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Analysis of design improvements for thermal bridges formed by double-brick façades and intermediate slabs for nZEB residential buildings in Spain

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ABSTRACT

The traditional construction systems of façades in Spain give rise to a large number of thermal bridges. Designers do not attach importance to their impact on the energy demand of buildings. This effect is increased with the introduction of greater thicknesses of thermal insulation required by regulations. One of the thermal bridges that has the greatest impact on energy demand in residential buildings is the junction of façades with intermediate slabs (slab fronts), which becomes more significant as the number of floors in the building increases. This paper analyzes this type of thermal bridges and proposes two novel construction improvements that reduce their impact on energy demand, while maintaining traditional façade construction systems. Thermal bridges (traditional construction system and improved systems) have been analyzed through the value of the linear thermal transmittance using THERM software. EnergyPlus was used to carry out an analysis of annual energy efficiency indicators of nZEB dwellings in three Spanish cities: Alicante, Barcelona and Madrid. This study shows that the application of the two proposed novel constructive improvements allows reducing the value of the linear thermal transmittance of the thermal bridge between 20% and 63.4% and the heating demand between 16.1% and 22.6%.

1. Introduction

Climate change is one of the major problems of today's society and trying to mitigate its consequences is one of the main challenges we face. To achieve this, our efforts should be focused on reducing the energy consumption associated with human activity as much as possible, and on using renewable energy sources instead of fossil fuels.

According to data from the European Commission [1], buildings are responsible for 41% of the European Union's energy consumption, above transport and industry. In Spain, energy consumption in buildings represents 31.9% of the total, of which 18.3% corresponds to residential buildings and the remaining 13.6% to buildings in the tertiary sector. Likewise, the high consumption of buildings is mainly related to heating services (47% of residential energy consumption).

Article 9 of Directive 2010/31/UE, EPBD - Energy Performance of Buildings Directive [2], stipulates that Member States must ensure that all new buildings are nearly Zero Energy Buildings nZEB as of January 1, 2021. This directive does not provide a quantitative definition for nZEB buildings, therefore EN ISO 52000-1 [3] in Annex H, proposes the following four indicators for assessing energy performance in these buildings:

- First indicator. Energy needs. Related to energy demands for heating and cooling as well as the quality of the thermal envelope (insulation, windows, etc.), bioclimatic design, thermal inertia, zoning, weather conditions and the need to guarantee adequate indoor environmental conditions.
- Second indicator. Total primary energy use. Related to the performance of the building's technical systems (HVAC, DHW and lighting installations) characterized by the energy use.
- Third indicator. Non-renewable primary energy use without compensation between energy carriers or the effect of exported energy.
- Fourth indicator. Use of non-renewable primary energy with compensation

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Nomenclatures

Symbols

A_i	Area of component i of the thermal envelope of the building [m^2]
C	Number of materials that make up a façade
$f_{Rsi,min}$	Minimum temperature factor at the internal surface
h_{si}	Inner surface film coefficient [$W/(m^2 \cdot K)$]
h_{se}	Outer surface film coefficient [$W/(m^2 \cdot K)$]
L_j	Length [m] within the two-dimensional geometrical model to which the value is applied Uj
L_p	Length [m] of thermal bridge p of the thermal building envelope
L^{2D}	Thermal coupling coefficient for two dimensional calculation [W/m·K]
N	Number of components with one-dimensional heat flux
R_a	Thermal resistance of the façade thermal insulation [$(m^2 \cdot K)/W$]
R_{si}	Internal surface resistance [$(m^2 \cdot K)/W$]
R_{se}	External surface resistance [$(m^2 \cdot K)/W$]
t	Thickness of each material that makes up a façade [m]
U	Thermal transmittance of the façade [$W/(m^2 \cdot K)$]
U_j	Thermal transmittance [$W/(m^2 \cdot K)$] of component j separating two environments considered
U_i	Thermal transmittance [$W/(m^2 \cdot K)$] of component i of the thermal envelope of the building

Greek symbols

Φ_l	Heat flux per linear meter of the thermal bridge [W/m]
Φ_T	Conduction heat flow [W]
θ_i	Indoor temperature [°C]
θ_e	Outdoor temperature [°C]
θ_{si}	Temperature at the internal surface [°C]
λ	Thermal conductivity of a material [W/(m·K)]
Ψ	Linear thermal transmittance of the linear thermal bridge separating two considered rooms [W/(m·K)]
Ψ_e	Linear thermal transmittance [W/(m·K)] measured with the external dimension system
Ψ_i	Linear thermal transmittance [W/(m·K)] measured with internal dimension system
Ψ_p	Linear thermal transmittance [W/(m·K)] of the thermal bridge p of the thermal envelope of the building

In the case of Spain, strategies for reducing energy demand include the use of thermal insulation thicknesses of 4–16 cm depending on the climate zone and the type of building element according to Ref. [4]. However, these thermal insulation thicknesses could be lower if a correct analysis and design of thermal bridges were carried out.

Thermal bridges (point and linear) that are generated at various points of the thermal envelope of buildings, are defined in the standard [5]. Several researchers have demonstrated the importance of thermal bridges in the analysis of the energy performance of buildings.

A. Capozzoli et al. [6], conducted an analysis of thirty-six types of linear thermal bridges found in the thermal envelope of buildings. From a building design point of view, the study emphasizes that in order to comply with the requirements of the EPBD [2], designers should pay attention to building design and in particular to thermal bridges as not acting on them will only reduce the one-dimensional heat flow and will not affect the two-dimensional heat flow that occurs at thermal bridges.

The study carried out by T. G. Theodosiou et al. [7] on a residential building in Greece with a typical double-brick façade construction, concludes that this type of façade is likely to generate a large number of thermal bridges. He indicates that the inclusion or not of the effect of thermal bridges in the design phase of the building affects its energy efficiency since the heating needs can be increased by 30% compared to those determined in the calculation without considering thermal bridges. He also points out that the inclusion or not of thermal bridges has little influence on the cooling demand.

V. Corrado et al. [8] carried out a study on a single-family house with three different cases of thermal insulation of the opaque portion of the thermal envelope: moderate (average U-value of 0.30 $W/m^2 \cdot K$); well insulated (average U-value of 0.25 $W/m^2 \cdot K$); and highly insulated (average U-value of 0.15 $W/m^2 \cdot K$). In addition, he compares two types of façade: External Thermal Insulation Composite Systems ETICS and double-brick façade with intermediate thermal insulation. He concludes that, in the case of double-brick façade, the influence of thermal bridges on heating needs varies between 30% and 67% depending on the climatic zone (Milan and Rome) and the average U-value considered.

G. Evola et al. [9] evaluate the energy impact of thermal bridges and the economic viability of correcting them in buildings located in the Mediterranean. Two types of buildings are analyzed: terraced houses and semi-detached houses. The research shows that the correct treatment of thermal bridges is an effective way to reduce primary energy demand for heating but has little impact on cooling.

The research by H. Ge et al. [10] on a residential building in Canada provides a comparison between seven types of linear thermal bridges with two design levels: one called “poor” where there is no treatment of the linear thermal bridge and one called “improved” where there is a correct treatment of the linear thermal bridge. The study covers four cities in Canada. The improvement of thermal bridges in these cities reduces heating energy needs by 3.7%–5.5%.

The study carried out by Cezary Misiopecki et al. [11] indicates that thermal envelopes (façade walls, floors, roofs, etc.) with a high thermal resistance value, produce a more pronounced effect in thermal bridges due to their greater effect in energy losses, being responsible for 36% of total energy losses.

The definition of the linear thermal transmittance Ψ is described in the standard [5]. Depending on the dimension system used (length or internal or external dimension) of the thermal bridge, a different value of the linear thermal transmittance Ψ will be obtained, resulting in the internal linear thermal transmittance Ψ_i or external linear thermal transmittance Ψ_e.

The document published at the 11th Nordic Symposium on Building Physics [12] presents a review of the requirements for thermal bridges and building regulations in several European countries: France, Austria, Cyprus, Greece, Spain, Belgium, Estonia, Romania and Sweden. Most of these countries use tabulated values of linear thermal transmittance. The ASIEPI (Assessment and Improvement of the EPBD Impact) report [13] also presents a similar review which has been updated by the report [14].

The summary of the three previous reports is that there are only three countries in Europe (France, Czech Republic and Denmark) that have set a maximum value for the linear thermal transmittance of thermal bridges. In the remaining countries, thermal bridges are generally considered in the energy calculations but do not include a maximum permitted value. Table 1 shows the maximum values allowed in these three countries as well as for the Passive House standard [15].

In Spain, the document DB HE 2019 Application Guide [4] provides an assessment of the linear thermal bridge according to its internal linear thermal transmittance: correct 0.01–0.20 W/m·K; dangerous 0.20–0.50 W/m·K; deficient above 0.50 W/m·K.

In Spain, buildings are constructed without adequate treatment of thermal bridges, and it is common for the thermal insulation layer of the façades not to be continuous throughout the thermal envelope. In addition, it is also common that construction projects for new buildings

Table 1
Maximum permissible values of linear thermal transmittance in linear thermal bridges, W/(m·K).

France	Façade junction with intermediate slabs			0.60
Denmark	Contour of heated floor foundations			0.40
	Façade junction with windows: windowsills, lintels and jambs			0.06
	Roof junction with skylights			0.20
Czech Republic	Type of junction	Required	Recommended	Recommended for passive houses
	Façade junction with any other element except windows	0.20	0.10	0.05
	Façade junction with windows: windowsills, lintels and jambs	0.10	0.03	0.01
Passive House standard	The design of the building should be considered as "thermal bridge free". For this purpose, the maximum value of the external linear thermal transmittance should be less than:			0.01

lack a detailed study of the treatment of thermal bridges. As demonstrated by the research mentioned above, this situation leads to an increase in energy needs and makes it difficult to achieve nZEB buildings.

It seems necessary, therefore, to propose improvement proposals aimed at reducing the effect of thermal bridges in new buildings in Spain in order to comply with the Spanish nZEB building regulations [4]. This being the aim of this research, adding that such improvement proposals should maintain the traditional construction system of the façade.

This paper develops a detailed study of the thermal bridges at the slab front. It analyzes the case of the junction of double-brick façades with intermediate slabs in which three types of slabs and five values of thermal transmittance of the façades are combined.

Two novel construction improvements are proposed to reduce the impact of thermal bridge on energy demand, while maintaining the traditional façade construction systems in Spain.

Thermal bridges (traditional construction system and improved systems) have been analyzed through the value of the linear thermal transmittance using THERM software [16]. EnergyPlus [17] was used to carry out an analysis of annual energy efficiency indicators of nZEB dwellings in three Spanish cities: Alicante, Barcelona and Madrid.

2. Material and methods

The cases analyzed and the constructive improvements proposed are identified below.

2.1. Thermal bridges in buildings

In Spain, the regulations that set the requirements for nZEB buildings [4], classifies linear thermal bridges into the following types of façade junctions with:

- TB1. Intermediate slabs. Slab fronts (with or without cantilever).
- TB2. Flat roofs (with or without parapet).
- TB3. External floors.
- TB4. Windows: TB4.1 windowsills; TB4.2 lintels and shutter boxes; TB4.3 jambs.
- TB5. Floors in contact with the ground.
- TB6. Other façade: external corners.
- TB7. Other façade: interior corners.
- TB8. Pillars. TB8.1 corner; TB8.2 integrated.

Fig. 1 shows a diagram of the above list of linear thermal bridges for better identification.

If we disregard the contribution of point thermal bridges, the conduction heat flow through the thermal envelope of buildings, between their indoor and outdoor environments, can be determined by Eq. (1), thus considering the superposition of the one-dimensional (U_i) and two-dimensional (Ψ_p) heat flow.

$$\varphi_T = (\sum U_i \cdot A_i + \sum \Psi_p \cdot L_p) \cdot (\theta_i - \theta_e) \quad (1)$$

The conductive heat flux generated by the two-dimensional

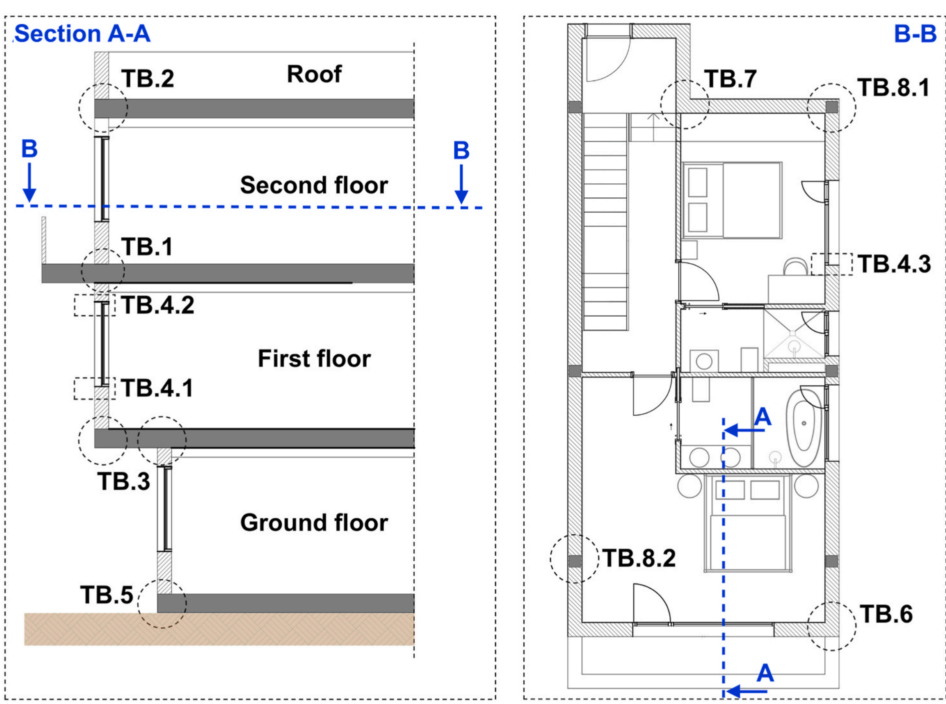

Fig. 1. Diagram for identification of linear thermal bridges types.

component of Eq. (1) is determined by the value of the linear thermal transmittance of the thermal bridge (Ψ_p) and by its length (L_p). Consequently, increasing the length of a linear thermal bridge generates more heat flow.

Fig. 2 shows the result of the analysis carried out in this research, on the geometry of a typical Spanish residential building, setting some basic data to the average Spanish construction values, obtained from Ref. [18] (window size 1.5 × 1 m, 4 homes per floor, 80 square meters per home, etc.).

It is found that as the number of floors of a building increases, the types of thermal bridges that have greater length and consequently generate greater heat flow, ordered from highest to lowest, are:

- Junction of façades with intermediate slabs. Slab fronts (with or without cantilever).
- Junction of façades with windows: jambs.
- Junction of façades with pillars (corner or integrated).
- Junction of façades with openings: windowsills, lintels and shutter boxes.

The study presented in this paper focuses on the first group listed above: the junction of façades with intermediate slabs (slab fronts without cantilevers).

2.2. Linear thermal bridge of traditional façades with intermediate slabs

The traditional construction system in Southern Europe consists of double-brick façades with intermediate thermal insulation. There are also some cases in which ETICS external thermal insulation systems are used, but this type only represents 8% of the European market [19] or the ventilated façade system, which in Spain is used very little in residential buildings due to the difference in cost compared to the traditional double-brick system.

To further facilitate the understanding of the problem of energy losses generated in a thermal bridge of a slab front, Fig. 3 shows a thermographic analysis carried out in a building located in Ciudad Real (Spain) on a façade with a double-brick solution and one-way slab with ceramic hollow (whose case is analyzed in depth in this study). The study was carried out in winter and the images were taken at 10:20 in the morning, with an outside ambient temperature of 12^{O}C. Even when a ceramic cladding was placed to conceal the slab fronts, these are perfectly detected in the thermographic image since, through these slab fronts a greater heat flow is being produced, increasing the exterior surface temperature in this area as can be seen both by the color of the thermography and by the temperature variation graph.

In order to establish the thermal transmittance values to be considered in the façade, the reference for the lowest value was the Passive House standard [15] of 0.15 W/(m^2·K) also used in the research of S. J. Chang et al. [20] and for the rest of the values the requirements for nZEB buildings in Spain [4] for the three cities under study. These values are shown in Table 2.

Fig. 4 shows the detail considered for the base case, showing the slab front with double-brick façades and the three types of slabs considered.

The properties of the material layers identified in Figs. 4, 5, 6 and 7 are described in Table 3. These properties have been obtained from the official document "Catalogue of Construction Elements CEC" [21]. These are design thermal values and include the effect of temperature and humidity according to ISO 10456 [22]. Unventilated air cavities are assigned to the predefined material in THERM [16], named as "Frame Cavity - CEN Simplified". This material will automatically calculate an "Equivalent Thermal Conductivity ETC" to the air gap according to EN ISO 10077-2 [23].

2.3. Thermal bridges with improved construction solutions

The Passive House Standard [15] sets the following design criteria to eliminate or minimize thermal bridges:

- Do not interrupt the thermal insulation layer in the thermal enclosure.
- Where the thermal insulation layer cannot be continued, the material that penetrates the thermal insulation layer must have the lowest possible thermal conductivity.
- At junctions, the layers of thermal insulation materials of the individual components must be completely and uninterruptedly connected to each other.

In addition, this research seeks that the proposed improvements

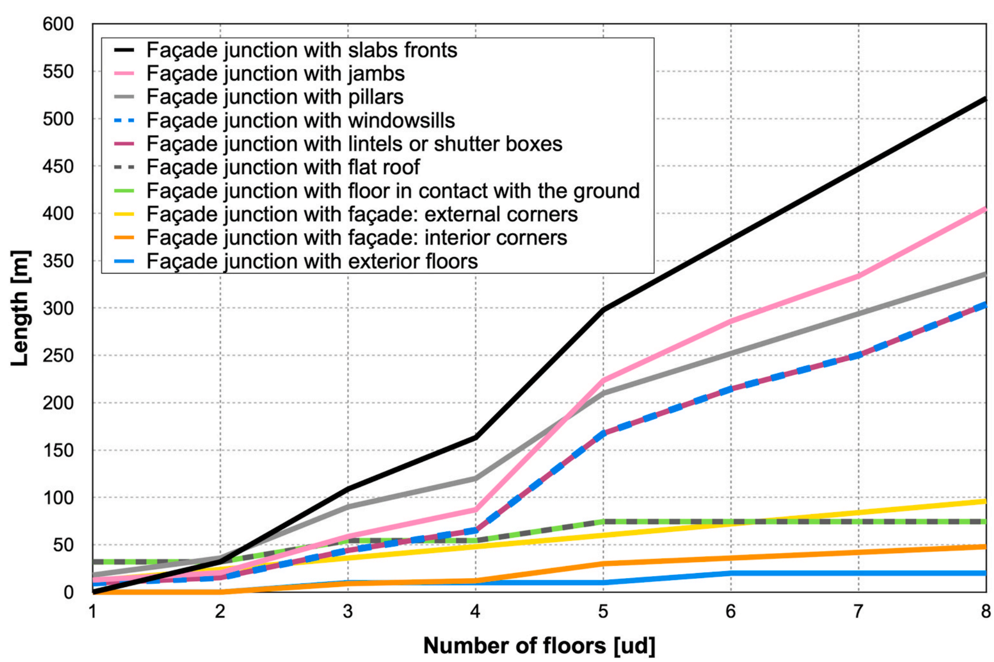

Fig. 2. Variation of the length of linear thermal bridges as a function of the number of floors of a typical Spanish residential building.

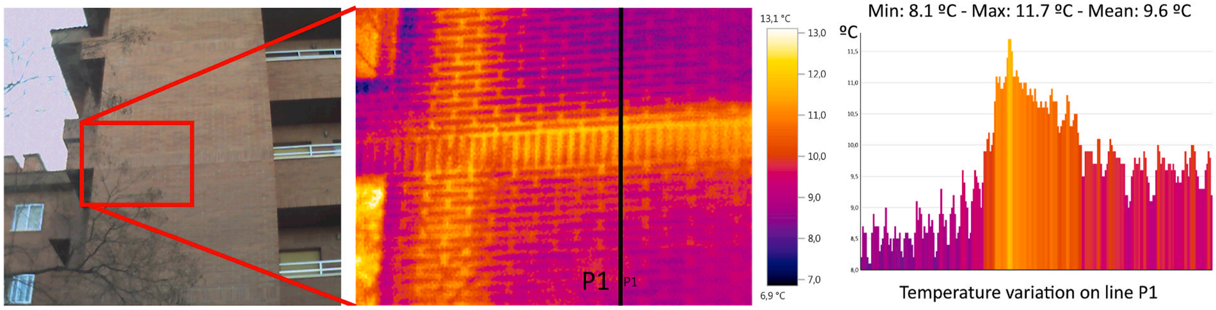

Fig. 3. Thermographic study carried out on double-brick façade.

Table 2
Thermal transmittance *U* values of the façade, thermal insulation thickness and types of floor slabs considered.

U-value of the façade W/(m^2·K)	Thermal insulation thickness with $\lambda = 0.034$ W/m·K	Intermediate slabs
0.40	68 mm	FR. Waffle slab with concrete panels and 30 cm edge.
0.35	80 mm	
0.30	96 mm	FUC. One-way slab with ceramic hollow block and 30 cm edge.
0.25	119 mm	
0.15	210 mm	FUE. One-way slab with EPS hollow block and 30 cm edge.

The suggested U-value for façades to comply with the requirements of the nZEB building regulations in Spain [4], for the three cities under study is: Alicante 0.38 W/(m^2·K); Barcelona 0.29 W/(m^2·K); Madrid 0.27 W/(m^2·K)

allow to reach an interior linear thermal transmittance value lower than 0.60 W/(m·K) (maximum value allowed in France).

Following the above criteria, the following constructive improvements of the slab front thermal bridge have been designed:

M1 improvement: self-supporting facing brick façade, supported on a L-shaped stainless steel profile (130 × 130 mm sides and 4 mm thick) anchored to the slab front with screws (various manufacturers offer such profile and anchoring systems such as [24]) and a 40 mm thick layer of thermal insulation is placed between the ceramic brick and the slab front. Fig. 5 shows a diagram of this improvement for the double-brick façades with waffle slabs (FR). These same improvements have also been applied to the rest of the FUC and FUE slabs. In addition, this figure shows a detail, obtained from the report [25], of a stainless steel profile model for face brick support with systems from the manufacturer Halfen-Deha SL [24].

M2 improvement: same as the previous case but also placing a 5 mm thick thermal insulation between the stainless steel profile and the slab front. The characteristics of the profile and its anchoring system are the same as in case M1; Fig. 6 shows a diagram of this improvement for double-brick façades with waffle slabs (FR). These same improvements have also been applied to the rest of the FUC and FUE slabs.

In both the M1 and M2 improvements, the stainless steel profile is anchored with bolts to the slab front. These bolts produce punctual thermal bridges that have not been considered in this study and are left for a future work.

M3 improvement: facing brick façade confined between the slabs, seeking to give continuity to the thermal insulation layer with three elements: replacement of the first line of floor slab lightning with expanded polystyrene EPS pieces; replacement of the first and last row of bricks of the inner ceramic sheet with cellular glass blocks; and placement, under the pavement and around its perimeter, of a thermal insulation layer 50 cm wide and 30 mm thick. For reasons of mechanical stability, it is not feasible to install thermal insulation in the slab front, as in cases M1 and M2, because there is constructively no space in the slab

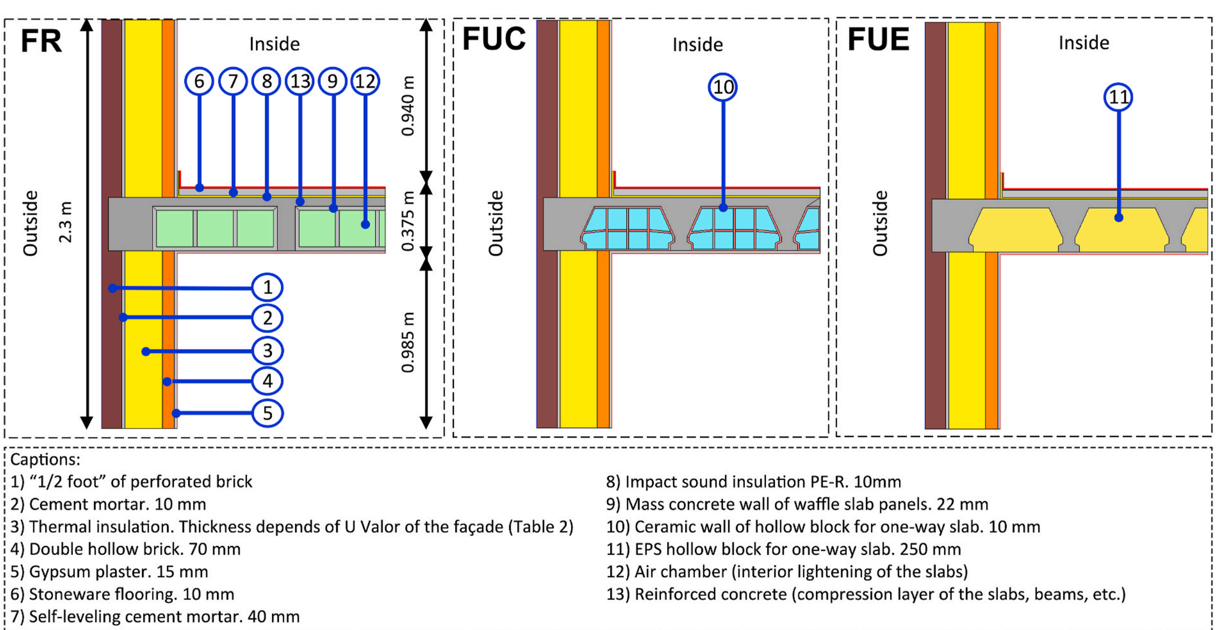

Fig. 4. Detail of the construction solution of the base case. Left with waffle slab (FR), center with one-way slab with ceramic vaults (FUC) and right with one-way slab with EPS vaults (FUE). Properties of the materials listed in Table 3.

Table 3
Properties considered for the materials.

ID	Material	Thickness mm	Thermal conductivity λ - W/(m·K)	Emissivity
1	"1/2 Foot" of perforated half brick	115	0.667	0.9
2	Cement mortar	10	0.550	0.9
3	Thermal insulation	Variable	0.034	0.9
4	Double hollow brick	70	0.432	0.9
5	Gypsum plaster	15	0.570	0.9
6	Stoneware flooring	10	2.300	0.9
7	Self-leveling cement mortar	40	0.550	0.9
8	Impact sound insulation, cross-linked polyethylene PE-R	10	0.046	0.9
9	Mass concrete wall of waffle slab panels	22	1.650	0.9
10	Ceramic wall of hollow block for one-way slab	10	1.000	0.9
11	EPS hollow block for one-way slab	250	0.046	0.9
12	Air chamber (interior lightning of the slabs)	variable	Frame cavity CEN	–
13	Reinforced concrete (compression layer of the slabs, beams, etc.)	50	2.500	0.9
14	Stainless steel profile	4	17.0	0.9
15	Cellular glass block	100 or 115	0.050	0.9

front to do so, as the outer facing brick is confined between the slabs.

Fig. 7 shows a diagram of this improvement for double-brick façades with waffle slabs (FR). These same improvements have also been applied to the rest of the FUC and FUE floors.

This improvement includes the use of cellular glass blocks to achieve continuity of thermal insulation, as this is a solution that is rarely used. Fig. 7 shows an image of the cellular glass block prepared for installation, with the aim of minimizing the thermal bridging of the contour of a flat roof, during the execution of a work in early 2021 in Elche (Spain) in the province of Alicante.

In Spain, seismic-resistant regulations do not require walls to be anchored to slabs or pillars. The cellular glass blocks have "European Technical Approval" for their use as support for brick masonry, guaranteeing their mechanical resistance.

It should be noted that only the M1 improvement is available as a standard solution on the Spanish market. The other solutions have been generated through this research. That is, while maintaining traditional building solutions, a number of materials (cellular glass blocks, insulation behind the metal support profile of the external brick, expanded polystyrene lightning, etc.) have been incorporated to reduce the heat flow in the thermal bridge and thus reduce its linear thermal transmittance.

The geometry definition of the slabs considered in this research includes the solid concrete zones at the supports. In addition, the use of lightning elements (concrete, ceramic or EPS) are common in the Spanish market and are included in the Spanish Structural Concrete Instruction EHE-08 [26]. On the other hand, EPS lightweight elements have been used in slab construction since at least 1980. There are patented systems such as the Forel System [27], which consists of EPS molded pieces with a continuous EPS board on the underside of the slab's resistant elements (beams, edge beams, etc.). Therefore, it is considered that the solutions provided in this research do not reduce the structural capacity of the slabs.

3. Calculation

This research has been developed through the following steps:

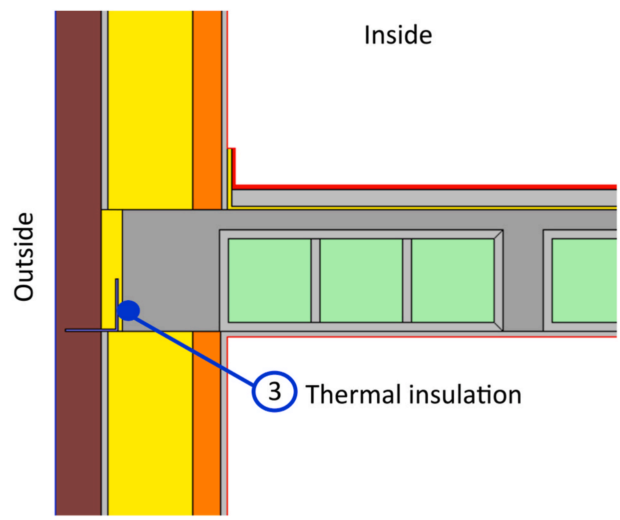

Fig. 6. M2 improvement considered to reduce the thermal bridge of waffle slab fronts. Properties of the materials listed in Table 3 (the rest of the layers coincide with those indicated in Fig. 4).

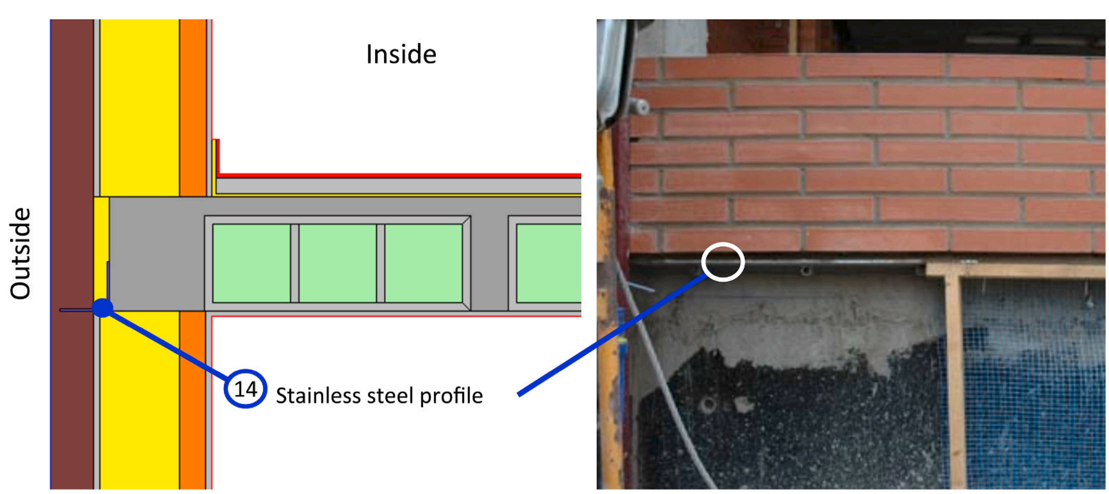

Fig. 5. M1 improvement considered to reduce the thermal bridge of waffle slab fronts. Properties of the materials listed in Table 3 (the rest of the layers coincide with those indicated in Fig. 4). Left: diagram of the M1 improvement. Right: detail of the stainless steel profile.

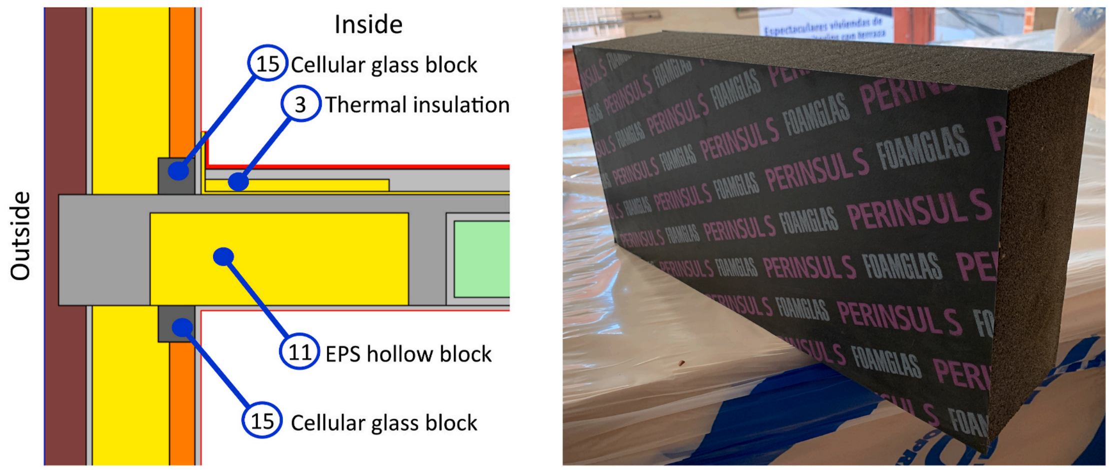

Fig. 7. M3 improvement considered to reduce the thermal bridge of waffle slab fronts. Properties of the materials listed in Table 3 (the rest of the layers coincide with those indicated in Fig. 4). Left: diagram of the M3 improvement. Right: detail of the cellular glass block.

a) Definition and characterization of the linear thermal bridging of the slab front with double-brick façades (base case);
b) Definition and characterization of improvements to achieve an indoor linear thermal transmittance value lower than 0.60 W/(m·K) (trying to design at least three cases of improvement that comply with this value);
c) Energy simulation of a residential building, to determine the impact of linear thermal bridging in terms of energy demand, total primary and non-renewable energy consumption, CO_2 emissions and cost overrun to reduce one tonne of CO_2 by year;
d) Comparison of the results obtained (baseline and improvements) and validation by comparison with official or reference values.

Fig. 8 shows the scheme followed for the development of this research. An iterative process has been carried out with the aim of finding those improvements that allow reaching a value of linear thermal transmittance within the thermal bridge of the slab front lower than 0.60 W/(m·K) (maximum value allowed in France), although in this paper, only the improvements that meet the criterion are shown. The generation of possible improvements has been done manually by designing possible solutions that give as much continuity as possible to the thermal insulation layer. The value of the linear thermal transmittance was then determined, as described in section 3.1, checking if it is less than 0.60 W/(m·K) or not.

In addition, the risk of surface condensation and mold growth in the area of the thermal bridge has been analyzed.

3.1. Determination of linear thermal transmittance and risk of condensation

The heat flux and the linear thermal transmittance of a thermal bridge can be determined by two methods: (i) using detailed methods that employ specific calculation software applying EN ISO 10211 [5]; (ii) using simplified methods that employ thermal bridge catalogues or the values given in EN ISO 14683 [28]. The equivalent wall method for thermal bridges proposed in studies [29,30] can also be used.

In this research, the detailed method has been used applying the EN ISO 10211 standard [5], for which different software tools are available for the finite element evaluation of the energy behavior of linear thermal bridges. The ASIEPI report P198 [31] provides a list and characteristics of the software frequently used in Member States. In our case, we will use the THERM [16] software in its version 7.7.10 (released on

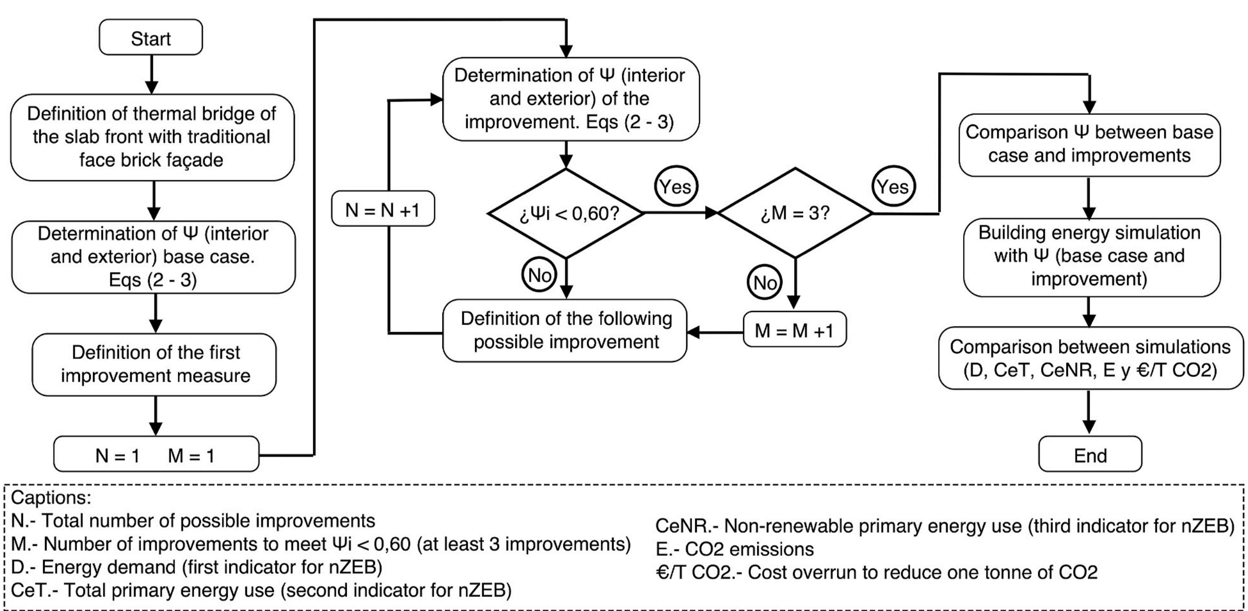

Fig. 8. Flow chart used for the evaluation of the thermal bridge of the slab front with double-brick façades and its possible improvements.

Table 4
Boundary conditions considered for slab front linear thermal bridges to be used in THERM.

Temperatures		Surface resistance		Film coefficient	
θ_e External	0°C	R_{se} External	0.04 $(m^2K)/W$	h_{se} External	25 $W/(m^2K)$
θ_i Interior	20°C	R_{si} Interior upward vertical flow	0.13 $(m^2K)/W$	h_{si} Interior upward vertical flow	7.69 $W/(m^2K)$

December 23, 2019, the latest version at the time of writing this article) which is also listed in the ASIEPI report [31].

THERM is a software for the evaluation of thermal bridges with a two-dimensional heat flow. Using the graphical interface, the detail of the thermal bridge to be evaluated is drawn (geometric model), the different materials that make up its construction elements are defined, the boundary conditions are defined and the simulation is launched.

The first step that THERM performs in the simulation is the generation of a mesh over the entire surface of the geometric model. This mesh is generated automatically through the “Finite Quadtree” algorithm and its operation is described in “Appendix C" of the THERM User Manual [16]. The mesh consists of a finite number of non-overlapping sub-regions, called elements, covering the whole region subject to analysis. When the mesh is created, THERM automatically sends it to the finite element solver called “Conrad".

Once the geometric model of the thermal bridge has been created in THERM, the materials that make up each construction solution have been defined according to Table 3 and the boundary conditions according to Table 4, the simulation is carried out with the software, thus obtaining the value of the heat flow Φ_L per linear meter of the linear thermal bridge. This heat flow is obtained for both the interior and exterior dimensions of the thermal bridge.

From the heat flux, L^{2D} can be determined using Eq. (2). L^{2D} is the thermal coupling coefficient for the two-dimensional calculation and is expressed for the interior or exterior dimensions of the thermal bridge, depending on the heat flux used.

$$L^{2D} = \frac{\varphi_l}{(\theta_i - \theta_e)} \tag{2}$$

Finally, the linear thermal transmittance Ψ of the thermal bridge is determined by Eq. (3). In the case of slab front linear thermal bridges, U_j represents the thermal transmittance of the façade and L_j represents the interior or exterior dimension of the façade at this linear thermal bridge. Depending on the dimension considered, the linear thermal transmittance inside (Ψ_i) or outside (Ψ_e) is obtained.

$$\psi = L^{2D} - \sum_{j=1}^{N} U_j \cdot L_j = \frac{\varphi_l}{(\theta_i - \theta_e)} - \sum_{j=1}^{N} U_j \cdot L_j \tag{3}$$

The thermal transmittance U_j of the façade is determined through Eq. (4) where R_{si} is the internal surface resistance, R_{se} is the external surface resistance (both obtained from Table 4), t_i and λ_i are respectively the thickness and thermal conductivity of each façade layer (both obtained from Table 3) and C is the number of layers forming the façade.

$$U_j = \frac{1}{\left(R_{si} + \sum_{i=1}^{C} \frac{t_i}{\lambda_i} + R_{se}\right)} \tag{4}$$

The geometrical model considered in the definition of the linear thermal bridge to determine L^{2D} complies with the requirements of EN ISO 10211 [5] in the definition of the cutting planes, dimensions, etc.

The boundary conditions indicated in Table 4 are valid for southern European countries. In Central European countries, −10 °C is normally used as the outside temperature and 30 °C as the temperature difference.

Applying the minimum interior surface temperature factor $f_{Rsi,min}$ indicated in Ref. [5] and the minimum value of this factor established in Spain in the document [4], it is obtained that the minimum temperature in the interior surface of the thermal bridge, so that surface condensation does not occur, is 12.8 °C. In this research it has been verified that, in the area of the thermal bridge, the interior surface temperature θ_{si} is always above this value.

3.2. Energy simulation

The EnergyPlus version 9.1 calculation engine was used to perform the energy simulation. EnergyPlus [17] is widely used in the scientific community to perform energy simulations of buildings. The energy simulation was carried out in three Spanish cities, Alicante, Barcelona and Madrid. For this purpose, EnergyPlus compatible climate data files were used, available at [17].

The results obtained are expressed in terms of energy demand, total primary energy consumption, total non-renewable primary energy consumption and greenhouse gas emissions CO_2.

These indicators have been determined using the efficiencies indicated in the Spanish legislation [4], being, for heating, a boiler with an efficiency of 92% and natural gas energy carrier, and for cooling, a refrigeration machine with an EER efficiency of 2.60 and electricity energy carrier. Likewise, the coefficients for primary energy consumption and CO_2 emissions correspond to those indicated in the Spanish standard [32].

As a complement, an economic analysis is carried out to obtain the extra construction cost required for each improvement measure to achieve a reduction of one tonne of CO_2 per year.

4. Results. Linear thermal transmittance of linear thermal bridges of slab front with face brick façades and the risk of condensation

The results obtained using the THERM software are shown below.

4.1. Base case: façades without any improvements implemented

Table 5 shows the results of both the heat flow per linear meter of thermal bridge and its linear thermal transmittance. The cases are shown classified according to the thermal transmittance value of the façades and the type of slab (FR for waffle slabs; FUC one-way slab with ceramic vault; FUE one-way slab with EPS vault), all according to the combinations shown in Table 2.

Comparison of the results shown in Table 5 reveal that the type of floor slab lightning has an influence on the reduction of heat flow. Slabs with concrete lightning will generate a higher heat flux. In floors with EPS lightning, the heat flow is lower and this reduction is more significant when the EPS lightning touches the thermal insulation of the façade, as there is a continuity in the thermal insulation layers reducing

Table 5
Base case. Results of the heat flow analysis for the case of unimproved façades.

BASE CASE			Inside dimensions			Outside dimensions		
Case	Façade		Φ_1 (W/m)	L^{2D} W/(m·K)	Ψ_i W/(m·K)	Φ_1 (W/m)	L^{2D} W/(m·K)	Ψ_e W/(m·K)
	U-value W/m²·K	Ra m²·K/W						
FR 40	0.40	2.00	35.692	1.785	**1.015**	35.692	1.785	**0.865**
FR 35	0.35	2.36	33.474	1.674	**1.000**	33.475	1.674	**0.869**
FR 30	0.30	2.83	30.995	1.550	**0.972**	30.995	1.550	**0.860**
FR 25	0.25	3.50	28.328	1.416	**0.935**	28.329	1.416	**0.841**
FR 15	0.15	6.16	21.377	1.069	**0.780**	21.377	1.069	**0.724**
FUC 40	0.40	2.00	33.628	1.681	**0.911**	33.628	1.681	**0.761**
FUC 35	0.35	2.36	31.255	1.563	**0.889**	31.254	1.563	**0.758**
FUC 30	0.30	2.83	28.696	1.435	**0.857**	28.696	1.435	**0.745**
FUC 25	0.25	3.50	25.900	1.295	**0.814**	25.900	1.295	**0.720**
FUC 15	0.15	6.16	18.616	0.931	**0.642**	18.616	0.931	**0.586**
FUE 40	0.40	2.00	29.948	1.497	**0.727**	29.948	1.497	**0.577**
FUE 35	0.35	2.36	27.371	1.369	**0.695**	27.371	1.369	**0.564**
FUE 30	0.30	2.83	24.616	1.231	**0.653**	24.616	1.231	**0.541**
FUE 25	0.25	3.50	21.640	1.082	**0.601**	21.640	1.082	**0.507**
FUE 15	0.15	6.16	13.773	0.689	**0.400**	13.773	0.689	**0.344**

Note: The numerical value indicated in each case represents the U-value of the façade.

the non-insulating areas.

This is clearly shown in Fig. 9 where zones with the same magnitude of heat flow are compared, while maintaining the same type of façade and its thermal transmittance (U-value 0.15 W/m^2·K) with the three types of floor slabs (FR 15 waffle slab with concrete vault, FUC 15 one-way slab with ceramic vault and FUE 15 one-way slab with EPS vault). It is clearly shown how, in the case of FUE 15, the first line of lightning touches the insulation of the façade and displaces the heat flow towards the compression layer of the slab. The approach is based on the premise of making improvements by giving continuity to the thermal insulation layer.

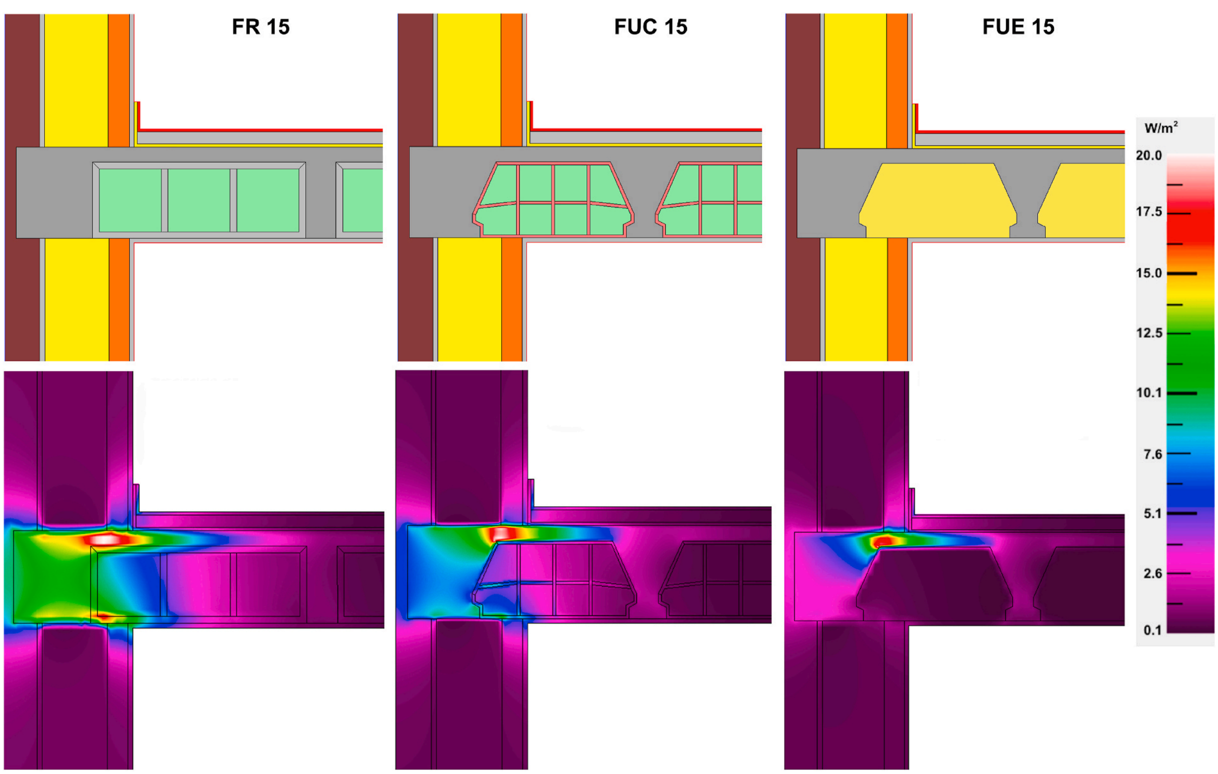

Fig. 9. Comparison of the zones with the same magnitude of heat flow for three different slabs. Slabs with concrete lightning (left) show a higher heat flux. In the EPS-lightened slabs (right) there is a reduction in heat flow because the EPS vault "touches" the thermal insulation of the façade.

4.2. Improvement M1: self-supporting brick façade with non-insulated support

Table 6 provides the results of both the heat flux per meter of the thermal bridge and its linear thermal transmittance.

As there is a practically continuous layer of thermal insulation on the façade, one might think that the result would be similar to the solution with the ETICS system, but the analysis carried out has shown that this is not the case, and this is due to the existence of a stainless steel profile for the support of the outer brick of the façade that is anchored to the slab front. Fig. 10 shows a detail of the slab front and the areas with the same magnitude of heat flow for case FR 15, where the increase in heat flow in the area of the stainless steel profile can be clearly seen, even though this profile is only 4 mm thick.

To further investigate the effect of the stainless steel support profile, a comparison of case FR 15, with and without a profile, has been made. The heat flux goes from 15.09 W/m if the profile is included to 10.57 W/m if the profile is not included, a difference of 30%. This shows that in order to reduce the heat flow in this type of façade, it is necessary to act on the stainless steel support profile of the face brickwork and that is why this analysis has been carried out.

Finally, for case FR 15 with stainless steel support profile, an analysis of the variation of the heat flux with increasing thickness of thermal insulation at the slab front has also been carried out. Table 7 shows this analysis, in which it can be seen that the decrease in heat flow is very small, and this is due to the fact that increasing the thickness of the

Table 6
Case M1. Results of the heat flow analysis for the case of face façades with improvement M1. The % column indicates the improvement regarding the base case in terms of linear thermal transmittance.

IMPROVEMENT CASE (M1)			Inside dimensions				Outside dimensions			
Case	Façade		Φ_1 (W/m)	L^{2D} W/(m·K)	Ψ_i W/(m·K)	%	Φ_1 (W/m)	L^{2D} W/(m·K)	Ψ_e W/(m·K)	%
	U-value W/m^2·K	*Ra* m^2·K/W								
FR 40	0.40	2.00	25.338	1.267	**0.497**	**51.0**	25.338	1.267	**0.347**	**58.9**
FR 35	0.35	2.36	23.295	1.165	**0.491**	**50.9**	23.295	1.165	**0.360**	**58.6**
FR 30	0.30	2.83	21.493	1.075	**0.497**	**48.9**	21.493	1.075	**0.385**	**55.3**
FR 25	0.25	3.50	19.509	0.975	**0.494**	**47.2**	19.509	0.975	**0.400**	**52.4**
FR 15	0.15	6.16	15.086	0.754	**0.466**	**40.3**	15.086	0.754	**0.409**	**43.5**
FUC 40	0.40	2.00	25.089	1.254	**0.484**	**46.9**	25.089	1.254	**0.334**	**56.1**
FUC 35	0.35	2.36	23.037	1.152	**0.478**	**46.2**	23.037	1.152	**0.347**	**54.2**
FUC 30	0.30	2.83	21.066	1.053	**0.476**	**44.5**	21.060	1.053	**0.363**	**51.3**
FUC 25	0.25	3.50	19.182	0.959	**0.478**	**41.3**	19.182	0.959	**0.384**	**46.7**
FUC 15	0.15	6.16	14.611	0.731	**0.442**	**31.2**	14.611	0.731	**0.386**	**34.2**
FUE 40	0.40	2.00	24.636	1.232	**0.462**	**36.5**	24.636	1.232	**0.312**	**46.0**
FUE 35	0.35	2.36	22.557	1.128	**0.454**	**34.7**	22.556	1.128	**0.323**	**42.7**
FUE 30	0.30	2.83	20.540	1.027	**0.450**	**31.2**	20.540	1.027	**0.337**	**37.7**
FUE 25	0.25	3.50	18.571	0.929	**0.447**	**25.5**	18.571	0.929	**0.354**	**30.3**
FUE 15	0.15	6.16	13.465	0.673	**0.384**	**3.9**	13.464	0.673	**0.328**	**4.5**

Note: The numerical value indicated in each case represents the U-value of the façade.

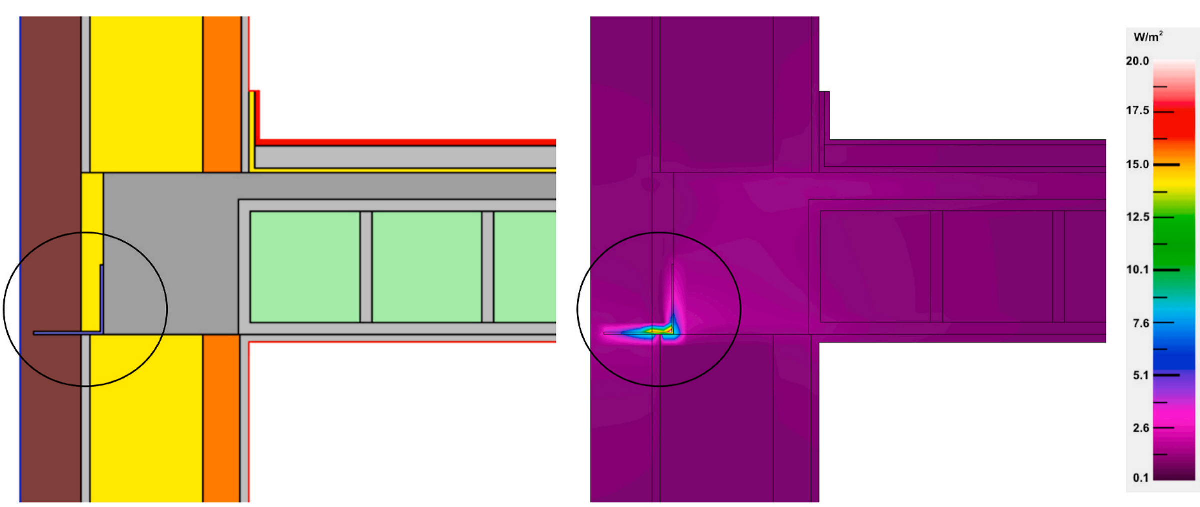

Fig. 10. Zones with the same magnitude of heat flux. Detail of the effect of the stainless steel support profile for the M1 FR 15 case. (Left model with materials. Right model with zones having the same heat flux).

Table 7
Dependence of the heat flow with the thickness of the thermal insulation at the slab front of case M1 FR 15.

		Inside dimensions			Outside dimensions		
Case	Thickness of thermal insulation at the slab face [mm]	Φ_1 (W/m)	L^{2D} W/(m·K)	Ψ_i W/(m·K)	Φ_1 (W/m)	L^{2D} W/(m·K)	Ψ_e W/(m·K)
FR 15	40 (original case)	15.086	0.754	0.466	15.086	0.754	0.409
	60	14.108	0.705	0.416	14.108	0.705	0.360
	80	13.337	0.667	0.378	13.337	0.667	0.322

thermal insulation requires the use of larger and thicker stainless steel profiles to support the facing brick, which will increase the effect shown in Fig. 10.

4.3. Improvement M2: self-supporting facing brick façade with insulated support

The analysis of case M1 shows that in order to reduce the heat flow in this type of façade, it is necessary to act on the stainless steel support profile of the facing brick. One solution could be to use non-metallic profiles, but as yet there are no solutions available on the market since it could compromise the mechanical stability of the façade. Therefore, the solution considered here involves introducing rigid thermal insulation (neoprene type or similar) between this profile and slab front, something similar to the "thermal bridge break" effect that exists in metal window frames.

In recent years, solutions without a continuous support profile have appeared on the market, which is replaced by numerous point anchorages of the outer brick both in columns and slab fronts, which generates point thermal bridges and also limits the thickness of the thermal insulation to a maximum of 200 mm, which does not allow the minimum U-value analyzed in this study (U-value of 0.15 W/m^2·K) to be reached. This is the reason why this solution has not been considered in this study.

Table 8 provides the results of both the heat flux per meter of the thermal bridge and its linear thermal transmittance.

4.4. Improvement M3: facing brick façade confined between slabs

Table 9 provides the results of both the heat flux per meter of the thermal bridge and its linear thermal transmittance.

The arrangement of the materials used in this improvement causes the heat flow to be displaced towards the compression layer of the slab. To analyze the possible improvement of the increase in the width of the

Table 8
Case M2. Results of the heat flow analysis for the case of face façades with improvement M2. The % column indicates the improvement regarding the base case in terms of linear thermal transmittance.

IMPROVEMENT CASE (M2)			Inside dimensions				Outside dimensions			
Case	Façade		Φ_1 (W/m)	L^{2D} W/(m·K)	Ψ_i W/(m·K)	%	Φ_1 (W/m)	L^{2D} W/(m·K)	Ψ_e W/(m·K)	%
	U-value W/m^2·K	*Ra* m^2·K/W								
FR 40	0.40	2.00	22.835	1.142	**0.372**	**63.4**	22.835	1.142	**0.222**	**74.4**
FR 35	0.35	2.36	21.005	1.050	**0.377**	**62.4**	21.005	1.050	**0.245**	**71.8**
FR 30	0.30	2.83	19.087	0.954	**0.377**	**61.2**	19.087	0.954	**0.264**	**69.3**
FR 25	0.25	3.50	17.188	0.859	**0.378**	**59.6**	17.188	0.859	**0.284**	**66.2**
FR 15	0.15	6.16	13.110	0.656	**0.367**	**53.0**	13.110	0.656	**0.311**	**57.1**
FUC 40	0.40	2.00	22.682	1.134	**0.364**	**60.1**	22.682	1.134	**0.214**	**71.9**
FUC 35	0.35	2.36	20.837	1.042	**0.368**	**58.6**	20.837	1.042	**0.237**	**68.7**
FUC 30	0.30	2.83	18.928	0.946	**0.369**	**57.0**	18.929	0.946	**0.256**	**65.6**
FUC 25	0.25	3.50	16.986	0.849	**0.368**	**54.8**	16.986	0.849	**0.274**	**61.9**
FUC 15	0.15	6.16	12.869	0.643	**0.355**	**44.8**	12.869	0.643	**0.298**	**49.1**
FUE 40	0.40	2.00	22.398	1.120	**0.350**	**51.9**	22.398	1.120	**0.200**	**65.4**
FUE 35	0.35	2.36	20.530	1.026	**0.353**	**49.2**	20.530	1.027	**0.222**	**60.7**
FUE 30	0.30	2.83	18.591	0.930	**0.352**	**46.1**	18.591	0.930	**0.240**	**55.7**
FUE 25	0.25	3.50	16.594	0.830	**0.348**	**42.0**	16.594	0.830	**0.255**	**49.8**
FUE 15	0.15	6.16	12.097	0.605	**0.316**	**21.0**	12.097	0.605	**0.260**	**24.4**

Note: The numerical value indicated in each case represents the U-value of the façade.

Table 9
Case M3. Results of the heat flow analysis for the case of face façades with improvement M3. The % column indicates the improvement regarding the base case in terms of linear thermal transmittance.

IMPROVEMENT CASE (M3)			Inside dimensions				Outside dimensions			
Case	Façade		Φ_1 (W/m)	L^{2D} W/(m·K)	Ψ_i W/(m·K)	%	Φ_1 (W/m)	L^{2D} W/(m·K)	Ψ_e W/(m·K)	%
	U-value W/m^2·K	*Ra* m^2·K/W								
FR 40	0.40	2.00	26.315	1.316	**0.554**	**45.4**	26.315	1.316	**0.396**	**54.2**
FR 35	0.35	2.36	23.683	1.184	**0.517**	**48.3**	23.682	1.184	**0.379**	**56.4**
FR 30	0.30	2.83	19.776	0.989	**0.417**	**57.1**	19.776	0.989	**0.299**	**65.3**
FR 25	0.25	3.50	17.146	0.857	**0.381**	**59.3**	17.146	0.857	**0.282**	**66.5**
FR 15	0.15	6.16	11.755	0.588	**0.302**	**61.3**	11.755	0.588	**0.243**	**66.5**
FUC 40	0.40	2.00	25.658	1.283	**0.521**	**42.9**	25.658	1.283	**0.363**	**52.3**
FUC 35	0.35	2.36	22.231	1.112	**0.445**	**50.0**	22.231	1.112	**0.307**	**59.4**
FUC 30	0.30	2.83	19.761	0.988	**0.417**	**51.4**	19.761	0.988	**0.298**	**60.0**
FUC 25	0.25	3.50	17.379	0.869	**0.393**	**51.7**	17.379	0.869	**0.294**	**59.2**
FUC 15	0.15	6.16	12.173	0.609	**0.323**	**49.7**	12.173	0.609	**0.264**	**55.0**
FUE 40	0.40	2.00	25.616	1.281	**0.519**	**28.7**	25.616	1.281	**0.361**	**37.5**
FUE 35	0.35	2.36	22.190	1.110	**0.443**	**36.3**	22.190	1.110	**0.305**	**46.0**
FUE 30	0.30	2.83	19.718	0.986	**0.414**	**36.6**	19.718	0.986	**0.296**	**45.3**
FUE 25	0.25	3.50	17.333	0.867	**0.390**	**35.0**	17.333	0.867	**0.292**	**42.4**
FUE 15	0.15	6.16	12.116	0.606	**0.320**	**20.0**	12.116	0.606	**0.261**	**24.1**

Note: The numerical value indicated in each case represents the U-value of the façade.

Table 10
Influence of the width of the thermal insulation board under the screed in the case M3 FR 15.

Thermal insulation band width under the screed - cm	Ψ_i W/(m·K)		Ψ_e W/(m·K)	
0	0.342		0.283	
50	**0.302**	**−11.70 %**	**0.243**	**−14.13 %**
100	**0.301**	**−11.99 %**	**0.242**	**−14.49 %**

perimeter thermal insulation board under the screed, the analysis shown in Table 10 shows that there is a significant reduction if a 50 cm wide board is installed, but that the increase in width has an insignificant effect (going from 50 cm to 100 cm only reduces the interior linear thermal transmittance by 0.29% and the exterior by 0.36% compared to the case without the perimeter insulation board), that's why it's not interesting to increase the width of such insulation board.

Fig. 11 shows the position of the 30 mm thick thermal insulation board under the screed (yellow color). Left without thermal insulation under the screed, center with a 50 cm wide board and right with a 100 cm wide board.

4.5. Risk of condensation

THERM makes it possible to identify, once the simulation has been carried out, the temperature at each of the points of the model. In all cases, the point with the lowest interior surface temperature is at the vertex formed by the lower face of the slab and the façade, obtaining the temperatures shown in Table 11. All of them are above the minimum value of 12.8 °C, so there is no risk of condensation or mold formation.

5. Comparison and discussion of results

These comparisons and analysis of the results are presented in the following sections:

- Between the linear thermal transmittance values of the base case and the proposed improvements to identify which are more effective in reducing heat flow. The results obtained are also validated by comparing them with two official sources: the EN-ISO 14683 [28] standard and the DA DB-HE/3 paper [4].

Table 11
Minimum internal surface temperatures θ_{si} for each case analyzed.

Case	Base case	Improvement M1	Improvement M2	Improvement M3
FR 40	13.7	16.7	17.5	13.2
FR 35	13.8	16.8	17.5	16.7
FR 30	14.5	16.8	17.6	17.7
FR 25	15.0	16.9	17.6	18.2
FR 15	15.6	17.1	17.7	19.0
FUC 40	13.5	16.4	17.3	13.2
FUC 35	13.9	16.5	17.3	16.7
FUC 30	14.4	16.6	17.3	17.7
FUC 25	14.9	16.5	17.3	18.3
FUC 15	16.4	17.4	17.9	19.1
FUE 40	13.2	16.0	16.9	13.2
FUE 35	14.6	16.0	16.9	16.7
FUE 30	15.6	16.0	16.8	17.7
FUE 25	16.6	15.9	16.7	18.3
FUE 15	19.0	18.0	18.3	19.1

Note: The numerical value indicated in each case represents the U-value of the façade.

- Among improvement measures in terms of energy demand, total primary energy consumption, total non-renewable primary energy consumption, and emissions of greenhouse gases CO_2.
- And a final comparison in terms of the construction cost overrun required with each improvement measure to achieve a reduction of one tonne of CO_2 per year.

5.1. Comparison of indoor linear thermal transmittance values

As shown in Tables 8 and 9, the application of the two proposed new construction improvements, M2 and M3, allow reducing the value of the interior linear thermal transmittance of the thermal bridge between 20% and 63.4%.

Fig. 12 shows a comparison between the four situations analyzed: the base case and the three selected improvements.

As can be seen in Fig. 12 (first graph on the left) the type of lightweight (concrete, ceramic or EPS) used in the slabs influences the resulting value of the interior linear thermal transmittance, for example, for a façade U-value of 0.40 W/(m^2·K) the linear thermal transmittance goes from 1.02 W/m·K (concrete lightning) to 0.91 W/m·K (ceramic lightning, reduction of 10.8%) and to 0.73 W/m·K (EPS lightning,

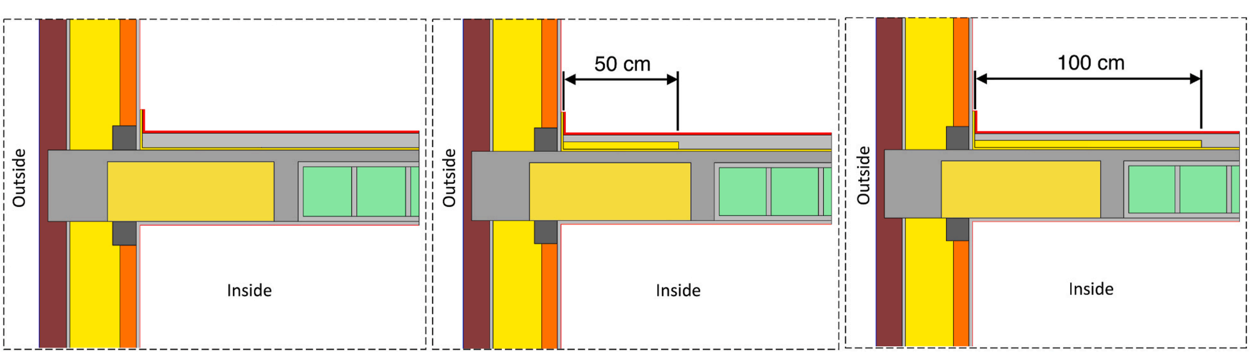

Fig. 11. Diagrams of the cases considered to analyze the effect of thermal insulation under the screed.

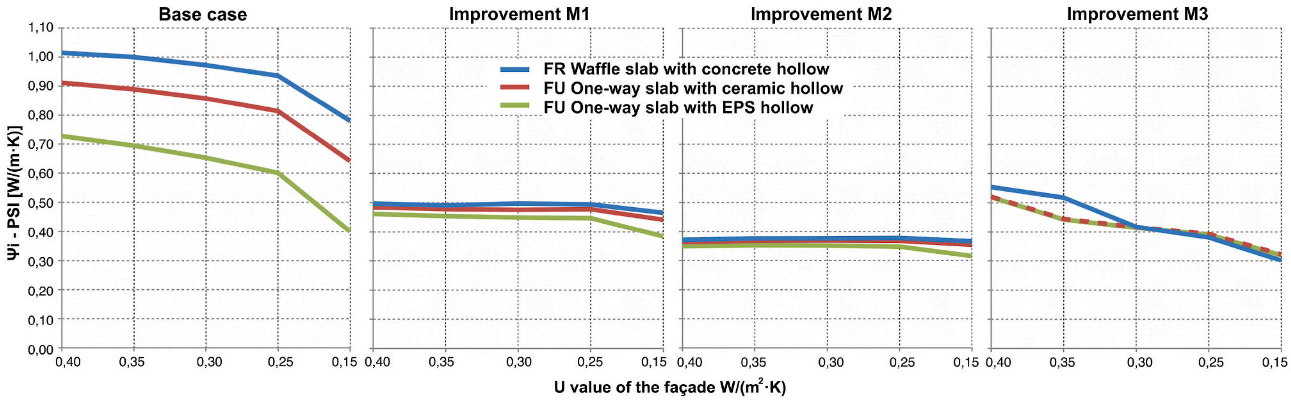

Fig. 12. Comparison between the analyzed cases of the indoor linear thermal transmittance Ψi.

reduction of 28.4%).

In the case of EPS lightweight slabs, due to the constructive arrangement of the materials, when the thickness of the thermal insulation layer of the façade increases, this touches the EPS lightning of the slab, achieving continuity in the thermal insulation materials.

In improvements M1 and M2, the continuity of the thermal insulation layer achieved at the slab front means that the value of the interior linear thermal transmittance remains very constant with a small change for a façade U-value of 0.15 W/(m^2·K) due to the reduced gap between the façade insulation and the first slab lightning, also a thermal insulation material.

In case M3 there are two different behaviors: for façade U-values higher than 0.30 W/(m^2·K), as there is no contact between the thermal insulation layer of the façade and the first lightning of the slabs (which is made of EPS and is also a thermal insulating material), there is a difference depending on the type of slab. For façade U-values equal to or less than 0.30 W/(m^2·K), as there is contact between the thermal insulation of the façade and that of the slab, there is no difference depending on the type of slab.

Fig. 13 shows the results of the temperature distribution analysis for the base case and the three proposed improvements. To facilitate the understanding of the figure, only the graphs corresponding to the maximum (0.40 W/m^2·K) and minimum (0.15 W/m^2·K) thermal transmittances for the façades and the three types of floor slabs are shown.

- In the base case, the effect of the thermal bridge and the temperature distribution in this area is clearly visible. The value of the linear

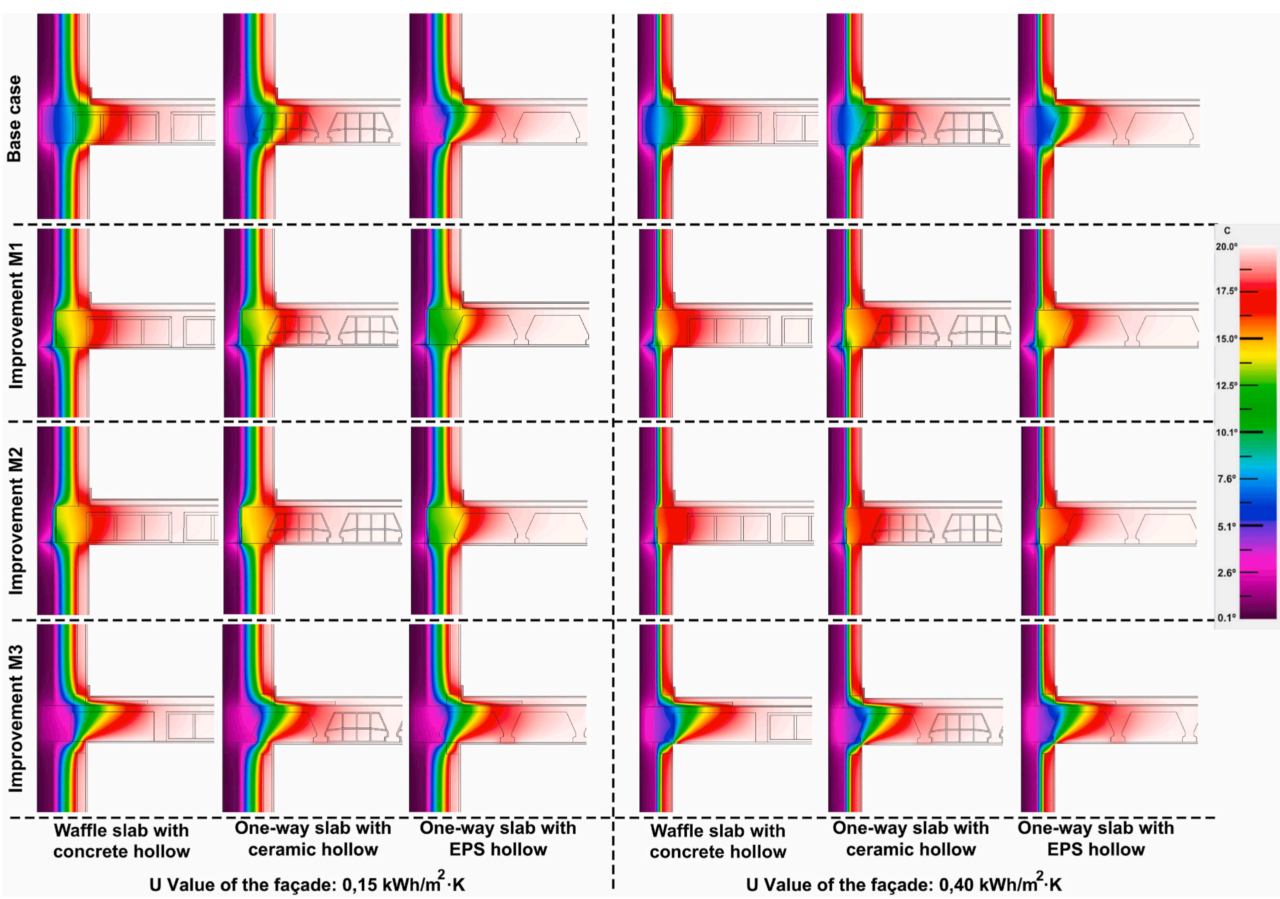

Fig. 13. Temperature distribution for the base case and proposed improvements.

Table 12
Average values of the indoor linear thermal transmittance Ψi for the base case and the three proposed improvements.

			U-value of the façade - W/(m²·K)				
			0.40	0.35	0.30	0.25	0.15
Indoor linear thermal transmittance Ψ_i W/(m·K)	Base case	FR - Concrete	1.02	1.00	0.97	0.94	0.78
		FUC - Ceramic	0.91	0.89	0.86	0.81	0.64
		FUE - EPS	0.73	0.70	0.65	0.60	0.40
	Improvements M1	Any type of slab	0.47				
	Improvements M2		0.36				
	Improvements M3		0.53	0.47	0.42	0.39	0.31

thermal transmittance of the thermal bridge is influenced by the type of slab, its lightning and the *U*-value of the façade.

- Improvements M1 and M2 show the effect of the thermal insulation layer on the left side of the façade: the temperature curves are shifted to the left, so that the value of the linear thermal transmittance of the thermal bridge is not influenced by the type of slab or its lightning, presenting constant values regardless of the *U*-value of the façade.
- Improvement M3 shows the effect of the thermal insulation layer on the right side of the façade: the temperature curves are shifted to the right. The value of the linear thermal transmittance of the thermal bridge is influenced by the *U*-value of the façade but not by the type of slab or its lightning if the U-values of the façade is equal to or less than 0.30 W/(m²·K).

Improvements M1 and M2 (self-supporting façade with thermal insulation at the slab front) show that the Ψi value of the interior linear thermal transmittance is little influenced by the U-value of the façade or the type of slab (waffle or one-way) or the type of slab light-weighting (concrete, ceramic or EPS). The Ψi value is very constant (in case M1 the variation between the maximum and minimum result is 0.097 W/m·K and in case M2 it is 0.111 W/m·K) and this is due to the fact that the continuity of the thermal insulation layer in the thermal bridge is achieved on the outside of the façade.

In the case of improvement M3 the continuity of the insulation layer in the thermal bridge is achieved on the inside of the façade and this means that the Ψi value is not constant, however the type of slab or light-weighting does not influence this value but it does influence it due to the *U*-value of the façade. Table 12 shows the average values of Ψi as a function of the U-value of the façade; these are the average values that can be taken as a result for this case.

In view of the above results, it is clear that the best solution is improvement M2 as it shows the lowest value of the indoor linear thermal transmittance.

The standard [28] or study [33] indicates the methods to determine the Ψ value and expected accuracy: numerical calculations according to EN ISO 10211 [5] (typical accuracy: ± 5%), thermal bridge catalogues (typical accuracy: ± 20%), manual calculations (typical accuracy: ± 20%) and default values according to EN ISO 14683 [28] (typical accuracy between 0% and 50%). This is of interest for validation of the results by comparison with official or reference values.

Table 13 gives the values of Ψi of the two official references used (DA DB-HE/3 [4] and EN ISO 14683 [28]). In these references, there are no cases similar to the improvements proposed in this research (M1, M2 and M3). It can be seen that the values obtained for the base case are in line with the reference values.

Table 13
Values of Ψi of the two official references used.

Method and accuracy			*U*-value of the façade - W/(m²·K)				
			0.40	0.35	0.30	0.25	0.15
DA DB-HE/3 [4]	Catalogue ± 20%	Ψi - W/(m·K)	0.89	0.86	0.83	0.79	0.69
EN-ISO 14683 [28]	Default values 0% a 50%	Ψi - W/(m·K)	1.05	No data			

Official sources consider the slabs as a continuous layer of material without differentiating between the different materials (reinforced concrete, lightweight elements, air chambers, etc.), nor do they differentiate by type of slab (one-way, waffle) or by type of lightweight (concrete, ceramic or EPS). Furthermore, standard EN-ISO 14683 [28] only provides a linear thermal transmittance value obtained for slabs with a 20 cm edge and a façade U-value of 0.375 W/(m2·K). Finally, they only provide data for the base case.

Comparing the base case with the two reference sources we can see the following:

- The values of DA DB-HE/3 [4] are perfectly in line with the values obtained with the one-way slab with ceramic lightning.
- Given that the EN-ISO 14683 [28] standard uses a façade U of 0.375 W/(m2·K), we can see that the Ψi value provided by this standard is perfectly in line with the values obtained for waffle slabs with concrete panels and façade *U*-values of 0.40 or 0.35 W/(m2·K).

5.2. Effect of improved thermal bridge of the slab-front on nZEB indicators

In order to analyze the contribution of the thermal bridge of the slab-front to the evaluation of the nZEB building indicators, an energy simulation of a real model of a building of 18 dwellings located in Madrid (Spain) was carried out. Table 14 includes the distribution by use of each floor and the net useable area per dwelling.

Fig. 14 shows the model developed with the energy simulation tool and a real image of the building. The model has been developed using the CYPETHERM HE Plus tool [34] which incorporates EnergyPlus [17] as an energy engine.

In addition to Madrid, winter climate zone D according to Ref. [4], the study has been extended to two other Spanish cities: Alicante, winter climate zone B according to Ref. [4] and Barcelona, winter climate zone C according to Ref. [4]. According to statistics published by official Spanish agencies [18], these three climate zones (B, C and D) have 83.9% of the existing housing stock in Spain, 84% of the population and 82.5% of the total new construction of residential buildings. And if we focus on the three selected cities and their provinces, they are the ones with the highest number of newly built dwellings in Spain: Alicante with

Table 14
Floor layout of the building under study.

	Use	Living area per dwelling (m²)	Number of bedrooms
Basement	Garage	–	–
Ground floor	Circulation areas and facilities	–	–
Floors 1 to 3	4 dwellings per floor	89	3
Floors 4 to 5	2 dwellings per floor	96	4
Floors 6	2 dwellings per floor	84	3
Floors 7	Exit to roof	–	–

Fig. 14. Model developed in CYPETHERM HE Plus and the real building.

Table 15
Reference thermal transmittance U-values for the studied cities.

Locality, altitude and climate zone according to [4]			Reference *U*-values [W(m²·K)]			
			Façades	Roof	External floor	Windows
Alicante	0 m	B4	0.38	0.33	0.38	2.00
Barcelona	13 m	C2	0.29	0.23	0.29	2.00
Madrid	667 m	D3	0.27	0.22	0.27	1.60

Table 16
Values of the interior linear thermal transmittance Ψi considered for the different thermal bridges of the building.

Type of façade encounters with:	Values Ψi [W/(m·L)] for thermal bridges		
	Alicante	Barcelona	Madrid
Roofs (without continuity of thermal insulation)	0.92	0.91	0.90
External floors (without continuity of thermal insulation)	0.83	0.83	0.83
External corners	0.07	0.06	0.06
Inside corners	−0.10	−0.08	−0.08
Windows: lintels (small gap between the insulation and the window frames)	0.72	0.75	0.77
Windows: jambs (small gap between insulation and window frames)	0.44	0.45	0.46
Windows: window sill (small gap between insulation and window frames)	0.16	0.17	0.17
Pillars (continuity of thermal insulation)	0.01	0.00	0.00

10.9%; Barcelona with 10.5% and Madrid with 27.1%. This is the reason why these three cities have been selected for this study. The same conditions of occupancy, ventilation and set point temperatures have been considered in all of them, which coincide with those indicated in Ref. [4].

The façade of the building is a double brick façade with no continuity of insulation on the slab fronts.

Table 15 shows the suggested values of the thermal transmittance U for each thermal envelope element according to Ref. [4].

Table 16 shows the interior linear thermal transmittance values of thermal bridges obtained from DA DB-HE/3 [4] by applying the U-values of Table 15. These values depend on the thermal transmittance value of the façades. The usual construction system in Spain has been considered in which thermal bridges are not improved.

Table 17 shows the interior linear thermal transmittance values considered for the slab front junctions. These values have been determined according to the façade U-value given in Table 14 and the corresponding Ψi values given in Tables 5, 6, 8 and 9, as indicated below. For the base case two values: the average value of the FR and FUC cases and the value of the FUE case; for each of the improvements, the average value of the FR, FUC and FUE cases of each improvement has been considered. In Alicante, the FR40, FUC40 and FUE40 cases have been used. In Barcelona the cases FR30, FUC30 and FUE30. In Madrid the cases FR25, FUC25 and FUE25.

Table 17
Indoor linear thermal transmittance values Ψi considered for thermal bridge of slab front.

Case study		Values Ψi [W/(m·K)] for slabs fronts		
		Alicante	Barcelona	Madrid
Base case	Waffle slabs or one-way ceramic slabs	0.963	0.915	0.875
	One-way EPS slabs	0.727	0.653	0.601
Improvements M1	All types of slabs	0.481	0.474	0.473
Improvements M2		0.362	0.366	0.365
Improvements M3		0.531	0.416	0.388

Fig. 15 shows, for the base case and the residential building analyzed, a comparison among the different types of thermal bridges identified in Fig. 1 according to their impact represented by each of them in terms of the two-dimensional component of the heat flow indicated in Eq. (1). The thermal bridge formed by the junction of façades with intermediate slabs (slab front) represents more than 52% of the total heat flow through thermal bridges.

5.2.1. Study in alicante (climate zone B4)

Fig. 16 shows the comparison of the nZEB indicators between the base case and the three proposed improvements. In all cases, improvement M2 leads to the greatest reduction in these indicators: 22.6% in heating demand (first indicator); 20.4% in total primary energy consumption (second indicator); 20.7% in non-renewable primary energy consumption (third indicator) and 21.1% in CO2 emissions.

5.2.2. Study in Barcelona (climate zone C2)

Fig. 17 shows the comparison of the nZEB indicators between the base case and the three proposed improvements. In all cases, improvement M2 leads to the greatest reduction in these indicators: 18.5% in heating demand (first indicator); 15.5% in total primary energy consumption (second indicator); 16.0% in non-renewable primary energy

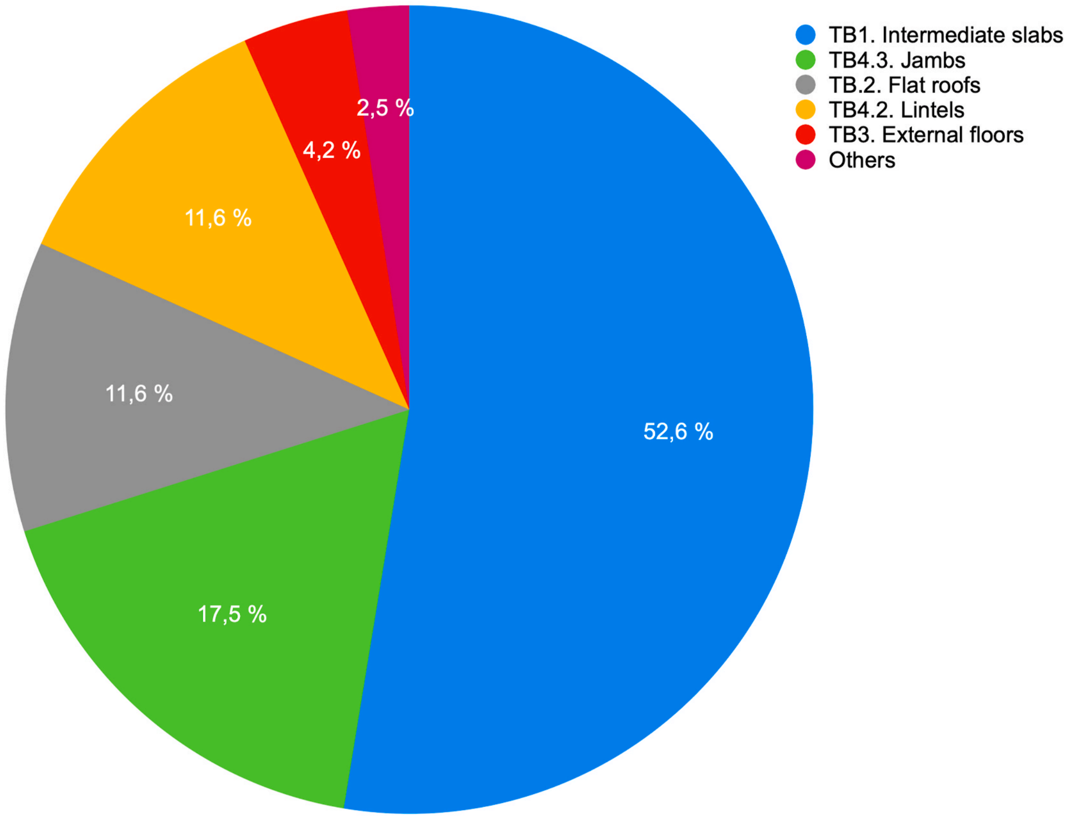

Fig. 15. Comparison between types of thermal bridges according to their contribution to the two-dimensional component of heat flow according to Eq. (1) in the base case of the building under study.

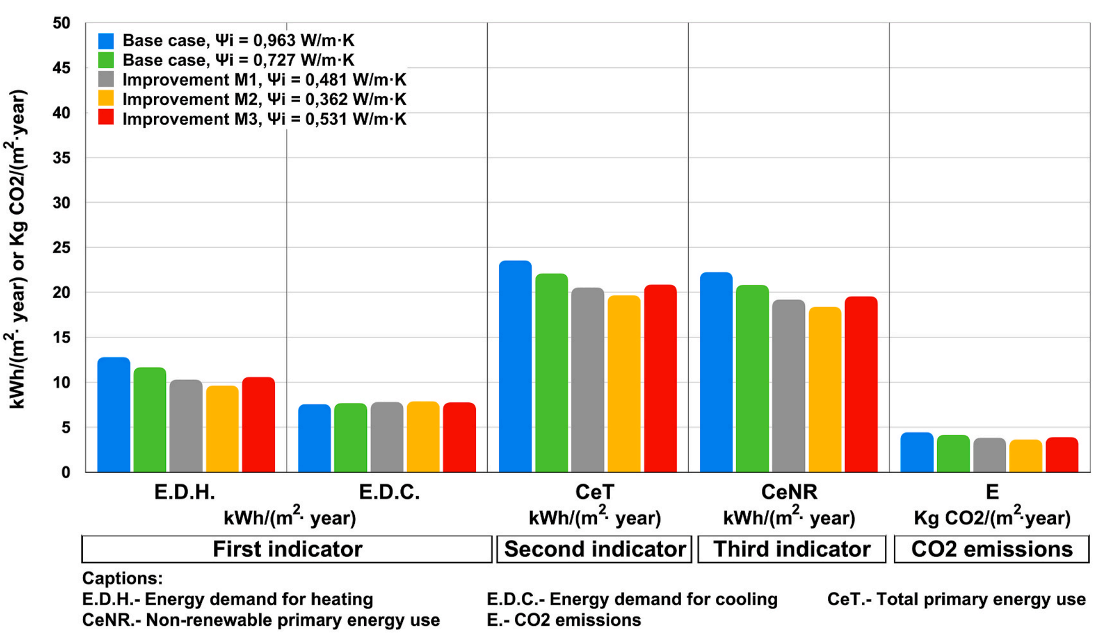

Fig. 16. Evolution of nZEB indicators for Alicante (climate zone B4). Base case comparison and improvements.

consumption (third indicator) and 16.4% in CO2 emissions.

5.2.3. Study in Madrid (climate zone D3)

Fig. 18 shows the comparison of the nZEB indicators between the base case and the three proposed improvements. In all cases, improvement M2 leads to the greatest reduction in these indicators: 16.1% in heating demand (first indicator); 14.4% in total primary energy consumption (second indicator); 14.6% in non-renewable primary energy consumption (third indicator) and 14.9% in CO2 emissions.

As can be seen from the three figures above, in the three cities under study, it has been observed that the cooling demand remains practically unchanged, as already indicated by T. G. Theodosiou et al. [7] and G. Evola et al. [9].

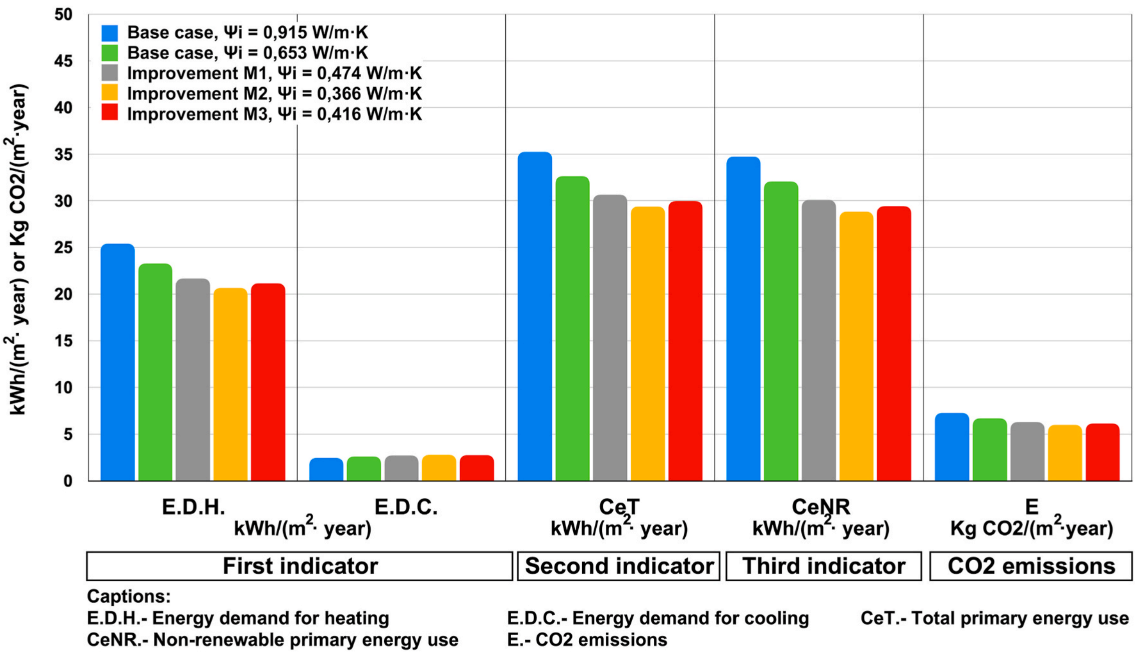

Fig. 17. Evolution of nZEB indicators for Barcelona (climate zone C2). Base case comparison and improvements.

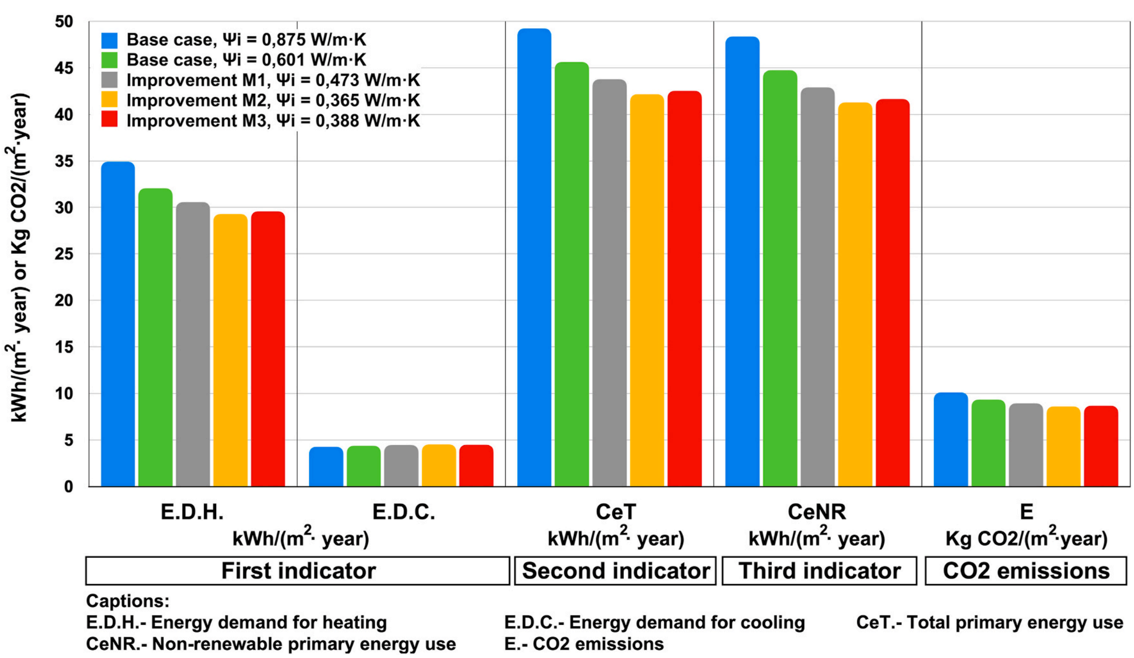

Fig. 18. Evolution of nZEB indicators for Madrid (climate zone D3). Base case comparison and improvements.

5.3. Analysis of the construction cost overrun required to reduce one tonne of CO2 per year

In order to determine the construction costs of each case (base and improvements), the construction price base implemented in the software "Construction price generator" [35] has been used, which uses the reference prices of the professional associations of architects in Spain.

The indicator "additional cost to reduce one tonne of CO_2" allows to analyze improvement measures and to find out which is the easiest to implement from an economic point of view. In this way, decisions can be made on which improvement measures are the best strategy to reduce CO_2 emissions.

The analysis of this indicator is straightforward, as the improvement measure with a lower value of the indicator implies that a lower cost overrun or lower investment is required to reduce one tonne of CO_2 per year.

Fig. 19 presents a comparison of the indicator for each study location and each improvement measure. Improvement M2 has the lowest value of the indicator for all three locations, and is therefore the measure that requires the lowest investment cost to achieve a reduction of one tonne of CO_2 per year. In addition, it is also observed that in the most severe climatic zones in winter (D3) the investment cost is lower.

6. Conclusions

In this paper, an analysis of three improvements of the thermal

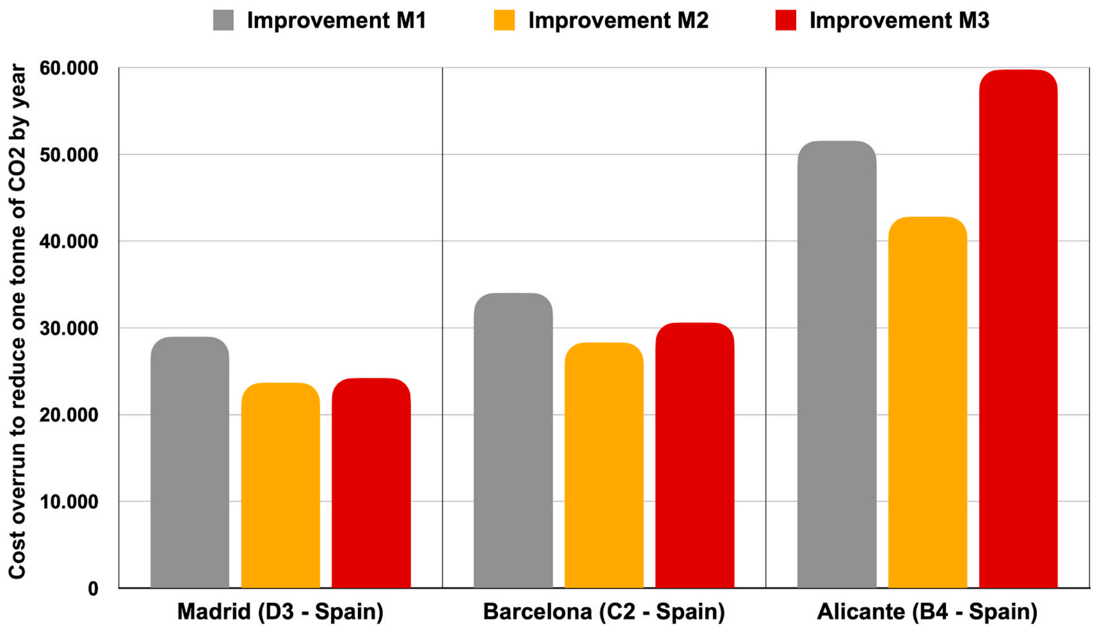

Fig. 19. Comparison between improvements. Cost overrun needed to save one tonne of CO_2 per year.

bridge formed by double-brick façades and intermediate slabs (slab fronts) has been carried out, two of which correspond to novel proposals by the authors (referred to as M2 and M3). In this study the traditional systems of façade construction in Spain has been used.

The M2 improvement consists of placing a 5 mm thick thermal insulation between the stainless steel profile used to support the exterior face brick and the slab front. The M3 improvements consists of replacing the first line of floor slab lightning with expanded polystyrene EPS pieces; replacement of the first and last row of bricks of the inner ceramic sheet with cellular glass blocks; and placement, under the pavement and around its perimeter, of a thermal insulation layer 50 cm wide and 30 mm thick.

The research has been carried out taking into account the indicators of nZEB residential buildings in Spain.

The conclusions of this research are:

- The two proposed new construction improvements, M2 and M3, allow reducing the value of the interior linear thermal transmittance of the thermal bridge between 20% and 63.4%.
- The M2 improvement is the one that provides the greatest reduction in the nZEB indicators:
- Alicante (climate zone B4): 22.6% in heating demand (first indicator); 20.4% in total primary energy consumption (second indicator); 20.7% in non-renewable primary energy consumption (third indicator) and 21.1% in CO2 emissions.
- Barcelona (climate zone C2): 18.5% in heating demand (first indicator); 15.5% in total primary energy consumption (second indicator); 16.0% in non-renewable primary energy consumption (third indicator) and 16.4% in CO2 emissions.
- Madrid (climate zone D3): 16.1% in heating demand (first indicator); 14.4% in total primary energy consumption (second indicator); 14.6% in non-renewable primary energy consumption (third indicator) and 14.9% in CO2 emissions.
- Likewise, improvement M2 presents a lower value of the construction cost overrun indicator to achieve a reduction of one ton of CO2 per year.

It can be concluded that the treatment, in terms of linear thermal transmittance reduction, of slab front thermal bridges has an effect of reducing the heating energy demand, especially when we increase the height of the buildings, as the length of the thermal bridge increases and, with it, the heat flow at that point. In addition, in the three cities under study, it has been observed that the cooling energy demand remains practically unchanged.

This study thus demonstrates that the analysis and design of building solutions to reduce the linear thermal transmittance of slab front thermal bridges is a strategy that contributes to achieving the requirements of the nZEB building standard in Spain.

CRediT authorship contribution statement

M.J. Romero: Conceptualization, Methodology, Investigation, Formal analysis, Validation, Writing – original draft, Writing – review & editing. **F. Aguilar:** Methodology, Investigation, Writing – review & editing. **P.G. Vicente:** Methodology, Writing – review & editing, Supervision.

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.

References

[1] Eurostat, Statistical Books. Energy data, 2020 edition, https://ec.europa.eu/eurostat/documents/3217494/11099022/KS-HB-20-001-EN-N.pdf/bf891880-1e3e-b4ba-0061-19810ebf2c64?t=1594715608000.
[2]) Directive 2010/31/UE of the European Parliament and of the Council of 19 May 2010, on the energy performance of buildings (recast, https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32010L0031&from=ES.
[3] EN ISO 52000-1, Energy Performance of Buildings. Overarching EPB Assessment. Part 1: General Framework and Procedures, 2017.
4 Technical Building Code, Basic Energy Saving Document DB-HE, its supporting documents DA DB-HE/2 and DA DB-HE/3 and the DB-HE Application Guide. https://www.codigotecnico.org/DocumentosCTE/AhorroEnergia.html.
[5] EN ISO 10211, Thermal Bridges in Building Construction. Heat Flows and Surface Temperatures, 2007. Detailed calculations.
[6] A. Capozzoli, A. Gorrino, V. Corrado, A building thermal bridges sensitivity analysis, Appl. Energy 107 (2013) 229–243, https://doi.org/10.1016/j.apenergy.2013.02.045.
[7] T.G. Theodosiou, A.M. Papadopoulos, The impact of thermal bridges on the energy demand of buildings with double brick wall constructions, Energy Build. 40 (2008) 2083–2089, https://doi.org/10.1016/j.enbuild.2008.06.006.

[8] V. Corrado, A. Gorrino, A. Gasparella, F. Cappelletti, Detailed assessment of thermal bridges in highly insulated buildings, in: Clima 2010, 10th Rehva World Congress "Sustainable Energy Use in Buildings", Antalya, 9-12 May, 2010.
[9] G. Evola, G. Margani, L. Marletta, Energy and cost evaluation of thermal bridge correction in Mediterranean climate, Energy Build. 43 (2011) 2385–2393, https://doi.org/10.1016/j.enbuild.2011.05.028.
[10] Hua Ge, Fuad Baba, Effect of dynamic modeling of thermal bridges on the energy performance of residential buildings with high thermal mass for cold climates, Sustain. Cities Soc. 34 (2017) 250–263, https://doi.org/10.1016/j.scs.2017.06.016.
[11] C. Misiopecki, M. Bouquin, A. Gustavsen, B.P. Jelle, Thermal modeling and investigation of the most energy-efficient window position, Energy Build. 158 (2018) 1079–1086, https://doi.org/10.1016/j.enbuild.2017.10.021.
[12] K. Kuusk, J. Kurnitski, T. Kalamees, Calculation and compliance procedures of thermal bridges in energy calculations in various European countries, Energy Procedia 132 (2017) 27–32, https://doi.org/10.1016/j.egypro.2017.09.626.
[13] M. Citterio, M. Cocco, H. Erhorn-Kluttig, Thermal Bridges in the EPBD Context: Overview on MS Approaches in Regulations, ASIEPI information paper, 2008, https://www.buildup.eu/sites/default/files/P064_EN_ASIEPI_WP4_IP1_p3073.pdf.
[14] D1.1, Requirements and drivers of EENSULATE module, WP1, https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5aeb8b494&appId=PPGMS.
[15] Passive House Institute (PHI), Passive house standard. https://passiv.de/en/02_informations/02_passive-house-requirements/02_passive-house-requirements.htm.
[16] Lawrence Berkeley National Laboratory (LBNL) THERM software. https://windows.lbl.gov/software/therm.
[17] US Department of Energy, Energy efficiency and renewable energy office, building technology program, EnergyPlus software. https://energyplus.net.
[18] INE. National Statistical Institute. https://www.ine.es/.
[19] ETICS Forum 2017, The European ETICS market. Do ETICS sufficiently contribute meet political objectives?. European Association for External Thermal Insulation Composite Systems. https://www.ea-etics.eu/files/dokumente-eae/4_ETICS_Forum/ETICS_Forum_2017/06_European_ETICS_Forum_2017_European_ETICS_Market_Pasker_final_2017-10-03.pdf.
[20] Seong Jin Chang, Wi Seunghwan, Sumin Kim, Thermal bridging analysis of connections in cross-laminated timber buildings based on ISO 10211, Construct. Build. Mater. 213 (2019) 709–722, https://doi.org/10.1016/j.conbuildmat.2019.04.009.
[21] CEC catalogue of construction elements. Ministry of transport, mobility and Urban Agenda. Spain. https://www.codigotecnico.org/Programas/CatalogoElementosConstructivos.html.
[22] EN ISO 10456, Building Materials and Products - Hygrothermal Properties -Tabulated Design Values and Procedures for Determining Declared and Design Thermal Values, 2007.
[23] EN ISO 10077-2, Thermal Performance of Windows, Doors and Shutters. Calculation of Thermal Transmittance, 2017. Part 2: Numerical method for frames.
[24] HALFEN brickwork support. https://www.halfen.com/en/.
[25] Adell J.M., García-Santos A., Vega S., López-Hombrados C., Peña J., Timperman P. y Yáñez E. "Ensayos en dinteles de fábrica de ladrillo atirantada, sobre los nuevos apoyos PI, distanciados 6m entre sí". Actas de.
[26] Code on Structural Concrete (EHE-08), Chapter 6. Materials. Article 36. Infill elements in floor slabs. https://www.mitma.gob.es/recursos_mfom/6_ehe08.pdf.
[27] Forli System Technical Manual, EPS lightweighting. http://www.forlisa.es/manual_tecnico/Forli_colocacionSistema.pdf.
[28] EN ISO 14683, Thermal Bridges in Building Construction. Linear Thermal Transmittance. Simplified Methods and Default Values, 2017.
[29] F. Aguilar, J.P. Solano, P.G. Vicente, Transient modeling of high-inertial thermal bridges in building using the equivalent thermal wall method, Appl. Therm. Eng. 67 (2014) 370–377, https://doi.org/10.1016/j.applthermaleng.2014.03.058.
[30] Sofia Real, M. Glória Gomes, A. Moret Rodrigues, J. Alexandre Bogas, Contribution of structural lightweight aggregate concrete to the reduction of thermal bridging effect in buildings, Construct. Build. Mater. 121 (2016) 460–470, https://doi.org/10.1016/j.conbuildmat.2016.06.018.
[31] A. Tilmans, D.V. Orshoven, Software and atlases for evaluating thermal bridges, ASIEPI information paper P198, https://www.buildup.eu/sites/default/files/content/P198_Software_and_atlases_for_evaluating_thermal_bridges_0.pdf.
[32] CO2 emission factors and primary energy conversion factors of different final energy sources consumed in the buildings sector in Spain. https://energia.gob.es/desarrollo/EficienciaEnergetica/RITE/Reconocidos/Reconocidos/Otros%20documentos/Factores_emision_CO2.pdf.
[33] Fabrizio Ascione, Nicola Bianco, Filippo de'Rossi, Gianluca Turni, Giuseppe Peter Valoni, Different methods for the modelling of thermal bridges into energy simulation programas: comparisons of accuracy for flat heterogeneous roofs in Italian climates, Appl. Energy (2012) 405–418, https://doi.org/10.1016/j.apenergy.2012.01.022.
[34] CYPETHERM HE PLUS, CYPE ingenieros. http://cypetherm-he-plus.cype.es.
[35] Construction price generator, CYPE ingenieros. http://generadorprecios.cype.es.