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Extending the concept of high-performance buildings to existing dwellings

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A R T I C L E I N F O

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A B S T R A C T

The ongoing energy crisis in Europe is highlighting the role of the building sector in energy consumption, particularly in countries like Spain, where 90.4% of existing dwellings lack thermal efficiency. Encouraging homeowners to undertake renovations can prove challenging, especially when complex thermal insulation techniques are involved. This study defines the optimal renovation package for six residential building models for 90% of southern Europe climates. Three methodologies were employed for optimal selection: a conventional cost-optimal approach, a method considering the impact of internal insulation on floor loss, and a CO_{2eq} emissions approach based. The findings reveal that, on average, the primary energy demand of existing buildings can be reduced by 57%, with potential savings reaching up to 75% for a cost-optimal approach. Internal insulation significantly has a significant impact on floor loss costs, accounting for up to 60% of a building's life cycle cost, where the property value plays a significant role in the choice of insulation material, especially when considering the same thermal resistance. On the other hand, the CO_{2eq} emission-based approach results in buildings with lower energy demand but more costly. Choosing the most suitable methodology for life cycle assessment requires a balance between economic constraints and environmental considerations.

1. Introduction

Europe is currently living with the consequences of the Russian-Ukrainian conflict, where energy cost volatility along the energy insecurity is inflating the European energy market. The first months of the conflict caused, on average in the EU, a cost increase of 15% for electricity and 34% for natural gas, comparing the first semester of 2022 with the first semester of 2021 [1]. Cutting the EU dependency on Russian gas is highlighted by the gas demand reduction plan of the European Commission, which asks all Member States to reduce their dependence on gas by 15% [2]. Each Member State should promote the integration of renewable power, fuel switching in industries and power plants, demand-side flexibility in the electricity sector as well as the reduction of heating and cooling demand in the building sector [3].

This energy crisis is underlining the fact of the building sector represents a non-depreciable impact on the energy demand. Over the lasted years we have seen a refinement of the requirements for the building's thermal envelope [4] to lead to buildings less energy-demanding without compromising the comfort of the occupants. But this refinement has a limited application to the new buildings or buildings subject to renovation. Nevertheless, renovating a building, if not mandatory by law, is in most cases a voluntary decision. The main motivations for renovating a building rely on reducing energy costs and vulnerability to the energy market, increasing the property value and the ability to return the investment [5]. Yet, why building renovation is a hot topic if the decision to renovate relies mostly on private entities? The interest in this topic relies on the poor reality of EU building stock where most of the buildings are not energy-efficient [6], especially if we consider that 85% of the existing buildings were built before the first Energy Performance Buildings Directive (EPBD) [7]. In light of that the European Commission developed an EU Renovation Wave program to improve the thermal envelope of existing building stock [7].

Currently, all Member States have already defined their program for building renovation with targets very ambitious [8]. The Spanish Government in their 2020 renovation program expects to reach 1.2 million renovated dwellings in 2030, i.e., 120 thousand renovated dwellings per year. But according to the last report of the Spanish Housing and Planning Observatory [9], between 2017 and 2022, 26.3 thousand dwellings per year, on average, were renovated, far behind the projections. The reality of Spanish dwelling stock is an alarming scenario where 90.4% of the existing dwellings, i.e., 23.5 million dwellings [10] will require

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Nomenclature

Abbreviations

ACH	Air-change per hour
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
COP	Coefficient of Performance
EPBD	Energy Performance Building Directive
EU	European Union
EPS	Expanded Polystyrene
XPS	Extruded Polystyrene
U-value	Heat transfer coefficient value
HVAC	Heating, Ventilation and Air-conditioning
LCA	Life cycle assessment
LCC	Life cycle cost
MW	Mineral Wool
PIR HFO	Polyisocyanurate Hydrofluoroolefin
TMY	Typical Meteorological Year

Symbols

n_{50}	Air–change rate at 50 Pa (h^{-1})
f_{CO_2}	CO_2 conversion factor (kg CO_{2eq}/kWh_f)
c_{100}	Coefficient of air permeability at 100 Pa (m^3/h·m^2)
η	Efficiency (-)
r_{inf}	Expected inflation rate (-)
c_{op}	Expected operation cost (€/year)
$c_{floor\ loss}$	floor loss cost (€m^2)
LCC	Life cycle cost (€/m^2)
LCC_f	Life cycle cost including floor loss cost (€/m^2)
LCE	life cycle emissions (kg CO_{2eq}/m^2)
r	Real interest rate (-)
r_{ref}	Reference interest rate (-)
ρ	Reflectivity (-)
$g_{\perp}$	Solar heat gain coefficient (-)
E_i	The building's final energy demand for the energy vector i (kWh/m^2•year)
U_G	The weighted average of the U-value of all building external surfaces (W/m^2•K)
e_{insu}	Total embodied CO_2 emissions of the insulation material (kg CO_{2eq}/m^2)
I_t	Total renovation investment (€)
$\Delta U\varphi$	Transmittance increment due to thermal bridges (W/m^2•K)
U_{wind}	Window heat transfer coefficient (W/m^2•K)

intervention due to a lack of thermal envelope requirements or a light building code [11] when compared to the Technical Building Code in force [12]. Despite the economic viability of many energy-efficient renovation strategies, there is a relatively low level of implementation of them, mainly because the decision relies exclusively on homeowners and, sometimes, on subjective criteria [5]. To overcome the economic constraints that householders face at the moment of setting up a renovation project, the Spanish government made available in the last semester of 2021 a rehabilitation funding programme [13], unfortunately, there is no data on program execution.

Motivating a homeowner to renovate their home could be a hard task, especially in cases where the urban or architectural restrictions oblige a non-invasive technique of thermal insulation increasing the complexity of the renovation project. Therefore, improving the sustainability of some built heritage may require a usable floor area loss to accommodate insulation systems, as introducing a new hygrothermal behaviour of the wall surface [14]. Finding a good balance between different aspects is still considered a challenge [15].

In a scenario where almost of existing buildings will be standing in the next decades, improving their thermal behaviour is a priority [16]. The main objective of renovating a building is to reduce the energy demand on conditioning systems, but the final impact of this process goes further, increasing its lifespan along with a conception of a comfortable indoor environment. This topic is highly explored and the literature is very clear on the benefits of requalifying the existing building stock (see Table 1). Still, the level of retrofit will depend on the characteristics of the building, and in some cases, the retrofit strategy can focus only on upgrading the ventilation and conditioning systems [17].

Most of the identified studies are concerned with the impact of retrofit measures on reducing heat losses through the building envelope. External thermal insulation is the typically adopted solution in renovation cases due to its almost "plug-in" characteristic and the possibility of correcting the thermal bridge effect without causing a significant impact on the building's liveability during the intervention [14,18]. The main objective of the identified studies is to define the optimal insulation solution for a certain building by exploring different insulation materials and thicknesses [19–26] along with other adjacent themes (innovative materials, renovation strategies, simulation tools, characterization of renovated buildings, etc…) [27,29–42]. Assuming the possibility of improving the thermal envelope by the outside layer can be very optimistic, especially in Europe where 90% of the EU building stock is built before 1990 and approximately 50% was constructed before 1970 [6]. Overcoming possible architectural restrictions, on a first approach, could pass by filling the façade wall air cavity with insulation foam, a possibility for most of the 20th-century EU buildings [55]. Yet, the air cavity length varies typically between 25 and 300 mm across Europe [55], so depending on the building case and location this measure efficacy can be limited by the available space in the cavity requiring an additional insulation layer to fulfil all the requirements.

In the end, the solution for ensuring a less demanding building stock should include internal insulation as pointed out in the RIBuild project [56]. This European project explored the constraints and impacts of integrating interior insulation to establish a guideline for suitable interior insulation solutions. Applying an interior solution will change the hygrothermal balance of the surfaces, making the original wall structure colder than the added materials [14]. Consequently, this represents a risk of moisture accumulation in the wall interlayer, and combined with the condensation effect can lead to a potential mould occurrence as well as damaging the surface integrity by freeze–thaw action [43,44,57]. The risks of damage can be mitigated when the insulation solution includes a vapour barrier and hydrophobic plasters or materials with low moisture absorption capacity [14,43]. Nonetheless, the energy performance of a building is improved by decreasing the heat losses through the thermal envelope as highlighted in the RIBuild project [14] and in other works where internal insulation was explored [43–54].

One of the limitations of internal insulation is the impossibility of correcting and mitigating all the existing thermal bridges caused by embedded elements (windows, partitions, slabs, ceilings, etc.) along with the consequence of causing a loss of usable floor area [14,54]. So far, the possibility of losing usable floor area seems a poorly quantified consequence. In most cases, this effect is neglected [45–52] or is not accounted [44,53]. The RIBuild project guidelines [14] mention that in some cases the loss of usable space could not be neglectable, but the developed web tool [58] for the assessment of internal insulation does not consider the possible impact on space loss. Also, the available methodologies developed for applying automatic architectural design to building renovation seem not to include any constraint on the loss of

Table 1
Summary of studies of building renovation strategies.

Building type (n° of models studied)		Location	Type of renovation	Insulation strategy	Impact on floor area	Comment	Reference
Detached Multifamily Semi-detached Multifamily	(1) (1)	Sweden (Gothenburg)	Full	External	n/a	Explores the impact of the renovation process on the resident's life quality.	[18]
Detached Multifamily Attached Single-family Detached Single-family	(6) (1) (2)	Albania	Partial	External	n/a	The optimal thickness of wall insulation is defined for the Albanian building stock based on a degree-day method.	[19]
Detached Office	(1)	Italy	Full	External	n/a	–	[20]
Detached Multifamily Semi-detached Multifamily	(2) (2)	Estonia	Full	External	n/a	Assess the cost of renovating existing buildings by applying the criteria for a major renovation, a new building, and a low-energy building.	[21]
Detached Multifamily	(1)	Russia (Moscow)	Full	External	n/a	–	[22]
Attached Multifamily Detached Multifamily Perimeter Block Multifamily	(11) (1) (5)	Spain (Bilbao)	Full	External	n/a	Evaluates the optimal insulation solution at the neighbourhood level.	[23]
Detached Multifamily	(4)	Portugal (Braga)	Full	External	n/a	Proposes a methodology for an assessment of cost-effective building renovation. Do not mention or considers the possibility of internal insulation and its impacts.	[24]
Attached/Semi-attached Multifamily	(1)	Spain (Bilbao)	Full	External	n/a	–	[25]
Semi-detached/ Attached Multifamily	(1)	Austria (Kapfenberg)	Full	External	n/a	–	[26]
Elementary School	(1)	Czech Republic (Brno)	Full	External	n/a	–	[26]
Semi-detached/ Attached Multifamily	(1)	Denmark (Hvalsø)	Full	External	n/a	–	[26]
Detached Multifamily	(1)	Portugal (Porto)	Full	External	n/a	–	[26]
Attached Multifamily	(1)	Spain (Tudela)	Full	External	n/a	–	[26]
Semi-detached Multifamily	(1)	Sweden (Gothenburg)	Full	External	n/a	–	[26]
Cultural Centre (Historical)	(1)	Korea	Partial	External	n/a	An innovative vacuum insulation panel for the ceiling is tested.	[27]
Multifamily[(a)]	(5)	Portugal (Lisbon)	Full	External	n/a	The authors do not mention the insulation solution applied. Is assumed external due to the recommendation of the Portuguese Building Code [28].	[29]
Detached Multifamily Attached/Semi-attached Multifamily	(2) (4)	Spain (Mengíbar)	Full	External	n/a	Explores the impact of introducing a ventilated roof integrated with an evaporative cooling system.	[30]
Multifamily[(a)] Single-family[(a)]	(4) (4)	Portugal (Lisbon)	Partial	External	n/a	Assess the global warming potential of different external insulation solutions.	[31]
Attached Multifamily Detached Multifamily	(1) (1)	Switzerland	Full	External	n/a	Proposes a methodology of an integrated life cycle cost analysis and life cycle assessment for building renovation. Do not mention or considers the possibility of internal insulation and its impacts.	[32]
Attached Multifamily	(1)	Italy, Greece Latvia	Full	External	n/a	Deep renovation based on adding external façade elements.	[33]
Semi-detached Single-Family	(1)	Poland (Gliwice)	Full	External	n/a	Assess on-site the impact of the thermal envelope improvement.	[34]
Attached Multifamily	(4)	Spain (Andalusia)	Partial	External	n/a	Neglects the effect of improving the roof insulation in a climate zone with a warm or very warm summer.	[35]
Semi-detached/ Attached Multifamily	(10)	Spain (Seville)	Partial/Full	External	n/a	Compares single and packaged improvement measures.	[36]
Attached Multifamily	(1)	Switzerland	Full	External	n/a	Explores external thermal insulation based on biomaterials.	[37]
Multifamily[(a)]	(3)	China (Tianjin)	Full	External	n/a	Assess the impact of improving the building's thermal insulation level through a quasi-stationary method.	[38]
Day-care centres[(a)]	(16)	Shout Korea (Seoul)	Varies	External	n/a	The renovation strategies are applied only to the building element that requires an improvement or replacement.	[39]
Multifamily Detached Multifamily Detached/ Semi-detached	(2) (1)	Shout Korea	Full	External	n/a	Explores the integration of modular insulation panel solutions for façade, roofs, and balconies.	[40]

(*continued on next page*)

Table 1 (*continued*)

Building type (n° of models studied)		Location	Type of renovation	Insulation strategy	Impact on floor area	Comment	Reference
Service /Commercial Detached	(1)						
Multifamily Detached	(1)	Greece (Moschato)	Full	External	n/a	Assess the impact of renovation strategies using a developed detailed dynamic software tool.	[41]
Attached/Semi-attached Multifamily	(1)	Italy (Bologna)	Partial/ Full	External	n/a	Compares two levels of renovation: roof and window thermal improvement versus all external surfaces thermal update.	[42]
Historical[(a),(b)]	(1)	Latvia (Riga)	Partial	Internal	Accounted	Based on a TOPSIS grey method assess which interior insulation corresponds to the best solution. The loss of usable floor is accounted as a ponderation factor, but its cost is not considered.	[43]
Historical[(b)]	(-)	Poland	Partial	External and internal	Not accounted	Assess the renovation strategies to improve the thermal transmittance of a timber-framed wall of historical buildings.	[44]
Multifamily[(a)]	(-)	Denmark	Partial	Internal	Not accounted	Focuses only on the wall insulation and the reduction potential of the wall U-value and thermal bridges. No building model is considered, and energy savings are based on the U-value reduction.	[45,46]
Multifamily[(a)]	(1)	China (Harbin, Beijing)	Partial	Internal	Not accounted	Explores the impact of internal insulation with fibreglass board on the wall and floor of an apartment building.	[47]
Student Dormitory (Semi-attached)	(1)	Denmark (Copenhagen)	Partial	Internal	Not accounted	Accounts for the impact of inside thermal insulation on the average indoor temperature and the surface wall temperature.	[48]
Multifamily[(a)] Single-family[(a)]	(5) (6)	Portugal	Full	External and internal	Not accounted	Internal and external insulation is applied depending on the age of the building.	[49]
Detached Multifamily	(1)	Sweden	Full	External and internal	Not accounted	Internal insulation is only applied to the basement walls.	[50]
Detached/Semi-detached Multifamily	(1)	Spain	Full	External and internal	Not accounted	A sensitivity analysis is performed for four locations in Andalucía to define the most suitable renovation solutions.	[51]
Multifamily[(a)] (Dwelling) Single-family Detached Hospital/Clinic[(a)] High School[(a)] Supermarket[(a)]	(1) (1) (1) (1) (1)	Portugal	Partial	External and internal	Not accounted	Studies the optimal thickness of insulation for external walls, considering the application of the insulation by the interior, exterior and by filling the wall airgap. A 5R1C model is applied to estimate the building's thermal behaviour.	[52]
Multifamily[(a)]	(1)	China (Beijing)	Full	External and Internal	Not accounted	Assess the economic benefits of building renovation based on a limit value method and a Lagrangian optimization method. A steady-state method is used to compute the building energy demand.	[53]
Multifamily Detached Multifamily Attached	(1) (1)	Serbia (Belgrade)	Full	External and internal	Accounted	Compares external and internal thermal insulation solutions applied on historical buildings using KnaufTERM 2 PRO software. The considered insulation material is not mentioned. Also, the cost of floor loss is not quantified.	[54]

[(a)]the urban context is not specified.
[(b)]the type is not stated.

usable floor area [59]. However, accounting for the impact of usable floor loss potential can condition the selection of the insulation material thickness [43,54].

Another challenge in building renovation is overcoming the risk of occurring overheating events by having a more efficient thermal envelope. This risk is well identified [60] and mitigating them is only possible if the renovated building is equipped with a passive or active cooling system [61,62]. Currently are being explored new techniques of external insulation that possibilities the adjustment of the thermal resistance of the façade to the prevailing environmental conditions. Introducing dynamic insulations on buildings can effectively reduce the overheating risk and therefore the cooling needs, but their integration in buildings envelopes, and especially in existing buildings, seems to be difficult since many of these systems are under development [63,64]. Even so, upgrading the existing buildings must include a global overview of the interventions and their implications on the thermal behaviour of the indoor environment, occupants and building aesthetics [65,66]. Additionally, this overview must include a procedure for materials selection and the reuse potential of materials to minimise the emissions embedded in building elements [16].

Nowadays, a sustainable renovated building besides its high energy efficiency must reduce, at possible, the integration of materials with a significant carbon footprint, including of course the insulation materials based on synthetic plastics or fibres [67]. Efforts are being done to develop natural-based insulation materials suitable for indoor environments with a thermal conductivity similar to mineral wool [68], and some natural fibre insulation panels can already provide thermal conductivities lower than the traditional solutions (0.0094 to 0.0125 W/m•K) [67]. Also, converting cardboard on insulation panels is already possible but has a high thermal conductivity compared to the synthetic solutions (0.076 to 0.112 W/m•K, depending on the binding agent) [69]. Still, the dissemination of natural-based insulation materials is limited by their low availability and high price as the susceptibility to moisture accumulation and thermal performance deterioration [67,70]. Along with that, data on their impact on indoor air quality health is currently missing [71]. In the end, the conventional solutions will prevail until the alternative solutions are fully developed and industrialized [67]. Therefore, making a selection of insulation materials should rely

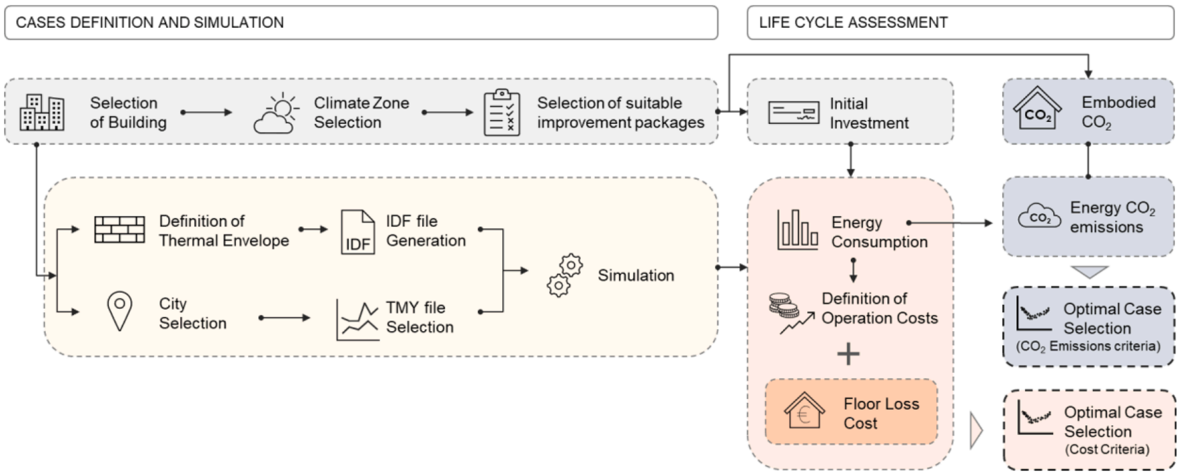


Fig. 1. Scheme of the optimal case selection procedure.

Table 2
Correspondence between the Spanish Peninsular Climates and the Köppen -Geiger Climate Classification.

Spanish Peninsular Climates	Köppen -Geiger Climate Classification
A3	BWk
A4	BWh
B3	BSk
B4	BSh
C1	Cfb
C2	Cfa
C3	Csa
C4	Csa / Cfa
D1	Cfb
D2	Cfa
D3	Csa
E1	Cfc / Dfc

on their impact on the building demand, the total embodied energy and carbon, the installation cost and the comfort level of the renovated space [72].

This study assesses the influence of floor loss area on the definition of the thermal envelope during building renovation. It introduces two novel methodologies for selecting internal insulation materials based on environmental and economic factors. A representative sample of six buildings from the Spanish building stock [73,74] is considered, consisting of three single-family buildings and three multifamily buildings. This allows for a comprehensive analysis of how geometry affects the impact of internal insulation on floor loss, as well as the assessment of energy savings potential in the renovated building stock. Different renovation packages based on typical insulation materials [56] are simulated across fifty locations in peninsular Spain, covering 90% of the Southern European climates. The novelty of this study relies on its comprehensive characterization of the influence of floor loss area on building energy performance, proposing a cost-optimal methodology adapted for building renovation. The findings of this research will provide valuable insights for regulatory authorities in their future review of building renovation programs, particularly in the definition of renovation packages suitable for each building typology and climate zone.

2. Methodology

Defining the optimal renovation strategy depends on the climate zone as well as on the building typology and geometry being a complex solving problem that demands intensive simulation procedures. In previous works, for residential buildings, as a strategy to overcome that limitation, some authors focused on one or few climate zones [21,23,29–31], in one building typology [34,51] or one building typology and one climate zone [24–26,35–38]. Also, some methodologies are based on simplified methods for energy demand calculation [45,52]. Moreover, when internal insulation is considered the impact of floor loss is neglected [44–47,49–54]. This work, in another way, considers six geometries (three multifamily buildings and three single-family buildings), a thermal envelope per climate zone giving a total of thirty building models. Also, full coverage of all nine Köppen-Geiger climates of the Spanish peninsular is guaranteed by considering a typical meteorological year (TMY) for each provincial capital, 50 in total. The energy demand is assessed considering the typical range of room temperature of 20–25 °C [12,75] using the most common conditioning systems in Spanish homes (boiler and air-conditioning) [76,77], no equipment replacement or retrofit is explored to ensure a fair comparison between cases. To perform this massive simulation was developed a VBA Excel® app that was able to define all the improvement packages, select those that fulfil the thermal envelope requirements and generate an IDF file according to the building model and their location, run a simulation on EnergyPlus and save the results. Three methodologies of optimal selection are applied to the study cases. The first one is the traditional cost-optimal approach referred on the last version of the Delegate Regulation (EU) n.° 244/2012 [78]. The second methodology accounts for the cost of floor loss caused by the internal insulation solution considering the average market price data for dwellings of the Spanish Housing and Planning Observatory [9]. The last method selects the optimal package with a lower CO_{2eq} emission. Fig. 1 schematizes the optimal case selection procedure considered.

Section 2.1 presents the considered climates (sub-section 2.1.1), building models (sub-section 2.1.2.) and indoor conditions (sub-section 2.1.3.). The improvement packages are found in Section 2.2. while the life cycle cost assessment and its methodologies are presented in Section 2.3.

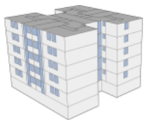
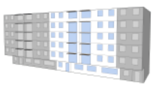
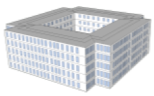
2.1. Case study

2.1.1. Climate

Southern and central Europe predominantly experience warm temperate (C) and continental (D) climates [79]. Based on data from the Spanish Meteorological Agency (ANMET) [80], approximately 77.4% of the peninsula is characterized by a warm temperate climate (60.2% Cs and 17.4% Cf), while 21.6% is classified as a dry climate (21.3% BS and 0.3% BW). Only 0.8% of the Spanish peninsula falls under a continental climate (0.3% Ds and 0.5% Df). It is worth noting that 90% of southern European climates are present in the Spanish peninsula [79,80].

For the purpose of this study, the climate zones considered are

Table 3
Geometrical characteristics of the studied buildings.

Building type		N.° floors	N.° dwellings	Wall Area[(a)] (m^2)		Glazed Surface Ratio[(b)] (%)	Roof Area (m^2)	Floor Area (m^2)	Conditioned Floor Area (m^2/dwelling)	Average Ceiling High (m)	Compactness (m)
Detached Multifamily		6	18	(N)	403.0	18.1	279.1	279.1	85.3	2.3	2.0
				(E)	275.9	9.4					
				(S)	403.0	16.5					
				(W)	275.9	13.3					
Attached Multifamily		6	13	(N)	302.6	22.6	214.5	163.8	89.6	2.6	3.3
				(E)	–	–					
				(S)	302.6	33.6					
				(W)	–	–					
Perimeter Block (Multifamily)		5	67	(N)	556.4	23.7	1 221.3	1 221.3	71.3	2.7	3.5
				(E)	567.4	23.6					
				(S)	556.6	23.7					
				(W)	566.8	23.3					
Detached Single-family		2	1	(N)	44.8	7.0	61.6	47.8	102.3	2.4	0.9
				(E)	39.7	16.1					
				(S)	45.0	8.7					
				(W)	39.8	19.5					
Attached Single-family		2	1	(N)	33.0	19.1	53.0	57.0	99.8	2.7	1.2
				(E)	3.0	–					
				(S)	33.0	34.3					
				(W)	–	–					
Semi-detached Single-family		2	1	(N)	3.0	–	53.0	57.0	99.8	2.7	1.5
				(E)	33.0	34.3					
				(S)	55.5	5.1					
				(W)	33.0	19.1					

[(a)]the wall area and the glazed surface area are presented by orientation, where (N), (E), (S) and (W) stand for North, East, South and West, respectively.
[(b)]the glazed surface ratio is defined as the square meter of glazed surface per square meter of the wall surface.

summarized in Table 2. This table provides an overview of the overlapping Köppen-Geiger climate classification for Spain's peninsula [80] and the climate classification defined by the building code [12,81]. The building code categorizes climates based on the severity of winter and summer seasons [82], dividing Spain into five winter zones (A to E, from hottest to coldest) and four summer zones (1 to 4, from coldest to hottest), indicating the climatic severity of each location.

To conduct building thermal simulations, a minimum of one year of weather data on an hourly basis is required. Consequently, a freely available weather database was utilized to generate typical meteorological years (TMY) that accurately represent the current climate for the 50 Spanish provincial capitals: Climate.OneBuilding.Org [83]. This database offers TMY files based on collected data from weather stations spanning the period from 2007 to 2021. The TMY files were created in the.epw format, enabling building thermal simulations using EnergyPlus. These simulations rely on accurate and representative weather data to evaluate the thermal performance of buildings under various conditions.

2.1.2. Buildings

The case study includes a sample of six buildings, three buildings of single-family typology and the remaining of multifamily typology (Table 3). These six buildings are defined as reference buildings of the building stock by the Spanish Directorate for Architecture, Housing and Planning [73,74], for the cost-optimal calculations report under the Energy Performance Buildings Directive (Directive 2010/31/EU). This building sample represents the new and existing buildings in Spain, such that, the reference buildings must be as representative as possible of the national building typologies and historic changes in building tradition [84].

52.4% of Spanish existing dwellings were built before 1979 under no regulation focused on energy performance, and 38.1% were built following the requirements of the first building code [6,10]. To overcome the poor characterization of the oldest dwelling stock is assumed that the reference building's thermal envelope is given by the first thermal building regulation. Spain adopted its first building thermal code in 1979 under the Royal Decree 2429/1979 of July 6 (NBE-CT-79) [11] as a consequence of the 1970 s oil crisis [85]. Is not considered the dwellings built after 2006 due to the refinement of the building code and these represent only 9.6% of the dwelling stock.

Each building's thermal envelope was defined to fulfil strictly the regulation requirements, i.e, each surface U-value and air permeability defined corresponds to the maximum allowed value by the building code. The thermal envelope is defined according to the climate zone and the building's compactness[(1)], where lower U-values are required for colder climates and less compact buildings. It also accounted for the lineal thermal bridge effect by incrementing the U-value of each surface. This increment corresponds to the average increment of the building's overall U-value. This effect was accounted for using the recommended values in the literature [86,87]. Table 4 presents the thermal characteristics of each building attending the regulation diploma and the climate zone.

2.1.3. Indoor conditions and energy systems

The reference indoor range temperature was defined as 20–25 °C, which corresponds to the definition of room temperature [75], as also the neutral comfort range indicated by ASHRAE [88] and the Spanish Building Technical Code [12]. The final energy demand is given by the HVAC template models of EnergyPlus for the most common heating and cooling technologies of Spanish homes, being these a gas boiler ($\eta = 0.92$) and an air-conditioner (split unit, COP = 2.90) according to Building Technical Code Standard DB-HE0 [77] and the housing characteristics survey [76].

The occupancy profile was defined according to Ahmed *et al.* [89]. Also was considered the suggested appliances and lighting usage profiles for residential buildings [89]. Regarding the last household survey in Spain [90], it was assumed for each dwelling a nominal occupancy of 3 persons. The HVAC model considers a minimum outdoor airflow to

(1) Is given by the ratio between the conditioned volume and the exterior surface area.

Table 4
Reference building thermal envelope characteristics by climate zone: the surface U-value, the solar heat gain coefficient of windows ($g_{\perp}$), the surface U-value increment due to thermal bridges ($\Delta U\varphi$), the surface average air permeability at 100 Pa (c_{100}) and the air-change rate at 50 Pa (h^{-1}).

Building type	Climate Zone	Surface U-value (W/m²•K)				$g_{\perp}$ (-)	$\Delta U\varphi$ (W/m²•K)	c_{100}(m³/h·m²)	n_{50} (h^{-1})
		Wall	Roof	Floor	Window				
Detached Multifamily	A	1.65	1.28	1.83	4.66	0.83	0.39	31.6	8.3
	B	1.27	0.99	1.41	3.60				
	C	1.06	0.80	1.20	3.25			27.9	7.3
	D	0.97	0.63	1.04	3.11				
	E	0.94	0.47	1.07	3.00				
Attached Multifamily	A	1.91	1.49	2.13	5.41	0.83	0.33	33.4	5.3
	B	1.48	1.15	1.64	4.18				
	C	1.22	0.92	1.37	3.73			27.1	4.3
	D	1.11	0.72	1.19	3.57				
	E	1.08	0.54	1.23	3.45				
Perimeter Block (Multifamily)	A	2.10	2.50	2.40	5.85	0.83	0.34	32.2	4.3
	B	1.76	1.37	1.96	4.99				
	C	1.47	1.10	1.65	4.50			27.6	3.7
	D	1.36	0.88	1.46	4.36				
	E	1.32	0.66	1.51	4.24				
Detached Single-family	A	1.43	1.12	1.59	4.05	0.83	0.21	30.9	18.5
	B	1.11	0.86	1.23	3.13				
	C	0.93	0.70	1.05	2.84			28.2	16.8
	D	0.86	0.56	0.92	2.76				
	E	0.84	0.42	0.95	2.68				
Attached Single-family	A	1.71	1.33	1.90	4.84	0.83	0.18	32.0	9.0
	B	1.32	1.03	1.47	3.73				
	C	1.10	0.83	1.24	3.37			27.7	7.8
	D	1.03	0.66	1.10	3.30				
	E	1.01	0.51	1.15	3.22				
Semi-detached Single-family	A	1.51	1.18	1.68	4.27	0.83	0.18	31.4	12.9
	B	1.17	0.91	1.30	3.30				
	C	0.98	0.73	1.10	2.99			28.0	11.5
	D	0.91	0.58	0.97	2.90				
	E	0.88	0.44	1.00	2.81				

Table 5
Packages and levels of improvements and their costs.

Packages	Levels of improvements and costs
Surface Insulation	Roof: external (material cost in Table 6 + 1.948 €/m²) (a) (b) Floor: internal (material cost in Table 6 + 2.380 €/m²) (a) (b) Wall: internal (material cost in Table 6 + 2.004 €/m² for MW and 5.00 €/m² for others) (a) (b)
Windows	Double glazing + PVC frame: U_{wind} = 2.60 W/m²/K + $g_{\perp}$ = 0.78 (291.6 €/m²) (c) U_{wind} = 2.00 W/m²/K + $g_{\perp}$ = 0.65 (311.0 €/m²) (c) U_{wind} = 1.80 W/m²/K + $g_{\perp}$ = 0.61 (319.2 €/m²) (c) Low emissivity double glazing + PVC frame: U_{wind} = 1.40 W/m²/K + $g_{\perp}$ = 0.45 (340.0 €/m²) (c) U_{wind} = 1.30 W/m²/K + $g_{\perp}$ = 0.39 (346.5 €/m²) (c) Low emissivity triple glazing + PVC frame: U_{wind} = 0.75 W/m²/K + $g_{\perp}$ = 0.43 (662.4 €/m²) (c) All windows have a c_{q100} of 3 m³/(h·m²) (class 4 of air permeability [96])
Night Ventilation System	ACH = 10 h^{-1} (8 €/m²) (d) ACH = 15 h^{-1} (12 €/m²) (d)
Solar Control of Southern Windows	Reflective shade (ρ = 50%, 90€/m²) (c) High reflective shade (ρ = 70%,140€/m²) (c)

(a) Insulation material thickness varies from 20 mm to 200 mm.
(b) Costs in euros per square meter of insulated surface.
(c) Costs in euros per square meter glazed surface.
(d) Costs in euros per square meter of usable floor.

ensure indoor air quality, which corresponds to 0.15 L/s•m² of floor area and 3.5 L/s•person for a ventilator with a nominal specific fan power of 1 000 W/(m³/s) [88].

2.2. Improvement packages

Improving the habitability and energy performance of a building rely primarily on upgrading the thermal behaviour of the building envelope. The proposed surface insulation solution aims to explore the cases where the wall and floor only can be insulated by the interior, on the other side it is assumed that external insulation can be applied on the roof. This work does not explore the possibility of filling wall air gaps with insulation to quantify the maximum expected impact of internal wall insulation on floor loss and property value. Along with the surface insulation strategies and windows improvement, the most common additional strategies identified in the reviewed studies (Table 1) for conceiving a high-performance building are the integration of solar shading systems (movable or fixed) and natural ventilation systems. A movable solar shading system is considered in the improvement packages [91,92], as well as a natural night cooling system that takes advantage of the outdoor air low temperatures during nighttime to cool the thermal mass of the building to reduce the cooling needs and the possibility of overheating events [61,62,93].

The surface insulation strategies explore the three most common insulation materials for interior applications (mineral wool, extruded polystyrene and expanded polystyrene [56]) and a new insulation material (Polyisocyanurate Hydrofluoroolefin) with low thermal conductivity (0.018 W/m²•K). All internal insulation solutions consider as a finishing layer a plasterboard panel suitable for interior retrofits with a low moisture accumulation capacity [94,95] along with an application of a vapour barrier. This solution will prevent and reduce the risk of moisture accumulation in the interlayers of the wall as explored in previous works [14,43,44,57]. The improvement was defined by combining all levels of improvement. Nevertheless, only the

Table 6
Properties of conventional building insulation materials adapted from [70,72].

Insulation Material	Density (kg/m^3)	Thermal Conductivity (W/m·K)	Specific Heat (J/kg·K)	Embodied Energy (kWh/m^3)	Embodied Emissions (kg CO_2/m^3)	Material Cost (€/m^3)
MW Mineral Wool	120.0	0.039	900	564.0	126.0	79.43
EPS Expanded Polystyrene	32.5	0.035	1 275	939.3	221.0	68.75
XPS Extruded Polystyrene	36.0	0.031	1 575	889.2	271.8	98.24
PIR HFO[(a)] Polyisocyanurate Hydrofluoroolefin	37.5	0.018	1 400	727.5	206.3	315.01

[(a)] is assumed the PIR HFO have similar properties to standard PIR.

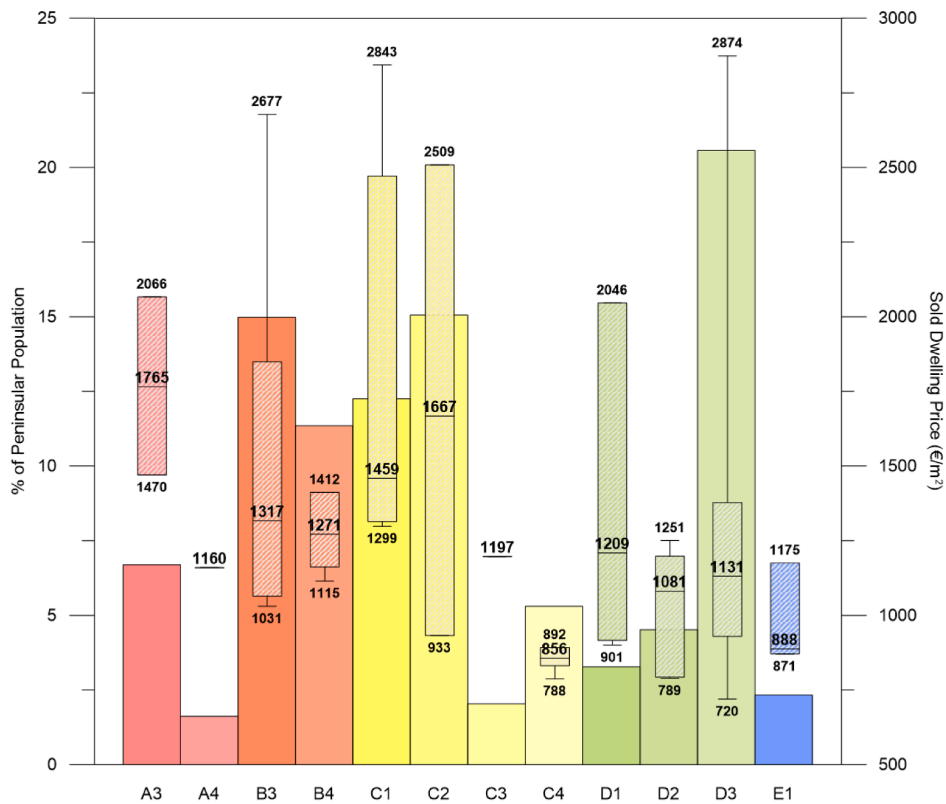


Fig. 2. Percentage of population and sold dwelling price per peninsular climate zone. The census data [101] and sold dwelling price data [9] per province were converted into climate zone data based on the climate classification established for each province in the Spanish Building Code [81].

Table 7
Average primary energy and CO_{2eq} emissions conversion factors for Spain during 2018–2022.

Energy Vector	kWh_p/kWh_f	kg CO_{2eq}/kWh_f
Natural Gas	1.00	0.182
Electricity	2.05 1.18 (no ren.) 0.87 (ren.)	0.130

improvement package that allowed the building to comply with the U-value requirements of the building code was considered for simulation.

Table 5 details the considered strategies and the respective cost of implementation and Table 6 details de insulation material's properties and cost. The considered costs were obtained from national databases, price inquiries to manufacturers and installers, and real experiences of building renovation. Insulation material properties correspond to the average properties value found in the literature.

2.3. Life cycle assessment

The life cycle assessment (LCA) of a building has the objective to quantify the overall impact of this during its lifetime. This impact can be assessed economically or environmentally, depending on the criteria used in the project. From the economic perspective comes the life cycle cost (LCC). An LCC of a building corresponds to the total lifetime cost of a building, where should be included the cost of the construction of the building, energy systems and operation [32,78]. Conversely, we have from the environmental perspective a life cycle emissions (LCE) assessment that aims to identify the direct and indirect total CO_2 emissions during the building lifetime [72]. This type of assessment aims to identify the thermal envelope solution and energy systems that will lead to a less costly or less pollutant building during its lifetime according to the LCA criterion chosen. A life cycle assessment should consider that typically a building is conceived to last a minimum of 50 years, but according to European Commission, the expected lifetime for a building should be considered 30 years for the application of the EPBD [78].

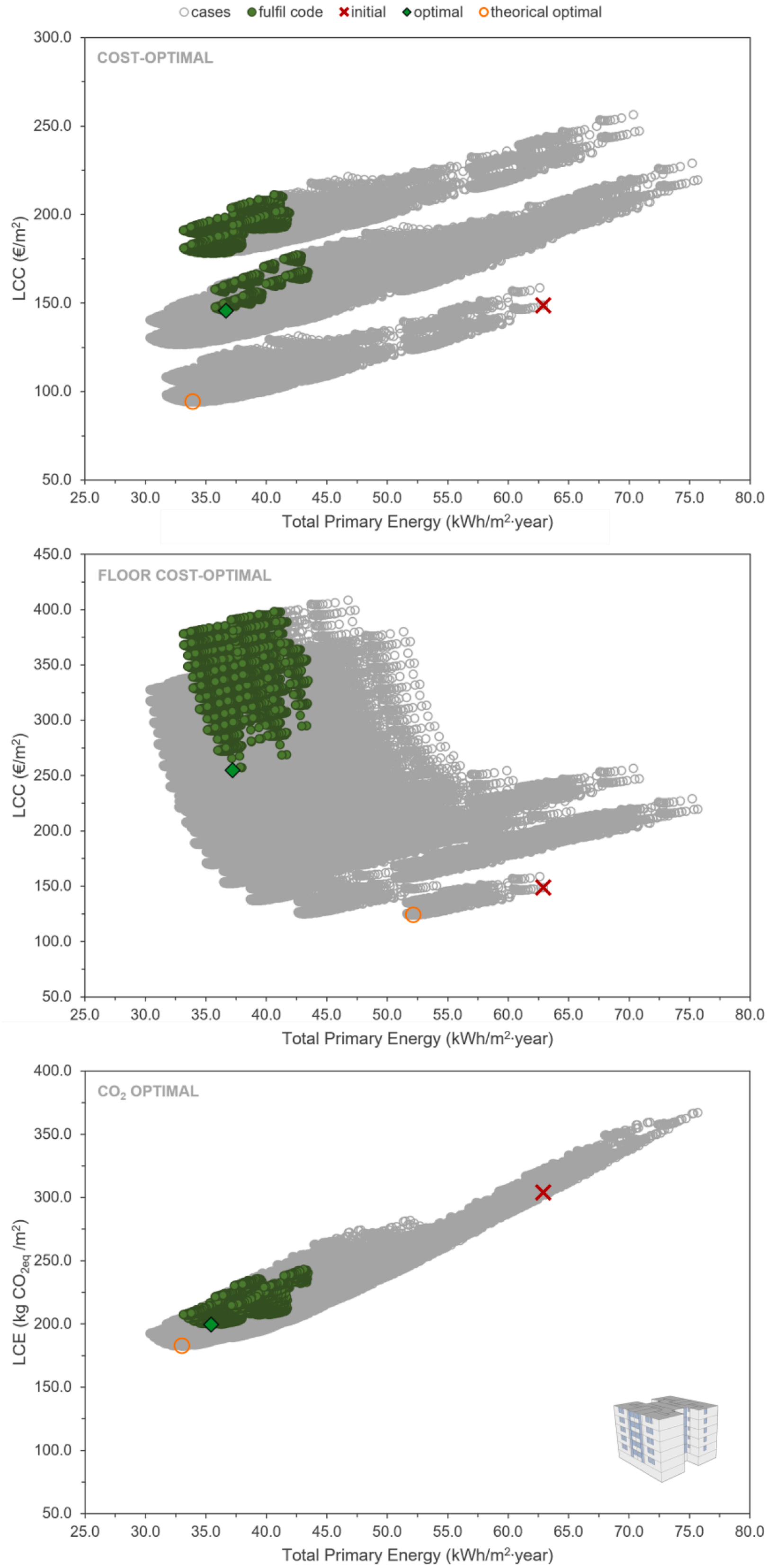


Fig. 3. Example of optimal case selection for the three optimal selection methodologies: multifamily detached building in Madrid (D3 climate zone) and XPS insulation system based.

Table 8
Impact of introducing the legal requirements in the definition of the optimal case. An example case for a multifamily detached building in Madrid (D3 climate zone) and XPS insulation system based.

Method	Legal Requirements	U_G ($W/m^2 \bullet K$)	E_p [(a)] ($kWh/m^2 \bullet year$)	LCC (€/m^2)	LCC_f (€/m^2)	CO_2 (kg CO_{2eq}/m^2)
Cost-optimal	complies	0.65	36.7	145.7	295.3	216.7
	not complies	0.89	33.9	94.1	206.4	190.4
Floor cost-optimal	complies	0.65	37.2	180.0	254.9	202.6
	not complies	1.35	52.2	123.7	123.7	263.2
CO_2 optimal	complies	0.62	35.4	188.6	300.9	199.6
	not complies	0.83	33.0	137.3	230.9	182.5

(a) Total Primary Energy Demand.

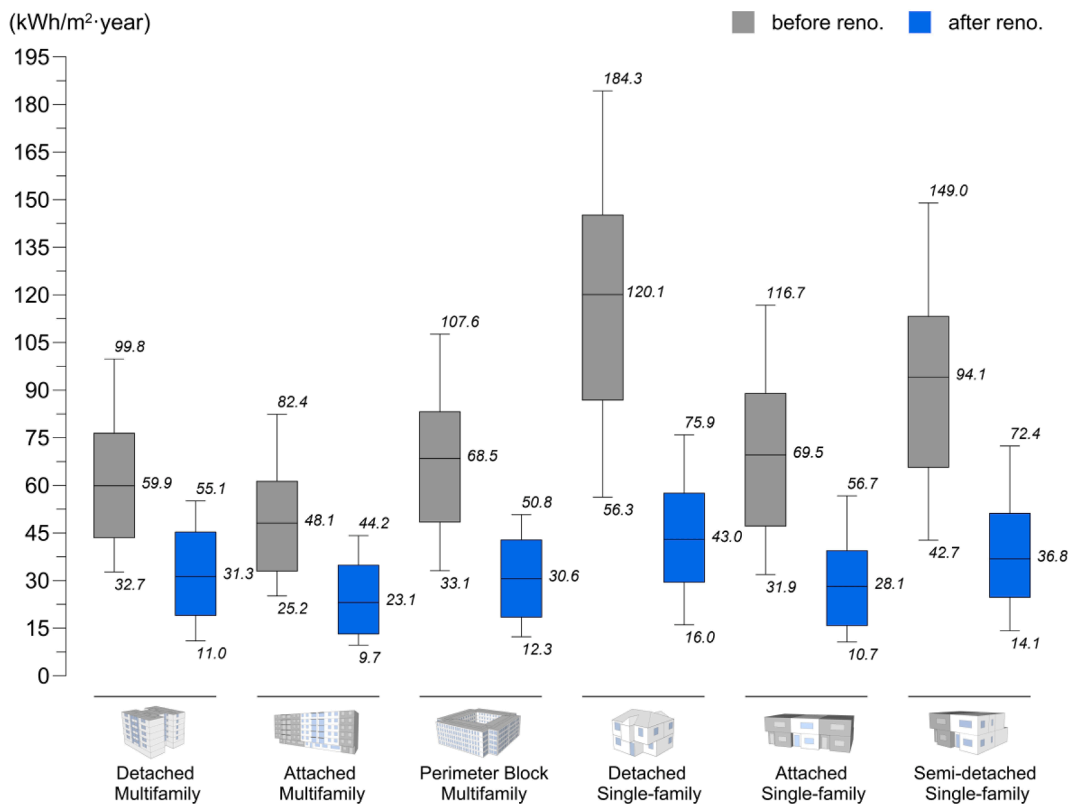


Fig. 4. Total primary energy demand for each building model before and after renovation in Peninsular Spain.

Table 9
Primary energy savings after renovation by building typology and winter climate zone: maximum, average and minimum value.

Primary Energy Savings (%)		Winter Climate Zone				
		A	B	C	D	E
Multifamily Buildings	min.	59.3	53.4	47.2	36.4	43.8
	avg.	65.1	59.3	53.7	44.4	49.3
	max.	70.0	66.0	59.6	51.8	54.3
Single-family Buildings	min.	64.7	59.0	57.6	52.3	51.3
	avg.	68.4	65.9	62.7	57.5	54.9
	max.	75.0	71.9	70.3	63.8	62.2

2.3.1. Life cycle cost and emissions

In a renovation project that does not include a building expansion or a partial reconstruction, the traditional LCC assessment focuses only on the investment cost for the retrofit as well as on the operation cost (maintenance, energy costs, etc..). For our case studies, the costs of building maintenance and equipment acquisition and replacement are not considered to neutralize their possible influence on the optimal case definition across the peninsula. The LCC, for the cost-optimal approach, is given by Equation (1), which relates the present value of total renovation investment (I_t), in euros, with the expected operation cost of heating, cooling and ventilation systems (c_{op}), in euros, across the building's lifetime to the present value. Is considered that the operation cost does not vary along the lifetime, being only corrected by the real interest rate (r), and obtained assuming an average cost for electricity of 0.274 €/kWh and for natural gas of 0.089 €/kWh with all taxes and levies included for 2021–2022 in Spain [97,98]. The real interest rate (eq. (2) corresponds to the reference interest rate (r_{ref}) adjusted by the expected inflation rate (r_{inf}). According to the Bank of Spain Statistics, the average reference interest rate for loans to householders for building renovation or intervention is 7.48% for the period between January 2021 and December 2022 [99]. Considering the same period, the verified average annual inflation rate in Spain was 5.81% [100], giving a real interest rate of 1.58%.

$$LCC = I_t + \sum_{i=1}^{N=30} \frac{c_{op,i}}{(1+r)^i} \quad (1)$$

$$r = \frac{r_{ref} - r_{inf}}{1 + r_{inf}} \quad (2)$$

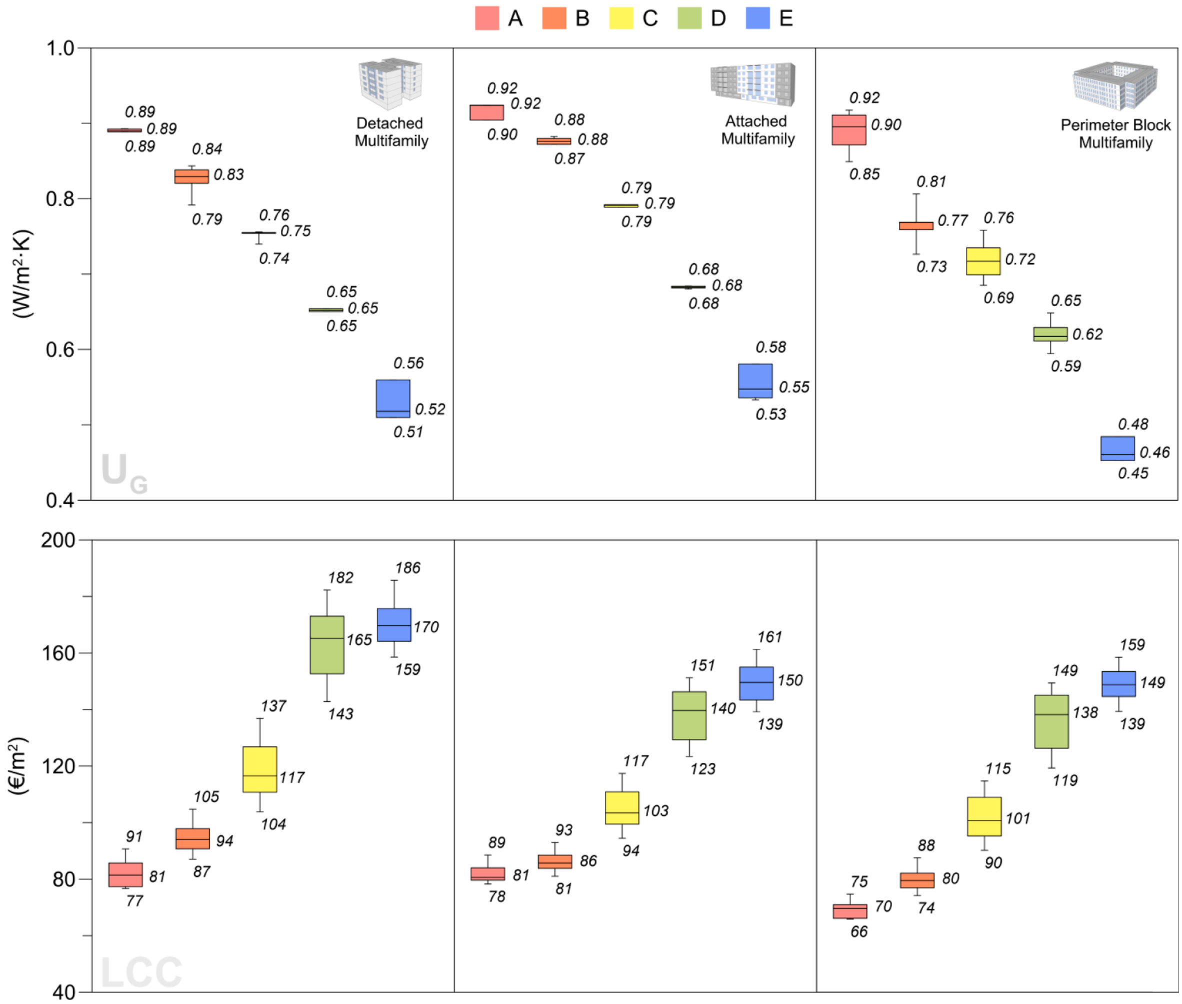


Fig. 5. Optimal global U-value and LCC range values for multifamily buildings per winter climate zone.

The possible floor loss caused by the internal insulation was evaluated considering the value of floor loss cost ($c_{floor\ loss}$) as an additional investment on the LCC definition (eq. (3). This value was estimated considering the floor loss area, given by the net extension of external walls[(2)] and the total insulation panel thickness, and the average market price of, new and existing, dwellings for each peninsular province available on the lasted Spanish Housing and Planning Observatory report [9]. Was considered the average value of all housing transactions, instead of the average market value of existing dwellings, to account for the effect of the added value to an existing dwelling after a renovation project. Fig. 2 summarizes the range of considered values for the average sold dwelling price (€/m^2) as well as the population distribution for each climate zone, where is possible to see climates more populated have higher house prices (C1, C2 and D3). The detailed price and population data are available in Table A1 of Appendix A.

$$LCC_f = \left(I_t + c_{floor\ loss}\right) + \sum_{i=1}^{N=30} \frac{c_{op,i}}{(1+r)^i} \quad (3)$$

On the other hand, the CO_2 optimal selection method aims to select the thermal envelope with a lower emission impact during the building lifetime, and instead of having an LCC as selection criteria, this method is based on life cycle emissions assessment. This method accounts for the generated emissions by the insulation material and the energy consumed by the building during its lifetime. Equation (4) presents the definition of the LCE considered, where e_{insu} is the total embodied CO_2 emissions of the insulation material used in the building renovation expressed in kg CO_{2eq} per square meter of the conditioned floor, E_i is the building's final energy demand for the energy vector i in kWh/m^2•year, and $f_{CO_2,i}$ the CO_2 conversion factors for the energy vector i in kg CO_{2eq}/kWh_f. Accounting for the embodied CO_2 of all materials used in the renovation is a difficult task and requires a significant amount of data that is dispersed in several databases along with a detailed characterization of the insulation solutions that not are the subject of this study. Additionally, all insulation solutions (external and internal) will be based on similar installation systems, so our method only accounts for the additional emissions generated by improving the thermal envelope.

$$LCE = e_{insu} + 30 \bullet \sum_{i=1}^{N=2} E_i \bullet f_{CO_2,i} \quad (4)$$

For having a unique value for the building energy demand in each method, the final energy consumption estimated through simulation was converted to primary energy considering a conversion factor for electricity and natural gas (Table 7). Being natural gas a primary energy source is assumed a conversion factor of 1.0 kWh_p/kWh_f, conversely, electricity is an energy vector with origin in different renewable and non-renewable sources and its conversion factor is given by a weighted average of all primary energy sources used to generate it. So, considering the considering statistics of the Spanish National Grid Operator [102] and the Energy Balance for Spain [103] was possible to define the real

(2) External wall extension excluding the length of openings with their starting point on the floor level measured by the interior of the building.

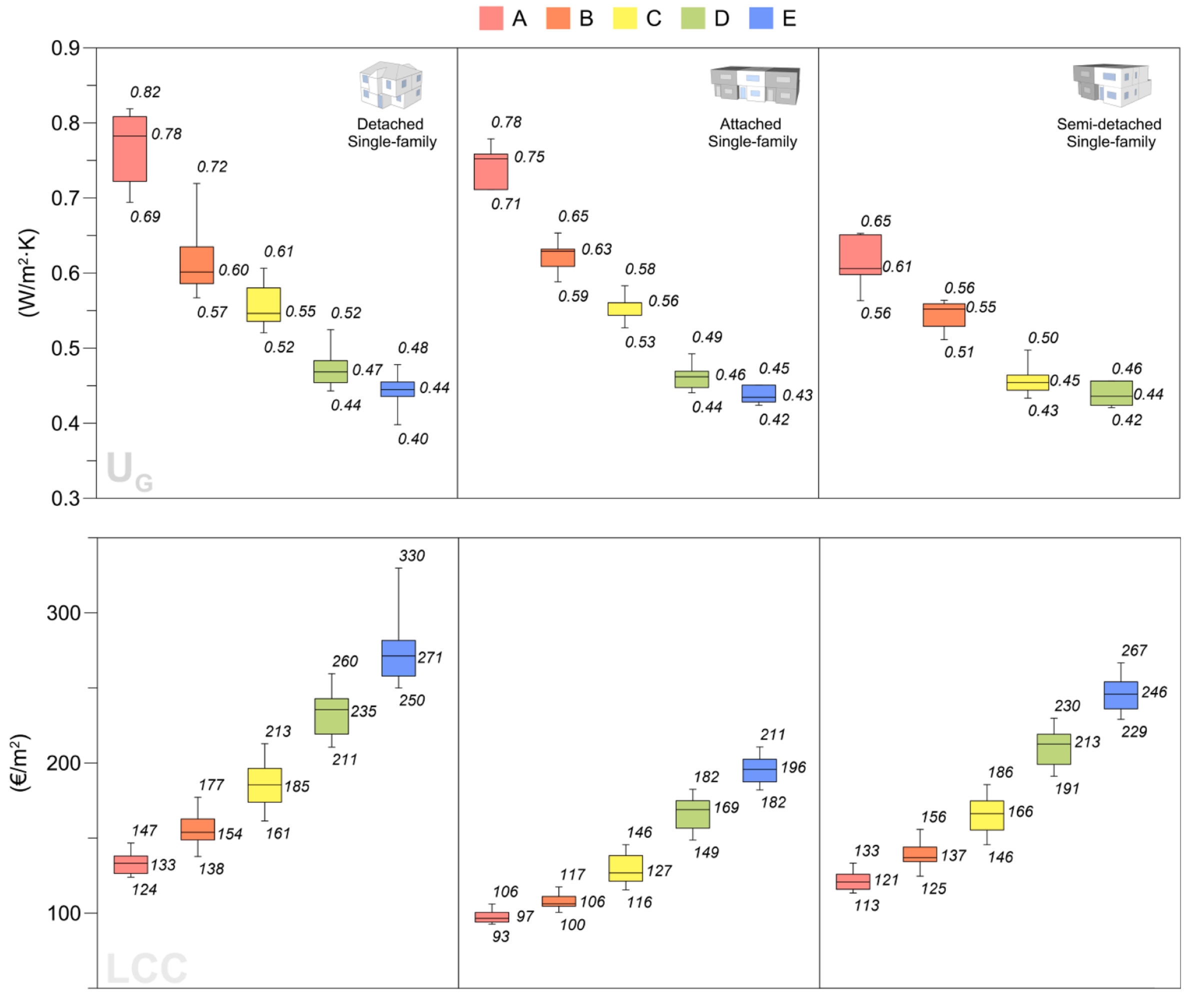


Fig. 6. Optimal global U-value and LCC range values for single-family buildings per winter climate zone.

primary energy conversion factor for electricity in peninsular Spain. A period of four years was considered to minimize the effect of the variability of hydropower availability. Table 7 also presents the CO_{2eq} emissions conversion factors considered for the two energy vectors presents in our study. The CO_{2eq} emission factor for electricity is given by the Spanish National Grid Operator [102] and for natural gas was obtained through the Spanish Carbon Footprint, Carbon Dioxide Compensation and Absorption Projects Registry [104]. A constant value is assumed for the conversion factors across the years because estimating the trend of integration of renewable power in the building sector, as in the electrical grid, falls outside the scope of this work's objectives.

2.3.2. Optimal case selection

A life cycle assessment allows the quantification of the cost or emissions that a building will generate according to its thermal envelope and energy systems. Applying this assessment to a set of possible improvements enables the identification of the case that minimizes the LCC or the LCE. However, this optimal case may not necessarily comply with the building legislation, so an LCA should only include the improvements packages or cases that possibilities compliance with the European and National regulations [78]. Therefore, each optimal selection method was applied also considering the requirements of the Spanish Building Technical Code [12] that transposes the latest version of EPBD [4] in Spain. The refinement introduced by the integration of nearly Zero Energy Building imposes a demand limitation (heating and cooling), a minimum energy efficiency for the energy systems, a minimum quality of the thermal envelope restringing the surface U-values, the global U-value[(3)] and the building air permeability, and obliges integration of renewables sources. Fig. 3 illustrates the identification of the optimal case for the optimal methodologies among all the possible combinations for the improvement packages of the thermal envelope (grey circles) and the initial stage of the building (red cross). From all combinations, a filter is applied and selected cases that fulfil the Spanish building code requirements that are represented by the green points, and inside of that set of data is selected that case that presents the lowest value possible for the LCC or the LCE. This figure also presents the theoretical optimal case (orange circle) obtained without legal constraints.

Table 8 presents the optimal case with and without legal requirements for the example of Fig. 3 where is possible to see that the optimal theoretical cases have a higher global U-value (U_G), i.e., a lower insulation level of the building envelope. Having a minimum level of insulation leads to having a building with a higher LCC or LCE. Nevertheless, the floor cost-optimal is the method where a major difference can occur due to the additional cost introduced by the floor area loss.

(3) The weighted average of all building external surfaces U-values. The limit for this values is adjusted according to the winter climate zone and compactness of the building.

Table 10
Cost optimal building thermal envelope characteristics by climate zone: U-value of the envelope, the solar heat gain coefficient of windows ($g_{\perp}$), the surface U-value increment due to thermal bridges ($\Delta U\varphi$), the average air permeability at 100 Pa (c_{100}) and the air-change rate at 50 Pa (h^{-1}).

Building type	Climate Zone	U-value (W/m^2•K)			$g_{\perp}$ (-)	$\Delta U\varphi$ (W/m^2•K)	c_{100} ($m^3/h{\cdot}m^2$)	n_{50} (h^{-1})
		Wall	Roof	Window				
Detached Multifamily	A	0.35–0.53	0.16–0.37	1.40–2.60	0.45–0.78	0.27	5.6	1.5
	B	0.33–0.53	0.11–0.33	1.30–2.00	0.39–0.65			
	C	0.23–0.35	0.14–0.29	1.30–2.00	0.39–0.65			
	D	0.15–0.28	0.10–0.21	0.75–1.40	0.39–0.45			
	E	0.22–0.25	0.14–0.23	1.30–1.40	0.39–0.45			
Attached Multifamily	A	0.36–0.65	0.17–0.35	1.40–2.60	0.45–0.65	0.21	5.4	0.8
	B	0.34–0.56	0.17–0.36	1.40–2.00	0.45–0.65			
	C	0.23–0.42	0.18–0.30	1.30–2.00	0.39–0.61			
	D	0.17–0.41	0.13–0.17	0.75–1.40	0.39–0.45			
	E	0.28–0.32	0.13–0.17	1.40–1.40	0.45–0.45			
Perimeter Block (Multifamily)	A	0.57–0.67	0.23–0.41	2.00–2.60	0.65–0.78	0.20	5.5	0.7
	B	0.36–0.54	0.24–0.36	2.00–2.00	0.65			
	C	0.34–0.45	0.18–0.32	2.00–2.00	0.65			
	D	0.33–0.41	0.15–0.30	1.40–1.40	0.45			
	E	0.30–0.36	0.14–0.21	1.40–1.40	0.45			
Detached Single-family	A	0.50–0.58	0.31–0.50	2.60–2.60	0.78	0.15	5.7	3.4
	B	0.46–0.52	0.22–0.44	2.00–2.00	0.65			
	C	0.42–0.47	0.18–0.39	2.00–2.00	0.65			
	D	0.21–0.41	0.14–0.25	1.40–1.40	0.45			
	E	0.16–0.29	0.11–0.22	0.75–1.40	0.43–0.45			
Attached Single-family	A	0.53–0.62	0.34–0.49	2.60	0.78	0.12	5.6	1.6
	B	0.44–0.53	0.26–0.40	2.00	0.65			
	C	0.32–0.49	0.19–0.32	2.00	0.65			
	D	0.31–0.40	0.16–0.27	1.40	0.45			
	E	0.31–0.37	0.15–0.24	1.40	0.45			
Semi-detached Single-family	A	0.51–0.59	0.33–0.47	2.60	0.78	0.13	5.7	2.3
	B	0.46–0.53	0.25–0.42	2.00	0.65			
	C	0.43–0.49	0.21–0.30	2.00	0.65			
	D	0.30–0.38	0.17–0.25	1.40	0.45			
	E	0.25–0.35	0.15–0.22	1.40	0.45			

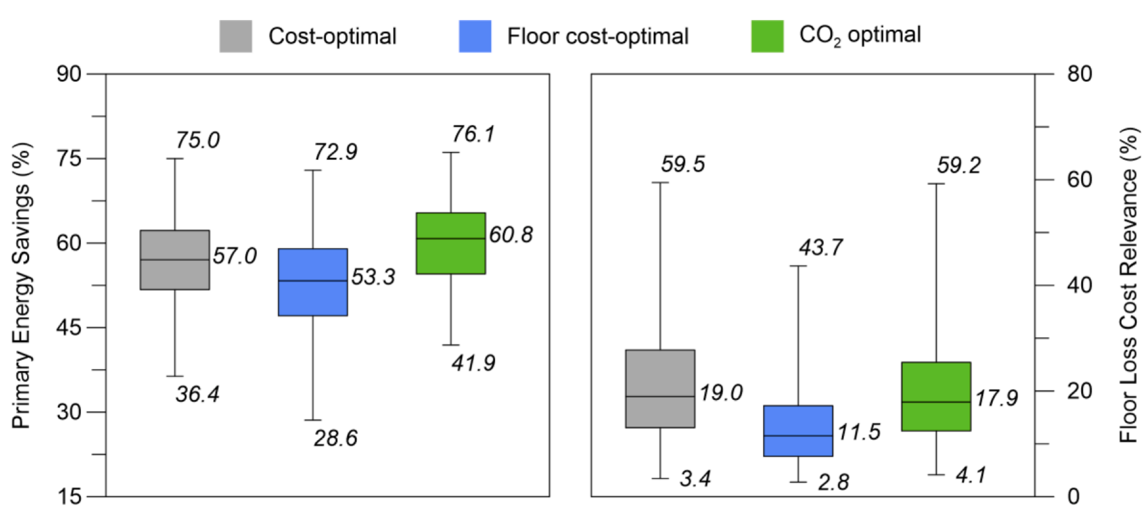


Fig. 7. Comparison results: primary energy savings and floor loss cost relevance percentage.

3. Results and discussion

3.1. Cost-optimal thermal envelope

Fig. 4 presents the primary energy demand for each building model, both in its initial stage and after implementing the new thermal envelope obtained through the cost-optimal method. This figure highlights the importance of renovating buildings, even when facing architectural limitations on the façade. It also demonstrates that the most significant demand reduction occurs in single-family homes. This effect can be attributed to the substantial improvement in buildings with lower compactness, as mandated by the latest version of the Spanish EPBD [12]. In contrast, multifamily buildings exhibit a less pronounced demand reduction due to their higher level of compactness, as indicated in Table 9. This table provides an overview of the savings potential for each building typology and winter climate zone.

On average, renovating a building its energy demand is halved and the reduction can reach up to 75% (Table 9). However, is expected a higher savings potential in warmer climate zones (A and B) compared to the coldest climates (D and E), where savings potential does not go further than ∼ 50% for multifamily buildings and ∼ 60% for single-family buildings due to the winter severity in this climates. The results are not present for each climate zone since was verified a slight value variation across the summer zones for the same winter zone.

A slight value variation across the summer zones for the same winter zone is also evident in Fig. 5 and Fig. 6 which summarizes the results

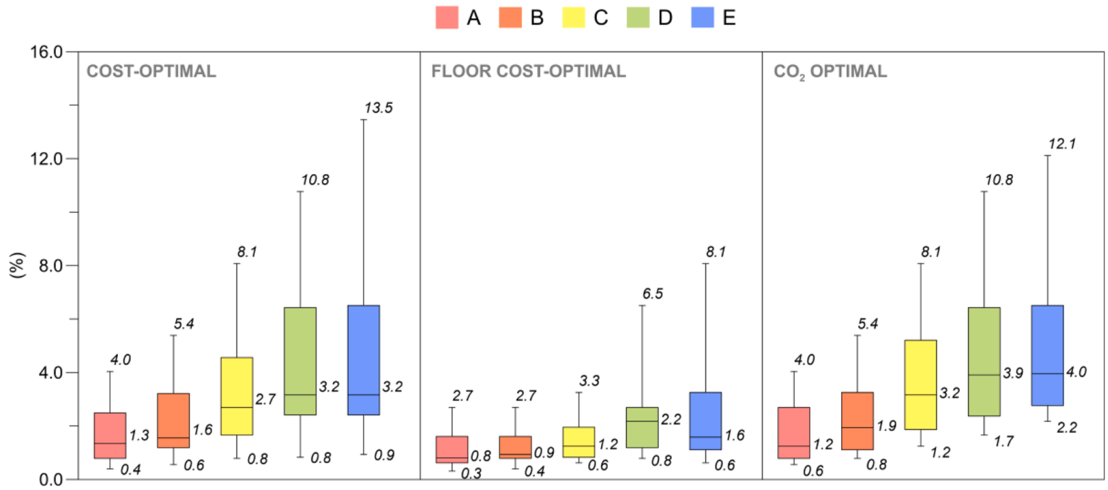


Fig. 8. Percentage floor area loss ranges per winter climate zone for each optimal selection methodology.

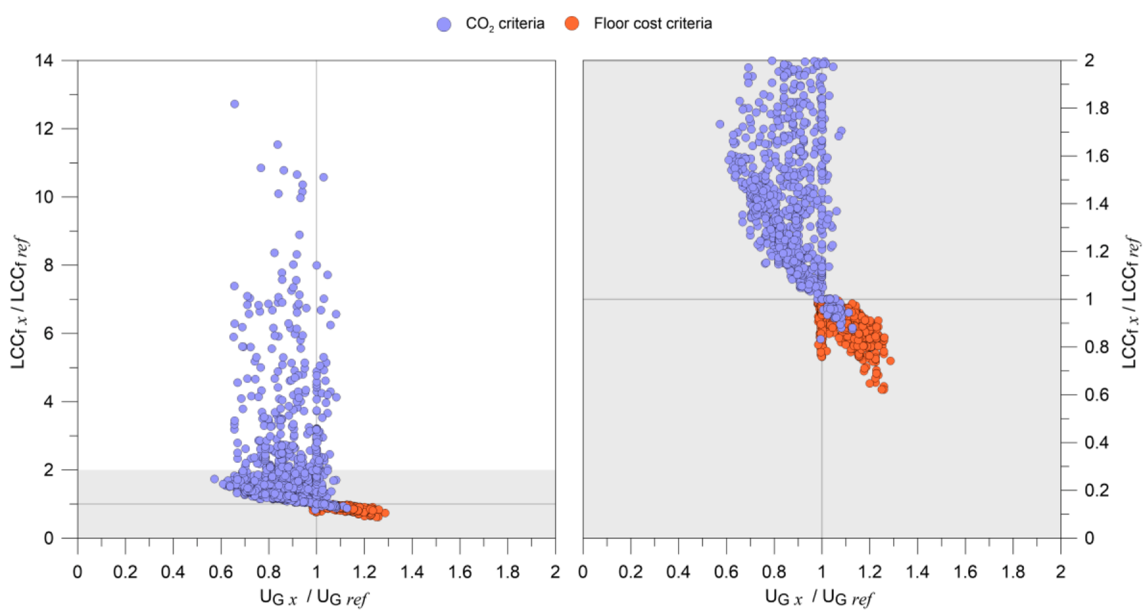


Fig. 9. Comparison of cost-optimal LCC and global U-value with CO_2 and floor cost criteria optimal selection results.

obtained for the optimal thermal envelope and LCC value, in euros per square meter of conditioned floor area, for each building geometry. The optimal thermal envelope is represented by the average U-value of the building envelope (U_G), i.e., the weighted average of all external surfaces U-values. The obtained ranges in each winter climate zone are very tight and the variability is only introduced by the costs and thermal properties of the studied insulation materials. However, in Fig. 5, for the multifamily building, is possible to observe a very small variation in the U_G-value, <0.1 W/m^2•K, for almost all the climate zones indicating a trend towards a common optimal value. For the LCC values, this trend is not so notorious, yet, the difference does not go further than 48.3 €/m^2. On the side of single-family buildings, the value ranges are wider for the warmer climate zones, A and B, (Fig. 6), not existing a trend to a common optimal U_G-value when compared to multifamily buildings. Nevertheless, families that live in colder climates will need to make an additional effort to renovate their homes, especially if they own a single-family home. Renovating a single-family home has, on average, an LCC value 1.5 times higher than a multifamily building. Although the single-family building typology represents only 40% of the Spanish building stock [74], the public authorities must ensure that householders have access to rehabilitation funding programmes or special loans to reduce the risk of not having renovated the higher-demanding residential buildings.

Table 10 presents the thermal envelope characteristics obtained for each building model and climate zone through the cost-optimal method, considering four insulation materials. This table indicates the expected range of U-values that should be observed in a building after a renovation project, based on the building type and climate zone. In all optimal cases identified by the cost-optimal method, was considered a traditional blinds shading system[(4)] combined with a night ventilation system (ACH = 15 h^{-1}) instead of a solar control shading system. Regardless of the insulation material and building type was verified a strategy to neutralize the floor transmittance despite the higher cost of floor insulation. This neutralization was achieved considering an insulation thickness of 20 cm and a floor U-value that varies from 0.10 to 0.18 W/

[(4)] The traditional blind system is activated only if the space is occupied and the indoor temperature is higher than 25°C, and have an average net transmissivity of 0.55.

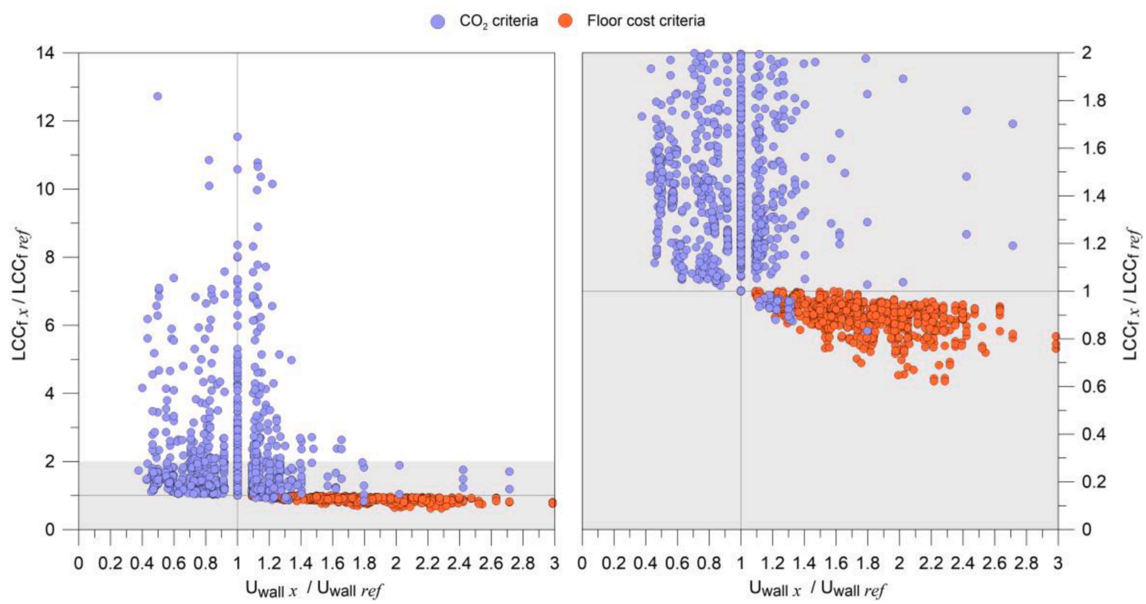


Fig. 10. Comparison of cost-optimal LCC and wall U-value with CO_2 and floor cost criteria optimal selection results.

Table 11
Percentage of optimal cases that fulfil the demand EnerPHit Standard requirement for the three optimal selection methodologies per insulation material, winter climate zone and building model.

		Cost-optimal	Floor cost-optimal	CO_2 optimal
Insulation Material				
MW		45.3	37.3	50.3
EPS		47.3	38.3	49.0
XPS		46.3	39.0	48.7
PIR HFO		42.3	39.7	55.7
Winter Climate Zone				
A		97.5	90.4	100.0
B		97.0	89.3	100.0
C		56.5	39.9	63.4
D		5.6	3.7	14.4
E		0.0	0.0	1.0
Building Model				
Multifamily	Detached	43.5	35.5	45.0
	Attached	66.0	60.5	74.0
	Block	45.5	40.0	49.0
Single-family	Detached	26.5	16.5	30.5
	Attached	53.0	49.0	66.0
	Semi-detached	37.5	30.0	41.0

m^2•K. Although the renovation packages allowed noticeable improvements, the thermal improvement on the side of thermal bridges was very limited. Only the thermal bridges caused by openings and joints between the external wall and floor (both insulated by the interior) could be corrected. Finally, by integrating openings with low air permeability along with external envelope requalification the average air permeability was reduced to a value well below the maximum allowed by the building technical code ($n_{50} = 6\ h^{-1}$).

3.2. Floor loss cost and CO_2 criteria

The objective of the cost-optimal methodology is to define which improvement can comply with all the legal requirements and minimize the LCC value of the building. Nevertheless, as mentioned previously this method can have limitations, especially if we are looking to have a building with a lower CO_2 footprint or if we are in a case where the floor area loss effect of internal insulation has no neglectable impact on the LCC of the building. This section presents the comparison results of the three optimal selection methodologies where the cost-optimal methodology is considered as a reference methodology. Additionally, to guarantee a fair comparison between the studied methodologies the LCC values obtained by the CO_2 optimal and cost-optimal criteria include the floor loss cost caused by the internal insulation. This consideration enables the identification of lost property value weight on the real LCC (LCC_f) for each method.

Fig. 7 summarises the relevance of floor area loss and its impact on the LCC_f of the building. Although its relevance varies according to the building location, is possible to see that internal insulation effectively has a no-depreciable effect on the LCC_f value of the building, and consequently on the lost property value, regardless of the optimal methodology. This effect can reach up to ~ 60% of the LCC_f value of a building if not accounted for, yet, the floor cost-optimal approach can limit this impact to 44% of the LCC_f.

Renovating an existing home can mean a floor area loss, on average, between 1.3 and 2.8% depending on the optimal selection method and can go up to 13.5% if adopted the conventional approach (Fig. 8). Higher floor area losses occurred in climates that require a better insulation level of the building envelope. On the other side, the primary energy savings reached for the three methodologies are very close due to the fact of all optimal cases must comply with the legal requirements (Fig. 7). Yet the CO_2 optimal approach leads to a higher savings potential, saving more on average 3.6% and 7.3% than the cost-optimal and the floor cost-optimal approaches, respectively.

Fig. 9 shows how the optimal cases defined by each methodology are related. A comparison of all optimal cases of each methodology is done considering as a reference the global U-value and the LCC given by the cost-optimal and the respective results for the same case (building, location and insulation material) by applying the floor cost and CO_2 criteria. In Fig. 9 left side is presented the global overview of the results where is possible to observe that the CO_2 optimal can present an LCC_f 13 times higher than the cost-optimal. Still, only 20% of the CO_2 optimal cases have an $LCC_f/LCC_{f\ ref}$ ratio greater than 2. Also is observed that the CO_2 optimal cases tend to have a higher level of insulation ($U_{G\ x}/U_{G\ ref} < 1$), having on average a global U-value 12% lower than a cost-optimal case. Making a zoom in Fig. 9 (right side) is possible to see that all cases from the floor cost criteria are confined in the lower right square. This indicates that from the floor-cost optimal methodology is obtained thermal envelopes that can have lower quality ($U_{G\ x}/U_{G\ ref} > 1$)

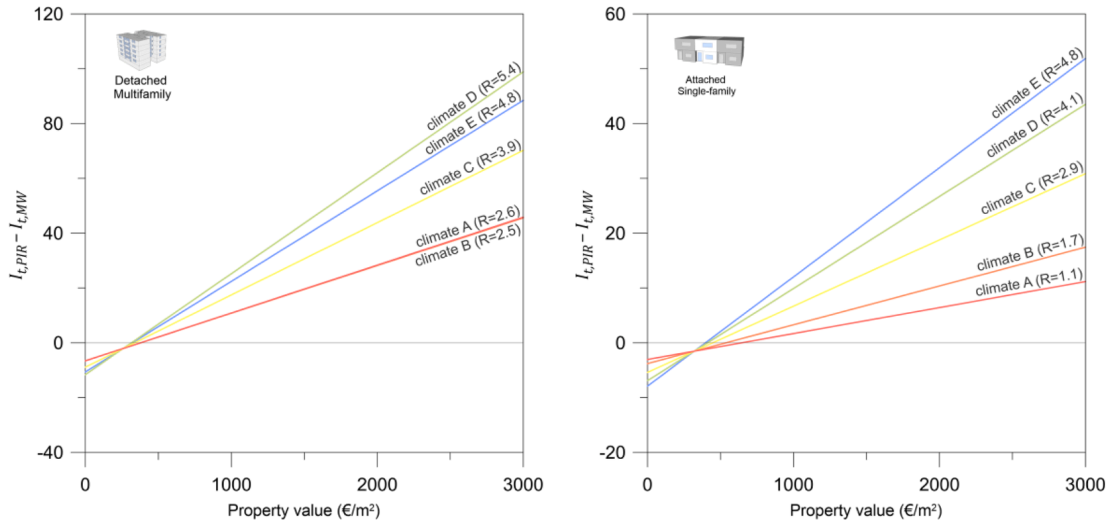


Fig. 11. Impact of the property value on the cost difference of wall insulation for PIR HFO and MW solutions at equal thermal resistance for the five winter zones: detached multifamily and attached single-family buildings cases. The thermal resistance, R, is presented in m^2•K/W.

Table 12
Minimum property value (€/m^2) that allows a PIR HFO wall insulation solution advantageous in comparison with remaining insulation materials studied for winter zone D.

PIR HFO vs.	Multifamily			Single-family		
	Detached	Attached	Block	Detached	Attached	Semi-detached
MW	316	344	316	340	411	411
EPS	407	435	391	413	501	498
XPS	428	456	411	434	526	524

but the real LCC is always minimized ($LCC_f/LCC_{f\ ref} < 1$).

The building surface that is directly affected by the economic constraints of the floor cost-optimal is the wall, and although the global U-value can have a maximum difference of 30% in comparison to the cost-optimal results, this surface can have its U-value strongly affected. According to Fig. 10 to reduce the LCC_f value an increase in the wall U-value must occur. This figure presents the relation of the optimal wall U-value between the three methods using the same comparison principles of Fig. 9. A building optimized by the floor cost criteria will have on average a wall U-value 1.55 times higher than if was optimized by the cost-optimal, but depending on the value of the property this ratio can go up to 3. On the other hand, the CO_2 optimal wall U-values do not show any trend as identified for the global U-value because this surface is not constrained, so the optimization is global.

The optimal thermal envelope obtained through the floor cost-optimal and the CO_2 optimal methods are available in Table B1 and Table B2, respectively, of Appendix B. These tables present the range of values of surface thermal characteristics for each building and winter climate zone. In these two methods was verified a similar optimization strategy occurred in the cost-optimal, where all optimal cases considered a traditional blinds shading system combined with a night ventilation system (ACH = 15 h^{-1}) and a floor insulation thickness of 20 cm.

3.3. Energy and economic impacts of renovation strategies

3.3.1. Impact of renovation strategies on Passive House Classification

The renovated buildings comply with the transposition [12] of the lasted version of the EPBD [4], to verify the effectiveness of the improvement packages this section assesses the compliance of optimal cases with the last version of EnerPHit Standard [105]. This standard is a Passive House standard applied to retrofit projects where the requirements are slightly more flexible, enabling the heating demand limits to adjust to the climate. For the Southern Eupore climate, a retrofit building can be considered a Passive House if its cooling demand is below 15 kWh/m^2•year and its heating demand is below 15 kWh/m^2•year for warm climates and 20 kWh/m^2•year for warm-temperate climates [105]. Additionally, the air permeability of a building is limited to an infiltration rate below 1 ACH at 50 Pascals, and the total primary energy demand must not exceed the 60 kWh/m^2•year (where is included the heating, cooling and appliances demand) [105].

For the Spanish existing buildings can be a not cost-effective measure of improving the building's air permeability to an n_{50} of 1 h^{-1}, so is assumed that criteria can be obviated because all legal requirements are fulfilled and the n_{50} of pot-renovation buildings are near to the standard limit. Not being an object of study on the impact of the energy efficiency of the energy systems, the assessment focuses only on the primary criteria of the EnerPHit Standard (heating and cooling demand) [105]. The heating demand limit was defined for each province according to the climate zone definition of the Passive House Standard [105]. Table B3 in Appendix B presents the correspondence between the Spanish climate classification, the Köppen -Geiger classification and the Passive House climate zones for each Spanish province. Table 11 summarizes the percentage of optimal cases that fulfil the demand criteria of the EnerPHit Standard [105] per insulation material, winter climate zone and building model for each optimal selection methodology.

The three optimal selection methodologies present a similar number of optimal cases that comply with the EnerPHit criteria. Almost the totality of the cases located in the winter climate zone A and B fulfils the demand limit, reaching 100% when a CO_2 optimal is applied. Still, for the winter zones where the winter is more severe fulfilling the demand requirements is very difficult (zone D) or almost impossible (zone E). For most winter severe zones to reach the demand levels of EnerPHit standard requires an integration of a ventilation unit with heat recovery. However, this type of unit is not cost-effective for Spanish reality [106]. Considering the area floor loss cost leads to less insulated buildings, making it more to meet the EnerPHit Standard [105] due to the high insulation required. The most compact buildings (attached types as well as the multifamily typologies), as mentioned previously, have lower demand and as a consequence can access the category of Passive House more easily. The type of insulation material used to improve the thermal envelope does not influence achieving the Passive House level. As evidenced in the analysis of the cost-optimal results, the global U-value have a tight variation range for each building in each winter climate zone.

Table A1
Spanish Climate Classification, resident population and average sold dwelling price at market value in 2022 for each Peninsular Spanish province.

Province	Capital	Spanish Climate Classification [12,81]	Population – 2021 (persons) [101]	Average sold dwelling price (€/m^2) [9]
A Coruña	A Coruña	C1	1 120 134.0	1 313.6
Albacete	Albacete	D3	386 464.0	929.2
Alicante	Alicante	B4	1 881 762.0	1 411.8
Almería	Almería	A4	731 792.0	1 159.7
Ávila	Ávila	E1	158 421.0	871.3
Badajoz	Badajoz	C4	669 943.0	892.2
Barcelona	Barcelona	C2	5 714 730.0	2 508.7
Vizcaya	Bilbao	C1	1 154 334.0	2 471.3
Burgos	Burgos	E1	356 055.0	1 175.3
Cáceres	Cáceres	C4	389 558.0	831.7
Cádiz	Cádiz	A3	1 245 960.0	1 469.8
Castellón	Castellón	B3	587 064.0	1 064.4
Ceuta	Ceuta	B3	83 517.0	1 849.5
Ciudad Real	Ciudad Real	D3	492 591.0	719.5
Córdoba	Córdoba	B4	776 789.0	1 115.4
Cuenca	Cuenca	D2	195 516.0	793.2
Girona	Girona	C2	786 596.0	1 667.4
Granada	Granada	C3	921 338.0	1 197.2
Guadalajara	Guadalajara	D3	265 588.0	1 230.4
Huelva	Huelva	B4	525 835.0	1 162.4
Huesca	Huesca	D2	224 264.0	1 161.7
Jaén	Jaén	C4	627 190.0	787.5
León	León	E1	451 706.0	870.5
Lleida	Lleida	D3	439 727.0	1 032.0
La Rioja	Logroño	D2	319 796.0	1 132.4
Lugo	Lugo	D1	326 013.0	900.6
Madrid	Madrid	D3	6 751 251.0	2 873.9
Málaga	Málaga	A3	1 695 651.0	2 066.1
Melilla	Melilla	A3	86 261.0	1 765.4
Murcia	Murcia	B3	1 518 486.0	1 030.5
Ourense	Ourense	C2	305 223.0	932.6
Asturias	Oviedo	C1	1 011 792.0	1 298.8
Palencia	Palencia	D1	159 123.0	916.4
Islas Baleares	Palma de Mallorca	B3	1 173 008.0	2 677.4
Navarra	Pamplona	D1	661 537.0	1 502.3
Pontevedra	Pontevedra	C1	944 275.0	1 360.6
Salamanca	Salamanca	D2	327 338.0	1 198.3
Guipúzcoa	San Sebastián	C1	726 033.0	2 843.4
Cantabria	Santander	C1	584 507.0	1 557.7
Segovia	Segovia	D2	153 663.0	1 030.4
Sevilla	Sevilla	B4	1 947 852.0	1 379.9
Soria	Soria	E1	88 747.0	904.0
Tarragona	Tarragona	B3	822 309.0	1 344.1
Teruel	Teruel	D2	134 545.0	789.0
Toledo	Toledo	C4	709 403.0	880.4
Valencia	Valencia	B3	2 589 312.0	1 288.9
Valladolid	Valladolid	D2	519 361.0	1 250.5
Álava	Vitoria-Gasteiz	D1	333 626.0	2 046.4
Zamora	Zamora	D2	168 725.0	789.1
Zaragoza	Zaragoza	D3	967 452.0	1 378.0

3.3.2. Impact of the property value on the insulation material selection

The impact of the property value on the LCC of the building is not neglectable as pointed out previously. However, the property value can be a preponderant factor at the moment of choosing the insulation material for interior applications, especially when we are comparing insulation materials with different thermal conductivities.

To enable that comparison is considered the average optimal thermal envelope obtained throughout the cost-optimal methodology for each winter climate zone, as insulation materials with the same thermal resistance reveal very similar energy performance. In this analysis, the thermal characteristics of the remaining surfaces (roof, floor, and windows) are kept constant. Considering, as an example, the detached multifamily and the attached single-family buildings, Fig. 11 illustrates the investment cost difference of wall insulation between mineral wool (highest thermal conductivity) and PIR HFO (lowest thermal conductivity) at the average optimal thermal resistance. This cost difference includes two cost variables: firstly, the cost of insulation material, application, and ancillary materials, and secondly the floor loss cost caused by the internal insulation. While the first cost is fixed for each insulation material, the second cost depends on the specific valuation of the rehabilitated property, represented in the x-axis in euros per square meter of usable floor area.

If no value is assigned to the preserved floor area, the initial cost of using mineral wool is logically lower than using PIR HFO. The cost difference ranges from −10.7 to −6.6 €/m^2 for the multifamily building and −7.9 to −3.1 €/m^2 for the single-family building. For property valuations around 500 €/m^2, the total cost of the two insulation solutions is almost the same. Taking the property average value for Spain (1336 €/m^2 [9]), the cost difference would range from 16.6 to 33.5 €/m^2 for the average optimal case of the multifamily building, and from 3.3 to 18.7 €/m^2 for the case of the single-family building. In other words, on average, if the householder chooses the insulation material with a low thermal conductivity a reduction of the renovation overall investment cost can be traduced from 1420 to 3206 €/dwelling for the multifamily building and from 327 to 1868 €/dwelling for the attached single-family building. Therefore, at the same thermal resistance, an insulation material with a low thermal conductivity compared with conventional materials, such as mineral wool, can allow a reduction of the investment cost when the floor loss is accounted for.

From Fig. 11, it is possible to observe that for each building and thermal resistance, a minimum property value is defined, which corresponds to the cost equivalence of both insulation solutions. This minimum value represents the threshold above which the application of PIR HFO becomes advantageous compared to an MW solution. Table 12 presents this value for all building models and alternative insulation materials to PIR HFO in the most populated winter zone in Spain (climate zone D, see Fig. 2). The obtained minimum property value is significantly lower than the average dwelling value in climate zone D (1204 €/m^2, Fig. 2), indicating the potential of using a higher-cost insulation material that offers better thermal performance compared to conventional solutions.

4. Conclusions

Europe's energy market is being inflated due to the ongoing Russian-Ukrainian conflict, causing volatility and insecurity in energy costs. The crisis highlights the non-depreciable impact of the building sector on energy demand and especially in countries like Spain where 90.4% of the existing dwellings will require intervention due to a lack of thermal envelope requirements or a light building code. Encouraging homeowners to renovate their homes can be difficult, particularly when restrictions require non-invasive thermal insulation techniques, making the project more complex. Finding a good balance between different aspects is still considered a challenge.

The results of this study point out that is possible to have an efficient residential building stock regardless of the thermal improvements limitations. On average the primary energy demand of an existing building can be reduced by 57%, reaching up to 75% in some cases for the cost-optimal approach. Renovating a single-family home, on average, costs 1.5 times more than a home in a multifamily building. Despite representing only 40% of the Spanish building stock, authorities must provide rehabilitation funding programs or special loans to homeowners to ensure the renovation of higher-demand residential buildings.

The main objective of the work was to identify the impact of floor area loss caused by internal insulation in the LCC of a building, that was not properly accounted for in previous studies. This impact has a significant effect on the LCC value, reaching up to ~ 60% of LCC when the floor loss cost is accounted for. Following environmental criteria leads to a building with a higher savings potential but also more costly when compared to the cases given by cost-optimal approaches. Conversely,

Table B1
Floor cost-optimal building thermal envelope characteristics by climate zone: the surface U-value, the solar heat gain coefficient of windows ($g_{\perp}$), the surface U-value increment due to thermal bridges ($\Delta U\varphi$), the surface average air permeability at 100 Pa (c_{100}) and the air-change rate at 50 Pa (h^{-1}).

Building type	Climate Zone	Surface U-value (W/m^2•K)				$g_{\perp}$ (-)	$\Delta U\varphi$ (W/m^2•K)	c_{100} (m^3/h·m^2)	n_{50} (h^{-1})
		Wall	Roof	Floor	Window				
Detached Multifamily	A	0.35–0.53	0.16–0.37	0.10–0.18	1.40–2.60	0.45–0.78	0.27	5.6	1.5
	B	0.33–0.53	0.11–0.33	0.10–0.17	1.30–2.00	0.39–0.65			
	C	0.23–0.35	0.14–0.29	0.10–0.17	1.30–2.00	0.39–0.65			
	D	0.15–0.28	0.10–0.21	0.10–0.16	0.75–1.40	0.39–0.45			
	E	0.22–0.25	0.14–0.23	0.10–0.16	1.30–1.40	0.39–0.45			
Attached Multifamily	A	0.36–0.65	0.17–0.35	0.10–0.18	1.40–2.60	0.45–0.65	0.21	5.4	0.8
	B	0.34–0.56	0.17–0.36	0.10–0.17	1.40–2.00	0.45–0.65			
	C	0.23–0.42	0.18–0.30	0.10–0.17	1.30–2.00	0.39–0.61			
	D	0.17–0.41	0.13–0.17	0.10–0.17	0.75–1.40	0.39–0.45			
	E	0.28–0.32	0.13–0.17	0.10–0.17	1.40–1.40	0.45–0.45			
Perimeter Block (Multifamily)	A	0.57–0.67	0.23–0.41	0.10–0.18	2.00–2.60	0.65–0.78	0.20	5.5	0.7
	B	0.36–0.54	0.24–0.36	0.10–0.18	2.00	0.65			
	C	0.34–0.45	0.18–0.32	0.10–0.17	2.00	0.65			
	D	0.33–0.41	0.15–0.30	0.10–0.17	1.40	0.45			
	E	0.30–0.36	0.14–0.21	0.10–0.17	1.40	0.45			
Detached Single-family	A	0.50–0.58	0.31–0.50	0.10–0.17	2.60	0.78	0.15	5.7	3.4
	B	0.46–0.52	0.22–0.44	0.10–0.17	2.00	0.65			
	C	0.42–0.47	0.18–0.39	0.10–0.16	2.00	0.65			
	D	0.21–0.41	0.14–0.25	0.10–0.16	1.40	0.45			
	E	0.16–0.29	0.11–0.22	0.10–0.16	0.75–1.40	0.43–0.45			
Attached Single-family	A	0.53–0.62	0.34–0.49	0.10–0.18	2.60	0.78	0.12	5.6	1.6
	B	0.44–0.53	0.26–0.40	0.10–0.17	2.00	0.65			
	C	0.32–0.49	0.19–0.32	0.10–0.17	2.00	0.65			
	D	0.31–0.40	0.16–0.27	0.10–0.17	1.40	0.45			
	E	0.31–0.37	0.15–0.24	0.10–0.17	1.40	0.45			
Semi-detached Single-family	A	0.51–0.59	0.33–0.47	0.10–0.17	2.60	0.78	0.13	5.7	2.3
	B	0.46–0.53	0.25–0.42	0.10–0.17	2.00	0.65			
	C	0.43–0.49	0.21–0.30	0.10–0.17	2.00	0.65			
	D	0.30–0.38	0.17–0.25	0.10–0.16	1.40	0.45			
	E	0.25–0.35	0.15–0.22	0.10–0.16	1.40	0.45			

Table B2
CO_2 optimal building thermal envelope characteristics by climate zone: the surface U-value, the solar heat gain coefficient of windows ($g_{\perp}$), the surface U-value increment due to thermal bridges ($\Delta U\varphi$), the surface average air permeability at 100 Pa (c_{100}) and the air-change rate at 50 Pa (h^{-1}).

Building type	Climate Zone	Surface U-value (W/m^2•K)				$g_{\perp}$ (-)	$\Delta U\varphi$ (W/m^2•K)	c_{100} (m^3/h·m^2)	n_{50} (h^{-1})
		Wall	Roof	Floor	Window				
Detached Multifamily	A	0.25–0.32	0.23–0.35	0.10–0.18	2.60	0.78	0.27	5.6	1.5
	B	0.19–0.33	0.18–0.43	0.10–0.17	2.00	0.65			
	C	0.13–0.21	0.15–0.21	0.10–0.17	2.00	0.65			
	D	0.11–0.20	0.12–0.21	0.10–0.16	0.75	0.43			
	E	0.11–0.18	0.11–0.19	0.10–0.16	0.75	0.43			
Attached Multifamily	A	0.36–0.60	0.31–0.45	0.10–0.18	0.75–2.00	0.43–0.65	0.21	5.4	0.8
	B	0.25–0.55	0.24–0.39	0.10–0.17	0.75–2.00	0.43–0.65			
	C	0.16–0.29	0.15–0.30	0.10–0.17	0.75–2.00	0.43–0.65			
	D	0.13–0.24	0.12–0.22	0.10–0.17	0.75	0.43			
	E	0.11–0.18	0.12–0.17	0.10–0.17	0.75	0.43			
Perimeter Block (Multifamily)	A	0.26–0.46	0.27–0.47	0.10–0.18	0.75–2.60	0.43–0.78	0.20	5.5	0.7
	B	0.20–0.40	0.19–0.41	0.10–0.18	0.75–2.00	0.43–0.65			
	C	0.14–0.26	0.13–0.27	0.10–0.17	0.75–2.00	0.43–0.65			
	D	0.12–0.22	0.11–0.20	0.10–0.17	0.75	0.43			
	E	0.12–0.17	0.11–0.17	0.10–0.17	0.75	0.43			
Detached Single-family	A	0.34–0.54	0.32–0.50	0.10–0.17	2.60–2.60	0.78	0.15	5.7	3.4
	B	0.19–0.38	0.22–0.41	0.10–0.17	0.75–2.00	0.43–0.65			
	C	0.15–0.27	0.14–0.30	0.10–0.16	0.75–2.00	0.43–0.65			
	D	0.13–0.23	0.12–0.23	0.10–0.16	0.75	0.43			
	E	0.11–0.17	0.11–0.18	0.10–0.16	0.75	0.43			
Attached Single-family	A	0.36–0.62	0.34–0.49	0.10–0.18	2.60	0.78	0.12	5.6	1.6
	B	0.24–0.53	0.23–0.40	0.10–0.17	0.75–2.00	0.43–0.65			
	C	0.15–0.31	0.15–0.34	0.10–0.17	0.75–2.00	0.43–0.65			
	D	0.13–0.24	0.12–0.24	0.10–0.17	0.75	0.43			
	E	0.11–0.18	0.12–0.19	0.10–0.17	0.75	0.43			
Semi-detached Single-family	A	0.35–0.56	0.33–0.47	0.10–0.17	2.60	0.78	0.13	5.7	2.3
	B	0.24–0.46	0.23–0.42	0.10–0.17	2.00	0.65			
	C	0.15–0.28	0.14–0.30	0.10–0.17	0.75–2.00	0.43–0.65			
	D	0.13–0.23	0.14–0.23	0.10–0.16	0.75	0.43			
	E	0.11–0.18	0.11–0.18	0.10–0.16	0.75	0.43			

Table B3
Correspondence between the Spanish Peninsular Climates, the Köppen -Geiger Climate Classification and the Passive House Climate Zones for the Spanish Peninsular provinces.

Province	Capital	Spanish Classification [12,81]	Köppen -Geiger Classification [80]	Passive House Classification [105]
A Coruña	A Coruña	C1	Cfb	Warm
Albacete	Albacete	D3	Csa	Warm-temperate
Alicante	Alicante	B4	BSh	Warm
Almería	Almería	A4	BWh	Warm
Ávila	Ávila	E1	Cfc / Dfc	Warm-temperate
Badajoz	Badajoz	C4	Csa / Cfa	Warm-temperate
Barcelona	Barcelona	C2	Cfa	Warm
Vizcaya	Bilbao	C1	Cfb	Warm-temperate
Burgos	Burgos	E1	Cfc / Dfc	Warm-temperate
Cáceres	Cáceres	C4	Csa / Cfa	Warm-temperate
Cádiz	Cádiz	A3	BWk	Warm
Castellón	Castellón	B3	BSk	Warm
Ceuta	Ceuta	B3	BSk	Warm
Ciudad Real	Ciudad Real	D3	Csa	Warm-temperate
Córdoba	Córdoba	B4	BSh	Warm
Cuenca	Cuenca	D2	Cfa	Warm-temperate
Girona	Girona	C2	Cfa	Warm
Granada	Granada	C3	Csa	Warm
Guadalajara	Guadalajara	D3	Csa	Warm-temperate
Huelva	Huelva	B4	BSh	Warm
Huesca	Huesca	D2	Cfa	Warm-temperate
Jaén	Jaén	C4	Csa / Cfa	Warm
León	León	E1	Cfc / Dfc	Warm-temperate
Lleida	Lleida	D3	Csa	Warm
La Rioja	Logroño	D2	Cfa	Warm-temperate
Lugo	Lugo	D1	Cfb	Warm
Madrid	Madrid	D3	Csa	Warm-temperate
Málaga	Málaga	A3	BWk	Warm
Melilla	Melilla	A3	BWk	Warm
Murcia	Murcia	B3	BSk	Warm
Ourense	Ourense	C2	Cfa	Warm
Asturias	Oviedo	C1	Cfb	Warm
Palencia	Palencia	D1	Cfb	Warm-temperate
Islas Baleares	Palma de Mallorca	B3	BSk	Warm
Navarra	Pamplona	D1	Cfb	Warm-temperate
Pontevedra	Pontevedra	C1	Cfb	Warm
Salamanca	Salamanca	D2	Cfa	Warm-temperate
Guipúzcoa	San Sebastián	C1	Cfb	Warm-temperate
Cantabria	Santander	C1	Cfb	Warm
Segovia	Segovia	D2	Cfa	Warm-temperate
Sevilla	Sevilla	B4	BSh	Warm
Soria	Soria	E1	Cfc / Dfc	Warm-temperate
Tarragona	Tarragona	B3	BSk	Warm
Teruel	Teruel	D2	Cfa	Warm-temperate
Toledo	Toledo	C4	Csa / Cfa	Warm-temperate
Valencia	Valencia	B3	BSk	Warm
Valladolid	Valladolid	D2	Cfa	Warm-temperate
Álava	Vitoria-Gasteiz	D1	Cfb	Warm-temperate
Zamora	Zamora	D2	Cfa	Warm-temperate
Zaragoza	Zaragoza	D3	Csa	Warm-temperate

the floor cost-optimal affects strongly the optimal wall U-value with an average value 1.55 times higher than in the cost-optimal approach, leading to less efficient buildings. This work makes available the optimal thermal envelope obtained through the three studied methods for the regulatory authorities, being a reliable source to define the most suitable renovation package for each building typology, climate zone and type of LCA.

Applying the Passive House Standard for renovated buildings (EnerPHit Standard) in the southern Europe context can be hard and not cost-effective in climate zones where the winter is more severe. Regardless of the flexibility introduced by the EnerPHit Standard converting an existing building into a Passive House will require a high level of thermal insulation that is outside of the cost-effective zone and the CO_2 optimal zone for the Spanish reality. Applying this standard in warm temperate climates can lead to buildings being counter-effective. Additionally, the latest transposed EPBD version for Spain is already restrictive enough, obliging to a building present a thermal envelope with a higher insulation level than the one obtained for any of the optimal selection methodologies studied.

Property value is an economic factor that significantly influences the choice of insulation material for internal wall insulation, particularly when considering materials with the same thermal resistance. Taking this variable into account, the space-saving benefits of using insulation materials with lower thermal conductivity can lead to an investment cost reduction. This consideration challenges a simplistic approach that exclusively relies on the cost of insulation materials.

Choosing the method to proceed with an LCA must follow a meticulous procedure where the economic constraints must be balanced with the environmental, where is essential to assess the relevance of the potential property value loss.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A

Appendix B

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