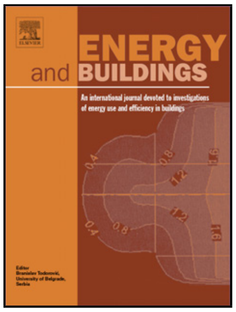

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Highlights

- Functional approximation to the design thermal conductivity of building materials
- Correction of the normative conductivity values established by building regulations
- Implementation in façades of 52 Spanish sites considering its climatic conditions
- Validation analysis regarding the design values calculated through ISO 10456:2007

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A correction factor to approximate the design thermal conductivity of building materials. Application to Spanish façades.

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Abstract

The thermal conductivity of building envelope materials varies according to the conditions of temperature and moisture content. Precisely determining the thermal conductivity is a primary challenge in developing more appropriate, realistic thermal designs for buildings. However, a detailed implementation of environmental conditions requires either the use of sophisticated software programs and the collection of a large set of climate data at each location or a laborious analytical calculation. To simplify the thermal design of buildings, regulations use normative conductivity values based on constant, standardised conditions of temperature and moisture content, which are independent of ambient conditions. This article proposes a correction factor that considers these conditions to functionally approximate the design thermal conductivity of materials based on their normative values. For this calculation, a procedure that simplifies the standard ISO 10456:2007 using the mean annual temperature and relative humidity data for each location is proposed. The procedure is applied in 52 Spanish cities to correct the conductivity values established by the Spanish regulation for façade materials. A correction map of Spain is presented. Finally, by using the ISO standard, the corrections are validated by comparing the values with the design thermal conductivities calculated for different case studies.

Keywords

Design thermal conductivity; Building envelope; Moisture content; Temperature; Spain

1. Introduction

Minimising the adverse effects of buildings on the environment is a key objective in achieving more sustainable development [1, 2]. This objective involves reducing the energy consumption of buildings, and thereby limiting CO_2 emissions to the atmosphere, while maintaining appropriate indoor environmental conditions [3-5]. To reduce consumption, different variables can be taken into consideration, from the incorporation of renewable energy sources and the application of passive designs to the appropriate usage of the building by its occupants [6-8]. Among these design variables, the hygrothermal performance of the building envelope is one of the most relevant factors that can be used to reduce energy losses, manage solar gains, and provide indoor healthy conditions [9-11].

Thermal and moisture transfers occur through the building envelope, between the interior and exterior sides of the building, determining its hygrothermal performance and energy consumption [12-14]. The properties of the construction materials characterise these transfer processes, with their thermal conductivity being one of the most relevant properties [15, 16]. Thus, the thermal transmittance and thermal resistance of building enclosures (U-value and R-value, respectively), used as design criteria in multiple building regulations, are determined based on this property. Therefore, it can be deduced that the precise characterisation of the thermal conductivity of materials is a fundamental task for the adequate thermal design of any building.

However, besides the intrinsic variability in many construction materials, the thermal conductivity of each material also varies according to its temperature and moisture content [17-19]. The influence of this variation and its consequences on the energy calculations have been addressed by various studies [20-22]. To consider the influence of both parameters, a design thermal conductivity that is representative of the actual conductivity of the material in the assumed environmental conditions of the building envelope is used [23-25]. Currently, the standard ISO 10456:2007 provides an analytical calculation procedure to estimate these design values. However, this calculation procedure is laborious and not functional in practical applications [26].

For this reason, multiple building regulations use constant conductivity values for thermal designs without regard for location or ambient conditions [27-30]. These normative conductivity values are determined based on the standardised conditions of temperature and moisture content that are established by each building regulation. As a result, the normative values do not represent the actual or design thermal conductivity that occurs at the environmental conditions of each location, contributing to the increase of the differences between the expected hygrothermal behaviour in buildings and their actual behaviour [31-32].

This article presents a conductivity correction factor for these normative values, thereby approximating the design conductivity values that actually occur under the characteristic environmental conditions of each location. To calculate this factor, the expressions from the standard ISO 10456:2007 are simplified by using various arithmetic averages and representative data of the climatic conditions of the building envelope are used. This correction factor improves the accuracy of the conductivity values that are currently used by building regulations for any location, and allows its functional application to the thermal design of a broad range of enclosure configurations.

These correction coefficients were calculated for 52 province capitals of Spain, representing different climates throughout the country. A map showing the conductivity correction factors associated with these locations was created. The design thermal values obtained through this correction were validated at several Spanish locations by comparing the values with those obtained using the international standard ISO 10456:2007 for different façade configurations.

2. Background

The influence of temperature and moisture content on thermal conductivity depends on the intrinsic characteristics of the material, such as its density and internal porous structure [30, 33-36]. Therefore, the response of different building envelope components to changes in the environmental conditions will vary by material. In general, an increase in temperature or moisture content increases the thermal conductivity of construction materials [37-38]. Characterising these variations with precision by determining design thermal conductivities λ_{design}, in the operating conditions of the building envelope, is a necessary challenge to improve the thermal design of buildings.

However, determining these λ_{design} values with precision is a complex task that includes several factors (Fig. 1). Thus, the temperature and moisture content of the materials vary according to their operating conditions, which vary with time and are dependent on both the climatic conditions of each location and the environmental conditions within the building. Both parameters also depend on the thickness L (m) and position of the material on the layers of the enclosure, which results in different environmental conditions for the materials in each possible enclosure configuration.

In turn, there is no proportional relationship between the moisture content of the material ψ (m^3/m^3) and the environmental conditions, such as relative humidity ϕ (-). The transport of moisture within a porous material occurs primarily through the mechanisms of vapour diffusion, surface diffusion, capillary condensation, and capillary flow. It is generally accepted that moisture content significantly increases when the capillary processes of liquid water are predominant. However, the predominance of one or several of these mechanisms depends on the geometry and size of each pore, which means that the transport processes of liquid water are intensified for different values of relative humidity in each material [13, 35, 39-40]. Therefore, the relationship between the relative humidity and moisture content of each material should be characterised empirically by progressively increasing the environmental relative humidity at a constant temperature (23°C) to obtain its moisture sorption isotherm [41-42].

Fig. 1. Factors that affect the design thermal conductivity of building materials.

An accurate determination of the various factors used to calculate the λ_{design} requires the use of modelling software that can perform complex dynamic and iterative analyses (Fig. 2) [43-45]. However, the climatic data required to adequately characterise the environmental conditions at each time (e.g., climatic data associated with short intervals) and the comprehensive description of the hygrothermal properties of the materials are typically unavailable.

To overcome these difficulties, the standard ISO 10456:2007 establishes a reference procedure to analytically determine the thermal conductivity for a given set of environmental conditions, λ_2 (W/(m·K)), based on a thermal conductivity λ_1 (W/(m·K)), which is obtained based on other environmental conditions [26]. For this purpose, a temperature conversion factor, F_T (-), moisture conversion factor, F_M (-), and ageing conversion factor, F_a (-) are defined (see Eq. 1).

$$\lambda_2 = \lambda_1 \cdot F_T \cdot F_M \cdot F_a = \lambda_1 \cdot e^{f_t(T_2 - T_1)} \cdot e^{f_\psi(\psi_2 - \psi_1)} \cdot F_a \qquad (1)$$

The temperature conversion factor F_T is determined based on the temperature difference between both conditions T_2-T_1 (K) and an empiric temperature conversion coefficient f_t (K^{-1}), which is tabulated in the ISO standard for different insulation and masonry materials. Similarly, the difference in moisture content (by volume) between both conditions ψ_2- ψ_1 (m^3/m^3) and a moisture conversion coefficient f_ψ (m^3/m^3) also tabulated in the standard are used to calculate the moisture conversion factor F_M. The ageing factor, F_a, associated with each material can be obtained based on theoretical models, which for any case, must be verified experimentally [26].

Thus, Eq. (1) can be used to estimate the λ_{design} (W/(m·K)) of any material based on other conductivity values established for known environmental conditions. In general, the conductivity values provided by construction material manufacturers (declared values) are determined at standardised temperature and relative humidity conditions, which are also established in the ISO standard [26]. Therefore, the declared values can be used as a reference to calculate the design values using Eq. (1). In addition, these declared conductivity values take into account ageing, which means that a F_a value of 1 can be used in the previous calculation.

In any case, because the design temperature and moisture content values for each material of the envelope are required, the calculation procedure is laborious and not functional in practical applications. In addition, the calculation must be repeated for each possible configuration of the enclosure considered in the building envelope design because any variation in thickness, material properties, or order of the layers in the enclosure modifies the environmental conditions to be considered for each material.

To expedite the design process by avoiding the laborious calculation specified by the ISO standard, multiple building regulations use normative conductivity values, λ_{norm} (W/(mK)), based on the same environmental conditions for all materials and operating conditions (Fig. 2). Frequently, these environmental conditions also coincide with those established for the declared conductivity values, which allows the values provided by manufacturers to be directly used in the thermal design of the building. Given that the design conditions can significantly differ from the normative or declared conditions, this simplification can reduce the precision of the thermal calculations for the building.

Fig. 2. Typical calculation approximations and description of the problem addressed in the paper (grey).

To improve the precision of the conductivity value used by building regulations, this study provides a conductivity correction factor *CCF* associated with each location, which represents the associated characteristic environmental conditions. By multiplying the λ_{norm} value for each material by this correction factor, it is possible to adequately approximate its λ_{design} for the environmental conditions of the location (Fig. 3). The simplicity of this correction makes possible its easy implementation in current building regulations without increasing the complexity of the thermal design.

Fig. 3. Functional procedure proposed to improve the normative values through a conductivity correction factor.

3. Determination of the correction factor to approximate the design thermal conductivity

To calculate a conductivity correction factor or *CCF* (-) that integrates the characteristic environmental conditions of each location, a functional simplification of the standard ISO 10456:2007 is proposed, which combines a temperature conversion factor $F_{T\,correction}$ (-) and a moisture conversion factor $F_{M\,correction}$ (-) (Eq. 2). Since the reference value λ_{norm} usually incorporates the ageing effect, an ageing conversion factor is not considered.

$$\lambda_{design} \approx \lambda_{norm} \cdot CCF = \lambda_{norm} \cdot F_{T\ correction} \cdot F_{M\ correction} = \lambda_{norm} \cdot e^{f_{t\ uniform}\left(T_{design} - T_{norm}\right)} \cdot e^{f_{\psi\ uniform}\left(\psi_{design} - \psi_{norm}\right)} \qquad (2)$$

This simplification considers the enclosures to be made from a single generic, uniform material, whose properties are representative of the typical materials used in the actual enclosures. The temperature conversion coefficient ($f_{t\,uniform}$) and the moisture conversion coefficient ($f_{\psi\,uniform}$) of this uniform enclosure are determined by weighting the f_t and f_ψ coefficients tabulated in the ISO standard for construction materials used in enclosures. To determine this weighting, the mean contribution of the insulation materials to the R-value of numerous enclosure configurations is evaluated. This average influence will determine to what extent insulation properties should be weighted regarding the masonry components, thus approximating the properties of the uniform material.

This uniform enclosure is used to approximately determine the variation in thermal conductivity caused by the difference between the mean annual temperature and moisture content conditions of each location (T_{design} and ψ_{design}) and the environmental conditions established in the building regulations for their normative values (T_{norm} and ψ_{norm}). The study of a single, uniform enclosure allows for the consideration of unique design conditions (i.e., T_{design} and ψ_{design}), common to all of the enclosures at a location, avoiding the laborious calculation process required to obtain the environmental conditions for each layer of each possible analysed enclosure. As a result, a single *CCF* value is obtained for each location, and this value is representative of that location's average weather conditions.

3.1 Step 1. Simplification of the temperature conversion factor

First, the temperature of the uniform enclosure T_{design} (K) is estimated, which is representative of the mean conditions of the construction materials at that location. To that end, the average between the mean annual exterior temperature and the interior temperature defined for the building is determined (Eq. 3). The mean exterior temperature T_{ext} (K) is generally known for the majority of the locations, whereas the interior temperature T_{int} (K) is generally specified in building regulations according to the use of the building.

$$T_{design} = \frac{T_{ext} + T_{\text{int}}}{2} \tag{3}$$

To estimate a temperature conversion coefficient, $f_{t\ uniform}$ (K^{-1}), that can be representative for any possible material included in the enclosure, the temperature conversion coefficients f_t (K^{-1}) tabulated in the standard ISO 10456:2007 for construction materials are used. The ISO standard establishes f_t values for the thermal insulation materials, which vary from 0.0026 (K^{-1}) for extruded polystyrene products with impermeable covers to 0.0069 (K^{-1}) for mineral wool products [26]. Thus, in a simplified way, an average value of $f_{t\ insulation}$ of 0.00475 (K^{-1}) can be used for all of the insulation materials. In turn, the f_t values for masonry materials are somewhat lower, varying between 0.001 (K^{-1}) for dense concrete, fired clay, or mortars and 0.003 (K^{-1}) for lightweight concrete products. Again, an average representative value $f_{t\ masonry}$ of 0.002 (K^{-1}) is considered for these materials.

Considering that both families of materials (insulation and masonry materials) are the primary determinants of the thermal resistance (R-value) of enclosures, the values of $f_{t\ insulation}$ and $f_{t\ masonry}$ can be weighted to estimate a representative value $f_{t\ uniform}$ (Eq. 4). To establish this weight, one must analyse the mean contribution $R_{contribution}$ (%) of the thermally insulating materials to the R-value of a representative sample of common enclosure configurations in the studied area. This analysis can be performed by using the λ_{norm} values tabulated for the materials present in each of the configurations analysed [28-30].

Combining the previous equations (see Fig. 4), the value of the temperature conversion factor $F_{T\ correction}$ associated with any location can be determined (Eq. 5). Given that building regulations establish the T_{norm} (K) value that defines its λ_{norm} values, the $F_{T\ correction}$ to be applied at each location depends only on the T_{design} that is characteristic of the location.

$$f_{t\ uniform} = f_{t\ insulation} \cdot R_{contribution} + f_{t\ masonry} \cdot \left(1 - R_{contribution}\right) = 0.00475 \cdot R_{contribution} + 0.002 \cdot \left(1 - R_{contribution}\right) \tag{4}$$

The mean annual exterior temperature values were proposed to calculate this T_{design}; however, other approximations are also possible (e.g., considering the most unfavourable mean monthly temperature of each location, which would result in a more stringent correction and a thermal design of the building with better performance).

$$F_{T\ correction} = e^{f_{t\ uniform}\left(T_{design} - T_{norm}\right)} = e^{\left[0.00475 \cdot R_{contribution} + 0.002 \cdot \left(1 - R_{contribution}\right)\right] \cdot \left[T_{design} - T_{norm}\right]} \tag{5}$$

Fig. 4. Overall scheme of the functional procedure used to estimate the temperature conversion factor.

3.2 Step 2. Simplification of the moisture conversion factor

The relative humidity conditions in enclosure materials can be established through hygrothermal relationships using the relative humidity and temperature of the interior and exterior environments. By using the mean annual relative humidity value of the exterior at the location ϕ_{ext} (-) and its mean temperature T_{ext} (K), the vapour pressure on the exterior of the enclosure $P_{v\,ext}$ (Pa) can be calculated [46]. This same hygrothermal relationship can be applied to obtain the interior-side vapour pressure $P_{v\,int}$ (Pa) using the temperature T_{int} (K) and the internal boundary condition ϕ_{int} (-) set by the building regulations according to the use of the building (Eq. 6).

$$P_v = \phi \cdot P_{sat\ T} = \phi \cdot 610.5 \cdot e^{\frac{17.269 \cdot T}{237.3+T}} \tag{6}$$

To estimate the relative humidity of the air within the porous structure of the uniform enclosure ϕ_{design} (-), the average of the values $P_{v\,ext}$ and $P_{v\,int}$ and the design temperature T_{design} (K) determined in step 1 are used (Eq. 7).

$$\phi_{design} = \frac{\left(P_{v\,ext} + P_{v\,int}\right) / 2}{P_{sat\ T_{design}}} = \frac{\left(P_{v\,ext} + P_{v\,int}\right) / 2}{610.5 \cdot e^{\frac{17.269 \cdot T_{design}}{237.3+T_{design}}}} \tag{7}$$

To characterise the relationship between the relative humidity of a material and its moisture content, different mathematical models have been developed; these models adjust to the moisture sorption isotherms of materials using empirical coefficients [43, 47-50]. One of the most widely used models characterises the moisture content of the material ψ_ϕ (m^3/m^3) based on its relative humidity ϕ (-) and the moisture content in free water saturation conditions ψ_f (m^3/m^3) [35, 40, 51]. The adjustment is performed using an approximation factor b (-) that is determined empirically by identifying the moisture content of the material ψ_{80} (m^3/m^3) in equilibrium at a relative humidity of 0.8 (Eq. 8). In this way, the moisture sorption isotherm of any material can be mathematically modelled if as few as two points on the curve

(ψ_{80} and ψ_f) are known. In addition, a moisture content of zero is assumed for a relative humidity of zero (ψ_0 = 0 m^3/m^3).

$$\psi_\phi \approx \psi_f \cdot \frac{(b-1)\cdot\phi}{b-\phi} \tag{8}$$

The use of this mathematical model in software has made available databases that currently gather the empirical values ψ_{80} and ψ_f of a wide range of construction materials [44]. Given that empirical moisture sorption isotherms are determined according to standardised test conditions (at a constant temperature of 23°C), there are no values of ψ_{80} and ψ_f associated with other temperatures, and it is commonly assumed that temperature has a negligible effect on these isotherms [42].

The available databases allow for the estimation of representative values of ψ_{80} for the thermal insulators ($\psi_{80\ insulation}$) and masonry materials ($\psi_{80\ masonry}$) found in enclosures (see Table 1). Both values can be weighted to determine a single value for the uniform enclosure by again considering the mean contribution of each family of materials to the R-value of a representative sample of the enclosure configurations (Eq. 9).

$$\psi_{80\ uniform} = \psi_{80\ insulation}\cdot R_{contribution} + \psi_{80\ masonry}\cdot\left(1-R_{contribution}\right) = 0.0052\cdot R_{contribution} + 0.0129\cdot\left(1-R_{contribution}\right) \tag{9}$$

Table 1. Moisture content at a relative humidity of 0.8 for a representative list of building materials [44].

This is completed with a simplification of the previous mathematical model to estimate the moisture content of the uniform enclosure based on its relative humidity. This simplification considers that the sorption isotherms of materials can be approximately represented through a straight line that joins the tabulated values ψ_0 and ψ_{80}. As shown in Fig. 5, due to the proximity of the ψ_{80} value to the range of the mean relative humidities that are common on the interior side of enclosures (primarily 0.5-0.7 as will be shown in the method application), this simplification does not lead to a significant variation with respect to the original mathematical model.

Fig. 5. Graphical estimation of the moisture content due to the ambient relative humidity in a uniform enclosure.

The straight line between the $\psi_{80\ uniform}$ and ψ_0 values (Eq. 10) provides a linear relationship to approximate the moisture content of the uniform material $\psi_{\phi\ uniform}$ (m^3/m^3) in its design conditions (ψ_{design}) and in the conditions established by the building regulations for the λ_{norm} values (ψ_{norm}). This requires only the previously obtained values of ϕ_{design} (-) and the relative humidity established for the normative values.

$$\psi_{\phi\ uniform} \approx \phi_{uniform} \cdot \frac{0.0052 \cdot R_{contribution} + 0.0129 \cdot \left(1 - R_{contribution}\right)}{0.8} \qquad (10)$$

Finally, a moisture conversion coefficient $f_{\psi\ uniform}$ (m^3/m^3) that is representative of the generic materials that could be included in the enclosure can be estimated based on the f_ψ values tabulated in the standard ISO 10456:2007. The standard presents moisture conversion coefficients for thermal insulators that vary between 1.8 (m^3/m^3) for wood wool boards and 5.0 (m^3/m^3) for phenolic foams, although the majority of these products have coefficients of 4.0 or less [26]. Therefore, for simplification, a mean $f_{\psi\ insulation}$ value of 3.4 (m^3/m^3) can be adopted for this type of materials. For masonry materials, the values vary between 4.0 (m^3/m^3) for dense aggregate concrete or manufactured stones and 10.0 (m^3/m^3) for fired clay products. Again, an average value for the $f_{\psi\ masonry}$ coefficient of 7.0 (m^3/m^3) for this family of materials is considered.

To weight the average values of each family of materials, again, the mean contribution $R_{contribution}$ (%) of the thermal insulators to the R-value of a representative sample of the enclosure configurations (Eq. 11) is used. As a result, a uniform moisture conversion coefficient $f_{\psi\ uniform}$, which is representative of the uniform enclosure, is obtained.

$$f_{\psi\ uniform} = f_{\psi\ insulation} \cdot R_{contribution} + f_{\psi\ masonry} \cdot \left(1 - R_{contribution}\right) = 3.4 \cdot R_{contribution} + 7 \cdot \left(1 - R_{contribution}\right) \qquad (11)$$

Combining the previous equations (see Fig. 6), the moisture conversion factor $F_{M\ correction}$ associated with each location (Eq. 12) is obtained. Given that the ψ_{norm} value is constant in all cases (building regulations establish a standardised relative humidity value for their λ_{norm} values), the $F_{M\ correction}$ to be applied at each location depends only on the characteristic design relative humidity ϕ_{design} of the location.

$$F_{M\ correction} = e^{f_{\psi\ uniform}\left(\psi_{design} - \psi_{norm}\right)} = e^{\left[3.4 \cdot R_{contribution} + 7 \cdot \left(1 - R_{contribution}\right)\right] \cdot \left[\psi_{design} - \psi_{norm}\right]} \qquad (12)$$

Even though the calculation of ϕ_{design} was based on the mean annual relative humidity of the location, other approximations are also possible (e.g., considering the least favourable mean monthly relative humidity of each location, which results in a more stringent correction and thermal designs of buildings with better performance). If the least favourable monthly values of the temperature and relative humidity of the location are used to calculate F_T and F_M, the possibility that both values do not correspond to the same month must be considered, which would result in an unrealistic calculation of the *CCF* value.

Fig. 6. Overall scheme of the functional procedure used to estimate a moisture conversion factor.

4. Application to Spanish façade materials

In Spain, the Building Technical Code is applied to the thermal design of buildings [23]. This Spanish regulation establishes a temperature of 10°C and an equilibrium moisture content with a relative humidity of 0.5 and 23°C, respectively, as the standard reference conditions to define the conductivity values that will be used in the building envelope design. These environmental conditions coincide with the declared value condition “Ib” established by the ISO 10456:2007, thereby allowing for the direct use of declared conductivity values provided by manufacturers as λ_{norm} without additional adjustments [26].

Adopting these constant design conditions for the entire country reduces the precision of any thermal calculations because the real environmental conditions of each location are not considered and the established λ_{norm} values do not represent the λ_{design} values of materials in their operating conditions. All of these results both in an imprecise characterisation of the hygrothermal behaviour of the building envelope and in the selection of enclosure configurations that may be inadequate to meet the objectives established for the thermal design.

In turn, the specific conditions of Spain, which is characterised by warm summers and a long coastline subject to high relative humidity values, implies that the declared value condition “Ib” provides λ_{norm} values that are always lower than the actual values [51, 52]. Thus, the Spanish Code provides the mean monthly temperature and relative humidity values for the main Spanish cities that are greater than those set for the declared value condition “Ib” during most of the year [53].

Next, the *CCF* values associated with 52 province capitals distributed throughout Peninsular Spain, the Balearic Islands, and the Canary Islands are determined. The mean monthly temperature and relative humidity values of each of these locations are presented in the Spanish Technical Building Code [53], thereby allowing for the calculation of the mean annual values of T_{ext} and ϕ_{ext}. These monthly values were averaged from daily mean records gathered at weather stations throughout the period 1971-2000. Interior environmental conditions are also established in this building regulation, which guarantees, by the use of thermal conditioning facilities and air renewal installations, a temperature T_{int} of 20°C and a relative humidity ϕ_{int} of 0.55 [23]. Using these input data in Eqs. (3), (6), and (7), it is possible to calculate the values of T_{design}, $P_{v\ ext}$, $P_{v\ int}$, and ϕ_{design} in each of the cities being analysed (see Table 3).

The $R_{contribution}$ value identifies the contribution of insulation materials to the R-value of the uniform enclosure and can be obtained by analysing a representative sample of common building enclosures in the country. In this case, the analysis is focused specifically on façade enclosures, considering a total of 25 different configurations (Table 2). Spanish buildings preferably use heavy facades formed by a combination of insulation materials and masonry bricks made of fired clay or aerated concrete [54]. Façades with facing bricks or hydraulic mortar coatings are the most widely used configurations, including air cavities with insulation. Other possible types of enclosures for the building envelope that may exhibit important variations in the average $R_{contribution}$ (e.g., roofs or curtain walls) should be analysed in a similar way to obtain a specific *CCF* value for those elements.

Table 2. Representative sample of masonry façades commonly used in Spanish buildings.

To approximate the contribution of the insulating materials to the R-value of each configuration, the following thermal conductivities were generically adopted: 0.04 W/mK for insulation materials, 0.6 W/mK for the main masonry layer, 0.14 W/mK for masonry used as the inner facing, and an R-value of 0.165 m^2K/W for common air cavities (see Eq. 13).

$$R\text{-value} = \sum \frac{L_{insulation}}{\lambda_{insulation}} + \sum \frac{L_{other\ materials}}{\lambda_{other\ materials}} = R_{contribution} \cdot R\text{-value} + \sum \frac{L_{other\ materials}}{\lambda_{other\ materials}} \quad (13)$$

In all cases, the thermal resistance of the outside and inside air layers was not considered. A more exhaustive calculation could be established in the regions with reliable statistical data that identify the types of façades and materials commonly used in buildings. Applying the $R_{contribution}$ obtained from Table

2, one can calculate the conversion coefficients associated with the uniform enclosure that is representative of the usual facades used in the country (Eqs. 4' and 11').

$$f_{t\ uniform} = 0.00475 \cdot R_{contribution} + 0.002 \cdot \left(1 - R_{contribution}\right) = 0.0036 \tag{4'}$$

$$f_{\psi\ uniform} = 3.4 \cdot R_{contribution} + 7 \cdot \left(1 - R_{contribution}\right) = 4.96 \tag{11'}$$

The same $R_{contribution}$ value is used in Eq. (10') to approximate the moisture content of the uniform enclosure $\psi_{uniform}$ based on its design relative humidity ϕ_{design} at each location. These values are shown in Table 3. Equation (10') can also determine the standardised ψ_{norm} value set by the Spanish Code considering a relative humidity of 0.50 for all materials (i.e., 0.0053 m^3/m^3).

$$\psi_{\phi\ uniform} \approx \phi_{uniform} \cdot \frac{0.0052 \cdot R_{contribution} + 0.0129 \cdot \left(1 - R_{contribution}\right)}{0.8} = \phi_{uniform} \cdot 0.0107 \tag{10'}$$

Table 3. Mean annual *CCF* values identified for the façade materials in 52 Spanish province capitals.

With these results, the conversion factors $F_{T\ correction}$ and $F_{M\ correction}$ (Eqs. 5' and 12') can be determined, and with them, the conductivity correction factor $CCF_{façades}$ that should be applied at each location to correct the λ_{norm} values set by the Spanish Code for construction materials used in façades (Eq. 2'). For this purpose, the mean annual values of temperature and relative humidity for each site are obtained from the monthly data included in the Spanish code [53]. Other ambient data (e.g. average of daily records) could also be used if available.

$$F_{T\ correction\ Spanish\ facades} = e^{f_{t\ uniform}\left(T_{design} - T_{norm}\right)} = e^{0.0036\left(T_{design} - 10\right)} \tag{5'}$$

$$F_{M\ correction\ Spanish\ facades} = e^{f_{\psi\ uniform}\left(\psi_{design}-\psi_{norm}\right)} = e^{4.96\left(\psi_{design}-0.0053\right)} \tag{12'}$$

$$\lambda_{design\ Spanish\ facades} \approx \lambda_{norm} \cdot CCF_{facades} = \lambda_{norm} \cdot e^{0.0036\left(T_{design}-10\right)} \cdot e^{4.96\left(\psi_{design}-0.0053\right)} \tag{2'}$$

As shown in Table 3, the $CCF_{façade}$ values vary between 1.0235 for Ávila (in the middle of the Iberian Peninsula and with a dry, cold climate) and 1.0434 for Las Palmas (Canary Islands), characterised by high temperatures and relative humidities. The average correction for the entire country is at 3.26%, thereby indicating a general inaccuracy of the λ_{norm} values used by the Spanish Code for the thermal design of buildings. In all cases, the correction factor increases the normative conductivity values, which suggests that currently, this design considers a lower thermal conductivity in materials than the actual conductivity in the mean environmental conditions of each city.

It can also be observed that the necessary temperature correction is significantly greater than the moisture content correction in all locations. The low temperature established by the Spanish Code for the normative values (10°C) and the high temperatures of the country are responsible for this effect because the mean T_{design} in the enclosures reaches 17.35°C. However, the difference between the relative humidity set by the regulation (ϕ_{norm} = 0.5) and the mean relative humidity of the air in the enclosures (0.6113) is significantly less. Moreover, this effect can be observed when considering the environmental conditions for each month rather than annual averages. Thus, higher correction factors are identified in the summer months (due to the temperature effect) regarding the winter months (despite the higher relative humidity).

In any case, both deviations reduce the precision of thermal designs, which results in an energy consumption that is greater than what was initially expected for the building. Similarly, these deviations can affect the selection of façade configurations that are more appropriate to meet the actual thermal demands of the building. Figure 7 shows the geographical distribution of the mean annual $CCF_{façades}$ values. Higher correction factors can be observed in coastal areas (given the higher mean relative humidities and smoother temperatures) and in southern Spain (due to the higher mean annual temperatures). On the contrary, lower correction factors are identified for the inner northern region of the country and the province capitals located at higher altitudes.

Fig. 7. Map that indicates the $CCF_{façades}$ values in Spain (percentage value).

The magnitude of these deviations is not negligible in the current context of seeking more energy efficient buildings, particularly given that future building models (e.g., nearly zero-energy buildings) are based on passive designs with exhaustive control of energy losses through the building envelope. Additionally, these corrections are likewise not negligible if the important efforts to improve the thermal design of buildings and the tools being used to that end are considered. Although a greater number of variables are included in a more precise manner, a fundamental and basic parameter, such as the thermal conductivity of the materials, is set by tabulated values that do not represent their real behaviour at each location.

In any case, it must be remembered that this *CCF* does not consider other atmospheric effects that may also modify the environmental conditions of the construction materials. Thus, solar radiation may increase the enclosure temperature to values above the environmental temperature, which would also affect the evaporation processes in materials. The wind exposure of the building can also modify these evaporation conditions. Other effects, such as wind-driven rain, provide important quantities of liquid water to the enclosure, increasing its moisture content [55, 56]. Finally, changes in indoor environmental conditions due to the usage of its occupants can also alter the expected conditions in the uniform enclosure. Integrating these aspects through a more detailed analysis could determine more precise *CCF* values. Similarly, a more exhaustive statistical study of the more typical enclosures in each region and of the contribution of their insulating materials to the total R-value in each case would provide greater precision in the determination of this correction factor.

On the other hand, the proposed correction does not translate into a similar improvement of the energy calculations, since other aspects such as thermal bridges, air tightness and convection in the air layers, can also affect the hygrothermal performance of the building envelope. Therefore, the optimisation of the thermal design will be always less than the percentages previously provided.

5. Validation of the proposed approximation procedure

To validate the obtained $CCF_{façades}$, the convergence between the design conductivity values obtained using the standard ISO 10456:2007 and those obtained when correcting the normative values was analysed. To that end, six usual configurations of building façades used throughout the country were considered and the two most populous Spanish cities (Madrid and Barcelona) were selected. The composition of these enclosures, the λ_{norm} of each material and its conversion coefficients (f_t and f_Ψ) are shown in Fig. 8. The mean environmental conditions established by the Spanish Code for both cities are also shown; these conditions define the boundary conditions for a steady-state thermal analysis.

Fig. 8. Analysed façade configurations and boundary conditions for the thermal analyses in Madrid and Barcelona.

Considering the thickness of the materials in each configuration and their λ_{norm} (based on the temperature conditions of 10ºC and an equilibrium moisture content with a relative humidity of 0.5), it is possible to calculate the R-value considered by the Spanish Code for each of these façades. This analysis does not consider the thermal resistance of the outside and inside air layers because their values are the same in all cases and do not depend on the conductivity considered for the enclosure materials. Given that temperature and moisture content conditions are considered to be the same throughout the country, these normative R-values are the same in both cities (Table 4).

Alternatively, the λ_{design} of each material was determined using the standard ISO 10456:2007. To do this, the temperature and relative humidity in every façade material were determined by means of the λ_{norm} of each material and the mean environmental conditions shown in Fig 8. As a result, the temperature and moisture conversion factors associated with the environmental conditions in every layer of the enclosures were determined. For this purpose, empirical sorption isotherms obtained from the databases of commercial software used for hygrothermal analysis were also considered for each material [44]. This comprehensive analysis allows to accurately characterise the R-value of the façade configurations on its mean environmental conditions, so it can be used as a validation reference for the proposed method with respect to the Spanish Code.

As shown in Table 4, the R-value obtained in each enclosure when using these values of λ_{design} is lower than that considered by the Spanish Code, with differences that vary from 2.3% to 5.7%. As expected, these differences are greater in Barcelona due to the higher mean annual temperature and the higher environmental relative humidity.

Table 4. Comparison among design results obtained by the Spanish regulation, the standard ISO 10456:2007, and the proposed correction factor.

Finally, the λ_{norm} values used by the Spanish Code for the materials were multiplied by the $CCF_{façade}$ associated with each city, and the new R-value of each enclosure based on these corrected conductivities (Eq. 14) was calculated. As a result, it was found that the values differ from those obtained by the ISO 10456:2007 by less than 1% in most cases (Table 4). In this way, despite the simplifications used to calculate the *CCF* value, this correction allows for reductions greater than 60% of the deviation of the Spanish Code and maintains a functional calculation that avoids the laborious application of the ISO standard.

$$R_{value\ corrected} = \sum \frac{L_i}{CCF \cdot \lambda_i} = \frac{1}{CCF} \cdot \sum R_{i\ norm} = \frac{1}{CCF} \cdot R_{norm} \tag{14}$$

The results suggest that the proposed conductivity correction factor can integrate the environmental conditions of the locations in the λ_{norm} used for building regulations and reaches a precision close to that provided by the standard ISO 10456:2007 with a greater functionality. The availability of climatic data for a greater number of locations could be used to define *CCF* values at any point in the territory, which would allow its implementation in building regulations and the calculation of the λ_{design} value throughout the country. Similar advantages could be obtained for the thermal design by considering less favourable conditions at the locations instead of the mean annual temperature and relative humidity values.

6. Conclusions

This study presents a correction factor or *CCF* that can be used to calculate the design thermal conductivity of construction materials at different locations based on the normative conductivity values tabulated in building regulations according to standardised and constant environmental conditions. For this purpose, the λ_{norm} values of the materials are multiplied by the *CCF* value obtained for each location, which is representative of the characteristic environmental conditions of the site. The simplicity of this correction makes possible its functional implementation in the current building regulations, which would improve the precision of thermal analyses currently used for buildings.

Available mean annual climatic data were used to determine the *CCF* values associated with façade materials in the main Spanish cities. As a result, a map that shows the correction factors to be applied in

52 province capitals of Spain was created. The thermal results obtained for various façade configurations were compared with those obtained using the design conductivities calculated by the standard ISO 10456:2007 for each material. This comparison demonstrated how the obtained *CCF* values allow for similar results to those calculated using the standard ISO to be obtained, thereby reducing deviations in the Spanish code by more than 60%. Their incorporation in this building regulation would provide better precision in the thermal design of buildings and would contribute to the progress towards performance-based regulation.

Obtaining climatic data gathered from a larger number of locations would allow the subsequent interpolation of these *CCF* values at any location of the territory (e.g., creating isopleth maps), which would thus improve the characterisation of the λ_{design} value in the entire country. Similarly, it is also possible to adopt less favourable environmental values, which would result in more stringent correction factors and more demanding thermal designs. Such research developments will be presented in future publications.

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Figure captions

Fig. 1. Factors that affect the design thermal conductivity of building materials.

Fig. 2. Typical calculation approximations and description of the problem addressed in this paper (grey).

Fig. 3. Functional procedure proposed to improve the normative values through a conductivity correction factor.

Fig. 4. Overall scheme of the functional procedure used to estimate the temperature conversion factor.

Fig. 5. Graphical estimation of the moisture content due to the ambient relative humidity in a uniform enclosure.

Fig. 6. Overall scheme of the functional procedure used to estimate a moisture conversion factor.

Fig. 7. Map that indicates the $CCF_{façades}$ values in Spain (percentage value).

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Table 1.
Mositure content at a relative humidity of 0.8 for a representative list of building materials [44].

Representative but not exhaustive list of building materials	**ψ_{80} (m^3/m^3)**	**Average ψ_{80} (m^3/m^3)**
Stone wool insulation (95% porosity) [1]	0.0002	0.0052 (insulation materials)
Cellulose insulation (50 kg/m^3) [2]	0.0078	
EPS insulation (20kg/m^3) [3]	0.0002	
XPS insulation (20kg/m^3) [3]	0.0002	
Woodfibre insulation panel (168 kg/m^3) [2]	0.0173	
Gypsum board (0.2 w/mK) [2]	0.0063	
PUR rigid foam panel (98% porosity) [2]	0.0041	
Cement plaster (1153 kg/m^3) [2]	0.0159	0.0129 (masonry materials)
Natural sandstone (2120 kg/m^3) [2]	0.0190	
Thermal clay brick (650 kg/m^3) [2]	0.0150	
Extruded brick (1630 kg/m^3) [4]	0.0087	
Solid brick masonry (1900 kg/m^3) [2]	0.0180	
Facing brick (1873 kg/m^3) [5]	0.0034	
Aerated concrete for masonry blocks (600 kg/m^3) [2]	0.0107	

Database: 1) North America; 2) Fraunhofer-IBP; 3) LTH Lund University; 4) Vienna University of Technology; 5) MASEA.

Table 2.
Representative sample of masonry façades commonly used in Spanish buildings.

Analysed façade configurations (thickness)				**R-value contribution (%)**
Main masonry sheet	Air cavity	Insulation material	Masonry inner facing	
0.115 m	-	0.02 m	0.07 m	41.95
0.115 m	-	0.04 m	0.07 m	59.11
0.115 m	-	0.06 m	0.07 m	68.44
0.115 m	-	0.08 m	0.07 m	74.30
0.115 m	-	0.04 m	0.04 m	67.68
0.115 m	-	0.06 m	0.04 m	75.85
0.115 m	-	0.08 m	0.04 m	80.73
0.240 m	-	0.02 m	0.07 m	35.71
0.240 m	-	0.04 m	0.07 m	52.63
0.240 m	-	0.06 m	0.07 m	62.50
0.240 m	-	0.02 m	0.04 m	42.17
0.240 m	-	0.04 m	0.04 m	59.32
0.240 m	-	0.06 m	0.04 m	68.62
0.115 m	Yes	0.02 m	0.07 m	36.85
0.115 m	Yes	0.04 m	0.07 m	53.86
0.115 m	Yes	0.06 m	0.07 m	63.65
0.115 m	Yes	0.02 m	0.04 m	43.77
0.115 m	Yes	0.04 m	0.04 m	60.88
0.115 m	Yes	0.06 m	0.04 m	70.01
0.240 m	Yes	0.02 m	0.04 m	37.01
0.240 m	Yes	0.04 m	0.04 m	54.03
0.240 m	Yes	0.06 m	0.04 m	63.81
0.240 m	Yes	0.02 m	0.07 m	31.94
0.240 m	Yes	0.04 m	0.07 m	48.42
0.240 m	Yes	0.06 m	0.07 m	58.48
			$R_{contribution}$ (average value)	**56.47**

Table 3.
Mean annual CCF values identified for the façade materials in 52 Spanish province capitals.

Location	***T_{ext}* (ºC)**	***T_{design}* (ºC)**	***T_{design} -10* (ºC)**	***ϕ_{ext}* (%)**	***Φ_{design}* (%)**	***Ψ_{design} –0.0053* (m^3/m^3)**	***$F_{Tcorrection}$* (-)**	***$F_{Mcorrection}$* (-)**	***$CCF_{façades}$* (-)**
	[53]	*Eq. (3)*	*Eq. (5')*	*[53]*	*Eq. (7)*	*Eq. (12')*	*Eq. (5')*	*Eq. (12')*	*Eq. (2')*
Albacete	13.47	16.74	6.74	62.67	59.15	0.00097	1.0243	1.0048	**1.0293**
Alicante	17.85	18.93	8.93	66.50	60.48	0.00111	1.0324	1.0055	**1.0381**
Almería	18.51	19.26	9.26	67.08	60.82	0.00115	1.0336	1.0057	**1.0395**
Ávila	10.35	15.18	5.18	59.75	59.06	0.00096	1.0186	1.0048	**1.0235**
Badajoz	16.38	18.19	8.19	65.83	60.14	0.00108	1.0297	1.0054	**1.0352**
Barcelona	15.33	17.67	7.67	71.58	62.67	0.00135	1.0277	1.0067	**1.0346**
Bilbao	14.03	17.02	7.02	72.67	63.16	0.00140	1.0253	1.0070	**1.0325**
Burgos	9.88	14.94	4.94	73.42	64.18	0.00151	1.0178	1.0075	**1.0254**
Cáceres	16.16	18.08	8.08	66.50	60.44	0.00111	1.0292	1.0055	**1.0349**
Cádiz	18.24	19.12	9.12	72.33	63.27	0.00141	1.0331	1.0070	**1.0403**
Castellón	16.70	18.35	8.35	68.00	61.11	0.00118	1.0302	1.0059	**1.0363**
Ceuta	16.06	18.03	8.03	80.33	66.55	0.00176	1.0291	1.0088	**1.0381**
Ciudad Real	14.31	17.16	7.16	64.83	59.88	0.00105	1.0259	1.0052	**1.0312**
Córdoba	17.44	18.72	8.72	64.25	59.42	0.00100	1.0316	1.0050	**1.0367**
A Coruña	14.11	17.06	7.06	77.75	65.26	0.00162	1.0255	1.0081	**1.0338**
Cuenca	12.22	16.11	6.11	63.17	59.66	0.00103	1.0220	1.0051	**1.0273**
Girona	14.09	17.05	7.05	71.58	62.70	0.00135	1.0255	1.0067	**1.0323**
Granada	14.84	17.42	7.42	60.50	57.97	0.00085	1.0268	1.0042	**1.0311**
Guadalajara	13.55	16.78	6.78	68.50	61.50	0.00122	1.0245	1.0061	**1.0307**
Huelva	18.33	19.17	9.17	64.83	59.73	0.00103	1.0332	1.0051	**1.0385**
Huesca	13.32	16.66	6.66	65.67	60.39	0.00110	1.0240	1.0055	**1.0297**
Jaén	16.90	18.45	8.45	63.00	58.85	0.00094	1.0306	1.0047	**1.0354**
León	10.75	15.38	5.38	66.50	61.38	0.00121	1.0194	1.0060	**1.0255**
Lleida	14.61	17.31	7.31	64.00	59.49	0.00101	1.0264	1.0050	**1.0315**
Logroño	13.43	16.72	6.72	64.25	59.79	0.00104	1.0243	1.0052	**1.0295**
Lugo	11.19	15.60	5.60	79.17	65.99	0.00170	1.0202	1.0085	**1.0288**
Madrid	14.31	17.16	7.16	56.42	56.37	0.00068	1.0259	1.0034	**1.0293**
Málaga	17.96	18.98	8.98	66.17	60.34	0.00110	1.0326	1.0055	**1.0382**
Melilla	18.43	19.22	9.22	70.92	62.64	0.00134	1.0334	1.0067	**1.0403**
Murcia	16.90	18.45	8.45	71.42	62.67	0.00135	1.0306	1.0067	**1.0375**
Orense	14.30	17.15	7.15	71.42	62.63	0.00134	1.0258	1.0067	**1.0327**
Oviedo	12.60	16.30	6.30	77.67	65.27	0.00162	1.0227	1.0081	**1.0310**
Palencia	11.73	15.87	5.87	70.92	62.77	0.00136	1.0211	1.0067	**1.0280**
Palma	17.70	18.85	8.85	64.92	59.74	0.00104	1.0321	1.0051	**1.0374**
Las Palmas	20.48	20.24	10.24	67.33	61.26	0.00120	1.0372	1.0059	**1.0434**
Pamplona	12.18	16.09	6.09	67.33	61.29	0.00120	1.0220	1.0060	**1.0281**
Pontevedra	14.97	17.49	7.49	69.58	61.82	0.00126	1.0271	1.0062	**1.0335**
S. Sebastián	12.99	16.50	6.50	78.00	65.37	0.00163	1.0234	1.0081	**1.0318**
Salamanca	10.78	15.39	5.39	68.75	62.20	0.00130	1.0194	1.0064	**1.0260**
St. Cruz Ten.	21.03	20.52	10.52	62.42	58.85	0.00094	1.0382	1.0047	**1.0431**
Santander	14.20	17.10	7.10	68.75	61.52	0.00123	1.0257	1.0061	**1.0319**
Segovia	11.77	15.89	5.89	63.25	59.83	0.00105	1.0212	1.0052	**1.0265**
Sevilla	18.21	19.11	9.11	65.42	60.00	0.00106	1.0330	1.0053	**1.0385**
Soria	10.44	15.22	5.22	66.67	61.55	0.00123	1.0188	1.0061	**1.0250**
Tarragona	17.18	18.59	8.59	63.33	59.00	0.00096	1.0311	1.0048	**1.0360**
Teruel	11.52	15.76	5.76	62.50	59.62	0.00102	1.0208	1.0051	**1.0259**
Toledo	15.50	17.76	7.75	61.00	58.08	0.00086	1.0280	1.0043	**1.0324**
Valencia	16.76	18.38	8.38	64.75	59.65	0.00103	1.0304	1.0051	**1.0356**
Valladolid	12.18	16.09	6.09	63.00	59.61	0.00102	1.0220	1.0051	**1.0271**
Vitoria	11.13	15.57	5.57	74.33	64.19	0.00151	1.0201	1.0075	**1.0277**
Zamora	12.51	16.26	6.26	65.50	60.50	0.00112	1.0226	1.0055	**1.0282**
Zaragoza	14.63	17.32	5.18	63.00	59.06	0.00096	1.0187	1.0048	**1.0314**

Table 4.
Comparison among design results obtained by the Spanish regulation, the standard ISO 10456:2007, and the proposed correction factor.

		Design R-value (m^2K/W)		
	Configuration	ISO 10456:2007 [26]	Normative value [23]	Corrected value
Madrid	A	1.548	1.588 (+2.58%)	1.543 (-0.32%)
	B	1.878	1.922 (+2.34%)	1.868 (-0.53%)
	C	2.730	2.819 (+3.26%)	2.738 (+0.29%)
	D	2.219	2.279 (+2.70%)	2.214 (-0.23%)
	E	2.238	2.323 (+3.80%)	2.257 (+0.85%)
	F	1.984	2.048 (+3.23%)	1.989 (+0.25%)
Barcelona	A	1.541	1.588 (+3.05%)	1.535 (-0.39%)
	B	1.875	1.922 (+2.51%)	1.858 (-0.91%)
	C	2.721	2.819 (+3.60%)	2.724 (+0.11%)
	D	2.215	2.279 (+2.89%)	2.202 (-0.59%)
	E	2.198	2.323 (+5.69%)	2.245 (+2.14%)
	F	1.975	2.048 (+3.70%)	1.979 (+0.20%)

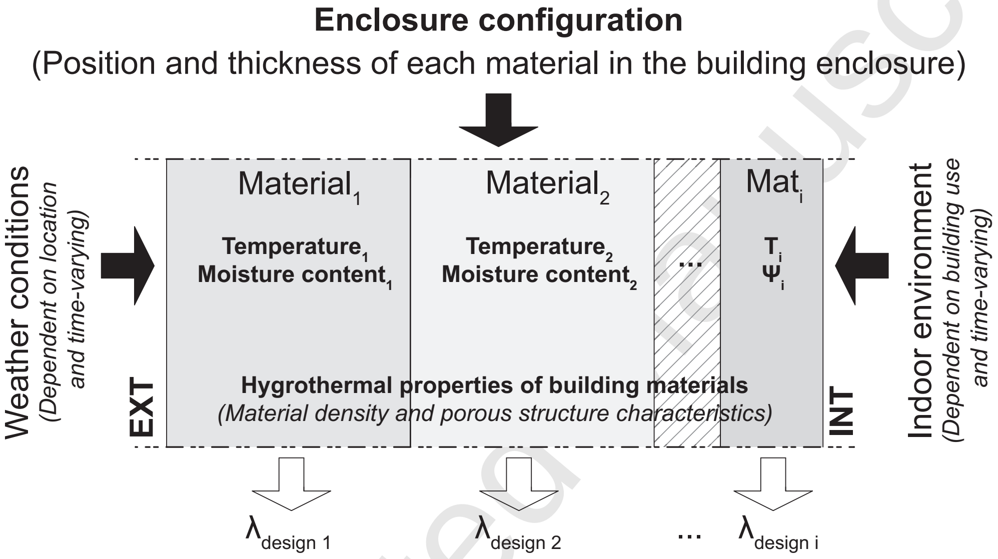


Fig. 1. Factors that affect the design thermal conductivity of building materials.

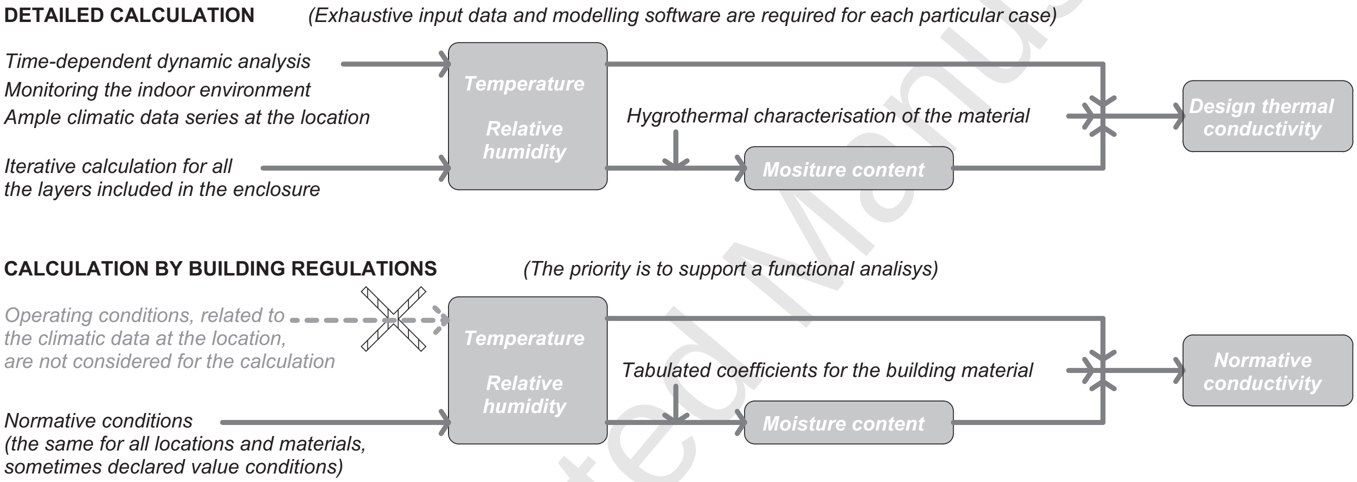


Fig. 2. Typical calculation approximations and description of the problem addressed in this paper (grey).

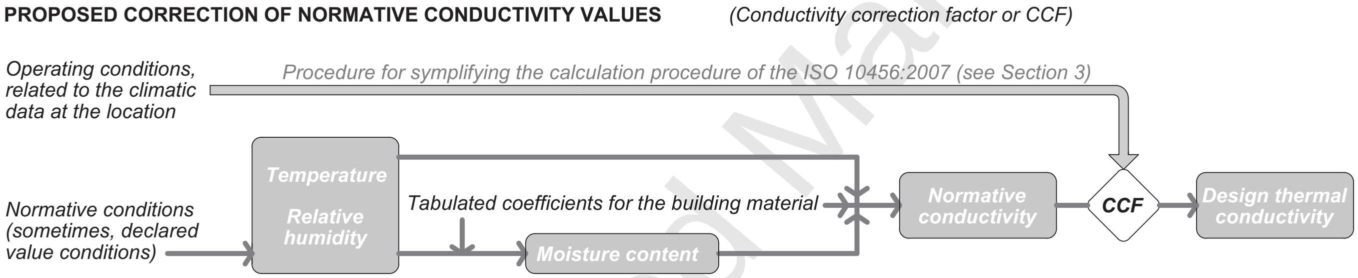


Fig. 3. Functional procedure proposed to improve the normative values through a conductivity correction factor.

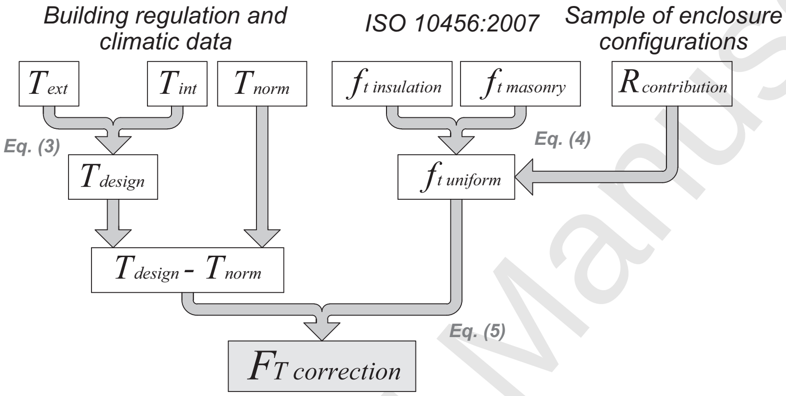


Fig. 4. Overall scheme of the functional procedure used to estimate the temperature conversion factor.

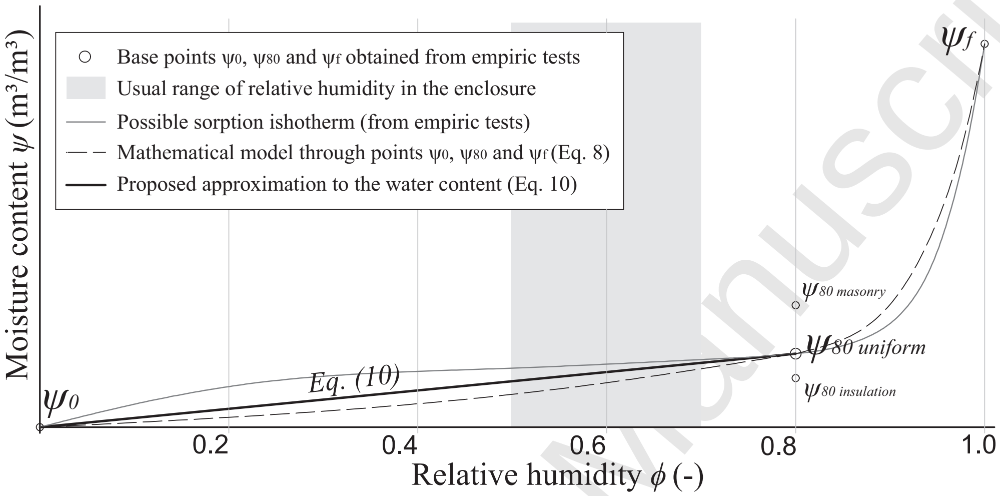


Fig. 5. Graphical estimation of the moisture content due to the ambient relative humidity in a uniform enclosure.

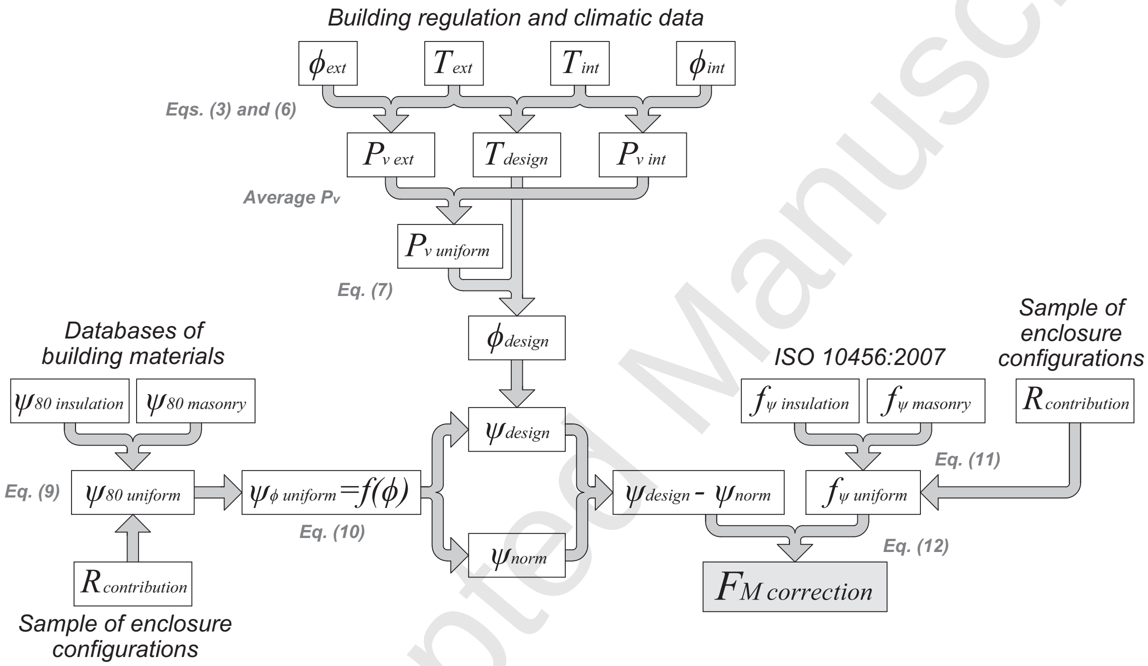


Fig. 6. Overall scheme of the functional procedure used to estimate a moisture conversion factor.

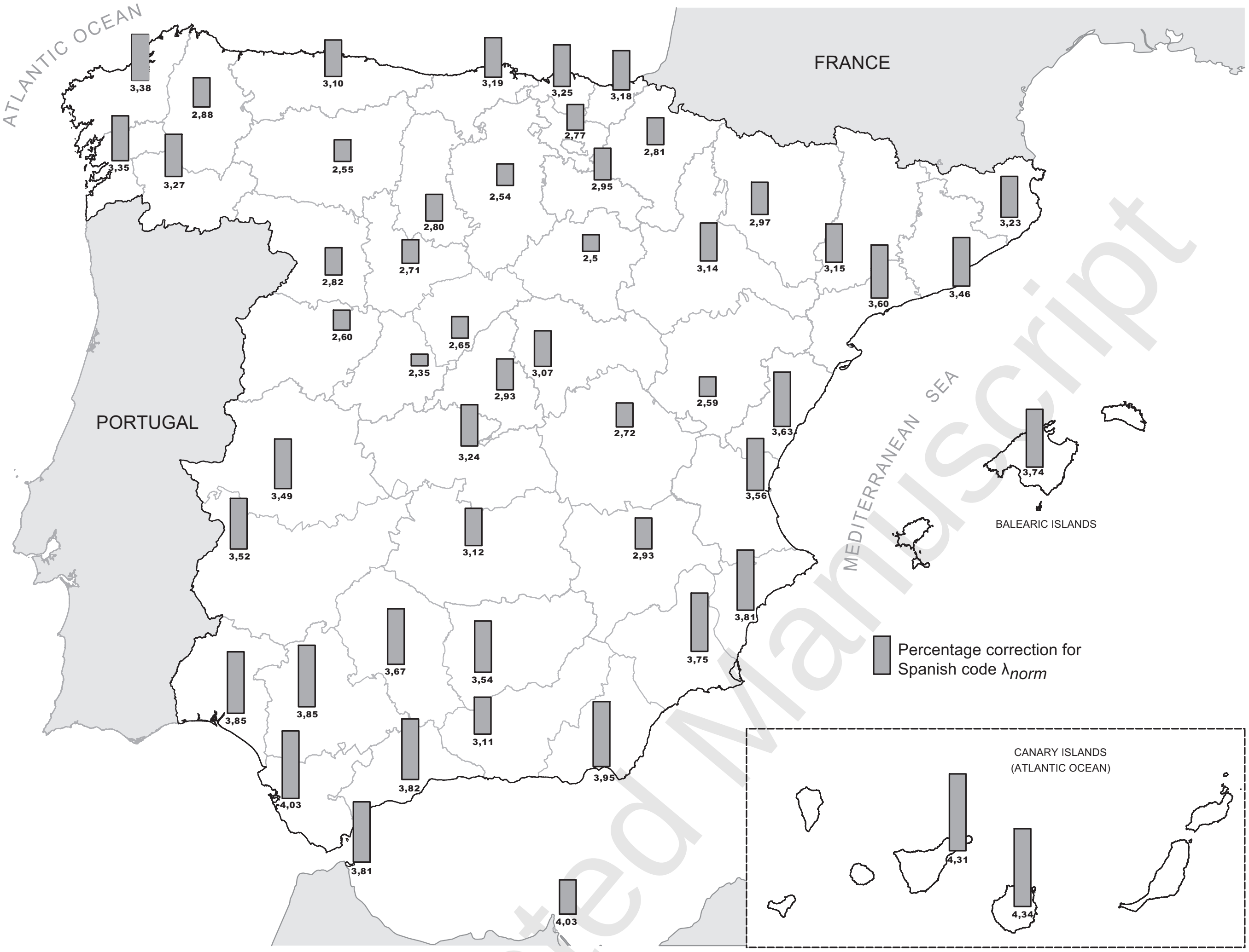
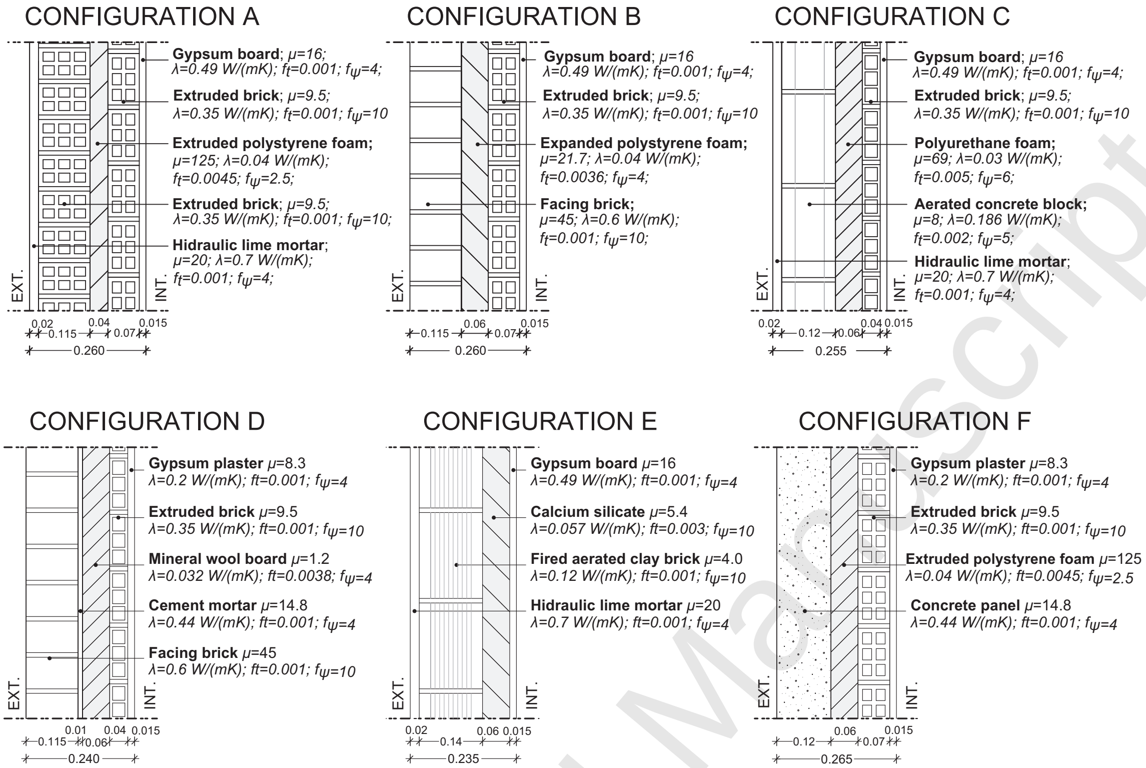


Fig. 7. Map that indicates the $CCF_{façades}$ values in Spain (percentage value).



Steady-state analysis input data (annual average data) [53]					**Proposed**
	T_{ext} (ºC)	Φ_{ext} (%)	T_{int} (ºC)	Φ_{int} (%)	***CCF**façades*
Madrid	14.31	56.42	20.00	55.00	1.0293
Barcelona	15.33	71.58	20.00	55.00	1.0346

Fig. 8. Analysed façade configurations and boundary conditions for the thermal analyses in Madrid and Barcelona.