# Hybrid numerical and experimental performance assessment of structural thermal bridge retrofits

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**Abstract**

*A methodological approach to the multi-dimensional heat transfer assessment of building envelopes is performed. The proposed method focuses on thermally weak points in envelope-structure junctions and the assessment of envelope retrofit alternatives. Thermal performance in these spots is seldom assessed in energy audit processes, although it is one of the main heat loss paths in many insulated façade solutions. An envelope-slab junction case is presented, where multi-dimensional heat transfer occurs. This paper proposes a methodology that allows for a hybrid experimental and numerical performance assessment in such circumstances. A numerical model is calibrated against experimental data, which is then modified to reflect various envelope retrofit solutions. Several possible analysis procedures are proposed, based on the capacities of transient thermal models.*

**Key words**

*Building envelope; Experimental assessment; Thermal bridge; Finite Element; Envelope retrofitting*

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# 1 INTRODUCTION

## 1.1 HEAT TRANSFER IN BUILDING ENVELOPES & ENVELOPE RETROFITTING

According to the Sustainable Building and Climate Initiative of the UN (UNEP, 2016), and other sources (DOE, 2008; Pérez-Lombard, Ortiz, & Pout, 2008; EU, 2002; EU, 2010), buildings are responsible for 40% of the global primary energy consumption. Within buildings, envelopes – roofs, façades, and glazed areas - represent the main heat transfer path from a building to its environment. ECOFYS (2007) studied the techno-economical optimum insulation level for building envelopes. In this study, optimal thermal transmittance levels were found to be substantially below the current insulation levels in building envelopes. Thus, there is great potential for heat flux reduction by incorporating additional insulation to building envelopes.

Once the decision to renovate a building is taken, incorporating additional thermal insulation is a robust solution, as it increases the overall thermal resistance of the building envelope. Commonly, this measure is the first energy efficiency measure taken in most buildings, and combined with other energy efficiency measures, provides for a medium to long-term return of investment (ROI).

There are various technical solutions such as external thermal insulation composite systems (ETIC), ventilated façades, cavity wall insulation, and internal insulation systems. The basic approach of all these systems is to improve the thermal transmittance of the wall, by means of the addition of insulation materials. In this context, the thickness of the insulation material and its insulation capacity are key variables (Elguezabal & Garay, 2015).

## 1.2 THERMAL BRIDGES. RELEVANCE & CALCULATION PROCEDURES

Commonly, retrofitting design decisions are made based on one-dimensional performance of insulation systems. Multi-dimensional heat transfer paths such as window sills, slab-façade junctions, balconies, etc. are disregarded. These items account for a relevant share of the heat loss coefficient of a building envelope.

Several sources, such as ASIEPI (2010), show that the relevance of thermal bridges within the heat balance of a building is up to 30% of heating energy loads due to these elements. This ratio is considered to increase for highly insulated buildings. The correct design and improvement of junction details is estimated to reduce the same ratio to 15%. For this reason, adequate thermal bridge calculation methods for highly insulated buildings are needed (Kuusk, Kurnitski & Kalamees, 2017).

One of the reasons to avoid multi-dimensional heat transfer in the assessment procedure of a building envelope retrofit lies in the complexities of numerical models and the lack of robust experimental procedures to conduct such assessments.

Regarding numerical models, multi-dimensional heat transfer codes such as Therm (LBNL, 2018) are freely available to designers, but, to the authors knowledge, these are seldom applied in construction projects. When related to the on-site experimental assessment of the thermal performance of architectural junctions, standard methods such as EN ISO 9869-1:2014 cannot be applied and only qualitative assessments can be made by means of methods like infrared imaging.

In Garay, Uriarte, and Apraiz (2014), numerical and experimental works were conducted over a 2-dimensional thermal bridge. In this work, it was observed that steady-state numerical models did not correctly match the dynamics of the thermal bridge. This same source showed that for cases with unknown thermal properties, models failed to correctly identify the steady-state and transient aspects of thermal bridges.

In recent dates, works including that by O'Grady, Lechowska, and Harte (2017) have studied the possibility of integrating thermal imaging as a quantitative source of information for thermal bridge assessment. However, their applicability is yet to be further demonstrated.

## 1.3 EXPERIMENTAL PROCESSES FOR BUILDING ENVELOPE ASSESSMENT

Experimental heat transfer assessment procedures in building envelopes have traditionally been focused on one-dimensional heat transfer assessment. In fact, it is common to find instructions to avoid the influence of thermal bridges in experimental setups within standardised assessment procedures.

Experimental procedures for on-site assessment heat transfer in buildings are standardised under EN ISO 6946:2007 and ASTM C1155 – 95 (2013). Although these standards integrate transient assessment methods, they are primarily focused on steady-state performance metrics. Their most common implementation is performed by means of averaging processes, which filter out the dynamics of building envelopes.

Within the research community, there is an increasing awareness of the need for transient assessment methods, which has led to specific transient methods (Gutschker, 2008, Strachan & Vandaele, 2008, Naveros, Bacher, Ruiz, Jiménez, & Madsen, 2014). In any case, all of this experience remains in the one-dimensional domain.

Atsonios, Mandilaras, Kontogeorgos, and Founti (2017) apply EN ISO 9869-1:2014 and ASTM C1155 – 95 (2013) procedures over datasets from field experiments on building envelopes with various levels of insulation, at different times of the year. For each case, the required campaign length is identified. In some cases, it is impossible to obtain satisfactory results from steady-state methods, while in others, campaign lengths up to 20 days are required. Transient methods perform substantially better, delivering robust results in 5 to 10 days.

The methodology presented in this paper does not intend to be a substitute for experimental methods to assess one-dimensional heat transfer. It will complement existing procedures with a novel system for the assessment of multi-dimensional heat transfer, which, to date, is outside the scope of experimental procedures.

## 1.4 GOAL AND LIMITATIONS OF THE PROPOSED METHODOLOGY

In this paper, a hybrid numerical and experimental procedure is proposed to assess the present thermal performance of an architectural junction. The procedure allows building envelope retrofit systems to be assessed. Ultimately, this allows for a more detailed assessment of the thermal performance of a retrofitting intervention.

The methodology is illustrated by means of a 2-dimensional façade-slab junction. The presented calculation method is also suitable for 3-dimensional heat transfer. The 2-dimensional heat transfer case is presented as it gives a greater representation of the performance gap illustrated in this section.

Singular 3-dimensional thermal bridges are known to be less relevant in terms of heat transfer, but critical in terms of cold spots, and potential locations for mould growth. Users trying to replicate this methodology for repetitive 3-dimensional thermal bridges such as cladding anchors may experience difficulties in doing so. For these cases, users are encouraged to deal with this phenomena by means of pseudo-2D models. Specific adaptations of the present methodology may need to be developed. Reference to multi-dimensional heat transfer in architectural junctions may be found in Atsonios, Mandilaras, Kontogeorgos, and Founti (2017).

## 2 THERMAL ASSESSMENT METHODOLOGY

Thermal bridges are construction details in which multi-dimensional heat transfer occurs. As such, heat flux in these locations cannot be measured directly by means of heat flow meters.

The proposed assessment method bases its assessment of the heat flow across architectural junctions on several localised temperature and heat flow measurements. Point measurements are used to calibrate a transient numerical thermal model. Once calibrated, the model can be used to provide an accurate assessment of the heat transfer of the architectural junction under examination. The impact of envelope retrofit alternatives on the heat transfer across the junction can be calculated with the calibrated model. In Table 1, the method is presented as a stepped approach.

| STEP | ACTIVITY |
|---|---|
| 1. Monitoring of present state | Define the location of sensors |
| | Monitorisation campaign, ~1month |
| 2. Calibration of thermal model | Construction of a numerical model |
| | Optimisation of thermal properties of materials |
| 3. Evaluation of retrofitting alternatives | Parametric study of retrofit possibilities vs performance indicators |

TABLE 1 Thermal assessment sequence.

The goal of this methodology lies in the identification of thermal and geometrical properties of an already constructed architectural junction based on insufficient data. Although geometrical details are commonly known in buildings constructed in the last 60 years, many thermal properties remain unknown and their determination is commonly performed by means of bibliographical research.

This method allows for the determination of critical information in the assessment of thermal bridges such as the effective thermal conductivity of insulation layers and air cavities, specific heat and density of concrete and brick constructions, etc.

This proposed hybrid methodology is complemented by state of the art one-dimensional heat transfer assessment techniques as shown in Fig. 1.

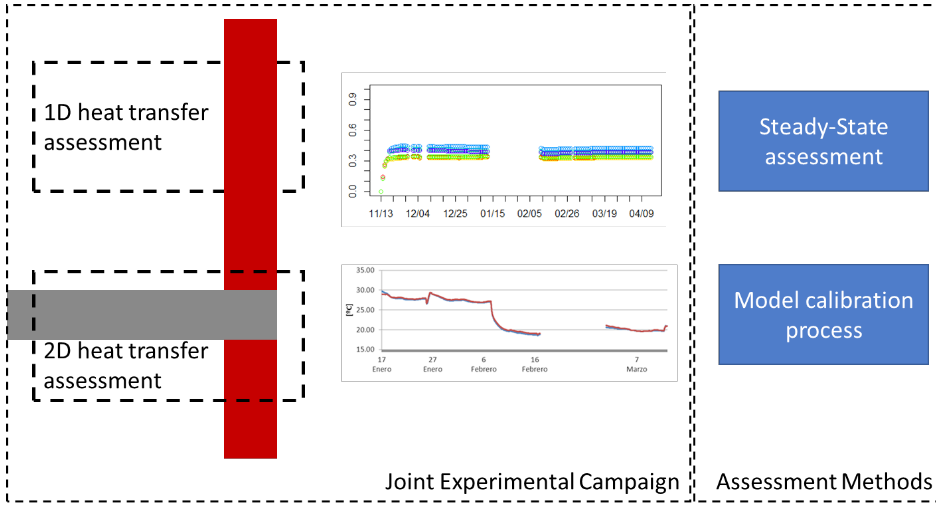


FIG. 1 Integration of assessment methods in a joint experimental campaign for on-site works

## 3 STEP 1: MONITORING

In this step, the geometrical detail is defined, and several spots are selected for the installation of sensors. Commonly, 3-4 sensors are sufficient to provide a detailed thermal map of the architectural junction. In the selection of the sensor location, sensors should be located in such a way as to allow the mapping of the architectural detail in all its relevant internal surfaces.

The particular location of sensors will depend on each architectural junction, and the feasibility of integrating sensors in some of the locations. Garay, Uriarte and Apraiz (2014) used steady-state thermal models to identify suitable locations for sensor placement. By doing so, better experimental conditions are achieved. Alternative processes such as thermal imaging are also possible means of identifying suitable sensor locations. The goal is to achieve spatial and transient representation of the measurement scheme:

- Spatial representation is achieved by means of sensor placement across the architectural junction, some of them mostly exposed to the external ambience, others in contact with indoor environment, and some of them in between.
- Transient representation implies that sensors are positioned in such a way that they are exposed to different dynamics. Sensors in contact with insulation materials will deliver faster responses than those in contact with concrete and other capacitive materials.

The number of sensors to be placed needs to be defined based on the scope of the selected assessment. Considering that standardised one-dimensional heat transfer assessment procedures (EN ISO 9869-1:2014) incorporate ambient and surface temperature sensors and at least one heat flow sensor, this amount should be increased to achieve good representation. Good practice should incorporate the following sensors:

- 1 ambient temperature sensor for each of the boundary conditions of the thermal bridge
- 1 surface temperature sensor for the coldest spot on each of the boundary conditions

- 1 heat flux on each of the internal boundary conditions
- 1 additional surface temperature sensor for planar systems not instrumented for EN ISO 6946:2007
- External weather conditions need to be measured, and comprise outdoor ambient temperature, wind speed & direction, and solar radiation over the façade.

For the application presented, Pt100 temperature sensors and PHYMEAS heat flux sensors are identified as suitable devices.

In Fig. 2, a monitorisation scheme is proposed for a slab-façade junction. In this figure, meteorological sensors are not shown.

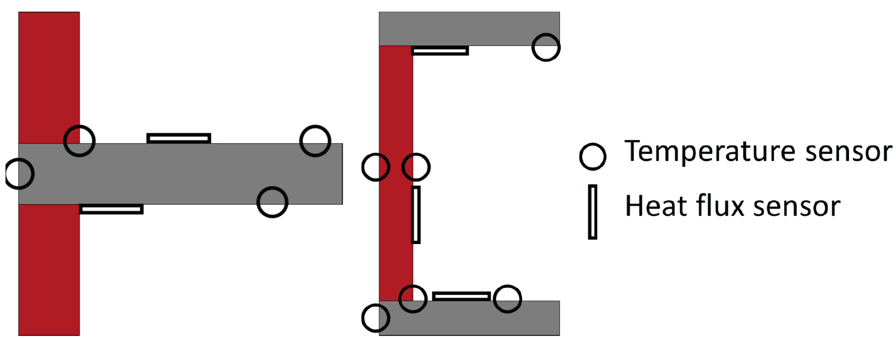


FIG. 2 Monitorisation scheme of a slab-façade junction (left), distribution of sensors in a multi-storey setup (right)

To facilitate the experimental process, the experimental campaign should be coordinated with the installation of other sensors for the one-dimensional assessment of the thermal performance of walls. This would allow for the common utilisation of data loggers. In the same figure, the monitorisation spots are redistributed, to allow for the installation of the data acquisition system within one floor of a multi-storey building. The presented experimental setup would only be valid in a multi-storey building in which boundary effects caused by foundations and roof can be neglected (i.e. central floor in a 7-storey building).

In Fig. 3, the detailed location of sensors in an architectural junction can be seen.

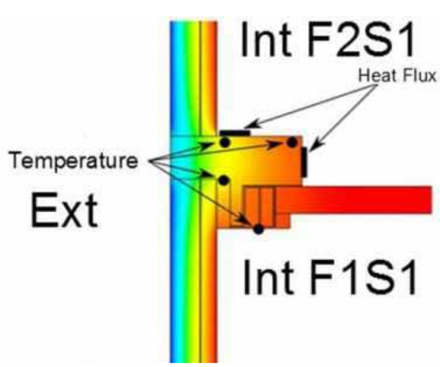


FIG. 3 Location of temperature and heat flux sensors in an experimental assessment of the heat transfer in a façade-slab junction (model height: 2.77m) (Garay Martinez, Uriarte Arrien & Apraiz Egaña, 2015)

Depending on the existing boundary conditions (i.e. indoor-outdoor temperature gradient), the insulation level of the construction etc., the length of the monitorisation campaign may divert. However, it is reasonable to assume that a proper result can be achieved with experimental campaign lengths in the range of 3 to 5 weeks.

In Atsonios, Mandilaras, Kontogeorgos, and Founti (2017), one-dimensional heat transfer assessment was performed by means of identification processes over various wall assemblies. Different climatic conditions, envelope compositions, and assessment methods resulted in variable campaign length requirements to deliver a result. When transient methods were applied, campaign lengths in the range of 10-20 days were required to achieve good identification of the system. In the proposed methodology, longer experimental campaigns are required to properly address heat dynamics in massive elements, such as concrete slabs. In any case, the prescribed campaign length is still inductive.

## 4 STEP 2: CALIBRATION

A thermal model of the architectural detail is constructed based on the available information relating to the junction. Commonly tabulated data from sources such as EN ISO 6946:2007 and Ministerio de Fomento (2013) are taken to complete project-specific data. It should be considered that, in most cases, retrofitting projects are performed over relatively old buildings, with non-professional owners (e.g. individual owners/dwellers, not involved in the construction process), with only minimal architectural data available.

The definition of architectural dimensions needs to cover the influence area where multi-dimensional heat transfer occurs. General criteria established in EN ISO 10211:2007 suggest that 1m of one-dimensionally homogeneous wall/slab length shall be modelled. The readers should consider that secondary criteria such as symmetry planes and wall thickness may modify this length.

Fig. 4 shows a thermal model of a façade-slab architectural junction.

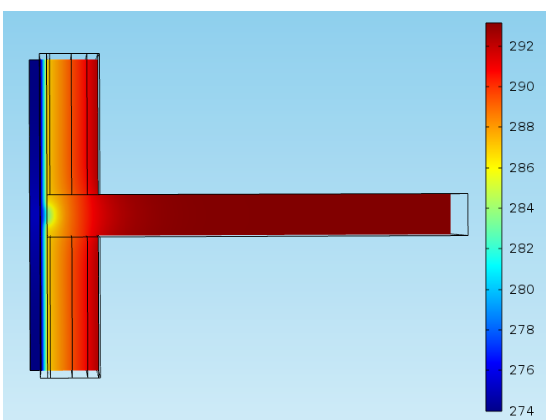


FIG. 4 Thermal model of an architectural junction. (Garay Marinez, 2017)

Boundary condition data from the monitorisation campaign is introduced in this model, and a transient thermal simulation is performed over the monitored period. The boundary conditions incorporated into the model are ambient temperature (on all surfaces) and solar radiation (for external surfaces only).

Thermal properties of materials and modelling assumptions are varied to minimise the observed error in output variables when compared with monitored spots in the physical junction within the monitored campaign.

In Fig. 5, output data from a calibrated model in VOLTRA (PHYSIBEL, 2009) is compared to experimental data taken from a façade-slab junction constructed in the KUBIK experimental building (Garay, Chica, Apraiz, Campos, Tellado, Uriarte, & Sanchez, 2015).

Error minimisation needs to be achieved simultaneously in all point measurements.
The comparison of the calibrated model against experimental data for all sensors installed in the junction can be found in Garay, Uriarte and Apraiz (2014) and Garay Martinez, Uriarte Arrien, and Apraiz Egaña (2015).

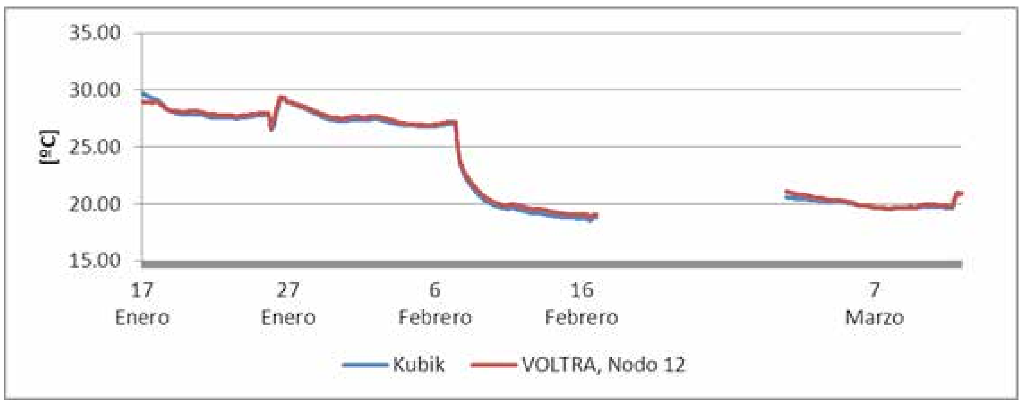


FIG. 5 Calibrated output signal on a thermal model. (Garay, Uriarte, & Apraiz, 2014) (Garay Martinez, Uriarte Arrien & Apraiz Egaña, 2015)

In Garay, Uriarte, and Apraiz (2014) and Garay Martinez, Uriarte Arrien, and Apraiz Egaña (2015), the model was parametrised to incorporate thermal capacity and conductivity of materials (concrete, steel, polyurethane, and XPS). It was found that minor tuning was required to identify the parameters of concrete. Concrete density and conductivity were varied in a range of 2000-2400kg/m3, and 2-2.6 W/mK respectively. The model best fit to experimental data was achieved with 2300kg/m3 and 2.2W/mK.

This same model was found to be more sensitive to internal convective heat transfer phenomena. Separate heat transfer coefficients were required for horizontal, vertical upward, and vertical downward heat transfer. Additional coefficients were required for corner areas. Each of these resulted in surface heat transfer coefficients in the range of 2.5-4 W/m2K, substantially lower than reference values in EN ISO 6946:2007. Full details on the calibration process can be found in Garay, Uriarte, and Apraiz (2014).

At the end of this process, the thermal model is classified as "Calibrated", and can be used for later assessment of retrofitting alternatives. In TECNALIA (2013), a visual inspection was used to identify the model that best fit the experimental data, but this process can be improved by using error minimisation techniques simultaneously over all measurement spots. From experimental data, the model was able to predict surface temperature within +- 0.2 °C, as can be seen in Fig. 4.

The calibration is performed based on punctual sensor locations, none of which are sufficiently reliable as to fully represent the thermal performance of the architectural junction. However, considering the accordance of the calibrated model with experimental data, it is reasonable to accept that the calibrated thermal model can be used to predict the thermal performance of the full architectural junction.

## 5 STEP3: EVALUATION OF RETROFIT ALTERNATIVES

The calibrated model from the previous section can be used to predict the thermal performance of architectural junctions targeted at various performance figures. The model itself is a transient thermal model, which can be used to perform both transient and steady-state calculations of the architectural junction for various purposes such as the following:

- Calculate thermal bridge coefficients and temperature factors of various alternative designs, based on calculation criteria and boundary conditions in EN ISO 10211:2007, but with calibrated thermal parameters for the baseline junction
- Calculate the overall coupling coefficient of the building envelope under standard EN ISO 13790:2008
- Calculate the transient thermal response of the architectural junction under harmonic boundary conditions similar to EN ISO 13786:2007 and that described in Garay Martinez, Riverola, and Chemisana (2017).
- Obtain transfer functions and response factors of the architectural junction by procedures, as described by Martín, Flores, Escudero, Apaolaza, and Sala (2010).
- Obtain equivalent one-dimensional thermal models for its integration into energy simulation programs by means of system identification techniques, stochastic procedures, etc. as proposed by Gacía Gil (2008).
- Perform heat transfer analysis of the architectural junctions for the verification of energy savings in energy performance contracts by means of IPMVP (EVO, 2012) or equivalent methods.

Overall, the proposed models allow for a detailed assessment of the architectural junction, with many relevant output parameters, which should be defined on a case-by-case basis, along with the particularities of each project from its many perspectives (architectural constraints, expected performance levels, engagement of contractors in the final performance, etc.).

In the following paragraphs, a case study on the assessment process for building energy retrofits is presented. The model for the façade-slab section presented in Fig. 3 is taken as baseline, and façade retrofit is performed by means of a ventilated façade system. This system is a closed joint ventilated façade cladding system (ULMA Architectural, 2018) based on vertical profiles and point anchors to the edge of concrete slabs (Garay Martinez, 2017).

The presented study was performed by means of multi-dimensional modelling of the junction. The ventilated façade model is parametrised to incorporate insulation thickness as the main variable. Anchor thickness is a dependent variable, as this parameter is required to be increased when the cladding is separated from the façade to meet mechanical criteria. The suitability of each alternative is assessed by means of surface, linear, and point heat transfer, and temperature factor is obtained. Fig. 6 shows the architectural detail and temperature field of the studied junction.


FIG. 6 Architectural detail and thermal field in the cross-section of the slab-façade junction

The U-value of the façade changes from 1.05 W/m$^2$K (Uninsulated) to 0.13 W/m$^2$K (20 cm of insulation). The achieved insulation levels are compared with normative requirements in Spain (Ministerio de Fomento, 2013).

In Fig. 7, the evolution of thermal transmittance and temperature factors is shown for varying thermal insulation levels. For the uninsulated case, there is a 12% surplus heat transfer due to the 2D heat transfer over the 1D study. When adding insulation over this junction, the 2D surplus heat is substantially mitigated. However, 3D heat transfer introduced by mechanical anchors becomes a relevant part of the heat transfer across the façade. This surplus heat increases from 16% (5cm) to 48% (20cm) when the façade is insulated externally. The surplus 3D heat transfer is stable in absolute terms for all cases, but its relative relevance increases substantially.

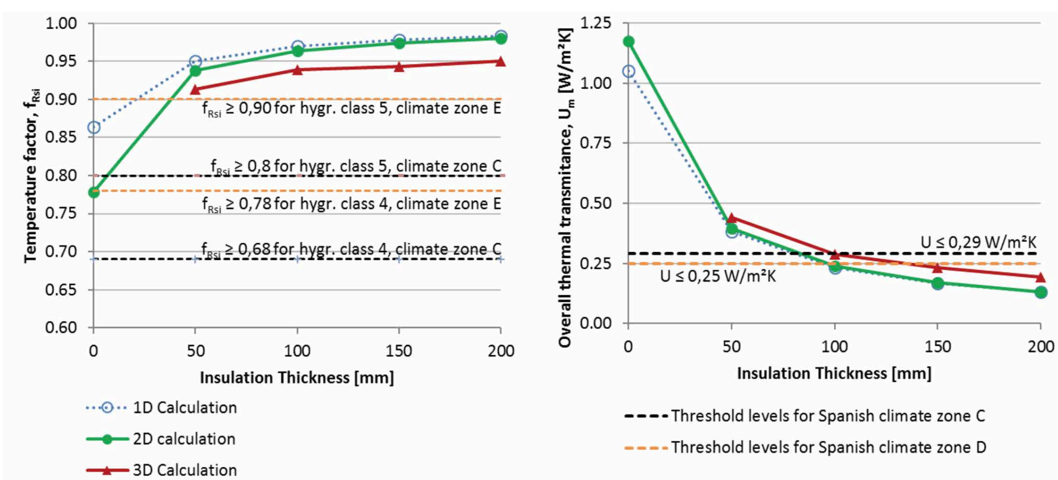


FIG. 7 Temperature factors and thermal transmittance values. (Arregi Goikolea, Garay Martinez, Riverola Lacasta & Chemisana Villegas, 2016)

The method results in a more precise assessment, where calculation errors due to 3D heat transfer are detected and corrected. As a result, the façade system is selected for compliance with the Spanish requirement of overall façade U-value (0.25 W/m$^2$K). In this correction, insulation thickness is increased from 10cm to 15cm of mineral wool.

# 6 CONCLUSIONS

With the increasing thermal performance levels required by national building codes in developed societies, steady-state thermal performance of one-dimensional sections of envelopes are not sufficient to guarantee the thermal performance of architectural envelopes. The need for detailed assessment is increasingly relevant in retrofitting projects, where architectural information and design alternatives face relevant constraints. Under such schemes, advances in design and assessment procedures are necessary, particularly considering that thermal bridges in these junctions are major heat loss paths, and cold spots exist in which surface condensation and mould growth are more likely to occur.

The proposed methodology provides a minimally intrusive methodology for the robust assessment of thermal performance of architectural junctions with many possible outcomes, which could be defined based on the requirements of each case. Considering the rapid adoption of wireless technologies in the sensor and monitorisation market, it could be expected that the intrusiveness of the methodology could be further reduced by removing wires in the monitorisation process.

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