature review, the goal and scope of the study must be defined considering the same functional unit for LCA and LCC.

Life Cycle Assessment (LCA)

LCA follows the ISO standards 14040 [16] and 14044 [17]. It is defined as “the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle” [16].

Life Cycle Impact Assessment

In the approach proposed the seven impact categories of the European (CEN) standard on environmental impact of buildings [18] are considered as there is a large consensus on their relevance and scientific robustness of the impact assessment models related to these. The following impact categories are included in the CEN standard:

abiotic depletion potential – non-fossil (ADP-non-fossil, kg Sb eq);
abiotic depletion potential – fossil (ADP-fossil, MJ net caloric value)
acidification potential (AP, kg SO_2 eq);
eutrophication potential (EP, kg $(PO_4)^{3-}$ eq);
global warming potential (GWP, kg CO_2 eq);
ozone layer depletion potential (ODP, kg CFC-11 eq);
photochemical ozone creation potential (POCP, kg C_2H_4 eq).

For each of the impact categories included in the current version of the CEN standards, several impact assessment models exist. In the overall aim to strive for harmonization, the CEN standards stipulate which impact assessment models shall be used for each of the impact categories. These mandatory impact assessment models, i.e. CML version 4.1 (dated October 2012), were used in the approach proposed in this paper in order to be in line with the CEN standards. The software used for life cycle impact assessment was SimaPro 7.3.3.

A multiplicity of individual impact scores is rarely a good basis for decision-making. Therefore, a weighting was used by means of monetary valuation. Monetary valuation is an optional evaluation step in LCA. A detailed elaboration of different steps of LCA can be found in the ISO 14000 standards [16,17]. The objective of monetary valuation in the research was to express, in monetary terms, how the welfare of current and future generations is affected by the environmental impacts caused by activities in the building sector. These environmental costs (also referred to as “external costs” or “shadow costs”) arise when the activities of one group of people have an impact on others, and when the first group fails to fully account for these impacts [19]. For each individual environmental indicator, the characterization values are multiplied by a monetization factor (e.g.: X kg CO_2 equivalents times Y €/kg CO_2 equivalents). This factor indicates the cost of the damage to the environment and/or humans for avoiding potential damage or settling any damage incurred [20]. The West-European monetary values from the OVAM:MMG method developed in Belgium were used in our approach [20,21]. For the analysis, the central values of the OVAM:MMG method (Table 1) were used.

Table 1. Overview of West-European monetary (central, low and high) values for CEN indicators, 2014 [21]

Environmental indicator	Unit	Central (€/unit)	Low (€/unit)	High (€/unit)
ADP-non fossil	kg Sb eq	1.56	0	6.23
ADP-fossil	MJ net caloric value	0	0	0
AP	kg SO_2 eq	0.43	0.22	0.88
EP	kg $(PO_4)^{3-}$ eq	20	6.60	60
GWP	kg CO_2 eq	0.100	0.050	0.200
ODP	kg CFC-11 eq	49.10	25	100
POCP	kg C_2H_4 eq	0.48	0	6.60

Environmental costs can be compared/added up with/to the financial costs. This offers significant added value compared with other weighting methods, such as the panel method, the distance-to-target method and damage methods for overall decision taking [22].

Life Cycle Cost (LCC)

For the Life Cycle Cost the methodological standard in the regulation ISO 15686-5 [23] has been adopted. According to this standard, LCC is defined as a technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors, both in terms of initial investment cost and future operational cost. The net present value (NPV) may be described as the sum of the discounted benefit of an option less the sum of the discounted costs [23] and was adopted for the LCC calculation on the basis of existing literature [6,13,24–26]. An energy efficient renovation of a building requires an investment cost, but generates savings in the energy consumption over the life span of the building. In order for the measure to be profitable, the energy cost saved over its life will need to be greater than the capital investment [27]. Therefore investment costs were considered negative while energy savings were considered positive. The NPV was calculated as follows:

$$NPV\ (r,N) = -C_R - \sum_{t=0}^{N} \frac{C_{MRm}(1+i_m)^t + C_{MRl}(1+i_l)^t}{(1+r)^t} + \sum_{t=0}^{N} \frac{S_G(1+i_g)^t + S_E(1+i_e)^t}{(1+r)^t} - \frac{C_{EoL_N}}{(1+r)^N}$$

Where r is the real discount rate (%), N is the time lifespan (years), t is the year (-), i_m, i_l, i_g, i_e are real growth rates of building materials, labor, gas and electricity respectively (%), C_R is the cost for renovation (€), C_{MRm} is the cost of the building materials for maintenance and replacement (€),C_{MRl} is the cost of the labor for maintenance and replacement (€), S_g is the gas saving (€), S_e is the electricity saving (€), and C_{EOL} is the cost of EoL (€).

The cost of renovation includes building material costs, labor costs, indirect costs (which include the costs for indirect labor, machinery and tools, temporary facilities, and quality control), fees of architects, and the VAT. The cost data were collected from a database valid for the Spanish context, for the year 2014 [28]. The cost of maintenance and replacements includes the costs of building materials and labor costs. However, as these will happen in the future, the increase in the price of construction materials and labor is taken into account. Energy savings are calculated for heating and cooling. Finally, the EoL cost includes the cost for the separation of waste, transport to the treatment place and the EoL treatment. For the cost data related to the EoL, the CYPE database [29] was used.

Specific prices for commodities and their real growth rates are shown in Table 2. Rates of increase of energy prices are based on projection of the observed past trend according to the references given in Table 2.

Table 2. Input data for costs and real growth rates for the LCC

Input data category	Value and reference
Price of natural gas	0.0752 €/kWh [30]
Electricity price	0.2252 €/kWh [31]
Discount rate	3% [32]
Growth rate of building materials	1.85% [33]
Growth rate of labor	0% [33]
Growth rate of gas	3.5% [30,34]
Growth rate of electricity	5% [31,35]
VAT rate	10%

Multi-criteria optimization

For the purpose of identifying the retrofitting scenarios in order of priority, an optimization of the environmental impact and financial cost is needed. A ranking of priorities can therefore only be established based on a multi-criteria optimization procedure. Within multi-criteria optimization there is typically no single global solution. It is therefore necessary to determine a set of optimal points which all correspond to a predetermined definition of optimum. As stated by Marler & Arora [36], the predominant concept in defining an optimal point is that of Pareto optimality. According to the Pareto principle, the options from the considered population are optimal if there is no other option that improves one objective without simultaneously worsening at least one other. This concept is used within this research. Since two objectives are strived for: minimum investment cost and maximum life cycle savings, a Pareto curve should be determined. Therefore, the following objectives were defined for the optimization of retrofitting scenarios in the context of this research:

Highest life cycle financial savings (LF savings) and lowest financial investment (IF)

Highest life cycle environmental savings (LE savings) and lowest environmental investment (IE)

Highest life cycle environmental savings (LE savings) and lowest financial investment (IF)

Highest life cycle environmental savings (LE savings) and highest life cycle financial savings (LF savings)

Sensitivity analysis

While the literature raises a number of concerns about the use of life cycle approach, there are steps that can be taken to minimize the inherent limitations of the methodology. The undertaking of sensitivity analyses on the most uncertain parameters can help to mitigate limitations of LCA and LCC by testing the impact of variations in key assumptions on the outcomes [37]. Sensitivity analyses were hence performed on the most important uncertain parameters. A first one is the life span of the building which potentially has an important influence on the economic and environmental outcomes [38,39]. Typically, the longer the life span of the building, the lower the yearly environmental impacts and the higher the economic benefits [40]. As there is no universal standard regarding the life span of a building, uncertain estimates need to be made. Based on literature for housing renovation, a base scenario of 50 years with a sensitivity service life of 30 and 60 years is assumed. A second one is the monetary valuation of the environmental impacts. As these include a certain level of uncertainty, sensitivity analyses of the monetary values are performed by considering the low and high values in table 1.

Concerning uncertainties in LCC, Moore and Morrisey [37] detected from their results that the discount rate has a significant impact on the net present value. Overall, the lower the discount rate the greater the net present value. According to the European Commission, a real discount rate higher than 4% reflects a purely commercial, short-term approach to the valuation of investment. While a lower rate, ranging from 2% to 4% excluding inflation, reflects more closely the benefits that energy efficiency investments bring to building occupants over the entire investment’s lifetime [32]. Therefore, a sensitivity analysis with real discount rates of 2% and 4% is conducted. The future price of energy is also relevant but uncertain. It is verified that the outcomes (and related recommended renovation strategies) would differ from the baseline scenario if the growth rate of energy was the same as the inflation rate. Two scenarios for the energy price evolution in time are considered: real growth rate of 0% and real growth rate of gas and electricity of 1.75% and 2.5, respectively.

Selection of a case study

Selection of a representative housing block

The difficulty in defining a building model that represents the total building stock is well known due to the complexity and heterogeneity of the existing stock. The most representative typology of the Spanish housing stock is the multi-family housing block built between 1950-1980, which represents 43% of the residential stock [5]. The housing development of this period, especially in industrial cities, was characterized by large-size social housing estates with a huge number of dwellings. The need for fast growing implied homogeneous construction, giving rise to similar building features. Based on an in-depth analysis of the housing stock in Madrid [41], where 13,000 hectares were urbanized in this period, a representative housing block has been identified.

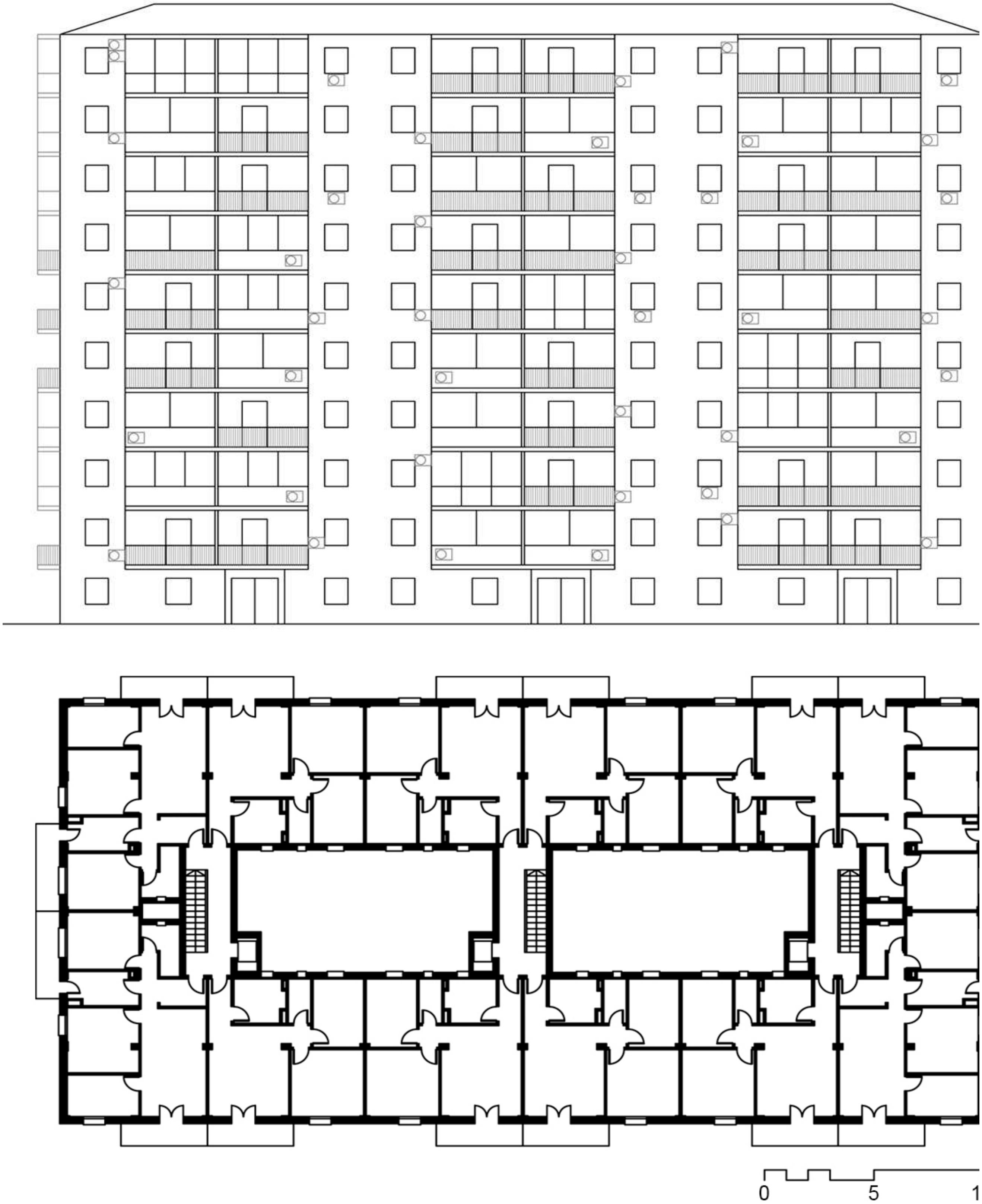

0
5
1

Fig. 1. Layout of the existing building: elevation, floor plan and vertical section of the top floor [41]

The studied building is from the 60s and is located in Madrid (Fig. 1). It is a ten-story building, containing 120 dwellings of 2 and 3 bedrooms, with a net floor area of 49 and 64 m^2 respectively and a floor to ceiling height of 2.50m. The roof is a pitched roof made of ceramic tiles placed over brick boards, supported by ventilated brick walls placed every 1-meter. The facade is composed of a brick veneer, air cavity, hollow bricks and gypsum plaster at the inside. Windows are made of aluminum without thermal break and single glazing. Balconies are randomly closed with aluminum carpentries (mostly without thermal break) and single glazing. The *U*-values of the roof, facades and windows are 1.48 W/m^2K, 1.69 W/m^2K and 5.7 W/m^2K respectively.

The average heating demand is 85.44 kWh/m^2 year, while the average cooling demand is 19.33 kWh/m^2 year. The calculation of the energy demand was performed using the building energy simulation software DesignBuilder and the calculation engine EnergyPlus [42] with the weather data of Madrid. The usage profile was taken from the Spanish Building Regulation [15], which defines a set-point temperature for winter (October to May) of 20ºC from 8h to 23h and 17ºC from 23h to 7h. The set-point temperature for summer (June to September) is 25ºC from 16h to 23h and 27ºC from 23h to 7h. A ventilation rate of 0.76 ac/h is assumed, according to the health requirements of the Spanish Building Regulation [15]. During summer, night ventilation with a rate of 4 ac/h is considered. As far as air tightness is concerned, the Simplified Spanish Certification Procedure, CE3 [43], defines an infiltration rate of 9 $m^3/h \cdot m^2$ at 4 Pa, for multifamily housing built before 1961-1975.

Definition of the retrofitting scenarios

The main objective of selecting this case study was to investigate whether the current retrofitting solutions in Spain are suitable from a life cycle perspective, and if the current requirements in housing renovation should be strengthened or not. As a first step, the case study of Madrid was considered because there is a large housing stock to be renovated in the short term. In order to know the real solutions currently applied in the housing retrofitting of Madrid, all the projects supported by the Municipal Housing and Land Company of Madrid (EMVS) in the period 2010-2012 were analyzed [44].

Initially three conditions were considered to define the retrofitting scenarios: Business as Usual practices (E1), solutions to achieve the Spanish Building Regulation for new buildings (E2) and actions to achieve the Passive House standard (E3). In the scenario E2 requirements for new buildings were considered, since the energy demand required for renovation was higher than energy demand achieved in BAU scenario. In this scenario, two solutions were proposed for the renovation of the windows: 1) replacement of the window, which is normally done in Spain (E2a); and 2) addition of a second window, which solved better the thermal bridge (E2b). Fig. 2 shows the requirements for each scenario for the city of Madrid.

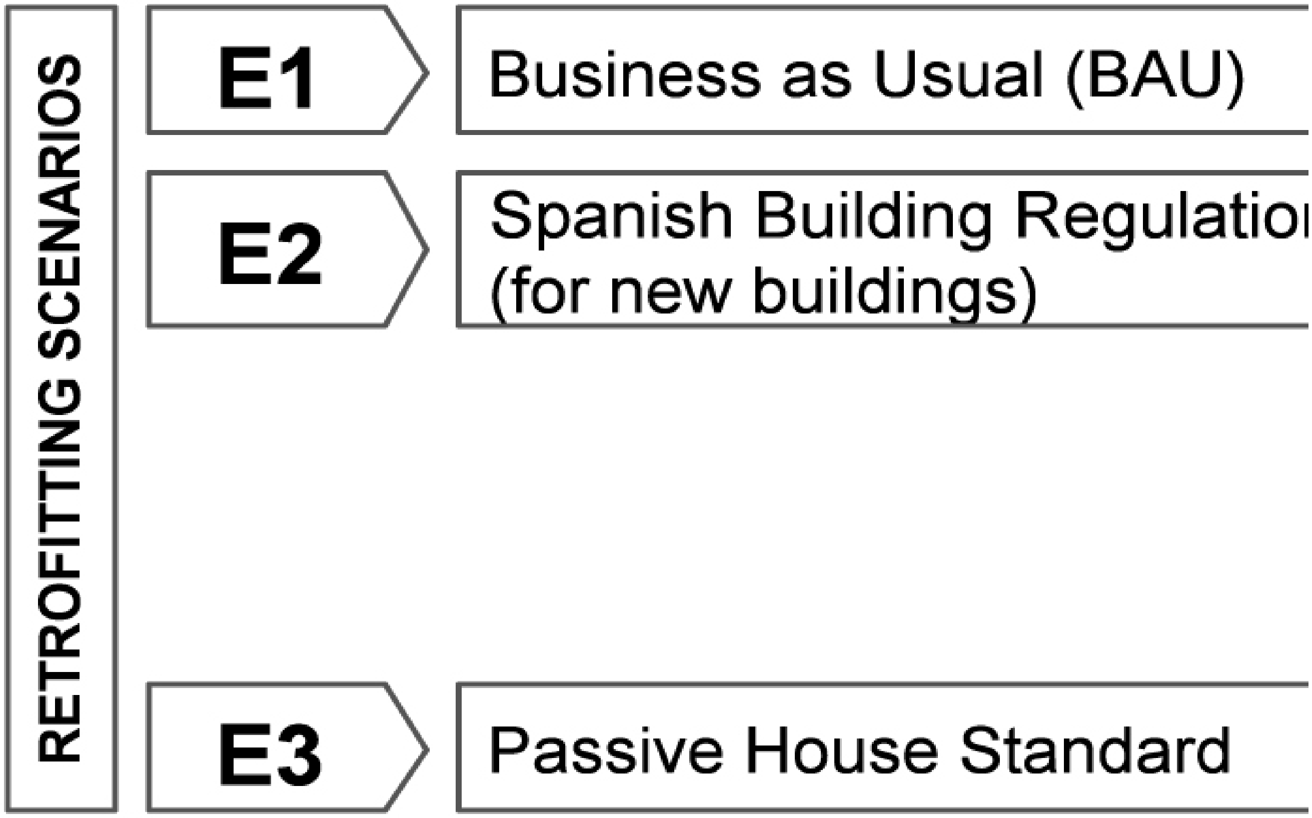


Fig. 2. Energy requirements for the retrofitting scenarios proposed in a first step

Energy saving measures for each scenario were defined according to the U-values and energy demand requirements presented in Fig. 2. To do so, DesignBuilder was used with the input parameters presented before (section 3.1). Due to the renovation, the infiltration rate is expected to decrease. The infiltration rate defined by the Spanish Certification tool Lider-Calener [45], for multifamily housing (new buildings), was therefore adopted, which equals 0.24 ac/h at 1 Pa. For the E3 scenario, the infiltration rate required by the Passive house standard was considered (0.6 ac/h at 50 Pa).

The preliminary results revealed that scenario E3 leads to a very high investment cost and is hence unaffordable for the majority of the people. Therefore, four additional scenarios were proposed (E4-E7) improving the current requirements of the Spanish Building Regulation but being less stringent than the Passive House standard. Based on the analysis of the information provided by the EMVS, nowadays materials used in housing renovation in Madrid are the same in every building. Therefore, in this research, the additional scenarios were proposed maintaining the same materials for roof and facade but looking for the preferred insulation thickness. This limitation is seen as justified as previous studies have shown that the type of insulation material does not provide essential differences in the life cycle impact and cost of a building [46,47]. For the definition of these additional scenarios roof, facade and windows were optimized separately, from both a life cycle environmental and financial perspective, i.e. based on LCA and LCC. For the roof, 24 cm of glass wool was identified as the maximum insulation thickness on the Pareto front, while for the facade it was 16 cm. Results showed that for higher insulation thicknesses, the initial environmental and financial costs increase while the life cycle savings decrease. As shown in Table 3, the maximum insulation thickness for roof and facade was adopted in scenario E7, while scenarios E4-E6 combined maximum insulation thickness only for one element (façade or roof) and intermediate thickness for the other. The ground floor was not renovated due to the limited floor-to-ceiling height (2.5 m).

Table 3. Renovation scenarios, Energy Saving Measures and U-values

	ESM				*U*-values		
	ROOF	FACADE	WINDOWS	OTHER	ROOF	FACADE	WINDOWS
E1	8 cm XPS	6 cm EPS	AL + 4/6/4		1,25	0,36	2,8
E2a	16 cm MW	12 cm EPS	N: PVC + Low-e 8/16/8 (Air) E/W/S: PVC+Low-e 8/10/6		0,21	0,26	N: 1,2 S/E/W: 1,6

			(Air)				
E2b	16 cm MW	12 cm EPS	Addition of double window: N: PVC + Low-e 6/12/4 (Air) E/W: PVC+Low-e 4/8/4 (Air) S: PVC + Double 4/8/4 (Air)		0,21	0,26	N: 1,2 E/W: 1,6 S: 1,8
E3	16 cm MW	12 cm EPS		Heat recovery	0,21	0,26	
E4	20 cm MW	14 cm EPS			0,17	0,23	
E5	20 cm MW	16 cm EPS			0,17	0,20	
E6	24 cm MW	14 cm EPS			0,15	0,23	
E7	24 cm MW	16 cm EPS			0,15	0,20	

XPS: extruded polystyrene; MW: mineral wool; EPS: expanded polystyrene; AL: aluminum; N: North; E: East; W: West; S: South.

Results and discussion

Goal and scope

The aim of our study was to define the most preferred renovation strategies for residential buildings in Madrid from an environmental and financial perspective. To reach this goal, a comparative analysis of the environmental impact and financial cost of different retrofitting solutions for a representative housing block located in Madrid was made, considering the whole life cycle.

Functional unit

The functional unit, which is the basis for the comparative analysis [16], was defined as 1 m^2 of heated and cooled net floor area of a single unit in a multi-family apartment block, located in Madrid in 2014. A life span of 50 years was considered for two reasons: firstly, the Spanish Building Regulation refers to a life span for building materials of 50 years; secondly, the standard

ECO/805/2003 [48] establishes a life span of 100 years for residential buildings. As it was a housing block with an average age of 50 years, the remaining life span was assumed to be 50 years.

System boundaries

As the scope of the study was to identify the most preferred renovation solutions and as the scenarios analyzed did not differ in amount of existing materials being demolished, the materials of the existing building were excluded from the analysis. Only the impact and cost of new materials and the reduction in energy consumption due to the ESM were considered. The analysis included the production of the required materials for the renovation, transport of the materials to the construction site, construction (limited to the material losses during construction), use stage (maintenance, replacements, heating and cooling energy savings compared to the existing situation) and the end-of-life (EoL) (limited to the separation of waste, the transport to the EoL treatment and EoL treatment, which included landfill and recycling).

Life Cycle Assessment (LCA)

Life Cycle Inventory

Due to the lack of Environmental Product Declarations (EPD) in the construction sector in Spain, the inventory data for the production stage were retrieved from the Ecoinvent version 2.2 database [49]. The best available representative Ecoinvent record was selected for each material [50,51]. The Ecoinvent database is mainly composed of data related to Swiss technologies. In order to make the data more representative for the Spanish situation, the Swiss electricity mix of the processes was adapted to the UCTE (Union for the Coordination of Transmission of Electricity) grid mix (average European grid mix). However, for the cooling of the building, the Spanish electricity mix was used. For the construction stage, data were lacking to quantify the energy consumption and water use related to the construction processes. However, the related emissions were assumed negligible compared to other life cycle stages [52]. Hence only material losses were considered during the construction stage. An average of 5% material loss was considered [20,52]. For the transport of the materials from the factory to the construction site, two types of lorries have been used based on the supplier information, lorry >16 ton and lorry 20-28 ton, for load rates of 18 ton and 24 ton respectively. The distances were considered from the company to the center of Madrid.

For the use phase, the replacements of the materials with a life span lower than 50 years were considered. For the energy calculation, energy savings for heating and cooling compared to the existing building were considered. The systems' efficiency adopted by the Spanish Rating System for existing buildings [53], are 75% for heating production with natural gas and 138.6% for cooling production with electricity. Energy consumption was calculated for every scenario and for the existing building with DesignBuilder based on which the energy savings compared to the existing building were.

With respect to the EoL phase, in Spain most of the waste is currently disposed in landfills, thus occupying a volume which clearly exceeds the volume occupied by domestic waste [54]. However, directives and legislation to reduce and manage building and construction waste have been drawn up both at the European level and at the level of the Member States. Therefore, the EoL treatment was defined according to the Regional Plan of Madrid for the construction and demolition waste management [55], where in addition to landfilling, recycling of certain materials has been considered (Table 4). Waste sorting was considered to be done on site, whereas the average distances to the landfill and treatment plant are 80 km and 50 km respectively. A load rate of 24 ton was considered. Therefore, a lorry of 20-28 ton was adopted.

Table 4. EoL scenario considered

	Product category / Waste category	Landfill (%)	Recycling (%)
17.01	Concrete, bricks, tiles and ceramic products	30	70
17.02.02	Glass	30	70
17.02.03	Plastics	100	0
17.03	Bituminous mixtures	100	0
17.04	Metals	5	95
17.06	Insulation materials	100	0

Energy savings

Regarding to energy issues, energy demand and demand reduction were assessed. The energy demand for each scenario and energy savings compared to the existing building (E0) are presented in Fig. 3. Two red lines are depicted in this graph. They represent the limit thermal demand imposed by the Spanish Building Regulation and the Standard Passive House. The heating demand set by the Spanish Building Regulation for new buildings was not possible to achieve by passive strategies, which can be explained by the technical limitations when retrofitting an existing building. In all the retrofitting scenarios the net cooling demand was lower than the limitation of the Spanish Building Regulation (15 kWh/m^2 year). It was observed that, because of the geometry of the building, the addition of solar protection decreased the cooling demand only 1 kWh/m^2 year, while it increased the heating demand. Therefore they were not considered in this analysis.

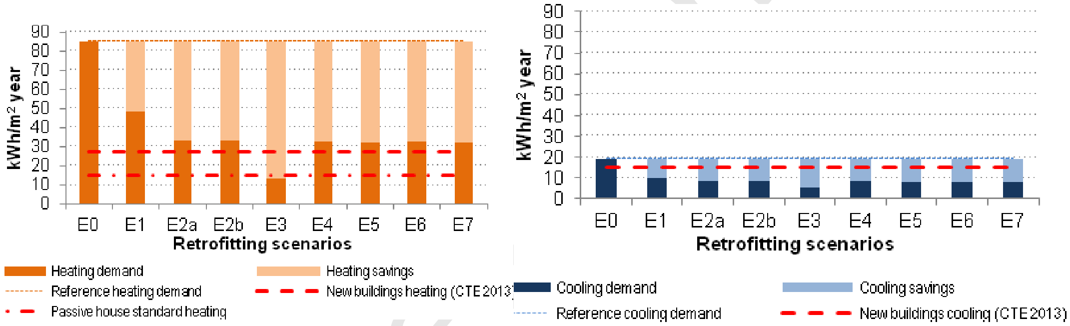


Fig. 3. Net Energy demand and energy demand reduction compared with the existing building of retrofitting scenarios for heating (left) and cooling (right)

Life Cycle Impact Assessment (LCIA)

From an environmental point of view, it was observed that energy savings for heating had the highest influence on the results (Fig. 4), which represented over 95% for ADP-fossil, GWP and ODP, 77% for POCP, 63% for AP, 42% for EP and 10% for the ADP-non fossil. The construction phase had a significant influence (≈20%) for the impact categories ADP-non fossil AP, EP and POCP. The contribution of EoL was small (1%) for all impact categories except for EP, which can be explained by the high impact of landfilling EPS (Expanded Polystyrene), where the chemical oxygen demand (COD) was the main influent substance on the results (85%) (detailed results in Supplementary Table S 1).

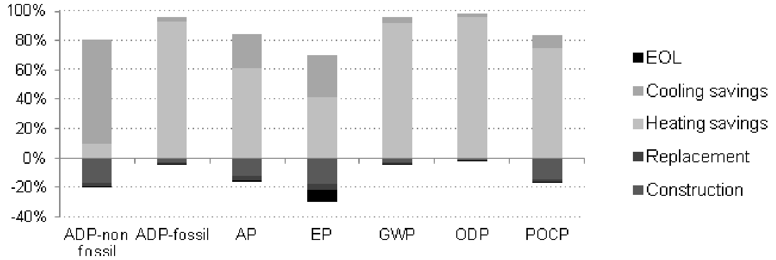
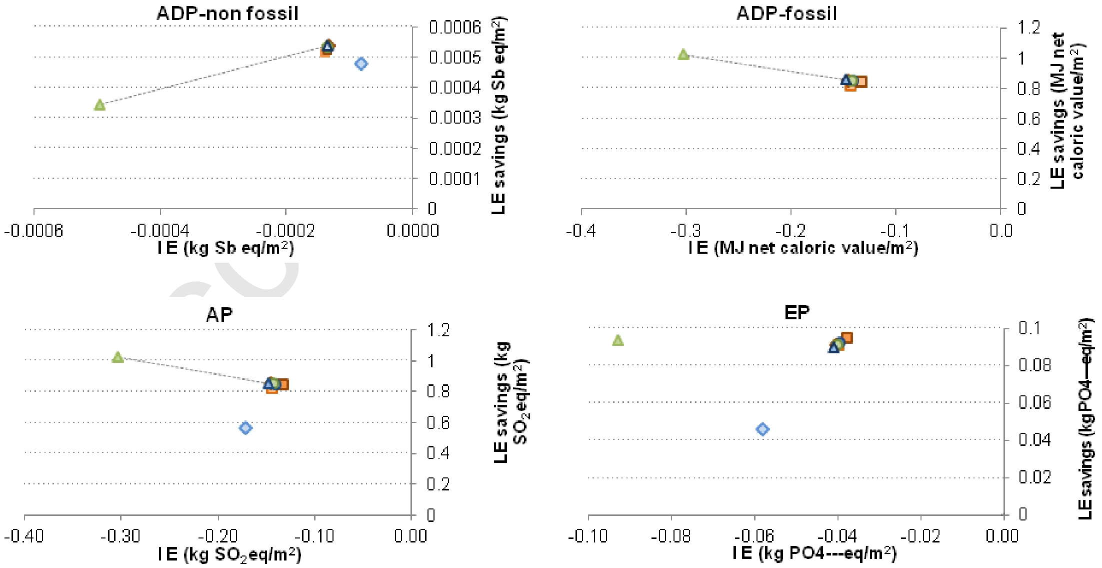


Fig. 4. Contribution of each life cycle stage to the life cycle environmental impact for the E2a scenario

Fig. 5 presents the results from the LCA, considering initial environmental impacts and life cycle environmental savings. According to this, different renovation strategies would be selected based on the impact category considered. For the acidification potential, for example, there are several renovation scenarios appearing in the Pareto front (E2b, E4, E5, E7 and E3), while for the eutrophication potential there is only one optimal scenario (E2b). This analysis highlights the need for aggregation in order to select the most preferred renovation strategies considering all the impact categories simultaneously. In this research, this single score is calculated based on monetary valuation as explained before.



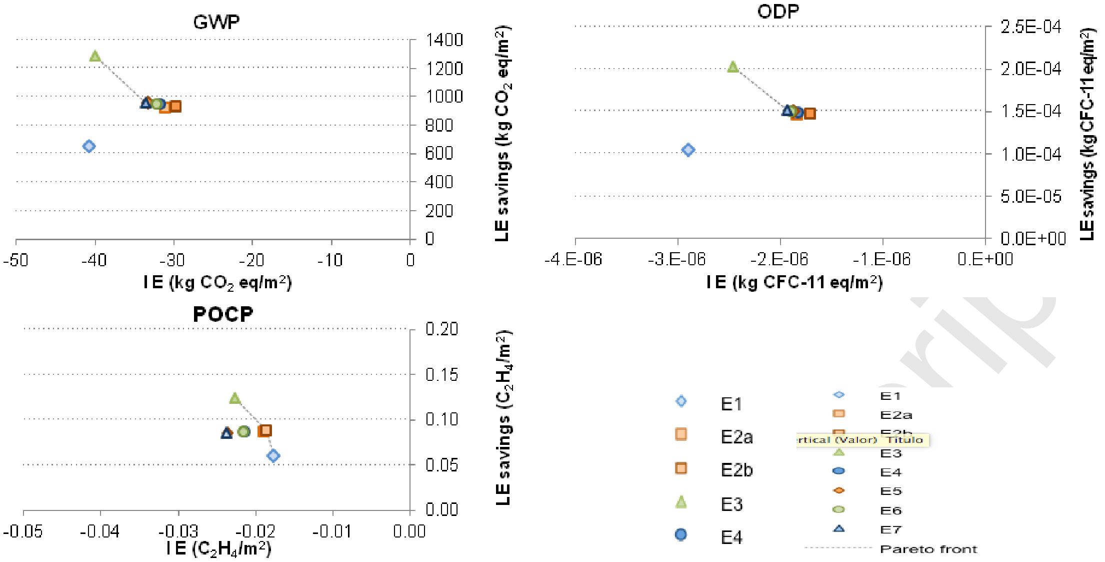


Fig. 5. Evaluation of environmental impacts: overview of the retrofitting scenarios

As illustrated in Fig. 6, the business as usual scenario (E1) has a high IE (environmental investment), while the LE (life cycle environmental) savings are the lowest. Even if the insulation thickness is lower in this scenario, the impact of the aluminum for windows and the XPS for the roof increased the IE cost compared to the other scenarios. The E2a scenario is neither an optimal scenario from the environmental point of view. At least the E2b scenario should be chosen. Scenarios E4, E6, E5 and E7 improve gradually the LE results (higher savings) with an increasing IE. Scenario E3 has the highest IE cost but also the highest LE savings.

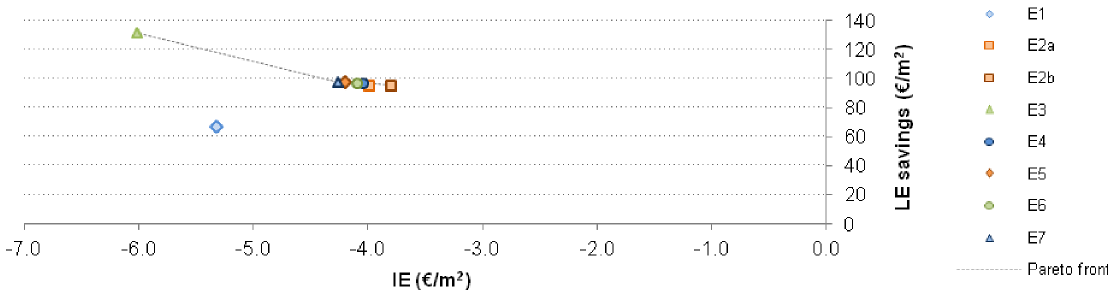


Fig. 6. Environmental cost: overview of the retrofitting scenarios

Life Cycle Cost (LCC)

The scenario to achieve the Passive House standard (E3) is so expensive that even if the energy savings during the life span are the highest, the life cycle financial (LF) savings are the lowest (Fig.

7). Scenarios E1, E2b, E4 and E6 are in the Pareto front. However, from the financial perspective, scenario E1 is not recommended as LF savings are only about half of the savings of scenario E2b which requires only a limited additional investment cost. Scenarios E5, E7 and E2a would be discarded because the initial financial (IF) cost is higher, while the LF savings are lower compared to scenario E6.

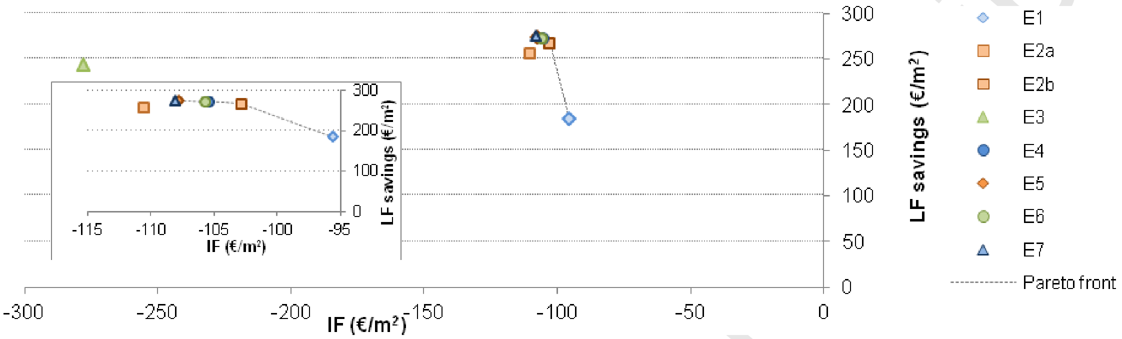


Fig. 7. Economic assessment: overview of the retrofitting scenarios

Multi-criteria optimization

With respect to multi-criteria optimization, the first two sets of objectives were discussed in the sections 4.2 and 4.3. Regarding the objective to achieve the highest LE savings for the lowest IF cost (Fig. 8), scenario E3 has been disregarded from the analysis because of the high investment cost. The high investment cost of scenario E2a, with similar LE savings as other scenarios, prevents it from being an optimal solution. Scenario E1 should only be chosen if the investment budget is limited, as the LE savings are lower (over 30%) compared to all other scenarios. Al least scenario E2b should be adopted, if financially feasible. Compared to scenario E2b, scenarios E4, E6, E5 and E7 lead to higher investment cost with a minor environmental improvement.

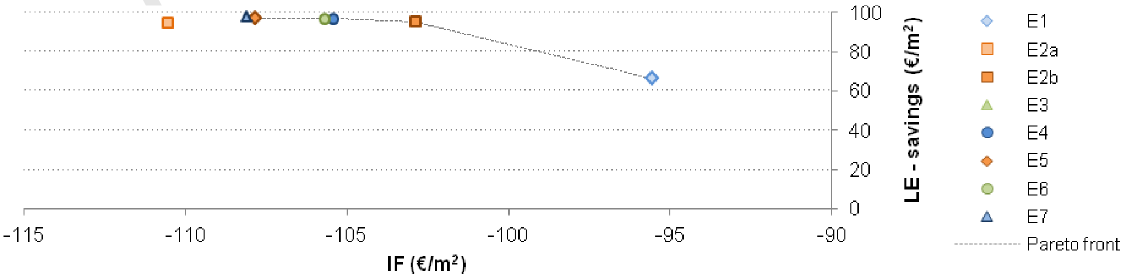


Fig. 8. Initial financial cost vs. life cycle environmental avoided costs of the retrofitting scenarios

As far as life cycle savings are concerned (Fig. 9), only E6 and E7 are optimal scenarios. Although E3 is also optimal, it is discarded due to the high investment cost required. E2b, E4 and E5 are close to being optimal solutions, while E1 (BAU scenario) is far from being an optimal solution.

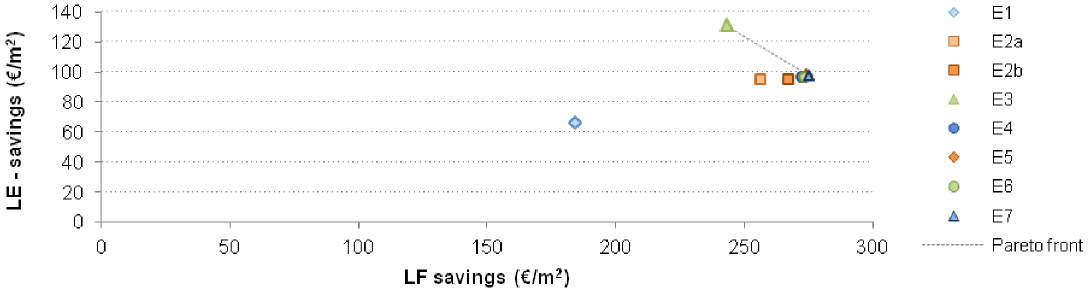


Fig. 9. Life cycle financial (LF) savings vs. life cycle environmental (LE) savings of the retrofitting scenarios

Sensitivity analyses

Sensitivity analyses were made varying the life span of the retrofitting scenarios, the discount rate, the growth rate of energy prices and the monetary values. The environmental and financial results for varying life span are presented in Table 5 indicating the optimal results for the environmental and the financial optimization. While from an environmental perspective, the optimal retrofit scenarios are identical to the ones for a life span of 50 years and hence prove to be robust, from a financial perspective different optima are obtained. The scenario E1 is not cost effective if the life span is reduced to 30 years, as the life cycle savings are negative. Moreover, scenario E7 is not optimal solutions (t=30).

The sensitivity analyses of the discount rate and the growth of energy price are presented in

Table 6. Although the savings decrease/increase to an important extent (around 70%) when increasing/decreasing the discount rate with 1%, the preferred solutions are identical for the three discount rates considered. When adopting a lower growth rate for energy (g=1.75, e=2.5), E3 is not a cost effective scenario anymore. When the growth of energy equals the inflation rate (g=0, e=0), E1, E2a and E3 would not be nether cost effective.

Table 5. Sensitivity analysis: overview of the environmental and financial optimization of the retrofitting scenarios considering varying life spans (30, 50 and 60 years)

Scenario	IE (€)	LEsavings (€) t=30	LEsavings (€) t=50	LEsavings (€) t=60	Scenario	IF (€)	LFsavings (€) t=30	LFsavings (€) t=50	LFsavings (€) t=60
E2b	-3.8	25175654425175756855.70	95.31	115.31	E1	-95.58	51.02	184.04	273.28
E2a	-3.99	55.52	94.93	114.96	E2b	-102.89	94.72	267.09	379.25
E4	-4.04	56.39	96.74	117.19	E4	-105.42	96.44	272.26	385.84
E6	-4.10	56.43	96.86	117.34	E6	-105.68	96.76	273.12	392.96
E5	-4.20	56.81	97.57	118.22	E5	-107.84	97.99	274.05	401.10
E7	-4.26	56.86	97.71	118.41	E7	-108.10	96.67	274.93	402.30
E1	-5.32	37.97	66.51	81.05	E2a	-110.55	87.06	256.24	368.40
E3	-6.01	76.18	131.26	158.69	E3	-	-71.05	243.15	223.69

278.08

◯ Environmental cost optima; ◯ financial cost optima; t: life span

Table 6. Sensitivity analyses: overview of the financial optimization of the retrofitting scenarios considering different discount rates and different growth rates of energy prices

Scenario	IF (€)	251951104 LFsavings (€) r=2	LFsavings (€) r=3	LFsavings (€) r=4	LFsavings (g=0;e=0) (€)	LFsavings (g=1.75;e=2.5) (€)	LFsavings (€) (g=3.5;e=5)
E1	-95.58	276.32	184.04	119.68	-23.68	48.02	184.04
E2b	-102.89	388.18	267.09	182.49	3.79	95.26	267.09
E4	-105.42	395.80	272.26	185.93	4.41	97.48	272.26
E6	-105.68	397.02	273.12	186.52	4.57	97.87	273.12
E5	-107.84	398.93	274.05	186.77	3.72	97.66	274.05
E7	-108.10	400.18	274.93	187.39	3.90	98.08	274.93
E2a	-110.5	376.23	256.24	172.44	-7.06	84.41	256.24

	5						
	-						
E3	278.0		243.15				243.15
	8	234.91		21.55	-161.19	-66.23	

◯ Financial cost optima (for different discount rates); ◯ financial cost optima (for different growth rates of energy prices); r: discount rate; g: growth rate of gas; e: growth rate of electricity

Finally, the sensitivity analysis of the monetary valuation is illustrated in Fig. 10. The same trend is found for low, central and high values.

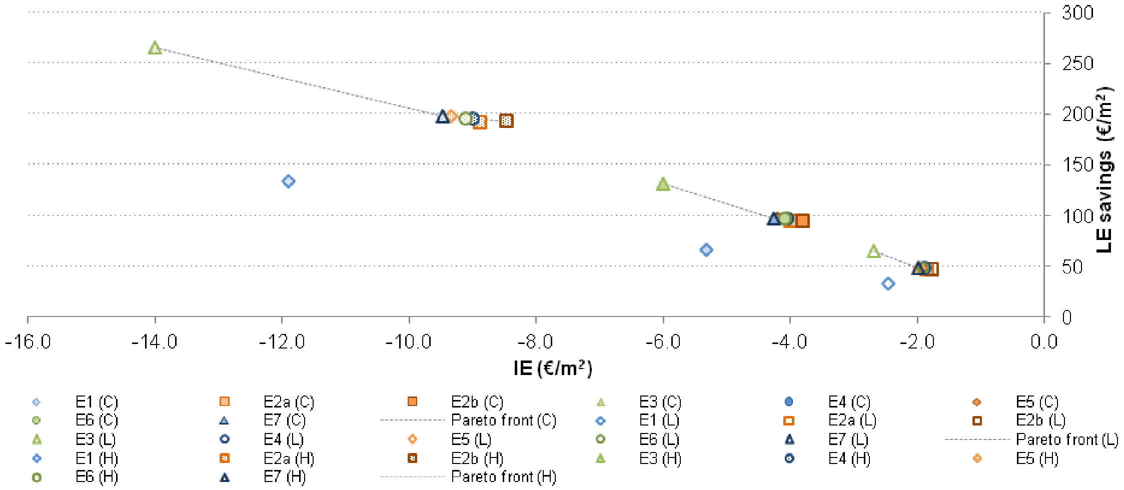


Fig. 10. Sensitivity analysis: overview of the environmental cost considering low (L), central (C) and high (H) values provided in Table 1.

Conclusions

In this paper, a methodology to assess different retrofitting solutions was proposed. It allows evaluating different energy saving measures from an environmental and financial perspective through the life cycle approach. This multi-criteria methodology was illustrated with a case study in Madrid. Spain. The developed methodology proved that monetary valuation allows environmental impacts to be considered as a single score, which enables decision taking in case of contradictory impact results and leads to a much easier comparison of the environmental and economic objectives.

For the building typology analyzed, located in Madrid, the current retrofitting strategies (scenario E1) are not optimal from an environmental point of view. The additional investment needed for a higher insulation level of the building envelope (i.e. scenario E2b compared to common practice to date) is not so high (8%) while it leads to important extra environmental and financial savings (i.e. 43% and 45% respectively). For this type of housing block in Madrid, the requirement of maximum heating demand for the *Passive House* Standard (i.e. 15 KWh/m^2) cannot be achieved through passive strategies. The implementation of a heat recovery system is needed but is so expensive, that from a financial point of view, it is not an optimal solution. With regard to the multi-criteria optimization, scenario E7 is the only one that fulfills all the objectives proposed in the optimization method. However, scenario E2b could also be chosen, as its investment cost is a bit lower (3%). while the difference in the life cycle environmental and financial savings is small (2% and 3% respectively). These small differences are insignificant seen the uncertainty level of the method and data used and hence both scenarios can be seen as preferred options.

Finally, sensitivity analyses were helpful to understand the robustness of the results obtained as a consequence of the uncertainty of parameters and assumptions made.

References

[1] R. Saidur, M.A. Sattar, H.H. Masjuki, H. Abdessalam, B.S. Shahruan, Energy and exergy analysis at the utility and commercial sectors of Malaysia, Energy Policy. 35 (2007) 1956–1966. doi:10.1016/j.enpol.2006.06.013.

[2] J. Terés-Zubiaga, A. Campos-Celador, I. González-Pino, C. Escudero-Revilla, Energy and economic assessment of the envelope retrofitting in residential buildings in Northern Spain, Energy Build. 86 (2015) 194–202. doi:10.1016/j.enbuild.2014.10.018.

[3] A. Aïssani, A. Chateauneuf, J.-P. Fontaine, P. Audebert, Cost model for optimum thicknesses of insulated walls considering indirect impacts and uncertainties, Energy Build. 84 (2014) 21–32. doi:10.1016/j.enbuild.2014.07.090.

[4] T. Häkkinen, Systematic method for the sustainability analysis of refurbishment concepts of exterior walls, Constr. Build. Mater. 37 (2012) 783–790. doi:10.1016/j.conbuildmat.2012.07.084.

[5] National Housing Institute, Population and Housing census 2011, (2014).

[6] F. Nemry, A. Uihlein, C.M. Colodel, C. Wetzel, A. Braune, B. Wittstock, et al., Options to reduce the environmental impacts of residential buildings in the European Union—Potential and costs, Energy Build. 42 (2010) 976–984. doi:10.1016/j.enbuild.2010.01.009.

[7] G. Dall'O', A. Galante, M. Torri, A methodology for the energy performance classification of residential building stock on an urban scale, Energy Build. 48 (2012) 211–219. doi:10.1016/j.enbuild.2012.01.034.

[8] C. Ahern, P. Griffiths, M. O'Flaherty, State of the Irish housing stock—Modelling the heat losses of Ireland's existing detached rural housing stock & estimating the benefit of thermal retrofit measures on this stock, Energy Policy. 55 (2013) 139–151. doi:10.1016/j.enpol.2012.11.039.

[9] É. Mata, A. Sasic Kalagasidis, F. Johnsson, Energy usage and technical potential for energy saving measures in the Swedish residential building stock, Energy Policy. 55 (2013) 404–414. doi:10.1016/j.enpol.2012.12.023.

[10] O. Pombo, B. Rivela, J. Neila, The challenge of sustainable building renovation: assessment of current criteria and future outlook, J. Clean. Prod. (2015). doi:http://dx.doi.org/10.1016/j.jclepro.2015.06.137.

[11] A. Bierer, U. Götze, L. Meynerts, R. Sygulla, Integrating life cycle costing and life cycle assessment using extended material flow cost accounting, J. Clean. Prod. 108 (2015) 1289–1301. doi:10.1016/j.jclepro.2014.08.036.

[12] I. Cetiner, E. Edis, An environmental and economic sustainability assessment method for the retrofitting of residential buildings, Energy Build. 74 (2014) 132–140. doi:10.1016/j.enbuild.2014.01.020.

[13] J. Vrijders, L. Wastiels, Nearly Zero Energy Renovation of houses□: Life cycle costs and environmental impact, in: A. Passer, K. Höfler, P. Maydl (Eds.), Int. Sustain. Build. Conf., Graz, 2013: pp. 87–94. doi:10.3217/978-3-85125-299-6.

[14] O. Pombo, B. Rivela, J. Neila, Is building renovation truly sustainable? The need for applying a multi-criteria assessment through life cycle approach, in: World SB14 Barcelona, Barcelona, 2014: pp. 16–22.

[15] Ministerio de Fomento, Código Técnico de la Edificación, Orden FOM/1635/2013, de 10 de septiembre, por la que se actualiza el Documento Básico DB-HE “Ahorro de Energía”, del Código Técnico de la Edificación, aprobado por Real Decreto 314/2006, de 17 de marzo, Spain, 2013.

[16] ISO 14040, Environmental management – life cycle assessment – principles and framework, CEN (European Committee for Standardisation), Brussels, 2006.

[17] ISO 14044, Environmental management - Life cycle assessment - Requirements and guidelines, CEN (European Committee for Standardisation), Brussels, 2006.

[18] EN 15978:2011, Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method, 2012.

[19] European Comission, ExternE—Externalities of energy. A research project of the European Commission, 2008. www.ExternE.info.

[20] K. Allacker, W. Debacker, L. Delem, L. De Nocker, F. De Troyer, A. Janssen, et al., Environmental Profile of Building elements, (2013) 181. http://www.ovam.be.

[21] L. De Nocker, W. Debacker, Annex: update monetisation of the MMG method (2014), Mechelen, 2015.

[22] K. Allacker, Sustainable Building: The development of an evaluation method, PhD dissertation, 2010.

[23] ISO 15686-5, Buildings and constructed assets -- Service-life planning -- Part 5: Life-cycle costing, 2008.

[24] R.W. Amstalden, M. Kost, C. Nathani, D.M. Imboden, Economic potential of energy-efficient retrofitting in the Swiss residential building sector: The effects of policy instruments and energy price expectations, Energy Policy. 35 (2007) 1819–1829. doi:10.1016/j.enpol.2006.05.018.

[25] J. Ouyang, M. Lu, B. Li, C. Wang, K. Hokao, Economic analysis of upgrading aging residential buildings in China based on dynamic energy consumption and energy price in a market economy, Energy Policy. 39 (2011) 4902–4910. doi:10.1016/j.enpol.2011.06.025.

[26] B. Risholt, B. Time, A.G. Hestnes, Sustainability assessment of nearly zero energy renovation of dwellings based on energy, economy and home quality indicators, Energy Build. 60 (2013) 217–224. doi:10.1016/j.enbuild.2012.12.017.

[27] M. Gorgolewski, Optimising renovation strategies for energy conservation in housing, Build. Environ. 30 (1995) 583–589.

[28] Precios Centro, Pecrio Centro de la construcción Guadalajara 2014, 30th ed., Colegio Oficial de Aparejadores, Arquitectos Técnicos e Ingenieros de Edificación de Guadalajara, Guadalajara, 2014.

[29] CYPE Ingenieros S.A., Generador de precios de la construcción, (2015).

[30] EUROSTAT, Gas prices for domestic consumers - bi-annual data (from 2007 onwards), (2015). http://ec.europa.eu/eurostat/web/energy/data/database (accessed April 20, 2015).

[31] EUROSTAT, Electricity prices for domestic consumers - bi-annual data (from 2007 onwards), (2015). http://ec.europa.eu/eurostat/web/energy/data/database (accessed April 20, 2015).

[32] European Commission, Guidelines accompanying Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings by establishing a comparative methodology f, Off. J. Eur. Union. 55 (2012) C 115/1–C 115/28. doi:10.3000/1977091X.C_2012.115.eng.

[33] INE, Material Price Indices and National Labour Force Indices, Constr. Hous. (2015). www.ine.es (accessed May 20, 2004).

[34] EUROSTAT, Gas prices for domestic consumers - bi-annual data (until 2007), (2009). http://ec.europa.eu/eurostat/web/energy/data/database (accessed April 20, 2015).

[35] EUROSTAT, Electricity prices for domestic consumers - bi-annual data (until 2007), (2009). http://ec.europa.eu/eurostat/web/energy/data/database (accessed April 20, 2015).

[36] R.T. Marler, J.S. Arora, Survey of multi-objective optimization methods for engineering, Struct. Multidiscip. Optim. 26 (2004) 369–395. doi:10.1007/s00158-003-0368-6.

[37] T. Moore, J. Morrissey, Lifecycle costing sensitivities for zero energy housing in Melbourne, Australia, Energy Build. 79 (2014) 1–11. doi:10.1016/j.enbuild.2014.04.050.

[38] C.B. Aktas, M.M. Bilec, Impact of lifetime on US residential building LCA results, Int. J. Life Cycle Assess. 17 (2011) 337–349. doi:10.1007/s11367-011-0363-x.

[39] M. Mequignon, L. Adolphe, F. Thellier, H. Ait Haddou, Impact of the lifespan of building external walls on greenhouse gas index, Build. Environ. 59 (2013) 654–661. doi:10.1016/j.buildenv.2012.09.020.

[40] T. Moore, Modelling the through-life costs and benefits of detached zero (net) energy housing in Melbourne, Australia, Energy Build. 70 (2014) 463–471. doi:10.1016/j.enbuild.2013.11.084.

[41] O. Pombo, B. Rivela, J. Neila, Modelo de edificación para el análisis multicriterio de la rehabilitación del parque residencia madrileño de los años 1950-1980, in: Archit. Res. Find. Build. Constr. Manag. Technol., Escuela Técnica Superior de Arquitectura de Madrid, Madrid, 2014: pp. 412–416.

[42] EnergyPlus, The official building simulation program of the United States Department of Energy. http:/www.eere.energy.gov/buildings/ [accessed 08.05.15]., (n.d.).

[43] IDAE, Manual de fundamentos técnicos de calificación energética de edificios existentes CE3, Madrid, 2012.

[44] O. Pombo, Approbed grant application dossiers by the Municipal Housing and Land Company of Madrid (EMVS). Subsidies to promote the improvement of the sustainability and the energy efficiency of buildings. Internal document, 2013.

[45] IDAE, Condiciones de aceptación de Procedimientos alternativos a LIDER y CALENER, Madrid, 2009.

[46] R. Dylewski, J. Adamczyk, Economic and ecological indicators for thermal insulating building investments, Energy Build. 54 (2012) 88–95. doi:10.1016/j.enbuild.2012.07.021.

[47] O. Kaynakli, A review of the economical and optimum thermal insulation thickness for building applications, Renew. Sustain. Energy Rev. 16 (2012) 415–425. doi:10.1016/j.rser.2011.08.006.

[48] Ministerio de Economía, Orden ECO/805/2003, de 27 de marzo, sobre normas de valoración de bienes inmuebles y de determinados derechos para ciertas finalidades financieras, BOE núm 85, 2003.

[49] Ecoinvent Centre, The ecoinvent version 2.2 database, 2010. http://www.ecoinvent.org/database/ecoinvent-version-2/ecoinvent-version-2.html.

[50] R. Frischknecht, N. Jungbluth, H.-J. Althaus, G. Doka, R. Dones, T. Heck, et al., The ecoinvent Database: Overview and Methodological Framework, Int. J. Life Cycle Assess. 10 (2005) 3–9. doi:10.1065/lca2004.10.181.1.

[51] R. Frischknecht, G. Rebitzer, The ecoinvent database system: a comprehensive web-based LCA database, J. Clean. Prod. 13 (2005) 1337–1343. doi:10.1016/j.jclepro.2005.05.002.

[52] W. Debacker, K. Allacker, C. Spirinckx, T. Geerken, F. De Troyer, Identification of environmental and financial cost efficient heating and ventilation services for a typical residential building in Belgium, J. Clean. Prod. 57 (2013) 188–199. http://www.sciencedirect.com/science/article/pii/S0959652613003752 (accessed January 15, 2014).

[53] J.M. Salmerón, A. Cerezuela, R. Salmerón, S. Álvarez, J.A. Tenorio, Escala de calificación energética para edificios existentes, Madrid, 2011.

[54] O. Ortiz, J.C. Pasqualino, F. Castells, Environmental performance of construction waste: Comparing three scenarios from a case study in Catalonia, Spain., Waste Manag. 30 (2010) 646–54. doi:10.1016/j.wasman.2009.11.013.

[55] Direccion General De Calidad y Medio Ambiente, Plan Regional de Residuos de Construcción y Demolición (2006-2016), 2006.

Highlights:

A multi-criteria methodology for the analysis of retrofitting solutions is proposed.

LCA and LCC are combined by expressing environmental impacts in monetary values.

A Pareto optimization is used to select the preferred strategies.

The methodology is illustrated by a case study in Madrid, Spain.

Business as usual scenario is far from being an optimal solution.