Analysis of the influence of different variables on the impacts related with the envelope of buildings for residential use, with estimation of the interaction of the user

Patricia Huedo, Belinda López-Mesa and Elena Muleta

aDepartamento de Ingeniería Mecánica y Construcción, Universitat Jaume I, Castellón de la Plana, Spain; bDepartmento de Arquitectura, Universidad de Zaragoza, Zaragoza, Spain

ABSTRACT
There is an important mismatch, or gap, between the predicted and actual measurements of the impacts that are produced, mainly during the use phase of buildings. In this study, the authors estimated the weight of the different explanatory variables used to define the model for predicting the impacts in the evaluation of the dependent variables considered: ‘CO₂ equivalent emissions’ and ‘primary energy consumption’. The study explores the extent to which the intervention of high- or low-energy users (depending on their purchasing power) influences the impacts of the use phase linked to the envelope, ‘user interaction’ being considered as a variable that modifies the impact predicted by the model. The results obtained show that, without taking the user into account, climate zone is the variable with the greatest influence, since it accounts for over 80% of the variation in heating consumption in the use phase. However, on analysing the influence of the user in zones with a continental climate, the results varied with respect to the predicted value, from 5% in the case of low-energy users up to more than 53% when they are very high-energy users.

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1. Introduction
Designers are faced with the increasingly more pressing obligation to provide data on the environmental impacts deriving from buildings and to justify with greater precision the use of building materials and solutions with a low-environmental impact. At the same time, they face the difficulty of combining two different but closely linked scenarios: they need to know to what extent the materials or the construction solutions used for the building are respectful to the environment and, at the same time, to what extent they are capable of guaranteeing a reduction in the energy demand, while maintaining the conditions of comfort of the building throughout the life thereof (Huedo, Mulet, & Lopez-Mesa, 2015).

The literature contains a number of studies based on Life Cycle Analysis (LCA) that have yielded accurate data on the weight of the impacts of each of the phases within the life cycle of a building, taking into account the envelopes and the emissions and
consumptions of the heating and air conditioning equipment (Alías & Jacobo, 2008; Alonso, Oteiza, & García, 2010; Estress Consultores, 2010; Gonzalo et al., 2000; Gustavsson & Joelsson, 2010; Iyer-Raniga & Wong, 2012; Mithraratne & Vale, 2004; Ortiz, Bonnet, Bruno, & Castells, 2009; Ruá, Vives, Civera, & Lopez-Mesa, 2010; Verbeeck & Hens, 2010; Villar-Burke, Jiménez-González, Larrumbide, & Tenorio, 2014; Wadel, López, Sagrera, & Prieto, 2011; Zabalza Bribián, Aranda Usón, & Scarpellini, 2009). Yet, given the number of variables that come to bear on this relationship and the widely varying results offered by these studies, more data are needed to develop models that allow this link to be established with greater precision.

Although LCA is a rigorous methodology that studies the environmental impacts that occur throughout the entire life cycle, there is an important gap between the predicted and the actual measurements of these impacts. The inaccuracy of the predictions in the different phases of the life cycle of a building may be due to a variety of factors that have already been analysed in the literature (Blázquez, Suárez, & Sendra, 2015; Burman, Mumovic, & Kimpian, 2014; De Wit, 1995; Dronkelaar, Dowson, Spataru, & Mumovic, 2016; Haas & Biernayr, 2000; Herrando et al., 2016; Li, Yang, Becerik-Gerber, Tang, & Chen, 2015; López-Mesa, Palomero, Ortega, & del Amo, 2013; MacDonald, Clarke, & Strachan, 1999; Menezes, Cripps, Bouchlaghem, & Buswell, 2011; Norford, Socolow, Hsieh, & Spadaro, 1994; Sendra, Domínguez, León, & Bustamante, 2013; UNE-EN 832/2000; de Wilde, 2014; Xexakis & Dobbelsteen, 2015). This gap not only affects new building projects, but also occurs in the predictions that are made regarding existing buildings before and after being refurbished, when neither the expectations concerning energy savings nor the term calculated to amortize the investment are met (López-Mesa et al., 2013).

This gap may be due to causes that can be attributed to the prediction methodology employed, since LCA studies on buildings have often had to simplify the methodology used and also carry out adaptations and approximations when it comes to working with the data available in the information sources (Ecoinvent, Buwal 250, Idema, Ivam, etc.). Moreover, the environmental impact inventories in LCA require a high level of information about materials and processes, which may not be available for a wide range of situations. It is also difficult to calibrate the environmental impacts produced during the use phase because there are many variables involved in this stage that are not always taken into consideration by simulation software (EnergyPlus, Ecotect, eQues, Lider, Calener, etc.), and basically affect the use conditions of each building (Huedo, 2014). Li et al. attributed this discrepancy to the occupancy data or to the conditions of the building chosen as a reference (2015). Hence, after analysing the causes of the gap they focused on developing systems with which to better calibrate the reference model. Other authors such as Blázquez et al. (2015) considered that the divergences between real and simulated results are due to uncertainty and a lack of information about usage and operational conditions. Likewise, Xexakis and Dobbelsteen (2015) claimed that the performance of a building is affected by a large number of interconnected parameters that vary according to the type, construction, location and, above all, the user’s way of life, which is one of the most unpredictable variables. In this same line, de Wilde (2014) and Hernando et al. (2016) claimed that the average difference between the predicted and the actual consumption of residential buildings stands at around 30%, and also analysed a number of different factors that could be responsible for this gap. This same author placed special emphasis on the impact of the outdoor climate and concluded that the maximum
variation occurs in the presence of extreme outdoor temperatures, whereas the gap is
closed considerably if the outside temperature is between 16°C and 18°C, which is
when it is not necessary to use heating or air conditioning (de Wilde, 2014).

López-Mesa et al. (2013) measured the energy behaviour of some dwellings in a block
of apartments on the Girón estate in Zaragoza (Spain) before and after being refurbished
and then compared the data obtained by means of simulation software with the real
measurements of consumptions. This study revealed that following the refurbishment,
the expected energy savings were not achieved. Thus, they concluded that this gap in
the predictions was due to two notable situations. In some cases, energy consumption
increased far less than was expected due to the fact that the energy habits of the
owners varied following the refurbishment, which allowed them to gain increased
thermal comfort in their homes. In other cases, the researchers found that the use con-
ditions varied depending on the socio-economic status of the user, since they observed
that users often did without an adequate level of thermal comfort so as to match their
energy consumption to their purchasing power. Accordingly, in some social sectors, econ-
omic savings prevailed over comfortable living conditions in situations of genuine ‘energy
poverty’ (López-Mesa et al., 2013).

From all the above, it is obvious that to be able to determine the energetic and environ-
mental behaviour of buildings, it would be essential to monitor them under real living con-
ditions. But even so, measuring real data for one building does not imply that the same
results are going to be found in other similar buildings.

Nevertheless, project planners must be able to ensure, in the initial stages of the design,
that the environmental requirements of the Regulations are complied with by maintaining
the required level of comfort, even though real measurements are still not available.

As we understand it, in order to aid designers, it would be useful to know which vari-
ables can exert a greater or lesser influence on the production of environmental
impacts throughout the life cycle of the building. Although imprecision of the predic-
tions can occur in different phases of the life cycle of the building due to the prediction
methodology itself, most authors, however, agree on attributing the greater part of the
gap to the imprecision that occurs in predicting the impacts generated during the use
phase.

In view of the difficulty involved in predicting the impacts and establishing the environ-
mental benefits that require the selection of certain alternatives in the design in both new
and refurbished buildings, our aim is to explore to what extent transversal user interaction
could help calibrate the gap between the predicted and the actual measurements of the
impacts. This study considers the importance of analysing the aspects that can affect the
assessment of the environmental impact of the building during the use phase, in both new
and refurbished buildings, by exploring how the user’s behaviour influences the outcome.

2. Aims

The specific aims of this research are:

- To estimate the weight of the explanatory variables (climate zone, orientation and the
type of façade, roof and window utilized in the envelope) in the impacts during the use
phase.
To adjust the weight of the estimated explanatory variables, taking user intervention into account as an effect-modifying variable.

To analyse the weight of other variables such as water consumption and waste generation during the use phase.

To estimate what proportion of the impacts could be considered as resulting from the manufacture and maintenance of the building with respect to the impacts produced during the use phase due to the heating and air conditioning equipment, bearing in mind user intervention.

With these data, the aim is to help reduce the gap between the predicted and real measurements of the impacts produced by helping designers to select building elements with a low-environmental impact that improve the conditions of comfort in the dwellings, both in new and in refurbished buildings, while taking into account the uncertainty due to user intervention.

3. Methodology

A diagram showing the methodology to be followed can be seen in Figure 1, where the main contributions of this paper are highlighted in bold type.

3.1. First phase

3.1.1. Description of the prediction model used

The prediction model that had previously been developed to evaluate the impacts generated by the envelope throughout the life cycle of the building is described in the following (Huedo, Mulet, & Lopez-Mesa, 2016).

This model was obtained by applying a simplified LCA method for a single-family terraced house with 180 alternative designs for the envelope in combination with two climate zones and two orientations.

In order to obtain the impacts of the manufacturing stage, the TCQ2000 tool was chosen, and more specifically its environmental management module TCQGMA (2013). This software, developed by the Instituto de Tecnología de la Construcción de Cataluña

Figure 1. Diagram of the application of the methodology.
(IteC), uses the database named BEDEC, PR/PCT (2013). This software application was chosen because it is readily available owing to the existence of agreements allowing it to be used by students and researchers at a low cost. These same tools were also used in some of the research studies mentioned above (Estress Consultores, 2010; Iyer-Raniga & Wong, 2012; Ortiz et al., 2009; Villar-Burke et al., 2014; Wadel et al., 2011; Zabalza Bribián et al., 2009).

The impacts during the use phase were obtained by means of the energy simulation tools LIDER (LIDER, 2011) and CALENER (CALENER, 2011) for calculating energy consumptions and CO₂ emissions, as these tools ensure compliance with the requirements set out in the Documento Básico de Ahorro de Energía del Código Técnico de la Edificación in Spain (Energy Saving Basic Document in the Technical Building Code) (Ministerio de Fomento, 2013). These software tools have also been used in some of the research studies mentioned earlier (Ortiz et al., 2009; Ruà et al., 2010; Zabalza Bribián et al., 2009).

In developing this model, when it came to applying the LCA methodology, a set of standard methodologies published by Technical Committee 350 of the European Committee for Standardization (CEN/TC 350) were taken into account. They are outlined below.

The case study chosen for use in this model was a single-family terraced house that has two floors and a usable floor area of 93.5 m² (Figures 2 and 3).

Since it would be impossible to cover all the possible combinations, the variables chosen for the purposes of this study were the ones explained and justified as follows:

The LCA was performed on the selected type of building, the construction assemblies of the envelope, in two orientations and two climatic zones, being taken as the variables. A functional unit of 1 m² of usable floor area and a useful lifespan of the building of 50 years were chosen.

In this case, the explanatory variables were taken as being each of the construction assemblies that make up the envelope (a type of roof C, a type of façade F and a type

![Figure 2. Section of the dwelling used as a case study.](image)
of window H). For the purposes of this study, the building solutions most commonly employed in construction in Spain were selected and can be seen in Table 1. Each construction assembly is designated with a capital letter that indicates the class (C = roof, F = façade and H = window) and their numerical index, which indicates the type of building assembly.

The calculations were performed by combining, in each alternative, a type of roof, a type of façade and a type of window, in a climate zone and an orientation.

For the purposes of this study, two climate zones were selected as the explanatory variables, B3 and E1, which cover most of the country (Spain) where the study was conducted. Climate zone B3 offers a temperate humid climate and covers nearly the whole of the Mediterranean basin, while E3 has a cold dry climate that extends inland across the Peninsula. Moreover, because of the extreme difference in the severity of the climates in the two zones, both in winter and in summer, these variables are the ones that allow a better comparison of the results obtained. Likewise, the most favourable orientation was considered as being NE and the most unfavourable was SE, bearing in mind the demand of the reference building used by the tools LIDER and CALENER. Table 2 shows all the explanatory variables that were taken into consideration.

Altogether 45 combinations of construction assemblies (3 types of roof, 5 types of façade and 3 types of window) were evaluated in two orientations and in two climate
Table 1. Characterization of the construction assemblies evaluated.

| C1 | Flat roof, conventional, not-ventilated, trafficable |
|----|-----------------------------------------------------|
| Material | Thickness (m) | Section |
| P_Finishing ceramic tiles | 0.01 | |
| 2_MA_Mortar | 0.04 | |
| 3_CCA_Polypropylene geotextile (125 g/m²) | 0.000128 | |
| 4_UI_Waterproof sheet bitumen LC-40/45V | 0.007 | |
| 5_CCA_Polypropylene geotextile (125 g/m²) | 0.000128 | |
| 6_AT_Thermal insulation XPS | 0.05 | |
| 7_B_Vapour barrier | 0.005 | |
| 8_FP_Aerated concrete for roof slope | 0.048 | |
| SRP_Reinforced concrete one-way slab, ceramic hollow plot | 0.3 | |
| 10_R1_Plastering | 0.01 | |
| **Total** | **0.47** | **U=0.44 W/m²K** |

| C2 | Flat roof ventilated, trafficable |
|----|----------------------------------|
| Material | Thickness (m) | Section |
| P_Finishing ceramic tiles | 0.01 | |
| 2_MA_Mortar | 0.04 | |
| 3_CCA_Polypropylene geotextile (125 g/m²) | 0.000128 | |
| 4_UI_Double waterproof sheet bitumen LC-40/45V | 0.007 | |
| 5_CCA_Polypropylene geotextile (125 g/m²) | 0.000128 | |
| 6_FP_Ceramic tiles for roof slope | 0.36 | |
| 7_GC_Ventilated air chamber | 0.003 | |
| 8_AT_Thermal insulation of mineral wool | 0.005 | |
| unidirectional fabric fusing with ceramic elements | 0.3 | |
| 10_R1_Plastering | 0.01 | |
| **Total** | **0.725** | **U=0.54 W/m²K** |

| C3 | Flat roof with insulation, conventional, non-trafficable |
|----|------------------------------------------------------|
| Material | Thickness (m) | Section |
| P_Finishing gravel | 0.02 | |
| 3_CCA_Polypropylene geotextile (125 g/m²) | 0.000128 | |
| 4_AT_XPS thermal insulation | 0.05 | |
| 5_CCA_Polypropylene geotextile (125 g/m²) | 0.002 | |
| 6_UI_Double waterproof sheet bitumen LC-40/45V | 0.007 | |
| 6_FP_Aerated concrete for roof slope | 0.048 | |
| SRP_Reinforced concrete one-way slab, ceramic hollow plot | 0.3 | |
| 10_R1_Plastering | 0.01 | |
| **Total** | **0.437** | **U=0.40 W/m²K** |

| H1 | Aluminium windows with thermal bridge breaking system |
|----|-----------------------------------------------------|
| Material | Thickness (m) | Section |
| Double glazing 6/6/6, low E glass | 0.012 | |
| Aluminium frame with thermal bridge breaking system | 0.001 | |
| Filter of neutral silicon | 0.005 | |
| Dry air space 6mm thick | 0.006 | |
| Ironwork of steel | 0.015 | |
| Galvanized steel 40x20mm subframe | 0.015 | |
| **Total** | **0.054** | **U= 3.7 W/m²K** |

| H2 | PVC windows with thermal bridge breakage |
|----|----------------------------------------|
| Material | Thickness (m) | Section |
| Double glazing 6/6/6, low E glass | 0.012 | |
| PVC frame with three chambers | 0.001 | |
| Filter of neutral silicon | 0.005 | |
| Dry air space 6mm thick | 0.006 | |
| Ironwork of steel | 0.015 | |
| Galvanized steel 40x20mm subframe | 0.015 | |
| **Total** | **0.054** | **U= 3.7 W/m²K** |

| H3 | Wood windows |
|----|--------------|
| Material | Thickness (m) | Section |
| Double glazing 6/6/6, low E glass | 0.012 | |
| High density wood frame | 0.019 | |
| Filter of neutral silicon | 0.005 | |
| Dry air space 6mm thick | 0.006 | |
| Ironwork of steel | 0.015 | |
| Wood frame 40x20mm | 0.015 | |
| **Total** | **0.072** | **U= 3.7 W/m²K** |

| F1 | Brick cavity walls, with outer wall of facing bricks, 5 cm thick insulation |
|----|---------------------------------|
| Material | Thickness (m) | Section |
| LC_External masonry wall of ceramic perkerated brick of 11.5 cm thick, with cement mortar joints | 0.115 | |
| RM_Intermediate coat. A plaster on the interior face of the principal with cement mortar (1.6) | 0.015 | |
| C3_Non-ventilated air chamber | 0.05 | |
| 4_AT_Thermal insulation, mineral wool | 0.05 | |
| LJ_Inner skin of double hollow ceramic brick | 0.07 | |
| 5_Tom thick with cement mortar joints (1.6) | 0.015 | |
| **Total** | **0.32** | **U=0.49 W/m²K** |

| F2 | Brick cavity walls, with coated outer wall of brickwork, 5 cm thick insulation |
|----|---------------------------------|
| Material | Thickness (m) | Section |
| RE_Coated outer coating with cement mortar (1.6) | 0.015 | |
| LC_External masonry wall of perforated 12 cm thick ceramic brick, with cement mortar joints | 0.115 | |
| 4_AT_Thermal insulation, mineral wool | 0.05 | |
| LJ_Inner layer of double hollow ceramic brick | 0.07 | |
| 5_Tom thick with cement mortar joints (1.6) | 0.015 | |
| **Total** | **0.32** | **U=0.49 W/m²K** |

| F3 | Brick cavity walls, with coated outer wall of brickwork, 10 cm thick insulation |
|----|---------------------------------|
| Material | Thickness (m) | Section |
| RE_Coated outer coating with cement mortar (1.6) | 0.015 | |
| Ceramic brick 11.5 cm thick with cement mortar joints (1.6) | 0.115 | |
| 4_AT_Thermal insulation, mineral wool | 0.1 | |
| LJ_Inner layer of double hollow ceramic brick | 0.07 | |
| 5_Tom thick with cement mortar joints (1.6) | 0.015 | |
| **Total** | **0.37** | **U=0.59 W/m²K** |

| F4 | Back-ventilated façade of brickwork, 5 cm thick insulation |
|----|---------------------------------|
| Material | Thickness (m) | Section |
| RE_Outer discontinuous coating of ceramic tiles mechanically fastened with aluminium fasteners type T | 0.02 | |
| C_Ventilated air chamber | 0.05 | |
| AT_Thermal Insulation of mineral wool | 0.05 | |
| RM_Coated outer coating with cement mortar (1.6) | 0.015 | |
| LC_Inner layer of double hollow ceramic brick | 0.115 | |
| 5_Tom thick with cement mortar joints (1.6) | 0.015 | |
| **Total** | **0.265** | **U=0.05 W/m²K** |

| F5 | Curtain wall |
|----|--------------|
| Material | Thickness (m) | Section |
| Double glazing 6/6/6, low E glass | 0.012 | |
| Aluminium substructure of tubular munitions and horizontal transoms | 0.009 | |
| Dry air 8 mm space | 0.006 | |
| Aluminium Composite Panel | 0.0016 | |
| **Total** | **0.0216** | **U=1.9 W/m²K** |
zones, that is, a total of 180 options. The other parameters, related to openings (percentage and geometry, protection from the sun, frame and glass surface, type of glass, air permeability and shadows that may be cast by obstacles on the façade) and the building itself (thermal bridges, hygrometry, the air flow required for ventilation, the surface temperature inside and outside the dwelling, the heating/cooling equipment and energy sources), are taken as fixed values, the ones used being those shown in Table 3.

In order to calculate the impacts, all the energy and material inputs and outputs were identified together with the emissions generated for each of the phases to be assessed, as can be seen in Figure 4.

In the manufacturing and installation phase, data concerning the constitutive materials (density, thickness, specific weight) were obtained from the catalogue of construction assemblies in the CTE and environmental and costs data were obtained from the BEDEC database (2013).

The impact in the manufacturing phase was obtained using the [TCQ2000 (2013) tool. The impact during the maintenance phase was obtained by assigning a reconditioning factor FR to each of the constituent elements.

The factor, FR, reflects the number of times that each material will have to be replaced throughout the lifespan of the building. The durability of each element within the building assemblies that were analysed was established by following the recommendations set out in Standard ISO 15686-1 (Hernández Moreno, 2011). The impact value is obtained by multiplying the impacts generated by each material by the corresponding FR minus 1 to discount the impact during the manufacturing and installation phases (Huedo et al., 2015).

The impact produced during the use phase of the building is essentially due to the installations and to calculate it, it is necessary to have geometrically defined the building, climate zone, orientation and building solutions employed for the envelope. The final and primary energy consumptions and CO₂ emissions of the building during its use phase were obtained by introducing the data on the 180 design options outlined earlier into LIDER and then calculating with CALENER. This model estimates the following impacts:

Table 2. Explanatory variables.

| Variable | Roof system | Façade system | Window system | Climatic zones | Orientations |
|----------|-------------|---------------|---------------|----------------|--------------|
| Notations | C1 | C2 | C3 | F1 | F2 | F3 | F4 | F5 | H1 | H2 | H3 | B3 | E1 | NE | SE |
| Units    | m² | m² | m² | m² | m² | m² | m² | m² | m² | m² | m² | m² | m² | m² |

Table 3. Parameters that were kept as fixed values.

| Variable | Percentage of openings in the envelope | Percentage of frame | Solar factor of the glass | Shade factor | Modified solar factor | Air permeability | Absorptivity | Hygrometry class | Minimum indoor surface temperature factor | Renewals hour |
|----------|----------------------------------------|---------------------|--------------------------|--------------|-----------------------|-----------------|--------------|-----------------|------------------------------------------|--------------|
| Notations | FM | g⊥ | F₅ | F₄ |  m³/h m² | Hₘₜ, min | h⁻¹ | 0.62–0.64 | 1.6 |
| Units    | % | % | | | | | | | |
The global warming potential, or greenhouse effect emissions, shows the total greenhouse gas emissions in kg CO₂ equivalent/m² of usable floor space in the building resulting from the production and transformation of the construction materials during the manufacturing and maintenance phase and the consumption of the installations during the use phase related to the construction solutions of the building envelope. Unit of measurement: (kg CO₂ equivalent/m²). Spanish Environmental Ministry publishes every year a study on the subject, providing a conversion factor for the emissions of CO₂. In this work, it has been considered the coefficient 0.204 kg CO₂/kWh used by the software CALENER in 2013.

The primary energy consumption per m² of usable floor area of the building due to the production and transformation of construction materials during the manufacturing and maintenance phase, as well as the consumption by the installations in the building during the use phase related with the building solutions employed in the envelope of the building. Unit of measurement: kWh/m².

Water consumption is the amount of fresh water consumed per square metre of usable floor area of the building, taking into account all the water consumed in the manufacture of materials and their on-site installation. Unit of measurement: m³/m².

Waste generated in kg/m² of usable floor area of the building, taking into account the hazardous and non-hazardous waste in the manufacturing and installation phase, including packing waste. Unit of measurement: kg/m².
The impacts obtained during the use phase were employed to develop a regression model with which the value of a dependent variable, \( y \), is predicted by means of the linear combination of the values of several explanatory variables, \( x_1, x_2, x_3, \ldots, x_n \), plus an independent term with a constant value \( b_0 \). The mathematical regression model is therefore as shown in the following equation:

\[
Y = b_0 + m_1x_1 + m_2x_2 + m_3x_3 + \ldots + m_nx_n,
\]

where \( m_i \) is the coefficient of the variable \( x_i \). Thus, the higher \( m_i \) is, the greater the influence of the variable \( x_i \) on the dependent variable, which in this case is the impact that is generated. The independent term of each equation \( b_0 \) is established by the regression model. Each coefficient \( m_i \) is the factor by which each explanatory variable influences impact \( Y \). Roof, facade, window, climate zone and orientation are categorical variables, in the equation each variable \( x_i \) is replaced by values of 0 or 1 depending on whether the envelope contains the variable or not. The regression model was calculated in such a way that one of the coefficients of each categorical variable is zero and therefore it does not appear in the equation.

As has already been discussed, for the purposes of this study, 3 types of roof, 5 types of façade, 3 types of window, 2 climate zones and 2 orientations were chosen as the explanatory variables, which when combined give the 180 different options. CO\(_2\) equivalent emissions of heating and air conditioning equipment per m\(^2\) of usable floor area and the primary energy consumption of the heating and air conditioning equipment per m\(^2\) of usable floor area were taken as the dependent variables.

LIDER predicts the energy demand of buildings on an hourly basis, in transitory regime of heat transfer and works comparing the demand of the object building with a reference building. The information obtained with LIDER is afterwards transferred to CALENER to carry out the analysis of the energy consumptions and of the CO\(_2\) emissions during the use phase of the building. CALENER provides results of consumption of primary energy, as well as information of the CO\(_2\) emissions per m\(^2\) and year.

Table 4 offers a summary of some of the values obtained on calculating the impacts of the use phase with CALENER software.

The block on the left contains the explanatory variables and the one on the right contains the dependent variables corresponding to the impacts being evaluated. Explanatory variables have been codified in a binary format in the form of ones and zeros to identify what type of element forms part of each construction assembly of the envelope. Thus, for example, bearing in mind that three types of roof have been considered, if the hot flat roof C1 is part of a construction assembly, then number 1 will appear in the corresponding box and box C2 will have a 0. Roof type C3 does not appear because it is accounted for with the coding of the roofs C1 and C2, so that if roof C3 is the variable, both box C1 and C2 will have a zero. The remaining construction assemblies are coded in the same way.

The equations from the regression model obtained from the impacts calculated during the use phase are as follows.

**CO\(_2\) Equivalent emissions due to heating in one year per m\(^2\) of usable floor area**

\[
\text{Em}_{eq,\text{CO}_2,\text{cal}}^{\text{uso}} = (23.6924 - 18.06B3 + 0.05NE - 0.07H2 + 0.20H1 + 2.31F4 + 0.84F3 + 2.28F2 + 2.62F1 + 0.67C2 + 0.49C1).
\] (1)
Table 4. Use phase impacts utilized in the regression model.

| Type | Variables | Environmental impacts of the use phase |
|------|-----------|----------------------------------------|
| Semi-detached house | Construction assemblies | Emissions from heating (kg CO₂/m²) | Emissions from air conditioning (kg CO₂/m²) | Consumption heating (kWh/m²) | Consumption air conditioning (kWh/m²) |
| C1 F1 H1 | C1 F2 H1 | C1 F3 H1 | C1 F4 H1 | C1 F5 H1 | C2 F1 H1 | C2 F2 H1 | C2 F3 H1 | C2 F4 H1 | C2 F5 H1 | C3 F1 H1 |
| 1 0 1 0 0 0 0 1 0 1 1 | 1 0 0 1 0 0 1 0 1 0 0 1 0 8.70 4.80 42.90 19.20 | 8.50 4.80 42.20 19.20 | 7.70 4.60 38.10 18.60 | 8.50 5.00 42.10 19.90 | 5.90 4.80 38.50 19.40 | 8.80 4.90 43.40 19.70 | 7.80 4.80 38.50 19.40 | 8.80 4.90 43.60 19.60 | 5.60 6.70 27.70 26.90 | 8.50 4.70 42.30 18.70 |
CO₂ Equivalent emissions due to air conditioning in one year per m² of usable floor area

$$\text{Em}^{\text{uso}}_{\text{eq,CO}_2\text{ref}} = (1.5787 + 4.66B3 + 0.01\text{NE} - 0.03\text{H}2 - 0.08\text{H}1 - 1.37\text{F}4 - 1.49\text{F}3$$
$$- 1.45\text{F}2 - 1.44\text{F}1 + 0.08\text{C}2 + 0.09\text{C}1).$$ (2)

Electricity consumption due to heating in one year per m² of usable floor area

$$\text{Con}^{\text{uso}}_{k\text{Whcal}} = (116.4009 - 89.40B3 + 0.10\text{NE} - 0.27\text{H}2 + 1.27\text{H}1 + 12.73\text{F}4$$
$$+ 5.36\text{F}3 + 12.93\text{F}2 + 14.32\text{F}1 + 3.21\text{C}2 + 1.44\text{C}1).$$ (3)

Electricity consumption due to air conditioning in one year per m² of usable floor area

$$\text{Con}^{\text{uso}}_{\text{epkWhref}} = (6.2829 + 18.65B3 - 0.01\text{NE} - 0.23\text{H}2 - 0.30\text{H}1$$
$$- 5.54\text{F}4 - 6.02\text{F}3 - 5.81\text{F}2 - 5.78\text{F}1 + 0.46\text{C}2 + 0.48\text{C}1).$$ (4)

The regression model obtained is considered to be sufficiently reliable, as the $$r^2$$ quality coefficients of the regressions that were performed are very close to 1. The $$F$$ statistic was also verified, to check whether the variables used for the regression models really explain the value of the impacts under analysis. When there is no relationship between the independent variables $$x_i$$ and the dependent one $$y$$, the value of the $$F$$ statistic must be below the critical $$F$$ value. The $$F$$ value for an error of 0.05, a sample $$N = 180$$ and 169 df has the following value:

$$N = 180$$
$$df = 169$$
$$n = N - df = 180 - 169 = 11$$

The critical $$F$$ value for an error $$\alpha = 0.05$$and $$n = 11$$ is 1.88.

Table 5 shows the $$r^2$$ value and the $$F$$ distribution for each of the regression models:

The $$F$$ value of each equation is therefore much higher than $$F_{\text{crit}}$$ (1.88), thereby indicating that the variables used do in fact explain the value of the final impact well. This constant term in Equations (1–4) results from adjusting the prediction of a quantitative value (impact) by means of the type of envelope, the climate zone and the orientation. This term represents a value that increases or decreases depending on combination of the variables.

Furthermore, the deviation between the values predicted by the model and the values obtained from the simulation was also studied. As can be seen in Table 6, the relative error is very small, except in the CO₂ equivalent emissions and the energy consumption due to air conditioning. In these particular cases, the model predicts a lower impact than the real one. This deviation is small in absolute terms but high in relative terms. This is due to the fact that some envelope combinations displayed a value for emissions close to zero, which is why the relative error was slightly high, but it was not deemed necessary to remove

| Table 5. $$r^2$$ values and the $$F$$ distribution for each of the regression models. |
|-----------------------------------------------|
| Use phase impacts | $$\text{Em}_{\text{eq,CO}_2\text{cal}}^{\text{uso}}$$ | $$\text{Em}_{\text{eq,CO}_2\text{ref}}^{\text{uso}}$$ | $$\text{Con}_{k\text{Whcal}}^{\text{uso}}$$ | $$\text{Con}_{\text{epkWhref}}^{\text{uso}}$$ |
|-----------------------------------------------|
| $$r^2$$ | 0.9963 | 0.9841 | 0.9978 | 0.9819 |
| Critical $$F = 1.88$$ | 4551.9 | 1048.84 | 7530.38 | 917.003 |
them from the regression model. Since these deviations are low except for the air conditioning in cold regions and with envelope combinations that display low values, it is considered that the model is valid enough to predict the impacts.

3.1.2. Calculating the weight of the explanatory variables in the impacts generated in the use phase

The equations that predict the impact of the use phase according to the explanatory variables were employed to check the contribution made by each of the explanatory variables in the assessment of the impact. Previous section shows that the equations are fair enough to predict the impacts. Even so, in order to estimate the contribution of each variable to the impact, there can be interactions between the variables. In this case, for CO2 emissions, the roof system interacts with the façade and the climate zone interacts with roof and façade. For air conditioning consumption, there is also an interaction between the façade and the orientation and in heating consumption between the type of windows and the climate zone. Thus, for instance, the influence of the façade system changes depending on the climate zone. Therefore, the influence of the façade system does not only depend on the type of façade, but also on the combination between the façade and the climate zone.

The amount of combinations of variables and interactions give rise to a very large number of coefficients that exceed the purposes and extension of this work. Since the aim is to compare the weight of each one of the variables on the final impact and the influence of the user, the mean effect of the envelope, zone and orientation, considered without the interactions is provided for two types of user: high demanding and low demanding.

Then, the weight of the coefficient of each explanatory variable was calculated with respect to the sum of all the coefficients of the regression model in each of the impacts. The results thus obtained are shown in Table 11 in the Results section.

In the second phase of the study, user interaction is analysed with the independent variables and with the impacts, user interaction being considered a new effect-modifying variable.

3.2. Second phase

3.2.1. Analysis of user interaction as an effect-modifying variable in the use phase

As highlighted in the introduction, there is an important gap between the predicted and the actual measurements of the impacts that are produced, this gap being mainly attributable to the user. The mean value of the gap is produced essentially during the use phase and stands at around 30% with respect to the value of the estimated impacts in buildings for residential use, according to data observed in the literature (de Wilde, 2014). Hence,

|                           | Absolute deviation | Relative deviation (%) |
|---------------------------|--------------------|-----------------------|
| CO2 heating emissions (kg CO2/m²) | −4.4               | 2                     |
| CO2 air conditioning emissions (kg CO2/m²) | 1.8                | 30                    |
| Electricity heating consumption (kWh/m²)   | −9.6               | 2                     |
| Electricity air conditioning consumption (kWh/m²) | 5.7                | 34                    |

Table 6. Absolute and relative mean deviations for the Equations (1–4).
one first option for reducing the gap between the calculated data and the actual behaviour of the building is to correct the value of the results, using data from the literature, so as to obtain a range and then adjust the weights, in accordance with the following equation:

\[ l_R = l_E + 30\% l_E, \] (5)

where, \( l_R = \) real impact, \( l_E = \) estimated impact.

The statistical data regarding actual consumptions, according to surveys of ‘living conditions’ published by Spanish National Institute of Statistics (INE, 2011), show that the gap is variable and that it largely depends on the climate zone. Thus, it reaches its maximum value under conditions of extreme outdoor temperatures and is considerably reduced if the outdoor temperature is between 16°C and 18°C (de Wilde, 2014).

Moreover, under certain circumstances, the variation between real and predicted consumption is only 5%, since the user with low purchasing power lives below the required conditions of comfort, in a state of ‘energy poverty’ (López-Mesa et al., 2013).

(1) From all the above, the authors believe that ‘user intervention’ (\( I_u \)) can be considered a new modifying variable in the relationship between the variables ‘climate zone’ and ‘energy consumption’. The following description outlines the procedure employed to test the interaction of ‘user intervention’ (\( I_u \)) in the relationship between ‘climate zones’ (B3 and E1) and ‘energy consumption due to heating’ by means of a stratified analysis, two strata from the climate zone being considered in terms of the outdoor temperature and taking into account the user’s purchasing power. User interaction \( I_u \) is understood as being the percentage value by which the environmental impact increases. First, the average monthly temperatures were obtained for each of the climate zones, according to data published in the *Guía técnica de Condiciones climáticas exteriores de Proyecto* (Technical Guide to Outdoor Climate Conditions of the Project) (Ministerio de Industria, Turismo y Comercio 2010).

(2) The next step was to establish the percentage of high-energy users and low-energy users, depending on the number of homes that do not fulfil the conditions of comfort required in winter for each climate zone.

(3) The next step was to establish the percentage of high-energy users and low-energy users, depending on the number of homes that do not fulfil the conditions of comfort required in winter for each climate zone, based on the results of surveys published (INE, 2011).

As has already been said, previous studies reveal that users mainly switch on the heating when the outdoor temperature falls below 17°C. Hence, in Table 7, the data in Table 8 were used to calculate the percentage of days on which the outdoor temperature is <17°C, where there is a demand for heating, and this was then applied to the percentage

| Table 7. Percentage of days on which the outdoor temperature is <17°C. |
|---------------------------------------------------------------|
| **Yes < 17°C** | **No < 17°C** |
| Mediterranean zone (B3) | 52.0 | 48.0 |
| Continental zone (E1) | 63.3 | 36.7 |
of high-energy and low-energy users in Table 9, the result being the data shown in Table 10. This analysis has made it possible to obtain a range of percentage values that indicate user intervention $I_u$ in each climate zone depending on the outdoor temperature and the user’s purchasing power.

These values can be explained by the interaction phenomenon, since the intensity of the relation between user and energy consumption is modified by the outdoor temperature and by the user’s purchasing power.

Once the incidence factor is known from the information in the statistical databases and from the climatological behaviour, we then need to know how the consumption will vary with respect to that predicted by the model (Equation (3)). The factors taken into consideration and the initial data are:

- User intervention only takes place if the outside temperature is below 17°C.
- Over a period of one year, a user intervention that was not predicted by the model will be taken into account, with values of 7.1% of the low-energy users and 56.1% of the high-energy users.
- The value of low-energy (poor) user intervention, $I_{und}$, is 5% ($I_{und} = 5\% I_E$) according to the actual measurements published by López-Mesa et al. (2013).
- The mean value of the gap between the actual and the predicted values is, without differentiating between types of user, 30%.
- Thus, the value of the high-energy (wealthy) user’s intervention, $I_{ud}$, was calculated by comparing the mean value of the gap with the average intervention of the type of user, in accordance with the following equation:

\[
0.3I_E = \frac{7.1I_{und} + 56.1I_{ud}}{100}.
\]

\[
7.1(0.05I_E) + 56.1I_{ud} = 30I_E.
\]

Thus, the $I_{ud}$ value that corresponds to a high-energy (wealthy) user is $I_{ud} = 52.8\% I_E$.

| Mediterranean zone (B3) |  
| August | September | October | November | December |  
| 25.7 | 23.1 | 19.7 | 14.1 | 10.2 |  

| Continental zone (E1) |  
| January | February | March | April | May | June | July | August | September | October | November | December |  
| 6.3 | 6.7 | 9.9 | 13.5 | 16.0 | 21.1 | 23.0 | 23.4 | 20.4 | 16.3 | 9.8 | 5.9 |
Hence, we know that the gap is produced between the values $[0.05I_e, 0.528I_e]$ and, therefore, by replacing these values in Equation (5), we can adjust the real impact of heating consumption to match the expected impact from the model, as indicated by Equation (7).

$$I_R = I_e + [0.05, 0.53]I_e.$$  \hspace{1cm} (7)

This equation allows us to adjust the real heating consumption depending on the estimated impact and on the interaction of the variable $I_u$ (user intervention), the value of which can be chosen depending on the purchasing power of the user.

### 4. Results

#### 4.1. Estimation of the weight of the explanatory variables in the use phase according to the prediction model

As we have explained in Section 3.1.1, the Equations (1–4) obtained in the first phase of the study allow us to confirm the contribution made by each of the variables in calculating the impact. Table 11 shows the coefficients obtained for each of the explanatory variables and the percentage that indicates the extent to which each of these variables influences the value of the impact. The value of the coefficients is the difference between the maximum and the minimum values of each of the coefficients of the explanatory variables (Equations (1–4)).

Table 11 shows the weight of each of the explanatory variables used in the regression model without taking user intervention into account. As can be seen, in this case, the variable that has most influence on the variation of the CO₂ equivalent emissions is climate zone, and the weight of the zone is greater in the case of heating (about 83%) than for
Table 11. Extent of the contribution made by each variable to the impacts of the use phase.

| Explanatory variables | kg CO₂ eq. emissions/m² by heating | kg CO₂ eq. emissions/m² by air conditioning | Consumption kWh/m² by heating | Consumption kWh/m² by air conditioning |
|-----------------------|-----------------------------------|---------------------------------------------|------------------------------|----------------------------------------|
| Zone                  | Coefficient | Percentage | Coefficient | Percentage | Coefficient | Percentage | Coefficient | Percentage |
| Orientation           | 0.05        | 0.22       | 0.01        | 0.14       | 0.10        | 0.09       | 0.01        | 0.03       |
| Window                | 0.27        | 1.27       | 0.09        | 1.39       | 1.54        | 1.42       | 0.30        | 1.19       |
| Façade                | 2.62        | 12.09      | 1.49        | 23.55      | 14.32       | 13.19      | 6.02        | 23.63      |
| Roof                  | 0.67        | 3.11       | 0.09        | 1.39       | 3.21        | 16.85      | 0.48        | 1.90       |
air conditioning (about 73%). The second variable with the greatest weight is the type of façade, which has more influence on the use of air conditioning (23%) than heating (12%). The other variables in the regression model have a much lower weight.

4.2. Estimation of the weight of the explanatory variables, considering user intervention, in heating consumption

As regards the results of the impacts predicted considering user intervention, Equation (7), which was developed in the second phase of the study, allows the real heating consumption to be adjusted taking into account user interaction, the value of which can be chosen depending on their purchasing power. Table 12 shows the coefficients of user intervention in calculating the heating consumption in climate zone E1.

All the explanatory variables were calculated by analysing the range of variation in heating consumption depending on the type of behaviour of a low-energy and a high-energy user.

Table 13 shows the influence of all the variables obtained in the regression model, considering user interaction as an effect-modifying variable.

As can be seen in Table 13, the weight of high-energy users in heating consumption is 35% and the relative weight of the climate zone predicted by the regression model obtained from the energy simulation programmes drops from 80% to 54%.

On comparing the results in Table 13, it can be seen that user interaction modifies the weight of the other variables; hence, if the user has a heavy energy demand, the influence of the climate zone falls from 78% to 54%. The influence of the envelope on the energy consumption of the building in the use phase was also calculated, the result indicating that the weight of the envelope has twice as much effect when the user is a low-energy consumer (Figure 5).

Table 12. Calculation of the coefficients of user intervention for heating consumption in climate zone E1.

| Data                                                                 | Numeric value |
|----------------------------------------------------------------------|---------------|
| Maximum heating predicted without user (maximum value Equation (3)) | 135.30        |
| Minimum heating predicted without user (minimum value Equation (3)) | 26.73         |
| Total variation without user                                         | 135.30 - 26.73 = 108.57 |
| Variation intervention low-energy user                               | 1.05 * 108.57 = 114 |
| Variation intervention high-energy user                              | 1.53 * 108.57 = 166.11 |
| Coefficient low-energy user                                          | 1114 - 108.57 = 5.43 |
| Coefficient high-energy user                                         | 166.11 - 108.57 = 57.54 |

Table 13. Degree of the contribution of each variable to heating consumption in climate zone E1.

| Explanatory variable | Coefficient | Weight (%) | Coefficient | Weight (%) |
|----------------------|-------------|------------|-------------|------------|
| Low-energy user      |             |            |             |            |
| Zone                 | 89.4        | 78.4       | Zone        | 89.4       | 53.8       |
| Orientation          | 0.1         | 0.1        | Orientation | 0.1        | 0.1        |
| Window               | 1.54        | 1.4        | Carpenter   | 1.54       | 0.9        |
| Façade               | 14.32       | 12.6       | Façade      | 14.32      | 8.6        |
| Roof                 | 3.21        | 2.8        | Roof        | 3.21       | 1.9        |
| Low-energy user      | 5.428       | 4.8        | High-energy user | 57.54     | 34.6       |
| High-energy user     |             |            |             |            |
4.3. Estimation of the proportion of the impact of the manufacturing and maintenance phases with respect to the use phase, considering user intervention

Likewise, the results obtained have allowed us to determine what proportion of the impacts that occur at the beginning of the life cycle of the building are due to the manufacture and installation of the materials with respect to the impacts produced during the maintenance phase as a result of refurbishment and also with respect to the impacts produced mainly by the heating and air conditioning equipment, taking into account user interaction in the use phase (Figure 5). It has been shown that during the use phase, the intervention of a high-energy user can raise the estimated value of the impact by about 50%, the weight of the user being 35% of the total for the use phase. A low-energy user, however, modifies the predicted impact by barely 5% (López-Mesa et al., 2013).

If, for example, we analyse the results obtained in zone E1, orientation NE, the difference between the primary energy consumptions related to the combination C1F5H1 (11,222.00 kWh/m²) and those related to the combination C3F3H3 (9773.1 kWh/m²) in a period of 50 years, with a high-energy user, is 1448.09 kWh/m², that is to say, 12.90% less consumption of primary energy over 50 years, depending on the combination that is chosen (Figure 6).

In this same climate zone and orientation, the difference between the CO₂ equivalent emissions related to the combination C1F5H1 (2497.04 kg eq. CO₂) and those related to the combination C3F3H3 (2097.11 kg eq. CO₂) is (399.93 kg eq. CO₂), that is to say, 16.01% less CO₂ equivalent emissions, depending on the combination that is chosen.

4.4. Impact of the envelope on water consumption and waste generation

It has also been observed that other impacts related with the envelope, such as water consumption and waste generation, occur mainly in the initial phases of the life cycle and have a lesser effect in the maintenance and use phases. These impacts basically depend on the building solutions evaluated and do not vary according to the orientation or the climate zone or the user.

With regard to water consumption, the difference between the solution that consumes the least water, C2F5H1 (0.01 m³), and the solutions that consume the most, C1F1H1 or
C3F1H1 (0.05m³), is 0.04 m³ of water per m² of usable floor area, which amounts to 80% less water. In general, more water is consumed by combinations that use concrete or mortar in the building phase, whereas less water is consumed by combinations that make use of prefabricated solutions (Figure 7).

**Figure 6.** Comparison of the impact due to the energy consumption on heating throughout the life cycle of the building, taking into consideration user interaction in the use phase.

**Figure 7.** Comparison of the impact generated by the water consumption of different construction solutions in the manufacturing phase.
These data do not seem significant, compared with the average water consumption in Spanish homes per inhabitant per day, which is around 154 L (Hernandez-Sanchez, 2012). Nevertheless, water has an economic, social and environmental value, and therefore any public or private intervention must take this threefold dimension into account.

As regards the generation of inert and non-hazardous waste, the solutions that combine a lightweight façade with an inverted roof C3F5 are those that generate less waste (Figure 8). The difference between the solution that generates the most waste, C2F1H1 (23.75 kg), and the one that generates the least, C3F5H1 (7.43 kg), is 16.32 kg, that is, 68.7% less. In absolute terms, adopting solution C3F5H1 yields a saving of 16.32 kg (0.016 metric tons) of inert and non-hazardous waste per m² of usable floor area in the manufacturing phase.

5. Discussion and conclusions

The regression model has allowed us to establish the weight of each of the explanatory variables in the impact resulting from heating consumption related to the building envelope during the use phase in two different scenarios: one, under the assumption of a low-energy user, with low purchasing power, and the other, under the assumption of a high-energy user with sufficient purchasing power. It is observed that the influence of some variables, such as climate zone, plays a very important role in the result. The weight of the envelope is also important although some elements used in it, such as the roofs, do not give rise to such notable alterations in the consumptions as the façades.

It can be seen that, on analysing the influence of the user on heating consumption in continental climate zones, the results vary with respect to the predicted value, from 5% when the user is not very energy demanding up to over 53% when they are very high-energy users. This means that the weight of the high-energy users on heating
consumption is 35% and the relative weight of the climate zone predicted by the regression model obtained by the energy simulation programmes decreases from 80% to 54%. These results show that, in order to draw the predictions regarding environmental impact of construction closer to reality, it is necessary to take into account a number of variables that have an influence on the users’ behaviour, such as their socio-economic status and the outdoor temperature. By taking this into consideration, it becomes possible to reduce the gap between prediction and reality.

The stratified analysis used to obtain these results is appropriate, since it is a method that estimates the influence of a factor that affects the environmental impact (the user), which is in turn conditioned by other variables.

The variation interval of the influence of the user obtained in this study is a first result concerning how to bring the predicted environmental impact of residential buildings closer to the real values. As it has been calculated on the basis of existing data found in the literature on real measured impacts, this interval could be adjusted as new impact data are obtained.

Water consumption also displays important relative variations depending on the type of envelope, whereas the generation of inert waste shows significant variations in the manufacturing and installation phase.

Nevertheless, in all cases, user interaction may be masking the result by substantially modifying the value of the impact during the use phase.

As a general conclusion, one of the paths to be followed in order to accomplish sustainable buildings is to achieve envelopes that guarantee the users' conditions of comfort so that their intervention on the energy demand is kept as low as possible. This will help to reduce both the impact resulting from the type of envelope and the gap in the impact produced through the intervention of the user, as their effect on energy consumption will also be reduced.

The results from this study provide numerical figures reflecting the extent to which economic and environmental advantages can be obtained from the construction solutions used in buildings, which offers the designer support when it comes to making decisions about the construction solutions to be employed.

It could be said that designers can contribute, both in new and in refurbished building work, to reduce the actual impact throughout the life cycle of the building without diminishing the required conditions of comfort by making an appropriate choice of building solutions that help to reduce the impacts. The gap between prediction and actual measurement of the impacts produced can be reduced by taking into account user interaction and selecting alternative types of envelope that help reduce the energy demand of the building regardless of the intervention of the user.

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