Design strategies in facades for the reduction of housing energy consumption

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Abstract

This article analyzes the energy-saving potential of various facade design strategies from a life cycle perspective, including the energy needed in the use stage and the embodied energy of materials. The results provide reference data on the behaviour of these systems in Spain and make it possible to identify the best strategies for reducing energy consumption in a wide variety of potential situations that may arise in both new construction and in the rehabilitation of existing facades. The impact categories studied are fossil fuel depletion and climate change, and design strategies are linked to climate data, orientation, air change rate, facade materials and wall composition.

Exchanges between the interior and exterior environments take place through the building envelope, some of whose key design parameters include lighting, ventilation and heat flux. Improving this envelope can greatly reduce environmental impact, ensuring indoor environmental quality.

This analysis confirms the need to consider the interactions among the parameters studied, as it shows that there are several design solutions with similar impacts, which can be adapted to project requirements. In both new construction and rehabilitation, some of these parameters may be determined by other design decisions not necessarily aimed at reducing environmental impact, so it can be very useful to be aware of a variety of design alternatives that can be implemented in specific projects.

Keywords: energy efficiency, facades, design strategies, social housing, fossil fuel depletion, climate change

Extended abstract

A key to achieving zero-emission housing is reducing heating and cooling demand. Improvements to the building envelope can considerably reduce the environmental impact caused by this consumption and ensure indoor environmental quality, as this envelope is the medium through which the exchange between the interior and the exterior takes place, where lighting, ventilation and heat flux are key design parameters. The envelope also has a significant influence on the flows of matter and energy contained in materials (roofs and facades)

This paper presents a preview of the work being carried out and analyses the role of the facade as a key to managing these energy flows. The analysis focuses on the impact of a number of facade design parameters (situation, orientation, ventilation, wall and window type, percentage of openings and sun exposure) on energy demand, including the energy needed in the use stage and embodied in the materials.

Combining the different variables gave rise to 41 472 cases with their respective results.

Heating and cooling demand (Q)

In all cases as a whole, the results for total demand Q range from no demand at all (Q= 0 KWh/m^2) to Q= 93 KWh/m^2, with a mean of Q= 30 KWh/m^2. All the selected parameters have influence on energy demand in the use stage. Climate zone for example, obviously influences demand, as in colder zones the demand for heat is higher; a higher air change rate has a positive effect in that it decreases cooling demand; conversely, it has a negative influence because it increases the demand for heat, and while openings insulation has more effect in heating demand, thermal mass has more significant effect on cooling demand.

Embodied energy of materials (P)

The type of wall and opening are the basic parameters used to determine embodied energy, because, they are the items that establish the position and gradient of the embodied energy, depending on the percentage of openings in the facade. In the cases studied, the average value is 7 KWh/m^{2}y, including the blind part of the wall and the openings on both facades.

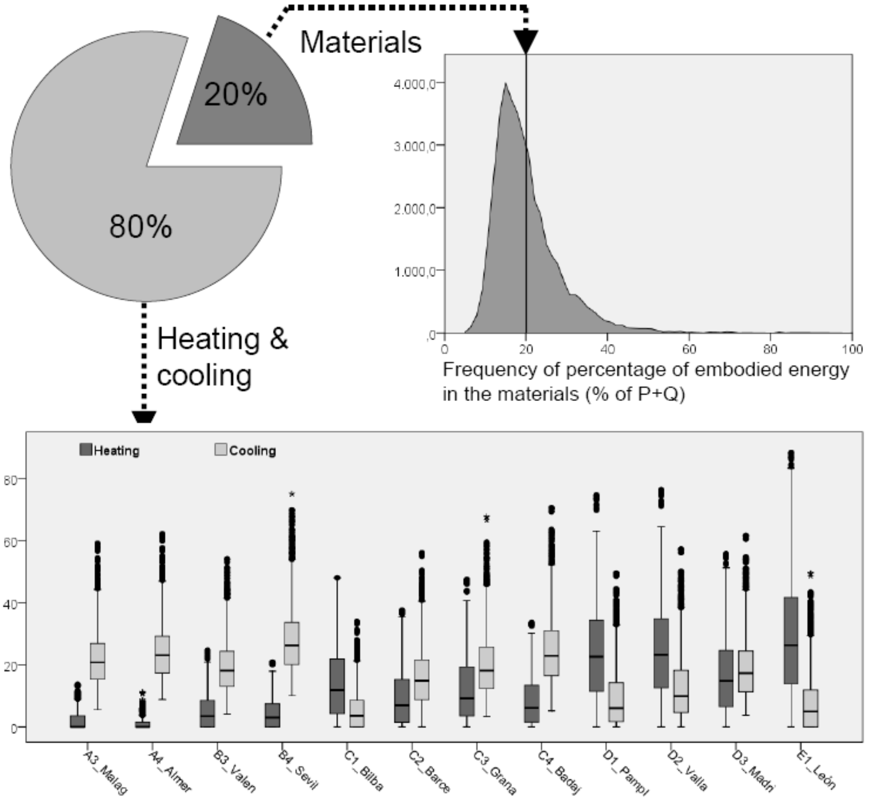

Fig.1. Heating and cooling energy demand (KWh/m^{2}y) in different climate zones and percentage of embodied energy in the materials (% of P+Q)

Heating, cooling and materials (Q+P)

To compare the values for the materials with those for heating and cooling demand, the units are given per net square metre of floor space and per year. In the cases studied, the average is P+Q = 37 KWh/m^{2}y, so the embodied energy of the materials (P) represents an average of 20 % of the total energy, compared to 80 % for heating and cooling. A significant spread is seen in the distribution of this percentage of energy in the materials; it reaches 100 % in cases with no use demand (Q) and is as low as 5 % in those with the highest total demand as shown in Fig. 1.

Because of the wide range of scenarios faced by the construction industry, and in particular the rehabilitation sector, simple solutions geared to different design determinants must be found. In this study, a series of specific cases was analysed with the aim of arriving at some general conclusions to assist in the identification of appropriate strategies in each climate zone. The impact of certain construction parameters and of facade design on a dwelling's energy demand was also studied, and it was concluded that the interactions among these parameters are essential to quantifying demand

To translate this energy demand into consumption and carbon emissions, the efficiency of the systems that generate and supply the required energy must first be determined, and to complete the study on primary energy consumption from a life-cycle perspective, other parameters such as treatment of waste or transport should be considered.

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This article analyzes the energy-saving potential of various facade design strategies from a life cycle perspective, including the energy needed in the use stage and the embodied energy of materials. The results provide reference data on the behaviour of these systems in Spain and make it possible to identify the best strategies for reducing energy consumption in a wide variety of potential situations that may arise in both new construction and in the rehabilitation of existing facades. The impact categories studied are fossil fuel depletion and climate change, and design strategies are linked to climate data, orientation, air change rate, facade materials and wall composition.

Exchanges between the interior and exterior environments take place through the building envelope, some of whose key design parameters include lighting, ventilation and heat flux. Improving this envelope can greatly reduce environmental impact, ensuring indoor environmental quality.

This analysis confirms the need to consider the interactions among the parameters studied, as it shows that there are several design solutions with similar impacts, which can be adapted to project requirements. In both new construction and rehabilitation, some of these parameters may be determined by other design decisions not necessarily aimed at reducing environmental impact, so it can be very useful to be aware of a variety of design alternatives that can be implemented in specific projects.

Keywords: energy efficiency, facades, design strategies, social housing, fossil fuel depletion, climate change,

1. Introduction

A key to achieving zero-emission housing is reducing heating and cooling demand. Reducing the energy buildings use and the CO_2 emissions they produce is an action already included in many short- and long-term plans and programmes. On an international level, the objective of zero-energy residential buildings set by the European Commission for 2019 [1], and the US DOE’s Building Technologies Program, whose primary aim is to achieve marketable net-zero-energy commercial buildings [2], are clear examples of this. Uihlein [3] states that “*in a scenario in which the renovation and refurbishment of windows, wall insulation and roof insulation is always performed according to the cost optimal energy efficiency level, an additional 25 % to 40 % of energy for room heating and associated greenhouse gas emissions can be saved compared to the savings* *expected from existing and already formally proposed EU policy instruments. In this scenario the energy cost savings outweigh the additional capital investment after about 10 to 15 years."*

The IDAE [Spanish Institute for Energy Diversification and Saving] [4] estimates that final household energy consumption in Spain is 7 894 kTep for heating (2 790 kTep petroleum products, 1 588 kTep gases, 1 452 kTep electricity, 2 043 kTep renewable), 4 564 kTep for DHW, 2 423 kTep for appliances, 1 140 kTep for cookers, 671 kTep for lighting and 139 kTep for air conditioning (electricity), which represents 48 % of the consumption used for heating and cooling. Improvements to the building envelope can considerably reduce the environmental impact caused by this consumption and ensure indoor environmental quality, as this envelope is the medium through which the exchange between the interior and the exterior takes place, where lighting, ventilation and heat flux are key design parameters. The envelope also has a significant influence on the flows of matter and energy contained in materials (roofs and facades), as it accounts for 18,5 % of the emissions, 20,4 % of the energy and 28 % of the weight of the building materials [5].

This paper presents a preview of the work being carried out and analyses the role of the facade as a key to managing these energy flows. Multiple factors are involved in the design and behaviour of facades [6] (climate, orientation, size and composition of openings and walls, inertia, transmittance, building technology, sun exposure, ventilation, interior temperature, light, noise and so forth), and the relationships among them are complex. This analysis focuses on the impact of a number of facade design parameters on energy demand, including the energy needed in the use stage and embodied in the materials.

2. Methodology

To limit the facade study to the scale of a building component, a typical geometry was considered: that of a dual-aspect flat, in which both horizontal surfaces and two of the vertical ones would be in contact with spaces with identical use conditions. Its net floor area is 78,7 m^2 (the area of an average flat in Spain [7]), its volume is 208,69 m^3 and the facade area in contact with the exterior is 39,75 m^2. To study energy demand, certain fixed parameters were established, and the changes caused by a series of variables (shown in Table 1) were analysed. These variables are:

- **Location:** Twelve provincial capitals were chosen to represent the different climate zones in Spain, according to the combinations of winter (SCI) and summer (SCV) climate severity [8] shown in Fig. 1.

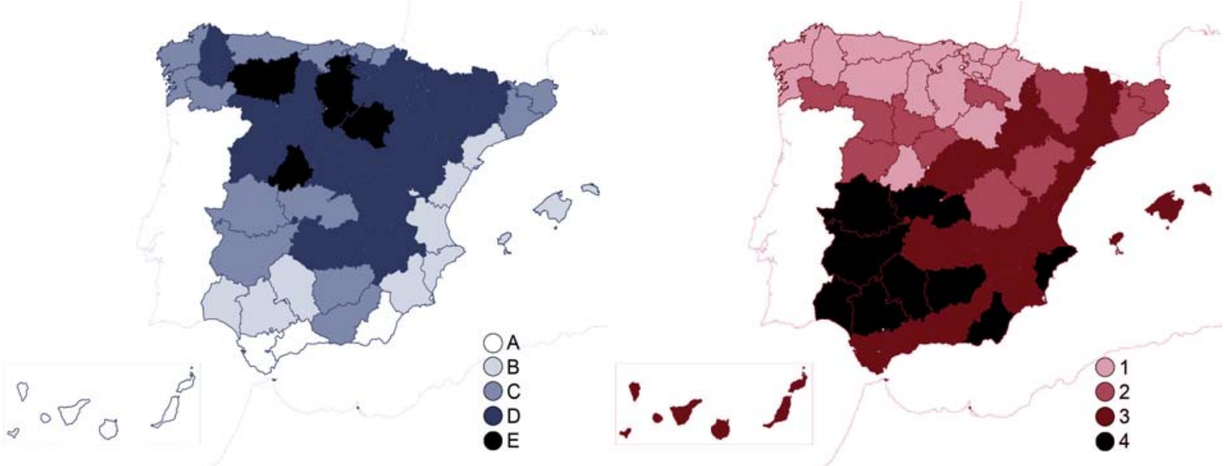

Fig. 1. SCI (A,B,C,D,E) and SCV (1,2,3,4) in Spanish provincial capitals

- **Orientation:** The following orientations were used: 0º, 90º, 135º, 180º, 225º, 270º.

- **Ventilation:** The room air change rate was also included as a study variable, with the Passive House standard [9] of 0,6 changes/hour being used as the reference value. Two other values were added, one higher (1,0 changes/hour) and the other lower (0,2 changes/hour).

- **Facade composition:** To limit the number of cases, the following facade treatments were used, differentiating between the blind part (wall) and the openings:

Location (climate zone and reference city)	Orientation (degrees)	Ventilation (changes/hr.)	Wall (type)	Opening (type)	O/W in A (opening %)	O/W in B (opening %)	Sun exposure
A3 Malaga	0	0,2	M1	H1	10 %	10 %	Yes (1)
A4 Almería	90	0,6	M2	H2	20 %	20 %	No (0)
B3 Valencia	135	1	M3		40 %	40 %	
B4 Seville	180				80 %	80 %	
C1 Bilbao	225						
C2 Barcelona	270						
C3 Granada							
C4 Badajoz							
D1 Pamplona							
D2 Valladolid							
D3 Madrid							
E1 Leon							
12	**6**	**3**	**3**	**2**	**4**	**4**	**2**
							Number of cases: 41 472

Table1. Summary of variables considered

Wall type: A wall with U=0,3 W/m²K with three different compositions was used, all with the insulating material on the outside. In this case, the solution adopted is between the Passive House design standard [9] (U=0,15 W/m²K) and the maximum currently established by Spanish standards for the most severe climate zone (zone E, U= 0,74 W/m²K). The main difference between them is the amount of mass inside the exterior wall: M1, insulation+mass, which corresponds to the most conventional facade, bearing in mind current building practice in Spain; M2, primarily comprising insulating material, representing a lightweight, insulating wall; and M3, with greater mass inside the wall, and therefore higher inertia.

Opening type: Two types of opening were used, both with aluminium joinery: H1, in which the thermal transmittance values of the glass and the frame are 1,6 W/m²K and 3,2 W/m²K, respectively (1,76 W/m²K average transmittance), and H2 with 3,3 W/m²K for the glass and 5,7 W/m²K for the frame (3,54 W/m²K average transmittance). The percentage of the opening covered by the frame was considered to be 10 % in all cases.

- **Opening/wall percentage:** The size of the openings acts independently as a variable in both facades. Four cases were selected with openings representing 10 %, 20 %, 40 % and 80 % of each facade, resulting in combinations where openings cover 10 %, 15 %, 20 %, 25 %, 30 %, 40 %, 45 %, 50 %, 60 % and 80 % of the surface of the two facades.

- **Sun exposure:** In analysing the different cases, data on the solar collection that takes place through the glazed openings was also used. Two further variables were added to the study: with and without solar collection.

The main methodological reference used was Nemry's study [10], which provides European-level data regarding the potential for reducing environmental impact in residential buildings. The functional unit of said study is the use of 1m^2 of living area over a one-year period. Five potential impact categories are quantified, and primary energy (renewable and non-renewable) and cost efficiency are also analysed. In Nemry's study, a database and software program were used to calculate demand and the life cycle of the materials. For this study, the LIDER program [11] was used to calculate energy demand in the use stage; while it is not a thermal analysis program, it does calculate building demand under the standard conditions required for energy certification in Spain. Furthermore, it was decided to estimate the impact of embodied energy for different materials based on information in the BEDEC database [12].

Study limitations:
Isolating the facade as the element under study means that other parameters that might influence the results are disregarded.
Heating and cooling demand results are the ones furnished by the LIDER software, which has its own calculation limits.
The data on the embodied energy of materials is widely disparate; therefore, the results may also vary, depending on the source used.
The building systems chosen for the walls are solutions with a high level of insulation that are not used in normal practice; even so, they are not up to the level required by the most restrictive standards.

3. Analysis of results

Combining the different variables gave rise to 41 472 cases with their respective results. This item will analyse the impact of the parameters on the flat's energy demand.

3.1 Heating (Q_{heat}) and cooling (Q_{cool}) demand (Q)

In all cases as a whole, the results for total demand ($Q= Q_{heat} + Q_{cool}$) range from no demand at all ($Q= 0$ KWh/m^2) to $Q= 93$ KWh/m^2, with a mean of $Q= 30$ KWh/m^2. The distribution, which shows a slight shift compared to a normal one, is included in Fig. 2. Without taking into consideration any obstructions that block the sun, whether remote obstacles or elements of the building itself (sun exposure=1), demand ranges from $Q= 88{,}5$ KWh/m^2 for the worst case to $Q= 1{,}6$ KWh/m^2 for the one with the lowest consumption, although both the mean and the median are around $Q= 30$ KWh/m^2.

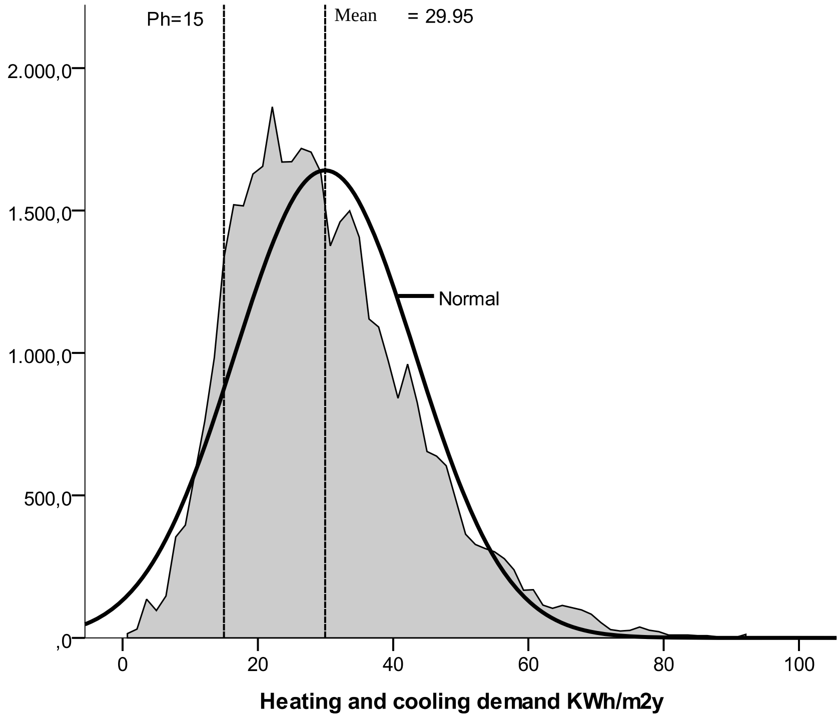

Fig. 2. Frequency of energy demand (Q) for all cases studied as a whole (KWh/m^{2}y)

As a reference, 10,1 % of the cases analysed would be below the maximum demand for compliance with the Passive House standard [9] ($Q= 15$ kWh/m²y), 46,9 % of which would correspond to 0,6 changes/hour, 42,4 % to 0,2 changes/hour, and 10,7 % to 1,0 changes/hour.
In general, the parameters selected gave rise to heating consumption levels that were lower than the ones for cooling, with averages of $Q_{heat}= 13$ KWh/m^2 for heating compared to $Q_{cool}= 17$ KWh/m^2 for cooling, with asymmetrical distributions.

3.1.1 Climate zones

Climate zone obviously influences demand, as in colder zones the demand for heat is higher, and in warmer ones, cooling is in greater demand. In general terms, the city with the lowest overall demand was Bilbao (C1), as it had very little demand for cooling, and winters are only moderately severe. The city with the highest demand was Valladolid (D2), as its climate combines the most extreme summer and winter conditions.

3.1.2 Air change rate

A higher air change rate has a positive effect in that it decreases cooling demand; conversely, it has a negative influence because it increases the demand for heat (Fig 3). As these flats have natural ventilation, this air change rate varies according to the use conditions; therefore, a high degree of uncertainty is attached to this factor in the quantification of demand. Nevertheless, results of this type may serve as a reference for optimising ventilation in different cases, with the minimum requirement being the air change rate necessary to ensure that the interior environment is healthful throughout the dwelling.

3.1.3 Orientation/sun exposure

In all zones, the worse-case orientation is east-west (90º and 270º), followed by 135º and 225º. The best-case orientation is 0º and 180º, which would correspond to north-south. Although these orientations are generally the best ones, the influence of other parameters often means that demand is lower for less favourable orientations that it is for better ones. This is the case with the effect of the percentage of openings in facades A and B, which makes it possible to adapt solar gain to different orientations. Logically, solar gain has a positive influence on heating demand and a negative one on the demand for cooling, decreasing demand in warmer places and increasing it in colder ones. The inclusion of such shade-giving elements as sunshades, which allow sunlight to enter in winter and block it in summer, would make the demand for heating and cooling favourable in both cases.

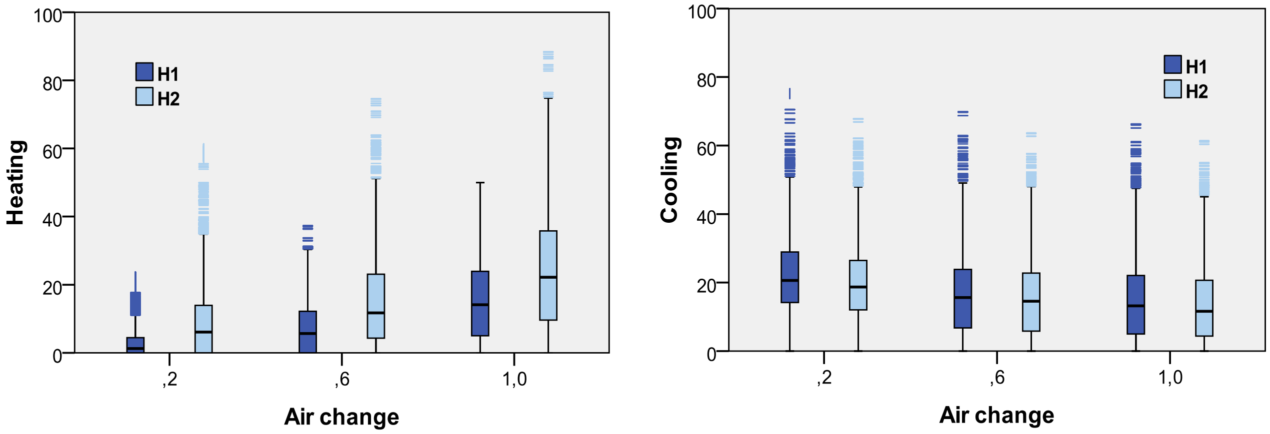

Fig.3. Heating (Q_{heat}) and cooling (Q_{cool}) demand (KWh/m^{2}y) by type of opening (H1, H2) and air change rate (h^{-1})

3.1.4 Type of wall/thermal mass

As there are three different compositions with the same thermal transmittance, the primary difference lies in the distribution of the wall mass toward the interior, which provides some information about the influence of the thermal inertia of this mass. Thermal mass has a significant effect on cooling loads, but not on heating loads. For cooling, the load varies throughout the day, while heating loads vary over the course of a year [13]. In any case, this mass has a positive effect on energy demand, and even more so when combined with other parameters, such as sun exposure and ventilation.

3.1.5 Opening type

This parameter is one of those with the greatest influence on heating demand. Gaterell [14] studied the potential impact of climate change uncertainties on insulation strategies in housing in the UK, mainly because of the variation in HDD and CDD. He concluded that double glazing is the strategy affording the greatest potential reduction in consumption. The potential for reduced consumption in the cases studied is in heating demand, as the opening providing the best insulation (H1) slightly increases the demand for cooling, as shown in Fig 3.

3.1.6 Opening/wall percentage

The main difference between these two types of facade elements (opening and wall) is their potential for solar gain and transmittance. The percentage of openings is closely linked to orientation (the potential for solar gain is greater if this percentage is higher) and composition (the larger the percentage, the more transmittance losses, as the blind part of both types of opening provides more insulation in the cases studied). An increase in the percentage of openings generally means an increase in both heating and cooling demand. For heating, the appropriate percentage is one where solar gain and transmittance losses are balanced, while for cooling, solar protection and ventilation are key parameters, as mentioned earlier. In any case, an increase in the proportion of openings in the cases analysed primarily increases cooling demand, even in cases where the sun is obstructed.

3.2 Embodied energy (P) of materials

The materials that comprise both the openings and the blind part of the facade are conventional ones used for construction in Spain, although the thermal resistance of the type of wall used in the study is higher than the norm, as mentioned earlier.

To compare the values for the materials with those for heating and cooling demand, the units are given per net square metre of floor space and per year, with the useful life of the materials considered to be 50 years. In the cases studied, the average value is 7 KWh/m^2y, including the blind part of the wall and the openings on both facades, although there are significant variations, mostly caused by the difference in wall mass and the proportion of openings in the wall. The difference in embodied energy for the solutions chosen more clearly illustrates the effects on demand.

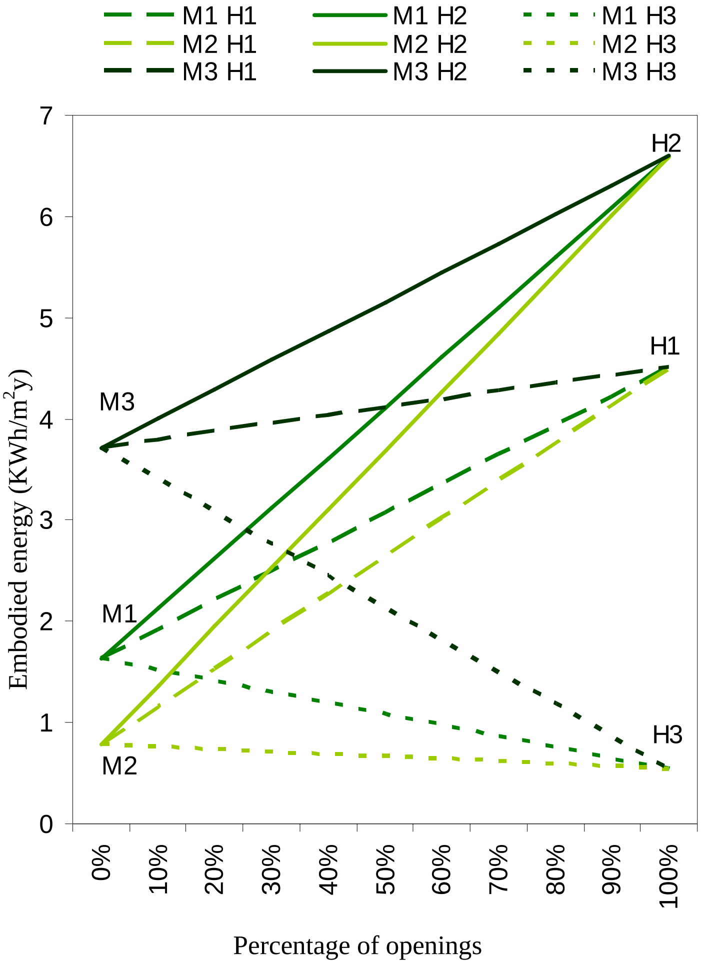

Fig 4. Embodied energy of the materials (KWh/m^2y) by wall and opening type, according to the percentage of openings in a facade (%)

3.2.1 Wall and opening type

The type of wall and opening are the basic parameters used to determine embodied energy, because, as shown in Fig. 4, they are the items that establish the position and gradient of the embodied energy, depending on the percentage of openings in the facade. In the cases studied, the differences in embodied energy make it possible to establish intermediate levels and estimates for other types of solutions.

3.2.2 Opening/wall percentage

The percentage of openings once again plays a decisive role, as the amount of material used for one component or another varies, depending on their proportion in the facade. If there is more embodied energy per wall area unit than is contained in the openings, then the way to reduce this energy would be to increase the percentage of openings; if the walls have less embodied energy, then the proportion of openings should be reduced. If the case of M1 H2 is used as a reference, it can be seen that the option with the least embodied energy is the one with no openings at all, as there is more embodied energy in the joinery than in the walls.

3.3 Heating, cooling and materials (P+Q)

In the cases studied, the average is P+Q = 37 KWh/m^{2}y, so the embodied energy of the materials (P) represents an average of 20 % of the total energy, compared to 80 % for heating and cooling, as shown in Fig. 5. A significant spread is seen in the distribution of this percentage of energy in the materials, and it shows a slight shift compared to a normal one, similar to the one shown in Fig. 2; it reaches 100 % in cases with no demand (Q) and is as low as 5 % in those with the highest total demand (Fig. 5). Bearing in mind the fact that the same embodied energy was taken into consideration for materials in all climate zones, the impact of the materials would logically be greater in those with more moderate climates.

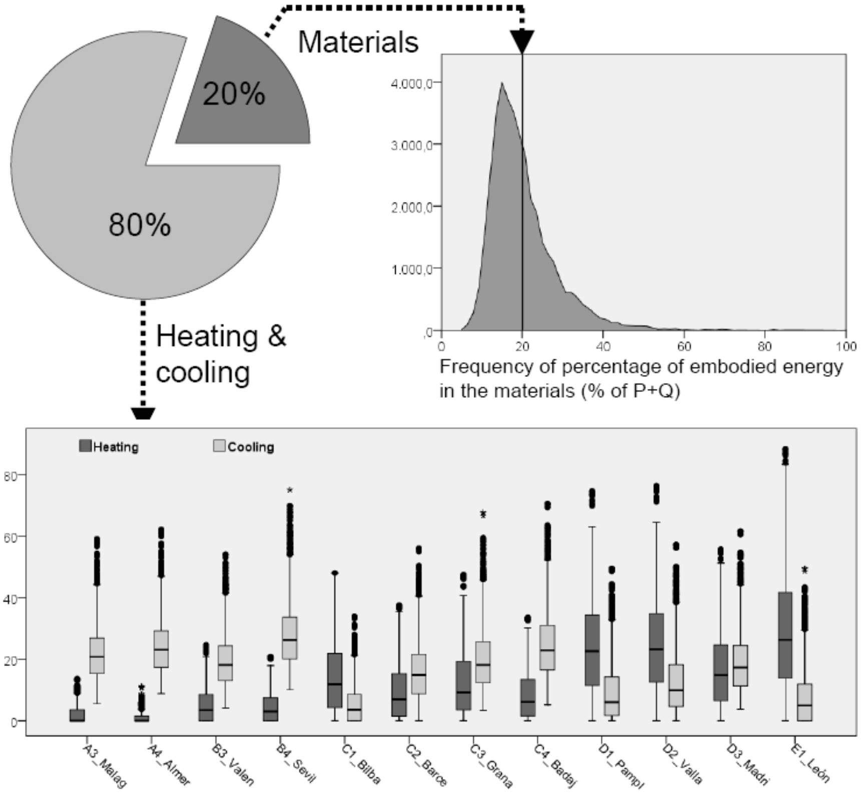

Fig.5. Heating and cooling energy demand (KWh/m^{2}y) in different climate zones and frequency of percentage of embodied energy in the materials (% of P+Q)

The percentage of openings is also a key factor in this case, as it affects not only end-use demand (especially for cooling), but also the energy in the facade. The differences with regard to the type of opening are less significant because of the initial choice of materials (H1 and H2).

For the wall composition with the highest embodied energy (M3) the average value is also higher, representing 26 % of the total. The next highest one (M1) averages 19 %, and the one with the lowest embodied energy (M2) accounts for 15 % on average of the total.

If cases are selected where consumption during the use stage is below 15 KWh/m^2, the impact of the embodied energy of the materials is greater than in all cases as a whole, averaging 33 %. In these instances with lower energy consumption during the use stage, the proportion of the embodied energy of the materials is logically greater, with 23 % for M2, 30 % for M1 and 43 % for M3, higher than the above percentages.

4. Discussion

In both new construction and rehabilitation work, some of the study parameters may be determined by other design decisions not necessarily aimed at reducing environmental impact. Therefore, it is necessary to be aware of a variety of design alternatives that can be implemented in specific projects. A database of heating and cooling results makes it possible to review case studies and obtain information on the best strategies for certain parameters. For example, for a specific climate zone or orientation, a range of values would be displayed for different strategies, such as the optimum proportion of openings, or the need for glass with better insulating properties.

Some of the variables analysed, such as the air change rate and the size of the openings, are directly related to the indoor environmental quality. If these parameters are established to meet use requirements (ventilation and lighting), significant variations would be seen in the energy demand data, so it would be possible to choose the best options based on the combination of the remaining variables. Room air change is one of the most influential factors in quantifying demand. For dwellings with natural ventilation, a standard of behaviour is difficult to quantify.

5. Conclusions

Because of the wide range of scenarios faced by the construction industry, and in particular the rehabilitation sector, simple solutions geared to different design determinants must be found. In this study, a series of specific cases was analysed with the aim of arriving at some general conclusions to assist in the identification of appropriate strategies in each climate zone. However, it is also evident that different building solutions can be found for certain design determinants that are less likely to reduce energy demand, such as a poor orientation or a lack of sun exposure.

The impact of certain construction parameters and of facade design on a dwelling’s energy demand was also studied, and it was concluded that the interactions among these parameters are essential to quantifying demand. This confirms the need for comprehensive consideration of the different variables. For example, one of the variables with the greatest impact on both end-use demand and on the demand for materials is the proportion of openings in the facade, where variations in energy demand depend on other factors such as location, orientation, sun exposure, or wall or opening type.

There are also other variables that were not considered that may significantly influence the results, as they also affect the behaviour of facades. These might include parameters relating to user behaviour (such as interior temperature), to the building system itself (such as thermal bridging), or those that affect other construction elements (such as the roof or the part of the building envelope in contact with the ground). Therefore, it is especially important to take the limitations and uncertainties set forth herein into account.

This study did not attempt to relate energy consumption during the use stage of a building to specific building systems; in other words, it is not intended to reflect heating consumption per unit of insulation or mass, to give an example. Other types of consumption in which the facade plays an important role, such as lighting, were also not taken into consideration at this time.

To translate this energy demand into consumption and carbon emissions, the efficiency of the systems that generate and supply the required energy must first be determined. These systems have not been considered in this research, nor have parameters relating to end-use behaviour and management.

One proposal to complete the study on primary energy consumption from a life-cycle perspective would be to compile data on the energy used for the transport, construction and treatment of waste materials from these building systems and propose different end-of-life scenarios.

6. Acknowledgements

This study forms part of the project AS51-08 “*Estudio especial relacionado con las propuestas de vivienda de protección oficial*” [Special study relating to social housing proposals], funded by Prointec S.A. through a cooperation agreement with IETcc.
Daniel Jiménez (IETcc) assisted in gathering and processing data using the Genede energy demand optimisation program, currently under development.

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